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Chamonix 2011 Workshop on LHC Performance

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During the Chamonix 2011 workshop on LHC performance, topics relevant to take decisions to guarantee efficient and safe exploitation of the machine both for the run 2011 and for the long term have been discussed. After a review of operations and achievements during the last run, two sessions focused on the preparations of the long shutdown required to prepare the LHC for operation with 14 TeV center of mass energy with particular attention on the impact of delaying this upgrade to 2013. Sessions on possible beam energy and luminosity aimed at optimizing the performance for the run of this year. Furthermore, the topics underground interventions, safety aspects comprising the performance of the access system and radiation monitoring and radiation to electronics have been discussed. Finally, upgrades of both the LHC the injector complex to guarantee efficient exploitation and to maximize the total integrated luminosity over the life-time of the LHC have been reviewed.

This workshop was an open exchange of views and opinions. The views expressed in individual presentations do not necessarily represent those of the management.

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CHAMONIX’11 SUMMARY: PROPOSALS FOR DECISIONS

S. Myers (Chair), F. Zimmermann (Scientific secretary)

CERN, Geneva, Switzerland

Abstract

The summary session of the LHC Performance Workshop in Chamonix, 24-28 January 2011, synthesized one week of presentations and intense discussions on the near- and long-term strategy for the LHC. In particular, Chamonix’11 discussed the timing and activities of the first long shutdown, the choice of beam energy for 2011, the 2011 beam-operation goals and schedule, the strategy for the longer-term LHC luminosity upgrade, the injector performance, as well as plans and options for the injector upgrade. Other workshop themes included a review of the LHC beam operation in 2010, with suggestions for possible improvements, as well as issues related to machine protection and intensity limitations.

We report the proposals for decisions which have emerged at this workshop.

INTRODUCTION

The LHC Performance Workshop at Chamonix is a technical meeting which proposes recommendations to the CERN Directorate. These recommendations are considered by the management, which also takes into account recommendations/advice from the CERN Machine Committee before making its final decisions.

The 2011 LHC Performance Workshop was organized in nine sessions, covering a review of 2010 operations, the planning and activities for the first long shutdown (two parts), the choice of beam energy for 2011, beam-intensity issues, machine protection in 2011 and beyond, the running plan and luminosity expectation for 2011, the high-luminosity LHC (HL-LHC), and the LHC injectors upgrade (LIU).

These were followed by a summary session featuring reports by the session chairs and secretaries, and by an overall synthesis of the Chamonix workshop containing proposals for decisions. These latter proposals are summarized in this report.

POINTS AWAITING DECISION

Two important items needed a (proposal for) decision:

(1) The operation after 2011, and the impact of a delay in the first **long shutdown** (“LS1”) from 2012 to 2013, concerning issues such as radioprotection (ALARA etc.), maintenance requirements, impact on future projects, and the effect on the following long shutdown (“LS2”; originally planned for 2016).

(2) The LHC performance in 2011, in particular the **maximum safe beam energy** and the **luminosity** (both peak and **integrated**, with a baseline goal for 2011 still equal to 1 fb^{-1}). The luminosity performance will be determined by the number of bunches, the bunch spacing (possibly limited by electron cloud, bunch instabilities, scrubbing, ...), the intensity per bunch (determined by the injectors, beam-beam effects, impedance and instabilities, …), the values of beta*, and crossing angles, with additional constraints and impact from collimation, machine protection, “unidentified falling objects” (UFOs), single-event upsets, and radiation to electronics, as well as by how ALICE and LHCb will be operated at low luminosity.

2012: PHYSICS OR SPLICES?

All relevant **technical issues** were reviewed. Concerning radioprotection, ALARA considerations with regard to a 1-year delay in the shutdown have turned out not to be a serious issue. For the splice consolidation, postponing the shutdown is beneficial both from the technical and from the resources points-of-view. For the cryo-collimation project the one-year delay would be essential. For kickers and dumps the delay is beneficial too. However, for **CV and EL**, a **delayed maintenance may reduce reliability**. As a possible mitigation for the latter, the possibility of carrying out maintenance during an extended Christmas Technical Stop will be studied. For access and alarms the delay is overall beneficial. The experiments also are in favour of the delay. In addition, they would appreciate a **new 10-year plan** including Christmas/Technical Stops. The CMS activities presently foreseen for the first long shutdown require a 15.5-months stop plus possibly 2 additional months for bake-out.

Postponing the “2012” shutdown (LS1) to “2013” will delay the work to be done in LS1 by one year, may allow some tasks already scheduled for the second long shutdown LS2 (2016) to be advanced to LS1 (**injectors, LINAC4, collimators with integrated beam-position monitors, detectors**, ...), will increase the need for maintenance and repairs to allow for efficient running through 2012 (EN/CV...), and may necessitate an increase in the duration of the technical stop over Christmas 2011-12.

Consequently postponement of the LS1 should be accompanied by a change in the date of LS2 as well as by modifications to the frequency and duration of the Christmas and technical stops.

The proposal, therefore, is to “do physics in 2012”, BUT at the same time to study the maintenance and repairs needs for such a long running period (2009-2012), e.g., considering how CV/EL maintenance could be carried out during the Christmas stop in 2011-2012, to make a new 10 year plan including all shutdowns and technical stops (LMC + experiments), and to try to keep to a minimum the duration of the shutdown in 2013, with a **critical review (in June 2011) of the need for including the cryo-collimation system in the LS1 shutdown and of the possibility to delay it to LS2**.

Comments and discussion on the long shutdown:

The first proposal for decision is to run in 2012. This proposal raises the issue of impact on the injector complex [1]. The injectors will have been running for 4 years. Injector maintenance indeed is the reason why 3-months Christmas stops are needed [2].

It is also important to know whether in 2013 the injectors will be running or not. With the dedicated LHC filling mode, less time is available for injector machine developments (MDs). Running the injectors without the LHC in 2012 would, therefore, be very useful for the injectors and the pertinent MDs [3]. Unfortunately, the financial impact demands to halt the full CERN accelerator complex when stopping the LHC [4]. In addition there is the issue of man power required the LHC shutdown activities [5]. However, at the end (and start) of the long shutdown there would be about a month of tests for hardware commissioning without the LHC beam; the injectors could use this time for MDs [6].

The consolidation work in the long shutdown should be done properly to avoid future similar discussions [7]. It is suggested to do the consolidation job of LS1 properly, and ideally aim to complete it within 9 months [8]. When consolidating splices, quality is of uttermost importance. The time of the consolidation should be squeezed while maintaining high quality of workmanship [9]. All teams and efforts should focus on the consolidation of the interconnects. The manpower for the injectors is valuable manpower in this regard. In fact, the key people from the injectors are exactly the supervisors for the LHC shutdown work [10]. The long shutdown requires a lot of careful planning, as well as a global look at the resource allocations [11].

The collimation team is in favor of a review for its proposed shutdown activity; it is also looking at all the work to be done and at the question if the work foreseen for the collimation system can be completed on time. Earlier it has been said that the collimation work could be performed if the injectors were stopped [12]. The need of a collimation upgrade in 2013 should be reviewed [13].

Coordination between accelerators, experiments, and physics department is essential; interference and inefficiency have to be avoided [14].

2011 BEAM ENERGY

An important question is the **return for the risk** associated with a beam-energy increase in 2011. This is illustrated in Fig. 1. Raising the beam energy from 3.5 to 4 TeV would be equivalent to a 30% increase in luminosity.

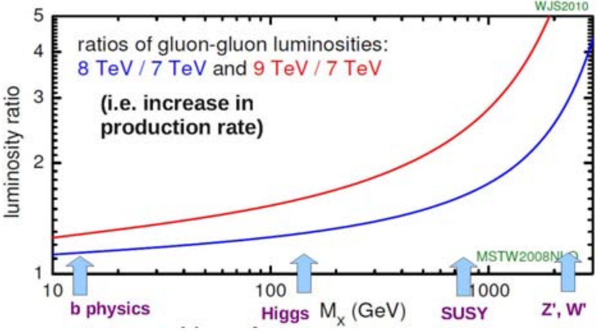


Figure 1: Effect of increasing the beam energy expressed as relative increase in production rate of various particles (James Stirling) [15].

The maximum safe beam energy is related to the **probability of burning an interconnect**, shown in Fig. 2, and to the consequences of a thermal runaway.

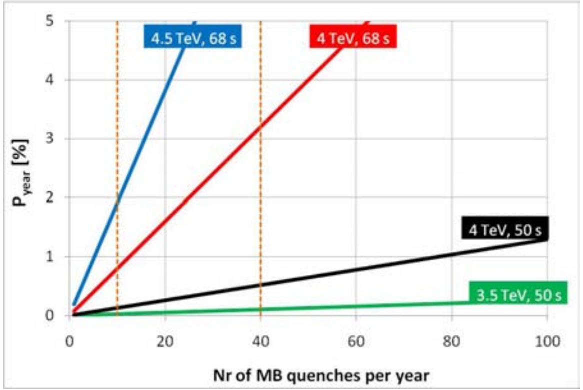


Figure 2: Probability per year of burning an interconnect as a function of the number of quenches per year [16]. The four lines correspond to three different beam energies and two different extraction time constants as indicated.

Operating with an extraction time constant of 68 s at 4.5 or 4.0 TeV implies a probability of a few percent per year for a thermal runaway, which is considered unacceptable. Therefore, the remaining choice is between 4 and 3.5 TeV with the present extraction time constant of 50 s. Going from 3.5 TeV to 4 TeV, at 50 s, still implies a significant increase in the risk of burning an interconnect. This risk is much higher than for any other component of the LHC machine, for example the beam dumping system [17].

The **impact** of an electrical arc in an interconnect is not negligible, even with the reinforcements and consolidation implemented after the 2008 incident [18]. Though the present consolidation, up to 5 TeV, will suppress **mechanical** collateral damages in adjacent sub-sectors, mechanical damage of the multilayer insulation (MLI) in the concerned sub-sector as well as contamination of the beam pipe(s) could require heavy repair work.

With the present consolidation status, a new incident will still imply a significant machine down time (8 to 12 months). PLUS a new incident would cause a severe damage to CERN's reputation.

An important question for judging the risk is the number of quenches expected. In 2010, there had been 20 quenches with current above 5000 A (none of which beam related).

Complementary issues with 4-TeV operation (at 50-s energy extraction time) include the possibility of interconnect quenches due to asynchronous dumps (affecting Sectors 5-6 and 6-7, which fortunately are two "good" sectors with little excess resistance), the UFOs (the event rate of which increases with intensity, whereas the magnitude of the UFO signal depends on the beam energy [19]). One dipole B30R7 (MB1007) has an insulation weakness which presently limits the maximum beam energy to no more than 4 TeV [20]. From the quench protection system, there is a strong preference to install and connect the snubber capacitors at the extraction switches, which will reduce the likelihood of false quench protection. The snubber connection will have little or no impact on the LHC set-up time.

The probability of another incident is relatively low but the impact would be high, i.e. the overall **risk factor is medium**.

In view of the above, and in particular given the unfavorable return/risk ratio of a beam-energy increase, the proposal is to **stay at 3.5 TeV for 2011**. Maintaining the same energy as in 2010 has the added small side benefit of a reduced need for luminosity calibration. The question has been posed if it would be a better risk investment to go for a lower beta* instead of for higher energy.

LHC should operate in 2011 with the "snubber" capacitors. The development of the "thermal amplifier" [21] during 2011 and measurements during the end-of-the-year shutdown will allow a decision about a possible energy increase for 2012, based on more solid information. The 2012 energy could then hopefully be even higher than 4 TeV.

Comments and discussion on the beam energy:

There are four positive facts that would support higher beam energy: revised value of copper-busbar RRR values, asynchronous dumps affecting two good sectors, installation of snubber capacitors, and efficient protection by the BLM system. One key information missing is the effect of the diode on the thermal runaway threshold. A decision could be taken after the measurements on a "good" dipole magnet [22].

From the experiments' point of view a higher energy is obviously better. The ATLAS representatives came to Chamonix'11 to support the idea of a higher energy in 2011. However, operating at 4 TeV would entail more risk than gain. This additional risk does not seem to be justified [23]. This is not only a question of the by-pass diode. There is no news about the splices, the time development of which is unknown. Also UFOs may limit the LHC in 2011. The ATLAS representative's point of view is not to take the risk of 4-TeV operation [23].

The big difference in risk factors for the interconnect burnout and for other LHC systems is striking [24]. The LHC beam dump system complies with security integrity level (SIL) 3 or 4, implying the probability of a catastrophic beam dump failure to be one event every 10,000 or 15,000 years [25]. The much higher risk from the splices is an anomaly [24] for the LHC machine, where otherwise SIL3-4 is the standard [26]. The damage to CERN from a second incident would be tremendous [27]. In any case it may not be possible in 2011 to operate at energies higher than 4 TeV due to a weak dipole magnet [28]. (The weak dipole could possibly be fixed, however.) Snubber capacitors will be installed and connected in any case; the discharging circuit will be modified etc. [29].

There were 20 quenches in 2010. Would the probability-related counting for this year start at 0 or at 20? [30]. More precisely, in 2010 there were 11 high-field quenches, and a total of 20 quenches above 5 kA current. The numbers should indeed be accumulated from year to year [31].

RUNNING IN 2011

The **number of days in 2011 available for LHC physics** is a concern. In a first assessment, from 262 days in total dedicated to LHC proton operation, after subtracting all other needs, less than half are left for high-intensity physics operation, as is illustrated in Table 1. This list will have to be refined and the cost in integrated luminosity be specified. It will be tried to improve the overall efficiency and to still perform all the necessary tasks shown in the list.

Table 1: Tentative beam-time allocation to various commissioning steps and to high-intensity physics proton operation, for the 2011 LHC run [32,33].

item	days
total *p* OP – 37 ½ weeks	262
11 MDs (2 days)	-22
6 TS (4+1 days)	-30
special requests	-10
commissioning	-28
intensity ramp up	-40
scrubbing run	-8
total HIGH INTENSITY	124

Start-up scenarios are under development. The most likely sequence is 75-ns beam re-commissioning, followed by scrubbing with 50-ns beam, and then either 75 or 50-ns operation. The recommissioning with 75 ns bunch spacing should take about 3 weeks. Next, increasing the number of bunches to about 300 will require another 2 weeks and scrubbing with the 50-ns beam, when needed, will take 1.5 weeks more. After the scrubbing experience the decision will be taken to go back to 75-ns spacing or to continue at 50 ns. In the following 50 or 75-ns operation the number of bunches will be further increased, during roughly 2.5 weeks, from 300 over 400, 600, and 800 to 936 or 1404 bunches, including machine protection and operations qualification. Physics operation can then proceed at 50/75 ns with either 936 or 1404 bunches, respectively. As a back-up, e.g. in case of strong electron-cloud effects, one could restore the 150 ns operation, which would require a couple of days.

An alternative sequence would be to start at 150 ns for the beam re-commissioning, then to scrub with 50 ns, and finally to go to 75-ns operation. Yet other bunch-spacing sequences would be "50-ns beam re-commissioning – scrubbing with 50 ns – 75-ns operation," or "50-ns beam re-commissioning – scrubbing with 50 ns – 50 ns operation."

Values of bunch intensity and normalized emittance at the exit of the SPS which have been obtained, or are predicted, for a bunch spacing of 150, 75 and 50 ns are shown in Table 2. The corresponding LHC parameters assumed for luminosity estimates are given in Table 3. For 150-ns bunch spacing, operation with 368 bunches, as listed in the table, was proven in 2010; it is expected that one should be able to go to 424 bunches.

Table 2: 2011 beam parameters at the exit of the SPS [32].

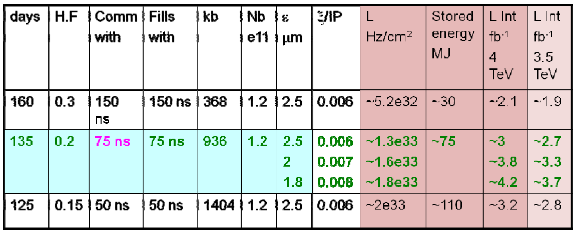
beam parameters	150 ns	75 ns	50 ns
bunch intensity [1e11 p/b]	1.2	1.2 (1-batch) 1.2 (2-batch) tbc	1.2 (1-b) 1.6 (1-b) 1.2 (2-b)
norm. emittance [µm]	2 (1.6 achieved)	2 ~1 to 1.5 tbc	2 3.5 ~1.5

Table 3: Beam parameters in the LHC assumed for 2011 luminosity estimates [32].

beam parameters	150 ns	75 ns	50 ns
bunch intensity [1e11 p/b]	1.2	1.2	1.2
normalized emittance [µm]	2.5	2.5	2.5
colliding bunches	368	936	1404

The **baseline luminosity goals for 2011 remain 2x10^{32} cm^{-2}s^{-1} (peak) and 1 fb^{-1} (integrated)**. But viewing the progress in 2010, there is some confidence to do better. Table 4 presents estimates of peak and integrated luminosity for different running scenarios with a bunch spacing of 150, 75 and 50 ns. According to this table, an **integrated 2011 luminosity of 2-3 fb^{-1} appears within reach**.

Table 4: Luminosity estimates for 2011, considering different operational scenarios and β^*=1.5 m [32].



days	H.F	Comm with	Fills with	kb	Nb e11	ε µm	ξ/IP	L Hz/cm²	Stored energy MJ	L Int fb-1 4 TeV	L Int fb-1 3.5 TeV
160	0.3	150 ns	150 ns	368	1.2	2.5	0.006	~5.2e32	~30	~2.1	~1.9
135	0.2	75 ns	75 ns	936	1.2	2.5 2 1.8	0.006 0.007 0.008	~1.3e33 ~1.6e33 ~1.8e33	~75	~3 ~3.8 ~4.2	~2.7 ~3.3 ~3.7
125	0.15	50 ns	50 ns	1404	1.2	2.5	0.006	~2e33	~110	~3.2	~2.8

Also for lead-lead collisions a substantial factor in luminosity gain is possible for 2011. Options for ion filling etc. will be clarified during the injector commissioning. The experiments are flexible.

The **year 2012** appears to be a g**ood opportunity for *p*-Pb collisions**, at an ideal centre-of-mass energy [34]. Otherwise it might be a long time before such collisions could take place. In addition, a feasibility test MD for *p*-Pb operation can be tried in 2011.

There is a request from ALICE to operate with the lead-ion design parameters already in 2011. More work on ion preparation will be needed in the first half of this year.

Comments and discussion on 2011 running:

The physics output before the end of 2012 should be optimized [35]. Intermediate physics targets were connected to summer physics conferences. In particular, the 2011 plan should aim at delivering physics output for the summer physics conferences of 2011. In view of this goal, the intermediate energy run at 1.38 TeV proton beam energy, presently foreseen for early 2011 [33], could perhaps be pushed to a later time [35]. However, ALICE has pointed out that this intermediate energy *pp* run is not meant for calibration purposes, but indeed important for physics. The run is presently scheduled so as to gather results in time for the Quark Matter Conference in May 2011. The main target is to provide a show case. About one third of the May-conference results depend on these results. According to information received by the accelerator team the intermediate-energy run is needed before May [36].

Contrary to the LHC plan for 2011, with 124 days of high-intensity physics planned, the Tevatron achieves about 260 days of physics per year. The LHC is a 21st millennium machine; why then might it run so few days for physics [37]? There are several answers to this question. First, the LHC has to serve four experiments with very different requests [38]. Second, the ratio of physics to non-physics days has also been quite different in the early year(s) of Tevatron operation [39]. The LHC is a new machine. Third, the LHC machine should be run in very well and at fastest possible speed, but at the same time machine protection should remain the highest priority [39].

The 2010 year of LHC commissioning was excellent and it provides a solid basis for 2011 and 2012 [39].

The CERN Directorate will carefully consider all Chamonix'2010 proposals, in particular those which did not find unanimous support [39].

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Special thanks go to Tjitske Kehrer for a superb organization, to Pierre Charrue and the CERN micro club for technical assistance, to the CERN Directorate, to the President of Council (Michel Spiro, attending the workshop), to the participating members of the CERN MAC, to the Session Chairs and Scientific Secretaries, to the Speakers, and, most importantly, to all the participants.

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Review of 2010 operations - DISCUSSION and SUMMARY

Malika Meddahi and Laurette Ponce
CERN, Geneva, Switzerland

LHC OPERATION - AS SEEN BY THE EXPERIMENTS (M. FERRO-LUZZI)

- **M. Lamont**: A comment concerning the possibility to use as well the intermediate energy run for EiC practice: as it will be low intensity and without squeeze, we will not practice the nominal sequence.
  M. Ferro-Luzzi: The question is more what is the reason behind the two weeks to increase intensity, is it to digest the data?
  M. Lamont: To ensure that all Machine protection checks are performed as agreed while increasing the intensity.

- **H. Burkhardt**: It could be quite challenging to reach 1-2% in luminosity calibration.
  M. Ferro-Luzzi: We should clearly not diverge from the physics program to reach this precision.

- **M. Lamont**: To comment on the “slow” ramp in intensity, it could be dictated by the e-cloud, and all other observations. We should proceed with care.

- **B. Goddard**:two weeks is already faster than what we did last year.
  M. Ferro-Luzzi: It is not clear to me why 100 bunches is so different to 300.

- **R. Schmidt**: Based on the experience of last run, a stable machine over a certain time is really useful to gain confidence. We should keep this in mind when discussing the planning.
  S. Myers: we have to choose between numerous sets of special runs or 5 fb^{-1}. We cannot do both. So it is probably better to concentrate all special runs in one period.
  M. Ferro-Luzzi: The priority is clearly for 5 fb^{-1}.
  S. Myers: After the technical stop, confidence has to be reestablished with the new parameters.

- **A. Siemko**: What is your data recording efficiency?
  M. Ferro-Luzzi: It is above 90 %, between 92 and 95% for ATLAS with 85 % for analysis.

- **S. Redaelli**: A comment on the handshakes, a lot of time is also lost during the ADJUST handshake and it should certainly be revisited.

- **M. Ferro-Luzzi**: As we should be able to dump the beam in any configuration, we can simplify the DUMP handshake, but it is a bit more complicated for the ADJUST as you have to guarantee the SAFE state of the detectors.

- **R. Assmann**: In your talk you mention that background is not a problem, but how far are we from the tolerance?
  M. Ferro-Luzzi: The background that OP can tolerate is already more strict than the specification for the experiments, it is difficult to quantify what is the tolerance for the experiments. ATLAS has seen some background from gas pressure increase but it should not be a lot of efforts to get rid of it.
  H. Burkhardt: ATLAS and CMS are high lumi experiments!

OPERATIONAL CHALLENGES (FEED FORWARD FROM EVIAN LHC WORKSHOP (M. LAMONT)

- **S. Myers**: Have we thought about working with a different tune value to avoid the hump?
  G. Arduini : The hump is continuously changing, crossing a large spectra over almost 0.25 units.

- **B. Goddard**: For the dedicated filling, we have to be careful not to put too much pressure on the injectors. We need time to check the parameters and we need more discussions and coordination between the various machines.
  K. Cornelis : Do not forget that the SPS spent some 20020 hours for filling the LHC, which represents half the year time.

- **R. Assmann**: We needed the transverse dampers for safe beam operation, and we also need to switch on octupoles.
  O. Brüning: We put the octupoles on purpose. Discussion on octupoles postponed to session 7 where E. Metral will cover the subject.

INJECTION - ISSUES AND POTENTIAL SOLUTIONS (V. KAIN)

- **B. Dehning**: Is the shielding for un-captured beam not the first priority?
  O. Brüning: Is the need of sunglasses for the BLM not an indication that thresholds are too low?
  E.B. Holzer: Some BLMs have filters but thresholds are already too high for circulating beam.
  B. Goddard: The time scale of the losses is typically

10 μs but it is propagating to all running sums.
R. Assmann: We should recall that there is no safety issue, TCDIs can support the load, so it should be possible to find a mechanics to cope with the problem.

- **S. Redaelli**: We have a quite aggressive scrapping in the SPS, so do we understand the tails at 4.5 σ in the transfer lines?
  V. Kain: The scrapping in the SPS is not fully understood and controlled. There could be also something wrong with the transverse blow-up.
  B. Goddard: The kicker wave is also visible for long batches.

- **P. Baudrenghien**: The experiments will just increase the thresholds for the BCM. Another comment concerning the possibility to have beam in the SPS while LHC is not master. It will be really useful to have the beam up to the SPS beam dump to tune the beam parameters.
  K. Cornelis: It is an machine protection issue, as if the LHC has the mastership, the triggering of the extraction is done by timing event only.

- **M. Lamont**: Can we over-inject over a nominal bunch? Where is the limit?
  B. Goddard: With 16 bunches on the TDI, we triggered the vacuum interlock, and vacuum valves went in.

VACUUM AND CRYOGENICS OBSERVATIONS FOR DIFFERENT BUNCH SPACING (J.M. JIMENEZ) AND BEAM OBSERVATIONS WITH DIFFERENT BUNCH SPACING AND OVERALL SYNTHESIS (G. ARDUINI)

- **L. Evans**: Why the high chromaticity is stabilizing single bunch instabilities?
- **F. Zimmerman**: The large positive chromaticity shifts the head-tail mode spectra with respect to the resonant frequency of the electron-cloud impedance, i.e. the electron oscillation frequency inside the bunch.

- **L . Evans**: What is the longitudinal Emittance, is it nominal?
  P. Baudrenghien: It was 0.6 eV/m.
  L. Evans: So it is quite small. We should increase it. We will always gain by reducing the peak current.

- **B. Goddard**: The plan for the scrubbing run assume 1.5 MJ injected in 3-4 days, it is very tough.

- **S. Myers**: If 25 ns is available, could we think about switching to a scrubbing run with 25 ns for a physics run with 50 ns?
  G. Arduini: We will probably not gain in efficiency because we have to first see what we gain with the scrubbing run and verify the model with the 50 ns scrubbing run. We also have less margin in changing the Emittance in the injectors with 25 ns, whereas we can try to push the emittance and change it during the run with 50 ns.
  M. Jimenez: The strategy used in October was the easiest one. We were injecting and while waiting the recovery of the pressure increase, we could optimize the parameters. This optimize the time to reach a stable situation. With the 25 ns, we will fight to keep the beam stable.

- **P. Collier**: We see that the scrubbing in the SPS is 2 times longer (SEY factor 2 lower in the SPS) than in LHC. Is it likely more difficult in LHC when SEY will decrease?
  M. Jimenez: It starts very fast and then needs more and more time (exponential decay). But during the ramp in the SPS, the orbit is moving a lot, which means that the cleaning is needed on a wider range or that the contamination is wider. It is not so favorable for SPS.

- **M. Ferro-Luzzi**: Can we already see a difference between cold and warm regions?
  G. Arduini: There is a largest weight on length for the cold part, for cleaning, we could go faster in the warm part.
  M. Ferro-Luzzi: Do we know the relative contribution to the emittance growth?
  G. Arduini: In dipole area, density is more in stripes. For tune spread, more sensitive to straight sections. For dipole, it is constraining the motion of the electrons. It is mostly the arcs which contributes to instabilities, the LSS contributes mainly to the emittance blow-up.

- **S. Myers**: Do we expect any benefit from scrubbing before stops? What could reduce the effect in the future?
  M. Jimenez: For the 100 m which have been vented, definitively, the benefit will be lost, but for the rest of the ring which have already been treated, there is no worry. For the stand-alone magnets, we have to be careful with the cool-down.

- **B. Goddard**: Do we expect the scrubbing done at 450 GeV to work at 3.5 TeV?
  G. Arduini: We observed last year that positive effect was seen at 3.5 TeV.

- **G. Arduini**: We have to observe carefully the effect in the region of the crossing angle, because of the change of the orbit.

B. Goddard: we should do the scrubbing with the final orbit, so that the stripe stays at the same place.
G. Arduini: At least we should check the effect of the orbit change.

- **O. Brüning**: Coming back to Evian Follow-up, do we have enough instrumentation with the cryo to observe the effect with high intensity beams?
  G. Arduini: The question is how far we can let the signal drifting at fix settings. There is another possibility to measure the heat load evolution in the arc by measuring the stable phase in the RF.

HOW CAN WE REDUCE THE ”NO BEAM” TIME? (W. VENTURINI DELSOLARO)

- **K. Cornelis**: Reviewing the planning of the technical stops could be a big problem for the injectors as there are a lot of MDs planned during theses periods
  M. Lamont: There is an quite aggressive MD schedule in the injectors, which indeed we have to consider.

- **S. Baird**: The principle of blocks during the run is also needed in preparation of the shut-down activities.
  M. Ferro-Luzzi: Concerning the experiments, I was surprised to get really few requests for access during the TS. For the experiments there are too many TS.
  P. Collier: there is no question to suppress the technical stops but to have a smaller number of longer stops.

- **F. Bordry**: Is the redundancy of the 60 A power converter really used?
  J. Wenninger: We had many cases where beam operation was continued without some 60 A converters. We will put in place an automated procedure to decide when one 60A is lost if we can continue without it or need to replace it right away.

OPTIMIZATION OF THE NOMINAL CYCLE (S. REDAELLI)

- **B. Goddard**: Are the fills lost because of bad manipulation not hidden in the statistics because the beam is lost? We also spent a lot of time at injection because of time to solve problems, the feedbacks, injectors, MDs...
  S. Redaelli: I tried to keep only the physics run in the statistics. This is representing the daily operation, not the MDs or other modes of operation.

- **R. Assmann**: A remark concerning the modification of the squeeze. If it is faster, the losses will also be faster so we should be ready to revert quickly to the last year functions in case of problems.
  S. Redaelli: We will take some fills to decide but then we will have to stick to that choice. The roll-back will be a significant effort. In 2010, the losses were below the percent level, and the beta-beat was a minor additional error.

- **M. Lamont**: Another improvement not mentioned is the removal of the spikes in current in the functions which were causing occasional trips of the converters.

- **B. Goddard**: The big advantage of having a unique function is the reduction of the human error factor.

- **R. Schmidt**: Are the spikes in loss maps observed during the squeeze at lower β^* linked to spikes in the functions?
  S. Redaelli: We did not establish a correlation with the lower β^*.
  R. Assmann: it could be related to β-beat spikes.

SUMMARY - OUTLOOK

A list of follow-up actions has been established from the different presentations.
In order to reduce the time spent at injection level:

- Beam quality and availability from the injectors
- Filling strategy
- Beam losses at injection

In order to improve the machine availability:

- Optimization of the ramp
- Turn around optimization pre cycle after short access approval of new procedure)

In order to improve the communication with experiments:

- Dump handshake procedure
- Data exchange (DIP): reliability to be improved

The approved manipulation during the end of fill studies have to be defined. The intensity ramping up strategy is to be approved. The bunch by bunch measurements for all beam instrumentation are mandatory. The list of Machine Developments will be done, together with priorities.
Concerning the reduction of the LHC time spent at injection level, an intermediate scenario is put in place for 2011, while a more robust solution is prepared for 2012. The intermediate solutions for 2011:

- Better communication and tools for better preparation of LHC beams
- 2 solutions will be prepared for over-injection : witness bunches or later over-injection

- Ready for exploiting dedicated physics cycles
- Continue the beam loss minimization campaign
- Use cleaning (abort gap and injection slot)

In preparation for 2012, efforts should be put on development of new type of LHC injection requests (number of PS batches and number of PSB rings on the fly.
Finally, for the Luminosity operation of the LHC, an optimum 2 hours nominal cycle is at reach. After the scrubbing period, the machine is expected to operate with 936 bunches, using 75 ns bunch spacing, with a machine efficiency between 0.2 and 0.3 during dedicated luminosity operation.

SUMMARY OF SESSIONS 2 & 3: SHUTDOWN 2012

S. Baird, K. Foraz, CERN, Geneva, Switzerland

Abstract

This paper summarises the two sessions, which were devoted to the activities planned for the next long LHC shutdown, which was originally planned to start in December 2011. The aim of the session was two-fold. Firstly to collect a reasonable idea of the major activities planned for the shutdown and secondly to highlight the potential impacts of delaying the shutdown by one year to 2013.

OUTLINE OF THE SESSION

There were 16 presentations covering the following topics: Testing for 7TeV operation before the shutdown, Radio-protection issues in case of a delay of one year, Splice Consolidation - what do we have planned and how will we do it, Collimator installation, Other cryo-magnet activities, R2E, Work planned in the experiments, Vacuum, QPS, Cooling and Ventilation, Electrical services, Access and safety systems, RF Kickers and dumps.

SESSION SUMMARY & CONCLUSIONS

The following questions will be tentatively answered: Which activities will drive the length of the shutdown? What could be a first estimate for the length of the shutdown? What are the critical activities which will be affected if we delay the shutdown from 2012 to 2013? The open issues highlighted during the sessions will also be addressed.

Critical activities, which drive the length of the shutdown

The activities presented are divided into two categories; those which are essential to allow high intensity operation at a beam energy of 7TeV and those which are necessary to ensure reliable operation of the LHC for physics at 7TeV.

Activities to allow high intensity operation at 7TeV

Since the energy of the beam is limited by the excess resistance in certain interconnections, the consolidation of the splices and the repair of cryo-magnets are essential to run at 7TeV. Moreover, the upgrade of the collimator systems (additional collimators in dispersion suppressor areas, and the upgrade of the existing phase 1 collimation system) will allow the machine to be operated at nominal beam intensity. In order to reach these nominal beam performances, the Radiation to Electronics (R2E) mitigation measures are also essential, in order to increase the Mean Time Between Failure for radiation induced failure in electronics installed underground.

The activities in the experiments should also be considered as vital for high intensity operation at 7TeV, as it is pointless to upgrade the machine without upgrading the experiments to fully exploit the improved LHC performance.

Finally, the plans to test LHC systems (except the main circuits) to 7TeV levels before the shutdown is very prudent as it would allow sufficient time for any repairs

Activities to ensure reliable operation of the LHC for physics

In order to ensure reliable LHC operation we must ensure that all the machine services are in the best possible operating condition. These services are principally Cryogenics, Electricity Distribution and Cooling & Ventilation systems. These systems need regular maintenance, which has been reduced over the last three years to minimise the LHC shutdown time. It is vital to allow the sufficient time for a full maintenance of all these systems. On top of this, all the other machine systems will need full maintenance and in many cases improvements/upgrades are planned.

During the last two years a number of weaknesses have been identified in the LHC systems. Some, such as the QPS, have been or are being corrected and improved. Others, such as the UPS systems and the redundancy of cooling and ventilation systems for the LHC cryo-plants as well as the CCC computing facilities can only be completed during the long shutdown.

Table 1: Time estimates for individual activities

Splice consolidation work in tunnel	minimum 12 months
Cryo-magnet repairs	8 – 10 months
DS collimator installation	12 months
Complete Cryo-plant maintenance	14 months
R2E activities	15 months
Work in experimental caverns	15 months

How long should the shutdown be?

Table 1 shows the time estimates taken from the longest activities. In order to accurately estimate the minimum length for the shutdown, we need not only to look at the length of each task, but also to consider the potential interference between the tasks and the underground logistics. This will mean that where activities cannot be executed in parallel, additional time and/or resources will be needed. The fact that the same expert resources will be needed for several different activities is also a bottleneck (see later section on Open Questions). One important hypothesis taken into account is that the overall length for the shutdown is based on the "activities to allow high intensity operation at 7TeV", while assuming that the activities to ensure reliable operation of the LHC" will fit inside this overall length.

The very approximate "plan'' is shown in Figure 1 and this gives a first estimate for the shutdown length of 19 months. The length is defined as the period from "beam off" to "beam on", including the time to warm-up and cool-down the sectors as well as a two month hardware re-commissioning period, but excluding the full beam commissioning and set-up period. 19 months are considered as a minimum in view of the extensive amount of work planned.

It should be emphasised that the co-activity has been included in a very approximate manner (the time for the splice consolidation was increased from 12 to 14 months to fit with the time required for the full cryo-plant maintenance). Also the shortfall in specialised expert manpower has not yet been included. This will have to be done.

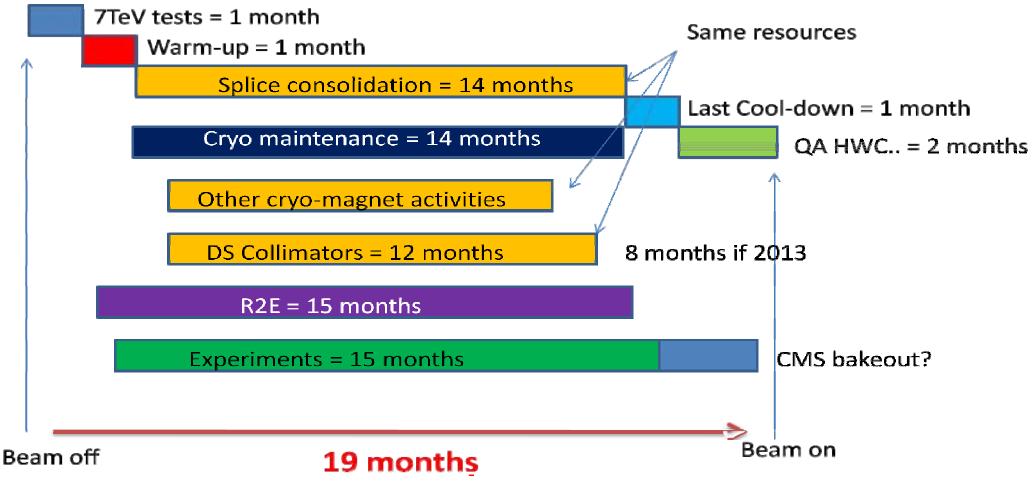

Figure 1: First estimate for the length of the shutdown, using the activities considered as critical. This does not include any real analysis of co-activity or any resource/manpower considerations

2012 or 2013?

The second question looked at during these sessions was what would be the consequences of delaying the shutdown from 2012 to 2013. Table 2 summarises these consequences.

There are a certain number of risks in delaying the shutdown, these risks concern mainly the maintenance of electrical, cooling and ventilation systems. There is also a question for the reliability of beam operation in 2012, if the R2E mitigation measures are not implemented. The question here is "Will the number of R2E induced failures expected disturb beam operation?" The answer to this question was not clear. Therefore it was not possible to really estimate the risk of continuing in 2012 from an R2E perspective. The answer seems to be "it should be just OK".

There are a certain number of advantages to delaying the shutdown to 2013. The full DS collimator hardware will only be available at the end of 2012; therefore a shutdown in 2013 allows more time and flexibility for installation. Similarly the delayed shutdown would allow more time for system development prior to installation. This was considered as important by the kicker and the access system teams. The R2E mitigation measures would also benefit from a delayed shutdown if it is necessary to plan for major underground civil engineering to displace the safe-room at Point 7. It will not be possible to prepare this work in time for a shutdown in 2012. Finally it should not be forgotten that the experiments will benefit from delayed shutdown, by, hopefully, making major new physics discoveries.

Table 2: 2012 or 2013?

Preference for 2012	**Preference for 2013**
Maintenance of services. No full maintenance done since January 2009.	DS Collimator installation Late availability of hardware
UPS reliability	Kicker and safety systems Additional development time
R2E: Will SEU perturb beam operation in 2012?	Experiments New Physics discoveries
	R2E: Civil engineering for safe room at point 7

OPEN QUESTIONS

As stated previously, we have not included here the constraint of the limited amount of expert manpower available to do this work, and in particular the problem that this expert manpower will be needed for more than one of the major tasks. As an example, the Splice consolidation, cryo-magnet repairs, and the modifications for the installation of the DS collimators all need to same expertise from TE/MSC. Therefore they cannot be scheduled completely in parallel. This shortage of expert manpower will be a driving factor in the length of the shutdown. It is estimated that 200FTE will be needed for the underground work on the splice consolidation alone. Today only 2/3 of this manpower has been identified and even this assumes that there is no other work for these teams, which will certainly not be the case.

The same is true for the teams that look after the electrical systems and the cooling and ventilation services, where the expert supervision of external contractors will be needed in many areas in parallel. At the same time as all the maintenance and upgrade activities in the LHC, these teams will also have to work on the R2E equipment displacement, the upgrade of the electrical supply and cooling for both the CERN Computer Centre and the CCC computing facilities.

In addition it should not be forgotten that this long shutdown will also be the only opportunity to do major work on the LHC injectors. Such work could be important for the LHC Injector Upgrade project and for the overall Consolidation of the LHC Injector chain, but it will compete directly for the available resources with the work on the LHC itself.

A certain number of tasks were also mentioned, which it is not planned to do, due to lack of time and manpower. The most significant of these was the proposal not to replace the inverted beam screens in 12 Main Dipoles and 3 Short Straight Sections. These beam screens were installed after the incident of September 2008, as there were not sufficient spare beam screens of the correct type to insert in all the damaged magnets that were replaced. Including such tasks will almost certainly mean that the shutdown will take longer

SUMMARY

Based on our present knowledge of activities, the minimal length of the next shutdown is estimated to 19 months to perform the activities to allow high intensity operation at 7TeV, and those to ensure reliable operation of the LHC for physics. The delay of the shutdown by one year will allow more time and flexibility for installation, as well as for development prior to installation. Moreover the experiments will benefit from a delayed shutdown, by, hopefully, making major new physics discoveries. The risks of a delayed shutdown are related to long period of operation for vital equipment (without full maintenance) and the risks associated with Radiation to Electronics. Some questions and issues are still open, especially the ones concerning resources. These two sessions are the start point of schedule and resource studies to be performed in 2011.

ACKNOWLEDGEMENTS

The authors would like to thank all the speakers, who presented their information in a very clear and concise manner. These presentations stimulated a lot of interesting discussion during the workshop, and make an excellent basis for the schedule and resources study to be performed in 2011.

SUMMARY OF THE LHC BEAM ENERGY SESSION

A. Siemko, CERN, Geneva, Switzerland
M. Zanetti, MIT, Cambridge, Massachusetts, U.S.A.

Abstract

In this session, the possible scenarios for the beam energy in the LHC 2011 run were discussed. The benefits for the physics reach for physics operations at √s larger than 7 TeV were reviewed. The main goal was, however, to establish the necessary information for a sound risk analysis by assessing the probability of thermal runaway and evaluating the consequences of a hypothetical incident. A new technique to improve the knowledge of joint resistances of the cooper busbars and therefore the reliability of the risk analysis has also been discussed.

PHYSICS REACH AT √S ≥ 7 TEV

Most of the physics searches would profit from centre of mass energies higher that 7 TeV [1]. The cross sections for the interesting processes in fact increase as a function of √s. The gain is remarkably large in terms of sensitivity for high mass resonances (W' and Z') and generically for SUSY models. The raise for the Higgs boson production rate is computed to be roughly 20%. What really matters for the Higgs discovery is however the total integrated luminosity delivered to ATLAS and CMS. For example, with 5fb^{-1} of data at √s=8 TeV, each of the two experiments would have 3σ sensitivity in the whole Higgs mass range. The same performances are achieved with 6fb^{-1} of data collected at 7 TeV.

All the LHC experiments stated to be ready for operations at energies higher than 7 TeV. In addition, merging and analyze datasets recorded at different energies (e.g. at 7 and 8 TeV) would not be problematic for the experiments.

WHAT HAS CHANGED SINCE BEFORE THE 2010 LHC RUN

Several new or improved data are now available with respect to the past year Chamonix workshop:

- A dedicated campaign of the copper busbars RRR measurements has been carried out in the whole machine, assessing a minimum value not lower than 200. The latter has to be compared with the previous more pessimist assumption of 100.
- The quality of the superconducting splices has been demonstrated to be very good: all the splices have been measured by means of the nQPS system and the maximum excess resistance for the main quadrupoles and dipoles resulted to be 3.2 and 2.7 nΩ, respectively, i.e. 2 orders of magnitude smaller than the one causing the sector 34 incident in 2008.
- The computer simulations of the burnout limits now treat also the case of a quench caused by the heat generated by the pass-by diode and propagated through the busbar.
- Not a single non-intentional beam induced quench occurred during the eight months of 2010 beam operations.

COMPUTATION OF BURNOUT PROBABILITY

The probability of three kinds of events leading to the burn out of a joint has been considered: the heat generated by a quench of a main magnet propagating to the joint through the busbar (P_B) or through the gaseous helium (P_G) and the direct quench of the splice (P_J) [2].

Several assumptions stand at the basis of the simulation, some of which are still not fully defined/constrained as the heat propagation time through the gaseous He and the number of copper stabilizer joints characterized by an excess resistance larger than a given limit value. The latter still relies on a very limited (134 joints out of ~10000) set of direct measurements performed in 2009.

The three probabilities are computed for four possible operational scenarios: 3.5 or 4 TeV beam energy and 50 or 68 second energy extraction time constant. The overall probability of a burnout as a function of number of quenches per year is shown in the plot of Figure 1.

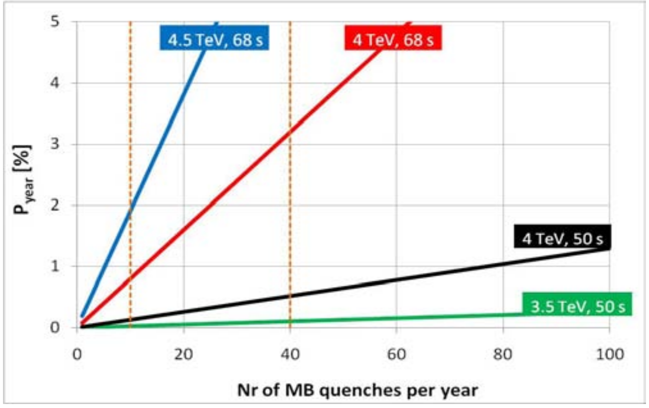

Figure 1: Probability of burnout as a function of number of quenches per year for the four scenarios considered in the simulation [2].

As ancillary information relevant for the analysis of these results, we remind that in 2010, due to various reasons, there were about 20 quenches of the RB circuits above 5 kA.

SUPERCONDUCTING CIRCUITS PROTECTION

The main challenge for the magnet quench detection system is to cope with the electromagnetic transients and the high inductive/resistive voltages caused by a fast power abort (FPA), involving switching off the power converter and activation of the energy extraction to the dump resistors [3]. The electromagnetic transients can cause spurious triggers both in the old and new QPS, with the consequent quench of a number of magnets. To remedy this effect, a delay has been added between switching off of the power converter and the energy extractions of the even and odd points of each sector. The snubber capacitors are being added in parallel to the switches to reduce electrical arching.

For a too short energy extraction time constant, the inductive voltage across a main magnet (U_{mag}) developed during a FPA could saturate the symmetric quench detection, leaving the circuit unprotected with this respect. Already at the current corresponding to 4 TeV with the actual time constant (52 sec), the nQPS operates in marginal conditions. For operations beyond 4 TeV, an increase of the time constant to 68 seconds is therefore necessary.

CONSEQUENCES OF A HYPOTETICAL INCIDENT

A critical study has been performed in the past year to review what would be the implication of an incident caused by an electric arc in light of all the consolidations and precautionary measures that have been implemented [4]. In particular the fault tree up to 5 TeV has been updated. It results that mechanical damages to adjacent sectors are highly suppressed; nonetheless the MLI still would be considerably damaged. Contamination of the beam pipes cannot be avoided too.

Considering all the activities involved (warm up/cool down, removal, reassembly and reinstallation of damaged magnets, pipes cleaning and vacuum restoration, conceivable assembly of a new DFBA, electrical qualification and re-commissioning), the repair of a damaged sector would require between 8 and 12 months.

OTHER CONSTRAINS FOR OPERATIONS BEYOND 3.5 TEV

Hardware Limitations

The non-conformities still present in the hardware of the machine have been reviewed; it resulted that none of them poses critical limitations for operations at energies up to 4 TeV [5]. A few points need to be tackled, in particular the HV withstand levels of the superconducting circuits needs to be reviewed including the cross talks between them. Several performance shortfalls can be addressed during the winter shutdown.

Beam Commissioning

The re-commissioning of the beams for energies higher than 3.5 TeV substantially does not require any additional effort with respect to what is already planned for resuming beam operation in 2011 [6]. If the decision of increasing the energy were taken later in the year, then around two weeks would be necessary to adjust the squeeze and the collimation setup. The time required by the hardware commissioning should be added to this estimate.

TOWARDS A MORE RELIABLE BURNOUT PROBABILITY ESTIMATION

The main input to the computation of the probability of a splice burnout is the condition of the copper stabilizer joints in the machine. At the moment the estimate of the percentage of joints with an excess resistance above a critical value relies on a very limited set of direct measurements. Defining a procedure allowing measure of the copper resistance that does not require the opening of the magnet interconnects is therefore of paramount importance to evaluate the maximum safe current. A procedure (Copper Stabilizer Continuity Measurement, CSCM) that can achieve that has been investigated in 2010 [7]. The CSCM method looks for anomalous thermal behaviour characteristic of the bad joints by injecting in the main circuits a few seconds long pulses of 2.7 kA with the sector kept at about 40K.

The qualifications of all the LHC sectors by means of the CSCM might well be performed during the next winter shutdown.

FOLLOW UP ITEMS

- F. Bordry’s proposal to perform a test to measure in situ the quench propagation time from the magnet by-pass diode to the interconnection splice.
- “R16 data analysis”, additional information is now available: a number of magnets and interconnections (extracted from sector 34) have been studied in the labs, more data are available and should be taken into account.
- Cooper Stabilizer Continuity Measurements project (so-called “thermal amplifier”). Measurement campaign to be prepared for the winter 2011-2012 shutdown.
- Commissioning of the snubber capacitors in all RB circuits during 2011 HWC campaign.

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DISCUSSION SUMMARY OF SESSION 5: HIGH INTENSITY: PRESENT AND FUTURE

R. W. Aßmann (Chairman) and S. Redaelli (scientific secretary), Switzerland

Abstract

This paper summarizes the discussions that followed the presentations of the “High Intensity: Present and Future” session at the LHC Performance Workshop, Chamonix 2011. The identified action items are also summarized.

INTRODUCTION

The fifth session of LHC Beam Commissioning Workshop was dedicated to the present and future of high intensities at the LHC and included six talks:

1) **Beam Cleaning and Collimation: Too Bad or Too Good?**, by Ralph Assmann (BE-ABP);
2) **Limits for Beam-Induced Damage: Reckless or too Cautious?**, by Alessandro Bertarelli (EN-MME);
3) **Radiation to Electronics: Reality or Fata Morgana?**, by Markus Brugger (EN-STI);
4) **Radiation Protection: How (radio)active are we going to be?**, by Stefan Roesler (DGS-RP).
5) **Collimator Improvements 2011 and Upgrade 2012: What Do We Plan?**, by Stefano Redaelli (BE-OP).
6) **RF System: Is It Working Well Enough?**, by Philippe Baudrenghien (BE-BI).

For each presentation of the session, summaries of the discussion that followed the presentations are given. A summary of the critical points and open actions is also given.

BEAM CLEANING AND COLLIMATION: TOO BAD OR TOO GOOD? (R. ASSMANN)

L. Rossi asked what are the limitations for going below 1.4-1.5 m in β^* in 2011. R. Assmann replied that β^* is limited by the aperture in the triplet. In particular, the uncertainty on the orbit in the interaction regions is one of the main sources of concern (orbit drifts reduce the effective aperture). *R. De Maria* asked if the present situation could be improved. Ralph replied that the orbit stability is already excellent but might be improved further. *J. Wenninger* clarifies that further improvements will only be possible if the BPM stability could be reduced: a control to better than 50 μm is required (assuming collimator retractions down to 0.5 σ).

S. Myers welcomed the good news that in the first year of operation we have a collimator performance that ensures already 30 % of the required performance for nominal intensities at 7 TeV (with intermediate collimator settings). Do we really need to change the layout and move the magnets in the dispersion suppressors or can we hope to achieve the nominal performance with the present system? *F. Bordry* shared the same question and asked whether the initial assumptions were too pessimistic. R. Assmann replied that his predictions for 7 TeV assume the same peak loss rates seen at 3.5 TeV. We cannot know at the moment if this good conditions will be maintained at higher energy. *S. Myers* also commented that the extrapolations to higher energy and intensities shall take into account the global picture, for example that we can now operate the machine with emittances well below nominal so we could have tighter collimator settings. There might be margin for further improvements of cleaning.

Referring to previously announced figures of collimation performance, compatible with only 40 % of nominal intensity at 7 TeV (cleaning without imperfections), *L. Rossi* asked where is the gain coming from. Possibly from smaller imperfection than assumed? R. Assmann replied that the predictions for imperfections actually match well the observed cleaning. The overall gain in cleaning comes essentially from the good beam lifetime that is much better than what originally assumed.

R. Schmidt commented that the 7 TeV operation will not be achieved immediately after the splice consolidation. Operation at a lower energy, e.g. 6.5 TeV, looks achievable in a shorter time scale. What are the performance estimates for energies below 7 TeV? R. Assmann replied that the estimates are included in the plots of his slides. The gain for small energy changes is not significant. The largest uncertainty remains the scaling of loss rates.

V. Shiltsev wondered if the collimation cleaning depends on any single-bunch parameter, like bunch intensity or emittance. R. Assmann replied that the collimation setup is validated by loss maps that are done with individual nominal bunches, then blown up by 3rd resonance crossing. The maximum loss rates with different bunch parameters and configurations have so far shown a similar behaviour of what is observed for single bunches. *S. Redaelli* pointed out that this is not the case for UFOs. More details about this topic are discussed in Session 6.

Considering the collimator upgrade programs, *S. Myers* commented that in the light of the good collimation performance, it seem reasonable to put more priority on speeding-up the collimation setup time rather then on improving the cleaning performance. For example, we should put more pressure on the production of collimators with BPM integrated.

B. Dehning asked if the possibility to reduce the setup time with faster BLM acquisitions is still being pursued. *S. Myers* asked if we could consider for example to use fast acquisition from diamond detectors. R. Assmann replied that optimized alignment based on faster BLM acquisitions are still being pursued. On the other hand, BLM-based setup will require still dedicated fills because one cannot "touch" the beams with many MJ stored whereas the BPM-based solution does not. The discussion on the possible scenarios for the different upgrade strategies was then postponed until the talk by S. Redaelli.

LIMITS FOR BEAM-INDUCED DAMAGE: RECKLESS OR TOO CAUTIOUS?
(A. BERTARELLI)

L. Rossi pointed out that, the assumption that all the bunches of one train hit the collimator jaw on the same spot on the callimator jaw, is not realistic. A. Bertarelli agrees but commented that in this stage of simulations, the exact bunch distribution in not relevant. The difference between bunch positions is anyway in the order of a fraction of a beam size (*B. Goddard*).

S. Myers recommended to repeat the simulations for the final 2011 beam parameters that will be agreed as an outcome of this workshop (bunch spacing, energy, emittance, ...). A. Bertarelli commented that the dependence on individual parameters has been addressed but he agreed to repeat the studies with the final parameter set. Results can be obtained in about 1 month. *R. Assmann* commented that then onset of damage threshold was not addressed by these studies and should be addressed in future work. For example, the emittance can have an impact can have an impact on the damage onset whereas the presented static simulations depend only on the deposited energy distribution (that has limited dependence on the emittance).

L. Rossi asked if the case of ion losses has been addressed as well. A. Bertarelli commented that studies are possible but not yet done. The difference between particle types are handled by FLUKA, which is used to generate energy deposition maps, then used as input the the simulations. R. Assmann reminded that ion losses are predicted to affect only the surface of the collimator.

R. Losito commented that at present we have no means to detect beam impacts on a collimator. He also asked if it is possible to experience collateral damage, e.g. vacuum leaks, even if the collimator itself remain without damage. A. Bertarelli replied that risks of water leaks were excluded in the simulated failure scenarios. *A. Dallocchio* reminded that was can use temperature sensors mounted on the collimators. *R. Assmann* said that serious damage levels can also be seen operationally from the collimator response on beam losses.

B. Goddard asked if the figure of 1 failure per 300 years given in the presentation covers the setup case periods. R. Assmann replied that this figure is calculated for standard operation. He also commented that during the setup the triplet remains protected in all cases because the alignment is carried out for small collimator gaps.

J. Wenninger reminded that the failure scenarios discussed involved combined failures and very big offsets between jaws and beam. At every beam dump we can cross check the relative alignment of the various collimators and a proper analysis should allow us to minimise the risk that such big errors occur (quality control by operation). R. Assmann agreed and states that this is indeed the reason while we have insisted to have regular loss maps during standard beam operation.

G. Arduini asked if there is a limit in the energy density of the beam that applied for the operation in 2011 and for the future years. This does not appear to be an important parameter according to the simulations presented. R. Assmann stressed that he expects that the onset of damage must depend on the beam emittance.

In response to the statement by A. Bertarelli that models could be improved if the material data from other laboratories were publicly available, *S. Myers* recommended that we must try to get material data from the Los Alamos laboratory.

RADIATION TO ELECTRONICS: REALITY OR FATA MORGANA?
(M. BRUGGER)

S. Myers asked if R2E issues can potentially limit the LHC peak luminosity. M. Brugger that this is indeed the case in the IRs, were dose to electronics scale with the luminosity. *S. Myers* also asked whether 3 months of work will be sufficient in the next shutdown to make significant improvements. M. Brugger reply that we cannot re-locate everything during 3 months but this time could certainly help fixing some weakest points to be identified during the 2011 operation. S. Baird commented that this aspect should be reviewed critically because it can potentially stop other foreseen activities in the IRs.

S. Myers also commented that in some cases the estimates are 3 times worst than originally predicted. M. Brugger warned that the error bars are also larger for the cases with a few data points.

J. Jowett asked about the understanding of the ion losses that caused some issue during the short ion operation in 2010. Are there serious problems that can be anticipated for 2011? M. Brugger commented that the problems encountered have been partly addressed by the QPS team (e.g., automatic reboot of QPS servers) and should not represent a limitation for the next year of operation. *R. Assmann* also commented that a different location of losses was found for B1 and B2, caused by a different dispersion function. The optics could be re-matched to reduce these difference and to optimize the loss pattern. *M. Giovannozzi* confirmed that the ABP optics team is looking into this problem.

P. Collier asked if the sensitivity of equipment could depend on the total absorbed dose. M. Brugger replied that this effect exist but in principle we will remain far from the regime where this becomes important.

L. Rossi commented that, according to simulations, we will need an access every 2 days in 2012. M. Brugger warned again that these figures depend critically on the equipment sensitivity, which could not yet be addressed experimentally due to the low statistics in 2011.

RADIATION PROTECTION: HOW (RADIO)ACTIVE ARE WE GOING TO BE? (S. ROESLER)

In response to a question by *L. Rossi*, S. Roesler reiterated the there should be no issue in 2011 or 2012 for people to carry out the splice work.

A. Siemko asked whether all the radioactive components will be marked as such in the tunnel. S. Roesler replied that the most radioactive components will be marked. In general, all the components in the tunnel should be considered as radioactive.

R. Assmann asked if the present baseline that foresee implementation of a fully remote collimator handling in 2015-16 is still acceptable. S. Roesler confirmed that this is the case.

COLLIMATOR IMPROVEMENTS 2011 AND UPGRADE 2012: WHAT DO WE PLAN? (S. REDAELLI)

R. Losito asked if we need to replace all collimators (or at least all TCTs) with BPM-integrated collimators. S. Redaelli replied that the gain in time for the alignment clearly goes linearly with the number of collimators equipped with BPMs. According to the 2010 experience, the bottleneck during operation are the IRs, mainly due to the frequent configuration changes requested by the experiments, so priority should clearly be put on the TCTs (16 collimators in total).

Referring to results from the impedance team that show how a few collimators can have significant impact on the total impedance, *O. Brüning* asked what is the impact on inefficiency by opening the gaps of a few collimators critical for impedance. S. Redaelli replied that this needs to be addressed. As a general figure, the global cleaning depends moderately on individual TCSG collimator positions.

In response to a question by *R. Schmidt*, S. Redaelli commented that R2E estimates predict that the radiation to electronics in IP3 will be about a factor 100 smaller than in IP7. This is the leading motivation behind the proposal of a combined betatron/momentum cleaning in IP3.

M. Lamont commented that in 2010 we also spend a lot of time for loss maps used to validate the collimation system settings. Any improvements foreseen there? S. Redaelli replied that there is work ongoing to use the transverse damper to blow-up individual bunches. This could enable performing loss maps for several cases within one single fill. This work has also to be combined with special configurations for setup beam flags as it does not help to have many bunches at top energy if we cannot mask the BLM to perform loss maps.

P. Collier encouraged to work on understanding the relation between measured orbit at the collimators and offsets found in the beam-based alignment campaigns. It should be possible to extrapolate the collimator settings at different times in the cycle. S. Redaelli agreed. This activity will be followed up. *R. Assmann* warned that an attempt was made for the TOTEM Roman pots but it was not success full and finally we had to use in all cases the settings established with beam-based alignment.

S. Bertolucci asked what is the time line for the production of collimators with BPM integrated. A. Bertarelli replied that for the moment this option was not given priority and was considered as less urgent than the activity on the dispersion suppressor in IP3. One could change priorities but still there is a need for a significant amount of work for prototyping and testing. *P. Collier* asked whether one should consider installing normal BPMs, not integrated into the jaw, next to the TCTs. *R. Jones* stated that this will not be a viable solution because the temperature effects on the BPM reading is still too larger. *S. Weiss* also commented that one must envisage early on additional cabling for the new BPM.

As a general conclusion after a lively discussion about the project priorities, it was agreed to follow-up with higher priority the option of installing collimators with BPM integrated already at the first long shutdown. The final choice on the project strategy will be agreed upon at the review foreseen for mid-2011.

V. Kain said that one could consider a BPM-integrated design also for the collimators in the transfer line. S. Redaelli asked if the study of line stability is not sufficient to address orbit issues in the collimators. V. Kain replied that there are relatively few BPMs that can be used for that.

RF SYSTEM: IS IT WORKING WELL ENOUGH? (P. BAUDRENGHIEN)

P. Collier asked if the 200 MHz capture system would reduce the injection losses further. *E. Ciapala* commented that even the capture system will not get it down to zero. Tolerance on injection losses are really tight due to the BLm thresholds. The 200 MHz system was dismissed due to operational risks and it should be be considered as an option. P. Baudrenghien also commented that the transfer to the 400 MHz system would then engender losses.

In view of possible issues for higher energies, P. Baudrenghien also commented that the controlled blow up stability does not depend on energy. The required voltage will be (slightly) increased at higher energy as well when full klystron power is available. But there should be no major issue.

R. Assmann asked how much time will be required for commissioning higher voltage. P. Baudrenghien replied that they would need some dedicated time needed at the start up. Time estimates are not available yet.

ACTION ITEMS

The following action items were identified for this session:

- **Future simulation of W collimator damage**:
  1) Realistic simulation with the 2011 operational parameters.
  2) Simulate onset of damage: damage threshold (emittance).
  3) Can we get additional material properties from Los Alamos?
- **Radiation to electronics**:
  1) Prepare as much improvement as possible for 2011/12 shutdown.
  2) Change B2 dispersion (IR7L): shorten region with cleaning losses into DS (ions).
  3) Continue efforts to reduce uncertainty in equipment sensitivity.
  4) Perform beam tests (quench test location + injection region) to improve radiation field calibration.
- **RF**:
  1) Allocate dedicated beam time for higher voltage commissioning in 2011.
  2) Above half nominal: Interlock strategy for RF trips (cavity, klystron, ...) to be decided but probably require beam dump.

ACKNOWLEDGEMENTS

We would like to acknowledge Frank Zimmermann for the helping with the notes of this sessions and the speakers for the excellent talks.

SESSION 6 – MACHINE PROTECTION IN 2011 AND BEYOND

M. Zerlauth and G. Papotti, CERN, Geneva, Switzerland

Abstract

The programme of session 6 was designed to provide a synthesis of the experience acquired during the commissioning and operation of the LHC machine protection system during the initial run in 2010. While the focus was on reaching the initial goal for the stored energy of 30MJ, the session aimed as well at identifying possible limitations or show-stoppers to increase the beam intensities beyond the 2010/11 targets. Special attention was given to ongoing work for the understanding of fast beam loss events observed for the first time in the LHC during the 2010 run as well as improvements for injection protection to overcome the present limitation of 48 bunches.

LIST OF PRESENTATIONS

The following presentations were made in session 6:

- Experience with MPS during the 2010 run, J.Wenninger.
- Can operations put the MPS into an unsafe state? , L. Ponce.
- Preparing the Machine Protection Systems for the 2011 run, J. Uythoven.
- Is the BLM system ready to go to higher intensities?, M. Sapinski.
- What are the issues with injecting unsafe beam into the LHC?, C. Bracco.
- Is there a limitation to the stored beam energy for 2011 and beyond?, R.Schmidt.

EXPERIENCE WITH MPS DURING 2010 RUN

Understanding and assessing the performance of the LHC machine protection system (MPS) has been one of the key factors driving the LHC commissioning and operation during 2010. With beam intensities and stored energies being increased along the year by more than a factor of 10.000, many valuable lessons have been learnt which will serve to further enhance the dependability of the protection systems and to further improve the operational procedures. Not a single accidental beam induced quench with circulating beam has been observed in 2010 (still some 20 high current quenches happened during activities related to hardware commissioning), which was not at least thanks to the very good stability of the orbit and the efficiency of beam cleaning. The end of the run was however dominated by yet not fully understood fast losses (UFOs), which eventually also limited the final slope of the intensity increase (shown in Figure 1). Nonetheless all of these events were captured by the machine protection systems, confirming the very good performance in 2010.

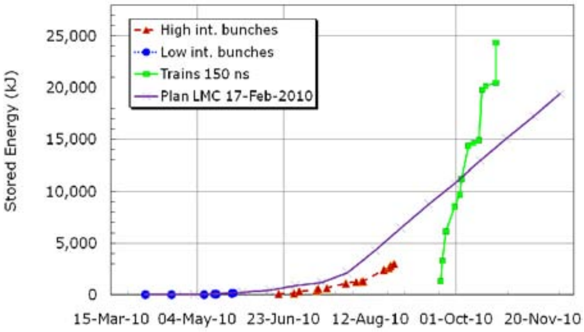

Figure 1: LHC run 2010: planned versus achieved stored energy.

No major loopholes in the machine protection system architecture were identified, still, when moving to higher intensities in 2011 beam induced magnet quenches will become more likely. Therefore the lessons learnt with the intensity increase in 2010 should be used to re-optimize the plans for 2011. More rigour has to be applied for tracking the changes related to protection systems as of 2011, including special running periods such as MDs or special physics run for TOTEM or at 1.38 TeV.

Discussion:

M.Ferro-Luzzi: Is there an estimate of how long it will take to get the MPS back in function, i.e. for the re-commissioning? **J.Wenninger**: J.Uythoven will answer this question in detail during his talk, but it is estimated to about one week. Slightly more time will be needed if the chosen energy will be above 3.5 TeV. **M.Zerlauth**: There is quite an impressive list of changes to the MPS that need to be re-commissioned.

F.Bordry: What about the UFO size, 10 um, how was this calculated? **J.Wenninger**: It was guessed from scaling losses from the wire scanner tests. It remains a rough guess, only to get the order of magnitude. In addition only a (small) part of the object actually sees the beam; it could be bigger than the observed losses suggest. The FLUKA team simulated the wire scanner quench test so far, next on the list is to try and nail down a more detailed UFO simulation.

S.Redaelli: Referring to the table where the dump statistics are presented, what is meant by false dumps? **J.Wenninger**: This includes dumps triggered by the MP system without reason. An example is when we had crate failures for the BLMs, problems with the connection between the BIC FESA and the SIS, or in one case the LBDS system having some problems with vacuum readings. Basically it was failures of the internal surveillance of MP components. **M.Zerlauth**: For example, if we lose one channel of a fail safe 1 out of 2 logic we decide to dump for safety reasons. **J.Uythoven**: We call them internal failures of the system.

R.Assmann: How do you get “half a false dump” in the dependability statistics of the MPS? **J.Wenninger**: That was an agreement between me and Bruno Puccio; we share the responsibility of one dump between the SIS and the BIC due to communication problems.

M.Ferro-Luzzi: A comment on this idea that the UFOs are charged up and then repelled: Can this be checked with the wire scanners in some way? **R.Schmidt**: Probably not, as the wire scanner is fixed on the fork. **J.Wenninger**: One idea would be to build a device that allows having small (dust) particles falling through the beam in a particular location, and thus creating similar events/loss patterns. **F.Zimmermann:** Such a device exists already at KEK.

R.Assmann: The statistics are very useful. It would be even more so if we could distinguish further in “expected/programmed dumps”: some of the dumps originate for e.g. from testing thresholds by moving collimators on purpose, loss maps, end of fill studies etc. This should be treated separately from real dump-triggered losses. **M.Zerlauth**: More granularities will be added in the Post Mortem classifications for exactly this purpose, so to be able to produce more significant statistics next year.

CAN OPERATIONS PUT THE MPS INTO AN UNSAFE STATE?

In parallel with the commissioning and validation of the LHC equipment system, the operational procedure has been improved and commissioned throughout this first year of operation with beam. While the MPS system was never (demonstrably) put into an unsafe state, a number of operational mistakes and/or an incorrect operational procedure have resulted in a degraded running of the protection systems, where for e.g. a redundant level of protection was bypassed. A number of improvements (mostly related to avoid erroneous manipulations) have been identified and already are or will soon be applied for the 2011 run. The major improvements are a rationalization and further automation of the nominal sequence and procedure, automatic unmasking of SW interlocks, additional interlocks for e.g. injection protection and further improvements for the orbit control and the related collimator alignment. Emphasis should be given to the development of an online aperture-meter, which will allow highlighting potential bottlenecks and limitations. The main remaining dangers are non-interlocked elements such as the abort gap cleaning, gas injection for BGI,… as well as non-standard operation such as during MDs or special physic runs. More rigorous procedures have to be put in place to make sure to recover the initial state of MPS and settings before returning from MDs, HW interventions or technical stops to normal physics.

Discussion:

R.Schmidt: Concerning the automatic HDS interlock, it would be wise to wait a certain time before dumping the beams (to allow for actions by operations), as it is not advisable to immediately dump under all conditions (e.g. with beam in the abort gap). **M.Zerlauth**: Such timeouts are configurable in the CIRCUIT synoptic supervision application. Currently the state of all HDS is read every 15 minutes. As soon as an alarm state is detected, e-mail warnings are sent and the alarm is clearly visible on the display. The actual removal of the power permit (and the following beam dump) would only be triggered in case no action is taken in the following 3 hours (current settings).

L.Ponce: Be careful, the QPS state not ok is already one of the Laser alarms, which is not necessarily always looked at. In addition a false QPS_OK is part of the injection permit in the SIS.

R.Assmann: We always said that the Sequencer is not a Machine Protection device, but clearly we must make sure that we execute the things in the right order: currently there is no protection against executing the wrong task at the wrong moment. It is reassuring to see that the state machine will start playing an important role. Obviously operations needs flexibility for certain phases of running, therefore a 100% strict order cannot be enforced. **L.Ponce**: It has to be noted how operations improved as time passed by. Jumping back and forth in the sequence happened often before the summer and in the beginning of the run, but not so much afterwards i.e. after a careful rationalization of the nominal sequence. In autumn, the only mistakes that remained were related to changes of references for the feedbacks. Indeed no more errors from not having executed a given task were made from this point. Certainly, the state machine will help in enforcing the execution of tasks in the right order.

R.Assmann: EquipState is the most powerful tool in the CCC, and because of that it is also very dangerous. **L.Ponce**: Its use is currently still not restricted, and restricting it for example with the use of RBAC EIC role would not be very useful. What is more important is that its use is avoided as much as possible, leaving it just as the ultimate tool to recover in extreme and weird situations. What we need to move in this direction is for example a dedicated “recovery” sequence, to reset tripped PCs and allowing precycling them directly through the sequencer.

PREPARING THE MPS SYSTEMS FOR THE 2011 RUN

The LHC machine protection systems have been undergoing an impressive amount of changes during the Technical Stop, and more than 65 items with sizable impact have been identified. To maintain the desired dependability of the MPS system, it is essential to rigorously track all relevant changes during technical stops and later machine operation. A clear need for better / dedicated tools for the 2011 run has been highlighted, as a first start any changes should be documented in the

MPS commissioning Website [1]. The applied improvements of the MP systems focus on known weaknesses observed during 2010 operation and aim at further improving the safety and availability of the protection systems.

Due to the amount of changes, a full re-commissioning of almost all systems will be required, estimated to last a total of around 12 days during the cold checkout and beam commissioning phases.

Due to some remaining non conformities, the operational envelope for 2011 as seen by machine protection systems is defined as follows:

- **Energy:** 4–5 TeV due to some noisy BLM cables and 4.5 TeV due to a high-voltage breakdown of a beam dump generator MKD (to be solved during 2011)
- **Intensity:**
  - Limited to 144 bunches per injection in present configuration
  - Nominal for circulating beam, but small risk of limited TCDQ damage in case of asynchronous dumps
- Effect of small **emittances** on TCDQ needs more studies
- **Limit β* ≈ 1.5 m** due to the increased risk of exposing collimators (depending on orbit stability, beta-beat etc.)

The latter limitation clearly needs to be balanced with the risk of further increasing the energy, which most likely could lead to more severe damage in case of quenches propagating to the magnet interconnects.

Discussion:

M.Pojer: Please remember that we need one extra week for the hardware commissioning if we decide to operate at 4 TeV, with the HWC campaign already starting next week. **R.Schmidt**: That is correct; we have to account for around 6 hours of additional tests per sector, with an additional overhead attached to perform the installation and instrumentation (assuming no bad surprises are revealed).

R.Jacobsson: As I understood it, the injection gap cleaning will not be available for the start-up. **J.Uythoven**: It needs time to be commissioned; it was not operational at the end of the last run.

B.Goddard: Concerning the problem of the TCDQ, we know about the fragility for the 7 TeV 25 ns spacing beam. We hope to be in the position to replace it with a more robust solution during the 2012 shutdown, if the simulations show that this can be done in the currently already available space.

M.Ferro-Luzzi: Are the snubber capacitors needed for 4 TeV operations? **J.Uythoven**: Yes, for the main dipole circuit the snubber capacitors are considered mandatory beyond 3.5 TeV. The time required to test them will be allocated during hardware commissioning / cold checkout. **R.Schmidt**: They are needed for operations, and an additional week of time is needed to test them properly for all sectors, as M.Pojer pointed out earlier.

M.Ferro-Luzzi: What about the possibility to inject 144 bunches; what will be the impact on when we can scrub? When can we do that efficiently? **G.Arduini**: We need the 144-bunch injection for scrubbing (four times 50 ns trains). **V.Kain**: We will need some time for injection setup, before we can inject 144 bunches in one shot: it will not be available one week after start-up. The BLM sunglasses will be available much later, but they are in principle not mandatory for 144 bunch injection. **B.Goddard**: At least a couple of weeks will be needed before we can inject 144 bunches in one shot.

M.Ferro-Luzzi: The 10 days that are scheduled for machine protection, does that already include machine availability? **J.Uythoven**: That is effective time. So it is about two weeks of checks in total before you can think of increasing intensity. **M.Ferro-Luzzi**: From experience of machine availability, this would mean at least 3 weeks.

S.Myers: Is the limit on beta star a real hard limit, or how could it be further reduced. **J.Uythoven**: It comes from collimation. **R.Assmann**: The limits come from orbit stability; it was extensively presented by R.Bruce in Evian. **S.Myers**: The danger last year was related to the TCTs. If we should increase the energy to 4 TeV in 2011, we also increase the risk for an interconnect to burn through. What we also saw from Laurent is that this would still require an 8-12 months shutdown for repair. So the risk factor that comes from multiplying those two is still a fairly high number to go to 4 TeV. But if you go down from 1.5 m to 1 m, you get the 30% for the Higgs by increased luminosity that you lose in not increasing the energy. I am trying to compare those two risks and to me it seems that one risk is a much smaller risk than the other one. **R.Assmann**: We saw it in A. Bertarelli's presentation earlier: one bunch impacting on a TCT is not a catastrophic damage; we could then use the in situ spare surface. Accepting such an increased risk, we could move one sigma closer. **R.Bruce**: One sigma closer represents around 0.2 m in beta star. **S.Myers**: There seems to be a big difference in the two risks. **R.Assmann**: It is correct that the collimators are designed to protect: it is not catastrophic if they are hit. We can measure the aperture locally, and there we can probably gain more. In view of the results, we should revisit the assumptions, and we can give better estimates. **B.Goddard**: Maybe we have some margin and we could move in the TCDQ a bit, to gain a fraction of a sigma. **R.Assmann**: But we already have losses in IR6. We do not know the aperture IR by IR, so there is some assumption in there. We will follow this up with R.Bruce. **B.Goddard**: We should also evaluate the risks originating from other causes (for example RF trips) and not only asynchronous dump, as they might happen more often. **R.Assmann**: Agreed, but it is much less damage than from one bunch.

M.Deile: Do not forget the moveable devices interlock test, for Totem and ATLAS pots. They need time without beam and it is not entirely transparent as it needs playing with the SMP flags.

IS THE BLM SYSTEM READY TO GO TO HIGHER INTENSITIES?

2010 has seen an excellent performance of the Beam Loss Monitoring System (BLM), both catching and accurately measuring as well unforeseen loss events such as triggered by the UFOs. Still, the loss patterns related to a few events remain to be fully understood, so do the rather large observed variations of losses between identical fills. Fast losses (UFOs) have certainly been the surprise in 2010 and, despite the still unclear origin of the events, much more is today known about these events, i.e.:

- Events are equally distributed around the ring
- More events are observed at higher intensities
- The loss signal shortens, i.e. the losses are faster at higher intensity
- Speed is different from the free fall, i.e. electromagnetic forces seem involved (1-2 'bouncing' UFOs observed)
- Signal amplitude does not increase with intensity

Although the latter point still remains to be finally confirmed through additional statistics, it suggests that a revision of the BLM thresholds on superconducting magnets could make the UFO effects acceptable for high intensity operation. BLM thresholds are raised for losses in the ms-scale (to be more immune against UFOs), but have to be reduced for losses longer than 1 s due to the outcome of the latest quench tests. The changes will be applied before the start of beam operation in 2011, provided the new thresholds are cross-checked against the losses observed during the latest fills with high intensities. Additional quench tests to benchmark the new simulations and thresholds should be included in the 2011 program.

Discussion:

M.Zerlauth: If I understood correctly, you need to increase another factor of 5 the thresholds, in addition to what was already done during 2010. **M.Sapinski**: In fact not. We had increased a factor 5 everywhere, now we want to bring everything back and we increase only the running sums concerned by the UFOs. **R.Schmidt**: The thresholds of the different running sums should be set as a function of the failure cases. Timescales are different for different events, for example in the millisecond range for UFOs, while losses at the aperture for MP are in much longer timescales. Playing with the shape of the curve allows adjusting the system for different failure scenarios. **M.Sapinski**: Losses from UFOs could produce very similar thresholds to losses on the beam screen.

O.Bruning: If UFOs are thought to be micrometer dust particles sitting on the inside of the beam screen, should sector 34 not be different? **M.Sapinski**: The UFOs are indeed seen everywhere, and sector 34 is not special in this respect.

P.Collier: For me the UFOs at low energy is still a mystery, have we seen any at this energy? **M.Sapinski**: One UFO was seen at injection, but at this energy they generate a much smaller signal. So in fact, it is possible that BLM system is insensitive to UFOs at such lower energies. **M.Zerlauth**: It could also be that for some (unknown) reason there are much less event at low energy. **P.Collier**: which is what worries me: if we go up in energy, there could be even more. **E.B.Holzer**: I would add that the data is consistent, but the statistics are extremely low, and from scaling the signals, we cannot exclude that there is a dependence on energy. Basically, we have one UFO expected, and one observed.

L.Rossi: Which magnet did you use for the quench test? **M.Sapinski**: It was the D4, and in another test, the MQ was used. **L.Rossi**: An error of a factor 3 for the thresholds seems too generous; the FLUKA simulations are more precise than that. **M.Sapinski**: The test on the D4 is not yet fully analysed. The factor 3 applied to the MQ magnet test, and we also have to take into account that some of the assumptions were not true. The loss shape is more peaked in the magnet longitudinally. Also the analysis was done for beam 1, while the test was done in the end with beam 2 (for which there was no BPM available in front of the magnet). The factor 3 difference could be understood, the analysis is ongoing, and the magnet is not less stable. **A.Siemko**: Remember that one case was not a real quench, but the QPS electronics detected a voltage signal and fired the quench heaters. **M.Sapinski**: In the D4 test however, we actually quenched the magnets, according to QPS experts. **B.Dehning**: The accuracy comes from the SM18 quench test, done some years ago. The agreement on heat flow for steady state seems to be very good. **L.Rossi**: Also measurements in Fresca were very precise, which should be complemented by new measurements which are available now.

R.Assmann: On the longer term, it would be useful to have some kind of pattern recognition, or logic functionality in the BLMs, for example to address the problem we have with losses at injection, which would allow the use of different thresholds for different scenarios. **M.Sapinski**: We have in fact a PhD student working on that.

V. Shiltshev: Given that UFOs are so important, is it plausible to install a dust generator, that drops a particle of know material and size? **M.Sapinski**: They have one in KEK. **V.Shiltshev**: Are there any other processes that lead to an increase in the losses? For example, in Tevatron, the loss spikes are mainly caused by orbit variations on the scale of 10 microns. **M.Sapinski**: We see some fast spikes on the collimators. **R.Schmidt**: From all the analysis, the UFO losses are completely different. **R.Assmann**: For orbit variations, losses would be at the primary collimators in IR 7, not in the middle of the arc.

WHAT ARE THE ISSUES WITH INJECTING UNSAFE BEAM INTO THE LHC?

For circulating beams the MP systems provide redundancy for capturing the most frequent failure cases (for example a failure of a power converter of a normal conducting circuit is captured by the powering interlock system, a Fast Magnet Current Change Monitor and eventually the BLM system). Injecting safely into the LHC however fundamentally depends on the correctness of the state machine and the setup of the injection protection collimators, in particular the TDI (which assures a safe machine even in case of other system failures). Already in 2010 unsafe beam was injected into the LHC, but injection was limited to 38 bunches mainly due to losses at the end of the transfer lines triggering Beam Loss Monitors in the LHC ring. The introduction of abort gap and injection cleaning as well as additional shielding which has been installed in TI2 during the technical stop should allow to inject in 2011 up to 144 bunches.

Additional modifications having an impact on the MP systems are currently under discussion, such as the installation of sunglasses/blind outs on the affected BLM channels or an increase of the TCDI aperture.

An upgrade of the logic for the injection protection collimators has been agreed between the injection and collimation teams, but will require a careful re-commissioning before high intensity injections can take place in 2011.

Discussion:

E.B.Holzer: There were two open issues/questions concerning BLMs. Firstly, concerning BLMs with filters and sunglasses - the filters should be removed for all BLMs which will have sunglasses, whereas we can continue using filters on BLMs for measurement purposes only. **B.Goddard**: Doing so we would probably run out of dynamic range, and we would need additional monitors installed for measuring the losses. **E.B.Holzer:** We have extra monitors for measurements already. We can keep the functionality separate: Machine protection and measurement, which is what we do in other locations. Secondly, concerning the possibility to use nearby monitors, the answer is no. We are already at the limit. **C.Bracco**: The point is that these losses are very localized. They are distinct from losses with circulating beams where the losses also appear in other locations, for example in point 7.

S.Redaelli: I think this was already discussed in Evian, but it seems still not completely clear to me. Why is it not possible to safely profit from the bigger aperture of the LHC ring, where we have 5σ more in the arc? I think it should be possible to open the TCDIs more? **C.Bracco**: For MP tests, we set the collimators to 5σ and for some phases we are already at the limit as we could observe some leakage at the LHC, especially at the septum. **V.Kain**: 5σ should be ok. The TCDI settings are for injected beam aperture, not for circulating beam aperture. We need the margin on energy errors and injection oscillations. We are currently still not well in control of injection oscillations, as we thought them to be much less. **R.Jacobsson**: If you think of sunglasses, you would think of something that temporarily puts a higher threshold, which is what for example has been put in the logic of the LHCb BCM. Is it true that you will be blinding out the BLMs completely for the time of injection? **C.Bracco**: Well, unfortunately for some of the BLMs the thresholds are already at the maximum, so there is nothing more we can do on that side. **M.Zerlauth**: The current approach to blind-out the signal at the entry of the BIS is mainly motivated by the requirement not to touch the critical internals (FPGA code) of the BLM system. **B.Goddard**: In fact, the responsible for both BIS and BLMs do not want to change the core of their systems. Additionally, concerning the tolerances, we chose them so that we can tolerate injection oscillations of about 2 mm. We could correct them back to 0.5 mm systematically, and have more opening in the TCDIs, but that would mean much less availability. **V.Kain:** We also know that the transfer lines are drifting all the time and correction is not straightforward.

R.Assmann: I think we must understand why the transfer lines are drifting, and correct this effect at the source. For the BLM sunglasses, if the blinding time has to be in the order of 1 second it would be definitely too long! We can only afford blinding for a few turns. Additionally, you mentioned the risk to damage the tertiary collimators with an asynchronous dump, which I believe not to be a big issue as they are in the shadow of the arc. **C.Bracco**: In our assumption the TCTs are moved to 4σ by mistake and that we 288 bunches are injected. **R.Assmann**: Then we have to make sure that the TCTs cannot be sitting at 4σ at injection. **B.Goddard**: We had the case that the TCDQ was in, so unfortunately such failure cases are possible. **R.Assmann**: In the IRs we are in the shadow of the arc as long as we are not squeezed. I do not see a reason why we need to have really tight thresholds for the TCTs at 450 GeV. For a subset of these devices we can increase the thresholds as they are in the shadow of the arcs, and so they are not limiting anymore. We can put this on the list of possible measures.

R.Schmidt: Maybe we could use the less sensitive ionization chambers, and put them in the interlock chain for when the BLMs saturate. Another question is whether the beam can be better prepared at the SPS, to reduce the losses? **C.Bracco**: We know that scraping helps. **B.Goddard**: Last year the SPS shift crews worked hard and prepared the beams very well, still this was not sufficient. We will verify whether we can move out the collimators at the very end of the transfer lines by a few mm. We might have to add an extra Fast Magnet Current Change Monitor (FMCM) on some circuits, but it could be a way around the need for scraping. But this cannot be envisaged for this year.

IS THERE A LIMITATION TO THE STORED BEAM ENERGY FOR 2011 AND BEYOND?

No serious limit for beam energy or intensity could be identified. Still a number of failure scenarios where damage (beyond repair) is still possible should be studied more quantitatively. Such serious failures may especially occur in the backbone of the MPS such as the beam interlock system or the beam dumping system, i.e. when despite a beam dump request the beams are not (or not fully) removed from the machine.

It was proposed to perform in the light of the 2009-2010 experience quantitative studies of such catastrophic failures using appropriate simulation tools.

These studies would then allow identifying and implementing additional mitigations such as redundant triggering interfaces between the BIC/LBDS, emergency procedures for the CCC, TCDQ consolidation programs and the development of new interlocks such as a Fast Beam Current Change Monitor.

Discussion:

S.Myers: The risk levels associated to the different scenarios are in inverted order with respect to this morning's presentation.

S.Myers: Concerning the asynchronous beam dump, what happens if the kick is too big? **B.Goddard**: In this case the beam would hit the Q4 and the septum.

B.Goddard: For the BLMs in point 6, they are in use and connected, but the thresholds are currently set to the maximum. **R.Schmidt**: We should indeed set the thresholds to a meaningful value. **B.Dehning**: This can be done but we would need beam time for additional tests then.

B.Goddard: Concerning the TCDQ we have to decide soon in case we want to include it in the consolidation. There is no way however that it can be made ready for the end of this year. **R.Schmidt**: Alternatively, we could also consider some additional passive absorbers.

O.Bruning: If at Tevatron and RHIC they had UFOs, would they be able to see them with their BLM system? Could they detect them? **W.Fischer**: RHIC can tolerate much more beam losses than LHC. It would probably be difficult to detect them with the current settings of the BLM system. **B.Dehning**: I can confirm that their monitors are much less sensitive. **M.Zerlauth**: The term UFO is borrowed from the fusion community who also observe UFO-like events, leading to sudden unexplained disruptions of the plasma.

B.Goddard: You mentioned very fast losses and their phase coverage. I seem to remember that the collimator hierarchy was suspect in one case, when there was a very fast loss. **R.Assmann**: The phase coverage was checked with a student of J.Wenninger, and found to be correct. We observed in this case off-momentum losses. The losses were not at the primary collimator, but at a secondary collimator: this is acceptable in the short term, but not in the long run. There was another case at injection, with very fast vertical blow up of a few turns, which you cannot intercept at the collimators. This effect was extremely fast, while you need a reasonably slow process to be able to intercept it. It was not a case of multiturn losses.

B.Dehning: We should keep in mind redundancy and criticality. We have a concentration of channels, and common errors could play a big role. The same code is used everywhere. **R.Schmidt**: That is why in the slides I used the word "unlikely". But I believe a different, independent system would be of interest, like a very fast beam current change monitor, or direct BLMs. Even if they are needed only once every 20 years, we would be very happy to have them activated if the event happens.

T.Petterson: May I recall why we have PLCs for the LHC safety system, and a cable loop. We want the technology to be redundant and different.

CONCLUSIONS AND ACKNOWELGEMENTS

Machine Protection and Safety has become a daily concern not only of MPS experts, but also operations and equipment experts. A lot of work has gone into additional improvements of the machine protection systems in order to make the machine safer and more available during the 2011 run. The good performance in 2010 will however not guarantee a 2011 run free of surprises, whereas special caution should be applied when starting to interleave (high intensity) physic runs with MDs and technical stops.

The session conveyers would like to thank all speakers and the MPS/OP teams for their dedication and hard work during the very successful 2010 run and for all their input and help in preparing this session.

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DISCUSSION SUMMARY OF SESSION “RUNNING IN 2011 – LUMINOSITY”

V. Kain, M. Lamont, CERN, Geneva, Switzerland

Abstract

The discussion during the session “Running in 2011 - Luminosity” is summarised.

EXPERIMENTS’ EXPECTATIONS – M. FERRO-LUZZI

Massimiliano Ferro-Luzzi discussed the requirements of the experiments for the 2011 run. He assumed 144 days of luminosity production referring to M. Meddahi’s presentation later in this session. The goals (1 fb^{-1}) and special desiderata were mentioned. Special desiderata comprised luminosity levelling for LHCb; a special energy run for ALICE; TOTEM and ALFA 90 m β^* runs; luminosity calibration.

Massimiliano proposed two options for the luminosity calibration. It can be done in parasitically as end of fill studies or in dedicated fills. W. Kozanecki replied that in case of 4 TeV top energy it will have to be dedicated fills due to instrumental issues on the detector side. R. Assmann commented on the rich physics program presented by Massimiliano. He said the number of changes to the machine should be minimised to reduce the overhead. Also, a plan should be established now and not be changed again in the middle of the year.

Concerning the 90 m β^* optics it was mentioned in Massimiliano’s presentation to prepare the optics in several MDs. B. Goddard replied that it would be probably better for overall efficiency to have one change to the machine and finish off the 90 m β^* optics preparation in one block. S. Myers mentioned that the 10 days of special physics for the experiments allocated in Massimiliano’s talk will mean 10 days less at the end of the proton physics period where normally the machine reaches its peak performance.

G. E. Tonelli presented his preference for collecting 1 fb^{-1} first before switching to any special physics program to make sure that this goal is definitely met. J. Schukraft replied concerning ALICE’s intermediate energy run. It was approved by the Research Board and will therefore have to be fitted in. The machine crew will have to decide when it is best. There is however an important deadline for the ALICE collaboration is a conference in May. A third of the data is impacted by the intermediate energy data.

R. Jacobsson mentioned that there was no mention of using β^* to level luminosity, only separation. Using β^* might be much more reproducible.

F. Gianotti was in favour of M. Lamont’s proposal to put the intermediate energy run around Easter before the possible scrubbing run. Flexibility in the planning will be required. R. Schmidt and G. E. Tonelli both stressed that it would be important to show the feasibility of running at 10^{33} first before switching to any special physics. UFOs and electron cloud might be more difficult to tackle than assumed. S. Bertolucci remarked that we should concentrate on short term planning and that we do not have a choice but do the intermediate energy run. It was approved by the Research Board.

PUSHING THE LIMITS – BEAM – E. METRAL

Elias Metral summarised the situation in terms of collective effects in 2010 with impedance, beam-beam and electron cloud and the measures which were taken to stabilise the beams. He also gave an outlook for the maximum expected performance from the injectors. Landau octupoles are required to stabilise nominal bunches due to very good field quality in the LHC. Extra non-linearities have to be introduced.

L. Evans asked why we did not use the nominal parameters for longitudinal emittance. It is supposed to be 2.5 eVs. This should reduce the need of Landau octupoles. K. Cornelis added that longer bunches would naturally see more non-linearities. E. Chapochnikova replied that we were running in this configuration due to the extra margin at 3.5 TeV. Beam life times are better like this.

R. Assmann asked why bunch intensities above nominal are not the target for 2011 as it would be beneficial for luminosity. In this regard 50 ns (bunch intensities up to 1.5×10^{11}) is better than 75 ns (bunch intensities up to 1.2×10^{11}).

L. Evans said that smaller initial emittances at the moment of collisions also result in shorter emittance growth times.

F. Zimmermann commented on the statement in Elias’s slides that 1.7 SEY was assumed for the electron cloud simulations where in reality it is rather between 2 and 2.5. He said that they had got the information from the vacuum team. M. Jimenez replied that in the simulations a situation after scrubbing is assumed. In addition there are long sections in the LHC with stainless steel surfaces, like beam position monitors and dampers which are not NEG coated. However, he anticipated a rapid drop in SEY with scrubbing.

PUSHING THE LIMITS: CROSSING ANGLES, APERTURE AND BETA* - WERNER HERR

Werner Herr presented the possibilities in terms of crossing angles and beta star to maximise the luminosity and providing sufficient aperture.

R. Assmann commented that there is even more margin as W. Herr had assumed nominal emittances for his estimates. B. Goddard asked whether we should not use the emittances at the end of the fill which are much larger than the initial ones to do the calculations. R. Assmann replied that the hierarchy should always be OK.

W. Herr mentioned that we should try to maximise the integrated luminosity and not the peak luminosity.

P. Collier asked whether the once proposed tilted crossing scheme could give more margin for LHCb. W. Herr replied that the beam screen orientation is fixed now. It could however give some margin at 7 TeV and 10 m β^*.

LUMINOSITY ANALYSIS – G. PAPOTTI

Giulia Papotti presented an analysis of the 150 ns run luminosity data.

B. Holzer commented on the fact that the lifetimes of the two beams were consistently different. Efforts should be made to equalise them in 2011.

G. Arduini wanted to know whether for the 50 ns fill any e-cloud typical bunch-by-bunch variations could be seen. Giulia Papotti said that there is not enough statistics as it was only a single fill, but the typical electron cloud bunch differences were not apparent.

S. Myers asked whether smaller emittances from the injectors were kept small throughout the fill. V. Kain replied that indeed if smaller emittances were injected, the emittances were also smaller at the beginning of physics. However, the emittance growth times became shorter and shorter with smaller emittances and larger bunch intensities. Towards the end of the 150 ns run period the growth times at the beginning of stable beams were partly below 10 h.

Giulia had also shown the detrimental effect of the hump on the emittance during a physics fill. She claimed about 20 % integrated luminosity loss for this particular fill. The hump is most certainly a dipolar field acting in the vertical plane mostly coupling into beam 2.

V. Shiltsev mentioned that a more realistic physics model should be used for analysing the luminosity. Exponential and double exponential functions as were used in the analysis do not describe any underlying physics process.

LUMINOSITY CALIBRATION – S. WHITE

S. White reported on the results of the 2010 van der Meer scan campaign and the requests scans in 2011.

S. Bertolucci commented on the 3 % expected accuracy for the proton total cross-section measurement by TOTEM and 4 % for luminosity. He said this was unrealistic. Time should rather be spent on getting the van der Meer method and beam-gas below 5 %. S. White replied that TOTEM would bring a valuable and complimentary cross-check. H. Burkhardt also added that the 90 m β^* optics should be declared a milestone for the machine. R. Schmidt mentioned that using the main quadrupoles for tune compensation as proposed for the high β^* optics might hit QPS limits. This would have to be checked before.

W. Kozanecki mentioned that it would be of interest for the experiments to have several bunches in the bunch trains with fewer collisions or none to understand the systematics between low and high pile-up.

S. Redaelli said that a Roman pot takes 3 times as long as setting up 1 collimator. In 2011 more pots will be in the machine and it will have to be decided how to proceed. Either not all pots are set up or more time will have to be foreseen for the Roman pot setting up.

P. Collier asked how important it is to know the luminosity below 5 % accuracy. F. Gianotti replied that in the first half of 2011 experiments can live with an accuracy of 5 % on luminosity, but in the second half of 2011 the accuracy should be below 5 %. M. Ferro-Luzzi remarked that prioritisation will be required for 2011.

HEAVY IONS IN 2011 AND BEYOND – J. JOWETT

John Jowett presented the machine results of the first LHC ion run and set the scene for the ion run in 2011.

John had projected running at higher luminosities in 2011. S. Myers asked whether this would be OK with the predicted rate of Single Event Upsets (SEU). M. Brugger replied that the main problem is coming from EPC and QPS equipment and losses far into the arc. These losses could be avoided with re-matching the dispersion at least for beam 2.

J. Schukraft wanted to know why nominal ion luminosities were not planned for 2011. John replied that there is still a lot to be learned about emittance preservation. The hump and IBS are not under control yet.

John had proposed additional cryogenic collimators for point 2 and point 3. O. Bruning asked why cryogenic collimators are not also required for point 1 and point 5, as they also want to take ions. In any case cryogenic collimators will probably not be ready to be installed before 2016 according to L. Rossi. J.P. Tock added that the situation for cryogenic collimators should however be easier for point 2 than for point 3 due to the empty cryostat.

John had also mentioned that fewer bunches would fit into the LHC than previously foreseen due to the abort gap keeper window length. B. Goddard added that this could possibly be adjusted. It would however need an access to the machine and cannot be done on the fly.

OPERATIONAL SCHEDULE 2011 & POTENTIAL PERFORMANCE – M. MEDDAHI

Malika Meddahi presented an overview of the performance reach for 2011 with the different options, a proposal for the operational schedule and the ramp-up of the intensity.

Malika proposed to directly start with 75 ns and skip 150 ns. G. Arduini disagreed. He argued with establishing first of all a known situation. With 150 ns, very small emittances are possible and different effects can be studied separately, like the effect of head-on beam-beam. P. Baudrenghien also mentioned that they still have a not understood an issue with one cavity with 75 ns bunch spacing. Having a period with 150 ns and then switching to 75 ns to watch the behaviour of that cavity would be beneficial. R. Schmidt said that the step up in intensity with 75 ns would possibly be slower than with 150 ns. The different bunch spacing might have different EMC effects on electronics and equipment nearby.

B. Goddard remarked that we should not decide yet whether to run with 75 or 50 ns for the rest of the year. The outcome of the scrubbing run should show the direction. R. Assmann agreed as 50 ns could bring more bunch intensity.

The maximum beam energy was also mentioned. S. Myers said that if we run at 3.5 TeV we would not have to redo the luminosity calibration right away.

SUMMARY SESSION 08: HIGH LUMINOSITY (HL-LHC)

L. Rossi, R. De Maria, CERN, Geneva, Switzerland.

Abstract

Session 8 of the 2011 Chamonix LHC Perfomance Workshop addressed the scenarios for the High Luminosity LHC upgrade project (HL-LHC). It covered the performance expectations without any upgrade, with very low beta* optics using a new scheme called ATS and with the full spectra of the hardware and beam parameter enhancements. In addition the session integrated a synthesis of the lessons from past colliders and a survey of the possible requests of the experiments Alice and LHCb.

INTRODUCTION

The HL-LHC project aims at exceeding the design LHC nominal performance to reach in a decade from the upgrade a total integrate luminosity of 3000 fb^{-1}, which roughly translates to 250 fb^{-1} per year, or 1 fb^{-1} per day. The goal can be achieved with an initial luminosity of $5 \cdot 10^{34}$ $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ sustained for several hours. This implies a potential (virtual) peak luminosity of at least $1 \cdot 10^{35}$ $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ with a leveling mechanism in which a parameter controlling the luminosity is kept below its maximum potential at the beginning and then pushed during the run to compensate the proton burning and keep the luminosity constant [1]. The session featured five talks: LHC performance expectations without an upgrade by Oliver Brüning [2], consequences and opportunities of a novel LHC optics scheme (ATS) for luminosity improvements by Stephane Fartoukh [3], an overview of the upgrade ingredients and possible roadmap by Frank Zimmermam [4], lessons on management and performance evolution from Tevatron and other collider by Vladimir Shiltsev [5] and future scenarios for Alice and LHCb in the HL-LHC era by Sergio Bertolucci [6].

DO WE REALLY NEED THE LHC LUMINOSITY UPGRADE?

Oliver Brüning explored the expectations of the LHC performance without an upgrade. Emphasis was given on the possibility of reviewing the limits coming from the head on beam beam perturbations, together with possibility to fine tune the long range beam-beam interactions. One can possibly target a beam-beam parameter of 0.02 or more since 0.03 was achieved in other machines although operation conditions did not satisfied the user needs. This would allow circulating higher beam current with smaller emittance by taking full advantage of upgraded injector performance. It was also noted that limits on beta* with the exiting triplets can be reviewed based on direct aperture measurements instead of relying on design margins. In that configuration the performance achievable may exceed the nominal goals up to around a peak luminosity of $4 \cdot 10^{34}$ $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, but cannot reach the HL-LHC goals. Emphasis was given to 50ns bunch spacing solutions. Other ingredients are then needed, in particular leveling tools such as crab cavities and long-range beam beam wire compensator. In the course of the presentation it was mentioned that IBS growth rates should be controlled to be smaller than the radiation damping rate and that, besides loss thresholds, attentions should be focused on the 3 sigma beam life time where resides the beam participating to the luminosity.

In the discussion several points were raised. S. Myers remarked that the beam beam limit might be even higher than what has been assumed. W. Fisher pointed out that the LHC has still to operate in conditions where the non-linearities of the triplets and the long range beam beam interactions have an effect on the beam dynamics, therefore the predictions based on 2010 experience might not be precise. R. Garoby pointed out that the presentation was focused on the beam parameters available for physics, while more relevant for the injector upgrade are the beam parameters needed at injection, which may be more demanding. E. Chaposnikova and R. Schmidt remarked that some of the combinations of emittance, intensity total current considered during the talk might be too optimistic for the injectors and LHC. S. Gilardoni commented that it is still difficult to predict the combinations of emittances and currents of the beam injected in the booster from Linac4. R. Brinkmann asked whether the luminosity lifetime should be taken into account for estimating the performance, luminosity lifetime is linked to the total beam current, therefore ideally one would like to operate at the maximum beam current limit of the machine. R. Assman asked if the present triplets will reach the radiation damage limit before the time of the LHC upgrade, the answer read that the damage limit is 300-500 fb^{-1}, which is likely to be reached only after 2020. V. Shiltsev commented that a premature optimization towards smaller emittances at a cost of total intensity may not be optimal for maximizing the integrated luminosity.

BREACHING THE PHASE I OPTICS LIMITATIONS FOR THE HL-LHC

Stephane Fartoukh, after a review of the HL-LHC goals, presented a novel LHC optic proposal, called Achromatic Telescopic Squeezing (ATS) Scheme, that allows very low beta* values with excellent chromatic properties, for instance beta*=15cm in both planes (round optics) or with even smaller beta* in the plane perpendicular to the crossing plane (e. g. 30/7.5cm, called flat optics) Both options needs the same hardware changes to achieve low beta* values, (mainly in IR1 and IR5, triplets, separation dipoles, matching quadrupoles), but also in IR6. For the new triplet, Nb3Sn technology is beneficial, but acceptable backup solutions can be found with NbTi technology as well. At ultimate intensity with 25ns bunch spacing, both optics give a similar (“virtual”) luminosity of the order of 8-9·10^{34} cm^{-2} s^{-1} with crab-cavities. Without crab-cavities, the above performance is reduced to 3.5·10^{34} cm^{-2} s^{-1} and 5.6·10^{34} cm^{-2} s^{-1} for the round and flat optics, respectively. The latter, obviously preferred, is only more sensitive to magnetic field errors and long range beam-beam interactions. The HL-LHC goals can be then achieved with smaller emittance (2.75 µm) and slightly shorter bunch length (6 cm) within the designed beam beam limit of 0.01. The crossing angle can be used as a luminosity leveling tool with a very modest cost in terms of aperture requirements.. The talk concluded that the ATS scheme is not only a necessary ingredient for most of the upgrade scenarios, but as well a novel path toward the LHC upgrade, based on flat optics and relying only on existing and well-characterized technology. The missing performance to reach the HL-LHC goals can be achieved with increased current, smaller emittance and shorter bunch lengths. Notably the ATS scheme can be tested in the present LHC under special conditions. An alternative bunch pattern with “micro-batches” has been proposed to eliminate the so-called pac-man effect.

In the discussion several points were raised mainly related to the impact of the large beta functions. O. Brüning asked whether there could be an impact on the orbit correction strategies, J. Wenninger replied that the scheme might be feasible although R. Schmidt remarked that machine protection might be more demanding due to faster orbit changes in case of magnet malfunctions. E. Todesco remarked that higher beta in the triplets translates in stricter margins for magnet field quality. Larger beta functions requires also larger aperture magnets, G. Kirby expressed concerns for the newly proposed wider MQY as Q4; S. Fartoukh remarked that smaller room available for coils compared to a standard MQY can be compensated by a weaker gradient coupled with a longer magnet. Instead D2 and D1 probably becomes much more challenging as remarked by S. Fartoukh and L. Rossi. Few modifications to the scheme presented have been proposed: eliminating one sextupole instead of adding one in Q10 by N. Catalan, but this would have a direct impact on performance. Answering to a question of R. Brinkmann, S. Fartoukh said that using different horizontal and vertical emittance instead of different beta* would not be compatible with an alternating plane crossing scheme.

HL-LHC: PARAMETER SPACE, CONSTRAINTS AND POSSIBLE OPTIONS

Frank Zimmermann explored the ingredients that are applicable to the HL-LHC upgrade and, after proposing three alternative scenarios, showed a possible road map. In particular a comparison of leveling strategies has been presented: beam offset at the IP, beta* or Piwinski angle with the crossing angle or crab cavity voltage. Once the maximum instantaneous luminosity is fixed the luminosity lifetime depends mainly on the initial beam current and the leveling potential. These three methods perform differently in terms of tune shift changes and it could be envisaged a combined used of them. Quantitative analysis of integrated luminosity were made on one single parameter change. Three alternative scenarios to achieve HL-LHC goals were proposed: low beta* and crab cavities; low beta*, Landau cavity and wire compensators; large Piwinski angle, flat longitudinal bunch profile and wire compensators. Their ingredients are analyzed, as well as intensity limitations, concluding that the performance goal can be achieved with a variety of options. The presentation ended with a road map that starts with machine development studies in LHC, continues installing the hardware for wire compensators, crab cavities, Landau cavities in the following two long shutdown to be ready in 2020 with the installation of the new magnets for low beta* optics.

During the discussions R. Garoby asked what are the schemes that would be more sensitive to the beam quality, that is the bunch by bunch variations of intensity and emittance, but the reply was no one in particular. R. Assman remarked that the beam already shows signs of beam-beam coherent instabilities since the transverse damper is needed during collision, although G. Arduini suggested that bunch by bunch variations might also act as a damping mechanism. V. Kain remarked that sources of emittance growth should be taken into account considering the present machine performance but O. Brüning added that synchrotron radiation damping will be stronger at 7TeV. S. Fartoukh remarked that in absence of crab cavities, the flat beam optimization results in larger luminosity even by just re-increasing beta* in the crossing plane up to 30cm.

EXPECTATIONS ON MANAGEMENT AND PERFORMANCE EVOLUTION: LESSONS FROM TEVATRON AND OTHER COLLIDERS.

Vladimir Shiltsev presented a synthesis of what has been learned from past colliders. He showed that the evolution of the peak luminosity follows an exponential law for a long period of time. The coefficient is related to the complexity of the accelerator defined as the ratio between the time it takes to reach a goal and the logarithm of the performance. In the Tevatron experience, he identified three periods characterized by very quick progress (start-up), moderate progress (development, upgrade phases), slow progress (operation phase). In addition, the improvements are always small in the order of few tens of percent, or even less, but the combinations of many of them may yield an order of magnitude or more. The presentations stressed also the importance of the expectation management and how it depends on the knowledge of the machine. He concluded with a prediction for the LHC: 6-9 years to bring the peak luminosity from 3 10^{33} up to $5 \cdot 10^{34}$ cm^{-2} s^{-1} .

During the discussion M. Ferro-Luzzi asked how much time has been spent in the Tevatron for machine development studies. The answer was that many studies were required at the very beginning as much as 3 slots per week and the number slowly reduced to 2 per month once reached the peak of performance. L. Bottura asked what determined the Tevatron crisis between Run 1 and Run 2. The answer stressed that it was related to a non sufficient understanding of the machine physics issues; in particular, the behaviour of the beam beam long range interactions was unexpected. E. Todesco asked what relative improvement would jusitfy an upgrade. For Tevatron there was not a single isolated upgrade but a campaign of improvements. It tooks 6 years to reach a 10 fold luminosity increase and some of the improvements proved to bevery effective for reasons different from the ones they were designed for. It was again stressed that the key for any improvement passed through a better understanding of the machine behaviour.

ALICE AND LHCB IN THE HL-LHC ERA

Sergio Bertolucci presented a projection of the Alice and LHCb scenarios after the HL-LHC upgrade when the LHC will operate at very high luminosity. The experimental programs need often reassessments driven by luminosity evolution, maintenance scenarios, upgrades and resources. In this moving frame is not always easy to keep the consistency of the decisions in advance. In this context answering to questions is very challenging but a way can be found by looking at the physics motivations that may support the choices. The presentation followed with a list of physics studies of extreme interest for the wide community behind the two experiments. For Alice they are jet quenching and high parton physics. Alice is already undergoing to a set of upgrade to improve the performance in order to extend the physics reach and improve the rate capabilities. LHCb has, as well, a rich physics program: direct searches for Higgs mass, lepton flavor physics, electro-weak physics, central exclusive production. In conclusion there are many compelling and exciting physics motivations to support the physics program for LHCb and Alice.

During the discussions S. Fartoukh asked the level of luminosities Alice and LHCb would likely expect in HL-LHC times. The answer was $1\text{-}2 \cdot 10^{33}$ cm^{-2} s^{-1} for LHCb while for Alice is $2 \cdot 10^{27}$ cm^{-2} s^{-1} and $5\text{-}10 \cdot 10^{29}$ cm^{-2} s^{-1} for ions and protons respectively.

CONCLUSION

The session produced lively discussions and follow up in particular in the close future concerning beam experiments and an exchange of specification between the injector upgrade project (LIU) and HL-LHC. During the summary M. Ferro-Luzzi expressed the opinion that when very high luminosity will come, experiments will prefer 25ns solution even at the cost of part of the integrated luminosity.

At this stage, it is possible to drive the following conclusions. Apart for – extremely important – reasons of hardware changes and robustness, an upgrade of the LHC is needed in order to increase the baseline performance and boost the luminosity leveling potential, as well as an injector upgrade in order to provide higher current at lower emittance. Several ingredients (high brilliance, low beta*, large aperture magnets, crab cavities, leveling strategies, wire compensators, landau RF cavities, flat longitudinal profile), combined in several alternatives ways, can provide a sound base for reaching the HL-LHC performance goals. Next years will be devoted to analyses, designs and experiments in order to understand machine issues, test the feasibility of the hardware solutions and validate the theoretical frameworks. As it has been stressed, the success of an upgrade will depend on the physics understanding of the machine components and behavior, as well as a good match with the injector performance (LIU project). As a final remark the HL-LHC project should make sure that the solutions that will upgrade the performance for ATLAS and CMS will be compatible with the upgrade needs of Alice and LHCb.

ACKNOWLEDGMENTS

We would like to thank the speakers for the excellent work in preparation of the workshop and for providing a very sound base for the progress of the HL-LHC project.

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LHC INJECTORS UPGRADE

Roland Garoby, Malika Meddahi, CERN, Geneva, Switzerland

Abstract

The performance of the LHC critically depends upon the characteristics of the beam provided by the injectors. Session 9 was devoted to the analysis of the status of the injectors and of the possibilities to upgrade their performance for satisfying the needs of the High Luminosity LHC.

PERFORMANCE REACH OF THE INJECTORS IN 2011

(Rende Steerenberg, BE-OP)

Summary

The results obtained in 2010 are a perfect illustration of the importance of the availability of beams with characteristics which exceed the initially planned needs and can flexibly be changed. After early tests with single bunches, trains with nominal bunch intensity and progressively decreasing bunch spacing (150, 75 and 50 ns) were successively used. The nominal beam ($1.15\ 10^{11}$ p/b, 3.5 μrad, 25 ns spacing) was readily available, but it was not requested by the collider.

A very satisfying observation is the smaller than budgeted transverse emittance blow-up between the exit of the PSB and the LHC at high energy, leading to smaller than expected transverse emittances in collision (typically 2.5 μrad instead of 3.75) and higher luminosity.

Brighter and more intense bunches were prepared in the PSB and PS for studying the SPS behavior during MDs. Up to $1.5\ 10^{11}$ p/b were successfully accelerated up to 450 GeV with 50 ns spacing and nominal emittances. With 25 ns spacing, however, bunches blew up transversely by a large factor, probably because of electron-clouds related effects in the SPS.

A higher Linac2 beam current and double batch injection in the PS will be used in 2011 to try and generate low emittance bunches with 75 and 50 ns spacings.

Discussion

R. Steerenberg: the work required to set-up the 150 ns beam competes with the optimisation of 75 and 50 ns beams. Is the 150 ns beam still necessary in 2011?

R. Assmann: Oliver Brüning has assumed $1.7\ 10^{11}$ p/b and 2 μrad with 50 ns spacing in his presentation. Is it feasible? R. Steerenberg: this is anticipated with double batch, but it remains to be confirmed in MD.

G. Arduini: which intensity can be reached with 150 ns bunch spacing? R. Steerenberg: no number can be given yet: to be tested!

M. Ferro Luzzi: why is 75ns bunch spacing less attractive in terms of intensity and emittance than 50 ns? R. Steerenberg: because of longitudinal instability in the PS resulting from reduced Landau damping (h=14 instead of h=21 during acceleration).

S. Myers: are RF tubes in Linac2 the main limiting factor to performance? M. Vretenar: limitations come from the ion source, not from the RF tubes.

W. Höfle (answering to the request of R. Steerenberg to apply transverse blow-up only in the SPS): The transverse blow up is not ppm in the SPS, but a clear procedure exists for the operators to apply.

M. Lamont: what are the CO plans for increasing the number of users? E. Hatzangeli: there is a technical limitation on the hardware. This is being addressed.

R. Steerenberg: There are currently a maximum of 24 possible users -the limit coming from the present electronics in the Front Ends. Up to now, a user was associated to each LHC beam type, leading to these numerous users. It is proposed (and actually will be implemented for 2011) to have 5 types of LHC general users (PROBE, INDIV, Setting-up, Production, MD) and to each of them attach the current requested user which is taken directly from the archive user library. So we will not have anymore a dedicated user to each beam type. Sometime will be requested to prepare the beam in the injectors, but with adequate pre-warning to the injectors, this will be done and ready when LHC will request this beam type. For the MD, again various beam types will have to be set-up and time needed to provide the requested beam.

P. Collier: cycles will also be available in the supercycle at the beginning of the LHC restart, as not all FT users will have to be served. R. Steerenberg: yes, this is an option which will be used for the MD requests, and this option is especially interesting with the new user implementation being performed for 2011.

POSSIBILITY OF A HIGHER PSB TO PS TRANSFER ENERGY

(Klaus Hanke, BE-OP)

Summary

The Task Force in charge of analysing the possibility to increase the transfer energy from PSB to PS has come up with a baseline scenario and drawn the following conclusions [1]:

- the upgrade from 1.4 to 2 GeV of PSB, transfer line and PS injection are technically feasible,
- the foreseeable increase of beam brightness in the PS is of the order of 65 %,
- the total cost (material budget), including consolidation, adds up to approximately 54 MCHF,

the main cost driver being the power supply for the dipole magnets,
- the modifications should rather be implemented simultaneously with the connection of Linac4, during a long shutdown in 2016.

A number of subjects deserve further investigation before a detailed project proposal can be submitted [1, 2].

Discussion

K. Hanke: although declared feasible, the 2 GeV injection equipment for the PS is still in work.

S. Myers: why is the PSB upgrade so expensive? K. Hanke: because the PSB has 4 rings with the same total beam pipe length than the PS, combined with complexity due to compactness.

S. Baird: are you planning for significant work during the first and second long shutdowns? K. Hanke: YES!

L. Rossi: there is clearly competition for resources! This will impact on the work that can be accomplished during the Long Shutdowns and on the overall planning of the PSB upgrade. R. Garoby: this is a goal of the LIU project to clarify these issues and propose a coherent approach for all injectors, in close collaboration with the Consolidation project.

A. Siemko: No upgrade of magnets and beam interlock systems were mentioned, are they not needed? B. Mikulec: They are indeed already included within work packages of the Linac4 project.

PS POTENTIAL PERFORMANCE WITH A HIGHER INJECTION ENERGY

(Simone Gilardoni, BE-ABP)

Summary

The expected performance increase of the PS remains to be demonstrated with beam. Transverse emittances may blow-up because of multiple mechanisms beyond space charge (dilution due to imperfect injection, head-tail instability, TMCI, e-clouds effect…). The same is true in the longitudinal phase plane, where coupled bunch instabilities and transient beam loading in the RF cavities must be mastered.

Taking into account the observed preservation of transverse emittances through the cascade of injectors, the following guesses can be made when the PSB will operate with Linac4 and inject into the PS at 2 GeV:

- with 25 and 50 ns spacing, between 1.9 10^{11} (realistic) and 3 10^{11} p/b (stretched) could be obtained within 2.5 µrad,
- the minimum emittance achievable at ultimate intensity with 25 ns spacing may be as low as 1.8 µrad,
- even smaller emittances can potentially be expected with up to 3 10^{11} p/b with 50 ns spacing.

For that purpose, numerous equipments must be upgraded or built (for injection, beam loading compensation, instability damping with feedbacks...). Consolidation shall not be forgotten as well as additional radio protection measures (e.g. shielding above road Goward).

Discussion

S. Gilardoni: a bunch intensity of 3.5 10^{11} p/b (as assumed by O. Brüning in his presentation) is not achievable due to longitudinal considerations. The optimistic goal after machine upgrades is of the order of 3 10^{11} p/b to SPS. Moreover, it is important to know the tolerance of LHC to imperfections in the longitudinal beam parameters (equality between bunches, ghost bunches...). A long list of MDs is being prepared and it is questioned if all of them can realistically be scheduled.

R. Garoby: the extensive need for magnets consolidation has to be added to this upgrade programme. Concerning cost, only the injection system equipment has been accounted for in the Task Force estimate, and not the other hardware required for upgrading the PS.

V. Mertens: is it possible to increase the PS transfer energy to the SPS? S. Gilardoni: the question is being studied for the 14 GeV Fixed Target beam (non-LHC). This is not possible for the LHC beam, due to transfer equipment limitation.

S. Myers: the cost of actions which are not for LHC has to be declared and approved separately from the LHC upgrade. Moreover, the PS could in the past extract at 26.6 GeV: what are the current limitations? R. Garoby: this needs to be revisited.

F. Zimmermann: What is missing for going beyond 3 10^{11} p/b? S. Gilardoni: longitudinal instabilities and transient beam loading in the RF cavities limit the intensity to about 2.8 10^{11} p/b! Don’t forget that the PS would probably have to provide more than 4 10^{11} p/b for getting 3.7 10^{11} p/b in LHC.

E. Shaposhnikova: experimental evidence has shown that increasing the RF voltage in the PS does not necessarily reduce the losses in the SPS.

LESSONS FROM SPS STUDIES IN 2010

(Elena Shaposhnikova, BE-RF)

Summary

MDs in 2010 were focused on improving the understanding of SPS limitations in the transverse and longitudinal phase planes and on studying/experimenting possible solutions. This was helped by the lower energy accelerators which provided beams of unprecedented intensity and brightness.

The nominal beam (1.15 10^{11} p/b, 3.5 µrad, 25 ns spacing) is readily available and suffers from less losses than in the past. From an injected beam in three batches of 1.9 10 ^{11} p/b within 5 µrad with 25 ns bunch spacing, 1.5 10^{11} p/b was accelerated up to 450 GeV where an emittance of 10 µrad was measured. With 50 ns bunch spacing, a similar intensity could be accelerated which stayed within the nominal emittances of ~3.5 µrad.

Promising results were obtained with a reduced γ_T lattice which increases the threshold of instabilities.

It seems nowadays reasonable to estimate that the SPS could provide bunches of ultimate intensity within nominal emittances for 75 and possibly 50 ns bunch spacings (provided that a higher intensity is injected within smaller emittances). After upgrade (200 MHz RF, e-cloud counter-measures, upgraded transverse feedback...), ultimate intensity bunches of nominal emittances can probably be obtained with 50 and 25 ns bunch spacings.

Using a reduced γ_T lattice appears as a potential option for reaching even better performance.

Discussion

J. Jowett: the low γ_T optics seems indeed to be very promising for protons, but what would be the impact on heavy ions? E. Shaposhnikova: the plan is to switch between the optics from cycle to cycle and to use the normal lattice for ions.

V. Mertens: is kicker heating still an issue, because it is excessive only during persistent running, e.g. during MDs, but not during LHC injection which is a quicker process. E. Shaposhnikova: the SPS must be ready for a long injection process, such as sometime experienced in 2010.

ELECTRONS CLOUDS IN THE SPS: PROGRESS IN THE ANALYSIS OF CURES/MITIGATION MEASURES AND POTENTIAL SCHEDULE OF IMPLEMENTATION

(Jose Miguel Jimenez, TE-VSC)

Summary

The demonstration has repeatedly been made that beam with 25 ns bunch spacing in the SPS suffers from electron clouds induced instabilities. This is comforted by simulations. Threshold with nominal emittance is nowadays slightly above nominal intensity. Among the possible counter-measures (suppression, mitigation or cure), low SEY amorphous Carbon (a-C) coating has been intensively studied since a few years. Before taking a decision, the advantages/drawbacks of other possibilities like clearing electrodes, feedback and scrubbing must be evaluated. In any case, prototype(s) of the preferred solution(s) shall be installed during the first long LHC shutdown (~2013) to be tested with beam during the following run. The full-blown solution shall be implemented during the second long LHC shutdown (~2017)

Discussion

V. Mertens: much effort has already been put in scrubbing and coating. Shouldn't we try to preserve the sectors which have been scrubbed in order to keep what has been achieved? J. M. Jimenez: indeed, we are trying to reduce as much as possible the number of sectors which are vented during shutdown. In the coated zones, we observed in any case that the machine re-start situation is only a little worse after venting.

S. Fartoukh: Why should 1 mm aperture reduction introduced by the clearing electrodes be a problem in the SPS? Paul Collier: this is due to the non-LHC beams which have much larger physical emittances.

E. Métral: why not use another bunch spacing to perform scrubbing? Jose Miguel Jimenez: this is certainly a possibility, depending upon other limitations. To be studied.

L. Rossi: If magnets are moved for coating purposes, we should profit to renovate them.

E. Shaposhnikova: clearing electrodes will increase the imaginary part of the impedance. Carbon coating is definitely better in that respect. With the feedback, coherent effects can be damped but incoherent effects will remain and lead to emittance growth.

S. Baird: moving all SPS magnets to coat vacuum chambers is envisaged during the first and second long shutdowns. Can it be done at the rate of 3 magnets/day? Jeremie Bauche: yes, provided that adequate support is available for transport.

R. Garoby: how can we get enough confidence in coating (e.g. because of ageing)? Jose Miguel Jimenez: tests can be made on samples in the laboratory with electron bombardment, and in HiRadMat with proton beam.

To the question "can magnetic measurements be performed on a coated magnet, without damaging the coating?", Jeremie Bauche replied: yes, a solution exists which avoids using a tool insertion in the magnets to perform measurements.

ALTERNATIVE / COMPLEMENTARY POSSIBILITIES

(Christian Carli, BE-ABP)

Summary

For the generation of the LHC beam in the PS, either 3 out of 4 or 6 out of 8 PSB rings are used and not all the protons available from the PSB are exploited. New scenarios are being proposed which make use of all the intensity that the PSB can deliver. However, because of size and harmonic number constraints, the ratio between the harmonic numbers at ejection wrt injection cannot be an integer, and batch compression is necessary. A direct consequence is that the number of bunches per PS cycle is lower than usual (72). In the first proposed scenario, 8 bunches are injected from the PSB and transformed into 64 bunches spaced by 25 ns before ejection to the SPS. With respect to the usual scenario, brightness and bunch intensity can in principle be increased by a factor 1.5. In the second scenario, the 8 PSB bunches are transformed into 48 bunches spaced by 25 ns before ejection to the SPS and the bunch intensity and brightness can potentially be two times larger than usual.

These scenarios are not expensive to implement in terms of material budget, but they need MD time and they add significant complexity to the already sophisticated PS beam control.

Considering the high cost of upgrading and consolidating the PSB (~60 MCHF), its replacement by a Rapid Cycling Synchrotron (~10 Hz) is another interesting alternative. Adding the requirements that (i) the energy range has to be 160 MeV – 2 GeV, (ii) beam characteristics have to be competitive with the PSB at 2 GeV and (iii) the PS operation has to be simplified, the most interesting size is 1/7 of the PS and the RF system should be able to operate on harmonic 2 or 3. To generate 25 and 50 ns bunch trains (72 or 36 bunches), the PS would be filled in 6 pulses of 3 bunches, giving 18 bunches on h=21 and suppressing the need for triple splitting. To generate 150 and 75 ns bunch trains (12 or 24 bunches), the PS would be filled in 6 pulses of 2 bunches, giving 12 bunches on h=14 and suppressing the need for double splitting at low energy.

Discussion

A great advantage of the RCS is that it could be built independently of the LHC operation in the centre of the PS ring, without much impact on existing buildings. In addition, beam commissioning could take place without interfering with LHC operation.

Y. Papaphilippou: collimators might be required in the RCS which will be hard to fit within the tiny straight sections.

L. Rossi: what would be the cost of such a machine? R. Garoby: no detailed study has yet been done. The RCS circumference being ~equal to the length of Linac4, it should not exceed the cost of Linac4 (100 MCHF).

S. Myers: the cost of the upgrade of the PSB makes it a very expensive machine. It should be understood why an RCS was not built instead. R. Garoby: this question has to be addressed during the pre-study of the RCS. For this work to take place, the proposal is to liberate resources from the PSB upgrade by “freezing” the work on the energy upgrade until the summer of 2011, when the first conclusions will be submitted to the management.

E. Métral: 48 bunches/ PS batch sounds very interesting.

M. Vretenar: operation at 10 Hz for the RCS has implications on Linac4. Some may be costly (e.g. klystron modulators) and deserve analysis.

MAIN MESSAGES

The specification of the beam required at LHC injection is essential for guiding the choices in the injectors. It should result from close interactions between the HL-LHC and LIU projects.

Testing a batch compression scheme in the PS can immediately bring important information for the generation of beyond ultimate 25 ns bunch trains. If successful, it will provide the possibility to explore the SPS potential without waiting for Linac4, PSB and PS upgrades.

Increasing the energy of the PSB is the primary solution for substantially upgrading the brightness that the PS can deliver.

However, a small size RCS replacing the PSB is an especially interesting alternative option.

The SPS remains the limiting accelerator in the injector chain. The well-identified improvements shall be implemented as soon as possible to allow studying the other limitations.

The possibility to connect Linac4 to the PSB during the first long shutdown is worth investigating.

Final remark: most of the subjects treated in this session have been addressed in more detail during the “LIU day” workshop [2] web page.

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LHC 2010 OPERATION - AS VIEWED FROM THE EXPERIMENTS

M. Ferro-Luzzi, CERN, Geneva, Switzerland

Abstract

This paper tries to summarize how the LHC experiments have perceived the 2010 run. A critical review of LHC operation, beam conditions and luminosity delivery will be given,a as well as proposals for improvements.

INTRODUCTION

First, a brief review of the 2010 LHC run is presented, with emphasis on physics operation. Second, lessons from the 2010 run, as seen by the experiments, are listed and proposals for improvements are made.

SUMMARY OF 2010 RUN

LHC proton operation started on February 28 and stopped on November 4. The LHC proton run can be divided in three phases:

- Phase 1: The initial phase started with commissioning to 3.5 TeV and first collisions at $\sqrt{s} = 7$ TeV. It proceeded with a first optics squeeze ($\beta^* = 2$ m at all IPs), and continued with an increase in the number of bunches (from 2 to 13) of small intensity (1 to $2 \cdot 10^{10}$ p). During this phase, physics collisions at 0.45 TeV/beam were also delivered, at injection optics and with close to nominal bunch intensities. The LHC physics fills of this phase are listed in table 1.
- Phase 2: After successfully testing physics collisions with nominal bunches at injection energy, the machine was prepared for collisions at 3.5 TeV/beam with $\beta^* = 3.5$ m at all IPs and with a small number of bunches of nominal intensity. The beam intensities and luminosities were pushed up by increasing the number of bunches from 3 to 50. This phase ended with a 1-month period of physics production with stable conditions and a stored beam energy of about 2 MJ (August). The LHC physics fills of this phase are listed in table 2.
- Phase 3: Finally, the machine was commissioned to work with bunch trains of 150 ns spacing (and nominal bunch intensities). The total number of bunches was increased from 24 to 368 (about 20 MJ per beam). A single test fill with 50 ns was attempted at the end. The LHC physics fills of this phase are listed in table 3.

The state of the LHCb dipole spectrometer and of the ALICE dipole and solenoid spectrometers are indicated in the tables. The polarity ('+' or '−') refers to the power converter polarity ('0' means 'off'). For IP2, the solenoid and dipole were always in the same state.

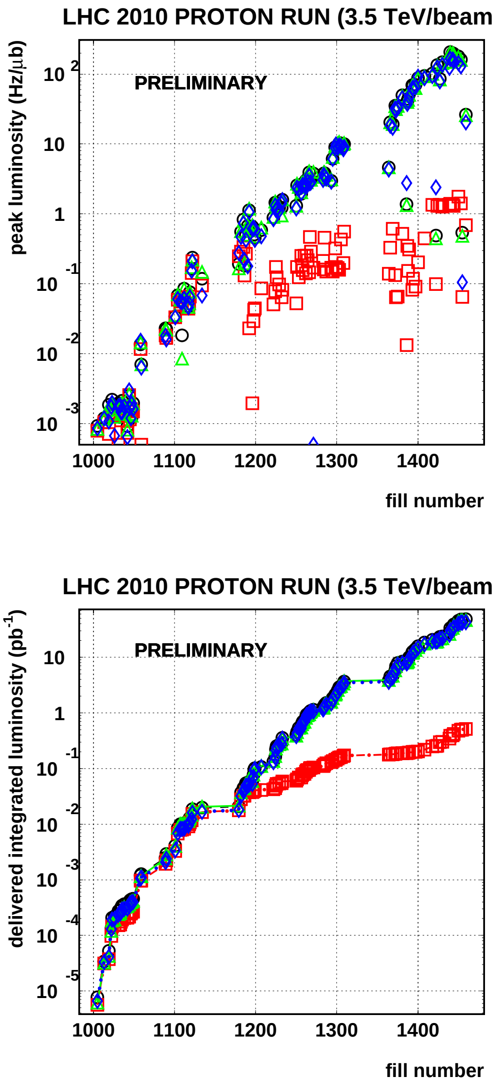

Figure 1: Overview of 2010 proton run. The top (bottom) graph shows the evolution of the peak (integrated) luminosity in the four interaction points. Symbols: ○ IP1, □ IP2, △ IP5, ◇ IP8.

There were six techical stops (starting on March 15, April 26, May 31, July 19, August 30, October 19) of 2 to 4 days during the proton run. During the ion run, a 3-day interruption of ion operation took place from November 17 to 20 to accomodate electron cloud studies with high intensity

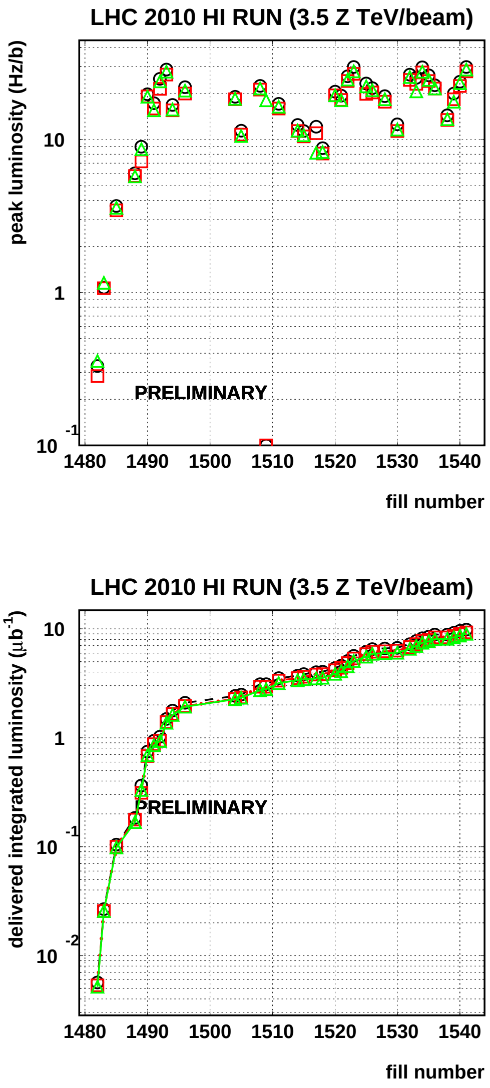

Figure 2: Overview of 2010 ion run. The top (bottom) graph shows the evolution of the peak (integrated) luminosity in the three interaction points. Symbols: ○ IP1, □ IP2, △ IP5, ◇ IP8.

proton beams (with 50 and 75 ns spacing).

An external crossing half-angle was introduced at IP1 (-100 μrad) and IP5 ($+100$ μrad) between the first and second phase. The angle at IP1 allowed LHCf to collect data with a different momentum coverage. The LHCf detector was dismounted during the July technical stop (the last 2010 physics fill for LHCf was fill 1233).

In order to facilitate operation with bunch trains, all IPs were set up with an external crossing angle between the second and third phase, An external horizontal crossing half-angle of $+100$ μrad in IP5 and of -100 μrad in IP8 was used (for LHCb the polarity reversals were applied to the internal angle only). External vertical crossing half-angles of -100 μrad in IP1 and of ± 110 μrad in IP2 were used (for ALICE the polarity reversals were applied to the spectrometers and to the external angle).

Since fill 1190, IR2 was operated with a horizontal parallel separation of 3 to 4 nominal beam sizes ($\sigma_{\mathrm{beam}} \approx 60$ μm) to maintain a luminosity between $\sim 10^{29}$ $\mathrm{Hz/cm^2}$ and $2 \cdot 10^{30}$ $\mathrm{Hz/cm^2}$.

A number of special activities were organized:

- A few fills at $\sqrt{s} = 0.9$ TeV were delivered (1068, 1069, 1128) to complement the 2009 physics run and to test collisions with nominal bunch intensities. This allowed the experiments to collect several million events.
- A first series of Van der Meer scans was carried out in Phase 1, fills 1058, 1059, 1089 and 1090 [1], which yielded a direct luminosity calibration. A second series of Van der Meer scans was organized in Phase 3, this time during dedicated fills (1386 and 1422), to obtain a more precise luminosity calibration (at the level of 5%).
- Length scale calibration measurements for the Van der Meer scans were performed in fills 1393 (IP1), 1422 (IP8 and IP5), 1439 (IP5) and 1455 (IP2).
- Beam-based alignment of the TOTEM Roman Pots was done during fill 1359 and followed by a short data-taking period (of about 1 hour) with the pots positioned at about $7\sigma_{\mathrm{beam}}$ from the beam orbit. A second special data-taking period was delivered for TOTEM during fill 1455 (about 4 hours).
- During fill 1455, about one hour was dedicated to the technical test of a longitudinal scan. The phase between the beams was varied from -15 and +15 ns in steps of 5 ns (and 0.2 ns between -1 and +1 ns) . Possible applications of such scans are: longitudinal separation and collapse to collisions, measurement of the crossing angle and measurement of satellite bunch distributions.

The LHC ion run drastically benefited from the operational and commissioning experience of the proton run. Ion operation started on November 4 and stopped on December 6. The beam rigidity and the optics remained untouched ($E = 3.5\,Z$TeV and $\beta^* = 3.5$ m), from the start of the ion run. Only the crossing angles were modified such as to give zero net angle in all IPs (IP1, IP2 and IP5), which is an advantage for interpreting data of the Zero-Degree Calorimeters (ZDC). The TCTVB collimators in IR2 were opened enough to not create any shadow on the ALICE ZDC. The bunch intensity was between 6 and $12 \cdot 10^7$ Pb from the first fill (thus exceeding 'nominal' intensity). The number of bunches was rapidly increased from 2 to 121, and later to 137. All LHC physics fills of the ion run are listed in table 4.

Van der Meer scans for luminosity calibration with ions were carried out in fill 1533 for IP1, IP2 and IP5. Note that

Fill	Stable beams		E	Filling	Magnets		β^*
nr.	start	stop	(TeV)	scheme	IP8	IP2	(m)
1005	Tue 30.03 13:22	Tue 30.03 16:29	3.5	Single_2b_1_1_1	+	-	11/10
1013	Wed 31.03 21:03	Thu 01.04 05:05	3.5	Single_2b_1_1_1	+	-	11/10
1019	Sat 03.04 04:23	Sat 03.04 07:23	3.5	Single_2b_1_1_1	-	-	11/10
1022	Sun 04.04 17:26	Mon 05.04 13:29	3.5	Single_2b_1_1_1	-	-	11/10
1023	Tue 06.04 02:44	Tue 06.04 14:59	3.5	Single_2b_1_1_1	+	-	11/10
1026	Wed 07.04 10:28	Wed 07.04 12:52	3.5	Single_2b_1_1_1	+	-	11/10
1031	Sat 10.04 06:13	Sat 10.04 15:47	3.5	Single_2b_1_1_1	+	+	11/10
1033	Mon 12.04 01:24	Mon 12.04 03:23	3.5	Single_2b_1_1_1	0	+	11/10
1034	Mon 12.04 08:54	Mon 12.04 17:25	3.5	Single_2b_1_1_1	0	+	11/10
1035	Tue 13.04 05:01	Tue 13.04 09:31	3.5	Single_2b_1_1_1	+	+	11/10
1038	Wed 14.04 05:50	Wed 14.04 10:53	3.5	Single_2b_1_1_1	+	+	11/10
1042*	Thu 15.04 06:22	Thu 15.04 08:54	3.5	Single_2b_1_1_1	+	+	11/10
1044	Fri 16.04 05:50	Fri 16.04 09:12	3.5	Single_2b_1_1_1	+	+	11/10
1045	Sat 17.04 05:55	Sat 17.04 14:58	3.5	Single_2b_1_1_1	+	+	11/10
1046	Sun 18.04 06:06	Sun 18.04 06:55	3.5	Single_2b_1_1_1	+	+	11/10
1047	Sun 18.04 11:28	Sun 18.04 14:39	3.5	Single_2b_1_1_1	+	+	11/10
1049	Mon 19.04 03:55	Mon 19.04 05:14	3.5	Single_2b_1_1_1	+	+	11/10
1058†	Sat 24.04 03:13	Sun 25.04 09:30	3.5	Single_3b_2_2_2	+	+	2
1059†	Mon 26.04 01:34	Mon 26.04 06:32	3.5	Single_2b_1_1_1	+	+	2
1068	Sun 02.05 14:33	Sun 02.05 21:44	0.45	Single_2b_1_1_1	+	+	11/10
1069	Mon 03.05 02:03	Mon 03.05 09:18	0.45	Single_2b_1_1_1	-	+	11/10
1089†	Sat 08.05 22:33	Sun 09.05 18:55	3.5	Single_2b_1_1_1	-	0	2
1090†	Mon 10.05 04:31	Mon 10.05 10:57	3.5	Single_2b_1_1_1	-	+	2
1101	Fri 14.05 12:57	Fri 14.05 23:39	3.5	Single_4b_2_2_2	+	+	2
1104	Sat 15.05 16:54	Sun 16.05 14:14	3.5	Single_6b_3_3_3	-	+	2
1107	Mon 17.05 06:27	Mon 17.05 15:25	3.5	Single_6b_3_3_3	-	+	2
1109	Tue 18.05 04:54	Tue 18.05 05:35	3.5	Single_6b_3_3_3	-	+	2
1112	Wed 19.05 06:10	Wed 19.05 07:33	3.5	Single_6b_3_3_3	+	+	2
1117	Sat 22.05 03:39	Sat 22.05 11:42	3.5	Single_6b_3_3_3	+	+	2
1118	Sun 23.05 06:05	Sun 23.05 12:34	3.5	Single_6b_3_3_3	+	+	2
1119	Sun 23.05 20:45	Mon 24.05 00:18	3.5	Single_6b_3_3_3	+	+	2
1121	Mon 24.05 15:01	Mon 24.05 17:27	3.5	Single_13b_8_8_8	+	+	2
1122	Tue 25.05 03:15	Tue 25.05 12:27	3.5	Single_13b_8_8_8	+	+	2
1128	Thu 27.05 15:07	Thu 27.05 16:03	0.45	Single_7b_4_4_4	+	+	11/10
1134	Sat 05.06 13:42	Sat 05.06 17:28	3.5	Single_13b_8_8_8	+	-	2

Table 1: All fills with STABLE BEAMS during the first phase of the 2010 LHC proton run. Magnets: IP8 = LHCb dipole, IP2 = ALICE dipole & solenoid. *The CMS solenoid was off during fill 1042. †Fill includes Van der Meer scans.

LHCb was switched off during the ion run (including the spectrometer bump).

In total, the LHC operated 1074 hours in STABLE BEAMS (851 hours with p and 223 hours with Pb) out of about 6600 hours. There were 147 fills with STABLE BEAMS (110 with p and 37 with Pb).

Figure 1 shows on the top graph the peak luminosity as a function of physics fill number. The peak luminosity increased from $8 \cdot 10^{26}\ \mathrm{Hz/cm^2}$ to $2 \cdot 10^{29}\ \mathrm{Hz/cm^2}$ (Phase1), then further to $4.6 \cdot 10^{30}\ \mathrm{Hz/cm^2}$ (Phase 2) and finally reached $2 \cdot 10^{32}\ \mathrm{Hz/cm^2}$ (Phase 3). The integrated delivered luminosities (2010 totals) were approximately $48\ \mathrm{pb^{-1}}$ (IP1), $0.5\ \mathrm{pb^{-1}}$ (IP2), $47\ \mathrm{pb^{-1}}$ (IP5) and $42\ \mathrm{pb^{-1}}$ (IP8).

Figure 2 shows the corresponding graphs for the ion run (LHCb switched off). In this case, the luminosity was increased from $3 \cdot 10^{23}\ \mathrm{Hz/cm^2}$ to $3 \cdot 10^{25}\ \mathrm{Hz/cm^2}$. The integrated delivered luminosities were approximately $9.9\ \mu\mathrm{b}^{-1}$ (IP1), $9.3\ \mu\mathrm{b}^{-1}$ (IP2) and $9\ \mu\mathrm{b}^{-1}$ (IP5).

Other yearly summary plots are available at the LHC Programme Coordinations site [2].

2010 LESSONS

Modus operandi: The early June experience with machine operation alternating between commissioning (at day time) and physics (at night) showed that this mode of operation had reached its limits (though its was useful during the initial phase). Subsequently, a clear separation between major commissioning steps and physics production was put in place, to the benefit of the LHC machine and LHC experiments. For 2011, such a separation between commissioning blocks (of several days) and physics production (of several weeks) should be maintained.

Technical stops: The impact of technical stops on operation, and in particular the recovery from a stop, was discussed elsewhere (see [3]). Originally, a 3-day stop every fourth week was planned for the LHC. From the 2010 experience, it seems that a space of 6 weeks between the start of two subsequent (4-day long) technical stops is acceptable. The frequency and length of such stops needs to be further optimized. The cooperation between the Technical Stop Coordinator and the LHC Machine Coordinator was strengthened in the course of 2010. This improved the supervision of interventions (hardware and software changes) and helped reducing collateral effects of technical stops on operation. Further strengthening of this cooperation will help minimizing the machine downtime.

Increasing stored beam energy: The increase of beam intensity (stored energy) in the LHC machine was driven by both machine protection aspects and operational considerations. The human factor and improvement of operational

Fill	Stable beams		E	Filling	Magnets		β^*
nr.	start	stop	(TeV)	scheme	IP8	IP2	(m)
1179	Fri 25.06 01:35	Fri 25.06 03:57	3.5	Single_3b_2_2_2	+	-	3.5
1182	Sat 26.06 19:28	Sun 27.06 10:15	3.5	Single_3b_2_2_2	+	-	3.5
1185	Tue 29.06 11:57	Tue 29.06 16:11	3.5	Single_3b_2_2_2	+	-	3.5
1186	Wed 30.06 08:15	Wed 30.06 10:36	3.5	Single_3b_2_2_2	+	-	3.5
1188	Thu 01.07 02:56	Thu 01.07 10:47	3.5	Single_3b_2_2_2	+	-	3.5
1190	Fri 02.07 05:40	Fri 02.07 06:27	3.5	Single_7b_4_4_4	+	-	3.5
1192	Fri 02.07 17:30	Fri 02.07 18:04	3.5	Single_7b_4_4_4	+	-	3.5
1196	Sun 04.07 00:46	Sun 04.07 01:35	3.5	Single_7b_4_4_4	+	-	3.5
1197	Sun 04.07 06:22	Sun 04.07 18:16	3.5	Single_7b_4_4_4	+	-	3.5
1198	Mon 05.07 02:28	Mon 05.07 13:43	3.5	Single_7b_4_4_4	+	-	3.5
1199	Mon 05.07 23:11	Tue 06.07 02:58	3.5	Single_10b_4_2_4	+	-	3.5
1207	Fri 09.07 04:16	Fri 09.07 10:17	3.5	Single_10b_4_2_4	+	-	3.5
1222	Mon 12.07 03:02	Mon 12.07 11:56	3.5	Single_9b_6_6_6	+	-	3.5
1224	Tue 13.07 05:08	Tue 13.07 14:59	3.5	Single_12b_8_8_8	-	-	3.5
1225	Wed 14.07 02:13	Wed 14.07 17:02	3.5	Single_12b_8_8_8	-	-	3.5
1226	Thu 15.07 04:19	Thu 15.07 13:15	3.5	Single_13b_8_8_8	-	-	3.5
1229	Sat 17.07 00:44	Sat 17.07 04:36	3.5	Single_13b_8_8_8	-	-	3.5
1232	Sat 17.07 19:19	Sun 18.07 01:11	3.5	Single_13b_8_8_8	-	-	3.5
1233	Sun 18.07 10:56	Mon 19.07 05:58	3.5	Single_13b_8_8_8	-	-	3.5
1250	Wed 28.07 22:28	Thu 29.07 10:35	3.5	Single_13b_8_8_8	+	-	3.5
1251	Thu 29.07 23:28	Fri 30.07 07:25	3.5	Multi_25b_16_16_16_hyb	+	-	3.5
1253	Fri 30.07 23:11	Sat 31.07 12:20	3.5	Multi_25b_16_16_16	+	-	3.5
1256	Sun 01.08 03:50	Sun 01.08 04:49	3.5	Multi_25b_16_16_16	+	-	3.5
1257	Sun 01.08 22:00	Mon 02.08 12:35	3.5	Multi_25b_16_16_16	+	-	3.5
1258	Tue 03.08 00:22	Tue 03.08 07:39	3.5	Multi_25b_16_16_16	+	-	3.5
1260	Wed 04.08 04:31	Wed 04.08 06:38	3.5	Multi_25b_16_16_16	+	-	3.5
1262	Wed 04.08 17:40	Thu 05.08 11:19	3.5	Multi_25b_16_16_16	+	-	3.5
1263	Fri 06.08 03:52	Fri 06.08 19:08	3.5	Multi_25b_16_16_16	+	-	3.5
1264	Sat 07.08 01:42	Sat 07.08 02:14	3.5	Multi_25b_16_16_16	+	-	3.5
1266	Sat 07.08 23:12	Sun 08.08 01:10	3.5	Multi_25b_16_16_16	+	-	3.5
1267	Sun 08.08 05:18	Sun 08.08 18:52	3.5	Multi_25b_16_16_16	+	-	3.5
1268	Mon 09.08 01:29	Mon 09.08 04:02	3.5	Multi_25b_16_16_16	+	-	3.5
1271	Tue 10.08 07:24	Tue 10.08 12:22	3.5	Multi_25b_16_16_16	+	-	3.5
1283	Fri 13.08 23:06	Sat 14.08 12:04	3.5	Multi_25b_16_16_16	+	-	3.5
1284	Sat 14.08 15:44	Sat 14.08 19:13	3.5	Multi_25b_16_16_16	+	-	3.5
1285	Sun 15.08 00:39	Sun 15.08 13:02	3.5	Multi_25b_16_16_16	+	-	3.5
1287	Sun 15.08 23:01	Mon 16.08 09:24	3.5	Multi_25b_16_16_16	+	-	3.5
1293	Tue 18.08 09:12	Tue 18.08 21:13	3.5	Multi_25b_16_16_16	-	-	3.5
1295	Thu 19.08 23:36	Fri 20.08 14:19	3.5	1250ns_48b_36_16_36	-	-	3.5
1298	Mon 23.08 00:52	Mon 23.08 13:50	3.5	1250ns_48b_36_16_36	-	-	3.5
1299	Tue 24.08 00:11	Tue 24.08 03:26	3.5	1250ns_48b_36_16_36	-	-	3.5
1301	Tue 24.08 17:35	Wed 25.08 07:53	3.5	1000ns_50b_35_14_35	-	-	3.5
1303	Thu 26.08 04:21	Thu 26.08 17:26	3.5	1000ns_47b_32_14_32	-	-	3.5
1305	Fri 27.08 06:11	Fri 27.08 09:41	3.5	1000ns_50b_35_14_35	-	-	3.5
1308	Sat 28.08 22:43	Sun 29.08 12:22	3.5	1000ns_50b_35_14_35	-	-	3.5
1309	Sun 29.08 18:17	Mon 30.08 05:35	3.5	1000ns_50b_35_14_35	+	-	3.5

Table 2: All fills with STABLE BEAMS during the second phase of the 2010 LHC proton run. Magnets: IP8 = LHCb dipole, IP2 = ALICE dipole & solenoid.

procedures shaped the ‘learning curve’. Operation in 2011 and beyond will greatly benefit from the enormous experience acquired during 2010. In future years, intensity increase should be largely driven by the state of the machine protection system and by intrinsic performance limitations of the machine itself (such as e-cloud effects).

Filling the LHC: The LHC currently hosts seven approved experiments (ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM, MoEDAL) with diverse requirements on beam conditions. Filling the LHC in such a way that all experiments are adequately served is a challenge. Constructing filling schemes became increasingly complex toward the end of the 2010 proton run, mainly due to the following features:

- The use of an intermediate intensity batch ($< 10^{12}p$) before transfering a high intensity batch from the SPS imposed to use the same number of bunches per PS batch throughout the whole filling process. This is due to the fact that the number of bunches from the booster to the PS can not be dynamically driven by the LHC. For 150 ns operation, this precluded the use of 12-bunch trains from the PS. The implications were a small fraction of lost collisions (more train edges) and a reduced reach in total number of bunches as compared to 12-bunch trains. For future years, ideally, the LHC should be able to drive dynamically the number of booster bunches to the PS.
- The compulsory use of the intermediate intensity batch also introduced a difficulty in constructing well-balanced filling schemes. Besides the breaking of the four-fold symmetry, it also “consumes” 950 ns of the LHC circumference. Ideally, this batch should be dumped before starting the actual LHC filling, or it should be possible to inject a full intensity batch over the intermediate batch. Preferably, the deployed solution should work for any bunch spacing (150, 75, 50, 25 ns).
- The Abort Gap Keeper (AGK) window length was set

Fill	Stable beams		E	Filling	Magnets		β^*
nr.	start	stop	(TeV)	scheme	IP8	IP2	(m)
1364	Wed 22.09 16:54	Thu 23.09 06:37	3.5	150ns_24b_16_16_16_8bpi	-	+	3.5
1366	Thu 23.09 19:10	Fri 24.09 09:12	3.5	150ns_56b_47_16_47_8bpi	-	+	3.5
1369	Sat 25.09 09:38	Sat 25.09 11:05	3.5	150ns_56b_47_16_47_8bpi	-	-	3.5
1372	Sat 25.09 19:39	Sun 26.09 11:18	3.5	150ns_104b_93_8_93_8bpi	-	-	3.5
1373	Sun 26.09 21:27	Mon 27.09 09:58	3.5	150ns_104b_93_8_93_8bpi	-	-	3.5
1375	Tue 28.09 02:23	Tue 28.09 11:23	3.5	150ns_104b_93_8_93_8bpi	-	-	3.5
1381	Thu 30.09 02:25	Thu 30.09 05:28	3.5	150ns_152b_140_16_140_8+8bpi11inj	-	-	3.5
1386[†]	Fri 01.10 13:30	Fri 01.10 16:24	3.5	Single_19b_6_1_12_allVdm	-	-	3.5
1387	Sat 02.10 05:08	Sat 02.10 07:06	3.5	150ns_152b_140_16_140_8+8bpi11inj	-	-	3.5
1388	Sat 02.10 10:57	Sat 02.10 13:08	3.5	150ns_152b_140_16_140_8+8bpi11inj	-	-	3.5
1389	Sun 03.10 13:16	Sun 03.10 20:27	3.5	150ns_152b_140_16_140_8+8bpi11inj	-	-	3.5
1393[‡]	Mon 04.10 20:00	Tue 05.10 09:43	3.5	150ns_200b_186_8_186_8+8bpi17inj	-	-	3.5
1394	Tue 05.10 23:58	Wed 06.10 01:41	3.5	150ns_200b_186_8_186_8+8bpi17inj	-	-	3.5
1397	Thu 07.10 04:23	Thu 07.10 10:54	3.5	150ns_200b_186_8_186_8+8bpi17inj	-	-	3.5
1400	Fri 08.10 02:36	Fri 08.10 09:10	3.5	150ns_248b_233_16_233_3x8bpi15inj	-	-	3.5
1408	Mon 11.10 21:20	Tue 12.10 07:17	3.5	150ns_248b_233_16_233_3x8bpi15inj	-	-	3.5
1418	Thu 14.10 03:38	Thu 14.10 12:06	3.5	150ns_248b_233_16_233_3x8bpi15inj	-	-	3.5
1422[†]	Fri 15.10 13:14	Fri 15.10 18:27	3.5	Single_16b_3_1_12_allVdmB	-	-	3.5
1424	Sat 16.10 02:30	Sat 16.10 03:23	3.5	150ns_312b_295_16_295_3x8bpi19inj	-	-	3.5
1427	Sat 16.10 22:56	Sun 17.10 09:31	3.5	150ns_312b_295_16_295_3x8bpi19inj	-	-	3.5
1430	Mon 18.10 04:25	Mon 18.10 05:03	3.5	150ns_312b_295_16_295_3x8bpi19inj	-	-	3.5
1439[‡]	Sun 24.10 09:59	Sun 24.10 20:41	3.5	150ns_312b_295_16_295_3x8bpi19inj	+	-	3.5
1440	Mon 25.10 02:35	Mon 25.10 13:54	3.5	150ns_368b_348_15_344_4x8bpi19inj	+	-	3.5
1443	Tue 26.10 05:35	Tue 26.10 07:49	3.5	150ns_368b_348_15_344_4x8bpi19inj	+	-	3.5
1444	Tue 26.10 13:35	Tue 26.10 20:47	3.5	150ns_368b_348_15_344_4x8bpi19inj	+	-	3.5
1450	Thu 28.10 00:45	Thu 28.10 15:17	3.5	150ns_368b_348_15_344_4x8bpi19inj	+	-	3.5
1453	Fri 29.10 04:16	Fri 29.10 10:36	3.5	150ns_368b_348_15_344_4x8bpi19inj	+	-	3.5
1455[‡]	Sat 30.10 05:33	Sat 30.10 06:32	3.5	Single_5b_5_1_1	+	-	3.5
1459	Sun 31.10 01:24	Sun 31.10 07:25	3.5	50ns_109b_91_12_90_12bpi10inj	+	-	3.5

Table 3: All fills with STABLE BEAMS during the third phase of the 2010 LHC proton run. Magnets: IP8 = LHCb dipole, IP2 = ALICE dipole & solenoid. [†]Fill includes Van der Meer scans (and length scale calibrations). [‡]Fill includes a length scale calibration.

to match the nominal transfer from the SPS of 288 bunches of 25 ns spacing, i.e. a length of about $8\ \mu$s (3200 LHC Rf buckets). The AGK prevented injection of the first bunch of a batch to fall in an LHC RF bucket larger than about 32040 ($35640 - 3200 - 400$, where the 400 comes from the abort gap). In practice, the longest proton batch used was about $5\ \mu$s (and $3.5\ \mu$s for ion operation). Therefore, the $8\ \mu$s AGK window introduced a dead space of at least $3\ \mu$s which, when combined with the four-fold symmetry requirements, created difficulties and limitations for constructing well-balanced filling schemes. For 2011 operation, it is likely that the transfer of full $8\ \mu$s batches will actually be used (for e-cloud scrubbing and for physics).

For the ion run, the smaller the dead space, the less collisions will be lost at IP2 (ALICE). Note that the possibility to rephase the abort gap near IP2 was discussed, but finally not implemented due to potential disruptions in the DAQ of some of the experiment. This option might be reconsidered for the 2011 Pb run.

- When the BPM sensitivity is set for high intensity bunches, the BPMs cannot measure low intensiy bunches (below $\sim 5 \cdot 10^{10} p$). For this reason, it was decided (initially) not to operate with schemes mixing high and low intensity bunches, as the trajectory of the latter bunches would have been invisible. This precluded the option of using the intensity of special bunches for adjusting the interaction rate at low-luminosity experiments (ALICE, LHCf, TOTEM). For IP2, the alternative method of parallel separation was used with great success. For TOTEM, a single test with small bunches was performed in the last proton physics fill (1459), showing no particular issues related to the small bunch. Since TOTEM is at the same IP as CMS, parallel separation cannot be used. For 2011, the use of a few small intensity bunches during physics fills would allow TOTEM to collect low pile-up data in parallel to high-luminosity production for CMS. This trick could be used as long as the small intensity bunches do not occupy space otherwise usable by high intensity bunches (for example, if operating at 400 bunches with 75 ns spacing).

- Much of the turn-around time was spent at LHC injection (2 to 5 hours ?). This was due to several reasons: loss of injection requests because of the management of injection checks, non-dedicated injector operation for LHC filling (long supercycle), lengthy beam checks at injection, handshakes with the experiments, etc. For details see [4]. For 2011, an improved treatment of injection requests/checks, dedicated operation of the injector complex for LHC filling, more automated beam quality checks, are expected to give a much reduced turn-around time for physics.

Polarity reversals: The spectrometer polarity changes interfered with beam commissioning and operation. In 2010, the LHCb dipole polarity was reversed 12 times. The ALICE dipole and solenoid polarities were reversed 5 times.

Fill	Stable beams		E	Filling	Magnets		β^*
nr.	start	stop	(TeV)	scheme	IP8	IP2	(m)
1482	Mon 08.11 11:19	Mon 08.11 20:02	3.5	Single_2b_1_1_0_1bpi2inj_IONS	0	-	3.5
1483	Tue 09.11 01:01	Tue 09.11 09:58	3.5	Single_5b_4_4_0_1bpi5inj_IONS	0	-	3.5
1485	Tue 09.11 22:49	Wed 10.11 12:43	3.5	500ns_17b_16_16_0_4bpi5inj_IONS	0	-	3.5
1488	Fri 12.11 00:53	Fri 12.11 06:39	3.5	500ns_69b_65_66_0_4bpi18inj_IONS	0	-	3.5
1489	Sat 13.11 01:04	Sat 13.11 10:41	3.5	500ns_69b_65_66_0_4bpi18inj_IONS	0	-	3.5
1490	Sun 14.11 00:32	Sun 14.11 08:21	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1491	Sun 14.11 18:04	Mon 15.11 00:38	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1492	Mon 15.11 07:42	Mon 15.11 08:44	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1493	Mon 15.11 12:48	Mon 15.11 22:04	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1494	Tue 16.11 02:28	Tue 16.11 09:00	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1496	Wed 17.11 00:33	Wed 17.11 06:14	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1504	Sat 20.11 23:00	Sun 21.11 06:16	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1505	Sun 21.11 11:00	Sun 21.11 13:05	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1508	Mon 22.11 01:36	Mon 22.11 09:49	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1509	Mon 22.11 14:06	Mon 22.11 15:16	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1511	Mon 22.11 21:59	Tue 23.11 08:00	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	-	3.5
1514	Wed 24.11 02:04	Wed 24.11 08:31	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1515	Wed 24.11 14:01	Wed 24.11 17:00	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1517	Wed 24.11 22:02	Thu 25.11 03:34	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1518	Thu 25.11 06:58	Thu 25.11 08:06	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1520	Thu 25.11 18:11	Thu 25.11 23:58	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1521	Fri 26.11 05:43	Fri 26.11 09:51	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1522*	Fri 26.11 13:32	Fri 26.11 21:35	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1523*	Sat 27.11 03:59	Sat 27.11 12:23	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1525	Sat 27.11 23:54	Sun 28.11 09:51	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1526	Sun 28.11 13:22	Sun 28.11 18:59	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1528	Mon 29.11 02:05	Mon 29.11 03:41	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1530	Mon 29.11 14:54	Mon 29.11 17:06	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1532	Mon 29.11 23:56	Tue 30.11 08:05	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1533†	Tue 30.11 13:31	Tue 30.11 22:04	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1534	Wed 01.12 08:38	Wed 01.12 15:18	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1535	Wed 01.12 22:49	Thu 02.12 01:38	3.5	500ns_121b_113_114_0_4bpi31inj_IONS	0	+	3.5
1536	Sat 04.12 13:54	Sat 04.12 20:38	3.5	500ns_137b_129_130_0_8bpi18inj_IONS	0	+	3.5
1538	Sun 05.12 11:07	Sun 05.12 11:22	3.5	500ns_137b_129_130_0_8bpi18inj_IONS	0	+	3.5
1539	Sun 05.12 17:59	Sun 05.12 23:41	3.5	500ns_137b_129_130_0_8bpi18inj_IONS	0	+	3.5
1540	Mon 06.12 04:01	Mon 06.12 09:56	3.5	500ns_137b_129_130_0_8bpi18inj_IONS	0	+	3.5
1541	Mon 06.12 14:10	Mon 06.12 18:00	3.5	500ns_137b_129_130_0_8bpi18inj_IONS	0	+	3.5

Table 4: All fills with STABLE BEAMS during the 2010 LHC ion run. Magnets: IP8 = LHCb dipole, IP2 = ALICE dipole & solenoid. *The ATLAS solenoid was off during fills 1522 and 1523. †Fill includes Van der Meer scans.

In addition, ALICE, ATLAS, CMS and LHCb requested "field off" collisions (see tables 1 to 4). The LHCb reversal had little impact (one spectrometer magnet and fixed external angle, when present), while the ALICE reversals (two magnets and a changing external angle, when present) required more attention due to the fact that the solenoid introduces a trajectory change in the horizontal plane which is not compensated by dedicated magnets (contrary to the dipole spectrometer fields). The number of polarity change requests will be similar in 2011. Acquiring similar data sets in both polarities for every new type of beam conditions is important for understanding systematic uncertainties in the experiments. Making the polarity reversals as transparent as possible for operation is important. In addition, keeping the beam conditions (pile-up, luminosity) at IP2 and IP8 as stable as possible will also contribute reducing the number of change requests. For 2011, two settings of tertiary collimators in IR2 should be validated (corresponding to the two polarities).

IR2 tertiary collimators: The TCTVB collimators in IR2 created a shadow to the ALICE ZDC during proton operation. The collimators were opened for the ion run and should again be opened for the 2011 ion run. The final solution is to replace the TCTVB by a different type located further downstream of the current TCTVB (much like in IR1 and IR5). This change is already planned and should take place as soon as possible.

Bunch current measurements: The luminosity calibration measurements highlighted the importance for the experiments of the LHC beam instrumentation, most prominently of the Beam Current Transformers (BCTs). This triggered a joint machine-experiments activity to extract best results on the bunch population product normalisation [5]. A few issues were encountered during 2010:

- The DCCT did not behave as expected when bunch trains were introduced (150 ns spacing). This was traced back to a saturation effect in the DCCT amplifier cards.
- Given our current understanding, the DCCT scale factor is now the main source of uncertainty. Calibration studies, in particular assessment of stability, are becoming increasingly important for the experiments. Such studies have started at the end of 2010 and should be pursued.
- The FBCT exhibited a dependence on bunch length and beam position. This needs to be understood and corrected. The experiments (ATLAS in particular) offer a cross-check of the FBCT data by measuring the

relative bunch populations with their beam pick-ups (BPTX).

- The raw FBCT data (not zero-suppressed data) were initially not logged. Given the importance of these data for the luminosity calibration, they should be logged in 2011. This may help understanding the offset and linearity of the FBCT.

- Cross-comparison of the BCT systems A and B would also be desirable, at least during luiminosity calibration measurements. In general, it would be useful to have a mechanism to trace when a BCT system underwent a development period and when it was considered stable.

This joint effort should be continued in 2011 to bring the beam and bunch current measurements to their specified accuracy. In a recent workshop [6], it was concluded that a luminosity calibration accuracy smaller than 5% seems feasible and would have significant impact on physics results. This may require additional beam-based measurements for narrowing down systematic uncertainties (of BCTs, beam displacements, beam-beam effects, pile-up, etc.), see [1, 6] for a discussion. Further desired improvements on beam instrumentation are given below.

Longitudinal profile: Ghost and satellite charge measurement and/or control could become a limiting factor in the precision reach of the bunch current normalisation for luminosity calibration. The Longitudinal Density Monitor was deployed (for ring 1) during the ion run. Its potential to thoroughly address the ghost charge issue was demonstrated. The luminosity normalisation experiments would greatly benefit from the full deployment, commissioning and calibration of these devices for both rings.

Emittance measurements: Emittance measurements were used for estimating the emittance growth during the luminosity calibration measurements. If needed, a correction to the measured convoluted shapes was applied. They were also used for studying the evolution of the specific luminosity during a fill. Bunch-by-bunch measurements became available during the year. Flexibility and ease of use of such measurements could be improved. Ideally, a user should be able to rapidly change between single bunch or multi-bunch acquisition (on a pre-defined set on bunch slots). A file-driven bunch slot selection could be considered. In 2011, bunch-by-bunch emittance measurements will be crucial to understand beam-beam effects. Continuous and automated logging of the emittance of each bunch (e.g. with the BSRT) would be extremely valuable.
The experiments support the effort to perform a cross calibration of the various emittance measuring devices (wire scanners, beam-gas ionisation monitors, synchrotron light monitors). With decreasing β^* and beam emittances, the beam sizes at the IPs may well become of the order of the vertex resolution, which will render the extraction of beam sizes from vertex detector data less reliable.

Beam position in IRs: The stability and accuracy of IR BPMs was not yet at the level of the design specifications. This will become increasingly important in 2011, with the use of smaller beams, higher intensities, and for forward experiments (such as TOTEM and ALFA). In particular, the BPMWF monitors should be commissioned and calibrated.

Luminosity Scan application: The Luminosity Scan application was extensively used for Van der Meer scans and associated length scale calibration scans. However, new scan procedures were proposed (to understand systematics or to speed up the procedure) which were not compatible with the application functionality. It has been proposed to upgrade the application functionality such as to allow the user to encode the scan sequence in an input file. Such a modification would greatly enhance the flexibility and functionality. Additionally, the possibility to scan simultaneously at different IPs has been implemented in the course of 2010. This may greatly reduce the cost of Van der Meer scans. The data exchange protocol and possible (cross-IP) systematic effects are yet to be tested [1].

Scan range (envelope): The scan range of luminosity calibration experiments was defined on the basis of tertiary collimator margins and restricted to $\pm 3\sigma_{\mathrm{beam}}$ displacements for each beam independently. This was sufficient for most experiments, but introduced some limitations for the special case of IR2 when operating with separated beams. In 2011, it is considered to move the tertiary collimators with the beams. This might facilitate larger scan ranges, which would be an advantage for Van der Meer scans.

Optics measurements: Optics measurements were carried out on several occasions and revealed again the excellent quality of the machine. The experiments are interested in these measurements, in particular in the IR optics. The β^* values enter in the luminosity formula. When combined with emittance measurements, these data allow one to cross-check the luminosity numbers in a totally independent manner. They may also allow one to understand possible differences between the various IPs (in particular, IP1 and IP5). A systematic and formal publishing mechanism of these results is of interest to the experiments. In the future, with the decrease of β^* values, waist position measurements and hourglas effects will become important. In addition, forward experiments (such as TOTEM and ALFA) have stringent requirements on the measurements of the machine optics.

Injection: Towards the end of 2010, injection losses became large enough to provoke BCM-triggered dumps in LHCb. This was traced back to ejection of uncaptured beam from previous injections. This was temporarily circumvented by permanently increasing the fastest running sum threshold of the BCM system by a factor 3. For 2011, both ALICE and LHCb will implement a more sophisticated mechanism to mitigate the effect of injection losses. A kicker pre-pulse from the RF (point 4) will be used to reduce the thresholds during a short time. However, AL-

ICE and LHCb would like that ways to reduce the losses by cleaning in the LHC (and by shielding, in the long term ?) are pursued.

Handshake: Generally, handshake between the machine and experiments worked well. Minor issues with the exact timing of the procedures were discussed and revisited (e.g. removal of the "imminent" flag). Training of shift crews in the experiment control rooms will be further improved to avoid the occasional loss of time due to misunderstandings. It is important to remember that a handshake is only required when the machine is about to go from a safer state to a less safe state (as gauged by the experiments). Occasionally, a DUMP handshake was initiated while the machine was in ADJUST mode. This is not required (the DUMP mode is not considered less safe than the ADJUST mode for the detectors). The procedures and documentation are now being revisited for 2011 [7].

Data exchange: The principal mechanism for data exchange between the machine and experiments relies on DIP. The service worked relatively well in 2010. A few hiccups were observed. As an example, the LHC fill number was occasionally not correctly transmitted (or not changed at the source ?). On the experiments side, this generates book-keeping errors which need to be treated manually. A method to force the fill number change during the LHC cycle is being discussed. Mechanisms for automated restart of DIP servers and automated signalling of lost DIP services could and should be further developed.

The data published by the experiments were not always archived in the LHC Logging Database, for various reasons (lack of human resources on both sides, occasional service breakdown, insufficient data integrity, etc.). The LHC and the experiments could benefit from a better documentation (definition) of the data to be transmitted from the experiments to the LHC.

In order to alleviate the impact of the missing data, a separate (offline) path for data exchange was set up. Summary files provided by the experiments for physics fills were stored as text files in a dedicated storage space on AFS [8]. These files contain luminosity data and luminous region characterisation data (sizes and positions). Additionally, LHCb (and initially also CMS) provided individual beam sizes and positions from beam-gas imaging. Some experiments delivered data per bunch pair for some of the fills. An advantage of these data files is that the data can be regenerated by the experiments quite easily (for example, if new detector calibration data are available).

These data were used to analyse (specific) luminosities, also per colliding pair [9]. Unfortunately, the bunch-by-bunch data were not produced coherently by all experiments (incomplete data set).

In 2011, this independent data path will be maintained and possibly improved. The persistency of these data is an issue. The idea of allowing these offline data to be stored centrally in the LDB (or a new central database) should be considered.

Vacuum: Strong pressure rises in the neighborhood of the IPs have been observed toward the end of the 2010 proton run, when e-cloud effects became important. This has raised the question "how much pressure increase could the experiments tolerate during physics fills ?". A precise and definitive answer cannot be given. ATLAS has, for example, seen effects of the pressure rise on the jet rate (increase of the "fake" jet rate), although it is believed that means to reduce this effect could be implemented. In general, a pressure not exceeding 10^{-8} mbar seemed bearable. Nevertheless, the experience and impact of such vacuum degradations needs to be further investigated and monitored.

Ghost charge / satellite bunches: The amount of charge outside the nominal buckets ("ghost charge") was larger in certain fills. In some occasions, this was traced back to issues in the SPS (800 MHz cavities). However, the amount of ghost charge is also expected to increase with the reduction of bunch spacing (in bunch trains). The experiments were asked to re-assess their requirements on the amount of proton charge not contained in the nominal (colliding) RF buckets. As a starting point, it seems that a fraction of up to 5% ghost charge (relative to the total beam intensity) could be acceptable. However, as for vacuum pressure degradation, a definitive answer cannot be given. The effects should be further investigated and monitored. For the special case of luminosity calibration runs (typically with largely spaced bunches) the required limits on ghost charge are more stringent (< 0.5%) and also depend on the ability to quantify the amount of ghost charge.

CONCLUSION

The LHC produced first pp physics collisions at $\sqrt{s} =$ 7 TeV in March 2010, starting with a luminosity of about $8 \cdot 10^{26}$ $\mathrm{Hz/cm^2}$ and finally reached $2 \cdot 10^{32}$ $\mathrm{Hz/cm^2}$ in October 2010, thus brilliantly surpassing the target.

The experiments took advantage of the gradual luminosity increase to step through (i) calibration of the detectors, (ii) "re-discovery" of particle physics (quarkonia, weak bosons, top quarks, ...), thus gauging the level of understanding of their detectors, and finally (iii) to actually produce physics results.

Cooperation between machine and experiments was again excellent and needs to be steadily continued, both for forthcoming operation and for offline data analysis. A detailed list of suggestions and points for possible improvements was presented. These now have to be followed up.

ACKNOWLEDGEMENTS

Above all, the experiments and myself would like to congratulate all our colleagues from the accelerator sector for the excellent work and for the truly impressive 2010 achievements.

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[9] See G. Papotti in these proceedings.

OPERATIONAL CHALLENGES (FEED FORWARD FROM EVIAN LHC OPERATION WORKSHOP)

M. Lamont, CERN, Geneva, Switzerland

Abstract

A summary of the second Evian workshop in 2010 is presented. An attempt is made to highlight necessary follow-up.

PREAMBLE

The second Evian workshop in 2010 came the day after last beam and was an intense two days spread over three. Following a brief introduction looking back at the successes of 2010, the sessions covered:

- **LHC beam operation**: review of 2010 and setting the scene for 2011, which looked at: experiments, efficiency, beam from injectors, experience with 75 & 50 ns. bunch spacing, intensity ramp up, and RF performance.
- **Driving the LHC**, which looked at: turnaround, software, the magnetic model, missing functionality.
- **Beam diagnostics and feedback systems**: bunch by bunch, feedbacks, transverse damper, BPMs, transverse beam size.
- Machine protection systems: MPS performance, LDBS, abort gap, minimum beta*, injection protection, the human factor.
- **Beam losses**: collimation, injection, extraction, UFOs, BLM thresholds.
- **Luminosity performance**: emittance preservation, the hump, beam-beam, luminosity optimization, optics, pushing the limits in 2011.

The wrap-up session included a look at 2011 running and possible integrated luminosity for the year.

2010 - OVERVIEW

The main milestones of the 2010 commissioning are outlined in table 1.

Table 1: main commissioning milestones 2010

Date	Milestone
March	Initial commissioning leading to first collisions
April	Squeeze commissioning
May	Physics 13 on 13 with 2e10 ppb
June	Commissioning of nominal bunch intensity
July	Physics 25 on 25 with 9e10 ppb
August	3 weeks running at 1 – 2 MJ
September	Bunch train commissioning
Oct - Nov	Phased increase in total beam intensity

The intensity ramp-up following the bunch train commissioning in August is shown in table 2.

Table 2: intensity ramp-up and associated performance

Date	Bunches	Colliding pairs	Luminosity
29th August	50	35	1 x 10^{31}
1 – 22nd Sept.	Bunch train commissioning		
22nd Sept.	24	16	4.5 x 10^{30}
23rd Sept.	56	47	2 x 10^{31}
25th Sept.	104	93	3.5 x 10^{31}
29th Sept.	152	140	5 x 10^{31}
4th Oct.	204	186	7 x 10^{31}
8th Oct.	248	233	8.8 x 10^{31}
14th Oct.	248	233	1 x 10^{32}
16th Oct.	312	295	1.35 x 10^{32}
25th Oct.	368	348	2.07 x 10^{32}
4th Nov.	Switch to heavy ions		
9th Nov.	17	16	3.5 x 10^{24}
15th Nov.	121	114	2.88 x 10^{25}

The two tables above tell a tale of remarkable progress and testament to an enormous amount of hard work before and during commissioning. Some of this is hopefully captured in these proceedings.

LHC BEAM OPERATION

Operational efficiency – Walter Venturini

The 2010 run was driven mainly by commissioning, and not operations for physics. In this regard, any analysis of operational efficiency should be regarded with some latitude. However for a first year the signs are very encouraging.

- Some huge equipment systems performed above expectations (considering mean time between failures etc.).
- Equipment groups are aware of the weak points and are working to improve them.
- Technical stops certainly caused problem initially but it got better through the year.
- There was truly impressive availability for a first full year.
- Fault statistics gathering must be improved!

Beam quality and availability from the injectors – Giulia Papotti

Beam quality from the injectors proved to be critical and a lot of time was spent at injection ensuring that things were up to scratch.

- Clear procedures are needed (covering scraping, blow-up etc.)
- Preparation must be made in good time; checklists should be implemented.
- We must be able to track beam quality through the injectors: emittances, intensities
- LHC requests must be communicated in good time to the injectors.
- There is a nice long list of RF improvements in the SPS. These must be followed up.
- Dedicated LHC filling is to be pursued.

Turnaround optimization – Stefano Redaelli

Analysis of last year's run showed that the injection process dominated the turn around time. Typically more than 2 hours was lost.

- A set of proposals was presented for reducing the length of time spent at injection. Significant improvement is required during this phase.
- "Manual" changes should be reduced to a minimum while driving the machine through the cycle. Clearly this opens room for mistakes and these tasks must be eliminated.
- 5 minutes can be saved with a faster ramp – to be tested in 2011.
- It is possible to gain 10 to 15 minutes by not stopping in the squeeze – a top priority.

We do not seem to be yet in the position to gain from more aggressive approaches, suggestions for which include: continuous functions for ramp, squeeze and collision; and a combined ramp and squeeze. These may become interesting when present issues are solved and a little more maturity has been brought to bear.

It should be noted that mistakes are expensive. It is a priority to eliminate these. One four hour turn around takes a lot of 5 minute savings to recuperate the lost time.

Software and controls – Delphine Jacquet

There is a long, well order list of improvements that includes: equipment control; injection sequencer; state machine; LSA; Alarms; Diamon etc. Of note:

- The nominal sequence needs to be nailed down in cooperation with the whole LHC section.
- Bunch-by-bunch diagnostics is required across the board.
- More exotic fixed displays might include: cryogenics heat load; vacuum activity; display of sub-threshold UFOs.
- Tune scans with on-line tune diagram and display of tune spread would be useful.
- Automatic plots, including bunch-by-bunch "Giulia plots", should be available after every fill.
- There is a long list of LSA improvements – thorough testing required.

There is a very short shutdown and some of the above will only be deployed during the year.

Magnetic model – Ezio Todesco

The deployment of FIDEL was a one of the year's major achievements. However, some improvements are still possible:

- Ramp-down/precycle for access (100 A in main bends) should be deployed having measured the effects on decay and snapback.
- The differences between precycle and ramp-down combo must be sorted out.
- There are procedures for individual circuit trips. The shift crews should recall these.
- Dynamic b3 compensation at injection. The magnitude of the observed decay is as expected by FiDeL but on much longer time constant. The decay should be measured and appropriate correction implemented.
- Remove hysteresis handling in the squeeze.
- Rollback decay driven trims (tune and chromaticity) before starting each injection.
- Chromaticity during ramp was tracked within ±7 units – we can improve in the initial part of the ramp.
- Tune decay is clearly observed at injection – source as yet unknown. Dynamic correction is to be considered.

The human factor – Alick Macpherson

- Documentation of procedures should be a lot better.
- Control room ergonomics must be improved.
- Machine protection envelope should be defined and implemented.
- Experience (or induction) can be a dangerous guide.

The LHC is a 5.4 GCHF investment. The personnel and material budget is around 299 MCF/year. There is an understandable desire to capitalize on the investment. One way of doing this is by having long operational years.

Operations and infrastructure teams with limited manpower have become stretched in some areas. Two points: potential risk of burnout of staff members; risk of less than fully safe operations and maintenance of the LHC.

RF, BEAM DIAGNOSTICS AND FEEDBACK SYSTEMS

Key systems have performed with a remarkable degree of maturity; inevitably some improvements are possible.

Bunch by bunch diagnostics will be required for: orbit; head-tail monitor; BCT; longitudinal profile; wall current monitor; longitudinal density monitor; synchrotron light telescope; the experiments' data; and if possible the tune.

Appropriate storage, access and display facilities should be provided.

RF: Operation 2010 and Plans for 2011 – Philippe Baudrenghien

It was a successful year all in all for the LHC RF team.

- Cogging works well
- 50 Hz is no problem in the ramp
- Blow-up in the ramp to avoid lost of Landau damping is operational and has performed…perfectly
- September - reconfigured the RF for higher intensity and faster ramp: no more idling cavities. All klystrons on.
- Counter phasing was implemented at 450 GeV.
- Capture losses: the sensitivity of the BLM dump system to injection losses must be decreased by 2 orders of magnitude (x100) or mitigating measures found.

- RF noise turned out to be a "no-problem" in 2010.
- We need a clear strategy for cavity trips in physics. But don't panic: 3 out of 8 cavities with 15% of nominal intensity was OK, but we will have to dump with nominal intensity.
- If you do fill the abort gap, wait. Strategy to be defined.

A number of technical problems were listed. Of note were the issues with noisy cavities: these problems are worrying. To be investigated during hardware re-start.

Incoming in 2011 are: SPS-LHC phase energy matching; longitudinal damper; and possible coupled bunch instabilities among other things.

Feedbacks – Ralph Steinhagen

Feedbacks performed well and facilitated fast commissioning. They were de-facto required during every ramp and squeeze with nominal beam and expect the same also for next year. More than half of all ramps would have been definitely lost without them although feed-forward would have clearly been pursued more rigorously had feedback not been available. Additional safety margin to operation can be provided if feed-forward is performed regularly – to be done in 2011.

- Tune peak-to-peak stability typically below 0.02 with margin to push it < 0.003
- There was little impact of residual tune error on transmission
- Most RT-trims correlated with $Q'(t)$ – a possible feed-down effect?
- $Q'(t)$ a bit neglected this year → some indication of trade-off: beam stability (low transmission losses) vs. beam size growth. Could we further explore this via dedicated/controlled measurements?
- Effective ADT noise floor and observed bunch-to-bunch cross-talk hinders reliable operation of LHC's Q/Q'-diagnostics and related feedbacks.
  Alternate BI diagnostic options have been explored. The ball is now on the RF group's side of the court.

There was good overall performance with little transmission losses and minimal hick-ups related to Q/Q' instrumentation, diagnostics and Q/Q' & orbit feedbacks. However in 2011 1% losses may become more critical.

Transverse dampers – Wolfgang Hofle

An impressive year for the transverse damper system:

- commissioned damper at 450 GeV, during ramp and with colliding beams;
- nominal damping rate reached and surpassed;
- commissioned operation with bunch train;
- commissioned damper for ions at 450 GeV and with colliding ion beams;
- abort gap cleaning and injection slot cleaning successfully used;
- diagnostics (logging, fixed display, multi-bunch acquisition) available.

There are lots of improvements incoming in 2011. The tune measurement options were listed and the team will work on compatibility with tune feedback. One suggestion was injecting witness bunches. The strategy is to be defined.

BPMs – Eva Calvo

- The global performance of the system was very good with around 97% channel availability.
- There were a number of improvements made throughout the year including temperature calibration/compensation.
- Synchronous mode will be available in 2011. This will solve the double trigger issue on the IR BPMs.
- Multi-turn orbit on selected bunches will be available.
- IR BPMs: cable adapters will be installed during the Christmas technical stop.
- Pre-flight checks with beam that will test acquisition and calibration should be routinely deployed.
- Intensity dependence crossover – the observed beam one behaviour was caused by a small impedance mismatch at the input of the intensity module. The intensity card will be replaced by a termination card in the IR BPMs this technical stop.

Transverse emittance measurements – Federico Roncarolo

- The wire scanners offer turn and bunch-to-bunch capabilities. They are the reference for transverse beam size measurements but care is required.
- The synchrotron light telescope (BSRT) is available in DC and pulsed mode. Resolution is given by the optics of the system. Given accuracy is via cross-calibration with the wire scanners, however correction factors are not stable. Things are complicated in ramp with changes of focusing etc. Bunch by bunch, turn by turn functionality is incoming via a fast camera.
- The BGI is in the commissioning phase. Calibration with bumps is foreseen. MD time is required

MACHINE PROTECTION

Machine protection system has functioned remarkably well with long list of improvements foreseen for 2011.

Intensity ramp up strategy in 2010 was well judged. The dangers must again be taken seriously in 2011. A clear strategy for 2011 is required.

Injection protection becomes essential, we are now injecting unsafe beam into the LHC. A more rigorous approach at injection is required following a beam dump/post mortem when there is more than 500 kJ in the machine.

Machine protection system response – Markus Zerlauth

- LHC Machine Protection Systems have worked extremely well during 2010 run thanks to a lot of commitment and rigor of operation crews and MPS experts.
- Most failures are captured before effects on beam are seen. We have still seen no quenches with circulating beam (with ~ 30 MJ per beam and 10 mJ required to quench a magnet).
- Beam dumps above injection are rigorously analyzed, we can do better at injection (avoiding repetitive tries without identifying the cause).
- Still a lot of room for improving tools for more efficient and automated analysis.
- No evidence of major loopholes or uncovered risks, but bypassing of protection layers was/is still possible. Follow-up of MPS Review recommendations is required.
- Still we have to remain vigilant to maintain current level of dependability of MPS systems, especially when entering longer periods of 'stable running'.

LBDS – Chiara Bracco

In general, it was a very good performance from the LBDS. Faults seen:

- 1 energy tracking error at 3.5 TeV due to instabilities of 35 kV power supplies (30/03/2010: media day)
- Asynchronous beam dump, during energy scan without beam (due to spark on the outside of the gate turn-off GTO thyristor): 1 at 5 TeV; 2 at 7 TeV.
- 4 internal triggers due to vacuum interlocks on the MKB for beam 2. These were due to false vacuum pressure readings. The logic has been changed to use only the VAC signal.
- 1 Asynchronous beam dump with beam
- 2 beam dumps induced by TCDQ faults

LBDS failures occurrence were in agreement and not worse than requirements and expectations. No damage or quench during synchronous and asynchronous beam dumps. Leakage to downstream elements within specifications. The TCDQ needs tender, loving, care, and long-term plans are to be defined.

Open questions include Machine protection validation tests, procedures and tests frequency: Is the strategy adequate (too often, too rarely)? Could the tests be improved? Do they really insure machine safety?

Injection protection – Verena Kain

Injection protection is fully operational and working well; all problems so far caught. In fact it has already saved the LHC from damage several times (beams onto TDIs).

- Are we taking it seriously? Most of it: yes. Injection interlocking etc. looks good.
- Injection oscillations + orbit will be tightening up in 2011.
- It has been too easy to put full injected batch onto TDI: to be improved.
- How can we make it safer? Concept of intermediate intensity + injection oscillation interlock; threshold management of injection protection; timing system fix for GPS problems; tightening up operational settings tolerances on MKI;
- Checks in Injection Scheme Editor for filling patterns to take abort gap keeper into consideration.

BEAM LOSSES

There was excellent performance of collimation system with no quenches with beam above 450 GeV. There are issues at injection with fast losses. UFOs are a primary concern.

Multiturn losses and cleaning – Daniel Wollmann

The phase-I LHC collimation system delivers expected collimation efficiency. The impact of imperfections is a factor 2 smaller than predicted (better orbit control in DS).

• The setup procedure has been refined and optimized (15-20 minutes per collimator needed)

• Validity of collimation setup is around 5-6 months, then close to the edge. Might require two setups in 10 months run in 2011.

• <u>The instantaneous peak loss rate about factor 9 lower than specified: with this we should be good for nominal intensity at 3.5 and 4.0 TeV (in terms of cleaning efficiency).</u>

• But: instabilities can increase loss rate and therefore cause collimation induced intensity limitations (possible for higher intensities and energies).

• Cleaning with ions much less efficient than for protons (as expected): Leakage in orders of percents into DS magnets and TCTs, very localized losses observed.

Injection and extraction losses – Wolfgang Bartmann

- Limits for 2011: 96 or 108 bunches per injection for operation look OK
- Injection Tests with higher intensity or 25 ns spacing might be possible depending on TL shower/capture loss mitigation.
- Extraction losses on Q4/Q5 are dominated by shower from TCDQ.
- Loss mitigation at injection are necessary to go beyond operational intensity scope. Potential techniques to further reduce losses need to be commissioned (e.g. Injection cleaning); installed (e.g. TCDI and TDI shielding - partly available in 2011); or deployed (e.g. BLM sunglasses).

Losses away from collimators: statistics and extrapolation – Barbara Holzer

UFOs are a big concern.

- Observed around the ring (triplet, IRs and arcs) but interestingly there are hot and cold regions out there
- Rate scaling up with total intensity – extrapolations look worrying.
- Beam loss events don't appear to get harder with intensity
- Loss duration falls with intensity

The first line of defence will be to maximize UFO acceptance by threshold adjustment at the appropriate time scales.

BLM hardware failures are acceptable!

LUMINOSITY PERFORMANCE

Beam-beam – Werner Herr

- In 2011 we should establish the limits by pushing the bunch population and small emittances. The full long-range effect should be probed; the established limits should set the boundary conditions for the squeeze.
- The offset in LHCb should be OK
- Effort should be made to equalize the beam sizes.
- MD time is required.

Luminosity optimization – Simon White

Fully automated scans with optimization in parallel were delivered – excellent performance.

- Very good fill-to-fill reproducibility +/- 60 micron fluctuations.
- Stability during a fill – excellent
- Should optimize vertical plan in Alice as well
- Could declare stable beams while optimizing (?)
- Should be able to speed up collision beam process by ramping down separation during ramp.
- Movement at TCTs is a concern: either tighter, enforced limits or move the TCTs during a scan. Functionality for the latter is in place but to be tested.
- The luminosity scan software has to be passed on as Simon moves to pastures new.
- Automatic luminosity levelling was raised as a possibility.
- Dithering was also mentioned as a possibility.

Optics – Rogelio Tomas-Garcia

The beating at injection, and during squeeze is well corrected and correction to the 10% level was achieved at 3.5 m. The beta functions at the IPs were also correct to within 10%. Excellent long-term stability is noted. There were, however, a number of issues.

- 2 m. mystery - a 10% drift was noted
- Beating was slightly worse when the correction were implemented in LSA. This turn out to be due to not driving IRs 3, 4, 6 and 7 after the global correction had introduced trims in these areas.
- It is estimated that hysteresis effects could cause up to 10% beating at 1.5 m.
- A non-negligible drift of 8% observed at injection
- Beating is going to get worse as we squeeze further, but it should be correctable.
- Local coupling correction in the interaction regions will become mandatory below 2 m.
- Hysteresis handling in LSA should be dis-continued

The hump – Gianluigi Arduini

The hump affects luminosity performance due to blow-up (particularly at 450 GeV). In collision it can excite beam-beam coherent modes or generate tails and therefore losses. The main mitigation measure is the use of low noise TFB at maximum gain.

Since middle of November turn-by-turn/bunch-by-bunch position with damper pick-up has been available. Ion filling scheme with basic spacing of 500 ns gave the possibility of determining the frequency of the hump $\pm f_0 + n \times 2$ MHz with $0 < f_0 < 1$ MHz. The frequency of the hump is less than 10 MHz.

The identification (and possibly eradication) of the origin remains the (challenging) goal of the on-going analysis and measurements.

- The hump is there all the time. Use the hump buster.
- It causes emittance blow-up at injection and faster decrease in luminosity in collision. (Tails, beam loss – nice plots).
- It is a constant magnetic field effect – goes linear with energy
- Incoming: transverse feedback on in the squeeze next year (possibly); optimization of gain in collision; more noise reduction in the feedback system.

The hunt continues.

2011

Given the performance of 2010 it is reasonable to look forward to 2011 with some optimism. However, it should be bourn in mind that there are problems lurking out there. These include: electron cloud; UFOs; beam-beam; and R2E. Of these UFOs probably have the most potential to wreak havoc with operational efficiency.

Questions subsequently answered:

- Energy – 3.5 TeV
- Squeezing further - minimum beta* - 1.5 m. Collimation, aperture, orbit look OK
- LHCb "luminosity levelling" via separation at 3 m
- Beta* = 10 m. at Alice. Accept overhead of commissioning squeeze for ion run.
- Start with 75 ns. with 150 ns. as back-up
- No limit on beam intensity from collimation
- Bunch intensity at least nominal
- 1.2e11 with emittance of 2 micron – 75 ns – single batch definitely sounds interesting

Experiments requirements – Massi Ferro-Luzzi

- Rationalization of polarity reversal procedures
- Van der Meer scans as required for luminosity calibration accompanied by accurate BCTs

- Luminosity levelling for LHCb with a maximum luminosity of 3 x 10^{32} $cm^{-2}s^{-1}$, maximum pile-up (mu) of 2.5
- A multi fb^{-1} year is anticipated for Atlas and CMS
- Max 4 x 10^{32} $cm^{-2}s^{-1}$ for Alice (beta*, separation)
- Special runs will include intermediate energy, 90 m. etc.

50 and 75 ns (electron cloud) Gianluigi Arduini

Electron cloud was initially observed with 150 ns. in the common beam pipe where it was driven by near coincident beam crossings. However electron cloud really kicked off with 50 ns. It was also seen in single beam warm sections with 75 ns.

- The scrubbing time constant is around 8 hours with 50 ns.
- Scrubbing at smaller bunch spacing than operational required buys margin.
- Scrubbing should be performed with the experiments solenoids off
- Heat load observed in the arcs with 50 ns but not 75 ns.
- Scrubbing at 450 GeV in the arc is good for higher energy
- 50 ns: see instabilities developing along the trains – curable with high chromaticity.
- Possible coupled bunch modes with 75 ns plus head-tail. Transverse feedback, low chromaticity as cures.
- 75 ns: incoherent effects observed with low e-cloud density and 30-40% emittance blow-up of some bunches (with high chromaticity).

Ramping up in intensity

Strategy was reasonable in 2010 despite all the discussion. It should be pursued in 2011.

- Reviews and staged increase served us well in 2010
- "Just because we have a checklist doesn't mean we're safe". Review the checklist.
- Review recommendations of the reviews – has everything been taken into account?

Re-commissioning in 2011 foresees:

- 3 to 4 weeks re-commissioning with a virgin set-up, new ramp, new squeeze, new beta*s, orbit, modified parameter space… it will be different.
- Full collimator set-up and full validation (loss maps, asynchronous dumps etc.)
- One would foresee a ramp backup to around 200 bunches in 50 bunch steps (with 75 ns. bunch spacing). In 2010 it took around 4 days (minimum) per 50 bunch step with most time lost to machine availability and lost fills (UFOs…). Thus it is reasonable to anticipate around 2 weeks to get back to 200 bunches
- After a 10 day scrubbing run larger steps of 100 bunches is foreseen driving through from 300 to a maximum of 900 bunches (for 75 ns.). This should take around 3 weeks.

It is important that a revised checklist and regular meetings of the rMPP are used to sign off each step up intensity. Regular beam-based checks should also be performed.

beta - how low can we go? Roderick Bruce*

Given that the measured aperture (at 450 GeV) is larger than expected and by scaling to 3.5 TeV and other assumptions (orbit uncertainty 3 mm, measured beam size…), the conclusion is that:

- Could go to 2.5 m without reducing present margins
- With decreased margins (TCT/triplet: 1.5 σ; reduce margin TCT-dump protection from 5.7 to 3.4 σ) and assuming:
  - nominal 0.7 mm separation – should bring it down in ramp;
  - using measured beating at injection and top energy with 5% reproducibility, 10% beating in n1 calculation;
  - 3mm orbit shift in pessimistic direction between measurement at injection and top energy;
  - 12 sigma beam-beam separation (larger than nominal);
  - triplet aperture at injection 2 sigma larger than global limit.

The proposal for 3.5 TeV running is a beta* of around 1.5 m.

Beam parameters from SPS – Elias Metral

Approximate beam parameters expected from injectors in 2011 (* indicates that the value has yet be established).

Bunch spacing [ns]	Batches from PSB	Bunch Intensity	Emittance [mm.mrad]
150	Single	1.1 x 10^{11}	< 2.0
75	Single	1.2 x 10^{11}	2
75	Double	1.2 x 10^{11}*	1.2*
50	Single	1.4 x 10^{11}	3.5
50	Double	1.2 x 10^{11}*	1.5*
25	Double	1.15 x 10^{11}	3.6

Luminosity estimates for 2011

A number of variations were shown. Typical assumptions were:

- 3.5 TeV
- 930 bunches (75 ns)
- 2.5 micron emittance
- 1.2 x 10^{11} protons/bunch
- beta* = 1.5 m
- Nominal crossing angle
- Hübner factor 0.2
- 130 days at peak luminosity

Given the above one should see a peak luminosity touch in the order of 1 x $10^{33}cm^{-2}s^{-1}$ and an integrated for the year of 2 to 3 fb^{-1}.

CONCLUSIONS

2010 saw the LHC come a phenomenally long way in 9 months. Among the notable features is the remarkable maturity of some key systems after just a year. This hasn't come for free; it's been years in the preparation; and the devil is, as always, in the details. There is still a lot to follow-up with possible improvements and consolidation detailed for all systems.

2011 clearly aims to leverage off of what's been learnt this year and the potential is encouraging. However there are some known problems incoming (UFOs, electron cloud, R2E) which could impact operability. Perhaps most importantly, we will be pushing up Ralph's stored energy plot during the year and working almost from the start with destructive beams. Awareness of the risks must underpin our approach.

ACKNOWLEDGEMENTS

The organization and determination were down to Malika Meddahi who, once again, made it happen. Many thanks to the Chairpersons (Roger, Gianluigi, Jorg, Brennan, Ralph, Malika) and Scientific secretaries (Giulia, Mirko, Reyes, Alick, Stefano, Verena) for putting together an excellent set of sessions. The speakers did a lot of hard work at the end of a hard year.

An excellent job was done by the workshop secretariat (Sylvia Dubourg, Flora Meric): the web site was in place, we all got there, had somewhere to sleep and had plenty to eat. This was not obvious - there were many "requests".

Pierre Charrue took care of the technical support impeccably. The editor of proceedings is the very generous on deadlines Brennan Goddard.

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INJECTION – ISSUES AND POTENTIAL SOLUTIONS

V. Kain, W. Bartmann, S. Bart Pedersen, P. Baudrenghien, A. Boccardi, C. Bracco, E. Gianfelice,
B. Goddard, W. Hofle, D. Jacquet, M. Meddahi, L. Norderhaug Drosdal, J. Uythoven, D. Valuch,
J. Wenninger, CERN, Geneva, Switzerland

Abstract

Due to the sensitivity of the LHC beam loss monitor systems combined with low thresholds, losses at injection became a limiting factor during the filling of the LHC. All parameters, longitudinal and transverse had to be well controlled not to trigger the beam dump at injection. The cause of these losses will be summarized and typical loss patterns and other diagnostics described. Mitigation measures together with promising first results will be presented together with the plans for 2011. Finally the weak points of the current injection procedure will be discussed in terms of efficiency and protection, improvements for the 2011 run will be proposed.

INTRODUCTION

Towards the end of the first year of LHC operation in 2010, optimisation of the overall turn-around times started to become important. A critical analysis of the achieved turn-around times during the 150 ns proton run from September to October was presented at the Evian LHC operation workshop. Most time was lost at injection corresponding to the LHC beam modes “injection probe beam” and “injection physics beam”. On average 3 h were spent in these modes [1]. Injection is one of the phases were LHC parameters are still extensively corrected by the operations crew, in the other phases LHC operation depends heavily on functions and feedbacks. Thus some of the lost time can be attributed to this fact. Part of the inefficiency is however due the injection process itself. Issues with over-injection, intermediate intensity injection, preparation of LHC beams in the injectors, the LHC filling tools and losses at injection all contributed to sometimes lengthy filling periods. This paper will summarise the observed problems and propose solutions for 2011.

OVER-INJECTION

Injection of high intensity into the LHC is only permitted by the interlocking system if beam is already circulating. Only probe intensity (currently < 10^{10} charges) can be injected into an empty machine. This is the concept of “beam presence”. A number of so-called “safe machine parameters” (different flags derived from beam current measurements in the SPS and LHC and other quantities distributed across the machine) are combined in the permit equation in the master beam interlock controllers for the SPS extraction to guarantee this condition.

In 2010 the probe bunch required for beam presence was injected into RF bucket 1 and then over-injected onto the TDI with the first high intensity injection. If however no beam was extracted from the SPS during an over-injection attempt, the probe beam was kicked out, the beam presence condition was lost and therefore the possibility to resume the filling was lost as well. Cycles in the injectors had to be changed to switch back to probe beam production and time was lost.

For 2011 it is therefore planned to place the probe bunch at a better location around the LHC circumference such that over-injection does not occur during the first injection but later. The injection scheme editor will calculate the appropriate position.

Keeping the probe bunch as part of the filling scheme as a witness bunch is another possibility. Both options will be used in 2011.

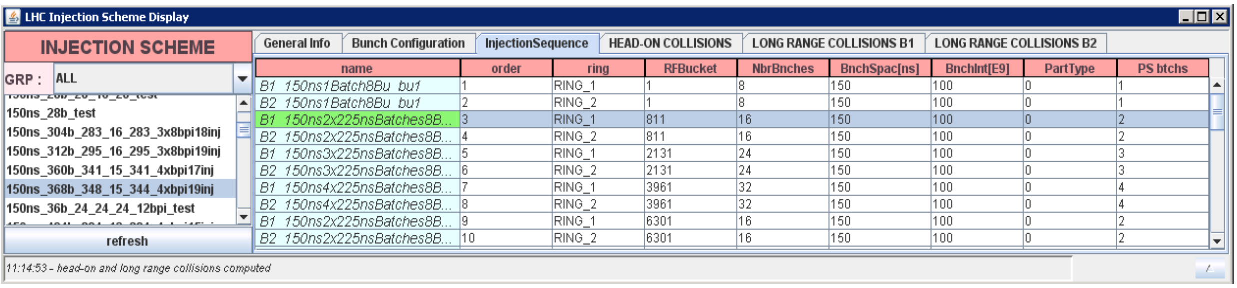
INTERMEDIATE INTENSITY INJECTION

The LHC does not change settings when switching from probe beam to nominal beam (except sensitivity settings for some BI equipment). The injectors however are running at different settings and hence different cycles for the different beams. As consistency of settings between the different cycles is not guaranteed, intermediate intensity beam is extracted from the SPS first before high intensity. The typical filling scenario therefore consists of a pilot bunch, an intermediate batch followed by full batches. The intermediate batches are the final validation of the injection process.

In 2010 the LHC was filled with single batch injections from the booster into the PS, with the booster RF running on harmonic 2 (+1). The intermediate intensity batch was generated by injecting a single booster ring into the PS instead of three. The other two were disabled manually followed by adjusting the splitting in the PS. Intermediate intensity batches could not be generated in an automated way.

For 75 ns the intermediated intensity corresponded to 8 bunches, for 50 ns to 12 bunches and for 25 ns taking a single booster ring with one injection from the booster would correspond to 24 bunches.

The required manual intervention of the operations crew and the tuning of the splitting then in the PS



150ns_28b_test
150ns_304b_283_16_283_3x8bpi18inj
150ns_312b_295_16_295_3x8bpi19inj
150ns_360b_341_15_341_4xbpi17inj
150ns_368b_348_15_344_4xbpi19inj
150ns_36b_24_24_24_12bpi_test

name	order	ring	RFBucket	NbrBnches	BnchSpac[ns]	BnchInt[E9]	PartType	PS btchs
B1 150ns1Batch8Bu bu1	1	RING_1	1	8	150	100	0	1
B2 150ns1Batch8Bu bu1	2	RING_2	1	8	150	100	0	1
B1 150ns2x225nsBatches8B...	3	RING_1	811	16	150	100	0	2
B2 150ns2x225nsBatches8B...	4	RING_2	811	16	150	100	0	2
B1 150ns3x225nsBatches8B...	5	RING_1	2131	24	150	100	0	3
B2 150ns3x225nsBatches8B...	6	RING_2	2131	24	150	100	0	3
B1 150ns4x225nsBatches8B...	7	RING_1	3961	32	150	100	0	4
B2 150ns4x225nsBatches8B...	8	RING_2	3961	32	150	100	0	4
B1 150ns2x225nsBatches8B...	9	RING_1	6301	16	150	100	0	2
B2 150ns2x225nsBatches8B...	10	RING_2	6301	16	150	100	0	2

11:14:53 - head-on and long range collisions computed

Figure 1: Current injection schemes: The current injection schemes consist of a number of injection requests. An injection request tells the injectors into which LHC ring and into which RF bucket the next injection should occur and how many PS batches should be injected into the SPS. The number of injections into SPS can be controlled on the fly. The same is not possible for the number of booster injections into the PS.

before and after the intermediate batch injections caused some considerable holdup during the LHC filling. Improvements of the mechanism to switch to intermediate intensities should be investigated for 2011.

Possibilities to speed up switching in and out intermediate batch injections

Two possibilities to make the switching to intermediate intensities more efficient are discussed:

1. Separate user for intermediate intensities
2. New type of LHC injection requests.

Separate user: this approach would not require any modifications of the existing way of controlling the LHC beams in the injectors. Nominal and intermediate intensity would be run on different cycles in the injectors. As the intermediate intensity cycle is also used to steer the SPS to LHC transfer lines and to avoid the complication of having to copy the steering settings to the nominal cycle which risks to be forgotten, the same user in the SPS should be used for intermediate and nominal. Only the PS and the booster would run with different users. The drawbacks of the "separate user" solution are the larger number of users locked for the LHC beams, the potential issue of the copy of the transfer line steering in case of different SPS users and that the switching from intermediate to nominal and vice versa cannot be done through LHC injection requests. The timing system would have to be re-configured to play the other user. In this way intermediate intensities could only be used as first injection. Mixed filling schemes using nominal and intermediate intensity injections throughout the filling to optimise the luminosities at the different interaction points would not be possible.

New LHC injection requests: the drawbacks of the first possible solution could all be elegantly avoided by the introduction of more flexible LHC injection requests. An example of a filling scheme with the current type of injection requests is shown in Fig. 1. Note that the number of PS injections into the SPS can be piloted on the fly by the LHC injection request with today's Central Timing. This is not the case with the number of booster rings. However, the concept of different destinations for different booster rings exists. And different PS equipment settings can be associated with these different destinations. The idea behind the "new LHC injection requests" is to use a possibility for different settings for different booster ring destinations or different number of booster rings and upgrade the "LHC injection request" to also pilot the number of booster rings between 1 and 6 (2 x 3 rings for 2 batch injection from the booster).

Despite the obvious advantages for injection protection and overall flexibility of building injection schemes of this proposal, there are some drawbacks. The 2010/11 shutdown is short and this proposal would require a major, but technically feasible, modification of the LHC and Central Timing System and settings management in the PS. Possibilities to exploit the "separate users" proposal or speeding up the tuning of the PS splitting will be investigated for 2011. In addition we will study and prepare a new type of LHC injection requests to be ready for implementation during the shutdown 2011/12.

PREPARATION OF BEAMS IN THE INJECTORS

The LHC physics beams have strict quality requirements. A set of parameters in the transverse and the longitudinal plane has to be verified and frequently tuned before the beams can be declared ready for filling. Regularly preparation in the injectors only started when pilot beam was already circulating in the LHC with the LHC crew waiting for physics beam.

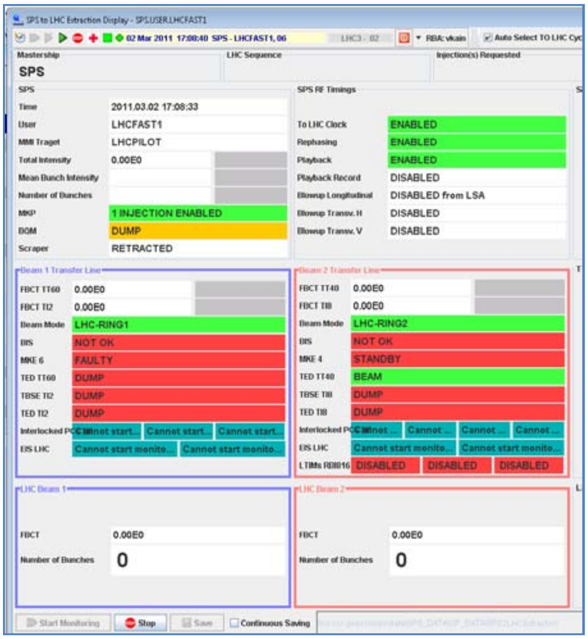
A list of issues has been compiled by the injector teams in connection with LHC beam preparation:

- "The LHC does not get rid of the mastership": the LHC mastership is a concept in the Central Timing under which the LHC is the master of the execution of the LHC beams in the injectors. Under LHC mastership there is no LHC beam in the injectors without request. And without beam no checks can be performed.
  In 2011 it will be possible to have the beam up to the PS if the LHC keeps the mastership and does not request any beam.
- Not everything is testable without mastership: the RF re-rephasing at SPS flattop for example can

only be tested under real conditions with an LHC injection request under mastership.

- Not enough diagnostics: there is no continuous emittance measurement in the injectors, no satisfying diagnostics for the 800 MHz cavities in the SPS, no summary status of the complex interlocking condition for SPS extraction to the LHC, etc.
- No well defined procedure for required parameters in the injectors: transverse blow-up on/off,...

For 2011 a series of improvements are planned including more discipline of the LHC crew concerning the handling of the LHC mastership, more tools like the example in Fig. 2 and more communication with the injectors and long term planning of requirements.



Mastership: SPS

SPS
Time: 2011.03.02 17:08:33
User: LHCFAST1
MMI Traget: LHCPILOT
Total Intensity: 0.00E0
Mean Bunch Intensity:
Number of Bunches:
MKP: 1 INJECTION ENABLED
BOM: DUMP
Scraper: RETRACTED

SPS RF Timings
To LHC Clock: ENABLED
Rephasing: ENABLED
Playback: ENABLED
Playback Record: DISABLED
Blowup Longitudinal: DISABLED from LSA
Blowup Transv. H: DISABLED
Blowup Transv. V: DISABLED

Beam 1 Transfer Line
FBCT TT60: 0.00E0
FBCT TI2: 0.00E0
Beam Mode: LHC-RING1
BIS: NOT OK
MKE 6: FAULTY
TED TT60: DUMP
TBSE TI2: DUMP
TED TI2: DUMP
Interlocked PC: Cannot start... Cannot start... Cannot start...
BIS LHC: Cannot start monito... Cannot start monito...

Beam 2 Transfer Line
FBCT TT40: 0.00E0
FBCT TI8: 0.00E0
Beam Mode: LHC-RING2
BIS: NOT OK
MKE 4: STANDBY
TED TT40: BEAM
TBSE TI8: DUMP
TED TI8: DUMP
Interlocked PC: Cannot ... Cannot ... Cannot ... Cannot ...
BIS LHC: Cannot start monito... Cannot start monito...
LTIMs RB816: DISABLED DISABLED DISABLED

LHC Beam 1
FBCT: 0.00E0
Number of Bunches: 0

LHC Beam 2
FBCT: 0.00E0
Number of Bunches: 0

Figure 2: “SPS to LHC extraction monitoring”: an application to summarising the conditions for beam extraction to the LHC.

FILLING SCHEMES AND TOOLS NOT OPTIMISED

In 2010 no dedicated LHC filling cycles were used. The LHC was filled in parallel to the fixed target program in the injectors. A typical supercycle constellation in the SPS can be seen in Fig. 3 with the LHC filling cycle at the end of the supercycle. The length of such a supercycle was about 40 s. In addition to the long supercycles, the LHC filling schemes consisted of many injections. The number of injections per beam for the different schemes during the 150 ns run are summarised in Table 1.

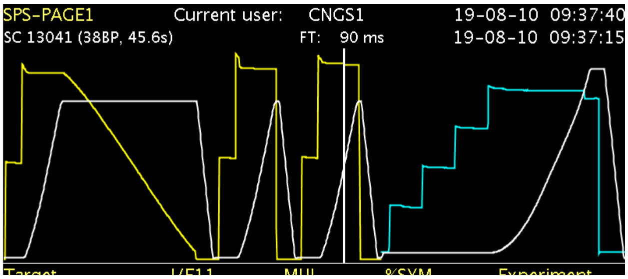


Figure 3: Typical supercycle in the SPS used for LHC filling.

Table 1: Number of injections for filling schemes during 150 ns proton run 2010.

Total number of bunches	# Injections
56	7
104	13
152	17
248	15
256	17
306	18
312	19
360	17
368	19

The LHC filling tools in 2010 were also not optimised yet for dedicated filling. The so-called “injection sequencer” was programmed such that it would wait for the response of the automatic “LHC Injection Quality Check” (IQC) taking place after each injection in the LHC. This did not leave enough time for the LHC beam to be prepared in the injectors for the next LHC cycle with a single cycle in the SPS supercycle. This constraint will be lifted for 2011 for interleaved injection schemes. As soon as the production of the first beam starts, the request of the other beam will be sent to the Central Timing depending on the result of this beam’s last injection.

Another issue associated with the filling tools consisted of the dependence of the injection logic on the BCTs. The logic of repeating the last injection, continuing with the next one or stopping all together depends on the result of the LHC IQC. This analysis used two BCTs per transfer line to compute the result in 2010. Unfortunately the transfer line BCTs turned out not to be fully reliable especially with ions. The applied logic of the injection sequencer broke down with wrong BCT results and manual intervention for the normally fully automated injection process was required. In 2011 the IQC will derive whether beam has been injected or not using three devices, two transfer line BCTs and the longitudinal LHC beam quality monitor (BQM), with more weight on the BQM than on the BCTs.

INJECTION LOSSES

The experience of 2010 showed that the regular losses at injection are close to the LHC injection region BLM thresholds on the short running sums. Frequently the losses even exceeded the thresholds. The reasons for these losses are:

1. Transfer line collimators (TCDIs) cutting transverse beam tails: losses on Q6, Q7 and Q8, see Fig. 4.
2. Uncaptured beam in the LHC: losses on TDI lower jaw and equipment downstream (triplets, TCTVb)
3. Satellites, uncaptured beam from the SPS: losses on the TDI upper jaw and equipment downstream (triplets, TCTVb)

In the following solutions for the different loss mechanisms are treated. Point 3 will not be further discussed as this can be fully avoided with sufficient diagnostics.

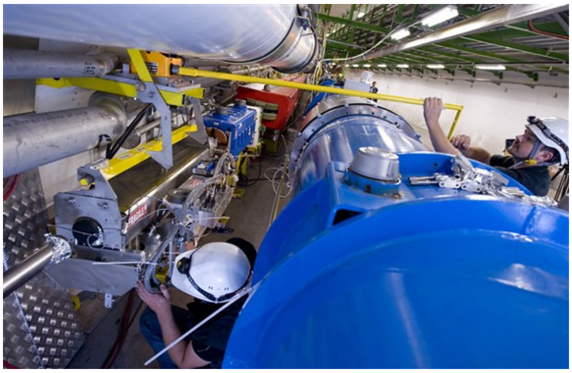


Figure 4: The transfer line collimators are located at the end of the lines where the transfer line is close to the LHC superconducting magnets. Showers created by the collimators are seen by the LHC beam loss monitors on the superconducting magnets.

Loss Evolution

The loss maxima for the injections during the 150 ns run period with higher and higher injected intensities are summarised in Table 2. The losses due the showers from the TCDIs grow almost linearly with intensity. The losses due to uncaptured beam depended on the parameter adjustments in the LHC (synchro error). It will however definitely be worse for nominal beams with the larger bunch length spread across the injected batch. 1 % of capture loss is expected for 25 ns bunch spacing, where it is used to be 0.3 % for 150 ns with the BLMs frequently triggering.

Table 2: Loss maxima per injected intensity in 2010.

Loss Type	**Losses in % of dump threshold B1/B2**			
	8 b	**16 b**	**24 b**	**32 b**
TCDI shower	1/2	3/5	4/6	5/8
Uncaptured beam	4/2	12/3	12/5	16/8

The results of 2010 were scaled to the expected maximum injected intensities required in 2011. The period with the highest intensity injected will be the scrubbing test at the beginning of the year. For these predictions, the 2010 injections with 48 bunches during the scrubbing test in November were used. The 48 bunch injections had not been optimised. Table 3 is summarising the estimates in terms of expected losses.

Table 3: Loss maxima per injected intensity: projection to 2011 using the non-optimised 48 bunch injection from 2010

Loss Type	**Losses in % of dump threshold B1/B2**		
	48 b	**96 b**	**144 b**
TCDI shower	23/24	<50	<75
Uncaptured beam	20/8	<40	<60

From Table 3 it can be concluded that for 2011 no mitigation is required to live with the injection losses. An uncertainty however comes from the losses on the transfer line collimators. The data of 2010 is based on small emittance beams, with emittances smaller than 2.5 µm. In 2011 partly nominal emittances will be used.

Mitigation: Transfer Line Collimators

Different possibilities of mitigation for the LHC BLMs triggering on transfer line collimator showers are being investigated. Placing shielding between the TCDIs and the LHC BLMs and opening up the TCDIs from 4.5 σ to 5 σ are possibilities which could be put in place without having an impact on the machine protection functionality of collimators or BLMs. If this is not sufficient so-called "BLM sunglasses" could be the solution. "BLM sunglasses" would ensure that the BLMs in the injection region do not take the losses during injection into account for interlocking, as under these conditions the losses come from the outside of the vacuum chambers and do not correspond to a loss scenario the LHC BLM thresholds have been designed for. "BLM sunglasses" would mean a modification of the machine protection functionality and have to be carefully designed if needed. More on the different mitigation possibilities for losses due to TCDI showers can be found in [2].

Mitigation: Uncaptured Beam

Like for the losses from the TCDI showers, shielding could be envisaged downstream of the TDI. Studies are ongoing. A reduction of the capture losses during capture itself is probably not realistic, especially not for nominal bunch spacing. A promising active method to reduce the amount of unbunched beam around the circumference is cleaning.

Abort gap cleaning switched on during injection reduces the maximum losses towards the end of the filling by a factor 3. The results of a test filling with and without abort gap cleaning is shown in Fig. 5. Abort gap cleaning is fully operational at injection and was extensively used during the scrubbing test, where injections took place over many hours.

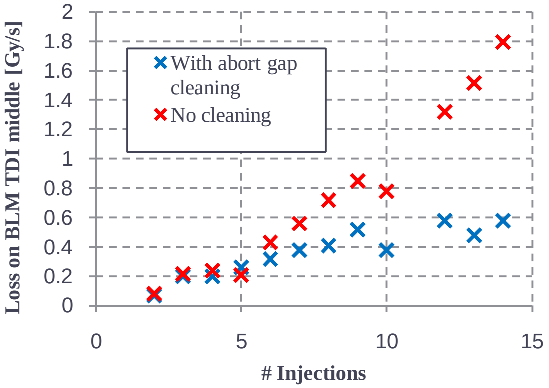


Figure 5: Abort gap cleaning on during injection reduces the losses towards the end of filling by a factor 3.

Even better results can be achieved by introducing injection gap cleaning in addition to abort gap cleaning. Injection cleaning cleans the location of the next injected batch before the new beam is injected using the same technique as abort gap cleaning [3]. Fig. 6 illustrates the optimum cleaning situation during filling with abort gap cleaning and injection cleaning. The results obtained with injection cleaning and abort gap cleaning during a test filling are shown in Fig. 7. The losses due to unbunched beam on the TDI are reduced by a factor 10.

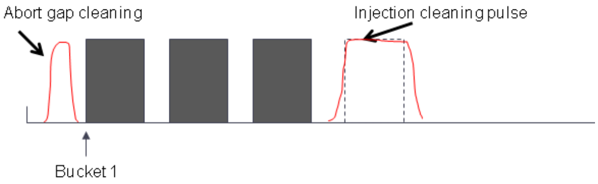


Figure 6: Illustration of injection cleaning: before the next batch is injected the longitudinal space for the next injection is cleaned using the same technique as abort gap cleaning. In grey the already injected batches are shown.

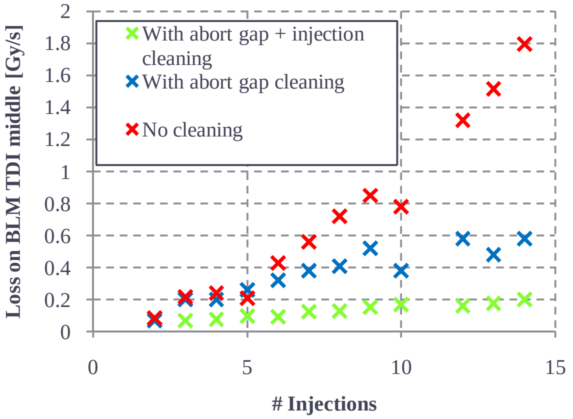


Figure 7: Abort gap cleaning and injection gap cleaning on during injection reduce the losses towards the end of filling by a factor 10.

SUMMARY

The LHC injection phase has been identified as the most inefficient period. On average 3 h had been spent at injection during the high proton luminosity phase in 2010. Improvements have been proposed for certain areas. The injection procedure will be adapted concerning over-injection, intermediate intensities and communication with the injectors. More diagnostics and improved tools are being prepared. Losses at injection might become a limiting factor for higher intensity injections. The expected maximum injected intensities in 2011 however do not require any mitigation yet. Mitigation is being studied and prepared. Abort gap cleaning and injection gap cleaning gave promising results in significantly reducing the losses due to unbunched beam during the injection pulse.

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VACUUM AND CRYOGENICS OBSERVATIONS FOR DIFFERENT BUNCH SPACING

J.M. Jimenez, G. Arduini, V. Baglin, G. Bregliozzi,
P. Chiggiato, S. Claudet, G. Lanza and L. Tavian
CERN, Geneva, Switzerland

Abstract

Following the observations of high pressure rises induced by an electron cloud building up in the LHC beam pipes, studies were launched with beams with 50 and 75 ns bunch spacing at injection energy and with a ramp to 3.5 TeV (only 50 ns bunch spacing).

This talk will summarize the observations made on the beam vacuum and cryogenic systems for both 50 and 75 ns bunch spacing and with a ramp in energy (only 50 ns bunch spacing). Some extrapolations will be presented based on the measurements. Finally, the decided mitigation solutions and beam parameters to be used for the 2011 run will be reviewed.

INTRODUCTION

The electron cloud build-up is a threshold phenomenon which depends on the bunch population and number of bunches in the train. Above the threshold and in presence of a fast build-up, the build-up is roughly linear with the number of bunches [1]. As the electron cloud results from an electron multiplication, the avalanche depends highly on the secondary electron yield (SEY, δ), on the number of photo-electrons and on the surviving electrons. The surviving electrons are the electrons, mainly low energy, which can survive the gaps between bunch trains because of the high reflectivity of the surface for the low energies. These electrons are participating right from the beginning to the multiplication. At the contrary, the build-up is attenuated by the spacing between bunches and bunch trains. The electron cloud is affected by many other parameters like the size of the beam vacuum pipe, the magnetic field and the temperature of the beam pipe walls.

ELECTRON CLOUD INDUCED LIMITATIONS

The electron cloud is responsible for accelerator performance limitations such as vacuum pressure rises, heat loads on cryogenic components, beam instabilities, beam-gas scattering induced radiation to cables and electronics and background to the experiments.

The vacuum pressure rise result from the bombardment of the inner beampipe walls by the electrons from the cloud, kicked off by the beam potential. The effect of this local electron stimulated desorption (ESD) will depend on the ratio of the multipacting beampipe length versus the available pumping speed for all desorbed gas species.

In the cryogenic sections, the electrons heating the beampipe wall will deposit their energy inducing temperature rises unless compensated by cooling. By design, the LHC has two intrinsic limitations: the maximum cooling capacity through the beam screen cooling capillaries and the total available cooling capacity of the cryoplants.

The electron cloud induced beam instability is of great concern since it can also become a limiting factor for the scrubbing run as it can result in emittance blow-up and beam losses. This effect depends on the electron density in the beampipe and on the multipacting length.

The pressure bumps increase the induced radiation to cables and electronics and the background to the detectors. The amplitude of this effect will vary with the gas density and length of the pressure bump.

The bending sections of the LHC (arcs) and the standalone magnets (SAM) installed in the long straight sections have, by design, a non bakeable vacuum system. The beams see a copper envelope and the beam screen's pumping hole provide the required pumping speed. It has to be noted that the recycling desorption yields are much larger than primary desorption yields ($\eta'_{\text{monolayer}} >> \eta$) thus implying that the beam screen's surface coverage should stay below a monolayer. This can be achieved by keeping the temperature of the cold bore always below that of the beam screen. Regarding the efficiency of the scrubbing, i.e. decrease of the secondary electron yields, δ, measurements carried out in the laboratory confirmed that the scrubbing of surfaces at cryogenic and ambient temperature behave similarly.

The long straight sections (LSS) are mainly operated at ambient temperature (except SAM magnets) and rely on the use of NEG coatings, a coating which provides distributed pumping speed, low stimulated desorption yields and a secondary electron yield of 1.1 (after activation) which prevent an electron cloud to build up. The regions of concern for electron cloud build-up are the non NEG coated parts, e.g. the cold/warm transitions, the warm/warm transitions and the beam components (collimators, beam position monitors, pick-ups, etc.). In these regions, the electron cloud induced pressure rise results from the ratio of the multipacting length (non-coated part) to the locally available pumping speed for the desorbed gas species, in particular methane (CH_4) since not pumped by NEG coatings.

RESULTS FROM 2011 RUN

150 ns bunch spacing

In the long straight sections, the pressure rise observed in the sections with only one beam circulating (3.5 TeV) can be explained by the synchrotron radiation (SR) since energy and intensity dependent.

In the recombination areas where the two beams circulate in the same beampipe, the pressure rises (Fig.1) are the result of different effects: SR induced by the D1 or D2 bending magnets and the electron stimulated desorption induced by the electron cloud. The measurements showed the larger effect in the Cold/Warm transition of the Inner triplets on Q3/DFBX side for ATLAS, ALICE and LHCb. This location coincides with the position where the bunches from the two beams are again superposed (takes place exactly at 45 m from the interaction point) (Fig.2). Thus leading to enhanced multipacting conditions: higher beam potential and bunch spacing configuration. No pressure increase is observed in IR5 due to the stray magnetic field of the CMS solenoid variable from 1 up to 15 mT. Indeed, solenoid fields (2-5 mT) are known to suppress the electron cloud. In presence of a solenoid field, the secondary electrons cannot escape out from the surface since bent back by the field.

In the arcs, nothing was observed using the cryogenics instrumentation (resolution of 5 mW/m/aperture). Vacuum instrumentation, installed at ambient temperature outside the cryostat, cannot see pressure rise since the pumping speed by cold surfaces is very high.

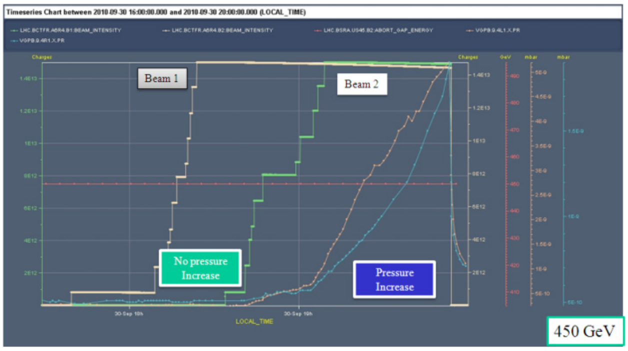


Fig.1: Pressure rise observed in the recombination areas with 150 ns beams

75 ns bunch spacing

With the injection of beams with 75 ns bunch spacing, pressures started to rise in most of the non NEG coated parts of the LSS (Fig.3). The variety in pressure rise results from the number of circulating beams in the beampipes (2 circulating beams enhance the build-up), the contribution of the photon stimulated desorption induced by the SR close to arcs or D1, D2, D3, D4 SAM magnets and the multipacting length versus pumping speed configurations. The pressure rises in the recombination areas are larger at 75 ns, in particular because of the superposition at 22.5 m and 45 m from the IP (Fig.4). The effects induced by the superposition taking place inside the cold sections are not detectable (no gauge and huge pumping speed by condensation).

In the arcs, nothing was observed using the cryogenics instrumentation.

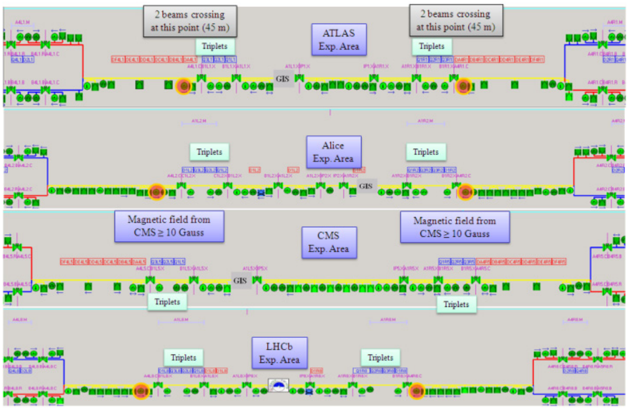


Fig.2: Localisation of the pressure rise in the LHC LSS with 150 ns beams

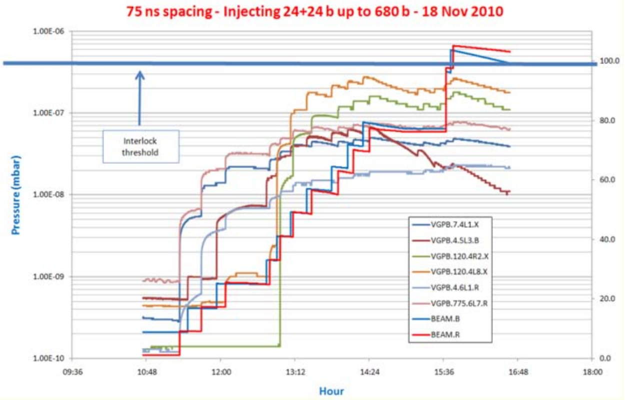


Fig.3: Pressure rise observed in all LSS with 75 ns beams

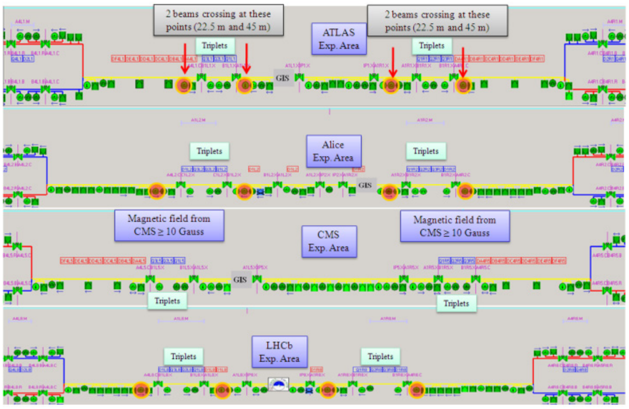


Fig.4: Localisation of the pressure rise in the LHC LSS with 750 ns beams

50 ns bunch spacing

The electron cloud build-up with 50 ns bunch spacing required nominal bunch populations to trigger the electron build-up (Fig.5). Similarly, the spacing between trains of bunches had to be reduced below 2 µs to enhanced the build-up (Fig.6) and long trains, at least 24 bunches in the train, had to be injected (Fig.7).

The observation of pressure rise confirmed that the pressure increase linearly with the number of trains (Fig.8) allowing pressure forecasts for given filling patterns. Globally, pressure rise with 50 ns are twice the one observed with 75 ns beams.

Operation with 50 ns beams showed for the first time a significant electron build-up in the arcs, a heat load of 40 mW/m was measured by the cryogenic instrumentation with 444 bunches at injection energy (Fig.9).

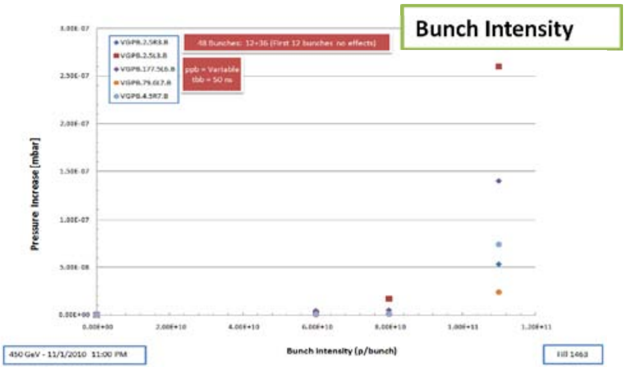


Fig.5: Pressure rise as a function of bunch population showing a shift of the electron cloud threshold to higher bunch populations

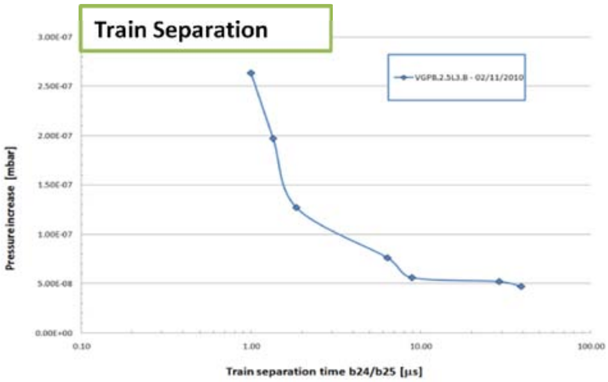


Fig.6: Effect of reduction of the spacing between trains on the electron cloud build-up

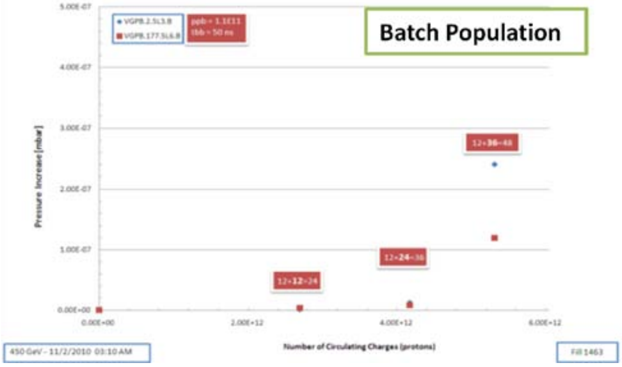


Fig.7: Effect of the number of bunches in the trains on the electron cloud build-up

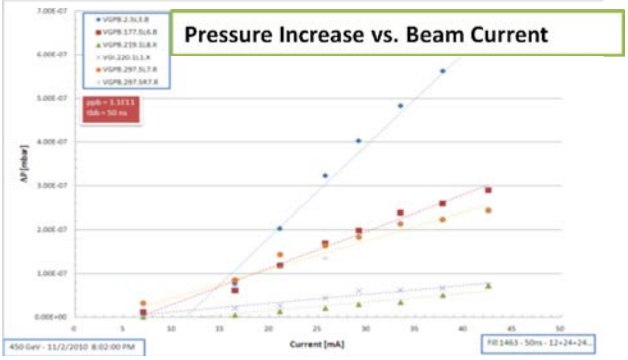


Fig.8: Pressure rise as a function of the number of circulating bunches

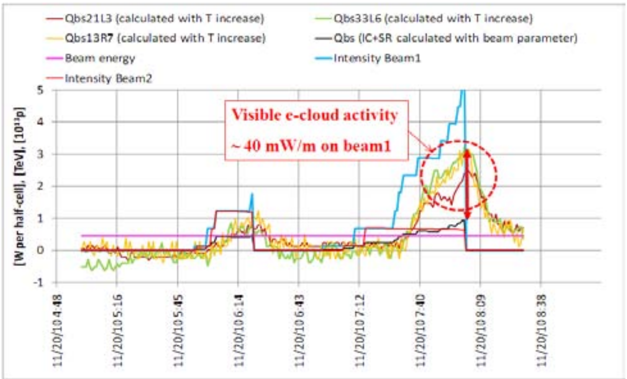


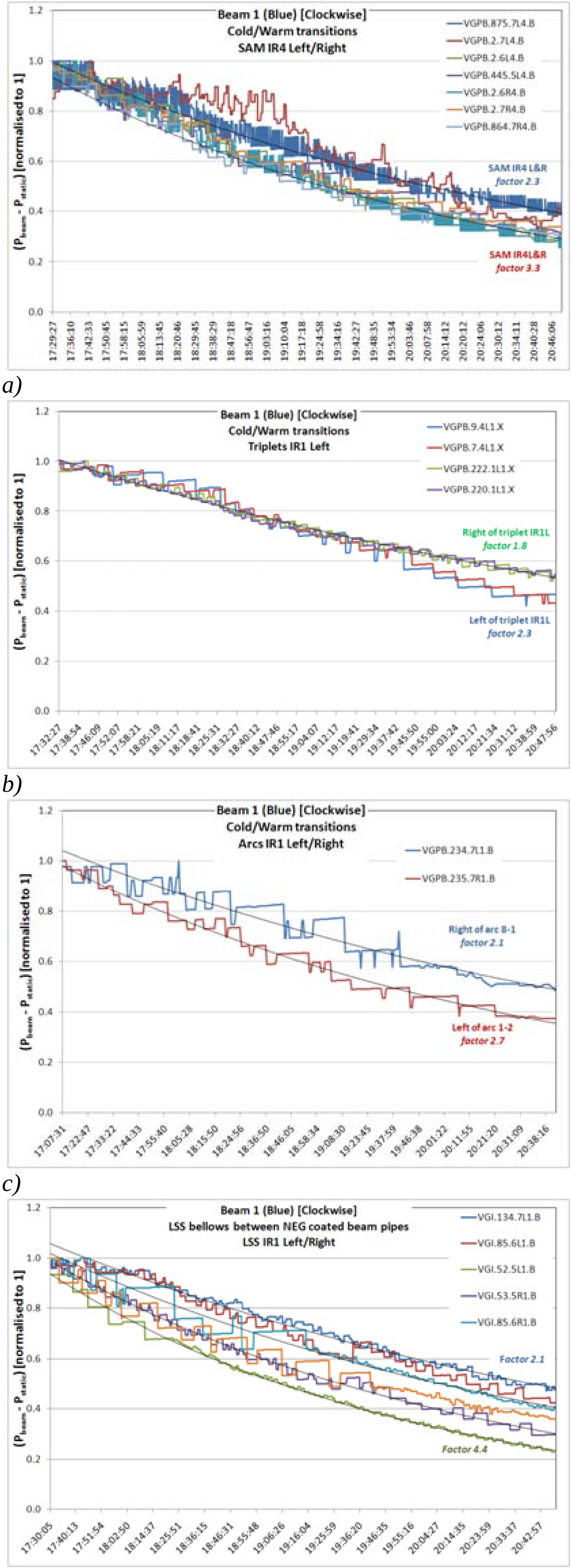
Fig.9: Heat load induced by 50 ns beams on the beam screens of the arcs

Vacuum conditioning and beam scrubbing

Vacuum conditioning is a dose effect induced by the electron bombardment which characterizes the reduction of the desorption yield, η, (i.e. the number of gas molecules desorbed from the surface/bulk by the primary electron). Beam scrubbing is also a dose effect which, characterizes the reduction of the secondary electron yield, δ, (i.e. the number of secondary electrons generated by impinging primary electrons). The pressure rise resulting from the electron stimulated desorption, decrease with the electron dose as a result of the combined effect of vacuum conditioning and beam scrubbing.

During the operation with 50 ns beams in Physics, clear evidence of vacuum conditioning effect were observed all LHC LSS and with similar behaviors, irrelevant of the operating temperature. Pressure rise decreased by a factor between 2.3 and 4.4 in about 3h15 (Fig.10), much faster than expected from the SPS measurements with LHC-type beams [1].

The vacuum conditioning effect shows an exponential behavior with electron dose, as expected (Fig.11). The trend indicates that a decrease of pressure rise by a factor of 100 at constant electron dose rates is expected after 16h of integrated beam time.



d)

Fig.10: Pressure rise evolution with beam time showing a vacuum conditioning effect in the cold/warm transitions of the SAM magnets, a), inner triplets, b), end of continuous cryostat arc, c), and warm transitions in the LSS, d).

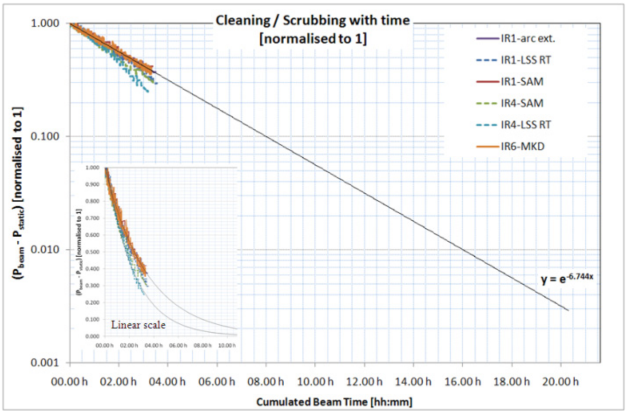
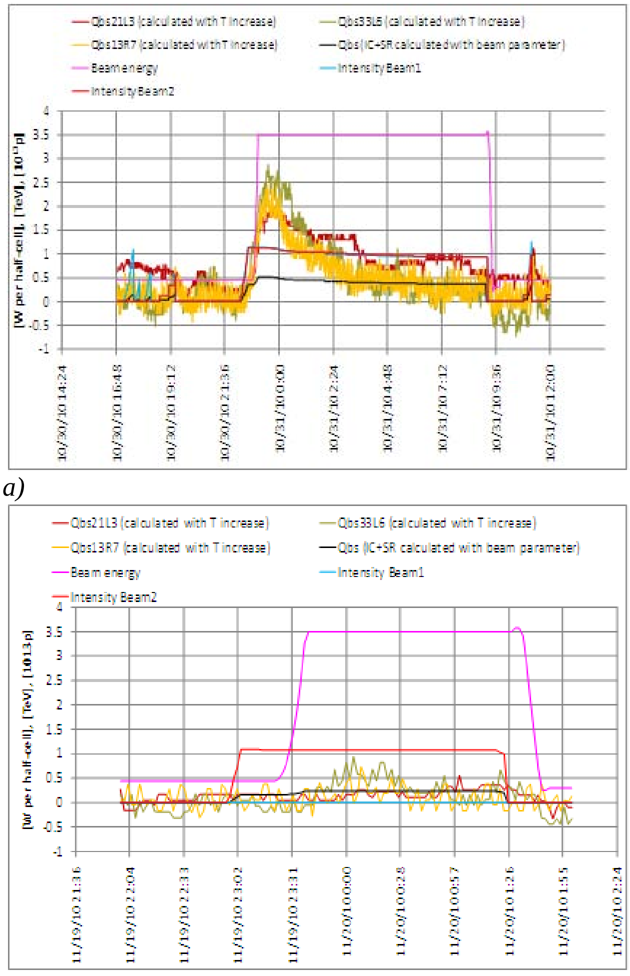


Fig.11: Prediction of vacuum conditioning as a function of beam time



b)

Fig.12: Heat load induced by 50 ns beams at 3.5 TeV before October's scrubbing run, a) and after the scrubbing run, b).

As mentioned earlier, the operation with 50 ns beams showed an electron build-up in the arcs, this build-up was seen by the heat load onto the cryogenic system. Indeed, this is at the moment, the only mean to evaluate the electron cloud activity in the parts of LHC operated at cryogenic temperatures. The scrubbing run showed that the electron cloud induced heat load decreased by a factor of at least a factor 4 from 20 mW/m to 10 mW/m (Fig.12). The observed decrease of the heat load due to electron cloud after scrubbing is an encouraging indication that scrubbing at 450 GeV can be effective also for operation at 3.5 TeV.

OPERATION IN 2011

Expected decrease η and δ

Predictions of electron dose effects on secondary electron yields, δ, and on desorption yields, η, are based on the assumptions made for the electron dose rates. For a given electron density, the flux to the wall will depend on the magnetic field configuration. The field free regions have a homogeneous bombardment of the inner surface of the beampipes while in dipole fields, electrons are confined in one, two or three (the number depending on the bunch intensity) stripes parallel to the field direction [1]. The ratio of the transverse length of the strips to the perimeter explains why 15 times more dose is expected in LHC arcs in presence of a dipole field as compared to LSS transitions in field free conditions. Therefore, an electron could density of 1 mA/m shall induce a flux to the walls of 5×10^{12} $e^-/s.cm^2$ in the field free regions and 8×10^{13} $e^-/s.cm^2$ in the dipole field regions (Fig.13).

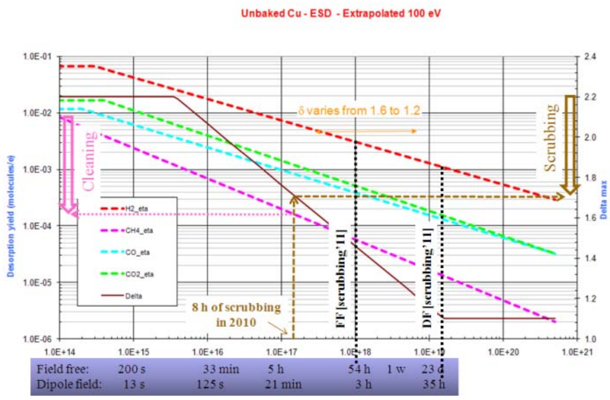
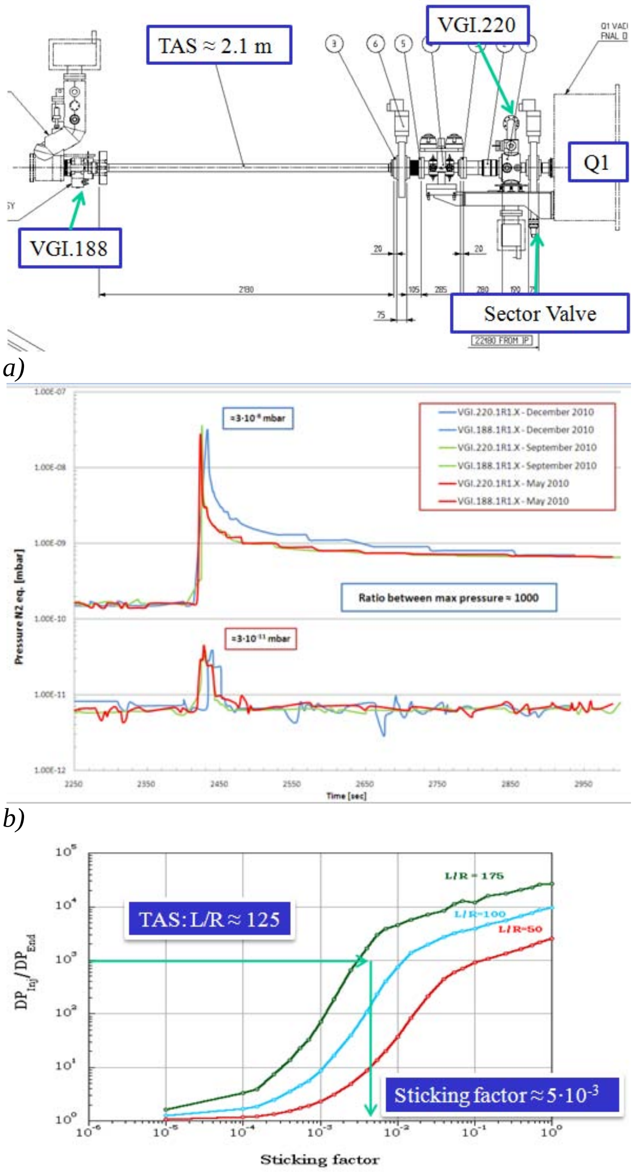


Fig.13: Expected decrease of the desorption yields, η, and secondary electron yield, δ, as a function of electron bombardment integrated dose.

Impact on NEG coatings

The gas released by the electron stimulated desorption is pumped out by the ion pumps and NEG coatings or condensed on the upstream and downstream beampipe surfaces at cryogenic temperatures (beam screens and cold bores). As the reactivation of NEG coatings requires a bake-out cycle which is expensive and time consuming, an evaluation of the impact of the vacuum conditioning on NEG coatings has been carried out, in particular in the experimental areas. The study case introduced here, concern the ATLAS experimental area, upstream and downstream of the TAS absorber (Fig.14a). The gas load being generated in the cold/warm transition of the Q1 quadrupole of the inner triplet, the pressure bump seen by the ion gauge on the other side of the TAS NEG coated chamber is proportional to the hydrogen transmission probability. Measurements show an attenuation of pressure bumps by 3 orders of magnitude (Fig.14b) and according to the Monte Carlo simulations, this correspond to a sticking factor of 5×10^{-3}, a sticking factor corresponding to a fully activated NEG coating (5×10^{-3} < Sticking factor < 5×10^{-2}) (Fig.14c). This result confirms that the vacuum conditioning during the 2010 run did not lead to the deterioration of NEG coating pumping performances.



a)

b)

c)

Fig.14: Measurement of the NEG activation level using the vacuum instrumentation upstream and downstream the ATLAS TAS absorber, a), the attenuation of local pressure rise induced by the sector valve closure, b), and

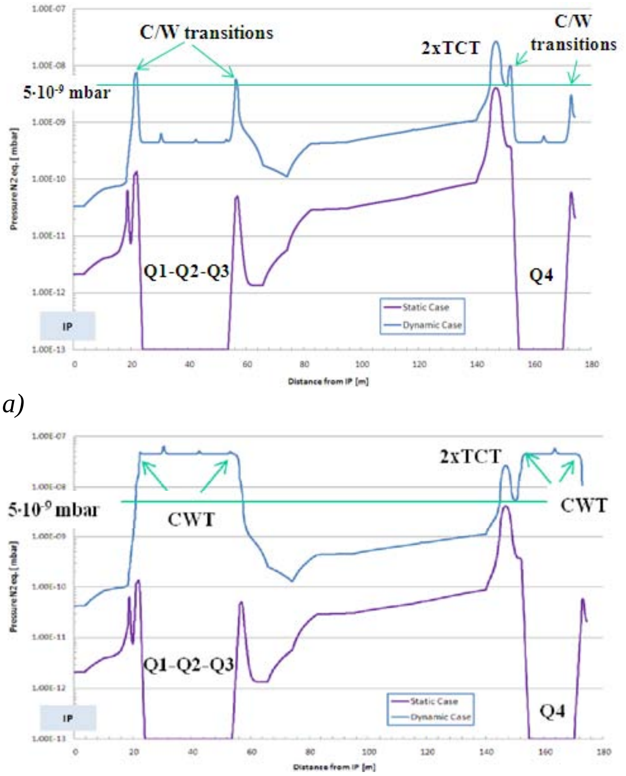
the Monte Carlo simulations of the expected attenuation of hydrogen through the beampipe, c).

Expected dynamic vacuum induced background

The operation with 75 ns beams resulted in an electron cloud build-up in the cold/warm transitions of all SAM magnets. Before the winter technical stop, about 9% in length of the LSS showed pressures higher than 5×10^{-9} mbar (Fig.15a). This corresponds to electron flux of 10^{16} e^{-}/m.s in the field free (outside magnets) sections at ambient temperature and 10^{14} e^{-}/m.s in cold sections (dipole field).

During the scrubbing run in 2011 with 50 ns beams, the pressure bumps above 5.10^{-9} mbar shall represent about 25% in length of the LSS (Fig.15b), 3 times more than with 75 ns beams.

As the NEG coatings provide a huge pumping speed for hydrogen, the pressure bumps will be quickly attenuated (Fg.16a) thus leading to residual vacuum dominated by methane since not pumped by NEG coatings (Fig.16b). The presence of ion pumps allows the pumping of this gas species and keeps the gas density at an acceptable level for the experimental areas.



a)

b)

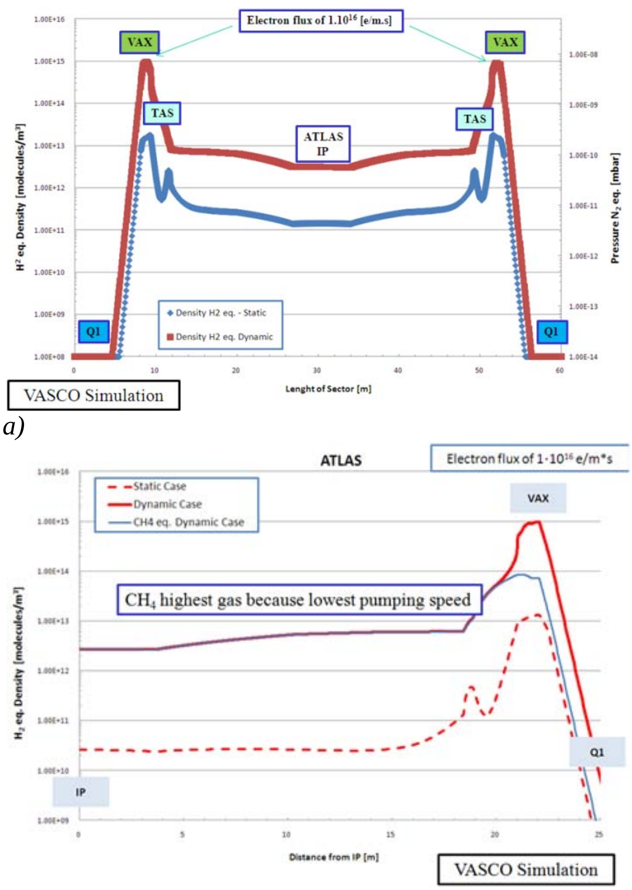
Fig.15: Pressure profile simulated for ATLAS upstream and downstream regions before the 2010 winter technical stop, a), and during the 2011 scrubbing run, b).

CLOSING REMARKS

The baseline for the operation of the LHC is to rely on vacuum conditioning and beam scrubbing and shortly after resuming the operation of the LHC with beams, a scrubbing run will be scheduled.

In case the scrubbing time does not provide the required reduction of electron cloud activities, solenoids are being installed in all cold/warm transitions and warm/warm transitions of the LHC LSS housing large detectors. LSS1 and LSS5 will be entirely equipped during the 2010-11 winter technical stop and only the recombination zones will be equipped in IR2 and IR8. For other non-NEG coated locations where huge pressure rise were observed e.g. IR3 and IR7, it was decided to rely on the vacuum conditioning. This work will be completed during the coming technical stops. In total, about 20 km of cables will be winded around the transitions!

In presence of an electron cloud build-up in the SAM magnets, the re-cooling sequence of SAM in case of failure of the cryogenics becomes critical. During the process of cool down, the beam screen shall be kept at a higher temperature than cold bore and in particular after a stoppage of a cryoplant. This procedure will imply longer recovery times but is absolutely required to avoid gas condensation on beam screens.



a)

b)

Fig.16: Pressure profile simulated in ATLAS assuming an electron stimulated desorption localised at the Q1 cold/warm transition (VAX), a). Methane (CH_4) which is

not pumped by NEG coatings become the dominant gas in the experimental beampipe, b).

CONCLUSIONS

The operation with 50 and 75 ns beams in the LHC has evidenced the efficiency of the vacuum conditioning and of the beam scrubbing on beampipes at cryogenic and ambient temperatures, as expected from laboratory measurements. The beam scrubbing resulted in a reduction of the induced heat load by a factor of 2 after about 8 hours of integrated beam time. The pressure rise decreased by a factor between 2 and 4 resulting from the combination of the vacuum conditioning and beam scrubbing effects. The range of pressure rise in LSS results from local configurations of the multipacting length versus pumping speed. In addition, the electron cloud is enhanced in the recombination areas where the two beams circulate in the same beampipe thus increasing locally the beam potential.

Since the measurements showed that pressure rise are expected to be twice higher at 50 ns as compared to 75 ns beams, no major limitation is expected for the scrubbing run from the pressure rise point of view. If the electron cloud activity is kept at a level which generate an electron flux to the wall of about 10^{16} electrons/s.m, 3 orders of magnitude of vacuum conditioning can be expected in beampipes at ambient temperature after a week of scrubbing (30% beam efficiency is assumed). The secondary electron yield is also expected to decrease below 1.4, a value which shall allow operating with 50 ns beams. The beam-gas scattering in these regions will also be significantly reduced.

The major concern being the feasibility of such challenging approach since these levels of electron cloud will probably generate beam instabilities and emittance blow-up.

ACKNOWLEDGEMENTS

Many thanks to our colleagues from the TE, BE, EN, PH and FP Departments for their help, contributions, helpful discussions and support.

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[1] Jimenez et al., "*Electron cloud with LHC-type beams in the SPS: A review of three years of measurements*", LHC-Project-Report-632, CERN (2003).

BEAM OBSERVATIONS WITH DIFFERENT BUNCH SPACING AND OVERALL SYNTHESIS

G. Arduini, V. Baglin, H. Bartosik, G. Bregliozzi, P. Chiggiato, S. Claudet, O. Dominguez, J.M. Jimenez, G. Lanza, K. Li, H. Maury, E. Métral, T. Pieloni, F. Roncarolo, G. Rumolo, B. Salvant, L. Tavian, F. Zimmermann, CERN, Geneva, Switzerland

U. Iriso, CELLS, Barcelona, Spain

Abstract

Machine studies have been performed at the end of the 2010 proton run to study the machine performance with bunch trains with 50 and 75 ns spacings in preparation for the proton run in 2011.

The results of the observations and measurements will be summarized and compared with existing models. Possible running scenarios for 2011 will be outlined.

INTRODUCTION

At the end of the proton run 2010 a series of Machine Development sessions, from Friday 29/10 to Thursday 4/11 were dedicated to the setting-up of the LHC with bunch trains with a spacing of 50 ns and the study of the beam dynamics at injection, ramp and high energy, including collisions. These sessions were interleaved with physics runs (TOTEM run, ALICE length scale calibration, longitudinal luminosity scan) and other machine development subjects (abort gap filling characterization and quench tests with a wire scan).

The main aim of the studies with 50 ns beams [1] was the investigation of potential problems for 2011 operation, e.g.:

- potential vacuum issues at number of bunches comparable with those achieved with 150 ns,
- long range beam-beam effects,
- electron cloud effects,
- RF and longitudinal aspects and issues related to the higher total intensity in the LHC and injectors (e.g. capture efficiency),
- background and luminosity/beam lifetimes in collision.

The setting-up and the studies with 50 ns beams spanned a period of 126 hours of which approximately 78 hours could be effectively used. The setting-up period took approximately 2.5 shifts (beam time) as initially expected [1].

After an initial physics fill with 108 nominal bunches (9x12 bunches) important dynamic pressure rises were observed at injection when filling with trains consisting of 24 bunches each. The first attempt led to the closure of the vacuum valves in point 7 (VVGSH.774.6L7.R) after the injection of 108 nominal bunches per beam as the vacuum interlock level of 10^{-7} mbar was reached on two vacuum gauges. The evolution of the vacuum pressure on the penning gauge VGPB.773.6L7.R on the (uncoated) cold-warm transition of Q6L7.B2 (warm-cold transition with NEG coating only on the warm side of the transition) is shown in Fig. 1.

In that area the two beams circulate in different vacuum chambers. It must be noted that pressure rises had been observed with 150 ns spacing beams only in common vacuum chambers, particularly at positions where the two beams overlapped. The pressure rise could be suppressed by applying a solenoidal field of ~ 50 Gauss indicating the presence of an electron cloud [2].

After these observations, emphasis for the machine studies has been given to the characterization of the electron cloud build-up and its effects and to the study of the evolution of these effects with time, to characterize the effectiveness of scrubbing at 450 GeV in suppressing the electron cloud effects at injection, during the ramp and at high energy.

The behaviour of the 75 ns beam with respect to electron cloud effects has been studied in another dedicated machine study period from Wednesday 17/11 to Saturday 20/11 for a duration of 74 hours of which 65 hours could be used for the setting-up of the injection and capture of the 75 ns beam and for the studies with 75 and 50 ns beams [3].

Fig. 1: Pressures and total intensity for the first two fills with 50 ns spacing. The gap in the data between 01:00 and 03:00 was due to an acquisition/logging problem related to the change from summer to winter time.

The electron cloud build-up with 50 and 75 ns spacing beams has been studied by means of vacuum pressure measurements in the straight sections and by cryogenic measurements for the arcs and is mostly discussed in a companion paper [2]. Simulations have been performed to benchmark the experimental data and the observations are consistent with a Secondary Electron Yield of 2-2.1 and a reflectivity coefficient of 0.6-0.7.

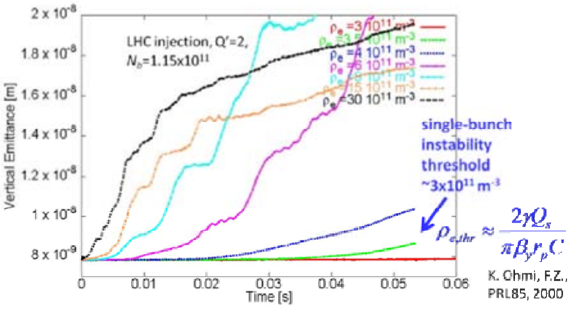
EFFECTS ON BEAM

The electron cloud building up along the bunch train interacts with the proton bunches and can couple the motion of consecutive bunches or even the motion of different longitudinal slices of a bunch as a result of the pinching of the electron cloud during the bunch passage. For that reason electron clouds can be responsible of single and coupled-bunch instabilities in the horizontal and vertical planes.

In a dipole field region electrons spiral around the magnetic field lines and their motion in the plane perpendicular to these lines is essentially frozen already at injection (magnetic field strength is 0.535 T). Therefore no pinching occurs in the plane perpendicular to the field lines and no horizontal single bunch instability is expected to originate from electron cloud in dipole field regions [4][5][6][7].

The single bunch instability occurs when electron cloud densities -before the bunch passage- exceed a certain threshold (typically in the range of 10^{11} electrons/m^3).

Fig. 2 shows the evolution of the vertical emittance of a single bunch for different values of the electron cloud density at injection energy in a field free region and for proton bunch with nominal parameters.

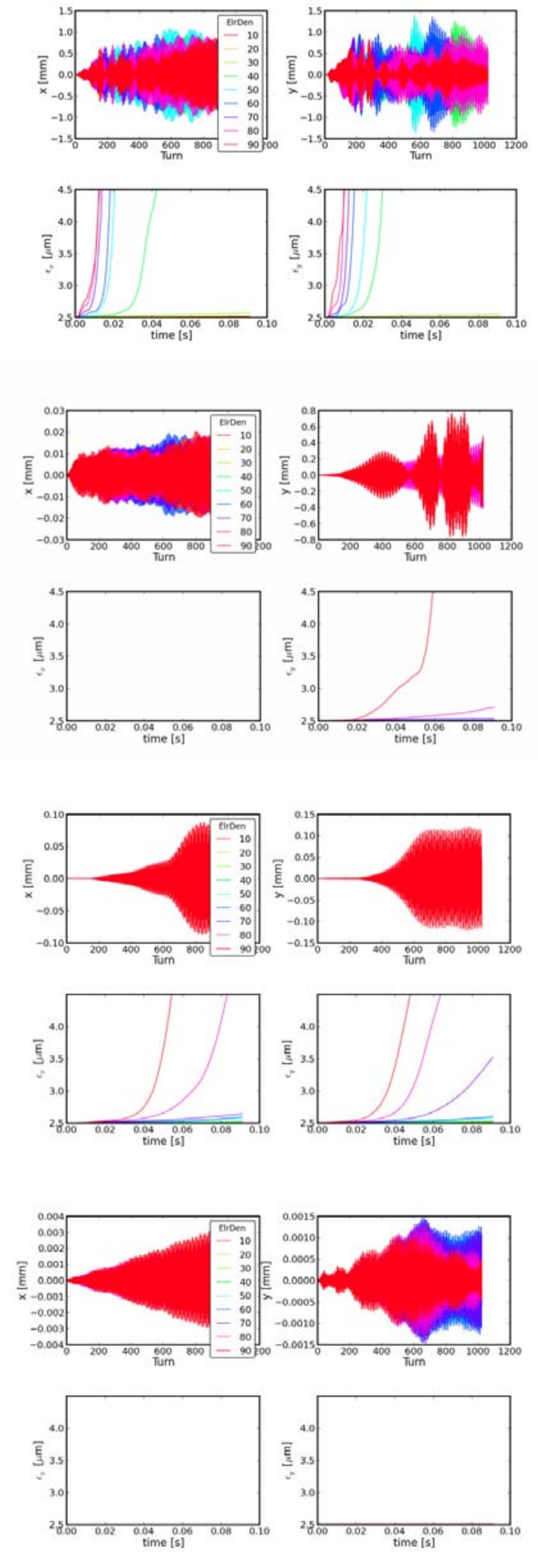


$$\rho_{e,thr} \approx \frac{2\gamma Q_s}{\pi \beta_y r_p C}$$

K. Ohmi, F.Z., PRL85, 2000

Fig. 2. Evolution of the vertical emittance of a single proton bunch for different values of the electron cloud density at injection in a field free region in the LHC and a chromaticity Q' of 2 units [8].

More recently, simulations have been performed with the beam parameters during the machine development session in October-November confirming the above expectations and indicating that the threshold electron density is minimum in the straight sections at injection energy (see Fig. 3).



1.

2.

3.

Fig. 3. Evolution of the vertical emittance of a single proton bunch for different values of the electron cloud density at injection in the LHC for low chromaticity in field free (1) and dipole regions (2) and at 4 TeV in field free (3) and dipole (4) regions. The electron densities are shown in 10^{10} e$^-$/m^3 units. The initial transverse emittance

of the beam was 2.5 μm and the vertical chromaticity Q'=2.

Below the threshold electron density for the onset of the single bunch instability, transverse blow-up is observed due to incoherent effects deriving from the highly non-linear fields generating during the bunch passage. As a result of these phenomena transverse emittance blow-up is observed along the bunch trains in correlation with the build-up of the electron cloud. Fig. 4 represents the tune footprint of the LHC beam at injection energy and for an average electron density of 10^{11} e^{-}/m^{3} under the pessimistic assumption that this density of electrons is distributed all around the machine and assuming that dipole fields are present in 70% of the machine circumference while in the remaining 30% of the machine no field is present.

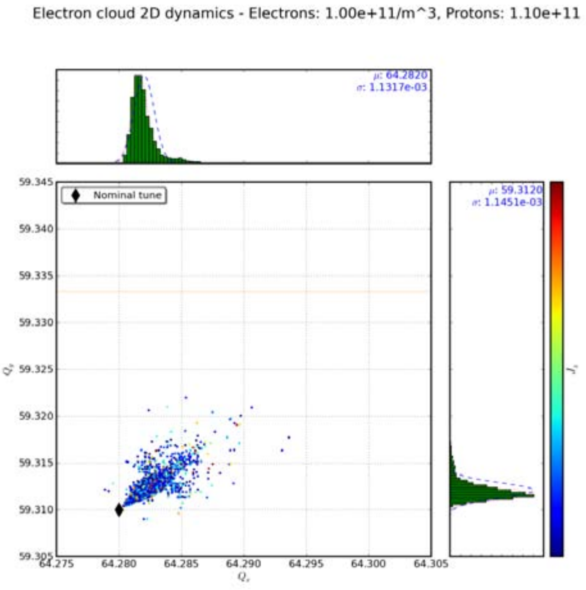


Fig. 4. Tune spread due to the pinching of the electron cloud during the bunch passage at injection energy. A transverse emittance of 2.5 μm was considered.

The tune spread due to electron cloud pinching can be as large as 0.01 at 450 GeV/c (worst case). It must be noted that for a large number of bunches (>600) with a spacing of 75 ns the heat load measured in the arcs was ~10 mW/m (close to resolution limit) corresponding to an average electron density of 5×10^{10} e^{-}/m^{3} assuming an average electron energy of 100 eV and ~800 bunches. For that reason the 75 ns beam was at the limit of single bunch stability and/or incoherent effects even for low heat load in the beam-screens of the arcs and in the pessimistic assumption that the electron cloud density is uniform along the LHC circumference.

Observations with 50 ns beam at injection

The transverse emittances measured along a bunch train of 36 bunches with 50 ns spacing (injected after a train of 12 bunches with a spacing of 35.7 μs) are shown in Fig. 5. A blow-up of the emittance is visible starting in the second half of the train. This is consistent with the observations on the dependence of the pressure rise as a function of the bunch train length [3]. These measurements were taken with typical machine settings at injection (damper gains close to maximum, 4 units of chromaticity in both planes).

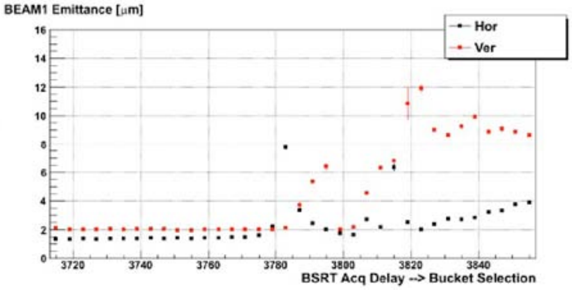


Fig. 5 Transverse emittance along a bunch train of 36 bunches for Beam 1.

The rise-time of the transverse instability observed at 450 GeV/c was ~1 s horizontally and a few tenths of a second vertically as shown in Fig. 6.

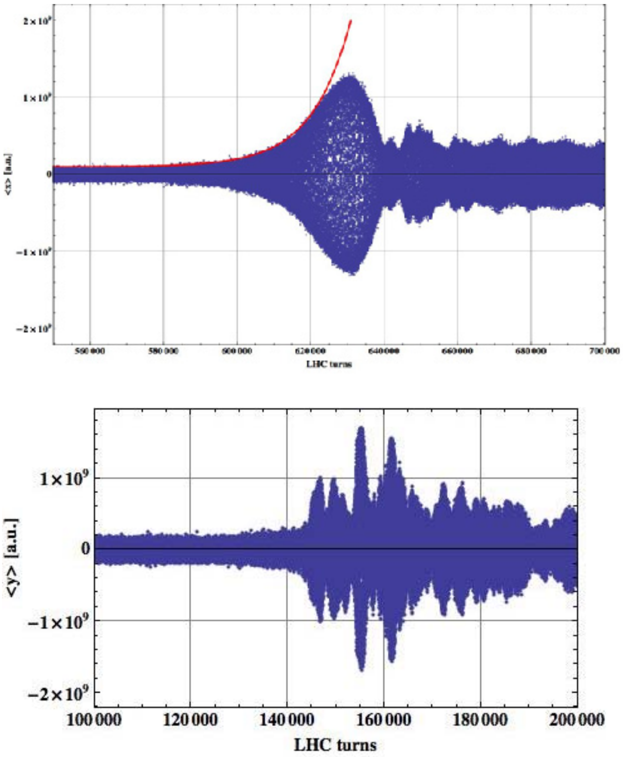


Fig. 6. Time evolution of the horizontal (top) and vertical (bottom) beam positions as measured by the BBQ after the injection of a train of 36 bunches in addition to 12 bunches circulating in the machine.

The transverse emittances measured along 4 consecutive trains of 24 bunches spaced by 1.85 μs (injected after a train of 12 bunches with a spacing of 35.7

µs) are shown in Fig. 7. The vertical blow-up is mostly affecting the last two trains.

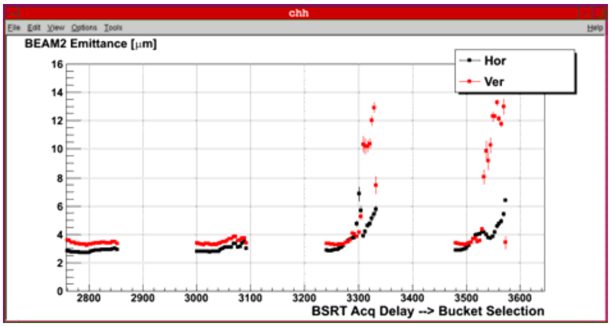


Fig. 7. Transverse emittance along 4 trains (spaced by 1.85 µs) of 24 bunches.

This is a consequence of the fact that the decay time of the electron cloud after a bunch train passage is larger than the batch spacing (in this case 1.85 µs) [2][3] and therefore the electron cloud density reaches a value critical for beam stability (perhaps saturation) only towards the end of the third batch. These measurements were taken with typical machine settings at injection (damper gains close to maximum and 4 units of chromaticity in both planes).

The smaller vertical emittance of the last bunch of the last two trains is the result of the losses mostly affecting those bunches.

Large chromaticity and large injected emittance have proven to have a stabilizing effect on the single bunch instability induced by electron-cloud both in simulations and experiments in other machines and in particular in the SPS [4][8]. The effectiveness of these cures has been demonstrated also in the LHC and they could be used to increase the number of bunches during scrubbing while minimizing beam instabilities and losses.

The transverse emittances measured along 7 consecutive trains, each consisting of 24 bunches, spaced by 1.85 µs (injected after a train of 12 bunches with a spacing of 35.7 µs) after having increased the horizontal and vertical chromaticities to 14 units in both planes are shown in Fig. 8. The measured emittance blow-up is reduced by more than a factor two also for the trailing bunch trains.

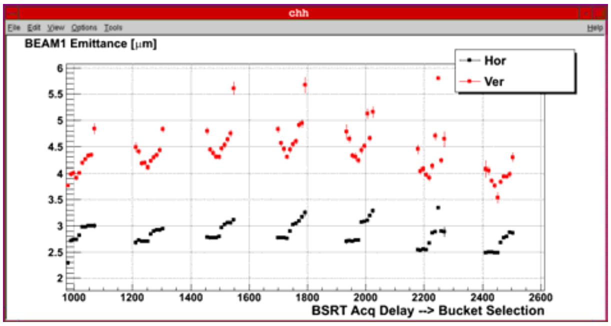


Fig. 8. Transverse emittance along 7 trains (spaced by 1.85 µs) of 24 bunches. Chromaticity was set to 14 units in both planes.

The blow-up is further reduced after having increased the chromaticity to 18 units and after increasing the transverse emittance of the beam delivered by the injectors from 2-2.5 µm to 3-3.5 µm (see Fig. 9).

In spite of that some blow-up is still observed that could be related to the above mentioned incoherent effects of the electron cloud pinching.

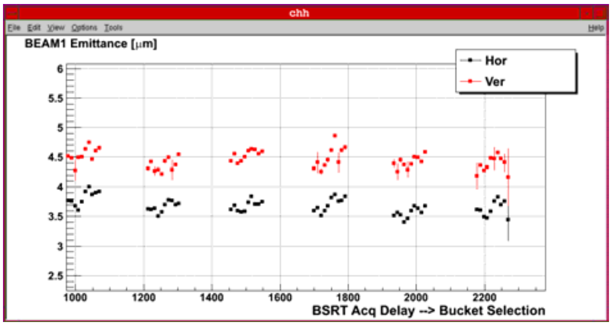


Fig. 9. Transverse emittance along 6 trains (spaced by 1.85 µs) of 24 bunches. Chromaticity was set to 18 units in both planes and transverse emittance blow-up was applied in the injectors.

Observations with 50 ns beam at 3.5 TeV

At injection, operation with large chromaticity seems to be required even for large gains of the transverse feedback pointing to single bunch instabilities at frequencies outside the bandwidth of the feedback as observed in the SPS [6].

At 3.5 TeV instabilities have been observed, when the transverse feedback is switched OFF, with beams consisting of trains of 24 bunches (12+4x24) instead of trains of 12 bunches (9x12) for the same total number of bunches (108) and with the same settings (tune, chromaticity, octupole strengths). The rise time of the instability was few tenths of a second in the horizontal plane and 1 to 2 seconds in the vertical plane as shown in Fig. 10.

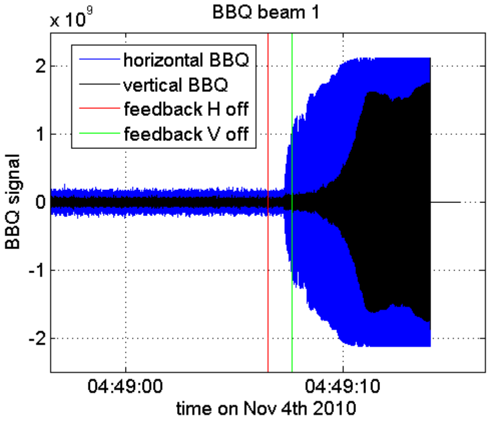


Fig. 10: Time evolution of the horizontal (blue) and vertical (black) beam position as measured by the BBQ at 3.5 TeV when the transverse feedback is switched OFF. The accuracy of the logged timing of the transverse feedback switch OFF is approximately 1 second.

Observations with 75 ns beam at injection

Coupled-bunch oscillations at low frequency (~1-2 MHz) were observed also for the 75 ns beam at injection (see Fig. 11), mostly in the horizontal plane, although it is not clear whether they are induced by the electron cloud. In the vertical plane blow-up was observed even when operating the machine to high chromaticity (Fig. 12). This is compatible with instabilities and incoherent effects generated by the electron cloud close to threshold electron density.

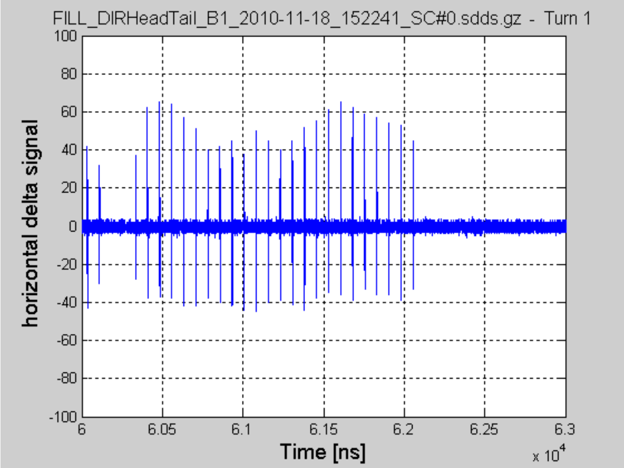


Fig. 11. Snapshot of the delta signal (product of the horizontal displacement and of the bunch profile) provided by the Head-Tail monitor for a train of 24 bunches at injection.

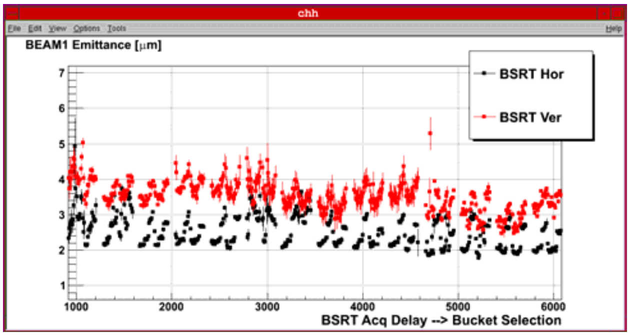


Fig. 12. Transverse emittance along 14 trains (spaced by 1.005 μs) of 48 bunches. Chromaticity was set to 20 units in both planes.

SUMMARY AND PRELIMINARY SCRUBBING RUN PLAN

Electron cloud effects (vacuum pressure rise in the straight sections, heat load in the arcs, instabilities and transverse emittance blow-up) have been observed for 50 ns beams. Although a reduced vacuum activity has been measured with 75 ns beams, acceleration of nominal trains of 936 bunches would lead to vacuum pressures larger than 2×10^{-7} mbar (interlock level) and scrubbing is required to accelerate and collide more than 200-300 bunches with 75 ns spacing with no significant pressure rise assuming that the vacuum conditions after the technical stop will remain the same as those after the scrubbing run (i.e. assuming that no intervention affecting the machine vacuum will be carried out).

Low values of heat load due to electron cloud in the beam screens (close to the detection limit of 5-10 mW/m/aperture) have been measured for the 75 ns beam while a clear increase of the temperature of the beam screen of the triplet-D1 magnets in point 2 and in point 8 has been observed and in particular on the left side of point 8. This implies that no significant scrubbing of the arcs can be expected with 75 ns beams.

The typical signatures of electron cloud instabilities have been observed with 50 ns beams. For the 75 ns beam vertical blow-up correlated to coherent and incoherent effects typical of electron cloud densities close to threshold have been evidenced. For both beams these effects translate into low beam lifetime and losses. For that reason a scrubbing run is recommended starting with a 50 ns beam.

The comparison of the dynamic pressure rise in the uncoated portion of the straight sections and the heat load in the beam screens of the arcs for a 50 ns beam at injection, during the ramp and at 3.5 TeV before and after scrubbing at 450 GeV clearly shows a reduction of both phenomena [2] although the electron current of 1 mA/m, corresponding to a heat load due to electron cloud of 100 mW/m/aperture (assuming an average electron energy of 100 eV) has not been achieved so far. Furthermore the above value of the electron current cannot be maintained during the whole period of the scrubbing and it will decrease with the progress of the scrubbing.

The aim of the scrubbing run is to reduce the electron cloud density at the beam centre to less than 10^{10} e^-/m^3 for 75 ns (and possibly 50 ns) beam operation with close to 1000 bunches to remain well below the threshold for the onset of the electron cloud single bunch instability and minimize the tune spread which is at the origin of the incoherent blow-up observed both with 75 and 50 ns beams. At the end of the scrubbing run the heat loads in the beam screens due to electron cloud should remain below the detection limits for 50 ns beams with more than 1000 bunches.

According to simulation results Secondary Electron Yield (SEY) lower than 1.8 are required in dipoles and field free regions in order to operate in the above regime of electron cloud densities ($<10^{10}$ e^-/m^3) for 75 ns beams at 450 GeV/c and at 3.5-4 TeV/c. The above values of the SEY are within reach within ~1 week of scrubbing with 50 ns beams assuming an efficiency of ~30% and an optimistic electron dose rate (e.g. not considering the reduction of the flux of electrons in the last part of the scrubbing) [2] and provided that the behaviour of the cryo-surfaces is similar to that of surfaces at room temperature as indicated by laboratory experiments [2].

Experience in the SPS (see Fig. 13) shows that scrubbing with 25 ns beams allows operation with 50 and 75 ns beams with no significant electron cloud build-up.

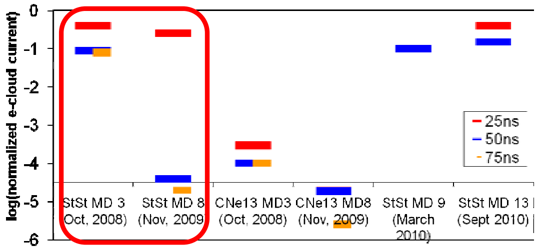


Fig. 13. Electron cloud signal measured for beams with different bunch spacing. A reduction by more than 3 orders of magnitude has been measured with 50 and 75 ns beams after scrubbing with the 25 ns beam in the SPS (see highlighted columns - courtesy M. Taborelli).

The following prerequisites must be present before the start of the scrubbing run:

- injection of 4 trains of 36 bunches (50 ns spacing) per SPS extraction up to nominal transverse emittance should be set-up in advance (this requires 3-4 days of preparation) [9];
- machine protection should be set-up for high intensity at 450 GeV/c (up to 1404 bunches);
- RF should be conditioned for operation at high intensity;
- the transverse feedback should be set-up for high intensity operation with 75 and 50 ns beams;
- solenoids (experimental and anti e-cloud) should be OFF in order to condition all the machine;
- vacuum interlock levels should be temporarily set to $2x10^{-6}$ mbar when and where pressure rises limit the progression of the scrubbing and compatibly with machine and experiment protection.

A preliminary schematic plan for the scrubbing run is presented below:

- In the first half of the scrubbing run (Day 1-2): an increasing number of trains of up to 4x36 bunches with 50 ns spacing ($1.3\text{-}1.5x10^{11}$ p/bunch assuming operation with 75 ns at $1.2x10^{11}$ p/bunch to allow for current decay) with nominal emittance and up to a total 1404 bunches will be injected compatibly with vacuum rise, heat loads and beam stability. Heat load on the beam screen and RF stable phase (proportional to energy loss) [10] will be monitored as well as vacuum evolution to follow up the scrubbing progress. Large chromaticity and nominal emittances will be required to stabilize the beams and low lifetime, as observed during the scrubbing run, can be expected.
- In the middle of the run (Day 3-4): the sensitivity to orbit excursion, radial position and energy will be studied. For that reason the separation bumps and crossing angles should be varied with a high intensity circulating single beam at 450 GeV in order to address the localization of the scrubbing in dipole field regions and possibly "scrub" in these conditions. A ramp with a 50 ns beam with a few hundred bunches according to progress should be planned to confirm the effectiveness of the scrubbing at 450 GeV for operation at 3.5 TeV. Injection of 75 ns beam should be considered as well to evidence any difference in the distribution of the electrons with 50 and 75 ns beams.
- Second half of the scrubbing run (Day 5-7): the transverse emittance of the beam should be decreased to maximize the energy of the electrons. Recent simulations have shown that, close to the multipacting threshold, smaller transverse emittances enhance the electron cloud build-up. The chromaticity should be reduced (if possible) to maximize the beam lifetime.
- End of the scrubbing run (Day 8): ramp with a 50 ns beam with few hundred bunches to assess effectiveness of the scrubbing and provide input for requirements for operation at 50 ns.
- Start physics with 75 ns with fast ramp-up in intensity to 900 bunches.

ACKNOWLEDGEMENTS

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HOW CAN WE REDUCE THE “NO BEAM” TIME?

W. Venturini Delsolaro, CERN, Geneva, Switzerland

Abstract

The operational efficiency of the LHC is analyzed by looking at the downtime statistics over the 2010 run. Hardware reliability is reviewed along with the mitigation actions put in place for the 2011 run. Recovery, duration and frequency of scheduled technical stops are also discussed. Finally, possible ways to reduce the setup time without beam are considered.

INTRODUCTION

The first year of LHC operations was dominated by a commissioning program aimed at establishing collisions at 3.5 TeV, and then pushing on the beam parameters (β^* and beam intensity), to reach peak luminosities in excess of 10^{32} cm^{-2} s^{-1}. Furthermore, despite clear focusing on commissioning, a significant set of data was delivered to the experiments. Here, starting from the assessment of the operational efficiency reached in 2010, possible ways of increasing the beam time in the future runs will be elaborated along three lines. Actually the time without beam can be split into three components: downtime due to faults, scheduled technical stops, and operational inefficiencies.

Fault statistics were analysed to highlight the top 5 systems responsible for downtime. For each of them, the mitigating actions undertaken will be outlined.

The scheduling of technical stops will be reviewed with a critical look.

Finally, the optimization of the phases without beam in the LHC cycle will be addressed, while the phases with beam are dealt with in a separate contribution [1]

MACHINE STATISTICS 2010

The machine statistics for 2010 were collected by inspection of the e-logbook. Each of the 6600 hours in the time span considered (March-November) was attributed (with an average time resolution of half an hour) to one of the following machine states: setup without beam, beam setup, stable beams, technical stop, and fault (machine not available due to some system fault). Time spent in supplementary hardware commissioning was included in technical stops, while the recycling time occasioned by faults was ascribed to the faulty system. As the information in the e-logbook by its nature is only a human reporting of a much richer scene, one should not expect extremely high accuracy from these figures, the aim of which was just to identify the major causes of downtime, thereby setting priorities for consolidation work. Several effects limit the accuracy of the time breakdown. The finite time resolution leads to an overestimation of the beam presence, as easily recovered problems, for instance small software bugs, go unnoticed no matter how frequent they may be.

Multiple faults are problematic as the criterion of attributing the downtime to the “leading” faulty system, i.e. the bottleneck, is not always of easy application.

Also, beam presence may coexist with stalled situations, typically when handling software issues.

The machine statistics for 2010 are shown in Fig. 1

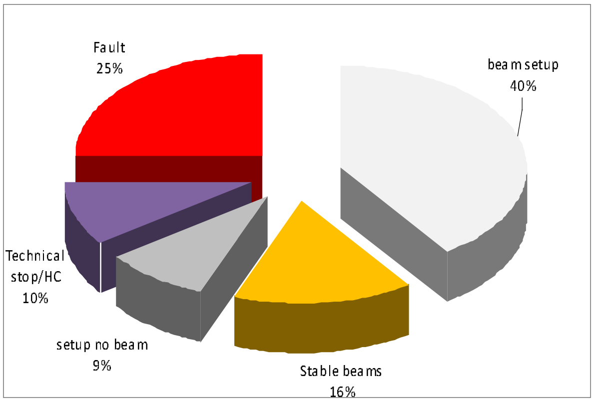

Fig. 1 Global 2010 machine statistics

The overall machine availability, as given by the sum of the setup without beam, beam setup and stable beam times, was 65% of the total time. The downtime due to faults reached 25%. The scheduled technical stops covered the remaining 10%. Setup with beam dominated, as expected for a commissioning year.

More insight can be gained by looking at the time evolution over the run of the time breakdown slices, displayed in Figs. 2-5.

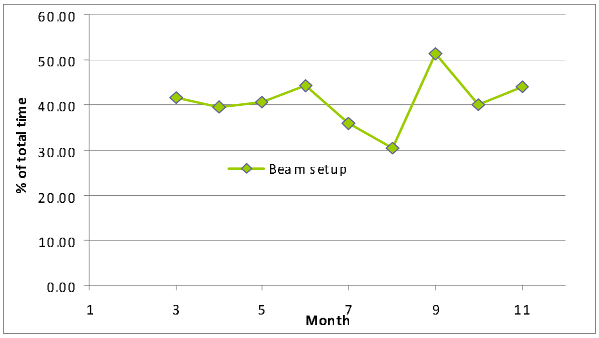

Fig. 2 Beam setup fraction along the run

The fraction of beam setup shows two maxima: in June and in September, when intense beam commissioning was concentrated. Correspondingly, the fraction of stable beams was a minimum (Fig. 3).

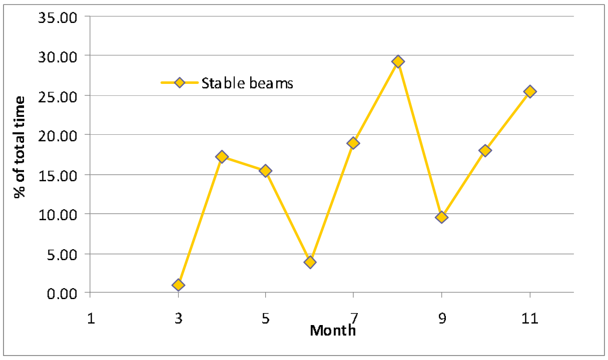

Fig. 3 Stable beams fraction along the run

The machine availability grew steadily during the run, reaching the record value of 80% during the ion run in November (Fig. 4)

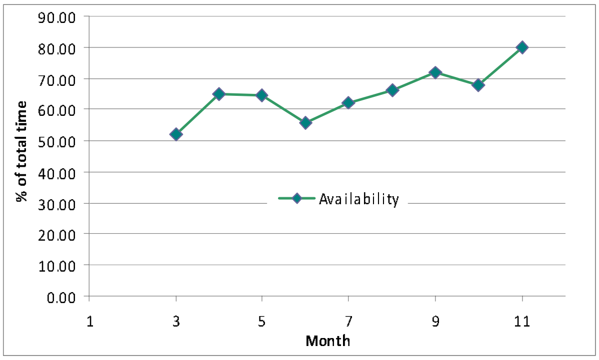

Fig. 4 Machine availability along the run

Finally, the downtime due to faults seemed to level off at around 20% towards the end of the run, which seems to indicate that further increase of the machine availability would have been unlikely (Fig. 5).

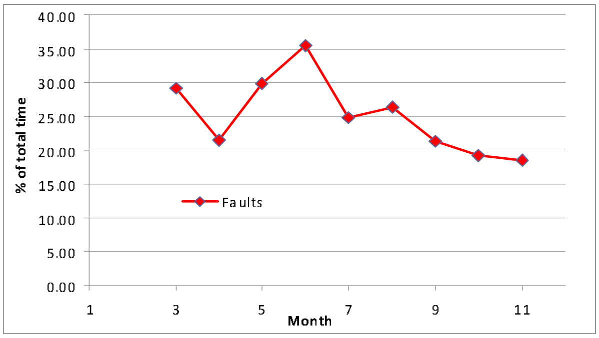

Fig. 5 Fault downtime evolution along the run

Several considerations on efficiency for physics can be made based on these data. One should distinguish between machine efficiency and operational efficiency. In all cases we consider the useful time to be the one spent in stable beams. Operational efficiency can be defined with respect to the minimum turnaround time, while machine efficiency must include all the machine non availabilities. Luminosity forecasts are usually based on the so-called Hübner factor, which accounts for machine efficiency and luminosity lifetime.

In the last two weeks of August 2010 the only aim of the operations crews was to deliver collisions to the experiments. During that time, the operational efficiency was 50%, while achieving systematically the minimum turnaround time would have brought that figure up to 83%. Finally, all estimates being based on short periods, it is advised to assume Hübner factors in the 0.2 – 0.3 range when trying to anticipate the 2011 luminosity harvest.

FAULTS AND MITIGATION ACTIONS

As shown in Fig. 6, about 70% of all the downtime due to faults was due to the "top 5 systems": QPS, cryogenics, power converters, electrical supply (network perturbations), and injectors. The latter are covered in [2].

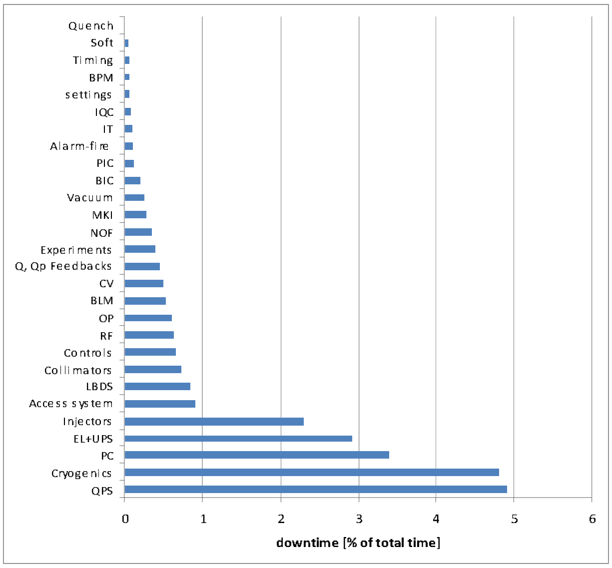

Fig. 6 histogram of LHC fault downtime

QPS detailed statistics and mitigating actions

Almost 5% of the runtime was taken by failures of the Quench Protection System. This is no surprise given its complexity. Table 1 gives a breakdown of the faults per subsystem, highlighting very high availabilities.

The majority of QPS faults were due to the failure of a single component, an input switch of the quench heater power supply. The switch was redesigned and after validation of the new version, replacement of some 5000 items in the tunnel has started. About 20% of them, serving for the main quadrupoles, will be changed during the 2010/11 winter stop. The quench heater circuits for dipoles, differently from quadrupoles, are redundant, and a single failure of this kind will not lead to a beam stop.

Equipment type	Faults	Quantity	Availability [%]	MTBF [hours]
Quench heater power supplies	26	6076	99.998	1145760
Quench detection systems	19	10438	99.999	3362135
DAQ caused by radiation (SEU)	12	1624	99.997	828240
DAQ other causes than radiation	8	2532	99.999	1936980
EE600	6	202	99.988	206040
EE13 kA	5	32	99.939	39168

Table 1 Detailed QPS faults statistics

Also, the quench detection system will be made more robust against electromagnetic interference, by removing the obsolete global bus bar detector for the main circuits, by increasing the signal to noise ratio for Q9 and Q10, and by re cabling the current sensor of the undulators.

Finally, the firmware of the systems most exposed to radiation will be upgraded to cope with SEU [3].

Cryogenics downtime and mitigation

Failures in the cryogenics systems come as the second cause of downtime. This is not driven by the fault frequency but rather by the fact that some cryogenics faults, typically those involving the cold compressors, have very long recovery times. The cold compressors were consolidated over the winter stop and new instrumentation was added to prevent unnecessary trips.

The long lasting issue of sub atmospheric filters clogging was addressed during the year; the last leaks were found and repaired during the end of the year stop. This issue had dictated the frequency of the technical stops in the past, as the filters needed regular de-icing.

A huge campaign to replace the regulation valves for the flow control on the current leads has reached 50% of all valves replaced, and no major contribution to the downtime is expected now from this particular issue.

Instrumentation failures were as well tackled during the winter stop. However the large number of gauges will still imply failures impacting the machine availability in 2011.

Finally, the decision to reduce to a minimum preventive maintenance in the winter stop is likely to bring as a consequence some additional faults, which the cryogenics team estimate in 2-5 events for the next run [4].

Power converters

The detailed fault statistics of the power converters is documented in [5]. Fig. 7 shows the number of faults occurred for the various converter typologies. Most problems affecting the statistics were fixed during the first part of the run and did not reappear. The main concern was given by the 600A circuits, where 70 faults have occurred, most of which not understood. The types of fault leading to a converter stop have been reviewed for the 2011 run; most faults occurred in 2010 in the 600 A converters will be downgraded to warnings, not leading to a beam dump [6].

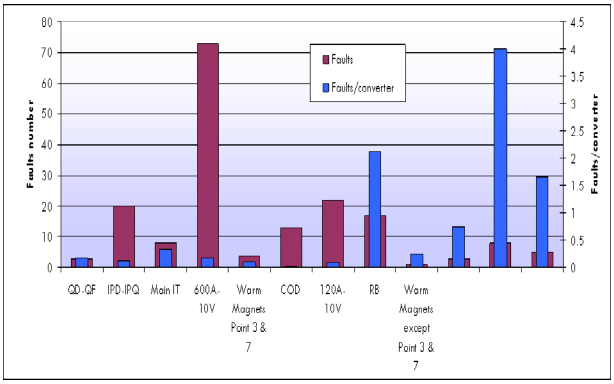

Fig. 7 Power converter faults, absolute and normalized

Electrical perturbations

The LHC is particularly sensitive to electrical perturbations from the supply network. Fig. 8 shows all the events which have shut down the collider in 2010. The innermost rectangle (zone specified in EDMS 113154) defines events which may occur during the normal operation of the network, to which the other CERN accelerators are not sensitive. The dashed region defines the LHC sensitivity area. The weak point is in the warm magnets circuits. Fast current changes are interlocked with the beam dump for machine protection purposes, and filtering is made difficult by the high power involved. The cryogenics were sensitive to electrical perturbations at the start of the run, but later on the cryogenics team managed to increase their immunity. No further improvements in this area are expected for 2011.

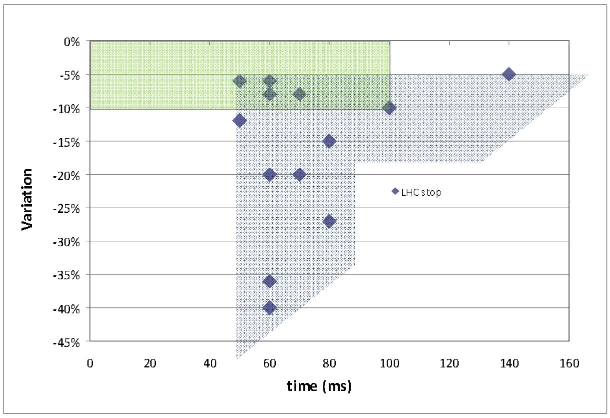

Fig. 8 Electrical perturbations leading to LHC stop [7]

TECHNICAL STOPS

During the 2010 run the LHC was stopped for six times for scheduled maintenance activities. The average duration of technical stops was 4 days, and the average spacing was 39 days.

The philosophy of preventive maintenance is to invest some runtime in order to increase the overall availability. It is therefore important to tune frequency and duration of the scheduled stops to balance costs and benefits.

Data seem to indicate that in 2010 the two parameters were not well optimized. For instance, considering a period of 72 hours and comparing the downtime due to faults before and after each technical stop, it is clear that the effect of the first three stops was detrimental to the machine availability. More problems were created by the many interventions in the tunnel than were actually solved. The effect was gradually reabsorbed in the course of the year, as shown in Fig. 9.

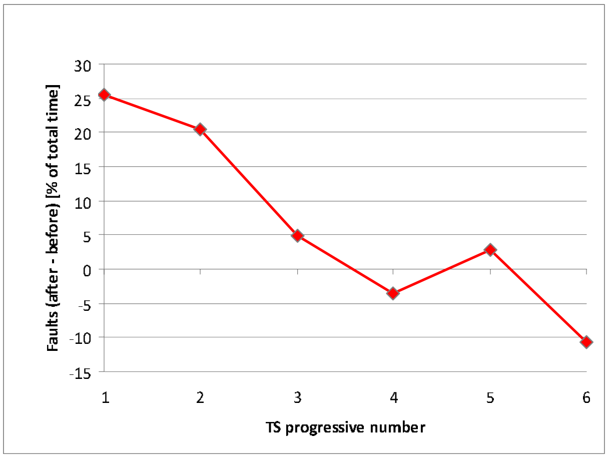

Fig. 9 Increment of faults after technical stops

A preliminary survey of the equipment groups has indicated a preference for longer but less frequent stops. However this might be difficult to accommodate, especially in view of the heavy machine development programs for the injectors, which are scheduled during LHC maintenance periods.

SET UP TIME WITHOUT BEAM

Ramp down times of unipolar power converters

The theoretical minimum turnaround time of the LHC is determined by the durations of the beam processes that compose the operational cycle. These in turn are limited by the voltage ratings of the power converters. In particular, unipolar power converters, supplying several types of quadrupole circuits, cannot provide negative voltages. This fact limits, in some cases severely, the ramp down speed. The times to ramp down the Q4 circuits from 3.5 TeV to injection are shown in Fig. 10. The figures in the plot do not include the time needed to complete the ramp, without overshoot, within the very strict specifications for the LHC power converters: in the case of the RQ4.R2 circuit, which is the slowest circuit of the LHC, soft landing takes about 10 additional minutes, just to bring the circuit from 100.3 A to 100 A. Note that the ramp down times for a given circuit type vary as a function of the warm cables resistance. In some locations the warm cables are shorter, and this trivial circumstance costs more than 10 minutes per fill.

Fig. 10 also shows the times needed to accomplish the same ramp if the circuits were left discharging with their natural time constants. A large margin of about 15 minutes appears to be available to all the circuits.

It should be noted that in the LHC, the ramp down from top energy is used as pre cycle to regenerate the magnetic fields, ensuring optics reproducibility.

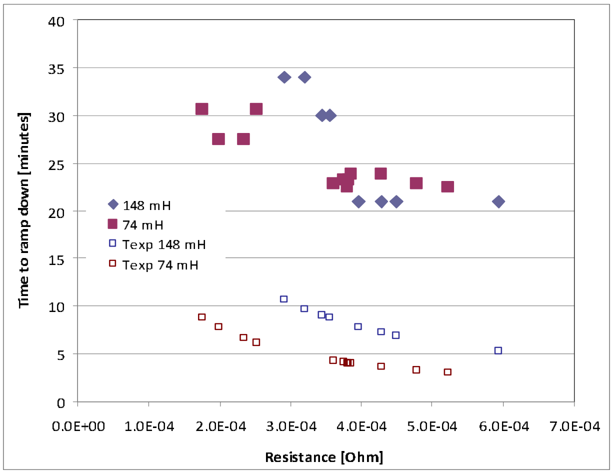

Fig. 10 Ramp down times of Q4 circuits versus resistances of the warm cables

From what has been shown above, two possible solutions can be envisaged to decrease the ramping down time. The first possibility does not entail hardware changes; it just consists of relaxing the specifications on current tracking for the phases without beam. In particular, ramping down in open loop mode would bring the discharge times close to their physical minima. This was tested successfully on the RQ4.R2 circuit, achieving a 19 minutes gain with respect to 2010. The overshoot was of a few tens of mA, not enough to change the magnetization of the superconducting filaments. However, running in open loop is not an option for the inner triplet quadrupoles circuits, which would trip because of the different current ramp rates of the nested circuits and the constraints on the diode voltages. The ramp down time will thus be limited at about 25 minutes, once the software parameters of the RQX circuits will be optimized.

The second possibility is to add extra resistance to the slowest circuits. An elegant way to do so, already proposed [8] as a means to achieve the high β* optics for TOTEM, is to double the intermediate cable which is presently shared between the B1 and B2 circuits. This would remove the resistive coupling between magnet apertures. The advantage of this solution is that it is applicable as well to the phases with beam, and would therefore speed up the squeeze to very low β*. However these changes cannot be implemented in a normal winter stop, and can only be considered for a long shutdown.

Pre cycling policy after short access

Out of safety considerations, in the previous run the superconducting circuits were switched off during access in the machine. This compelled to carry out a pre cycle before taking beam back; otherwise the magnetic machine, and therefore the beam parameters, would not be reproduced.

In the course of 2010 the safety conditions have been revised and reformulated in terms of the energy stored in the circuits. It was considered [9] that the probability of having an electric arc strong enough to piece the beam pipe is negligible below 100 kJ stored in the circuit. This condition is satisfied if the circuits sit at injection current and the (standby) current of the main dipole circuits is downgraded at 100 A. A new access procedure has been prepared [10], allowing to give access in the above described powering state. The advantage of not switching off the circuits is mainly a reduction of the failure probability. Moreover, it becomes possible to make identical powering histories after physics and after access, thus eliminating the need to pre cycle the machine after access. To this end, it is sufficient to set the minimum current of the ramp-down function to 100 A.

It should be noted that pre cycling will still be needed in case the beam is lost at injection and access is required.

SUMMARY

In the light of 2010 experience, improvements of the machine availability are pursued by tackling the main failure contributors, by reviewing the frequency and duration of technical stops, and by minimizing the length of the operational cycle.

The breakdown of systems failures pointed at QPS, cryogenics, power converters and electrical supply as the major sources of downtime. For some of these, mitigation actions in place for the next run were enumerated.

The operational efficiency was good considering that this was the first year of operations; however there seem to be margins to improve it even further.

From estimates carried out on short time periods fully dedicated to physics, it seems that Hübner factors in the range 0.2 – 0.3 can be assumed for the next run.

Analysis of the machine availability before and after technical stops showed that in 2010 technical stops were scheduled too frequently, at least for some systems. It is advised to increase the duration of technical stops up to 5/6 days, and reduce accordingly their frequency, which in 2011 will not be any more constrained by the need of de icing the cryogenics filters.

The bottleneck in ramp down time was located in the Q4 circuits in point 2. The ramp down of unipolar power converters can be considerably accelerated by running in open loop. This is not possible in case of the inner triplets, which will need some fine tuning in order not to become the next bottleneck. The feasibility of such an option was demonstrated, also in respect of the reproducibility of the superconductor magnetization. This change will allow saving about 20 minutes for each fill.

Finally, a necessary condition to skip pre cycles after short accesses was identified and will be implemented for the 2011 run. The related gain in time is about 50 minutes for each access following a beam dump at top energy.

ACKNOWLEDGEMENT

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OPTIMIZATION OF THE NOMINAL CYCLE

Stefano Redaelli, CERN, Geneva, Switzerland

Abstract

The energy ramp and the betatron squeeze are critical phases of the LHC operation. During the squeeze, delicate optics manipulations take place when the stored energy is maximum. In 2010, ramp and squeeze were commissioned rapidly and smoothly became operational. On the other hand, during the first commissioning exercise, the focus was put on machine safety and on operational robustness rather then in efficiency for luminosity production. After having accumulated a full year of experience on the operational cycle and having gained important feedback on machine behaviour and operational procedures, it is now time to address the optimization of the LHC cycle, while still respecting safe boundaries. In this paper, the experience with the LHC operational cycle is reviewed, possible bottlenecks are identified and paths for improvements are addressed. Proposals for improvement are based on a critical look at the limiting factors encountered in the different phases of the cycle. More complex operation configurations, like combined ramp and squeeze, are also discussed.

INTRODUCTION

The optimization of the machine cycle will be a crucial parameter for the LHC performance during stable running conditions in 2011 at a luminosity above $10^{32}\text{cm}^{-2}\text{s}^{-1}$. Minimizing the turnaround time will have a direct impact on the integrated luminosity. While in the first commissioning year the focus was rather put on bringing up safely the peak luminosity performance in preparation for the 2011 run, it is now important to address optimization issues in view of maximizing the LHC physics reach. Clearly, machine safety remains the priority and the optimization process must be carried out within well-defined safety boundaries.

At the LHC, energy ramp and betatron squeeze are carried out with functions of well-defined time length. An optimization of the duration of these functions has a direct impact on the machine turn around. On the other hand, other important phases of the operational cycle (injection, flat-top setup, preparation of collisions, ...) are also important. The duration of these phases depends on a large number of aspects, such as operational efficiency, status of procedures, availability of automated sequencer tasks, etc. There is often much margin for improvement there. An optimization of the machine cycle must hence take into account the various aspects of the whole operational phases while ensuring a reasonable machine flexibility. Indeed, the results presented here are based on a statistical analysis of the time spent in the various phases, as presented in [1] with the aim to find the real bottlenecks.

In 2010, ramp and squeeze settings have been prepared taking conservative assumptions and the hardware and beam parameters. For example, all the available matched optics where used and stepped through while squeeze, with a subsequent lengthening of the squeeze duration (every new optics adds some extra time due to the constraints on the power converter settings). This approach ensured minimum errors of key beam parameters and full flexibility in the commissioning, at the expenses of longer collision setup time during physics fills. These aspects will be reviewed in preparation for the 2011 run.

After a brief recap. of the different phases of the LHC operational cycle, the outcome of previous studies on turnaround optimization [1] are recalled. For each operational phase, possible improvements are outlines. The feasibility of combining ramp and squeeze is also discussed, with an outline of pro's and con's and with a proposal for the actions in 2011. Finally some conclusions are drawn.

LHC OPERATIONAL CYCLE IN 2010

The main phases of the LHC cycle are illustrated in Fig. 1, where beam intensities (top) and magnet currents (bottom) are given as a function of time. The current of a main dipole circuit and of a matching quadrupole circuit (Q5-L1B1) indicate the times when ramp and squeeze take place. In the cycle, four phases involve execution of time functions of well-defined time length:

- *energy ramp*: 1400 s for are required to ramp from 450 GeV to 3.5 TeV, at a maximum dipole ramp rate of 10 A/s, including a 380 s flat-top *plateau* for field decay compensation;
- *betatron squeeze*: 1041 s for the change to β^*=3.5 m at 3.5 TeV in all IPs (initially commissioned to β^*=2.0 m in 1285 s;
- *collision functions* to collapse the parallel separation bump: 108 s for protons, 180 s for ions that also required a change of crossing angle;
- *magnetic pre-cycle* without beam: 2100 s if started from top-energy, 3100 s if started from injection.

While time-functions are being executed for the main accelerator systems (power converters, collimators, RF), the

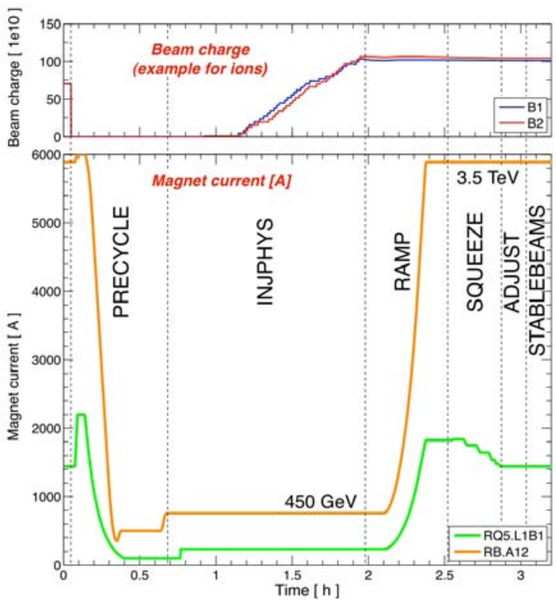


Figure 1: LHC operational cycle with the main phases, illustrated by graphs of beam intensity (top) and magnet currents (bottom) as a function of time. The current of a matching quadrupole is used to show when the squeeze takes place.

machine is essentially "frozen" and no trims of any parameter are possible. Feedback systems for tune and orbit use dedicated real-time channels that are added on top of the operational settings being executed by the hardware.

Other operational phases that do not have a well-defined duration, are

- *injection* of probe beams for machine setup and physics beams for filling;
- *ramp preparation*;
- *flat-top adjustments*;
- *adjust* at the end of the squeeze to prepare collisions;
- *stable beams* for physics data taking.

In these phases, the machine sits at constant "actual" settings that can be changed as discrete trims, not synchronized across the systems, depending on the operational needs (optimization of injection oscillations, orbit steering, changes of tune and chromaticity, etc.). The duration of these phases depends of various aspects and the details of the operational procedures. During 2010, the mode of operation kept evolving from a paper-based procedure towards fully sequencer-driven operation (less room for mistakes, faster execution of tasks, better reproducibility of machine configurations).

The optimization of the duration of ramp and squeeze is important because on paper these phases are the ones that take the longest times. On the other hand, in practise it is important to maintain a good overview of the time spent in all the phases in order to achieve an optimized strategy: it does not pay off to propose aggressive buts in the squeeze time until the machine is being limited but other bottlenecks. A reduced operational flexibility must always be justified by a real gain. The overview of the bottlenecks for turnaround performance is based on the statistic analysis of the physics fills on 2010.

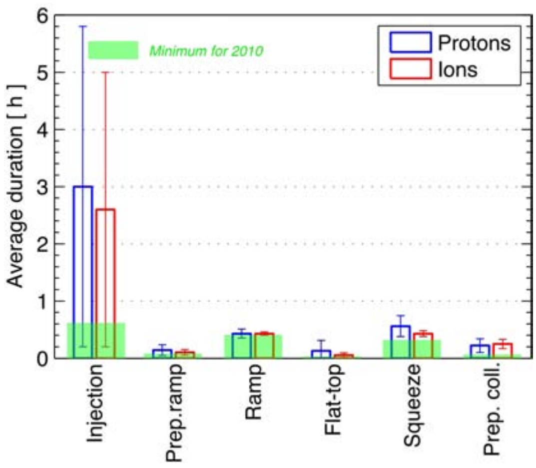


Figure 2: Distribution of average times spent in the different operational phases, calculated over about 30 physics fills at the end of the 2010 run. The theoretical minimum durations calculated for the 2010 parameters are indicated by the green bars [1].

2010 TURNAROUND EXPERIENCE

This section summarizes the results presented in [1] that are based on the statistical treatment of approximately 30 successful physics fills achieved with a stable machine configuration at the end of the 2010 run. The period that saw the performance ramp up to $2 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, with total stored beam energies up to about 30 MJ, is considered. To a large extend, the mode of operation at the end of 2010 is closest to what has to be expected for the 2011 run (well-established procedures, high level of automation through appropriate software, minimum change of machine configuration during standard operation). The last month dedicated to ion operation has also been considered in the study.

The time spent in the various operational phases in the running period considered as a reference, are given in Figs. 2 and 3 (the latter is a zoomed out version of the former to show details of the phases that took in average less than 1 hour). As pointed out in [1], the theoretical minimum durations for the 2010 parameters are actually longer than the nominal values as of LHC design report [2]. For example, the injection times in 2010 were much longer than foreseen initially because we could not achieve dedicated filling of the LHC, due to time required for the quality checks.

The minimum LHC turnaround time from beam dump to next stable beams was about 2h45 for the case with

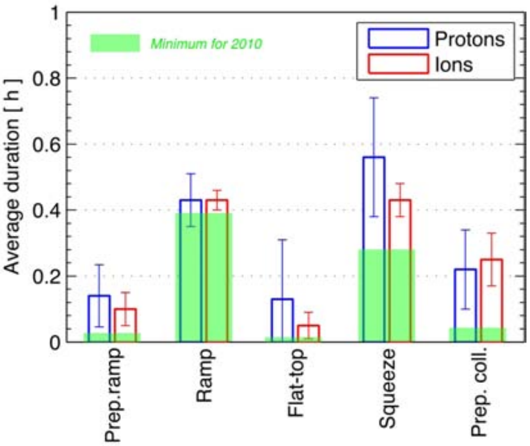


Figure 3: Zoomed version of Fig. 2 for the operational phases that took in average less than 1 hours.

dipole ramp rate of 10 A/s and 3h40 for 2 A/s. The average turnaround time for the successful physics fills considered above, without taking into account faults that stopped the beam operation [3], was well about 4h30 (sum of the blue bars of Fig. 2). The pre-cycle time has to be added to this duration, for a total time of about 5h30. A detailed analysis of the time spent in the various operational phases shows that:

- The turnaround efficiency is by far dominated by the filling time. This includes machine setup with probe beam and filling of physics beams (bunch trains).
- The squeeze took in average twice its minimum time. This is mainly caused by the manual actions required to prepare the squeeze and by the fact that in 2010 we stopped at intermediate points to change references of tune and orbit feedbacks and to move collimators. This mode of operation has also the draw-back that collimator settings are not optimized for triplet protection (evolution of local beam size not followed smoothly).
- Stopping points in the squeeze, involving delicate beam manipulations and setting changes for the feedbacks, were a primary source of operational mistakes that causes time consuming beam dumps at top-energy.
- The ramp itself took in average the expected time (functions were executed without interruptions). The preparation for ramp can certainly be improved as it took in average 30 minutes.
- In general, all the phases that required manual interventions took significantly longer than foreseen.
- With long turnaround times, operational mistakes are are time consuming and should be minimized through well-established procedures and sequences. Optimized strategy should not jeopardize a robust operation.

The considerations above are used as a guideline to identify areas of improvement for the overall machine cycle. In general, it appears clear that in 2010 the operational cycle duration was not yet limited by the intrinsic duration of the functions for ramp and squeeze but rather from the injection process and from the manual interventions associated to the beam setup, preparation of functions, beam measurements, etc. This must be taken into proper account while proposing “aggressive” strategies for ramp and squeeze.

It is however important to stress that the turnaround performance in the first year of operation was certainly remarkable for a machine of the complexity of the LHC. It is nevertheless legitimate to have a critical look at the experience accumulated in order to identify paths for improvements.

IMPROVEMENTS FOR 2011

Pre-cycle

Issues related to the pre-cycle are discussed in detail in [3, 4] and are not reviewed here. It is just reminded that at the end of the operation in 2010 we achieved an efficient machine setup without beam: all the preparatory task for re-establishing injection after a beam dump (or a powering failure requiring a pre-cycle) can be done in the shade of the pre-cycle. Operationally, it is therefore difficult to optimize further the setup time without beam unless the magnet hardware parameters are changed to allow a faster pre-cycle.

It is also worth mentioning that a dedicated access procedure has been established [5] to allow access in the machine while keeping the main dipole magnets at the stand-by current of 100 A/s and the rest of magnets at injection currents. A reduction of the minimum dipole current during pre-cycle has been foreseen accordingly to avoid a full pre-cycle after a short access [3]: in some specific cases, the dipoles can be kept at 100 A/s while people are in the machine and then ramped directly to their injection currents. The impact on dynamic effects of the magnets will require a dedicated validation by beam measurements [6].

Injection and ramp preparation

Aspects related to possible reduction of the duration of the filling time have been addressed in various companion papers at this workshop [7, 8] and at the Evian2010 workshop [1, 9, 10, 11]. A few proposal that came out as strong operational requests are listed here:

(1) Injection losses caused by halo tails or by un-captured beam in the LHC [7, 8]. This issue was inducing loss of time also due to tight loss thresholds in the injection quality checks, which often caused injection interlock without serious issues for the machine (operational tolerances were too tight and the operation crew was instructed to simply ignore them).

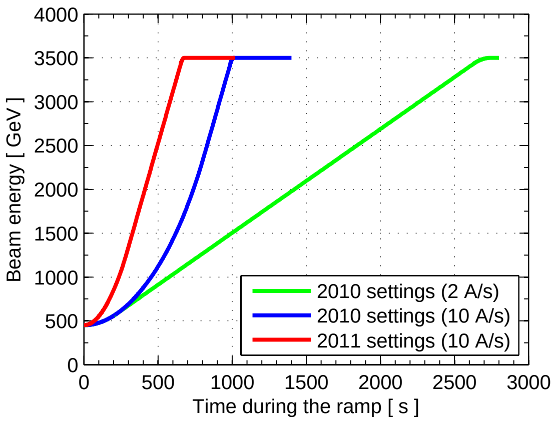


Figure 4: Different ramp settings for the main dipoles used in 2010 and foreseen for 2011. Courtesy of M. Lamont.

(2) Interleaved injection requests must be possible. In 2010, the injection request of one beam was only possible after injection and quality checks of the other beam were completed. In case of problems or analysis delays, the other beam would be stopped for up to a few SPS cycles of more than 40 s. This was a recurrent problem that caused significant losses of time.

(3) Injection times were often increased due to the long preparation times for the LHC beams in the injectors. The LHC beam preparation is very demanding for all the injector chain and hence the beam preparation must start early on in order to be ready for the LHC injection.

(4) The LHC setup at injection was also often long. Preventive trims of tune and chromaticity are under preparation by FiDeL and LSA teams to speed-up the setup of probe beams prior to the high-intensity injection. This will minimize the dependence on dynamic effects at injection.

These issues and being addressed together with other proposals to improve the injection process [7].

Ramp and flat-top

Once the preparation for the energy ramp was completed, rarely problems were experiences with the energy ramp. Possible improvements are still possible:

(1) Faster ramp functions have been prepared to reduce the intrinsic duration of the energy ramp. This is shown in Fig. 4, where ramp settings used in 2010 and a proposal for the 2011 operation are given. The proposed change does not rely on modifications of the hardware parameters but on an improved algorithm for the parabolic-exponential branch at the start of acceleration.

(2) The decay *plateau* at flat-top will be reviewed after having gained experience with the new ramp settings. For the time being, 380 s are used to compensate decay of orbit, tune and chromaticity.

(3) In 2010, the parallel separation in all IPs was kept constant at the injection value of ± 2 mm and was reduced only after the squeeze in order to bring the beams in collision. In 2011, it will be reduced during the energy ramp with the beneficial effects of (1) improving the top-energy aperture in view of the squeeze and (2) reducing the time required to steer the beams in collision. Also the the crossing angles will be changed during the ramp to their final values for collision. This will simplify considerably the operation of the orbit feedbacks at top energy (operator manipulations have been often the source of errors).

It is important to not that a pre-requisite for item (3) is that the orbit feedback must be updated to allow dynamics changes of reference. This new implementation is foreseen [12] and will be addressed by beam tests as soon as possible at the beginning of the 2011 operation.

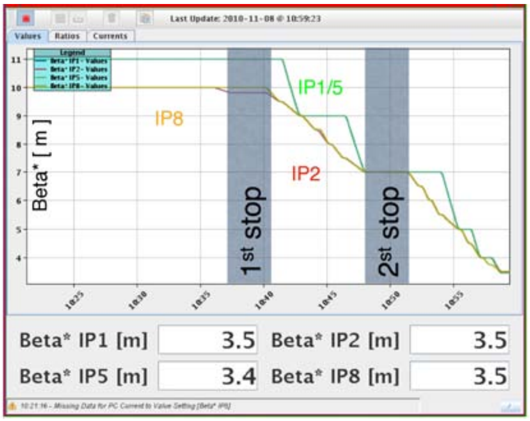
It is also noted that in 2011 focus will be put in establishing one single orbit reference throughout the operational cycle, to simplify the handling of reference and to reduce to a minimum the changes of feedback configurations.

After the ramp, the preparation for the squeeze required a certain number of manual actions (change of orbit references, preparation of tune feedback configuration to allow the change of tune at the beginning of the squeeze, switching off transverse damper, etc.) that will be automatized/improved in 2011.

Squeeze

As shown in Fig. 3, on average the squeeze in 2010 took a factor two longer than its minimum time given by the length of the functions for power converters and collimators (1041 s to achieve 3.5 m in all IPs). This figure improved by more than 20 % during the ion operation, thanks to better established procedures and automated sequences, but still is well above the minimum achievable. The main source of delay in the squeeze was caused by the fact that we stopped in 2 points to (1) updated orbit feedback reference with different crossing angle values and to (2) move the tertiary collimators at $\beta^* = 7$ m in all IPs with a discrete step to bring them at their final protection settings. In addition to the time lost, these manual interventions where often the source of operational mistakes that caused beam dumps.

One of the main aims for the commissioning in 2011 is to operate the squeeze in one single step from injection optics to the final β^* values. This will be possible if (1) feedbacks will allow execution of time-dependent reference, as already required for the change of orbit reference during the ramp, and if (2) the tertiary collimators in the IRs will be moved as well with functions of time to follow the evolutions of the local beta functions (collimator settings are expressed in units of local beam sizes, which change while



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Beta* IP1 [m] 3.5 Beta* IP2 [m] 3.5

Beta* IP5 [m] 3.4 Beta* IP8 [m] 3.5

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Figure 5: Example of β^* versus time in all IPs during the betatron squeeze. The two stopping points are indicated by the gray rectangles.

the optics is modified). Moving collimators with functions is possible and was already achieved in 2010 [13, 14] but is only possible if there are no stop points. Due to the present implementation of the handling of critical settings [15], collimator limit functions can only be run through continuously. This was not possible last year due to the stop point for updating the orbit feedback reference.

In addition to removing intermediate stop points, the length of the squeeze functions has been significantly reduced by optimizing the number of matched points [16]. Simulations have shown that a number of matched points at $\beta^* > 5$ m can be safely removed while maintaining under control tune, chromaticity and orbit errors. In addition, a bug in the generation was found which caused setting functions about 30 % longer than necessary. The new squeeze functions for the 2011 baseline values [17] of $\beta^*_{\mathrm{IP1/5}} = 1.5$ m and $\beta^*_{\mathrm{IP8}} = 3.0$ m are 475 s long, as shown in Fig. 6. Details of the calculations that allowed this reduction are given in [16].

Note that removing matched points, not only increase the maximum deviations from the nominal optics, but also prevents the possibility to stop the function execution (by construction, only at matched points the conditions of zero rate and acceleration for power converters are met). The squeeze length optimization has therefore been done by removing only points already tested in 2010: all the available optics below 3.5 m have been used.

Preparation of collisions

In 2010, the time required to bring the beams in collisions was limited by the ramp rate of the IP orbit correctors RCBX that are used to collapse the separation bumps and change the crossing angles. This time will be reduced in 2011 by a factor 2-3 for a total of less than 60 s instead than 108 s (protons) and 180 s (ions). While the hardware parameters will remain the same, the reduction in time is achieved by reducing the IP beam separation already during the ramp, from ±2.0 mm to ±0.7 mm. Dynamic orbit reference for the feedback will also allow to reach during the ramp the collision values for the crossing angles.

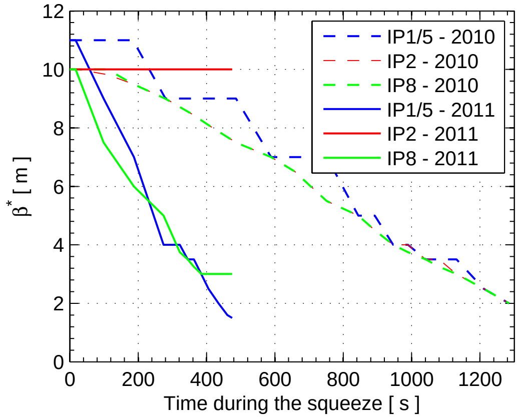

Figure 6: Beta functions in all IPs as a function of time during the squeeze in 2010 (dashed lines) and in 2011 (solid lines). The 2011 proposal must be validated during the beam commissioning. Details in [16].

COMBINING RAMP AND SQUEEZE

From the 2010 operational experience, it is seen that the machine cycle can be significantly optimized without necessarily reducing the length of the ramp and squeeze functions (even though there is indeed the plan to gain something there as well). To other options are in principle possible to optimize further the machine cycle:

(1) drive the machine through continuous settings functions for ramp, squeeze and collision;

(2) perform part of the squeeze already during the ramp.

These options have two main advantages: (i) they would reduce the duration of the nominal cycle; (ii) they would virtually reduce to zero the risk of human mistakes associated to the manipulations presently required in the different preparatory phases. Both options are in principle possible. The machine reproducibility is excellent and there are no indications that problems could occur, as it is proved by the fact that rarely in 2010 manual trims were required after the injection setup. The present architecture of the LHC controls software allows to achieve both options with some software development: (1) would required minor modifications and a more optimized mechanism to handle stop points; (2) required a new implementation to handle properly ramp and squeeze generation that presently are handled separately.

On the other hand, both methods have also possible draw-backs: (i) the potential gain in time might be jeopardized by the fact that more test ramps with pilot intensities will be needed during the year for setup, as in standard operation with high intensities it will never be possible to optimize the machine (tune, orbit, chromaticity, ...) until the end of the squeeze; (ii) the operational flexibility will be reduced in various ways; for example, it will not be possible to stop at flat-top or at intermediate β^* steps during the ramp; (iii) for option (2), the critical squeeze steps can only be performed at top energy due to aperture limitations; the most time-consuming steps will remain to be done at top energy; (iv) all together, if the new proposal of cycle optimization are implemented, the new operational cycle will be shorter than in 2010.

Taking into account pro's and con's, it has been agreed that the two options will not be pursued in preparation for the 2011 operation. Focus will be put in achieving the improvements an the other fronts, as outlined in the previous section. The options described here remain interesting for the future and will be addressed in dedicated MD studies.

CONCLUSIONS

The performance of the LHC in 2010 has been excellent in various respects. The machine cycle and the turnaround times have reached a maturity which has rarely been achieved in such a short time in accelerator of a complexity comparable to the LHC. The experience gained in the first commissioning year, has nevertheless enlightened possible ways to improve significantly the machine turnaround time. Possible paths for an optimization of the LHC operational cycle have been identified and are being addressed in preparation for the 2011 re-commissioning. There is a very concrete hope that in 2011 the cycle will be significantly shorter (probably 1 h less than in 2010, without taking into account the time for filling), less human error prone, more stable and easier to operate (less changes of reference, more and more automated through sequences). A critical item that must be addressed with high priority is the duration of physics fill injection. These results will be obtained thanks to a close collaboration between the operation and controls teams, in collaboration with the system teams.

The potential gains that are already on the table, and the clear need for commissioning flexibility, have for the moment lessened the appeal of more aggressive paths for cycle improvements, like combined ramp and squeeze in various forms. These studies remain attractive as future options and will be pursued as MD studies in 2011. In 2011, also aspects related to the dynamic squeeze with colliding beams will be addressed as a possible option for luminosity levelling.

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WHICH SYSTEMS (EXCEPT MAIN CIRCUITS) SHOULD BE COMMISSIONED/TESTED FOR 7 TEV OPERATION BEFORE THE LONG SHUTDOWN?

M. Pojer, CERN, Geneva, Switzerland.

Abstract

The key driver of the long 2012/13 shutdown is the consolidation of the 13 kA splices. Once the machine will be back to operation, the increase of energy to 7 TeV should be possible. Are all circuits and systems ready for 7 TeV operation? This paper focuses on what else could limit LHC high energy operation and how we can know that in advance. A period of dedicated testing at the end of operation and before the long shutdown could give a precious knowledge on the status of the machine.

INTRODUCTION

The energy at which the LHC is operated has been progressively reduced since 2008. This is the result of the evidence of the long training required to reach 7 TeV in the main dipoles and, above all, because of the problem with the splices between main magnets: at the origin of September 08 incident, it will require a long shutdown to repair all splices. Following the simulations performed on a safe energy level without splice consolidation [1], the machine energy (and therefore the main dipole current) was halved with respect to the design value, leading to a scaling of the current needed for all circuits around the ring.

Because of the gradual current reduction, there might be limits in the machine that we have not yet discovered. A series of tests could be envisaged in order to highlight these limits (if any) and avoid restarting operation after the long shutdown without fixing them.

STATUS OF COMMISSIONING IN 2008

After the first commissioning campaign, at the end of 2008, the preparation of the machine for operation at 7 TeV was well advanced. The long training required to bring the main dipoles to high current in the first sector (a maximum of 6.6 TeV equivalent current had been achieved in sector 56 [2]) had brought to a short period objective of 5.5 TeV, even if most of the circuits had been already commissioned for 7 TeV operation. Excluding sector 34 (where all circuits had to be considered as brand new after September 08 incident), all circuits in the machine were indeed commissioned to the design value, excluding [3 to 9]:

- the main circuits were commissioned to 5.5 TeV, with the exception of RB.A78 (which was stopped to less than 5 TeV due to training below 9.3 kA), RB.A56 (commissioned to 6.6 TeV) and RQD/F.A56 (commissioned to 7 TeV);
- RQX.L5 was commissioned to less than 5 TeV, as a result of an *a posteriori* change of the nominal current;
- RD3.R4 and RD4.R4 were commissioned to 6.6 and 6.3 TeV, respectively, as a result of an *a posteriori* change of the nominal current;
- RD2.R8 quenched four times (at 5816, 5788, 5856 and 5854 A) at less than 6.8 TeV (this probably constitutes a real limitation for the 7 TeV operation);
- few 120 A magnets showed problems and had to be limited in current;
- the 600 A circuits were somehow jeopardized, due to the reduction of the nominal current and the change of specifications.

For completeness, all Inner Triplets (excluded RQX.L5, as mentioned above) and all the individually powered quadrupoles reached the design value for 7 TeV operation.

According to this status, a first suggestion to discovered hidden machine limitations in circuits different from main dipoles and quadrupoles would be to try and push to their nominal current all 600 A circuits, plus the three IPDs and the IT in L5.

STATUS OF COMMISSIONING IN 2010

After September ‘08 incident, investigations were carried out to establish a safe current value for operation of the main circuits without re-machining all splices. In particular, simulations were performed [1] that showed that the LHC could safely run to 3.5 TeV. This is why the machine was re-commissioned in 2009/10 for this energy level. The details of the commissioning parameters used for all circuits can be found in [10-17].

During the preparation of all circuits for powering, few non-conformities were discovered during the Electrical Quality Assurance tests, which will be treated during the long shutdown: a weak insulation on sector 78 dipole line, in position B30.R7 (the circuit was ElQA-tested up to 1.6 kV instead of 1.9 kV); a badly insulated quench heater on the circuit RQ4.L8; a weak electrical insulation to coil and/or ground for a quench heater on RQX.R1.

Quench and training

To speed up the commissioning, a new *modus operandi* was adopted: the high current circuits were all commissioned to 3.5 TeV; for the low current circuits, the agreed plan was to commission them up to 5 TeV (for the 600 A circuits) or 7 TeV (120 A and 60 A circuits). Once a circuit was quenching twice, its nominal current was reduced (compatibly with the 3.5 TeV operation). This two-quench criterion resulted in a limitation of current for a number of 600 A and 120 A circuits, for which non-conformity reports were created. These circuits are listed in Table 1, which contains the name of the circuit, the quench currents, the non-conformity number and the nominal current value used in 2008 and in 2009/10.

Some of the circuits of the table were already limited in 2008, but most of them were successfully powered up to 7 TeV equivalent current. To confirm whether real limitations exist and if important detraining is present in some cases, it is necessary, before entering the long shutdown, to power all circuits up to 7 TeV equivalent current. In case of quench, the circuit has to be re-powered, up to a maximum number of quenches (number to be defined by magnet protection experts). If, after this training campaign, the circuit has not reached 7 TeV, then diagnostics have to be carried out to identify the problem; in case of a serious problem, a decision must be taken:

- lowering the nominal current in agreement with the reviewed machine parameters or if there is the possibility of a new optics;
- performing a repair, whenever possible;
- replacing, as a last solution, the superconducting circuit with a warm magnet, as already done at point 8 (RCBCHS5.L8B1 - NC 831927).

Table 1: Circuits with current limitation in 2009/10

Circuit	**Quench currents [A]**	**NC report**	**I_nom '08/'10 [A]**
RCD.A45B1	300, 391	1035252	550 / 400
RCD.A56B2	479, 496	1026728	550 / 450
RCD.A81B1	351, 484	1043522	550 / 450
RQTL11.L2B2	544.85	1020622	550 / 500
RQTL11.R5B1	501, 492	1027448	400 / 450
RQTL11.R5B2	550, 533	1027413	400 / 450
RQTL11.L6B1	353, 292, 340, 350, 384	1026809	300 / 300
RQTL11.L6B2	267, 348, 384, 354, 382	1026747	400 / 300
RQTL8.L7B1	240, 257	1046464	300 / 200
RQTL9.R3B2	359, 400, 396	1046992	200 / 400
RQT13.L5B1	-	1060679	550 / 400
RCBCV5.R5B2	69.4, 76.9	1029792	80 / 72
RCBCH7.R3B1	98, 95	1046994	100 / 80
RCBYH4.R8B1	55.6	1051795	72 / 50
RCBYV5.L4B2	63.3, 65.7, 64.7	1049055	- / 50
RCSSX3.L1	62.9(4 times)	1053719	locked
RCBYHS5.R8B1	quench-back	1063839	72 / 20
RCBYHS4.L5B1	weak magnet	1053709	72 / 50

Splices, shorts and open circuits

There are three circuits in the LHC which were in 2008 condemned due to suspicious connections: RCBCHS5.L8B1 (NC831927, shows high resistance on the cold side and was replaced by warm magnet installed in the vicinity), RCO.A81B2 (NC 955048, current leads and coil resistance too high) and RCOSX3.L1 (NC 948545, cold taps of current lead found open and circuit isolated from ground and from the other circuits).

Other circuits showed, during 2009/10 powering tests, high splice resistance and non-conformities were created:

RQT12.R7B1 - NC 1027412
RQTL10.R7B1 - NC 1026729
RCBCH6.L2B2 - NC 1020424
RCBCV6.L2B1 - NC 1020423
RCBCH7.L2B1 - NC 1084848
RCBCV7.L2B2 - NC 1084849
RCBH31.R7B1 - NC 1017094

The last one of the circuits above was condemned, together with another circuit (RCO.A78B2 - NC 1029807) which quenched three times while ramping up the current from 55 A and it is as well probably affected by a splice problem.

Very important for the circuits where a splice issue was evidenced, it will be to perform dedicated ElQA diagnostics, narrowing (wherever possible) the fault localization to provide extremely useful information to the people in charge of carrying out the repair; also specific transfer functions could be executed to better understand their strange behaviour. Moreover, specific powering cycles (i.e. with modified parameters) could be done.

As already stressed by K.H. Meβ in 2009 [18], the strange behaviour of some other circuits might also hide some real problem, as it is the case of RQT13.L5B1 and RQTF.A45B2: the circuits reached their design current value, but quenched several times at the flat-top. These two circuits might contain a bad splice. For the same reason, before the long shut-down all circuits will have to be as well submitted to a stress test (a long heat run) to the design current value to emphasize weak splices.

QPS and other issues

Some other issues were identified during the 2009/10 campaign, which will have to be addressed possibly before the long shutdown. It is the case of a QPS hardware problem on the circuit RCBXH3.L5 or the limitation in ramp rate of the circuits RQ6.L7B1 and the RSD/F-1/2, or the new protection of the Inner Triplet correctors RCBXH/RCBXV, to be set to limit the cross-powering of the nested horizontal and vertical corrector to 550 A total. All these problems should be possibly addressed before the shutdown to check whether an easy solution can be found or a hardware modification is required.

WHAT ELSE CAN WE TEST WITHOUT BEAM?

Another important matter to be verified is the adaptation of the energy extraction for the main circuits for the operation at 7 TeV: the consequences on the n-QPS will have to be demonstrated.

Other specific tests were required by the QPS responsible: dedicated powering of few 600 A circuits where we might get problems with quench detection settings if going to higher energy (e.g. trim quads, IT correctors) and the test of the n-QPS for IPQ configuration (installation, re-commissioning of the circuit plus specific tests will be needed) and the validation of the earth voltage measurement system for the main circuits.

If not completed before the shutdown, we will have as well to carry on with the validation of the splices inside the individually-powered quadrupoles (in the dispersion suppression region plus stand-alone regions) and individually-powered dipoles.

As a final validation of all circuits, a heat run with the whole machine (excluding Mains) powered to 7 TeV equivalent current plus the Mains to half current, will have to be carried out, followed by the execution (in the same current conditions) of operational cycles, including the squeeze to nominal β*.

Recently, it has been noticed that the ElQA tests are presently executed with a “reduced” voltage on the RQD/F and the 600 A circuits: the actual value does not take in fact into account the simultaneous powering of circuits routing through the same line. A re-test to higher voltage level (i.e. 480 V instead of 240 V for RQD/F) will be needed before entering the long machine stop, to highlight non-conformities.

The last verification we could carry on without beam concerns the cryogenic system and the LHC vacuum: for the first one, the quench lines between QUI and helium tank in all even points were never tested and important information could come from a stress test; the vacuum group required, on the other side, leak detection investigation before ventilation of the insulation vacuum in all the sectors, to identify weak points to repair.

WHAT CAN WE TEST WITH BEAM?

Before switching off the beams for the shutdown, there is as well a serious of investigation which could be performed. What listed below certainly constitutes a preliminary catalogue, but it is an exemplification of what we could do, to check other machine limitations.

Wire scanner tests could be performed in two setup conditions: with a proton beam at injection, 900 bunches, wire speeds between 1 and 0.3 m/s, to break the wire and test why we had breaking at different conditions in SPS and in LHC in 2010; with an ion beam at injection, 150 nominal bunches, wire speeds of 1-0.2 m/s, to break the wire with ions and see if it agrees with models.

A *quench test*, with 900 bunches at top energy was also suggested, to repeat the test from last year with a quench provoked in 1-5 ms scale instead of 30 ms. It is the only way to provide data about the quench level for the losses in ms timescale.

A problem was recently identified on the *BLMs*, where the change of threshold for high energy may result in a noise-to-signal ratio too high; verification and test of possible improvement will have to be carried out.

To compensate for the loss of one *orbit dipole corrector*, a solution applying real time trims on the others correctors could then be possibly tested.

From the *collimation* point of view, the stability and impedance with closed collimators (at nominal gaps) could be tested, together with combining the betatron and momentum cleaning in IR3.

The *injection and dump* responsible also formulated some hypothesis of tests before the end of beam operation:

- injection of full intensity trains of 288 bunches
- squeezing to 0.5 m beta* and checking the protection hierarchy there
- quench tests with beam at different time scale losses
- deliberate asynchronous dump tests with high intensity and also with 25ns (asynch dump of all MKDs synchronous, but asynchronous to the abort gap or a real pre-trigger with 1 or 2 MKDs being asynchronous to the other MKDs and also synchronous to the abort gap)
- with small intensity beam force a power abort of the dipoles in one octant but not dump the beam and see where it ends up (could be part of a study to install another big TCDQ like absorber in the machine).

TIME ESTIMATE

Summing up the different requests, we could imagine the following timeline for the period preceding the long shutdown:

- 1 week of dedicated tests with beam;
- minimum 1 week for Mains extraction reconfiguration and all kind of dedicated powering tests;
- about 4 days per sector, for a massive ElQA campaign to qualify all circuits to the nominal voltage level and to better identify all non-conformities;
- 2 days of cryogenics verification plus 4 days for vacuum leak test;
- additional 2 days/sector at warm for ElQA investigation.

It is important, for completeness, to remind that once the splices will be consolidated and the machine cooled back to 1.9 K, another massive ElQA campaign will have to be carried out, followed by several weeks of powering tests (the length of which will depend as well by the energy level to attain).

CONCLUSIONS

Before going into the long shutdown, all limits of the machine will have to be highlighted. The main point of the proposed strategy is to try and push all circuits (Mains excluded) to 7 TeV equivalent current, also by performing heat runs and nominal powering cycles. Many special tests will be performed to exclude or cope with anomalies and a massive ElQA campaign will be carried out.

For the present time, the circuit RD2.R8 constitutes the (second) most important problem in the machine, after the splices on the main circuits. A replacement could be envisaged, but tests could also be performed before the shutdown.

Special setups with beam can be as well figured out, and many other systems will have to be tested, even if most of them can be tested at any time, also with a warm machine.

ACKNOWLEDGEMENTS

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WHAT ARE THE CONSEQUENCES OF DELAYING THE SHUTDOWN FROM 2012 TO 2013 FOR RADIATION PROTECTION?

C. Adorisio, D. Forkel-Wirth, S. Roesler[#], CERN, Geneva, Switzerland

Abstract

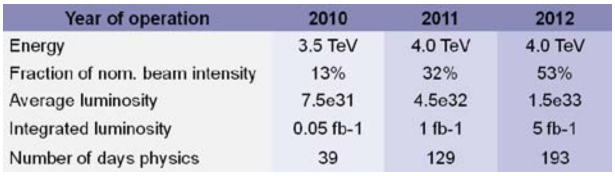
The residual induced radioactivity in the LHC underground areas in 2012 will is estimated and compared with the levels that would be expected in 2013. With these estimations consequences of delaying the shutdown from 2012 to 2013 will be assessed.

The present paper summarizes only the main conclusions. A detailed discussion can be found elsewhere in these Proceedings [1].

CONCLUSIONS

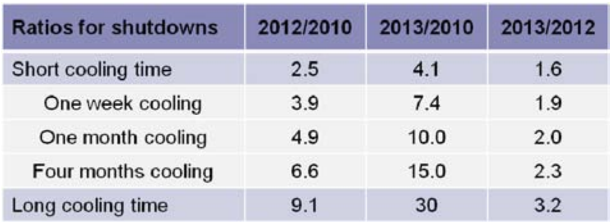
Based on the operational scenarios for the LHC during the years 2011/12 [2] (see Table 1), beam-intensity-dependent activation and residual dose rates are expected to increase by about a factor of 4-7 during the 2011 run and by another factor of two during 2012 [1] (see Table 2). Thus, radiation protection constraints and recommendations for shutdowns in 2012 and 2013 are quite similar. Of course, it assumes that losses scale linearly with beam intensity and neglects the contributions from scrubbing or ion runs. The luminosity-dependent activation (mainly the detectors and inner triplets) will increase by a factor of 20-100 until 2013.

Table 1: Operational parameters [1].



Year of operation	2010	2011	2012
Energy	3.5 TeV	4.0 TeV	4.0 TeV
Fraction of nom. beam intensity	13%	32%	53%
Average luminosity	7.5e31	4.5e32	1.5e33
Integrated luminosity	0.05 fb-1	1 fb-1	5 fb-1
Number of days physics	39	129	193

Table 2: Scaling factors derived from operational parameters for short and long cooling times as well as obtained with the generic study for three dedicated cooling times [1].



Ratios for shutdowns	2012/2010	2013/2010	2013/2012
Short cooling time	2.5	4.1	1.6
One week cooling	3.9	7.4	1.9
One month cooling	4.9	10.0	2.0
Four months cooling	6.6	15.0	2.3
Long cooling time	9.1	30	3.2

Presently the entire LHC is classified as Supervised Radiation Area [2] with low activation and dose rate levels (January 2011: maximum dose rate in the aisle: 3μSv/h, maximum dose rate on contact to a passive absorber in Point 7: 70 μSv/h). During technical stops and shutdowns in 2012 and 2013 a few limited areas (*e.g.*, IR3/7) will have to be classified as Controlled Radiation Areas where job and dose planning is obligatory.

Residual dose rates in the arcs after the 2012 run are estimated to be very low (no limitation in duration of work) [1]. A few localised areas in the dispersion suppressor regions (loss points of protons or heavy fragments "leaking" from the straight section) might show measurable residual dose rates (<10 μSv/h). Despite low residual dose rates in these areas, components might become "radioactive" according to CERN regulations and dissipation or incorporation of this radioactivity must be prevented (ALARA principle).

Due to significant uncertainties it is important to continuously monitor the evolution of activation (*e.g.*, survey measurements, material samples) to be able to further optimise work plans and schedules. In areas where civil engineering will be required (*e.g.*, dispersion suppressor regions in IR3) concrete samples should be placed in order to demonstrate absence of activation prior to the work.

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SPLICE CONSOLIDATION: WHAT WE WILL DO: STATUS OF MAIN TECHNICAL SOLUTIONS.

P. Fessia on the behalf of the Splice Task Force, TE-MSC-LMF, TE-MSC-SCD, TE-MSC-MNC, TE-MSC-TF, TE-MSC-CI, EN-MME-AP, EN-MME-MM, EN-MME-AS, EN-MME-ED

Abstract

The present paper will provide an overview of the main technical developments that have been carried out during the year 2010 in order to prepare methodologies, procedures and tooling to consolidate the 13 kA LHC splices and to make them capable to run without any risk at the LHC ultimate current.

Many successive interventions and operation are necessary to allow intervening on the above mentioned interconnections, but in this work we will describe only few of them trying to put in evidence the goals and the advantages respect to previous adopted solutions.

REDOING THE 13KA INTERCONNECTIONS

A not negligible fraction of interconnections will require complete rebuilding, meaning de-soldering, reshaping of the superconducting Rutherford cable, re-soldering of the joints with new interconnection copper pieces. Present estimation indicates that about 15%-20% of the LHC 10200 13 kA magnet to magnet interconnects should require this type of intervention. The reasons that can lead to decide to completely rebuild an interconnect are

1) High resistance superconductor to superconductor. It would be known beforehand thanks to machine survey via the nQPS system (about 10 units).
2) High resistance of the copper to copper junction on the interconnect extremities, showing the lack of good connection between the bus bar stabiliser and the interconnection copper piece. These interconnects will be identified thanks to local warm electrical measurements performed after having opened the sleeves protecting each line.
3) Very bad alignment between interconnection components that could impair the results of the following consolidation activities

The new development had has goal to

1) Improve the temperature distribution during the soldering process in order to guarantee a proper copper to copper junction, minimising the region of solder affected in the bus bar
2) Make possible the execution of the connection working through the spool corrector buses that are running on the top of the qudrupole lines. The aim is not to open the connection of these buses, activities that would engender many correlated control work and require the bridging of the interconnect, substituting each connection with two new connections
3) Possibly reduce and optimise the intervention time

In order to reach the described objectives the following technical development have been carried out

1) The modification of the heating profile (thanks to newly developed inductors) in order to shorten it down and reduce the heating of the nearby bus bar by conduction
2) The mechanical modification of the soldering clamping system to allow intervening through the spools cable
3) The introduction of a cooler system to reduce cooling time

As results of these modifications the region inside the bus bar, where the solder alloy was partially melted, has been reduced halved and the machine interconenction time was reduced from 15 mn to 8 mn.

SHUNT DESIGN

Present baseline features for the

1) RB lines two fully redundant shunts on each side of the interconnect. Figure 1
2) RQ lines one shunt on each side of the interconnect. Figure 2.

The design team is pursuing the efforts in order to find a way to apply a second redundant shunt also on the quadrupole bus bar, where the presence of the spools and the important deformation of the interconnection pieces, which occurred during the installation phase, make this operation more complex and risky for the integrity of the spools circuit.

The present dipole shunts (Figure 3) design features

1) The capability to carry 13kA withstanding large soldering defects (4 mm X 15mm), low RRR value of the bus bar copper (100) and of the shunt (150) and maximum temperature reached of 300K (Figure 4).
2) Incorporated SnPb solder alloy reservoirs to eliminate operator intervention, to make the process more reproducible.
3) Soldering by capillarity to originate a solder wave capable to reduce gas enclosure and therefore improve the solder joint quality. This is helped by the presence of degassing holes and grooves and grooves to enhance the capillarity.

Unfortunately it has been shown that despite all the efforts it has been impossible to guarantees an acceptable rate of successful soldering on rough interconnection surfaces because of

- The possible presence of large shape defects

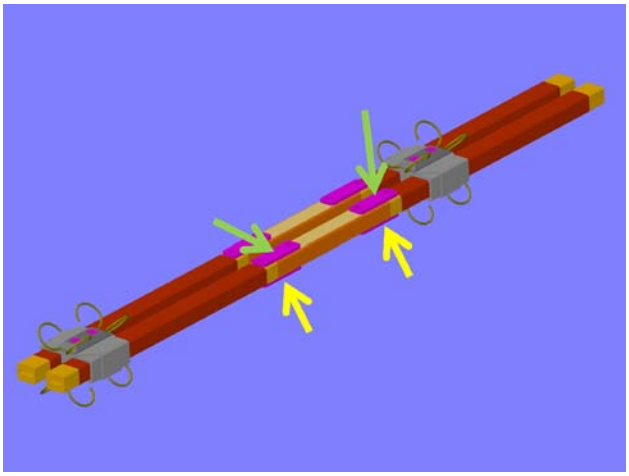

Figure 1. The shunts applied on the dipole bus bar

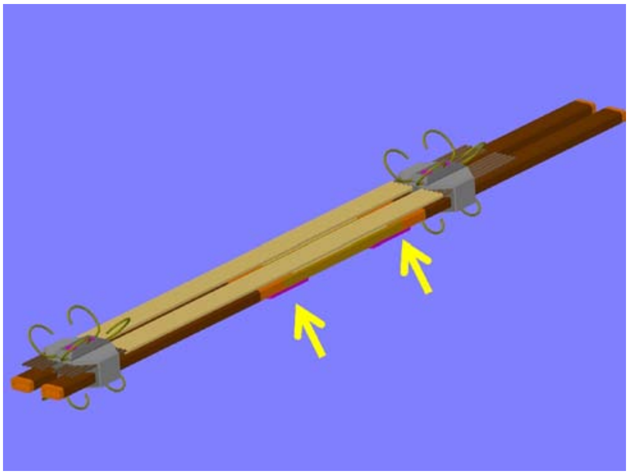

Figure 2. The shunts applied on the quadrupole bus bar

Figure 3. Shunt prototype integrating solder alloy reservoir, capillarity grooves and degassing holes

- The important surface oxidation and contamination

In order o achieve a systematically good quality it has been necessary to recover a flat, planar and clean surface on the two sides to the copper to copper connection. This has been possible thanks to the use an ad hoc milling tool that allow eliminating up to 1 mm of copper thickness.

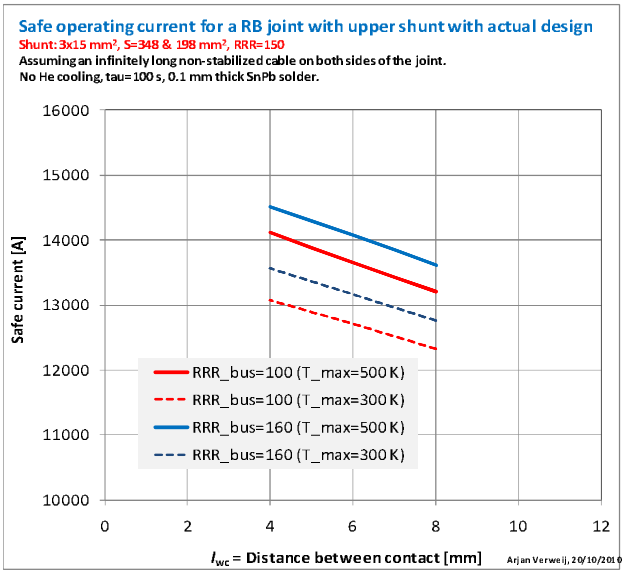

Figure 4. Safe current that can be carried by the interconnection equipped with one shunt in function of the distance between the nearest soldered points

THE INSULATION BOX

The new insulation system shall fulfil many different requirements:

1) Provide the insulation strength better or equal to present insulation
2) Restrain the lateral deformation (due to Lorentz forces) of the interconnect in order to significantly reduce associated stresses
3) Being of easy assembly, not constraining the bus bar in unnatural positions, positions that could generate new unforeseen stresses, complying with bus bar shape defects up ±3 mm in horizontal and ±5 mm in vertical
4) Fulfil cryogenic conduction and hydraulic impedance requirements
5) Withstand radiation dose of the worst arc interconnect for 20 years (1 MGy including a safety factor 10)
6) Providing enhanced cooling
7) Improve electrical separation between spools and main circuits

The developed design (Figure 5) fulfil all the previous requirements with the exception of the dielectric strength that is larger than the LHC design requirement (3.1kV in helium gas 1 bar), but lower respect to the present LHC insulation. New feature will be added to increase this margin.

From the mechanical point of view the new box allow reducing the induced stresses from 40 MPa and 58MPa, on the two interconnection extremity regions, to respectively 17 MPa and 5 MPa.

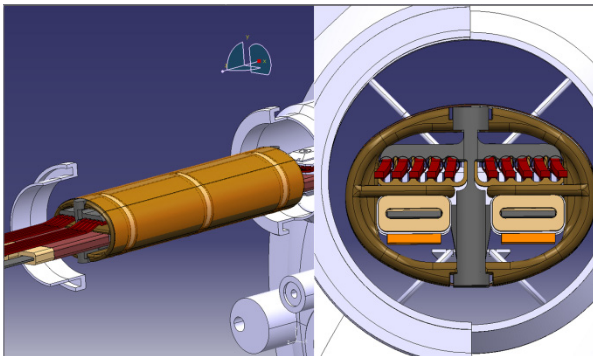

Figure 5. Insulation and restraining box for quadrupole line

INTERCONENCTION REINFORCEMENT

Tow type of mechanical reinforcement for the interconnection are foreseen. Their goal is to keep the interconnection pieces in mutual contact in case of hypothetical mechanical failure. The first piece will block together the U and wedge piece of the interconnect. The second component will block the shunt in position. Both systems are under the conceptual design phase.

THE SM18 TEST

In order to validate the design a test has been conceived and set up using the test benches installed in the SM18 facility. A Q8 and Q9 spare cryostated magnets have been used in this experience. This has allowed rebuilding a real LHC interconnect with the real cryogenic environment. The use of MQM type magnets has allowed not having active magnets on the fed circuits providing much more flexibility for the test (no inductance) and no risk to damage the coils. The interconnect has been heavily instrumented and equipped with large defects (equivalent to 40-50μΩ). In addition the shunts have been soldered simulating large solder defects (up to 8 mm). The interconnect has been quenched using heaters installed directly on it. Results show that in this condition the interconnect is extremely stable and that no thermal runaway occurs (Figure 6). This even with very large current up to 14kA kept constant. In this condition the bus bar look to be more unstable then the interconnect. (Figure 7).

THE INTERNATIONAL REVIEW

Between the 18th and the 22nd October 2010 an international independent review has scrutinised the advancement of the design work.

The main indications provided have been:

1) The work carried out has been the results of a thoughtful and in deep analysis of the interconnection behave and needs
2) The design is well progressing and targeting one by one all open points

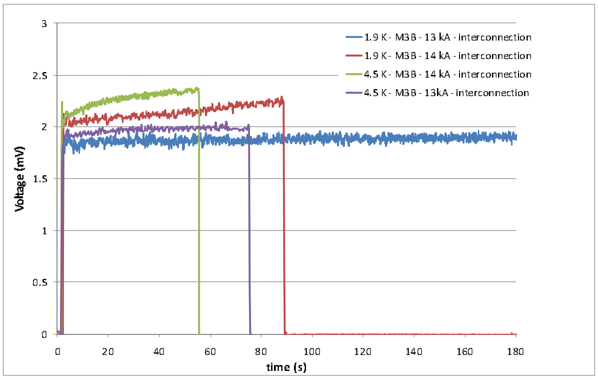

Figure 6. Voltage developed in the interconnects while quenched. Constant values show the creation of a normal zone but without thermal runaway

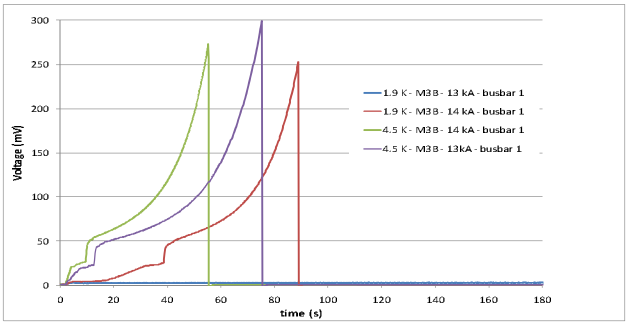

Figure 7. Voltage developed in the bus bar while quenching the interconenct. Rising values show the creation of a normal zone, with start of thermal runaway

3) The LHC present interconnect is not a reliable connection also when re-built.
4) The application of redundant shunt should be pursued also for the quadrupole line as well as the clamp application
5) The understanding of the data of SM18 should be pursued looking at the implication for a fully adiabatic case

CERN takes in the highest consideration these recommendations and it will do the maximum effort to fulfil them, balancing their application respect to added operational risks that could be risen (for example) by the application of quadruple redundant shunt. This action could put at risk the spool integrity due to proximity.

CONCLUSIONS

The development of technical solutions foth e LHC consolidation is ongoing. It is targeting the development and test of components, but also the improvement of tooling and procedures. The correlation between quality, time and costs has been taken into account since the design phase. Present solutions are sounds and have been deeply scrutinised at CERN and by an international review.

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WORK ORGANISATION FOR SPLICE CONSOLIDATION

F. Bertinelli, CERN, Geneva, Switzerland

Abstract

The Splices Task Force has worked in 2010 to prepare the necessary interventions for 7 TeV operation. The design solution for consolidating the main interconnection splices is well advanced. The required activities to implement it are described, highlighting working assumptions, missing resources and schedule considerations.

Progress has also been made in assessing other splices, 6 kA praying hands and corrector circuits: results and ongoing work are presented, highlighting priorities for the remaining work.

LHC SPLICES TASK FORCE

The LHC Splices Task Force is composed of twelve members from the EN, PH and TE Departments bringing together different skills and experience. The mandate is to review the status of all superconducting splices in the LHC machine and prepare the necessary consolidation actions for 7 TeV operation.

The first work priority in 2010 was to develop the design consolidation of the main interconnection splices [1]. The second priority was the 6 kA praying hands splices, and thirdly the assessment of other splices, in particular for 600 A circuits and triplets.

Minutes of meetings, presentations and supporting material are available in www.cern.ch/LHCsplices.

The work progress was reviewed by an international committee at the First Splice Review at CERN on 18-22 October, 2010: presentations are available in http://indico.cern.ch/conferenceDisplay.py?confId=109100 and recommendations are available in https://espace.cern.ch/lhcsplices/First%20Splice%20Review/default.aspx.

Each recommendation resulted in an action item for specific work and studies to be carried out and followed up under the CERN group structure responsibility, mainly within TE-MSC and TE-MPE, see https://espace.cern.ch/lhcsplices/Meeting%2036/default.aspx for example:

- develop comprehensive integrated electrical diagrams → action TE/MPE: N. Catalan Lasheras
- develop comprehensive circuits models → action TE/MPE: R. Schmidt
- double shunt be applied to the quad bus → action TE/MSC: P. Fessia.

The Second Splice Review was planned for September 2011, mainly to discuss production readiness. With the shutdown moved to 2013, this review will be re-scheduled.

SPLICE CONSOLIDATION

The strategy for consolidation was described in [2]. It will be required to open all interconnects, including cutting all M sleeves, in order to access the splices for invasive, local resistance measurements. It is foreseen that ~15-20% of the splices will require redoing, i.e. desoldering and resoldering according to the improved procedures of 2008-09. In addition it is foreseen to systematically add a parallel shunt and clamp to increase the long-term safety margin.

The "interconnection work" is defined as starting with the first opening of the large W bellows and ending with the closing of the last one. It consists of a sequence of work activities involving several teams and technologies, see Fig. 1. In order to estimate the work duration, some important assumptions are made:

- work sequentially through adjacent sectors as a continuous "IC train" of activities;
- no constraints from radio-protection issues, access (cryogenics, electrical testing, ...), coactivity (transport, ...) ;
- 2 work shifts (6h to 15h and 12h to 21h) for different activities, Monday to Friday, 40 h working weeks for all teams;
- all non-standard magnet and interconnection activities are finished before the arrival of the "IC train", specifically the completion of the DN200 pressure relief nozzle installation and work by the Special Intervention Team (SIT), see [3]. The current preference allowing the longest time at point 3 for DS collimator activities, is to start the IC train work at Point 4 progressing clockwise to adjacent sectors.

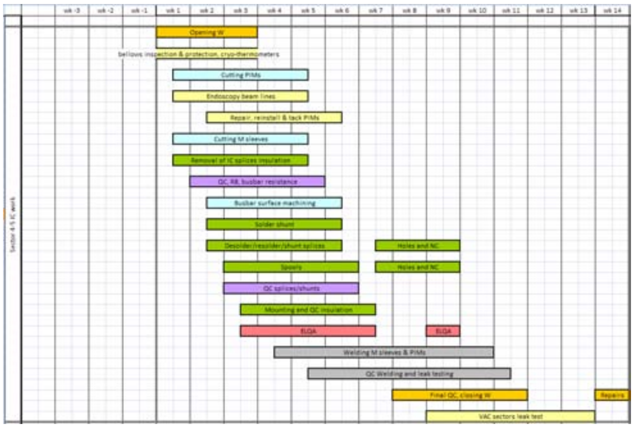


Figure 1: Sequence of work activities for IC Train

These conditions allow the optimal use of working time by the IC train, specifically minimising loss of time for moving teams and equipment around the tunnel.

The work rate for the IC Train is taken to be 50 IC activities / week. Without further contingency included (learning, holiday periods, ...) this implies a duration of "interconnection work" for the train alone of minimum 12 months (14 weeks for the first sector and 5 additional weeks to complete each following sector).

The necessary resources required for the IC train, DN200 and SIT teams are estimated at ~200 persons in the tunnel. A break-down per activity is shown in Fig. 2, showing Quality Control activities representing ~40% of the total.

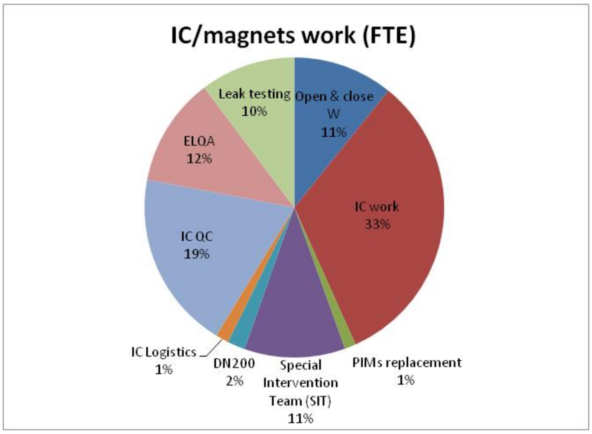


Figure 2: break-down of magnet/interconnections activities

Of the necessary resources, ~1/3 are identified and experienced, although not all present on the CERN site (e.g. Project Associates from Krakow and Dubna) nor staff, see Fig. 3.

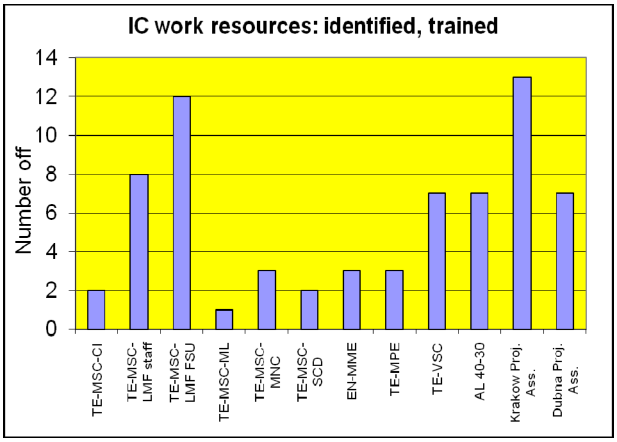


Figure 3: Group origin of experienced resources

For a minimum shutdown duration, we cannot account for an initial slower training and learning period in the tunnel under the real working conditions. The experienced resources are therefore the backbone of the magnet/interconnection shutdown team: they ensure coordination, control, guidance and quality. To maintain these for critical activities, the ratio of "newcomers" to "experienced" should not exceed 1-to-1. These are the considerations that limit the overall resources that can be envisaged to work on shutdown activities, and hence determine the duration of the desired volume of work.

During the year 2010 an important effort was made to identify other resources, inside and outside CERN. A further ~1/3 was identified, see Fig. 4, based on the important assumption that injectors will be stopped to free resources (who are also to be "free" from any injector maintenance). It was clearly easier to identify resources for activities of Quality Control, inspections, measurements, data analysis etc. than for mechanical work. With the exception of the Dubna DN200 team, it was not possible to identify within potential collaborating Institutes resources for mechanical work.

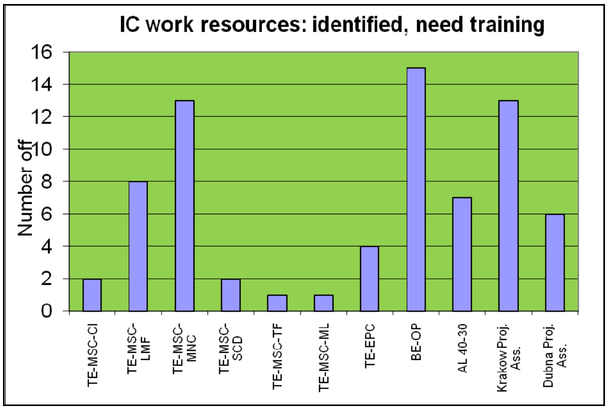


Figure 4: Group origin of identified resources needing training

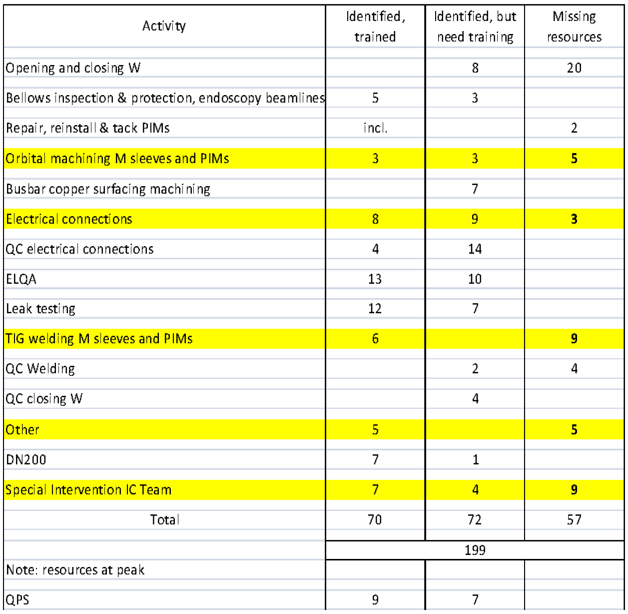
The final ~1/3 of resources, mainly mechanics, is still not identified, with the only current option being employment of FSUs. It must be noted that for some critical activities, see Table 1 in yellow, the "healthy" ratio of 1-to-1 is not satisfied, implying an unacceptable increase in risk. To be stated clearly: after considerable efforts to identify suitable additional resources in 2010, we do not have the necessary experienced resources to perform the desired volume of work/quality/risk within a duration of 12 months.

Some mitigating options available in this planning stage are:

- increase duration of the long shutdown, specifically by 2-4 months. This would allow to shift valuable, experienced resources ending some "early" activities of the IC train to the SIT activities. With today's knowledge and uncertainties, the estimate of interconnection work duration is therefore minimum 14-16 months.
- lower the workload, specifically of the SIT (e.g. number of magnets to be replaced)
- early recruitment and integration of 5-10 FSUs in the coming months.

In addition to the interconnection work, significant activities need to take place after beam operation but before the first W bellows opening (electrical tests at cold, localisation of defects, warmup, leak testing, ... see [4]) estimated ~2 months. Similarly, significant activities will take place after the last W bellows closing (electrical tests, cool-down, hardware commissioning, ...) estimated ~3 months before beam on again [5]. The minimum shutdown time defined as "beam off-beam on" is therefore estimated 19-21 months.

Furthermore, the overall integration planning in the coming months will study the effects of coactivity between the different shutdown projects: IC train, SIT, DN200, R2E (e.g. effect of shielding installation at Point 5 blocking passage for 2 months, see [6]), collimators. This has a high likelihood to increase the above estimates of duration.



Activity	Identified, trained	Identified, but need training	Missing resources
Opening and closing W		8	20
Bellows inspection & protection, endoscopy beamlines	5	3	
Repair, reinstall & tack PIMs	incl.		2
Orbital machining M sleeves and PIMs	3	3	5
Busbar copper surfacing machining		7	
Electrical connections	8	9	3
QC electrical connections	4	14	
ELQA	13	10	
Leak testing	12	7	
TIG welding M sleeves and PIMs	6		9
QC Welding		2	4
QC closing W		4	
Other	5		5
DN200	7	1	
Special Intervention IC Team	7	4	9
Total	70	72	57
		199	
Note: resources at peak			
QPS	9	7	

Table 1: estimate of required resources for magnet/interconnections long shutdown activity (highlighted are critical activities lacking experienced resources)

A further effect of coactivity between some of these shutdown projects (magnets/interconnections and collimators) is a strain on the same experienced resources already today, namely for mechanical engineering, design, mechanics and welding. An urgent prioritisation among these – and indeed other projects (e.g. LINAC4, SPL, ...) – is advocated.

The work organisation structure for the magnets/interconnections activities is planned as previously to rely on three entities: technical work, Quality Control and tunnel coordination, see Fig. 5.

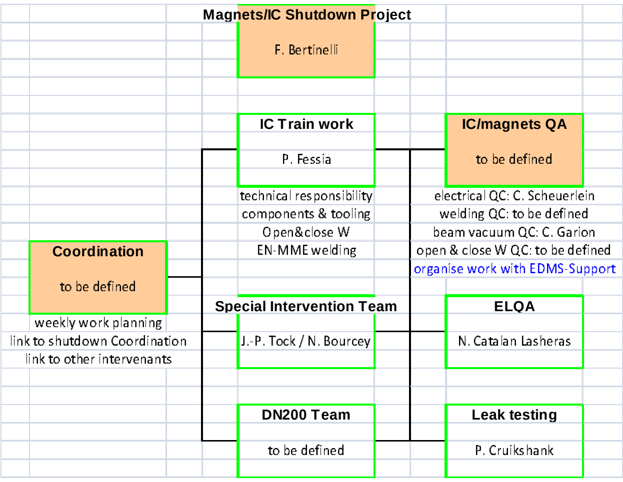


Figure 5: Magnets/interconnections organisation structure for the long shutdown

The overall budget for the magnets/interconnections long shutdown has been revised to 26 MCHF.

6 KA PRAYING-HANDS SPLICES

Considerable progress has been made in 2010:

- detailed electrical schematics showing number and type of splices;
- collection and review of existing documentation, specifically photos showing splices made in the tunnel;
- during the long shutdown, plan to perform partial inspections in some sectors where documentation is incomplete;
- mapping measurements in the tunnel of resistances at cold (segments of bus bars and splices in series) showing an average splice resistance of 1.14 nΩ and no outliers;
- the Quench Protection System will be upgraded to include these segments [7];
- fatigue testing at cold in Block4 of three samples in series: 12 000 cycles to 9 kA, then 12 000 cycles to 6 kA after introduction of a known defect. There was no deterioration of splice electrical resistance, and microscopic examination of the solder showed minimal crack initiation.

It was concluded that the current design can be maintained, this being endorsed by the First Splices Review.

OVERALL SPLICE RISK ASSESSMENT

The objective was to review full circuits, from current lead to current lead. Initial progress in 2010 was achieved in assessing the sextupole and octupole spool circuits. This work involves patient fact finding covering the corrector magnet production and testing, its integration with the dipole cold mass, testing at the Cold Mass Assemblers, testing upon reception at CERN, HWC, and experience with beam operation. These initial results show that the assessment inevitably extended from splices to general electrical and mechanical circuit aspects, specifically insulation, singular points (spiders), test and operation voltages. Also it became apparent that the assessment exercise was indeed fruitful and justified the new effort. Considering the difficulty in collecting the dispersed information, it also appears to be a unique opportunity to document and preserve it.

A further work consisted in performing an inventory of electromechanical singularities in the MB circuit.

To organise this work, mandate was given in September 2010 to H. Ten Kate / PH. Each circuit is being reviewed by an independent specialist, and then assessed by a group of magnet experts. This work is ongoing, aiming to reach final recommendations by May 2011.

CONCLUSIONS

Considerable progress has been made in 2010 on the design of the consolidated interconnection splice, on the 6 kA praying hands splices and on the general circuit risk assessment.

Progress has also been made in the organisation of the magnets/interconnections long shutdown, now based on a scenario with January 2013 as starting date. The bulk of IC work will be performed by an "IC Train", non-standard operations by a Special Intervention Team. The overall resources needed are estimated at 200 persons.

One third of these is identified and experienced, several in collaborating Institutes or FSUs.

One third was identified internally at CERN and with collaborating Institutes during 2010 but will need training. This type of personnel will be used mainly for activities of quality control, inspections, data collection and analysis. It is important to clarify the conditions for injectors stop during this long shutdown since this has a big impact on the availability of these additional resources.

Finally the last third is still missing, needed mainly for mechanical work. It seems unrealistic after the 2010 efforts to expect these to come from collaborating Institutes. They will therefore be employed as FSUs, and it is recommended to start this recruitment early in order to start the integration and training process.

The ratio of 1-to-1 between experienced and newly introduced persons to ensure adequate work conditions in critical activities is currently not satisfied, thereby increasing the project risks.

By taking important assumptions on workload, tunnel work conditions and coactivity, it is estimated that the magnet/interconnection work alone will take minimum 14-16 months.

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VACUUM – MUCH ADO ABOUT NOTHING

V. Baglin, P. Cruikshank, M. A. Gallilee and R. Veness CERN, Geneva, Switzerland

Abstract

During the next long shutdown, the majority of the 557 LHC beam and insulation vacuum volumes must be vented and opened. The activities proposed by the Vacuum, Surfaces and Coatings Group will be elaborated, including their implications for other Groups, together will an estimation of the extensive VSC workload that is generated by other activities e.g. splice consolidation, new collimators and experimental area upgrades.

LHC INSULATION VACUUM

The work carried out for the insulation vacuum during the next shutdown will be done by mixed team of CERN staffs and industrial support. About 7 teams of two people each are required to perform the job. The total workload is estimated to be ~ 50 weeks. A better estimation will be given when a detailed planning will be done by EN-MEF.

VSC requests

Table 1 shows the list of insulation vacuum activities requested by VSC. For each activity is indicated the motivation of the work and the groups other than VSC with are affected. It is also said if the activity has a potential conflict with the splice consolidation.

The pressure relief system on the LHC cryostats [1] will be further consolidated by upgrading the un-sprung flanges, which open with flows up to 1 kg/s, with self-closing valves. In the event of a limited discharge, the insulation vacuum will then be protected from air ingress.

Figure 1: Self closing over pressure valve

Following the sector 3-4 incident, 5 of the 8 arcs were warmed to room temperature. So-called by-pass valves were installed at the SSS vacuum barriers which were not already equipped with by-pass pumping groups. The by-pass valve permits the linking of adjacent subsectors and creates redundancy and flexibility in pumping configurations. Three arcs, namely 2-3, 7-8 & 8-1 remain to be equipped. With the completion of the by-passes, all long subsectors of the LHC will have pumping redundancy except for the extremity subsectors A & I of each QRL. Hence 16 additional fixed turbo groups will be installed, requiring new cabling. On a similar theme, the 500 m cables from UJ33 to the 2 fixed turbos at 8R3, require replacement in order to achieve full functionality of the fixed pumping groups.

Preventive and corrective maintenance will be performed on the 170 fixed pumping groups of the QRL, arc and LSS magnet cryostats.

At a late stage in the installation of the LHC, a leaking beam screen capillary was identified on a fully installed magnet. The helium leak was localised 1.8 m inside the cold bore aperture of dipole #1060, cell 21L1, in sector 8-1. The capillary was subsequently isolated from the standard cooling circuit. The cause of this unique leak has not yet been understood. An endoscope has been procured that will allow an inspection of the capillary bore without removal of the bean screen or magnet from the tunnel.

A number of compact Penning gauges in the mid-arc continue to give erroneous reading despite several attempts to understand the issue. Further investigations will be made on the integrity of the cabling.

Table 1: VSC insulation vacuum activities

Activity	Motivation	Other Groups Affected	Potential conflict with splice consolidation
Install Flap Valves - arc, LSS, QRL	Self closing over pressure valves		no
Install by-pass valves - arcs 2-3, 7-8, 8-1	Create pumping redundancy		no
Install additional turbos (& cables) - QRL extr	Create pumping redundancy	EL	no
Install long cable for turbos IR3R - LSS3	Eliminate turbo restart problem	EL	no
Localise and repair known leaks - all arcs	Eliminate helium leaks	MSC,CRG	**yes**
Leak test envelopes (global) - arc, LSS, QRL	Check tightness integrity	CRG	**yes**
Maintain turbo pumping groups - arc, LSS	Maintenance - preventive & corrective		no
Inspect b.screen capillary in arc 8-1	Understand helium leak origin		no
Repair gauge cabling in mid arcs - all arcs	Eliminate faulty gauge reading		no

It is important to have the tightness status of all subsectors before the start of venting and modification works. This includes helium to insulation vacuum and air to insulation vacuum tightness. At temperatures above 80K, helium and air leaks are no longer pumped on the cryogenic surfaces. Leaking testing can therefore be performed if the pressures in the cryogenic headers are constant. With several teams working in parallel in an arc, all subsectors could be measured in 2 days.

In some subsectors, helium leaks and or air leaks are already known to exist. Although the level of these leaks permits normal operation of the LHC, the leaks generate many difficulties for cryogenic operations team, as small temperature fluctuations can results in large pressure bumps and variation of heat loads. The localisation and elimination of the helium leaks requires a coordinated effort between TE/VSC, MSC and CRG. Longitudinal leak localisation in a subsector can be performed once the subsector temperature is above 20 K and the helium header pressures are constant. The measurements, taking 1 day per subsector, will give an indication of which magnet interconnection(s) to open. For some subsectors, variation of the header pressures will be required to confirm the leaking circuit (1 day). Once the measurements above are complete, and the system is at room temperature, the leaking subsectors can be vented and the identified interconnects opened (1 day). Leak localisation is then performed with helium pressure (5 bars) in the identified leaking circuit (2 days minimum). It is estimated that the above procedures to localise helium leaks will require a total of 5 days. Combining leak localisation of known leaks in an arc and systematic checks of all subsectors in an arc, having several VSC teams working in parallel and full availability of cryogenic hardware, software and operators, the minimum duration of leak localisation works is 5 days. The scheduling of these activities must be carefully prepared in collaboration with MSC, CRG and other tunnel activities, and will impact on the availability of magnet interconnections for splice consolidation.

VSC involved

VSC is also involved in several activities which are already planned or proposed. Table 2 shows the list of known activities where VSC will provide leak testing support.

Table 2: VSC involved insulation vacuum activities

Activity
Splice consolidation
Cryomagnet replacement
IR3 DS - bypass cryostat for collimators
Connnection cryostat consolidation
Y-Lines repair
New DN200 & Reclamping of instrumentation flanges
SAM helium gauge consolidation
Triplet braid

The details of these activities are provided in other reports from this Chamonix workshop. As all interconnect of the machine will be opened for modification or repair, the leak testing activities will be extensive and intensive. It is vital that the shutdown planning is made in such a way that VSC resources can be smoothed over the shutdown period, and contingency is added for the elimination of the leaks appearing during acceptance tests.

LHC BEAM VACUUM

The work carried out for the beam vacuum during the next shutdown will be done by mixed team of CERN staffs and industrial support. About 10-12 teams of two people each are required to perform the job. The total workload is estimated to be ~ 30 Wk. A better estimation will be given when a detailed planning will be done by EN-MEF.

VSC requests

Table 3 shows the list of cold beam vacuum activities requested by VSC. For each activity is indicated the area, the motivation of the work and the groups other than VSC with are affected. It is also said if the activity as a potential conflict with the splice consolidation.

The consolidation of the Plug-in-Module (PIM) is an important part of the work to be done during next shutdown in order to guarantee beam aperture or guarantee leak tightness with time of damaged bellows. Of course, ideally all the PIMs would have been exchanged but this could not be afforded for budget and time reasons. A detailed analysis has shown that the exchange of PIMs located at dispersion suppressors and at each vacuum barrier would give a satisfactory result with a low probability of RF finger’s buckling during warm up cycle. However, to shorten the shutdown activity, it has recently been decided to consolidate only the PIMs located at the arc extremity in the dispersion suppressor areas [2]. Beam vacuum protection shells will be installed at each interconnection to protect the bellows and minimise the amount of debris entering the beam tube in the event of an incident. Similarly, rupture disk will be installed at each Short Straight Section to avoid the overpressure in the beam pipe protecting the nested bellows in the event of an incident. During the interconnection activities and at the end of this job, leak detections and RF balls test are requested too. It is worth recalling that the RF ball test will be also done at the beginning of the shutdown in order to evidence PIMs which failed during warm up. After the sector 3-4 repair, a total of 12 dipoles and 2 quadrupoles have beam screens with reverse sawteeth. Their exchange is considered a low priority for vacuum performance issue, but the influence on the beam due to local enhanced electron cloud activity should be addressed. Installation of additional gauges in the arc is proposed to consolidate the vacuum instrumentation; this activity will require cable laying. Finally, mobile pumping groups and diagnostic benches will be installed at the start of the arc and stand alone warm up to check the helium tightness of the beam screen capillaries. These equipment will be used in a second stage before final cool down to evacuate gas in order to minimise the impact onto the beam performance of gas desorption stimulated by the electron cloud.

Table 3: cold beam vacuum activities

Activity	Area	Motivation	Other groups affected	conflict with splice
Exchange PIMS	Arc, LSS	Eliminate critical PIMs	MSC	YES
Install beam vac. Protection shells	Arc, LSS	Protection against electrical arcs	MSC	YES
Exchange beam screen with reverse sawteeh	Arc 3-4	Dynamic vacuum	MSC,EL, SU	YES
Install additional rupture disc	Arc SSS, LSS	Protection beam vacuum against overpressure	-	No
Install additional gauges in the arcs	Arc	Consolidate instrumentation	EL	no
Install/remove mobile pumping groups	Arcs, LSS	Remove desorbed gas/recondition	-	no
Leak test envelope-arc, LSS	Arcs, LSS	Check tightness integrity	-	Yes
RF ball test	Arcs	Aperture check	-	no

Table 4 shows the list of warm beam vacuum activities requested by VSC. With the LHC machine performances progressing towards nominal values, it is vital to ensure that the vacuum system keep its nominal performance. Particularly, the installation of NEG pilot sectors will help to estimate the NEG parameters in presence of beam around the experimental areas and will allow defining the time between two successive NEG activations. Figure 2 shows a NEG pilot sector to be installed in a vacuum sector. The injection of gas at one extremity with the monitoring at the other, allows estimating the pumping performance of the NEG coating [3]. Installation of electron clouds monitors will allow increasing the understanding of the electron cloud in the LHC and will allow diagnosing the scrubbing efficiency of each run.

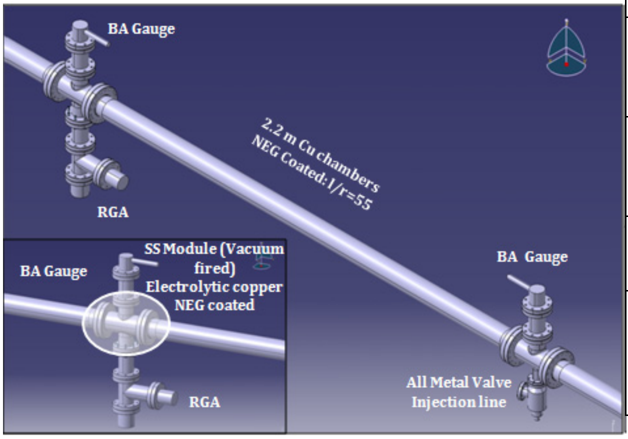

Figure 2: NEG pilot sector [3]

Inspections following the LHC installation have revealed that some RF fingers inside vacuum modules have bad contact due to a loose spring. A campaign of systematic inspections of vacuum bellows has just been launched with the support of EN-MME. A film and an X-ray source are used to do imaging and on-line analysis of each vacuum module. It is estimated that about 10 vacuum sectors around LHC could be re-opened to fix this issue. The 2 vacuum sectors around the MSD in LSS6 are ~ 155 m long. In case of intervention, the NEG reactivation of these sectors could last 4-6 weeks / sector due to their length and complexity. It is therefore of interest to perform an integration study and define a new layout around these components. Of course, the implementation should be done if necessary and therefore has low priority. However, a feasibility study with EN-MEF is required. Similarly, a minor layout change is required in LSS 2 and 8 to correct 4 vacuum modules which are out of their tolerance with a potential risk of RF buckling. The installation of thermocouples is foreseen in LSS3 and 7 to monitor the beam heating effect induced on the flanges by the collimators. Optimisation of the vacuum ion pump powering by laying new cables is proposed to consolidate the valve interlocking system and vacuum diagnostics around collimators. Finally, to protect sensitive LHC equipment, the modification of pneumatic valves and / or installation of fast shutters in the vicinity of RF cavities are foreseen [4].

Table 4: warm beam vacuum activities

Activity	Area	Motivation	Other groups affected	conflict with splice
Install NEG and electron cloud pilot sectors	LSS	Diagnostic instrumentation	EL	no
Inspection with X-ray of vac modules	LSS	Identify RF finger issues	Access restriction	YES
Exchange vac. Modules as required	LSS	Reduce LHC impedance	-	no
Layout change at MSD	LSS 6	Reduce vac sector length	EL, MEF	No
Layout change at BPM/DFBX	LSS 2 and 8	Vac module over extended	EL, MEF	no
Install thermocouple near collimators	LSS 3, 7	Monitor effect of collimators	EL	no
Install new cabling and instrumentation	LSS	Improve logic for sector valves	EL, MPE	no
Install fast shutter and modify pneumatic valves	LSS 4 + other LSS	Protect sensitive LHC equipment	EL, MPE, MEF	no

VSC involved

VSC is also involved in several activities which are already planned or proposed. Table 5 shows the list of activities where the group is currently involved. The R2E project will require a systematic check of the electrical connections of each vacuum equipment. A 5th MKB should be installed in LSS 6 to complete the beam dump system as designed. Collimators should be installed in LSS 3 and LSS 6 according to the collimator project schedule. Four new collimators operating at room temperature but to be installed in the dispersion regions around LSS 3 with implications on the layout of LSS 3 are planned. The implementation of a new layout and installation of a TCT collimator in LSS 2 to optimise the physic of the ZDC is also planned. A proposal of the new layout is shown in Figure 3. The solution requires the construction of a new ID800 vacuum chamber and the design of new vacuum modules.

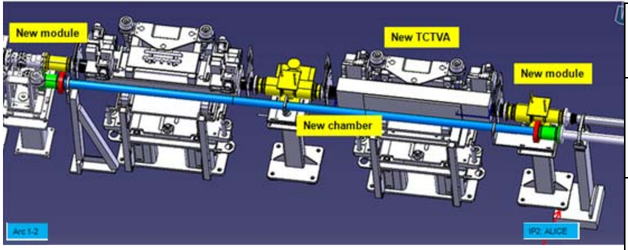

Figure 3: Proposed layout in the LSS 2 ZDC area

Repair of equipments are also required such as BQSH or other BI equipments. Finally, the neon venting and pumping of each LHC experiment will be required. It should be underlined that if a LHC experiment needs to be vented to air, a NEG re-activation of the experimental vacuum chamber will be required. The time to perform such an activity accounts to months.

Table 5: VSC involved beam vacuum activities

Activity	Area
R2E – move racks and cabling	UJ79 to TZ76
Connect 5th MKB	LSS 6
Connect collimators	LSS 3
Connect collimator W	LSS6
Connect collimator IR3 DS	DS LSS 3
Layout changes due to IR3 DS collimators	LSS 3
Layout change, TCT, ID800, ZDC in LSS2	LSS 2
Intervene on BQSH & BI equipment	LSS4
Vent and re-pump experimental chambers. NEG re-activation when vented to air.	Experiments

EXPERIMENTAL AREAS

The work carried out in the experimental caverns will be spread out over the full duration of the shutdown. Current schedules presented by the experiments show 15 months intervention time from beam to beam.

VSC consolidation

Table 6 shows the list of activities in the experimental caverns requested of VSC by the LHC experiments. Table 6 outlines the motivation and the affected groups for each task. None of the experimental activities will conflict with the splice consolidation in terms of access requirements.

All of these activities represent an important part of the consolidation and upgrade of the experimental areas. Installation of the IBL detector (Figure 3) is of particular importance for ATLAS in order to maintain the integrity of their inner detector. LHCb require an important intervention to change a piece of central vacuum chamber which had non-conformities during installation and was temporarily repaired in order to allow the program to continue. CMS plan modifications to the vacuum chamber support in the forward parts of the detector.

Table 6: Experimental Vacuum Activities

Activity	Area	Motivation	Other groups affected	conflict with splice
Replace UX85/3 Chamber	LHCb	Eliminate non-conforming chamber	LHCb coordination & survey	no
Change supports UX85/2 and UX85/3	LHCb	Improve transparency of supports	LHCb coordination & survey	no
Change supports in HF and forward regions	CMS	Improve access and reduce intervention risk	CMS coordination & survey	no
Replace ATLAS VI, VA, and VT chambers	ATLAS	Improve transparency, reduce activation and install IBL detector	ATLAS coordination & survey	no

As the current work packages stand, it is estimated that the interventions within the experiments will require 1.2 FTE of category 2 staff and 2.9 FTE of category 3 staff, plus industrial support. Work will be spread out over a 15 month period. Table 7 contains a breakdown of the estimated duration the resources within VSC for cavern activities related to installation and re-commissioning of the vacuum sectors for each activity. Resource estimates are taken from work packages agreed with each experiment [5]. Possible replacement of the central CMS beryllium chamber, which was proposed at the workshop is not included in Table 7. NEG activation will take approximately 2 months per experiment, with resources included in table 7.

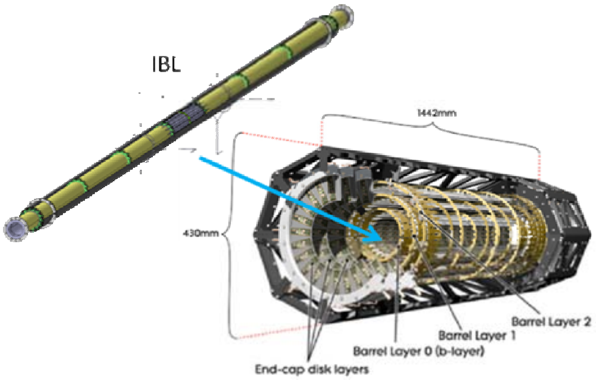

Figure 4: ATLAS IBL Detector

Survey will be required during most of the VSC/EIV activities. This activity will be undertaken by members of BE/APB Group who are dedicated to the experimental caverns.

Table 7: Estimated Time for VSC Integration Activities

Activity	Estimated staff resources (FTE)	
	Cat.2	Cat.3
Replace UX85/3 Chamber	0.3	0.8
Change supports UX85/2 and UX85/3	0.1	0.5
Change supports in HF and forward regions	0.2	0.6
Replace ATLAS VI, VA, and VT chambers	0.6	1.0

CONCLUSIONS

Elimination of known leaks in the insulation vacuum is a primary objective for VSC. The insulation vacuum system will be extensively modified during the splice consolidation and other machine modifications. As its reassembly will be made in a much reduced time compared to its initial installation, ensuring that a more leak tight system exists after the long shutdown than before will require considerable effort, coordination and flexibility from the multiple teams involved.

The intervention required to be made by VSC on the beam vacuum system are divided into 2 categories: requested and involved activities. Consolidation of the PIMs in the arcs and installation of the NEG pilot sectors and electron cloud detectors are the most important activities for the LHC beam vacuum system. However, activities linked to collimators or experimental projects are time and resource demanding. A total workload of 30 Wk for 10-12 teams is estimated.

The work to be performed for the experimental vacuum systems extends to 15 months. The described activities are to be done for ATLAS, CMS and LHC-B experiments.

ACKNOWLEDGEMENTS

The authors would like to acknowledge colleagues of the VSC group for their inputs for this report.

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INSTALLING COLLIMATORS IN THE NEXT LONG SHUT-DOWN: PLANS, STATUS AND CHALLENGES

V.Parma, CERN, Geneva, Switzerland

Abstract

The first part of the collimation upgrade plan features the installation of 4 collimators in the 2 DS of point 3, in addition to the upgrade of the existing collimation system.

What makes this upgrade so special is that for the first time collimators will be placed within the continuous cryostat of the LHC sectors. For this purpose, 16 main dipoles and 8 main quadrupoles will have to be disconnected and displaced by about 4.5 m, as well as the 2 electrical feedboxes (DFBAs) on either side of the DS, in order to create the space required for installing the additional collimators. The collimators themselves, although remaining of the warm type, feature a design substantially different from the others, mainly imposed by tight space constraints. These collimator modules will have to be complemented by a special bypass cryostat whose function is to preserve the continuity of the technical systems along the arcs (magnet powering, cryogenics and insulation vacuum), while providing cold to warm transitions to the beam tubes where the collimators are placed.

The status of this collimation upgrade project is presented, with special emphasis on the collimation in the DS of point 3; design & integration studies in this point, as well as the status of the design and manufacturing of all the associated new equipment (DS collimators, Short Connection Cryostats, and new cryogenic extensions to the QRL) are outlined. An overall plan of the surface and tunnel preparation activities, in the perspective of a 2012 shut-down implementation, is discussed.

INTRODUCTION

This first collimation upgrade is aimed at improving the collimation efficiency by a factor 5-10, and to implement flexibility in the loss locations of IR3 and IR7. These goals call for the installation of 4 horizontal collimators in the DS regions around point 3, and the installation of vertical collimators, in the warm regions of point 3, the latter providing the possibility of betatron cleaning in IR3 in case of SEU problems in point 7.

In addition, debris absorbers are planned to be installed around the experiments in IR1 and 5, and the possibility of tertiary collimators around point 2 are under discussion. Table 1 summarizes numbers and positions for the collimation upgrade of the next long shut-down.

THE DS COLLIMATORS IN PT.3

In order to create the space required for fitting compact warm collimators within the continuous cryostat of the Dispersion Suppressors (DS) zones, the DFBAs, together with the Q7 and two adjacent dipoles have to be moved by 4.5 m towards IP3, whereas a new 4.5 m shorter connection cryostat (so-called Short Connection Cryostat, (SCC) will allow moving the Q10 and two adjacent dipoles towards Q11. As a consequence two slots, each of 4.5 m long, become available for integrating the 2 new DS collimator assemblies close to Q10 and Q8. The magnets between Q10 and Q8 will have to be moved towards the center of the machine by 46 mm to comply with the new optics layout. The longitudinal translation of the DFBAs forces the displacement of its proximity ancillaries (instrumentation and control panels and electronics racks) and of adjacent equipment like the TCLA, DQS (and BTVM in 3L, for which a suitable position is still to be decided). The layout changes to the DS zones are schematically illustrated in Figure 1. Space constraints in the tunnel in these locations make the integration studies particularly challenging and though most of the issues have been solved, a few outstanding issues still need to be tackled. Since the QRL will not be modified, the new position of the cryogenic feeding of the magnets and DFBAs require new transfer lines to bridge the longitudinal gap to the QRL distribution points. Their integration above the main cryostat or along the QRL has been studied and is now almost final. As an example, Figure 2 illustrates the integration study around Q7 in L3. Accessibility over the interconnection between Q7 and the adjacent dipole is limited obliging the interconnecting work to be done prior to the installation of the cryogenic distribution link.

Table 1: Collimators for the upgrade, part 1.

Type	**Orient.**	**To be installed**	**Location**
DS coll.	Hor.	**4**	DS pt.3
TCP (primary)	Ver.	2	LSS pt.3
TCSG (secondary)	Ver.	8	LSS pt.3
TCLP (debris absorber)	Hor.	4	LSS pt.1,5
TCTVA (tertiary), to be confirmed)	Ver.	2	LSS pt.2
Totals		20	

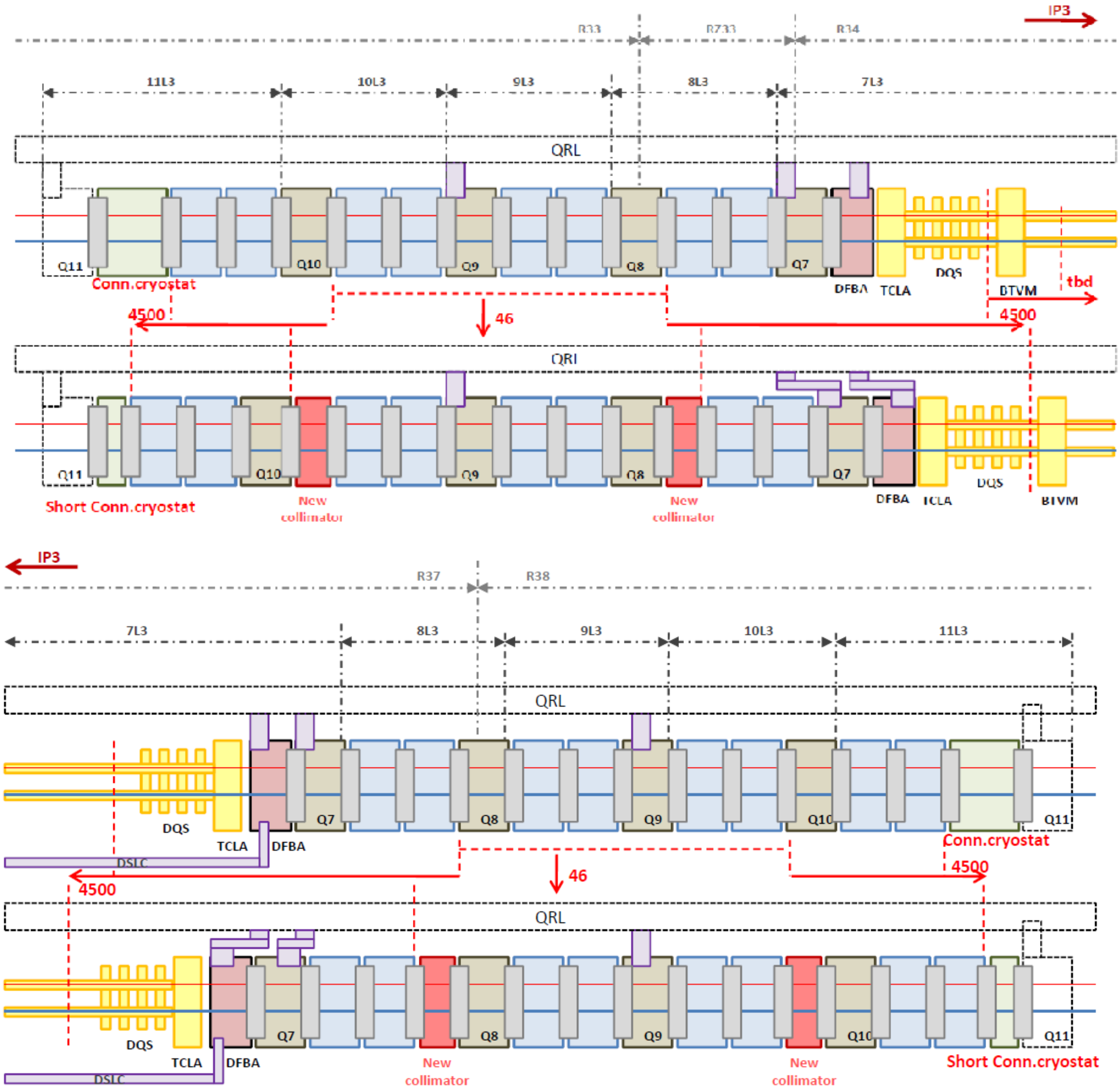

Figure 1. New proposed DS layouts around Pt3.

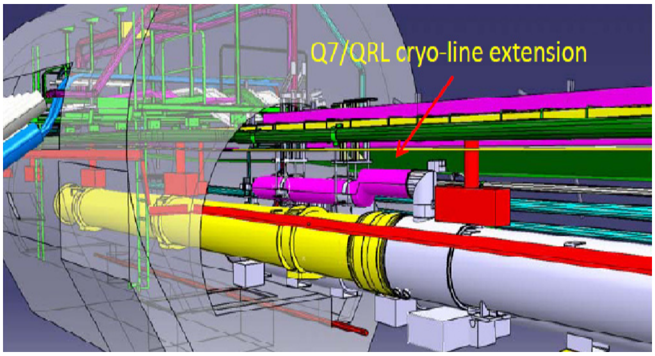

Figure 2: Integration study 3L: cryogenic extension to Q7

A challenging work will be the re-routing of the bundles of several hundreds of cables in the limited space of this zone. The drilling of a new cable duct through the wall between UP33 and R34 is being studied to create a new routing for some of the cables.

The DS collimator assembly (TCL)

The DS collimator assemblies are composed of a cryostat bypass which provides the continuity of the technical systems along the arcs (magnet powering, cryogenics and insulation vacuum), while providing transitions to warm beam tube segments where the collimators are placed (Figure 3).

The cryostat and the collimators are physically two separate entities which allow installation of the cryostat part first whereas the collimators can be installed later.

The two equipments stand on independent supporting systems. The advantage of this approach is double-fold: firstly it allows the continuous cryostat to be completed with the DS cryostat, which enables the test and commissioning of the technical systems in advance (the collimator can be installed later and removed from the cryostat independently in case of need, provided warm beam tubes are installed in its place); secondly, the precise mechanical positioning and adjustment of the collimators is ensured independently from that of the cryostat which is intrinsically less precise and stable due to the large vacuum forces involved. The drawback of this approach is that the integration of the collimator in the reduced space of the cryostat is not easy, in particular due to the presence of the line X cooling tube with its cryostat vessel, positioned in the top part of the center plane of the cryostat. The design of the DS collimator cryostats and collimator module is well advanced and the manufacturing drawings should be released in April 2011.

The long-lead components have been launched; those which are today on the critical path are the bus-bar sets which are being produced at CERN by TE-MSC in a newly set-up facility.

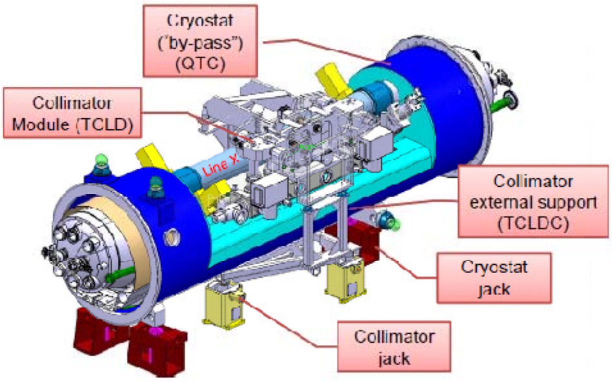

Figure 3: DS collimator assembly

The Short Connection Cryostats (SCC)

The SCC is a shorter version of the existing connection cryostats of the machine, which allows a 4.5-m gain in length in each DS. Due to their shorter length (8 m), their cold mass can be supported on 2 internal supports only, yielding a simpler and mechanically sounder iso-static configuration. The design is essentially based on existing solutions and components, though a major change concerns the design of the bus-bars which will have one lyra box at one side of the cryostat. Most of the components are available except the vacuum vessels for which the procurement is to be launched this year, and the bus-bar sets which are also to be produced by TE-MSC. The design of the SCC is close to final and the manufacturing drawings will be ready by end March 2011.

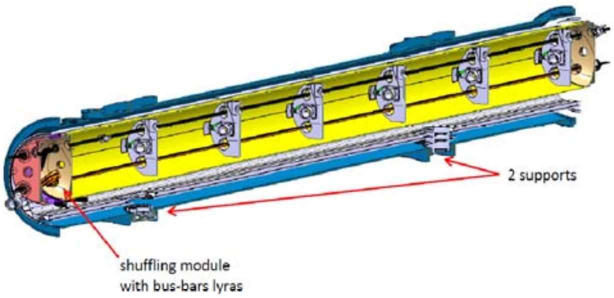

Figure 4: Short Connection Cryostat

SCHEDULES OF SURFACE AND TUNNEL WORK

The preparation of the new equipment is progressing steadily and is aimed at being ready for installation during a long shut-down in 2012. The schedule for the construction of the collimators (based on input given by EN-MME in November 2010) [1], yield availability dates stretching between February 2011 and April 2012, the DS collimators being the latest ones to become available. However, the preparation of the DS collimator cryostats, with their assembly starting in June 2011, will make the first cryostat available starting in March 2012 and the last unit will be available only by December 2012. According to these dates of availability, the provisional tunnel work schedule shows that the shut-down related to the installation of DS collimators in IR3 would not be terminated before September 2013.

The schedule for tunnel work has been elaborated under the following assumptions:

- first estimate of activity durations given by system responsible;
- work on single shifts, with night shifts dedicated to transport;
- 3L and 3R work mostly done in parallel;
- all magnets moved up to surface;
- DFBAs moved and stored in P4;
- re-cabling done by 4 teams;
- no resource sharing with other shutdown activities/projects;
- no sharing of transport with other shut-down activities/projects;
- no co-activity interference;
- no contingency.

These assumptions will have to be checked when elaborating an integrated shut-down schedule.

Under these assumptions, and assuming that the new equipment (DS collimators, SCC, ...) is ready on time for installation, the shut-down activity for the DS collimators project would last at least 8 months. These conditions would typically be those of a 2013 shut-down, for which the installation would take place between February and September 2013.

SUMMARY AND OUTLOOK

The Collimator Upgrade (part 1) project, aimed at improving collimation efficiency (by a factor 5-10), has started in July 2010, is now structured and proceeding full steam. The DS collimators part requires a challenging re-layout and integration study, which is well advanced but with some issues still outstanding (but no show-stopper have been encountered so far).

The design of the new DS equipment (DS collimators, and Short Connection Cryostats) is well advanced, and will be finished by Spring 2011.

The manufacture of bus bars at CERN is in good progress but deserves close follow-up as it is, so far, on the critical path for a shut-down in 2012.Procurement of other long-lead components is under control.

Planned availability dates for installation of the DS collimator cryostats are: 1st unit available in May 2012, 4th unit available in December 2012.

A preliminary schedule for a 2012 shut-down, conditioned by the availability dates of the DS cryostats and SCC, yields a ~12 months installation for the DS collimators (including the installation or the LSS collimators), in the period February 2012 – February 2013. The same schedule shifted to a 2013 shut-down, yields a ~8 months installation, in the period February-September 2013.

This preliminary schedule needs consolidation and matching with those of other shut-down projects (resources allocation, co-activity, transport sharing, etc.) so its duration could result longer.

ACKNOWLEDGEMENTS

I would like to acknowledge the contributions from the collimation up-grade project team, in particular: R.Assman, O.Aberle, A.Bertarelli, J.Coupard, Y.Muttoni, D.Ramos, J.Ph.Tock, D.Wollmann, and all the WP holders involved in the project.

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CRYOGENIC SYSTEMS : WHICH CONSOLIDATIONS SHALL BE DONE IN 2012/13 ?

O. Pirotte

Abstract

The operation of the cryogenic systems during the first two years at half of the nominal energy has highlighted a number of required consolidations. The main projects will be reviewed with emphasis on safety issues, LHC downtime risk and cryogenic systems performance. Finally their status, cost, resources and planning will be summarized.

CRYOMAGNETS, INTERCONNECTIONS, SUPERCONDUCTING CIRCUITS: WHAT TO DO IN 2012/13 IF YOU ARE NOT CONSOLIDATING SPLICES?

J.Ph. Tock, CERN, Geneva, Switzerland,

Abstract

The interventions affecting the cryomagnets, the interconnections and/or the superconducting circuits, excluding main splices consolidation and QPS interventions will be presented. All the tasks not covered in other talks of this session will be detailed, especially:

- the repair of existing leaks,
- the intervention on Plug-In-Modules,
- the replacement of cryomagnets,
- the consolidation of the connection cryostats,
- the repair of interrupted Y-lines,
- the installation of safety pressure relief devices (DN200 & 160),
- the consolidation of some SAM helium level gauges,
- the use and possible addition of radioprotection samples
- the investigations of open issues like high resistance splices and superconducting circuits non-conformities

Finally, the present plan, work organization and workload for these activities including DS collimators installation, interventions on the beam lines and leaks localization and repair, will be summarized.

INTRODUCTION

Despite the fact that the consolidation of the main splices will be the most resources consuming activity on the cryomagnets during the next long shutdown, there is in parallel a long list of special interventions on the superconducting circuits and cryomagnets that have to be carried out. Both types of interventions will interfere strongly because:

- they will take place in the same limited space (the LHC tunnel)
- the experienced resources being scarce, a fair sharing will have to be done
- they are often involving work on the same vacuum, cryogenics and/or electrical circuits so a strong coordination will be necessary; first to ensure the safety and also to minimise the losses of time.

IN-SITU WORK OR CRYOMAGNET REPLACEMENT

Whenever possible, in-situ repair will be carried out. It is in general less time consuming. It has to be reminded that to replace a “standard” cryodipole in an arc:

- more than 6 different teams have to intervene with heavily interleaved tasks,
- for various reasons, work is taking place on a length of 216 m,
- this could create interference on 3-km long non-sectorised circuit(s),
- it takes 6 weeks between the opening of the first interconnection to the reclosure of the last one,
- about 600 man hours are necessary.

Additionally, some cryomagnets are even more difficult to replace : SSS with jumper, cryomagnet in the dispersion suppressor zones, ...

VACUUM RELATED ISSUES

Leaks

Presently, the LHC machine is operated with about 20 acceptable leaks spread around the whole circumference. The leaking subsectors are identified but time has to be allocated before the start of opening of the interconnections outside sleeves (W-bellows) and during the shutdown for localising the leak precisely, for fixing them in-situ and then for validating the repair. Among them, only one is critical: it is located in subsector A27L4 in the sector 34. This is the only one that could trigger a cryomagnet replacement if it cannot be fixed in-situ. The goal will be to fix all of them but it is not excluded that acceptable ones will be left if their repair is not feasible or has a too huge impact. On the other side, new leaks can appear before or during the shutdown that will require intervention.

Plug-In Modules (PIMs)

During the PIMs fabrication, a non-conformity affecting the RF fingers was encountered. It could lead to a failure of this component during the warm-up of the machine.

All the PIMs that will have buckled during the warm-up will obviously be exchanged after localisation thanks to the RF ball. Based on previous sectors warm-up, it is estimated that about 18 units will have to be replaced.

Additionally, some of them were heavily damaged during the initial assembly of the interconnections. To avoid delaying the schedule, they were left as they were but their lifetime could be reduced. The unacceptably damaged ones will be replaced if an inspection by the specialists confirms the need. There should be less than 10 units to replace.

When the LHC machine is left floating, its temperature is slowly increasing. While the centre of the arcs remain very cold, the extremities are warming-up faster and so increasing the risk of PIMs failure or reducing the autonomy. During the 2008-09 shutdown, some sector extremities were already consolidated with conform PIMs. It is proposed to consolidate the remaining ones during the next long shutdown, leading to the replacement of 18 units.

The present baseline is thus to replace about 45 PIMs.

In case of a local warm-up, the failure of a PIM is not excluded. If this happens, this can be detected thanks to the X-ray tomography but the repair will require warming of the neighbouring subsector and venting the beam line to replace the PIM and then, after restart of the LHC, a scrubbing run will likely be necessary to recover the adequate vacuum level. It is important to note that the X-ray tomograph is not a practical systematic inspection tool as it takes several hours to inspect one of the 1700 interconnections. To decrease the risk of PIMs failure in case of a local warm-up, the replacement of QQBI and/or QBQI types PIMs is discussed but is presently not included in the baseline.

Nested bellows

During initial interconnections assembly, about 55 nested bellows were damaged; two of them quite heavily and they were consolidated (see Fig. 1). A thorough analysis by the expert concludes that they can survive a few cycles. As they are working only in case of an error in the cryogenics operation, it is not planned to replace them. This will be confirmed after a very careful inspection. The present procedure to replace them requires a complete exchange of the beam screen so the disconnection of the cryomagnet.

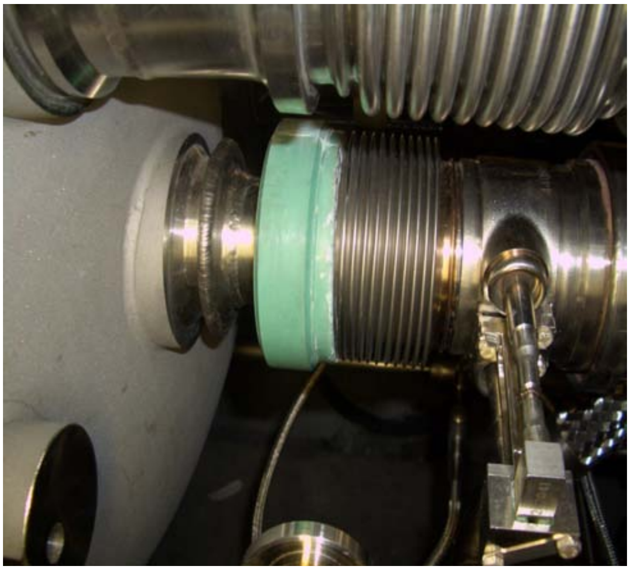

Figure 1: Repaired nested bellows (QBQI.10L5)

Beam screens

After the 34 incident, due to the lack of beam screens with the correct saw-tooth profile orientation, reversed ones were installed [1]. This concerns 12 dipoles in sector 34. Also, there are 2 SSSs equipped with the wrong type of beam screen (see chapter 6 of [1]). This could be an issue for electron cloud build-up and so affecting beam physics and cryogenics. A study is presently on-going to check the necessity to change them. Presently, it is not planned to replace them. Should the study concludes that the correct type needs to be installed, this would involve the exchange of 14 cryomagnets so a very huge work.

In sector 81, one beam screen has a leaking cooling capillary. It was bypassed. The equipment responsible confirmed that its exchange is not necessary.

CRYOGENICS RELATED ISSUES

Stand Alone Magnets helium level gauges [2]

Since the beginning of cryogenics operation, it was noticed that (Semi)Stand Alone Magnets(SAM) helium level gauges readings were not very stable. During the 2008-09 shutdown, two of them were not accessible without major delay: Q6R2 & Q6L8. The baseline is to consolidate them in the next long shutdown.

Leaking Y-lines

The Y line is a copper line, part of the bayonet heat exchanger. Two of them are presently leaking. The impact is that recooling of the concerned cells takes slightly longer. As the interconnections will be opened, the baseline is to fix them: S78:17-19R7 & S81:19-21R8.

Safety pressure relief devices [3]

In the 2008-09 shutdown, some sectors were not warmed up and so, it was not possible to install the DN200 pressure relief devices. Also, the safety pressure relief devices could not be installed on Q6R2 & Q6L8. It is planned to complete the new protection scheme during the next shutdown. About 600 relief valves have to be installed.

Inner triplet passive heaters [4]

During assembly of the Q1 magnet, the applied configuration of the passive heaters (copper braids) on the phase separator reservoir was wrong. The most critical cases (R1&L5) were corrected during the 2008-09 shutdown. The proposed baseline is to intervene on the two most critical cases (L1&R5) in the second part of the shutdown. Time permitting, the four other cases (L&R 2&8) will be also corrected but they are not included in the baseline.

Cryogenics instrumentation

Several cryogenics sensors are not functioning nominally but this does not prevent a smooth operation. During next shutdown, as most of the interconnections will be opened, access will be given to cryogenics instrumentation team for them to solve as many cases as possible.

ELECTR(OMECHAN)ICAL INTEGRITY

Connection Cryostats

In 2008, a short to ground was detected on the RQF circuit in sector 78; it was traced back to the shuffling module of the Connection Cryostat (CC) [5]. It was consolidated in all CC but in sector 56 that was not accessible as already under cool-down. During consolidation of the CC in 11L6 in the 2008-09 shutdown, another non-conformity was detected [6]. A consolidation solution was defined but, again to avoid major delays and as tests have proven that the risk was very low, two CC (L1&3) were not consolidated and one was even not inspected (L8). During the next long shutdown, the baseline is to inspect the CC L8; consolidate it if necessary and also the 2 remaining ones. Note that to install the DS collimators in IR3 [7], the CC in 11L3 has to be replaced by a shorter one. As all the busbar lines in the interconnections will be opened, the opportunity will be taken to perform a careful inspection of the 17 CC and confirm that the fixes applied are sound.

Circuit issues [8]

There are several issues on superconducting circuits. To save time and minimize the risks, they were condemned. It is planned to complete the investigation at cold before the long shutdown and at warm. Then, after identification and localisation of the defect, a repair procedure will be defined and implemented.

Special splices

The 6 kA pray-hand splices have been analysed and presented [9]. The design has been validated by the review committee [10]. In parallel, an exhaustive splice mapping is on-going. During the shutdown, some such line N boxes will be opened for inspection to check the correct workmanship.

During the assembly of the first sector (78), some 600 A line N connections were found non-conform. Most of them were inspected and redone if necessary. For the non-inspected ones, sampled inspections are planned.

The main circuits contain also non-standard splices, namely the 13 kA splices in the DFBAs. Their consolidation will require a specific access procedure. The need for consolidation will be discussed by the LHC splices task force [11].

High inner splice resistance

Thanks to the nQPS system, all inner splices of the main dipole and quadrupole cold masses were measured. [12]. The maximum value in a dipole is 28.1 nΩ and about the same in a quadrupole. Figure 2 shows the cumulative number of dipole cold masses with an inner resistance higher than a certain value. These high resistances are not worrying from the cryogenics or electrical point of view. The concern is that a high electrical resistance can reveal a very bad mechanical contact that could fail and open when submitted to electromechanical forces, for example if the splice quenches.

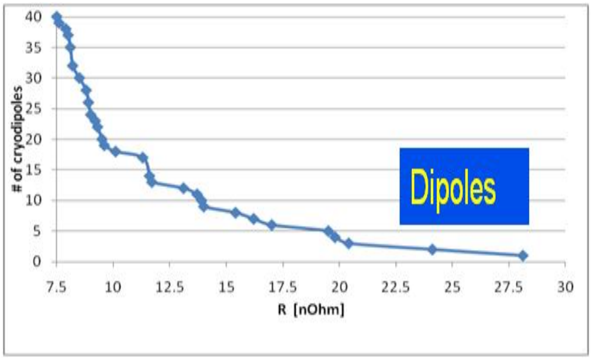

Fig. 2: Dipoles inner splice resistance

In order to estimate the resources and as it is judged a reasonable value [13], the proposed baseline is to replace 8 cryodipoles and 1 SSS, reducing by a factor 2 the highest inner splice resistance in the LHC machine. In parallel, a study and a test programme are launched to gain knowledge on the behaviour of these possibly weak splices.

Electrical non conformities

Some cryomagnets are affected by non-conformities [8]; they mainly concern quench heaters and high voltage withstand level. For various reasons, investigations were stopped as a method to allow continuation of operation was available. Cold and warm diagnostics are planned for all the identified cases. It will be first tried to repair in-situ and, if not feasible, the cryomagnets will be replaced by spare ones. Based on reasonable assumptions, it is estimated that 5 cryodipoles will have to be replaced.

BEAM DYNAMICS

Following the incident of 19/09/2008 in sector 3-4, it was necessary to substitute several SSSs. For 4 slots, the limited availability of spare Arc-SSS cold masses has not permitted to install SSSs compatible with the LHC baseline layout 2008 [14]. Consequently, some lattice correctors are missing. The RQS.R3B1 is not available anymore and the power of 3 other circuits (RQS.A34B2, ROD.A34B1, ROF.A34B2) is reduced. To restore them completely, four SSSs should have to be exchanged. Discussing with BE/ABP, the priority should be put on the skew quadrupole circuits that require to change the SSSs Q23R3 and Q27R3.

The baseline is to exchange these last two SSSs (Q23 & Q27 R3). This involves a lot of surface work to prepare the spares and their replacement will be quite time consuming as these SSSs are equipped with jumpers, increasing the work to be carried out and the interferences created.

Also, one cold corrector RCBCHS5.L8B1 in Q5L8 is missing [15] but it is replaced by a warm magnet installed next to Q5L8. A replacing SSS is under manufacturing. It is not a priority to perform the exchange unless there are other issues to be considered, such as a potential short in the five remaining dipole correctors.

DS COLLIMATORS

Ref [7] presents the activities required to install the DS collimators at point 3. This involves the disconnection, displacement and re-interconnection of 32 cryoassemblies. It is not really exchanges of cryomagnets as the baseline is that the removed ones are placed back at their original position.

MISCELLANEOUS

Many local interventions will be required for giving access for short interventions, like for example BPM cables checks and possibly repairs, recovery of the radioprotection samples for analysis [16] or installation of new ones.

Last but not least, interventions will be required to solve new issues appearing before the shutdown and also to manage non-conformities generated by the other activities during the shutdown. These last ones will require each time dedicated delicate procedures. 26 % of the resources are allocated to these works which is judged a little too low. 30 % seems more appropriate. Fig. 3 represents the work sharing of the special intervention team based on a team of 20 persons and a work period (opening of the first interconnection to the re-closure of the last one) of 12 months.

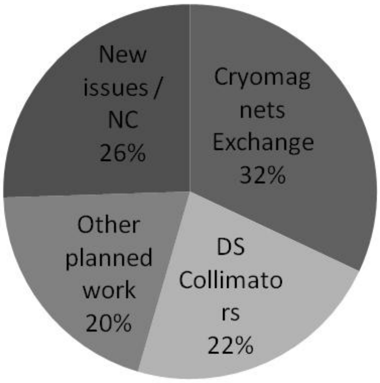

Fig. 3: Allocation of the special intervention team resources

CRYOMAGNETS EXCHANGE

Table 1 summarizes the current status of the quantity of cryomagnets to exchange. The 32 cryoassemblies concerned by the installation of the DS collimators are not included in this table.

Table 1: Cryomagnets exchange

Reason	**Dip**	**SSS**	**Tot**
High inner splice resistance	8	1	9
Electrical integrity	5	0	5
Beam optics (Q23R3, Q27R3)	0	2	2
Leaks	1	0	1
Reversed beam screens (*)	0	0	0
TOTAL	14	3	17

(*) Note that if cryomagnets with a reversed beam screen have to be exchanged, this would add 12 dipoles and 2 SSSs so almost doubling the total amount.

For this baseline, the spares cryomagnets are expected to be available at the surface before the start of the shutdown.

THE SPECIAL INTERVENTION TEAM

To fit this work in a period of 12 months between the first opening and the last reclosure of an interconnection, a team of 20 persons is necessary. The objective is that this team completes its work before the arrival of the teams (train) in charge of the consolidation of the main splices. As the work is specific and sometimes will have to be finalised in-situ, a ratio of minimum one experienced/ one new staff is judged acceptable to ensure a reasonable progress without taking exaggerated risk. The present situation is that 6.5 persons are identified out of the 20 required so leading to ratio lower than 1/3 of experienced staff; it is critical and risky. To lower this risk, the options are :

- To accept a longer shutdown duration allowing to shift experience resources working on the main splices to the special intervention team (eg. Orbital machining of sleeves team)
- To reduce the scope of work of the special intervention team (eg. Number of cryomagets to be replaced)
- To shift experienced resources planned for the main splices consolidation to the special intervention team.

It is important to remind that work will take place all around the LHC circumference, making the coordination and follow-up quite demanding in terms of supervision staff.

CONCLUSIONS

The list of tasks has been presented. Some of them needs to be confirmed or detailed. In particular, the need or not to replace cryomagnets with reversed beam screens has a strong impact on resources and time needed. Also, the issue of cryomagnets with high inner resistance will be revisited when data is available from analysis and test programme. The special work will extend all over the 27 km of the LHC. The presently identified and available staff leads to a critically low ratio (<1/3) of experienced staff in the team.

ACKNOWLEDGMENTS

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QPS/LHC ACTIVITIES REQUIRING IMPORTANT TUNNEL WORK DURING A FUTURE LONG SHUTDOWN

Knud Dahlerup-Petersen, CERN, Geneva, Switzerland.

Abstract

The MPE/circuit protection section is presently establishing a road map for its future LHC activities. The tasks comprise essential consolidation work, compulsory upgrades and extensions of existing machine facilities. The results of a first round of engineering exertion were presented and evaluated at a MPE activity review in December 2010. The technical and financial aspects of this program will be detailed in the 'QPS Medium and Long-Term Improvement Plan', to be published shortly.

The QPS activities in the LHC tunnel during a future, long shutdown are closely related to this improvement chart. A project-package based program for the interventions has been established and will be presented in this report, together with estimates for the associated human and financial resources necessary for its implementation.

INTRODUCTION

The different parts of the consolidation and upgrade package are motivated and justified by a variety of different circumstances, for which the main incentives are:

- Mandatory repairs to maintain a high level of system availability
- Improvements for performance enhancement, based on operational experience
- Adjustments required for the future energy increases
- Modifications imposed by new machine integration layouts
- Extension and completion of the enhanced quench protection system (nQPS)
- Upgrades imposed by R2E features
- Maintenance prior to magnet training with requirements for highest QPS performance
- Installation of pilot facilities of next-generation QPS and EE equipment

The shutdown work with tunnel interventions has been defined in five separate project packages:

Package 1: DQHDS: Improvement and extension plan for the 6'078 quench heater power supplies. Comprises repair work, introduction of new hard- and software and integration into the DQLPU's.
Package 2: nQPS: Completion of the existing enhanced protection scheme and its extension to circuits outside the arcs.
Package 3: EE: Consolidation and upgrade plans for both the 13 kA and the 600 A energy extraction facilities.
Package 4: Controls and ACQ topics: General and specific upgrades.
Package 5: R2E: Mitigation and relocation programs.

PROJECT PACKAGE OVERVIEW

Package 1:

Important changes are foreseen for the quench heater powering circuit and its monitoring features. The modifications endeavour an improvement of the acquisition as a tool for making early diagnostic of a faulty heater, a reduction of the stress on the heater strips during discharge testing, introduction of a permanent circuit continuity check and some repair work.

I) *Introduction of a discharge current and voltage measurement as a complement to the existing capacitor charge voltage monitor.*
The combined measurements will provide information about the phase and amplitude of the load impedance at any moment during the discharge and herewith increase the chances for early fault detection. Only in rare cases (fig.1) the voltage measurement alone could allow a disclosure of a heater defect prior to a breakdown which could have a potential risk of damage to the cold mass.

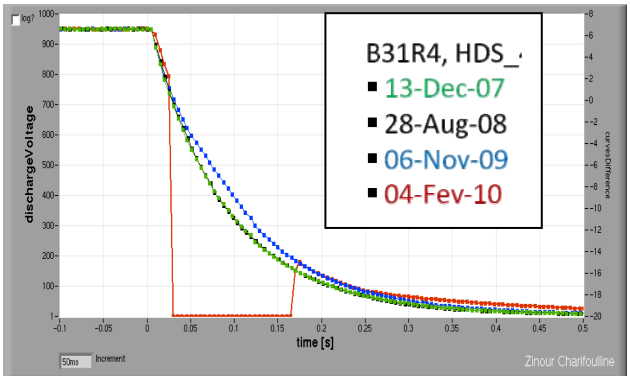


Figure 1. One early warning possibility was observed on discharge voltage plots (November 2009).

The new baseline design features a 1 mΩ, 1%, 7 W shunt resistor (272 mJ/cycle), a RADhard isolation amplifier and ADC, located in a separate compartment, possibly a part of a renewed 'Crawford' shuffling box, reducing to a minimum the interventions on existing hardware. The upgrade will require new DQAMC boards (1700 units) as the required 8 additional analogue channels are not available in the existing dipole controller, neither the 4 channels in the quad controller. The sampling frequency shall be increased from 200 Hz to at least 500 Hz. Verification of discharge voltage and current profiles will comprise automatic, point-by-point comparisons with stored data from earlier discharges.

The estimated resources for the tunnel work associated with this upgrade total 1.7 FTE, not including the required extension of the MicroFIP network. The estimated resources are included in the cost figure of point 1.

II) *Introduction of a 'tickling' circuit.*

Continuous verification of the integrity of each heater discharge circuit will be provided by associating the above voltage and current measurement feature with the insertion of a small d.c. source in mA range. Apart from the moment of discharge, where this 'tickling' circuit will be disconnected and isolated, the circuit will produce an alarm in case of increased heater circuit resistance. Also these sources will be located in the new shuffling module.

III*) Implementation of a low-voltage (low-power) trigger to allow regular verification of heater integrity through safer discharge tests.*

A software solution is considered safer and simpler than options requiring additional hardware. A special test mode will allow thyristor firing at a programmable threshold voltage (100-300V). The discharge will be triggered during the capacitor charging so to have the controls powered. This method requires no modification to the existing installation or any addition of new hardware. The new test mode will be power permit prohibiting. It may occasionally replace the full power test. The procedure will be tested at Technical Stops in 2011 and implemented everywhere during the long shutdown.

IV) *Replacement of the failing switches for power input and internal capacitor discharge.*

Now that the origins of the switch failures (design and production mistakes) and the likely continuation of the failure process are understood, the decision to replace this component by a new, qualified switch on all 6'078 DQHDS units is taken. Substitution of the first 1'000 units took place in the 2010-11 winter stop, involving all LHC quadrupole heaters. Every TS of 2011 and 2012 will be used for further replacements on the dipoles, starting at the most inaccessible areas (points 3 and 7). With an exchange rate of 62 units/day approximately 2'000 units will remain for replacement in the long shutdown 2013, representing 0.53 FTE.

It shall be noted that new DQHDS failure alarm and abort interlock system will partially make the problem transparent to operation. Repair will be in the shadow of other mandatory tunnel interventions and will not cause any additional machine-down time.

Package 2:

The completion of the first phase of the existing nQPS system is related to the arc magnets, whereas its extension concerns new circuits to be equipped with distributed busbar detectors and new detection boards.

I) *Completion of the 'Voltage-to-Ground' measurement system – nQPS / DQQDE, phase 1 and 2.*

When fully deployed, the system will allow continuous monitoring of the busbar voltage w.r.t. ground at the dipole 'B' and at the quad of each half-cell. Furthermore, it will allow busbar-to-busbar voltage monitoring such as QF-QD, QF-QF, QD-QD and RB-RB, for voltage distortion or short-circuit detection. Phase 1 comprises the installation and commissioning of 30 DQQDE boards (fig. 2) in the three main circuits across a single sector, foreseen for TS#8, March 2011. At the same time the associated software will be checked. The rest (phase 2, 1278 boards) will be installed in either the winter stop 2012 or in the long shutdown. The required resources represent 0.1 FTE.

II) *Extension of the nQPS-BS splice monitor to cover the individual busbars of all stand-alone magnets.*

One hundred powering circuits are affected by this extension (all IPQ's, IPD's and IT's). The principle of 'one circuit – one detector crate' will be applied, requiring design, production and installation of 30 new DQGPU crates, 30 new DQAMG controller boards and at least one cable patch per circuit. The associated signal cables, however, were already installed during the nQPS arc cabling campaign in 2009.

It shall be noted that opposite the BS systems in the arcs, the SAM systems will exclusively be allocated to precision resistance measurements of the busbars; an additional interlock is not required as the present, global detector provides full protection of both magnet and busbars.

A few prototype systems will be available for installation in the winter stop 2012. For the installation and connection in the tunnel of the series 0.5 FTE is required.

III) *Partial upgrade of the digital detection boards (nDQQDI) in radiation exposed areas (RR's) in LHC points 1 and 5.*

The logic controller of the new cards (fig. 3) is based on the FPGA ProASIC3, such as the DQQDS detector. They feature display of data from both boards 'A' and 'B' and also post-mortem files are created for both detectors. The new boards are designed for direct replacement in the existing crates. Estimated resources for installation is 0.1 FTE.

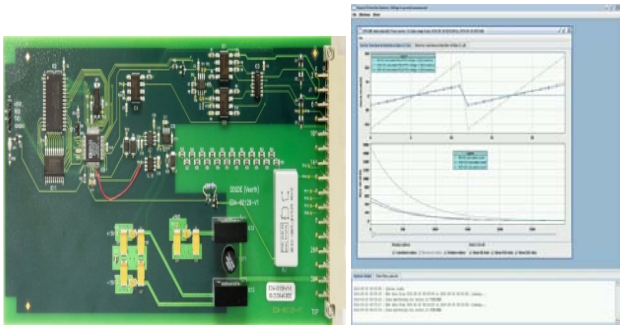


Figure 2: DQQDE board and simulated voltages to ground across one sector.

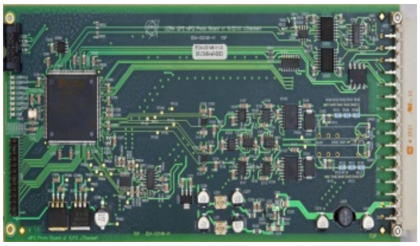


Figure 3: nDQQDI board with Actel ProASIC3

Package 3:

The upgrade of the 234 EE facilities is defined in eight sub-packages.

I) Installation of snubber capacitor banks in the RQF/RQD circuits.

Following the successful deployment of the dipole snubbers and the validated results from type testing of the quad units it has been decided to prepare for their installation across the DQSQ's during the long shutdown. Routine testing of the 16 installations will begin shortly, along with the production of the auxiliary components and the protection circuits. The estimated installation time is 0.8 FTE total.

II) *Relocation of the two DQSB extraction switch assemblies in point 3 (4.5 m displacement on both sides).*

The integration phase requires close coordination with TE/VSC for co-existence with beam pipes and other vac equipment inside the DQSB shield enclosures. The cable adaptations will be outsourced to EN/EL. Relocation of the DQRB's and the DQRCS seems not necessary. The resources from QPS are estimated to 0.4 FTE for the two sides.

III) *Upgrade of the DQRB's (53 units):*

Replacement of all H.T. thermostats has become necessary after discovery of a drift in the transition point of the existing, Curie-temperature based thermo-switches (a CERN/IHEP development). Replacement will be with conventional bi-metal units.

Second issue concerns the capability of the DQRB's to (exceptionally) absorb without damage twice their rated energy, i.e. 440 MJ each. During a double-energy test at IHEP, RU, simulating an accidental non-opening of one of the two extraction switches, the risk of damage to the H.V. power bushings and even short-circuit of a part of the resistor related to the thermal expansion was revealed. The intervention consists of modifying the current feedthroughs (fig. 4). Because of the co-existence with the Roman Pots in point 1, access to the dump resistors requires temporarily removing them and supporting the beam pipes during the intervention. The two issues require 0.30 FTE.

IV) *First complete overhaul of the 256 extraction switches of main dipole- and quadrupole circuits.*

This preventive maintenance program includes the adjustments of the gaps and contact pressures in the electro-mechanical systems for main- and arcing contacts as well as execution of the voltage withstand tests according to the instructions of the manufacturer. The associate resources total 0.18 FTE.

V) *Replacement of the arc chambers on the quadrupole breakers for a 500 V version (if necessary and approved).*

This task is required only if the decision is to continue operating the quad circuits with a 9.6 s time-constant at energies above 4.5 TeV [1]. The resources needed are 0.05 FTE.

VI) *Consolidation of the 'holding coil' assembly of the 600A extraction switches.*

During the first year of operation of the EE facilities, QPS has detected five cases of unclamping of the so-called 'holding coil' which provides the contact pressure on the breaker's main contacts for closing and maintain. The intervention consists of applying a reinforcement to the coil clamping system (fig. 4). A method which allows an installation without removing the switches from the rack is under development. If applied everywhere the intervention will need allocated 0.3 FTE.

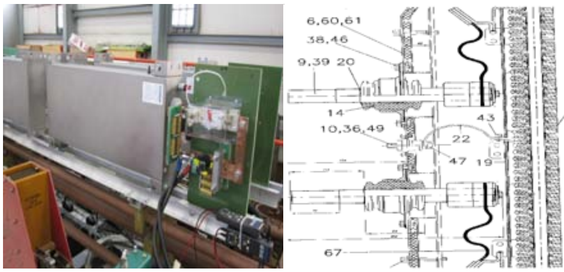
VII*) Further improvements:*

The mitigation package contains two further tasks:

-Replacement of the voltage dividers for U_{dump} by a non-linear electronic meter for precision monitoring of both U_{dump} and ΔU_{switch} in closed state. Estimated 0.25 FTE needed.

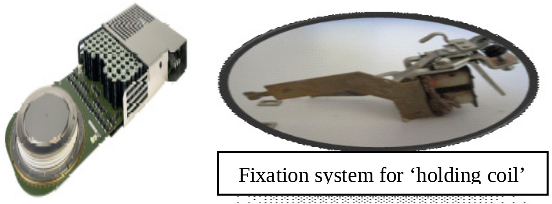
VIII) *Pilot EE systems based on water-cooled IGCT static switches for the 600A corrector circuit protection.*

Two existing 600A EE racks will be replaced by four pilot switches based on bipolar, integrated gate, commutable thyristors combined with blocking diodes and a non-RADTol gate drive electronics. The purpose is to perform final validation of such systems under real operating conditions. The estimated resources for the installation / connection of the four systems are 0.15 FTE.



Quad Snubber Caps with protection circuits

DQR feedthrough modification



Fixation system for 'holding coil'

IGCT

Package

Fig. 4. Issues related to the EE upgrades.

I*) Field-bus changes.*

The operation of the present QPS, nQPS and EE equipment loads the existing DAQ transmission system to 90% of its capacity. An extension of these systems will rapidly saturate the data transmission lines. Consequently, a gain in the margin of the transmission bandwidth will be required. This task involves a reconfiguration of the present field-bus from 4 to 8 segments per sector, a doubling (from 2 to 4) of the tunnel gateways, a doubling of the number of repeaters and some infrastructural changes. Furthermore, the extension comprises the installation of new optical fibers in the tunnel and in the shafts, from the alcoves to the surface, representing a total length exceeding 2/3 of the LHC circumference. It will heavily involve BE/CO and EN/EL with resource requirements estimated at 0.40 FTE / sector.

II) *New controller boards.*

New DQAMC boards for the local protection units shall feature:

-minimum 8 additional analogue input channels

-integration of the new nanoFip

-a built-in remote rest unit

-a programming plug on front panel for easy loading of modified software

New firmware will be developed for these new controller boards which will be tested in the winter stop 2012 in some selected LHC areas. Their installation will have minimum impact on the shutdown planning.

Package 5:

I) R2E Mitigation: Changes to firmware for overcoming the consequences of SEU events.

The experience from operating the quench detectors during the first year of LHC exploitation indicates that charged particles cause triggers due to their interference with sensitive electronic components, e.g. digital isolators. Such cases mainly occurred during the ion runs and in the higher loss areas L2, R8, point 3 and point 7, affecting the AMC controllers. The interferences did never impinge on the protection features but created unwanted post-mortem triggers after which the DAQ entered into a stalled state, with loss of the QPS_OK signal (injection permission) and no return to logging condition. Also a new PM buffer filling was inhibited.

Mitigation consists in a modification to the associated firmware by forcing a re-launch of the logging and resetting of the PM system. The upgrade was successfully implemented in points 7 and 8. The required resources for extending the improvement to points 2 and 3 and then the rests of the machine are estimated to 0.2 FTE.

II) Relocation of Quench Protection Equipment.

Bringing QPS equipment to more shielded areas is only relevant in the locations P1 left, P1 right and P5. In each case the move concerns the inner triplet protection systems, i.e. the RQX quench detector crate, its associated eight quench heater power supplies and the seven IT corrector protection units RCBXH1, RCBXV1, RCBXH2, RCBXV2, RCBXH3, RCBXV3 and RQSX3.

Each of the three equipments consists of two instrumentation racks (DYPG01/02). The UJ14 and UJ16 racks will be moved to UL14 and UL16 whereas the UJ56 racks will go to UL55.

The estimated resources are 0.15 FTE, plus outsourcing to EN/EL of the re-cabling.

CONCLUSION

QPS will not wait for the long shutdown to undertake the improvement and extension campaign for the quench detectors, heater firing equipment and energy extraction systems, such as defined by the consolidation and upgrade project packages. As it was the case in 2010, every technical stop will be used to advance the various programs. However, tasks which require important re-commissioning are planned for the long shutdown.

With this long shutdown, now scheduled for 2013, the total resource estimate for execution of the QPS project packages in the LHC tunnel during this stop amounts to 8.9 FTE. To this figure shall be added 4 FTE for assistance with logistics, Q.A. and tests.

External resources shall be obtained through contracts and collaboration agreements with traditional partners:

-FSU (occasionally up to eight people): For package I activities mainly.

-UPAS from AGH, Cracow (5 people): For Package II and V.

-UPAS from IHEP, Protvino (4 people): For package III activities.

TE/MPE staff: For packages IV and V - and supervision of the other project packages.

The budget estimates related to the installation work amounts to 4.11 MCHF, with 3.60 MCHF for equipment, materials and consumables and 510 kCHF for the cost of external labor. The figures do not include the expenses related to the associated R&D.

Many on-going QPS issues are not included in the above project listing as they are meant to be completed and implemented before the long shutdown. This concerns the EMI sensitivity reduction campaign on all IPQ's and IPD's, de-commissioning of the eight 'global' busbar detectors (now obsolete), the '4L Undulator' upgrade for noise reduction and new reset procedure, the new closing procedure for the 600A extraction breakers and the improvement of the QPS acquisition tools.

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KICKERS AND DUMPS

V. Mertens, CERN, Geneva, Switzerland

Abstract

Envisaged major interventions on the systems under the responsibility of TE-ABT include the completion of the staged dilution kicker system in LSS6, upgrade of the extraction protection elements TCDQ and possibly the replacement of a number of injection kickers. The reliability overhaul of the extraction and dilution kicker generators will be completed, and numerous improvements of electronics and controls components of the various systems be carried out, followed by a thorough test and re-qualification programme.

DUMP SYSTEM

Several activities are foreseen on the beam dumping system, concerning the extraction kickers MKD, the dilution kickers MKB and the protection elements TCDQ. No modifications are presently planned on the dumps itself, i.e. the TDE absorbers with their associated gas handling system, vacuum windows etc.

MKD

Following the initial reliability run, which qualified the dump system kickers up to 7 TeV, a number of teething problems were discovered during the first year of operation. By carefully analysing the results of the post-operational checks slight deviations from the default values were observed, and traced back to various hardware problems in the MKD and MKB high voltage pulse generators. Using a wrong torque when tightening some of the high current connections led to contact erosion and a small but progressive drop of the magnetic field amplitude for a couple of kickers. The addition of a temperature stabilisation inside the generator cabinets (to reduce the variation of the GTO (= Gate Turn-off Thyristors) switch resistance, and thus variation of the magnet field strength, with the operating conditions), increased the risk for corona discharges (which could cause asynchronous dumps). The mechanism leading to this is not entirely clear; one interpretation is [1] that the forced air flow around the GTO stacks causes static charging on insulating pieces. Forced cooling has in the past also caused some condensation and corrosion on metallic parts in the vicinity of the air conditioning units; the working point has meanwhile been raised slightly above the ambient temperature.

Since the construction of the HV generators the specification for the mechanical pressure to be applied when assembling the stack of 10 GTOs (Fig. 1) has been revised downwards by the manufacturer, in the interest of longer component lifetime, from 24 to 20 kN. An improved trigger transformer is also under development which will allow injecting more current into the GTO gates, to ensure more reliable firing and again improve the lifetime of these devices.

A systematic overhaul programme to address the above issues was launched in 2010, to make the generators really fit for 7 TeV without struggling with a higher than expected failure rate or requiring excessive maintenance. Their present state enables reliable operation up to 4.5 TeV. During the various technical stops the 30 MKD and 16 MKB generators are successively replaced by modified spares; the outgoing generators are modified in turn in between the stops. To speed up this process, two additional MKD generators are being constructed (besides the two initial spares), and a second MKD test stand will be built in the new kicker laboratory in building 867. The overhaul programme will be completed during the long stop.

Figure 1: One of two HV switches of an MKD generator: GTO stack (centre), partly hidden behind the voltage distribution resistors; trigger transformer (right); snubber capacitors (left).

Considerations are also being made towards a higher number of GTOs per stack, to increase the margin against breakdowns caused by radiation. The voltage applied across the 10 GTOs at 7 TeV beam energy is about 29 kV. The maximum nominal voltage an individual GTO is able to withstand safely had been revised downwards but meanwhile restored by the manufacturer to 2.8 kV (DC voltage for 100 FIT at ambient cosmic radiation at sea level in open air; 1 FIT = 1 failure in 1e9 device hours). Tests are going on to assess the sensitivity of the GTOs to stray radiation that might leak through the cables ducts into the galleries where the generators are located. Very preliminary findings are rather positive [2], meaning that no or only few GTOs would need to be added per stack. It is noteworthy that in 2010 the increase in radiation from the operation of LHC, at the location of the generators, has been negligible [3]. In case the number of GTOs would need to be increased, up to 12 would still be compatible with the present mechanical layout of the generator cabinet; anything beyond that will require a major reworking. To note that the fabrication of GTOs with identical characteristics is also an activity with long lead time.

MKB

In 2001 it had been decided to stage the manufacturing and installation of the dilution kicker systems in time, because the full dilution was not required for LHC start-up. By now, 4 of the 5 MKB vacuum tanks are installed per beam; each tank comprises 2 magnets. The two remaining MKBV magnets per side are ready and will be installed in the long stop, along with the 4 last pulse generators. Without these two last magnets the dilution system is already sufficient for nominal beam (25 ns) at 7 TeV; the last two tanks will complete the system for ultimate intensity.

TCDQ

The protection element TCDQ (Fig. 2) is located upstream of the superconducting quadrupole Q4, and protects it and other downstream elements, in combination with a passive shielding TCDQM and another collimator TCS, against damage (quenches) in case of asynchronous dumps or excessive beam excursions.

The TCDQ features a total single sided absorber length of 6 m, all 1.77 g/cm^3 graphite, distributed over two vacuum tanks mounted on a mobile girder. The present TCDQ absorber design is based on the initial static mechanical stress analyses of the TCDS (fixed shielding in front of the extraction septa MSD; the TCDS design parameters were later revised to take also the dynamic stress results into account, and the TCDS were immediately built for ultimate beam intensity). The reassessment of the load to the TCDQ in various failure scenarios, together with the operational experience gained in 2010, led to the conclusion that the TCDQ needs to be upgraded to withstand the impact of bunches at higher energy and intensity. Approximate estimates of the maximum safe limit in the present configuration, for the case that 28 bunches at 7 TeV would impact on the TCDQ during an extraction sweep (asynchronous dump), range between 7e9 and 7e10 protons per bunch. A procedure is being devised to verify as far as possible the integrity of the TCDQ after beam incidents, without having to open the vacuum [4].

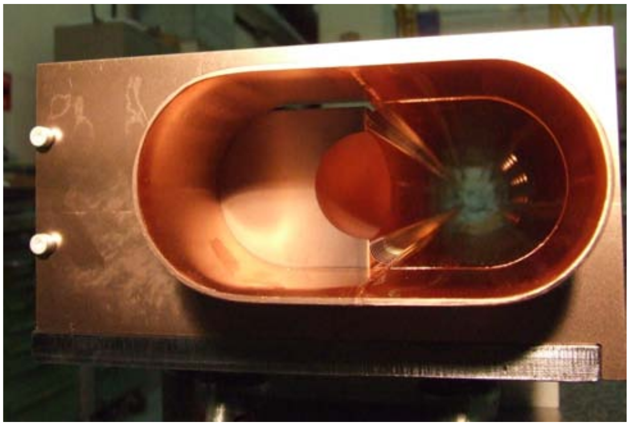

Figure 2: View inside a TCDQ, showing the copper coated tapered graphite jaw to the left. The beam circulates to the right and is shielded from the vacuum tank by a copper beam screen.

The time consuming simulations focus on a C-C absorber, assuming ultimate beam (1.7 p+/b, 25 ns, 7 TeV). Inquiries on the technical feasibility have been started with potential suppliers. Although the present design is deemed to be safe for 50 ns beam with nominal intensity it is desirable to increase the robustness of the TCDQ as soon as possible. If the simulations can be concluded in time and the diluter length does not need to be changed it seems possible to carry out the necessary swap in a short winter stop (2011/12); in the other case one would need one more year for re-design and construction (upgrade in a long stop in 2013).

INJECTION KICKERS

After the decision to increase the number of spares for the LHC injection kickers, two further magnets are presently under construction and should become ready for use in 2012, thus completing a full injection system comprising 4 magnets, Fig. 3.

Figure 3: MKI system in LSS8R.

Developments are going on to further improve the voltage holding of the beam screen, and thus to improve the margin against internal flashovers. The manufacturing of the 3 m long ceramic screen support tubes comprises many stages and is therefore a lengthy process. If the new tube version confirms the expected better performance all spare magnets will eventually be equipped with it. Depending on the work progress, the test results, and the operational problems encountered during the coming running period, these spare magnets could replace the operational kickers in future stops. While only up to 2 such replacements look feasible in a long stop in 2012, up to 4 MKI could ideally be upgraded in the course of 2013.

Modifications are also planned on the hydraulic pipework in between the MKI tanks (cooling of terminating resistors), to make all magnet positions compatible with using tanks fitted with 6 vacuum valves (i.e. spares which could be used in either LSS2 or LSS8).

ELECTRONICS AND CONTROLS

A large number of modifications and upgrades are planned on nearly all of the control systems of equipment under ABT responsibility. These are aimed at further improving performance, reliability and diagnostics capabilities. Examples include the modification of the dump system triggering logic for compensation of the turn-on delays over the complete energy range (induced by the decision to work at a fixed triggering voltage), the re-configuration of the low-level communication networks to increase the data transmission capabilities, and the deployment of a new version of the Trigger Synchronisation Unit (TSU) implementing the improvements recommended by a technical review. Regarding TCDQ the position and interlock logic, presently combined in the same programmable logic controller, will be split into 2 controllers which will be physically separated to reject the probability of common failures induced by single event upsets. The high voltage power supplies and high voltage dividers will also be recalibrated, if needed, to keep the system performance within specification.

In addition enhancements likely to be undertaken by CO, including the replacement of LynxOS by RT-Linux, the upgrade of VME CPUs, or the deployment of FESA version 3, must be accompanied at the equipment level.

After these modifications a thorough test and re-qualification programme will allow to confirm that all systems work well and safely. The pre-conditions for this testing phase, and the resulting constraints, must be carefully accounted for in the overall planning.

OTHER POTENTIAL WORKS

The addition of a TCT-like collimator, between TCDQM and Q4, has already been considered [5], but the need is not confirmed yet. Based on loss maps for higher intensities and new knowledge on the Q4 quench limits, such a device is supposed to gain a factor 2 in heat load on Q4 for steady state beam losses.

In 2007 a number of elements in LSS6 were installed with inverted tilt. Twelve of those have not been realigned yet (BPM, TCDS, TCDQ, BTVSE). The reading of the BPM has been corrected for in software, and the resulting aperture loss at the TCDS/Q (order of 0.1 – 0.2 mm) is considered marginal with respect to other error sources. Nevertheless, if the vacuum in the relevant zones will be opened anyway one day, the alignment should be corrected to bring it in agreement with the specifications and the corresponding documentation.

The electrical distribution of the AC-dipole in LSS4 (which uses the MKQA magnet to excite the beam) needs to be made more robust to avoid frequent tripping (re-arming the electricity requires tunnel access). The low-level control of the AC-dipole will also be reviewed to improve its integration into the MKQA controls and solve incompatibilities observed in case of failures.

GENERAL COMMENTS

The work mentioned above will compete for resources with other more standard LHC maintenance activities, not listed, as well as maintenance and project related tasks in other machines. Good planning across the complex should help optimising the use of the workforce and avoid too strong interferences.

Established procedures exist for nearly all of the above mentioned works, and practical experience has already been gathered in earlier interventions. The works should therefore not give surprises in the planning phase or during execution. The required services are typically well defined (see presentation).

The exact plan of interventions depends on the progress until the long stop. Part of the work is already ongoing (MKD overhaul), some parts with long lead-time are either under development (ceramic tubes for MKI), or the requirements need still to be confirmed (GTO stacks). The concrete work programme will also be conditioned by the workload from other activities, and could be affected by new problems which might surface in the meantime.

Most interventions are point-like in time and can be planned in where it fits best; some activities (MKD overhaul) will stretch over extended periods.

Besides unforeseeable mishaps the risks of undertaking the described work consist mainly in not finding easily back the expected performance (vacuum or high voltage). Experience shows that periods of intensive (co-)activity bear a risk by itself (e.g. accidental venting, transport incidents, stepping on equipment). High care should be exercised to preserve the performance of these devices which are vital for the LHC performance.

The risks of *not* doing the work consist in persisting limitations and progressive degradation of the performance (e.g. further contact erosion, requiring unscheduled interventions, or causing more frequent asynchronous dumps).

Postponing the long stop from 2012 to 2013 is likely to be an advantage in terms of ABT equipment, disregarding the foreseeable increase in radiation from the longer operation period (deemed relatively small), and any rapidly progressing performance degradation. It will enable to prepare more thoroughly – or render at all possible – a GTO upgrade of the MKD generators (should this turn out to be necessary), allow more MKIs to be prepared with improved beam screens (should these have significantly superior voltage holding capability), and prepare a layout change of the TCDQ (should this be required).

ACKNOWLEDGEMENTS

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LHC RF: PLANS FOR THE LONG 2012/13 SHUTDOWN

O. Brunner, on behalf of the RF group, CERN, Geneva, Switzerland.

Abstract

The potential limitations for future running of the LHC RF systems are presented. In particular the problems of trips, hardware failures and limitations encountered during 2010 operation period are discussed, with emphasize on the possible hardware modifications and upgrades during the next long shutdown. The main technical challenges as well as the consequences of delaying the shutdown from 2012 to 2013 are highlighted.

INTRODUCTION

In 2010 the energy of LHC has reached for the first time 3.5TeV. The experience gained with the ACS system together the big effort made to improve its reliability has resulted in good performances. The key problem this year was the klystron collector power limitation: all klystrons were limited to 7A and 50kV (instead of the nominal 8.4A, 58kV). A dedicated cavity field dephasing gymnastics was also implemented to limit the DC power in the collectors at injection.

The damper system (ADT) was also extensively used, and all the studies and measurements that could be made with all kind of beam configuration have allowed putting in evidence the good performance of this system. Lessons learned have also shown the reliability of the ADT system.

Some of the potential upgrades, or special maintenance operations, which have been identified during the 2010 operation period, can only be done in a long shutdown.

THE RF POWER SYSTEM

In LHC the RF power source required for each beam comprises eight 300 kW klystrons. The output power of each klystron is fed via a circulator and a waveguide line to the input coupler of a single-cell superconducting (SC) cavity. Four klystrons are powered by a 100 kV, 40 A AC/DC power converter, previously used for the operation of the LEP klystrons.

The HV interfaces are housed in fireproof bunkers in UX45 close to the four klystrons to be powered. It comprises a HV switch, a smoothing capacitor, a thyratron crowbar system and four hard tube modulators to individually adjust the klystron power.

For reasons of HV insulation and/or cooling all HV interface components with the exception of the smoothing capacitor are immersed in silicon oil.

Klystron modulators

The klystron current, and therefore the RF power, is controlled with a modulating anode. This HV control system is embedded in an oil tank which comprises the klystron heater transformer, measurements circuitry, and the modulation anode divider (see figure 1.)

The tetrodes which are used in the voltage divider scheme have a limited lifetime, and are no longer produced. A mid-term replacement solution is therefore necessary. Development of a modulator based on a solid state solution is ongoing and validation tests should take place in 2011.

The modulator upgrade can be done either in series, during a long shutdown, or progressively. The date of the next long shutdown is therefore not critical from this point of view.

Figure 1: Klystron modulator.

The fast protection system (crowbar)

The klystron fast protection system is based on a five-gap thyratron crowbar. In case of an arc occurring inside a klystron, due to the high d.c. operating voltage, the high voltage must be removed from the klystron within less than one microseconds in order to avoid damage.

The diversion of the HV energy is achieved by triggering the thyratron which then becomes conducting and acts as a short circuit to the HV power supply.

Double ended thyratrons require very fine adjustment and are very sensitive to noise. Although they are very reliable from the safety point of view, they suffer, from time to time, from auto-firing, which result in beam dumps.

A solid state replacement s under development and shall be tested during the year. Once fully validated, the crowbar upgrade solution could be implemented either in series, during a long shutdown, or progressively.

Oil re-conditioning

The oil insulating properties degrade with time. For this reason the silicon oil quality of the twenty-four 300 litres high voltage tanks is carefully checked every year. Reconditioning of the silicon oil must be done every 5 to 6 years. This operation cannot be done "in situ", in the LHC underground. All HV tanks must therefore be disconnected and transported to the surface for reconditioning, re-installed and re-tested. This time consuming operation must be done during a long shutdown.

Although the oil reconditioning should in principle be done next year at the latest, the tests performed recently have not shown any signs of oil quality degradation.

The klystron's collector saga

The premature death of a klystron, in 2007 –due to a severe vacuum leak in its collector-, as well as the sign of overheating observed on all other tubes (see figure 2), were found to be due to a bad design of the water cooling jacket, causing a local water speed deficiency. The so called hypervapotron mode, which is used in these collectors, is indeed not efficient for water speeds below 1.5 – 2 m/s. In the blue zone shown in figure 3 the water speed is less than 1.2 m/s.

Figure 2: Damaged collector.

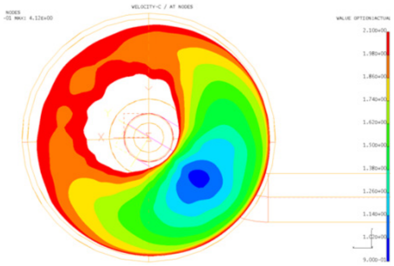

Figure 3: Water speed simulation in the collector region.

Modifications were made to the water cooling jacket by the klystron manufacturer in order to solve the problem and all boilers were replaced in 2008. Investigations made during the 2009 winter shutdown have shown that the situation was not perfect: slight overheating traces could still be observed. Decision was taken to limit the klystrons DC power to 50 kV and 8 A in 2010.

Further improvements were made and validated during the year 2010. Four klystrons have been equipped during the shutdown with the new "boilers". The other twelve tubes will be gradually upgraded during the next shutdown(s) (≈ three months).

THE SUPERCONDCUTING CAVITIES

The 16 superconducting cavities installed in LHC have performed very well in 2010. They have been responsible for a very small fraction of the RF trips. So far two activities have been identified for the next long shutdown:

Cavity tuning system

Following the rupture of one of the cavity tuning system cable in 2008, a campaign was launched to open all sixteen cryostats in order to check, modify and replace mechanical parts of the tuning systems.

Although no problem have been reported during the last operation period, careful inspection of -at least some- cavity tuning systems shall nonetheless be performed. The next long shutdown will be the right moment; whatever is will be in 2012 or 2013.

Cavity 3B2

Since the LHC start-up, in November 2009, a strong field limitation @ 2.2 MV is observed on cavity 3 beam 2 (3B2), leading to sharp helium pressure spikes and relatively high radiation levels.

This cavity is very stable below 1.2 MV, but has a rather unpredictable behaviour between 1.2 and 2.2 MV: long stability periods are interrupted by sudden He pressure spikes and temperatures increase of one of the four HOM antennas. Multipactor in the cavity equator region could be the culprit. Time is necessary to further investigate and try to re-condition this cavity. Eventual replacement of the full SC module could be envisaged for the next long shutdown.

TRANSVERSE DAMPERS (ADT'S)

Replacement of damaged pick up cables

The sixteen RF pick-up cables, which go from tunnel (Q7, Q9) to the SR4 building, at the surface, have been damaged during LHC installation (picture 4). Although the worst segments were replaced during the 2008/09 shutdown, the pick-up impulse response still suffers from periodic reflections: the signals are distorted and their quality is affected.

The impact on the ADT system performances may increase with short bunches spacing & high intensity beams. It is therefore of prime importance to replace these cables during the next long shutdown.

Figure 4: Damaged pick-up cable.

Transverse dampers upgrades

Three upgrades are linked to the next long shutdown:

- Additional pick-ups:

  The use of additional pick-ups (Q8, Q10 or warm section) will further reduction of the signal/noise performance of the whole ADT system. This implies pulling sixteen new cables from tunnel to SR4 (surface).

- Power amplifier RF drive cables:

  The crosstalk between bunches can be reduced by replacing these 3/8” by 7/8” cables. This is an important step towards stronger, cleaner & sharper pulses for abort gap cleaning for higher frequencies (up to 20MHz).

  This concerns 32 cables from UX45 to UX45 and 8 cables from UX45 to SR4 (surface). The integration of these cables is difficult and must still be studied in details.

- HOM observation & diagnostic system:

  This system is used to observe interaction between the transverse dampers and the beam, on a bunch to bunch basis. With better quality cables the signal quality will be improved. This is crucial for ADT setting up and diagnostics. As for the drive cables, 22 cables from UX45 to UX451 (ADTs) and 8 cables from UX45 to SR4 (surface) are concerned.

CONCLUSIONS

Several activities concerning the LHC RF systems have been identified for the next shutdowns. Some of them, e.g. the replacement of the damaged ADT pick-up cables, are very important and require a long shutdown. Postponing the next long shutdown by a year shall nevertheless not affect significantly the performances of the RF systems.

R2E RELOCATION AND SHIELDING ACTIVITIES

A. L. Perrot on behalf of the EN/MEF and R2E Project teams, CERN, Geneva, Switzerland

Abstract

In the framework of the R2E (Radiation to Electronics) mitigation project, relocation and shielding campaigns will be performed during the next long shutdown in parallel in Points 1, 5, 7 and 8. About 15 groups will be involved in these R2E activities with work periods from few days to several months. The baseline for these relocations and shielding installations is today defined. The status of the integration studies and their constraints will be discussed aiming for the different teams to be ready for the 2012 shutdown. The impact on the work achievement of a possible delay of the R2E activities by one year will be presented.

INTRODUCTION

The R2E Mitigation Project assists LHC operation and equipment owners with expert knowledge and assessments of radiation-induced failures in electronics. It is responsible to implement a mitigation plan to minimise radiation induced failures in electronics and respectively optimise the LHC operation. To that purpose different working groups are related to the R2E Mitigation Project. Amongst them, there are the Monitoring and Calculation Working Group (MCWG) and the Radiation Working Group (RadWG). The MCWG discusses FLUKA simulations and early measurements of the radiation levels around LHC. The RadWG helps the equipment owners to estimate their equipment failure rate due to Single Event Effect (SEE) though irradiation tests campaigns and is the forum in which radiation tolerant solutions are discussed. For what concerns the R2E mitigation Project, a crosschecking of the results of the MCWG with the RadWG allows identification of the equipment to be relocated [1, 2, 3, 4] and ensures that the best new locations for the shielding and equipment are found. In the framework of the R2E Mitigation Project the EN/MEF group is in charge of the relocation and shielding activities integration and implementation tasks [5].

The level of flux of hadrons with energy in the multi MeV range expected from the collisions at the interaction Points 1, 5 and 8 and from the collimation system at Point 7 will induce Single Event Error in the standard electronics present in many of the control equipment. Furthermore, a risk of SEEs induced by thermal neutrons cannot be excluded. Such events would perturb the LHC, possibly leading to a stop of the machine. The R2E Mitigation Project foresees to shield or to relocate into safer areas the sensitive equipment, in terms of hadron fluence / SEE, installed in these critical areas. These mitigations activities will have to be performed in parallel in Points 1, 5, 7 and 8 during the next long shutdown.

This document describes the strategy in terms of shielding and relocation proposed for reducing the SEE risk associated to equipment installed around Points 1, 5, 7 and 8.

RELOCATIONS AND SHIELDING

The levels of radiation expected from the collisions at Points 1, 5 and 8 and from the collimation system at Point 7 have been simulated with the FLUKA code for the beam conditions foreseen for the LHC operation between 2011 and 2014 and for the LHC nominal operation conditions [6-10]. In 2011, in UJ14/16, UJ56, UJ76 and US85, the flux of hadrons with E>20MeV will exceed 10^7 cm^{-2}. It would exceed 10^8 cm^{-2} per year in the operational period after the next long shutdown and even exceed 10^9 cm^{-2} per year in nominal operation conditions. In the RRs adjacent to Points 1, 5 and 7 the flux of hadrons with E>20MeV could reach up to 10^7 cm^{-2} in 2011 and exceed 10^8 cm^{-2} per year afterwards. At such levels, one does not expect any radiation damage resulting from the total ionising dose (corresponding values range from 0.05Gy to a few Gy/year). However, single particle energy deposition can induce changes in the data state of a memory cell, register or flip-flop. For comparison, at CNGS, SEE failures leading to the stop of the facility were observed for hadrons with E>20 MeV fluences of the order of 10^7 cm^{-2} per year.

Point 1

Sensitive equipment, in terms of hadron fluence /SEE, has been identified in the UJs and RRs on both sides of Point 1 [1]. The sensitive equipment, today located in UJs14/16, will be relocated into the ULs14/16 (see Figures 1a and 1b). The sensitive equipment located in the RRs will stay there (except the fire detectors) but its shielding will be improved, replacing the concrete walls

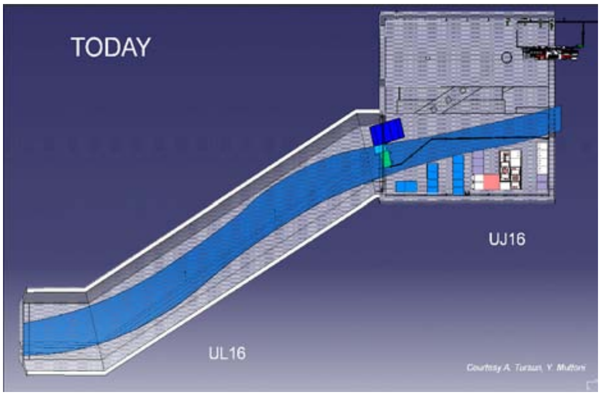

Figure 1a: Equipment location today in UJ16 (symmetric situation in UJ14).

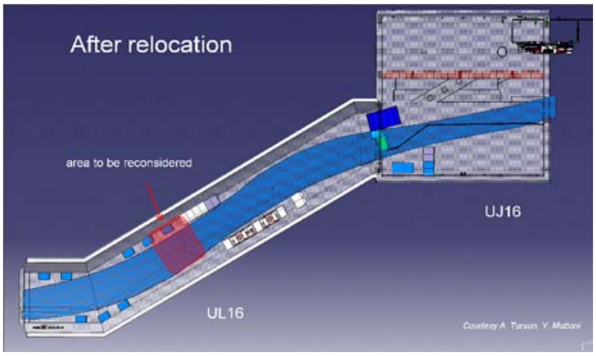

Figure 1b: Equipment after relocation in UL16 (symmetric situation in UL14).

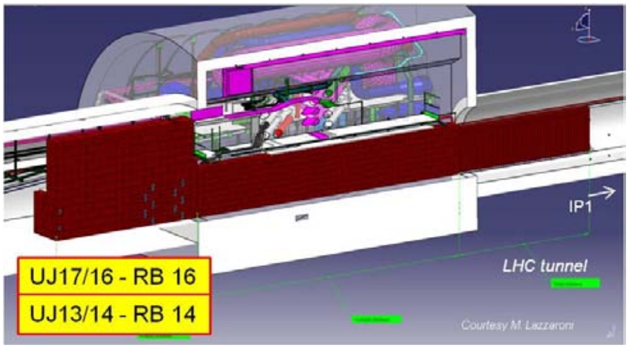

Figure 1c: New shielding implementation in UJs and RBs around Point 1.

by cast iron ones. 10 groups will be involved in the relocation activities at Point 1 during 7 months (see Table 1).

Additional cast iron shielding walls will be installed on both sides of Point 1 in the RBs and UJs (see Figure 1c). The overall shielding installation is estimated to 4 months for the EN/HE team. During the shielding activities in the RRs (3 weeks per RR), the access to RR and thus to the ARCs will not be possible.

Point 5

Most of the equipment installed on the first floor of the UJ56 and 5 racks of the UJ56 safe room (on the ground floor) has been identified as sensitive in terms of hadron fluence /SEE [2]. This equipment will be relocated inside the UJ561- bypass (see Figure 2). This relocation implies the following civil engineering work for cables and pipes passage; drilling 16m long ducts between the UJ56 first floor and the bypass; drilling holes between UJ56 first floor and LHC tunnel and drilling holes in the separation wall of the UJ561. 12 groups will be involved in the relocation activities of Point 5 during 15 months. This period estimation takes into account that the EN/EL team will work on a 2 shifts/day basis during 12 months (see Table 1).

Similar to Point 1, the existing concrete shielding walls in the RRs will be dismantled and replaced by cast iron ones. The overall shielding installation is estimated to take 2 months for EN/HE team. During the activities in the RRs (4 weeks per RR), the access to the RR and thus to the ARC will not be possible.

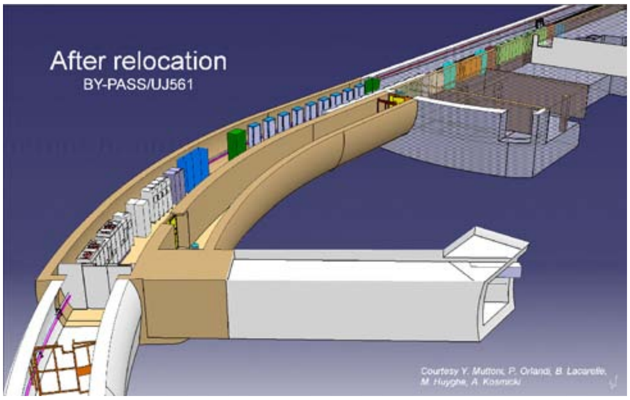

Figure 2: Equipment relocated in the by-pass/UJ561.

Point 7

Most of the equipment installed on the first floor of the UJ76 and 5 racks of the UJ76 safe room (on the ground floor) has been identified as sensitive in terms of hadron fluence /SEE [3]. This equipment will be relocated inside the TZ76 (see Figure 3). 11 groups will be involved in these relocation activities during 10 months (see Table 1).

Additional shielding walls have already been implemented in the UJ76 and in the RRs [11, 12].

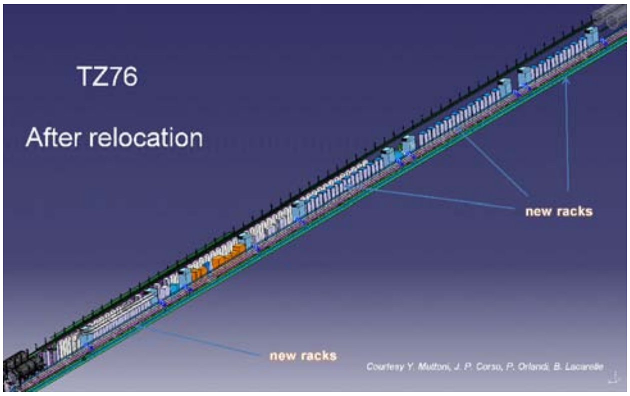

Figure 3: Equipment after its relocation in the TZ76.

Point 8

Equipment located in the US85 (on the first and second floors) has been identified as sensitive in terms of hadron fluence / SEE [4]. This equipment will be relocated in the US85 on ground floor, in the ULs84/86 and in the UA83. 7 groups will be involved in these relocations during 10 months (see Table 1).

An additional cast iron shielding wall with a movable chicane will be installed in the US85 at the ground floor (see Figure 4). It will protect the cooling and ventilation equipment located in the UW85 and cryogenics equipment relocated in the US85 on the ground floor. Due to technical constraints it was not possible to relocate this cryogenics equipment further away. The installation of the

Table 1: Teams involved into the R2E relocation and shielding activities with the estimated duration of their respective activities in Points 1, 5, 7 and 8 (as provided by the responsible groups).

	Equipment / activity	Point 1 activity [weeks]	Point 5 activity [weeks]	Point 7 activity [weeks]	Point 8 activity [weeks]
BE/APB	survey eqpt.	-	3	-	-
BE/BI	BTV, BLM	-	-	1	-
BE/CO	timing & remote-reset WorldFip	<1 -	<1 1	<1 1	<1 1
DGS/RP	RAMSES	-	-	2	-
EN/CV	cooling/ventilation eqpt	3	10	8	8
EN/EL	electrical eqpt & cabling activity	25	52 (2 shifts)	25	16
EN/HE	eqpt. transport shielding inst.	2 19	3 9	2 done	1 2
EN/STI	collimator control eqpt	6	5	-	-
GS/ASE	fire/ODH access	5 -	6 6	4 6	done -
GS/SE-CE	duct activities	-	11	-	-
IT/CS	ethernet	t.b.c.	2	t.b.d.	2
TE/CRG	cryogenics eqpt	7	6	6	4
TE/EPC	power converters	9	9	2	-
TE/MPE	QPS* PIC* current leads heaters BIS WIC	1 <1 6 - -	1 <1 3 <1 -	- - - - -	- - - - 3
TE/VSC	vacuum eqpt	-	-	9	-

* additional re-commissioning during the hardware re-commissioning and powering

shielding is estimated to 2 weeks for the EN/HE team.

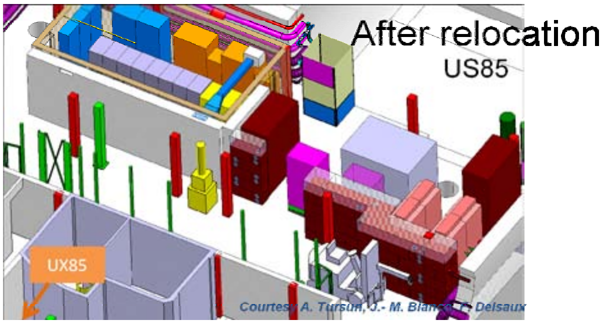

Figure 4: US85 after relocation and shielding installation.

OPEN ITEMS

Integration study update

During investigation into a possible direct contribution of the UX15 (ATLAS experimental cavern) to the radiation levels in the ULs the MCWG noticed that the wall thickness between UX15/ULs used in previous simulations (according to provided specifications) was thicker than the reality (3 m instead of the real 1.4 m). New simulations have thus been performed at the end of 2010 pointing out an area in the ULs with a hadron fluence above 10^7 cm^{-2} (see Figure 1b), in which SEE occurrence in sensitive equipment may be important [10]. To cross-check these simulation results, RadMon dosimeters have been installed in the UX at the end of 2010. Depending on the LHC operation, the first set of measurements will be available in June 2011. In the integration study performed in summer 2010, it has been proposed to relocate equipment in the ULs and especially in this sensitive area. To be ready for 2012 long shutdown, R2E has decided to review the integration study at Point 1, taking into account the removal of all equipment from this newly defined sensitive area. After the interpretation of the RadMon dosimeters measurements, most probably at the beginning of summer 2011, the relocation strategy will be chosen between the two available options. It may occur that the cables with require a long purchase delay would have to be ordered before the results of the measurements would be known.

'Safe rooms'

The AUG, anti-panic lightning and general electric network control equipment have been identified as sensitive in term of hadron fluence/SEE. This equipment, today located in the UJ56 and UJ76 safe rooms, has to be relocated in the UJ561- bypass and TZ76. Due to space constraints, the implementation of a 'safe room' in the existing TZ76 gallery is not possible. The only possibility would imply long and costly civil engineering work. Before launching such an activity, R2E together with DGS/SEE and EN/EL have launched studies to find out if the equipment could be relocated without the creation of an equivalent 'safe room'. It has been agreed that DG/SEE will study the existing fire risk in a safe room and in the TZ76, taking into account all the equipment to be relocated. EN/EL has agreed to study the technical feasibility of the relocation and the technical functionality after the relocation. The conclusions of both 'safe room' studies will be discussed within R2E and then a proposal for the relocation of the 'safe rooms' equipment will be submitted to the LMC. Once approved, R2E will provide a new updated integration solution for Points 5 and 7. Today a compromise has been found for Point 5 with the implementation of a 'mini safe room' with siporex walls which are fire resistant up to 2 hours.

CRITICAL DATES

Long shutdown in 2012

The ordering process of the water cooled cables for the power converters to be relocated drives the critical date for the activities in Points 1 and 5. EN/EL estimates this process to be 10 months long. To be ready for the 2012 long shutdown, the relocations integration studies of Points 1 and 5 have thus to be finalised by the end of February 2011.

Following the conclusions of the 'safe rooms' studies, the relocation integration study of Point 7 will have to be reviewed. If the decision is to relocate the racks to a location without a 'safe room' equivalent fire protection, the separation wall along the TZ76 would have to be removed to allow the relocation. This activity is categorised as 'minor' civil engineering work. GS/SE estimates that it will take 9 months to define the work, find a firm and be ready for intervention. Therefore to be ready for the 2012 long shutdown the integration study would have to be finalised by the end of March 2011 and the 'safe rooms' studies delivered before March 2011. If the decision is to relocate the racks to a location with a 'safe room' equivalent fire protection, a new excavation would be needed. This activity is categorised as 'major' civil engineering work. GS/SE estimates that it will take 18 months to define the work, find a firm and be ready for intervention. In this case, it is impossible to be ready for 2012.

All the remaining cast iron blocks required for the construction of the different shielding walls will be delivered to CERN by the end of 2011. The purchase process has already been launched.

Long shutdown in 2013

Even if the start of the long shutdown is postponed by one year, the R2E project has decided to keep 2012 as a target to be able to intervene if necessary all along 2012. An actions plan for the 2011-2012 'Christmas break' will be defined anticipating work. The goal is to anticipate when possible the relocation of the most sensitive equipment and already install shielding walls.

To be ready in Point 7 for the 2013 long shutdown the integration study of the 'major' civil engineering scenario has to be finalised by the end of June 2011 and the 'safe rooms' studies' conclusions have thus to be delivered before June 2011.

SUMMARY

The R2E relocation and shielding activities will be performed by 15 groups working in parallel in Points 1, 5, 7 and 8. The relocations activities in Point 5 are estimated to be the most important in term of time with 15 months of work. Due to a possible radiation leakage from the UX15 to the adjacent UL, the relocation integration study of Point 1 has to be reviewed. 'Safe rooms' studies by DG/SEE and EN/EL will impact on the relocations integration in Points 5 and 7. Without them a final optimised solution cannot be found in Point 7. Keeping the present work effort, R2E relocation and shielding activities may be performed during a long shutdown in 2012 in Points 1, 5 and 8. For Point 7, the conclusions of the 'safe rooms' studies are the driving factor. If 'major' civil engineering work is required then it will not be possible to implement the full relocation in Point 7 in 2012. The R2E project management keeps 2012 as its target even if the long shutdown is postponed to 2013.

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The author is grateful to the equipment owners, the colleagues of EN/EL, EN/CV, EN/HE, EN/MEF, the LHC integration team and the R2E team for numerous discussions and their contributions.

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CV ACTIVITIES ON LHC COMPLEX DURING THE LONG SHUTDOWN

M. Nonis, Y. Body, M. Obrecht, S. Moccia, G. Peon, S. Deleval, CERN, Geneva, Switzerland.

Abstract

The presentation gives an overview of the major projects and work foreseen to be performed during next long shutdown on cooling and ventilation plants. Several projects are needed following the experience of the last years when LHC was running, in particular the modifications in the water cooling circuits presently in overflow. Some other projects are linked to the CV consolidation plan. Finally, most of the work shall be done to respond to additional requests: SR buildings air conditioning, the need to be able to clean and maintain the LHC cooling towers without a complete stop of cooling circuits, the upgrade of the air conditioning of the CCC rack room cooling etc. For all these activities, the author will detail constraints and the impact on the schedule and on the operation of the plants that will however need to run for most of the shutdown duration. The consequence of postponing the long shutdown from 2012 to 2013 will be also covered. .

MAINTENANCE

During the long shutdown, one of the main activities will be the maintenance of the CV equipment. An important part of the maintenance has not been done for the last years because of the non abilities to stop the cooling plant.

. Table 1: Status of the maintenance for the CV equipment

Equipment	Maintenance done	Maintenance not done	1/1/2012 Missing since
Cooling	Cleaning of the cooling tower Mechanical maintenance	Safety test Instrumentation Electrical maintenance. Test alarm transmission	3 years
Ventilation underground units	Filters and belts replacement	Instrumentation Mechanical maintenance Electrical maintenance. Test alarm transmission	2 years
Ventilation on the surface, sump, and compressed air.	Complete maintenance	-	1 year

For example for the primary circuit only 3 days stop have been allowed to respect the legal requirement [4] to avoid legionella growth in the cooling towers. This allows CV to stop the plant, drain it down, clean it and refill it but not to maintain it properly. In table 1 there is a status of the maintenance which has or hasn't been done for the last years.

To be able to restore a normal situation a stop of the cooling circuits for about 4 weeks per point during the long shutdown is needed. For the underground ventilation units an access for 2 weeks per points is mandatory.

PROJECT

During the long shutdown, several projects are to be completed. In the table 2 the number of project for CV, between 2011 and 2017 is detailed. The important list of project represent 87 projects for 6 years, 37 of which are presently foreseen in 2011 and 2012 in case if the long shutdown is in 2012. In case the long shutdown is in 2013 the distribution will be changed but the achievement of those projects is not affected. It is worth to remind that each project might include work activities in several LHC (or SPS) Points

Table 2: Number of project for CV between 2011 and 2017

Type	Example	Number of project
Upgrade	UW, CCR, Chilled water point 2	18
New installation	Linac 4, critical power 513, CMS clean room, Isolde, bldg 107	21
Original CV Consolidation plan [1]	PM32, PS and Booster ventilation	36
Consolidation (25 years)	Cooling of the PS magnet and Central bldg	12

In the next paragraphs several of those projects will be detailed.

UW upgrade

One important upgrade issue is related to the LHC cooling sector which is cooling most of the underground equipment (power converter, cooled cable, collimator, alcoves, etc.) During the LHC installation phase it's been decided not to buy the redundant pump for budgetary reasons. Those pumps have been bought in 2009 but there has been no opportunity to install them. In addition, a too high consumption from users with respect to design values is noted. In the table 3 the percentage of overflow measured by sector is given; some of these circuits are presently at the limit of their working conditions and major breaks might appear.

Table3: Measured overflow in the cooling secondary circuits in the underground

Cooling sector	Present overflow
Sector 1-2	30 %
Sector 2-3	18%
Sector 3-4	38%
Sector 4-5	9%
Sector 5-6	18%
Sector 6-7	0%
Sector 7-8	25%
Sector 8-1	17%

To restore good working condition of the installation, four motor pumps have to be replaced. The integration of the future need for collimators is included. The onsite work should take 8 months with 6 weeks of stop per circuit. It’s been estimated to 850 kCHF.

Backup for the primary cooling of the LHC cryo

The aim of this project is to provide backup cooling water for the LHC cryo systems during the cooling towers maintenance at Point 4, 6, 8. The solution proposed will allow to keep in operation critical cryo equipment housed in the SHs buildings (like compressors, cold boxes etc.), resulting in highly reduced thermal cycling, improved durability of the whole cryogenic systems and faster restart of the LHC operations. For the point 2 there is no need to create a backup system as the two cryo plants are already cooled by two separate primary circuits connected to SF2 and to the SPS loop. The proposed solution for Point 6 and 8 foresees the installation of a backup system with its own open cooling towers and pumping system in the proximity of each of the SF’s buildings and the connection to the existing main primary water system. Isolation valves will allow switching from the original system to the backup system when needed.

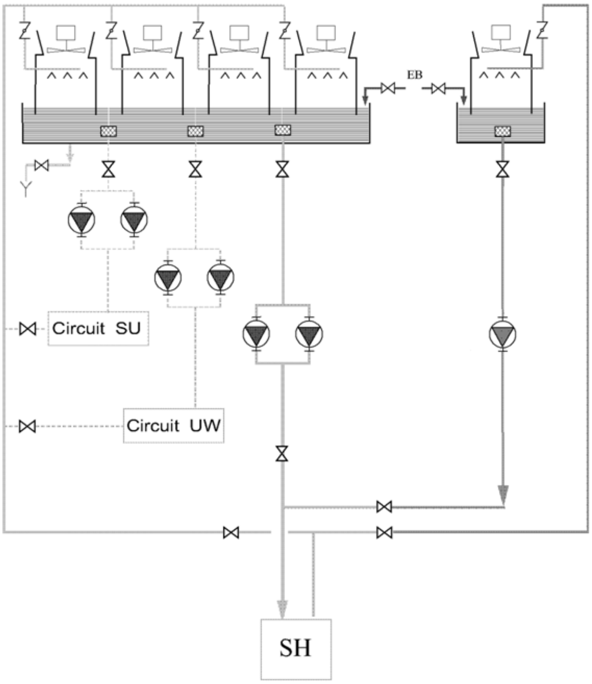

Figure 1: Layout of backup primary cooling for point 6 and 8

The backup system shares with the main system only the piping that goes to the SHs, while filters, heaters, pumps, piping accessories, electricity and controls are completely independent. This solution will allow, in addition, to carry out all the functional and safety tests of the main primary water system components (mainly the pumps) after the cooling towers have been cleaned. For the primary cooling in point 4 the present installation is different (closed circuit) and the use of an open cooling tower is therefore forbidden. The duration of the work will be 3 months per point with 2 weeks stop of the cryo. The project has been estimated to 3.6 MCHF.

Backup for the primary cooling of ATLAS

The aim of the project is to provide a primary water cooling backup for Point 1 during the SF1 cooling towers maintenance for cryogenic plants and part of the ATLAS detector. The proposed solution foresees to use the SPS primary water cooling loop as backup. In order to connect the SPS and SF1 system, it is planned to connect to the SPS loop close to BA6 building using the tappings originally used for BA6 and ensure therefore a backup solution for SH, USA and SUX buildings.

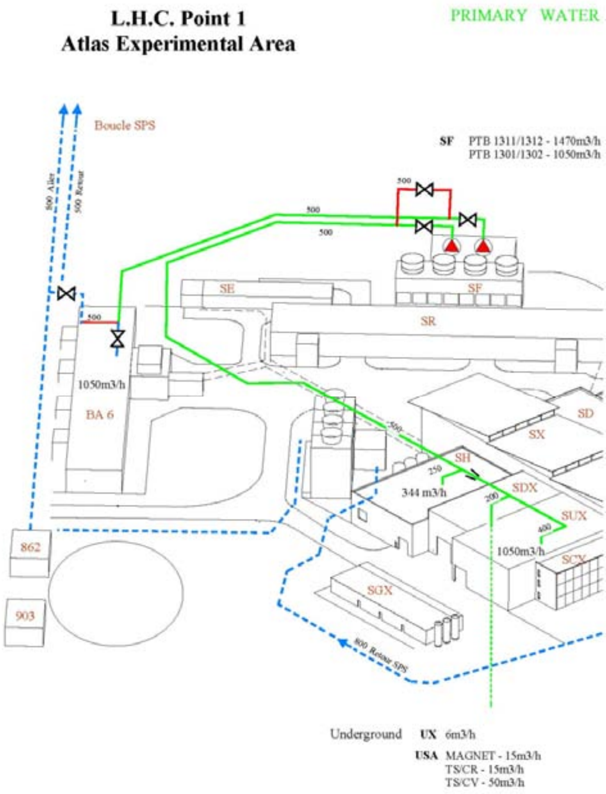

Figure 2: Layout of backup primary cooling for ATLAS connexion with the SPS ring

The duration of the work will be 4 months with 4 weeks complete stop of ATLAS cooling.

CCC upgrade

The aim of the project is to remove the dependency from the BA3 chilled water which is always a problem for example to perform the AUG test. Another objective of this project is to increase the cooling capacity of the rack room. In addition, the objective is to improve the reliability by having a redundant system to resist to possible power cuts. The project consists of adding a redundant chilled water production dedicated to the rack room. The modification of the electrical supply with new UPS and diesel, the installation of new air handling units and mixed water cooling the rack in the CCR is also foreseen. For CV the work should take 6 months with one month of total cooling stop in the rack room. For the CV work it has been estimated to 2 MCHF without civil engineering costs. The objective is to perform as much work as possible in advance of the long shutdown in order to minimize the workload during the shutdown.

Upgrade of the primary cooling in point 4

The primary circuit in Pt 4 for RF and cryogenic equipment consist of three distribution pumps but no spare pump is available. In case of failure on one of those pumps, motor or flow switches will affect the cryo and the RF and therefore stop the LHC. The risk is estimated as high. To reduce the risk a standby pump has to be added; in addition, frequency speed drive will be implemented and allowing a reduction of the energy consumption; this part shall be partly financed by EDF.

Upgrade of the chilled water production in point 2

The chilled water production is overloaded and can provide the required temperature in summer without any redundant chillers. The aim of the project is to increase to capacity of chilled water production by adding new chillers. The connexion has already been done but for the test of the new installation a stop of the whole production will be needed anyway.

Overpressure in point 8 tunnel vs LHCb

This project which has already been detailed in the Chamonix workshop 2010 [2] is foreseen during the long shutdown. The project consists of creating ventilated sas in RB84 and RB86 to avoid having the tunnel in overpressure with respect to the UX85.

Monitoring of the air in the LHC tunnel

The project has already been detailed in the Chamonix workshop 2010 [2] is also foreseen for the long shutdown and consists of adding air speed, differential pressure and temperature sensors in the tunnel.

PM32: Evacuation of the underground water

This project which is in the original CV consolidation plan [1] since several years has to take place during the long shutdown. There are no available spare parts for the old control system and with the new access constraint the manual intervention to remove the sand can’t be done while the LHC is running. At the present 6 submerged vertical pumps are installed. Water collected in the pit is lightly charged with very fine sand. Furthermore the geometry of the pit and the pumps location inside it, allow the sand to separate from the water and to pile up on the bottom of the pit. After a while the sand cannot be evacuated anymore and clogs the pumps. In order to recover to correct working conditions, about 4 m^3 of sand have to be removed by hand every 3 months. The proposed solution foresees to modify the geometry of the pit by adding a 3D (diamond point shaped) inclination of the pit bottom in order to continuously direct the incoming water towards a pipe that is connected to a manifold feeding three dry pumps that will lift the water to the surface using the original piping. This way, the sand doesn't have the time to separate from the water and the stagnation points are eliminated. If one dry pump fails, the water overflows towards the side where the original backup pumps are.

SR building ventilation refurbishment

This project is foreseen in the original CV consolidation plan [1] with a lower priority since, during the LHC design phase, the SR building was considered not critical and therefore no cooling was foreseen for that building [3].During 2010 run, it has been remarked that any temperature variation in the building affects the BLM and then the LHC beam. The refurbishment of the SR ventilation system has therefore to be done in next long shutdown. The project includes the replacement of the control cubicle and the electrical parts but also the instrumentation and several mechanical parts of the existing units.

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The EN/EL activities during the next long shutdown

F. Duval, CERN, Geneva, Switzerland.

Abstract

The EL group will participate in many activities during the next long shutdown. They are divided in four categories:

- Projects which require an extension or modification of the distribution network.
- Consolidation work of the electrical distribution infrastructure led by EN/EL.
- Scheduled maintenance activities and, in addition, the maintenance activities postponed since the start of the LHC.
- Many upgrades of EN/EL infrastructure following an evolution of the power request (from EN/EL or other groups).

It should be noticed that so far, we know only a small part of the work for which we will be involved. Indeed, projects must be sufficiently defined by our colleagues before submitting us their request.

Furthermore, it should be noted that the decision to delay from 2012 to 2013 the long shutdown will lead to a schedule change of some projects and will increase the risk of failure of EN/EL equipment due to a lack of maintenance. This postponement of the long shutdown will be preceded by an additional Christmas break; we hope it will be longer than the past two. The work program is too tight and leaves us no time to repair any defects found during the various tests and increases our rate of human mistakes.

INTRODUCTION

The EN/EL group activity volume will be multiplied by about 4 during the next long shutdown as seen by the past. This increase is made possible through the group's experience to handle such situations by converting part of its capacity to run studies into capacity to lead worksites and also with our subcontractors who know how to increase their manpower in such a ratio keeping a good level of professionalism.

The group's activities during the next shutdown are shared between maintenance activities and projects. Some projects are carried out by our colleagues who “subcontract” to EN/EL the cabling, optical fibre installation or even a modification in our distribution network required by the project. EN/EL also conducts its own projects to consolidate its infrastructure mainly because of the obsolescence of some equipment. Moreover, the evolution of the needs for the organization led us to reorganize our network, to upgrade it in order to meet these new requests.

Finally, many requests have not been received by EN/EL yet; except the last-minute requests that might be anticipated, it is a bit early for most of our users. Their projects have not yet reached the point that they can define precisely their needs in term of cabling and in terms of necessary additional power.

PROJECTS

Under the project R2E, EN/EL will be responsible for moving approximately 80 racks (re-cabling operations included) outside areas where the radiation level might affect the operation of equipment. LHC points 1, 5, 7 and 8 are involved. Most of equipment installed in the safe room is concerned; because of the lack of available space, the concept of "safe room" (resistance to fire for 2 hours minimum) will be redefined. Besides the lack of space to relocate equipment, we also face the problem of finding space for the new cables and their trays. An important part of the work will be to run the functional tests after relocation. The estimated budget for this project is about 5MCHF.

Just after installation in 2008, the water cooled cables in the LHC started showing signs of unexpected deterioration. These cables are made of a small section of conductor located inside a hose made of reinforced rubber similar to the technology used for car tires. The circulation of a cooling fluid in the hose provides an acceptable temperature of the conductor. After various tests we realized that the hoses show evident manufacturing defects. Negotiations are underway with the manufacturer. Without waiting the outcome of the discussions, EN/EL foresees to replace more than 3 km of these hoses in the sector whose signs of deterioration (cracks) are worse than others; we identify those located in points 4, 6 and 8 of the LHC. The replacement work will be followed by a complete campaign of tests (hydraulic, mechanical and electrical) before re-commissioning operations.

The UPSs are used to eliminate glitches and to provide power supply during mains losses for a limited time (depending on the size of the batteries). In the LHC tunnel, 74 UPS Silcon have been installed in 2004. At this time they were about to be withdrawn from the market, replaced by newer models. In addition, Silcon was taken over by APC and recently, APC was acquired by its competitor MGE UPS of Schneider Electric. This information seems to be trivial but has generated a complete loss of competence from our supplier. Furthermore, the availability of spare parts is now uncertain. Our statistics show that these machines present worrying signs of decline: the unavailability rate is two times higher than for competitors UPSs which are even on average more than 10 years old. Each incident on these UPSs requires human intervention in the tunnel for inspection and, possibly for the replacement of the faulty component. We have a plan to replace these machines. This plan will include the modification of the downstream circuit meeting new model requirements and meeting users requirement (e.g. QPS distribution). It includes the implementation of the supervision of the equipment and the commissioning tests as well. A quick estimate shows that the cost of such an operation would be around 6MCHF.

The above three projects are mainly held in the tunnel and must be programmed during a shutdown.

The following projects do not require intervention in the tunnel but have an impact on the LHC operation. Part of the work can be carried out outside the shutdown period, but the connections and most of the final tests should be performed when the accelerators are stopped.

In the Computer Center (bldg 513), IT has to face problems of autonomy during power losses of normal network. IT has to also face a lack of redundancy of the infrastructure and they have to face a sharp increase of power needs up to 3,5MW (mainly for critical loads). The critical loads are supplied via the safety network (powered by diesel generators) through a UPS, which ensures an uninterruptible power supply unlimited (except by the size of diesel generator's fuel tank). The other loads called "physical" are supplied by the normal network through UPS to ensure uninterrupted power with battery autonomy of 10 minutes in case of loss of the normal network. The project consists mainly of significant changes in civil engineering and cooling systems in bldg 513, of the addition of two cubicles on the dedicated 18kV substation, of two 18kV power transformers and of two UPS systems (for a total of 9 modules 400KVA) with their 4 low voltage switchboards. This project is running from December 2010 until June 2012. The project Budget is 10.5MCHF.

The CERN Control Center (CCC) is powered from a dedicated electrical substation called SE0. This supply is guaranteeing uninterrupted power from the safety network through an UPS system. But the required redundancies for maintenance operation to avoid a potential failure are not sufficient. Furthermore, the EN/CV infrastructure have insufficient autonomy, they depend for part of the building 870 distribution infrastructure. The cooling power is no longer sufficient and the ventilation in the CCR must be modernized. For this, a project of consolidation and modernization is being finalized. This project will include:

- The redundancy of electrical installations since the safety network which supplies the CCR machine room and EN/CV facilities via diesel generators. This redundancy includes the UPSs and control distribution 48Vdc. This redundancy will allow the annual maintenance operation during the CCC operation.
- A new cooling and ventilation infrastructure taking advantage of the new distribution scheme.
- A new building for EN/CV and EN/EL infrastructure.

The project will start before the long shutdown but will require a stop of the CCC and therefore the LHC and its injectors. The project will be led by EN/EL, EN/CV and GS/SEM, the budget is estimation is around 5MCHF excluding the civil engineering costs (study ongoing).

CONSOLIDATION OF EL INFRASTRUCTURE

The consolidation of electric power distribution facilities for the next 15 years will be described in a document to be published soon. The first phase will be run until the next long shutdown and consists of 4 main activities:

- The 66kV protection system is about 25 years old and shows more and more its decline especially due to aging electronic components. It will be replaced by a modern system that will, in addition, implement modern features such as digital interlock and block for a better selectivity. The studies and manufacturing of components for this project will take place during operation of the machines. But the installation and the final testing will require the substation stop and will take place during the next long shutdown.
- The required power (especially from the safety network) for the installation of the CCC upgraded (see above) leads us to design and build a new substation for normal power distribution and a power generation system in order to increase the safety available power.
- The first step in the renovation of obsolete equipment in Meyrin site will start by replacing the substation SW (ME59) (commissioned in 1968) located in the basement of bldg 112. This new substation will be powered by a new power supply via a 66/18kV transformer located just outside the existing substation. This transformer will be powered by the main 66kV substation in Prévessin site, using a new cable link which will be installed together with the consolidation works of SPS cable (see below).
- After the installation of buried cables to replace the stable and pulsed loops and the SMB power supplies cables in 2011, the consolidation of the SPS infrastructure will continue in 2013 with the installation of complete modern substations (including their protection system, power supplies 48Vdc for the control circuits, etc.). 4 substations will be renewed, located in points 1, 2, 4 and 5 of the SPS.

The budget for the long shutdown activities on this project will be around 10MCHF.

MAINTENANCE

Since the start of the LHC, many maintenance operations were delayed: the RTE requests for the Bois-Tollot substation and the OHL 400kV line Génissiat/Bois-Tollot which is the only to supply full power to CERN. The scheduled maintenance of the main power plant 400kV and 66 kV including the power transformers have also been postponed twice. All these activities, in addition to the scheduled operations, will be run during the next long shutdown.

More than 10 faulty circuit breakers were identified during AUG tests last December. After a tripping signal, the trip was delayed; 150mS for some, 1 minute for other and even worse for some others. The tripping mechanism was clogged by old dried lubricant.

UPGRADE PROJECTS

Many small or medium CERN projects lead to a need for upgrading EN/EL infrastructure such as changing the capacity of switchboards, of a cable or of a circuit breaker.

The main upgrade project concerns the PLCs used for an automatic reconfiguration of LHC network. They are mostly used on the auto-transfert, the connection of the diesel generator to the network or for UPS load shedding. Most of the PLCs have been installed in the 90s for LEP and are aged of twenty years of service and must be replaced. Furthermore, these PLCs must be reprogrammed to take in account network changes since their installation and to address the need of a homogeneous solution for the LHC.

SHUTDOWN POSTPONED TO 2013: IMPACT ON EN/EL

The failure rate will increase.

- At the SPS there has been no irradiated cables replacement campaign (formerly 1/7 of total per year) since 2009.
- Due to a lack of tests and maintenance (400kV substation, UPS for QPS, etc.). A failure of this type could lead to a major event.

Several projects will have to be rescheduled.

- IT bldg 513 upgrade.
- CCC powering upgrade.
- EL infrastructure consolidation (new substations commissioning).

A new Christmas break will be held by the end of 2011.

EN/EL is requesting to have a longer break because we have learned from the previous breaks that:

- The time schedule is too tight.
- The workload during tests led to an increased rate of human mistakes.
- No time available for repairs (even small) on fault detected during tests.
- The program is jeopardized by many "urgent" last minute requests.

ACCESS AND ALARM SAFETY SYSTEMS – ACTIVITIES FOR THE 2012/2013 LONG SHUTDOWN*

S.Grau, C.Delamare, T.Ladzinski, P.Ninin, R. Nunes, CERN, Geneva, Switzerland.

Abstract

This paper presents the 2012/2013 long shutdown activities for the access, emergency evacuation, gas and fire detection systems. First, an overview of the required minimal annual maintenance and tests is presented; including the first feedback from the 9 weeks of the Technical Stop. Second, planned upgrades, new installations and consolidation activities, such as the R2E relocations and systems improvements, are discussed. For all these activities, the required resources are estimated, the constraints on other groups are listed, the associated risks analyzed and time estimation provided. The evaluation of the required resources takes into consideration the activities in the injector chain during the long shutdown.

ALARMS SYSTEMS

This chapter describes the long shutdown activities for the fire and gas detection systems, the emergency evacuation and beam imminent warning systems and for the SNIFFER systems (the combined fire and gas detection systems for the LHC Experiments). Maintenance activities are presented first, followed by the consolidation activities.

Activities discussed concern alarm system's preventive and recurrent maintenance operations. Preventive maintenance shall be performed at least on an annual basis [1]. Quarterly maintenances are not compulsory but they are important to minimise spurious alarms and identify latent faults. A non execution of preventive maintenance would lead to an accumulation of latent faults and therefore to a reduction of safety and, most probably to an increase of physics downtime.

Annual preventive maintenance covers three main operations. First, a visual inspection of the system components to verify their physical external status is correct. Second, a functional test to verify that equipment is working as expected. This point includes an alarm test with the triggering of all sensors thresholds, the generation of all alarms and defaults and their transmission through the CERN Safety Alarm Monitoring system (CSAM) to the CERN Safety Control Room (SCR).Third, the replacement and repair of components when necessary.

Automatic Fire Detection Systems

Two activities are foreseen in the long shutdown for the automatic fire detection systems, the preventive maintenance and the relocation of smoke detectors in critical radiation areas (R2E activities).

Annual and quarterly preventive maintenance are foreseen for the long shutdown. Quarterly maintenance is especially important for air sampling smoke detectors to clean the accumulated dust in the air sampling networks and minimise spurious alarms during the operation.

If the long shutdown is delayed to 2013, the annual maintenance for underground installations would be performed during the 9 weeks of Xmas Break, and quarterly maintenance during the Technical Stops.

This planning is realistic only if the inter-site doors are open. The sectorisation of the alarm systems does not correspond to the sectorisation of the inter-site access doors. Therefore, when executing the maintenance on a site it is required to pass beyond the adjacent sector's inter-site doors to complete the maintenance. This constraint affects not only the fire but also the gas and the emergency evacuation systems. A conclusion from the 2010 Xmas Break is that 9 weeks with the inter-site doors opened would be more adequate to complete the alarm system's annual maintenances, before the hardware commissioning phases start.

For surface installations, the preventive annual and quarterly maintenance is to be performed during the Run and the Technical Stops.

In the context of R2E activities, the relocation of air sampling smoke detectors in critical radiation areas is foreseen.

Table 1: R2E smoke detectors relocation

Current location	Future location	Number of fire detectors
RR13/17	UL14/16	4 non-standard air sampling smoke detectors
UJ14/16	UL14/16	8 standard air sampling smoke detectors
RR53/57	UJ561	4 non-standard air sampling smoke detectors
UJ56	UJ561	4 standard air sampling smoke detectors
RR73/77	TZ76	4 non-standard air sampling smoke detectors
UJ76	TZ76	8 standard air sampling smoke detectors

This relocation is required to minimise the impact of radiation, particularly due to Single Event Effects (SEE), to the alarm systems' electronics that would perturb the LHC operation, possibly leading to the decision to stop the machine. Fire detector units were tested in the 2010 CNRAD test campaign and showed destructive failures, as well as a moderate soft failure cross-section [2].

The relocation of smoke detectors is summarised in Table 1, with the current and future locations, the number of sensors to be relocated and the type of detectors to be installed per location (Figure 1).

If the long shutdown is delayed to 2013, the relocation would be partially implemented during the 2011 Xmas Break (up to 4 weeks of preparation work per location). This consolidation depends on the cabling activity performed by EN/EL. In addition, up to 3 days of sensor's detection interruption per location are foreseen.

Figure 1: Air sampling smoke detectors with aspiration boxes (in this note referred as non-standard air sampling smoke detectors).

Automatic Gas Detection Systems

Two activities are foreseen in the long shutdown for the automatic gas detection systems, the preventive maintenance and the consolidation of two underground gas centrals located in Point 1 (SGGAZ-00153) and 5 (SGGAZ-00148). By gas detection it is meant oxygen deficiency and flammable gas detection.

Annual and quarterly preventive maintenance are foreseen for the long shutdown. During the annual maintenance the replacement of 1/3 of the LHC machine and Experiment oxygen deficiency cells is performed. During annual and quarterly maintenance, gas sensors are recalibrated when required. Because oxygen deficiency cells need to be calibrated at certain temperature, pressure and humidity values, the changing of this conditions with time creates a derive in the detector that needs to be corrected. These operations are essential to minimise spurious alarms.

If the long shutdown is delayed to 2013, the annual maintenance for underground installations would be performed during the 9 weeks of Xmas Break, if the inter-site doors are open. Quarterly maintenance would be performed during the Technical Stops.

For surface installations the maintenance would be performed during the Run and Technical Stops.

Figure 2: Oxygen deficiency gas sensor in the SD and SDx surface buildings.

Consolidation of the underground gas centrals in Point 1 and 5 is required because the current racks where the centrals are installed are saturated. There is no space available to add any new sensor or any contact to trigger safety actions. Rack centrals need to be split in two separated racks. In Point 5, one will be dedicated for the machine and another for the experiment. The identification of additional rack space is not yet completed.

During the migration there will be a gas detection interruption in UX15, USA15, USC55 or UXC55. Therefore, procedures and compensatory measures will need to be discussed with the concerned GLIMOSes, EN and BE DSOs and the LHC Coordination.

If the long shutdown is delayed to 2013, this consolidation will be delayed.

Emergency Evacuation and Beam Imminent Warning Systems

Annual and quarterly preventive maintenance are foreseen for the Emergency Evacuation and Beam Imminent Warning systems for the long shutdown.

Annual preventive maintenance implies the triggering of all underground sirens in the LHC machine and Experiments. It is organised together with the triggering of all oxygen deficiency flashes in the same area. Nobody shall be present in the area where the sirens and flashes are triggered, because the personnel would not be able to distinguish between a real alarm and a test. Cryogenics shall be in *Cold Gas He standby phase*, which means that no He liquid under pressure is present in the area where the flashes are triggered, because the maintenance team would not be able to distinguish between a real He release and a test.

To minimise the impact on underground activities, this maintenance is performed during the Xmas Closure of CERN. Therefore, if the long shutdown is delayed to 2013, the maintenance would still be performed during the CERN 2011 Xmas Closure for underground installations.

SNIFFER – combined fire and gas detection inside the LHC Experiments

The SNIFFER system is a combined fire and gas detection system that uses air sampling technology to reach inside the confined areas inside the LHC Experiments. There is a SNIFFER system per LHC Experiment. SNIFFER systems are composed of detection modules, each of them associated to an air sampling line. Each module contains a pump and up to 3 detectors (smoke, oxygen deficiency and flammable gas or carbon dioxide detector) depending on the risks associated to the air sampling area. Certain components of the modules need to be replaced on an annual basis to ensure a correct pumping. This includes pump's valves and membranes, and the filter. The replacement of these components is performed during the preventive annual maintenance

To maintain a total of 235 detection modules, a minimum of 12 weeks are required. Two constraints are considered when organising this maintenance. First, for ATLAS and ALICE, the detection modules are located in a non accessible area during the run (in the US15 for ATLAS and in the UX25 for ALICE). Second, the maintenance cannot be performed during the run because an interlock to cut off the Experiment could be triggered (through the Detector Safety System). Because the 9 weeks of a Xmas Break are not enough, maintenance is organised so that it can also be performed during the Technical Stops.

Figure 3: SNIFFER systems.

When performing the maintenance of a module a detection interruption of the module in the concerned sampling area is required.

If the long shutdown is delayed to 2013, the maintenance would be performed during the Xmas Break and Technical Stops.

ACCESS SYSTEMS

This chapter describes the long shutdown activities for the LHC Access Safety System (LASS) and the LHC Access Control system (LACS). Preventive maintenance is presented first, followed by the consolidation and upgrades activities: the relocation of access electronics in critical radiation areas, the video and IT network improvement, the interlock of “overpressure doors”, the external envelope modification for maintenance purposes, and the new access points in TZ32 and PZ65.

Preventive maintenance

Preventive maintenance for the LHC Access Safety System (LASS) and LHC Access Control System (LACS) consists of performing a mechanical verification of all doors and access points, followed by a test of all acquisition chains, from the interlocked equipment (doors, power converters, etc) to the PLC.

This maintenance needs to be performed once per year, as stated in the “Regles Générales d'Exploitation du LHC”. The correct signal acquisition is verified before the start of the LHC, more precisely before the DSO tests. The DSO test is to be organised with the different equipment groups to verify that all equipment conditions are correctly seen and that all the safety interlocks are correctly applied by the LASS.

If the long shutdown is delayed to 2013, the maintenance would be performed during the 9 weeks of the Xmas Break. The disadvantage of performing this maintenance during the Xmas Break is that it limits other activities during this period, and the access point under maintenance is unavailable. This is the reason why the possibility of performing maintenance during the Run is analysed in section “Access envelope modification”.

Figure 4: LHC Access System's access point. Two Personnel Access Devices (PAD) and a Material Access Device (MAD)

Video system and IT network

A first consolidation activity is the improvement of the video system and the IT network.

The objective behind the development of the video system is to avoid problems of image freezing and to improve the fluidity of images. This implementation concerns the installation of encoders as well as reviewing the archiving architecture of the PAD. To deploy this upgrade, all video cameras of all access points need to be migrated at the same time. A progressive migration is not possible.

The objective behind the improvement of the IT network is to increase the Access Point availability by reducing the dependency on network components. Indeed, associated to each Access Point there are many network connections with several routers and switches. As a consequence, the access point unavailability increases with the unavailability of the network components.

The design phase of IT network consolidation is to be done in close collaboration with the IT department. The modifications will mainly concern IT.

If the long shutdown is delayed to 2013, the consolidation activities would be delayed. There is no potential risk associated to the non implementation of this task.

R2E effects

In order to minimise the impact of radiation onto the access system's electronics, the relocation of LACS racks in UJ56 and UJ76 is required, as well as the displacement of the UJ561=YCPY01 door. The risk associated if not performed would be a reduction of the availability of the affected access points.

This consolidation depends on the cabling activity performed by EN/EL and on the network connections carried out by IT. Several weeks of work preparation are required per location, and a minimum of 3 days test with access interruption to the concerned octants is foreseen.

If the long shutdown is delayed to 2013, this consolidation activity would be only partially implemented.

Interlock of "overpressure doors"

This activity concerns enlarging the LASS scope to include additional ventilation doors (mainly the newly installed "overpressure doors") in the access beam interlock and creating a reliable framework for an access powering interlock. The ventilation doors participate to the protection against two risks. First, the containment of a major He release during a magnet powering phase. Second, ensure a correct ventilation path for activated air in the tunnel.

The interlock of "overpressure doors" within the LASS system would imply the deployment of a reliable acquisition of safety signals from these doors and the implementation of the associated safety actions. The risk analysis and the specification of the associated safety actions are currently under discussion. A deployment during a long shutdown in 2012 would be unrealistic unless the specification is finalised by spring 2011. A delay of the long shutdown to 2013 would be favourable in this case.

Figure 5: An example of "overpressure door" in the LHC machine

An important work with TE/MPE is foreseen to define a reliable interface with the Power Interlock Controller. This link is necessary as during a magnet test the opening of an overpressure door should interlock the powering of the magnets.

Access envelope modification

In order to allow the maintenance of the external envelope (access points in the PM shafts) during run periods the possibility of an additional temporary physical barrier is analysed in this paragraph. This temporary barrier would be used to move the interlock during the maintenance of the surface access points.

The advantage of this modification is the possibility of perform the surface access point maintenance during the LHC run, when there are no accesses. This would allow maximum availability of the access points during the access periods, when they are used. The risk of not implementing such a modification is a reduction of the system availability.

The technical solution for the temporary barrier needs to be defined, but a possible impact on civil engineering should not be excluded.

If the long shutdown is delayed to 2013, this would be favourable for this project.

New access points in TZ32 and PZ65

Possible installation of two new access points is foreseen for the long shutdown. First, a new access zone in TZ32 to enable CLIC alignment studies. Second, a new access point in PZ65 to access Point 6 in case of PM65 elevator unavailability. An alternative solution to the new access point in PZ65 would be the improvement of the lift reliability in PM65.

In both cases, a possible impact on civil engineering cannot be excluded. This installation depends on the cabling activity performed by EN/EL and MME for the integration exists.

If the long shutdown is delayed to 2013, implementation would be delayed.

ACTIVITIES IN THE INJECTOR CHAIN

The renewal of the PS Primary Areas Access System is foreseen for the next long Shutdown. The renewal implies the deployment of new access points and access doors, as well as the deployment of the new access safety system for the execution of safety interlocks. It also includes the deployment of a Beam Imminent Warning and Evacuation system.

If the long shutdown is delayed to 2013 it would be favourable in the sense of providing more time for the validation of the new system and more time for preparing the migration.

CONCLUSION

- 9 weeks with the inter-site doors opened would be more adequate to complete the alarm system's annual maintenances, before the hardware commissioning phases start.
- A delay of the long shutdown to 2013 would be favourable for the alarms and access systems consolidation and new installations activities.

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WHAT DO THE EXPERIMENTS HAVE PLANNED?

A. H .Ball, CERN, Geneva, Switzerland,
on behalf of the LHC experiment Technical Coordinators.

Abstract

The shutdown originally planned for 2011-13 is the first opportunity since physics operation started for the experiments to conduct comprehensive maintenance. This long shutdown will also be used to consolidate and upgrade the experimental apparatus so as to fully exploit the expected improvements in LHC performance in subsequent years. This talk will summarize the planned activities in all experiments and attempt to identify areas where resource conflicts may arise.

BASELINE PLANNING

In the current baseline planning [1] around 60 months of p-p running and 8 months of heavy ion running are envisaged before the end of this decade. Maximisation of the physics rewards obtained from the data taken during this period will be the driving factor in deciding how to distribute the remaining time, which is dedicated to technical stops and shutdowns. At present, 3 substantial long shutdowns, LS1 (15 months, 2011-2013), LS2 (15months, 2015-2017) and LS3 (19months, 2019-2021) are foreseen, in addition to year-end technical stops of about 10 weeks duration at the end of years 2013, 2014, 2017, 2018. At this point it is instructive to examine what use the experiments have made of year-end stops like the one just being completed. The evidence suggests that they will be an important ingredient in the overall consolidation and upgrade plan as well as being essential for maintenance and repair.

YEAR-END TECHNICAL STOPS

The experience of 2009-10 and 2010-11 shows that all four experiments can successfully complete complex interventions, requiring partial opening, during a year-end Technical Stop of 10 to 12 weeks, with work spanning the CERN closure if necessary. It is interesting to review some of what the experiments have been able to achieve in the last two year-end stops. During 2010-11:

ALICE [2] partially opened to install 3 TRD modules and 6 EMCAL modules.

ATLAS [3] completed a very substantial programme involving opening both ends of their detector, including work on the electronics of their Liquid Argon Calorimeter and TILECAL, as well as installing the ALPHA detectors in the very forward regions.

LHCb [4] removed and re-installed both RICH1 HPD boxes, having exchanged both electronics and HPD’s.

CMS and TOTEM [5] installed the TOTEM T1 tracking system.

To these must be added the full opening of both ends of CMS during the 2009-10 year-end stop to definitively repair a cooling system fault.

These successfully completed programmes demonstrate that besides routine maintenance, emergency repairs, consolidation, new installations and even upgrade are feasible. So far experiment work has been tailored to stay entirely within the shadow of LHC work, but in future stops, this may not always be compatible with the work programme being attempted.

FUTURE SHUTDOWN ACTIVITIES

Detailed objectives for the different technical stop or shutdown periods are interdependent and will evolve progressively, depending at each stage on past achievements and future expectations. Postponing the 2011-13 shutdown (LS 1) to 2012-14, will, in most cases:
-delay the whole LS 1 task-list by one year.
-allow some tasks scheduled for LS 2 to be pre-empted.
-tend to put pressure for more maintenance and repair tasks (and even upgrade tasks) during year-end stop 2011-2012.

Once the schedule is confirmed, further evolution is likely.

LONG SHUTDOWN 1

The provisional plans of the experiments for the first long shutdown are described below. To this list must be added yearly maintenance of the infrastructure and safety systems, infrastructure consolidation and fault repairs, as necessary. Changes to the shielding of the high luminosity experiments to control activation, backgrounds and the dose to maintenance personnel will also be mandatory.

ALICE

ALICE [2] plans a full opening of the detector, moving the TPC to parking position and accessing the Silicon Tracker for repair and consolidation, particularly of the Pixel tracker cooling system. Simultaneously, six more supermodules of the EMCAL upgrade will be installed, along with support structures for the photon spectrometer.

ATLAS

ATLAS [3] plans to replace steel beam pipes, flanges and ion pumps with aluminium ones to reduce activation and induced background

The Pixel Tracker may be brought to the surface for replacement of all services and optical transmitters, a precautionary fix for faults predicted as possible from 2015 onward due to failing optical transmitters inside the detector. The decision to extract or not will be taken during 2012. This is a major operation! Profiting from this and the revised timing of LS1, the Pixel Insertable B Layer (IBL) project, originally targeted for 2016, may be accelerated to be ready to install in 2013. This additional pixel layer will improve vertexing and b-tagging capabilities at nominal luminosity and beyond, but would require a new beryllium central beam pipe with smaller diameter (45 mm) to be ready in early 2012.

Further substantial tasks are:

-The installation of a new C_3F_8 Inner Detector evaporative cooling plant based on a passive syphon concept.

-The replacement of all on-detector DC-DC converters in the Liquid Argon and Tile Calorimeters with a new generation of devices.

-Completion of the installation of the “EE” muon chambers (which better cover the transition region between barrel and toroid end-caps) and instrumentation of existing trigger chambers in the toroid feed region to improve geometrical acceptance

CMS

CMS plans to upgrade its Endcap Muon System, which was de-scoped for the low luminosity detector. This upgrade involves restoring granularity in the inner layer of Cathode Strip Chambers (CSC’s), installing an additional (fourth) layer of CSC’s and Resistive Plate Chambers in each endcap and constructing a mobile shielding wall which will complete the forward shielding system and protect the newly installed detectors.

The revision of Hadron Calorimetry will start with the replacement of photo-transducers in the outer barrel and in the CASTOR forward calorimeter.

The Forward Shielding and support structures will be revised to give more reproducibility under magnetic cycling and to allow forward detectors to be installed for heavy ion running. Improvements to the beam monitoring system will include the Pixel Luminosity Telescope and the barrel endcap humidity seal will be improved to allow for colder Tracker operation.

Given the prospect of a one or two year delay to LS2, plans are being made to advance to LS1 the preparation and installation of the reduced diameter beampipe needed for the upgrade of the Pixel Tracking detector. This would also result in a newly baked-out pipe for 2014 and open the way for a lower risk logistic sequence with the beampipe removed for much of the shutdown.

The first detailed CMS planning exercise for LS1 has identified in excess of 230 discrete operations, spanning a 15 month period. Beampipe replacement or bakeout would add another 2 months to the time required.

LHCb

As in the ATLAS case, LHCb [4] plans changes to the beampipe and vacuum system to reduce material budget, reducing activation and backgrounds whilst increasing transparency. Exchange of the largest beryllium section (the third, ~6000mm in length), requires moving out the fourth section as well. Machined aluminium bellows between Sections 1 & 2 and between Sections 2 & 3 will be replaced by units with a formed bellows technology**.** Spider-web fixed point supports will also be replaced by a higher transparency design.

One or more detector modules of the Inner Silicon Tracker will be replaced with scintillating fiber technology (as part of the upgrade project) and, depending on the accumulated radiation dose, exchange of both VeLo halves, including the RF boxes, may be considered necessary.

TOTEM

TOTEM [5] is retaining options for servicing of the T1 and T2 telescopes and their test or re-commissioning at beam height, which could have impact on the CMS opening and closing timescales.

Similarly, service requirements, including possible dismount, of Roman pot detectors, may affect local LHC scheduling in the straight sections either side of pt 5.

POINTS TO WATCH

Beampipes:

Change of schedule may lead to more overlap between experiments in both construction and installation of improved beampipes, with the distinct prospect of ATLAS, LHCb and CMS all changing beryllium pipes and other vacuum components in 2013. Whether this transpires or not, the pumping effectiveness of the NEG coatings needs to be regularly monitored so that saturation can be predicted. Bakeout or pipe exchange is complex and the steps must be explicitly included in shutdown scheduling

Survey:

Despite contributing substantially to their own survey efforts, each experiment needs a minimum of one staff surveyor to oversee the survey programme, make sure survey and its documentation is carried out coherently throughout CERN and ultimately to take responsibility for survey work of complex-wide criticality.

Infrastructure:

All experiments require very substantial consolidation of shielding ventilation, cryogenics, cooling, inertion and dry air systems, RP measures, safety systems, and beam diagnostics between now and the end of LS 1, to maintain the good match between experiment and LHC performance and availability obtained during 2010.

LONG SHUTDOWN 2

The existing programme of work for LS 2 is likely to be strongly affected by the knock-on delay resulting from the decision to postpone LS 1, recalling that the baseline date of 2016 was already a compromise between different interests requesting 2015 & 2017.

Presumably the LS 2 start date and duration will be re-considered based on the physics achieved pre-LS 1 and targeted between LS 1 and LS 2, the actual start and duration of LS 1, the capabilities and weaknesses of LHC and the experiments in the period between LS 1 and LS 2, the credible ready for installation dates of various upgrades to the machine and experiments and finally the gains and risks to performance involved in projected LS 2 work.

There are many common features to the plans of the 4 major experiments [2,3,4]. All will execute or complete beampipe and tracking upgrades (although in the case of ATLAS and CMS, part or all of those currently planned may be pre-empted to LS1 and intermediate technical stops) and all have substantial trigger or readout upgrades in mind to cope with anticipated higher luminosities. Upgrades to Calorimetry and in some cases Muon Systems also feature.

CONCLUSION

The LHC experiments plan an intensive programme of maintenance, consolidation & upgrade work for the first Long Shutdown (LS 1) of the LHC. However, this work-plan must be seen as part of an interdependent and coherent set of objectives for all three Long Shutdowns currently foreseen, with proven options to also exploit the intervening year-end technical stops.

Activity overlap and possible resource conflicts have been identified for: beampipe construction and replacement, experiment survey and infrastructure modifications, all of which depend crucially on resources from CERN technical departments.

Delaying LS 1 from 2011-13 to 2012-14 will cause most of the baseline task list to be postponed by 1 year without serious consequence, although urgent exceptions may put more pressure on the 2011-12 year-end stop**.**

The inevitable feed-forward of a one or two year delay to LS 2 (current baseline 2015-17) will likely feedback more tasks to LS 1 and the intervening year-end technical stops. For the experiments to plan correctly, an overall revision of the next 10-15 years including all 3 long shutdowns is needed. In addition to shutdown start times and durations, the capabilities of the LHC after each shutdown are an important input for experiment planning, since the likely boundary conditions for instantaneous and integrated luminosity, bunch pattern and bunch intensity can substantially influence the priority given to different consolidation or upgrade projects.

ACKNOWLEDGEMENTS

I would like to thank the organisers for the opportunity and privilege of providing part of the experiment input to the 2011 Chamonix decision-making process. As usual the workshop was well-organised and well-focussed, confronting the facts head on, and providing an excellent forum for cross-department discussion as well as social activity. I am indebted to my fellow Technical Coordinators: Joachim Baechler, Rolf Lindner, Marzio Nessi and Werner Riegler for the comprehensive material they provided and for their solidarity.

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LHC potential: Energy and Luminosity

W. J. Murray, CERN - STFC/RAL, Harwell Science and Innovation Campus, Didcot, Oxon., UK
On behalf of ALICE, ATLAS, CMS and LHCb

Abstract

The prospects for discovery physics in 2011 at LHC are reviewed. With 3.5 TeV per beam and 1 fb^{-1} per experiment the exclusion of the Standard Model Higgs boson by ATLAS and CMS combined is possible from 120 GeV up to over 600 GeV. Raising the beam energy to 4 TeV will gain 30% in the Higgs cross-section while for many other searches the gain is even larger.

THE SCENARIOS BEFORE US

The excellent performance of the LHC machine in its initial run in 2010 has encouraged speculation into the energy and integrated luminosity which might be achieved before the long shutdown. The influence on the physics potential of these is considered here, with the focus on ATLAS and CMS because the programmes of ALICE and LHCb are not as influenced by increasing energy, and their luminosity requirements do not press as hard upon the machine performance. In contrast, ATLAS and CMS essentially want as much luminosity as possible at the highest energy which can safely be reached.

The experiments are working remarkably well. The first 50 pb^{-1} delivered has been recorded with excellent efficiency and detector performance, and modelling are better than could have been hoped for. The detectors have reported the observation of all the fundamental SM particles (except the Higgs boson), usually with cross-sections and more measured too.

Searches for new physics have been made with sensitivity well beyond the Tevatron in many areas, which are changing and constraining our picture of the HEP world. So far most surprises in the p-p physics have been in details of QCD predictions, which are interesting but not paradigm-changing. The lead ion run produced good evidence that matter formed in these collisions is denser, hotter, and larger then that at RHIC, still having properties close to ideal liquid.

LHCB GOALS IN 2011

The principle requirement of LHCb is to run stably at about 2-3 10^{32} cm^{-2} s^{-1}, for as long as possible. Such a run should produce of order 1 fb^{-1} which will allow the possibility of discoveries in many channels. A few highlights are $B_s \to \mu\mu$, B_s CP-Violation (CPV) measurements, $B_s \to K^*\mu\mu$ studies, CPV search in the charm system and of course the unitary triangle angles, especially γ.

Each of these will have the worlds best sensitivity already with less than a third of the data discussed, and so there are exciting prospects for new physics. It should be noted that the beam energy plays a relatively minor role in those searches.

ALICE PROGRAMME

The instantaneous luminosity for p-p collisions in ALICE must be limited to 10^{30} cm^{-2} s^{-1}, (or possibly a little more), and the limitation of interpreting the Pb-Pb data often comes from the p-p statistics used for comparison. Therefore ALICE is interested in maximum stable running of p-p collisions. In addition, in pp collisions ALICE will be studying soft processes and charm production.

There is the need for a special p-p run of about 50M events with the beam energy reduced to 1.38 TeV to match the Pb-Pb energy per nucleon. This is to allow direct comparison between the two sorts of collisions, and will take a few days. There is no need to repeat this if the beam energy is changed to 4 TeV.

HIGH ENERGY FRONTIER

The main reason to wish to raise the beam energy is the increased production rate of heavy objects. This fractional increase is shown in Fig. 1 [1].

Standard Model

The 2011 data will be used to extend the suite of measurements, particularly in heavy gauge bosons, W and Z, and top quark studies. The production rate of these particles, and the quality of the detectors, gives good prospects for precise measurements such as the mass of the W boson, a key ingredient of the Standard Model. However it is top studies where the advantage of the LHC energy is most apparent. The first measurements of the top cross-section at LHC have been made on the first 3 pb^{-1} of data and have errors of order 40%. This helps to understand the gluon distribution inside the proton and hence better estimate the expected Higgs cross-section. The errors will be reduced enormously, but the top pair production would gain a 40% rate enhancement from 4 TeV operation, which would of course help greatly.

Another interesting subject in top physics is the production of single top quarks. This is an important test of the model and detectors and was only first reported by the Tevatron in 2009. The expected error in two different production modes [2] can be seen in Table 1. A dataset of

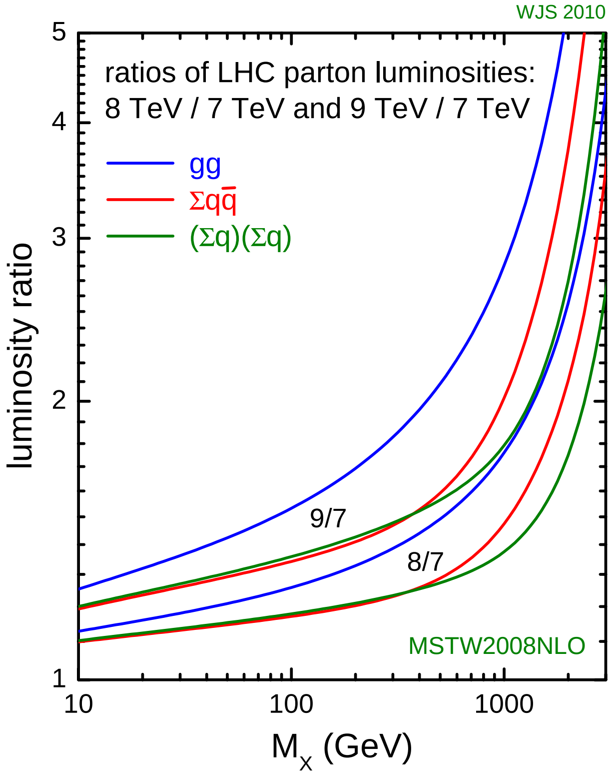

Figure 1: The effective gain in the rate of interactions from raising the centre-of-mass energy to 8 or 9 TeV.

around 5 fb^{-1} will be required to make meaningful measurements of the more difficult W plus top mode, but the signal rates in these channels increase 20-40% by raising the beam energy 0.5 TeV. This will be an important test of the experiments abilities to undertake searches for rare objects.

Table 1: Predicted error on the single top cross-section in two production modes as projected by the ATLAS experiment.

Mode	**1 fb^{-1}**	**5 fb^{-1}**
t-channel	32%	13%
Wt production	68%	32%

Exotics searches

There is a large range of exotic models which have been investigated with a large range of possible signatures. The example of the sensitivity of the search for a Z' [3] is used here. Figure 2 shows the sensitivity of the expected limits to the energy and luminosity available.

As the current data provides limits at just over 1 TeV, raising the E_{CMS} by 1 TeV roughly halves the amount of data required to set a new limit. For higher mass exotic scenarios, such as quark substructure or black hole production, the increased cross-section will in general give rise to a larger increase.

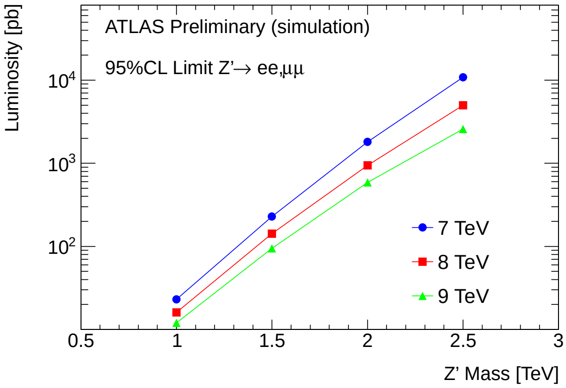

Figure 2: The estimated mass limits on a Z' from the ATLAS collaboration which can be obtained as a function of centre of mass energy and integrated luminosity.

SUSY Searches

The search for supersymmetry is one of the key goals of LHC. CMS produced the first result on the total 2010 dataset [4], which placed limits on the CMSSM model using events with jets and missing energy. The results can be seen in Fig. 3. These are complemented by ATLAS results [5] showing that, in a very simplistic scenario where squarks and gluinos have the same mass, that mass scale is over 0.7 TeV.

The limits obtained with 35 pb^{-1} are a significant extension of the previous bounds. They represent a major constraint on SUSY model building, and are one of the most important LHC results to date. It can be seen that they approximately match the sensitivity which was estimated for 100 pb^{-1} [6]; there is a certain tendency to be conservative in making these estimations. ATLAS has provided some sensitivity projections showing how the discovery reach in the future evolves with energy and luminosity which are shown in Table 2. It can be seen that there is good discovery potential passing 1 TeV, provided 5 fb^{-1} at 7 TeV or 2 fb^{-1} at 8 TeV is available.

Table 2: The projected 5σ SUSY discovery ranges in TeV by ATLAS for different scenarios of energy and luminosity. Note that exclusion limits would be larger.

E$_{CMS}$	Integrated Luminosity			
	1 fb^{-1}	2 fb^{-1}	5 fb^{-1}	10 fb^{-1}
7 TeV	0.7	0.8	1.0	1.2
8 TeV	0.8	1.0	1.2	1.4
9 TeV	0.9	1.1	1.3	1.6

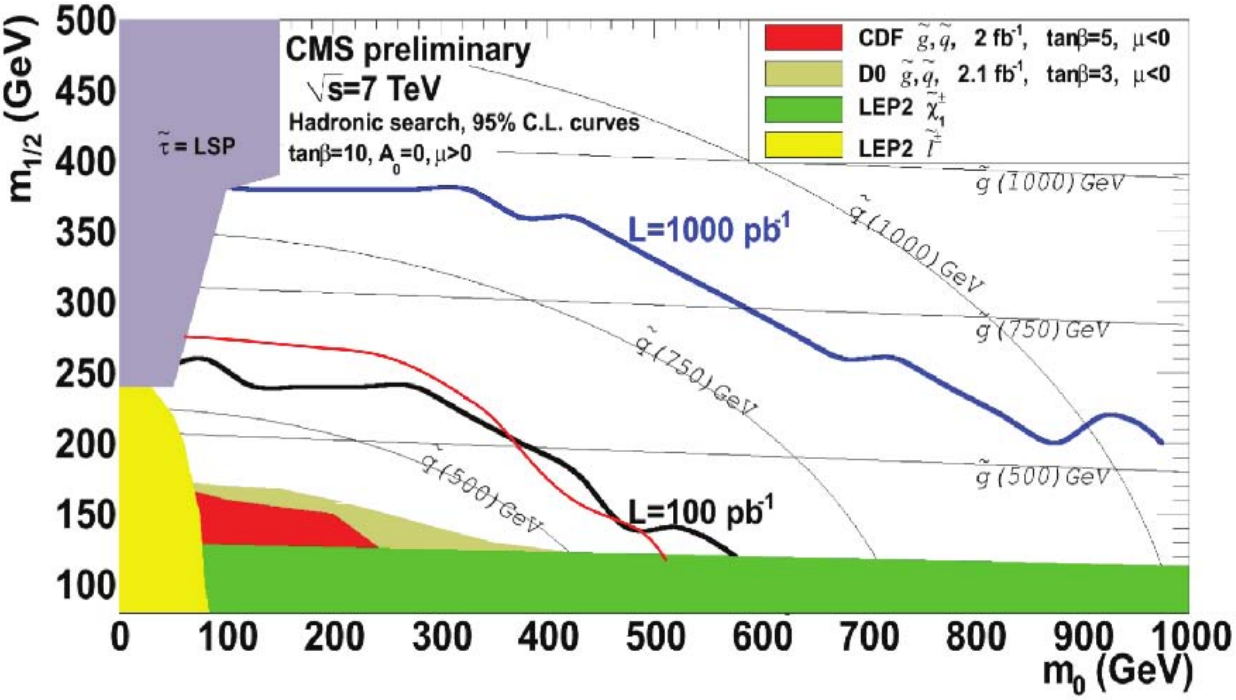

Figure 3: Limits on SUSY parameter space from the CMS experiment. The coloured (grey) lines show the expectations for sensitivity, calculated beforehand and the black is the actual limit obtained.

Higgs searches

A major goal for the current run is to maximise sensitivity to the Standard Model Higgs boson. The LEP [7] lower limit of 114.4 GeV has been augmented by the Tevatron [8] exclusion of the region from 158-175 GeV. The consistency of fits to the electroweak data [9] points to an upper limit of 185 GeV, but this limit assumes no additions to the Standard Model. The LHC will be sensitive to a SM-like Higgs from the LEP bound to over 600 GeV.

The search strategy depends upon the Higgs boson mass and hence its decay modes, but it depends critically on the production cross-section. The gain in this from increasing the beam energy is shown in Fig. 4 for various production modes, of which the gluon fusion is probably the most important. The gain can be seen to be 30% for a light Higgs boson in this channel on raising the energy to 8 TeV.

The sensitivity of ATLAS and CMS has been assessed by the collaborations [10], [11], and is very similar. The sensitivity of the CMS experiment, combining several decay modes, can be seen in Fig. 5. With a baseline run of 1 fb^{-1} at 7 TeV the two sigma sensitivity region covers 130 to 600 GeV. 5 fb^{-1} at 8 TeV allows three sigma evidence across the entire region investigated.

The gain from higher energy can be assessed in terms of the amount of integrated luminosity at 8 or 9 TeV giving the same Higgs boson sensitivity as 1 fb^{-1} at 7 TeV. This is done in Fig. 6. If can be seen that for a low-mass Higgs, favoured by the electroweak fits, 20% less data is needed to have the same sensitivity at 8 TeV.

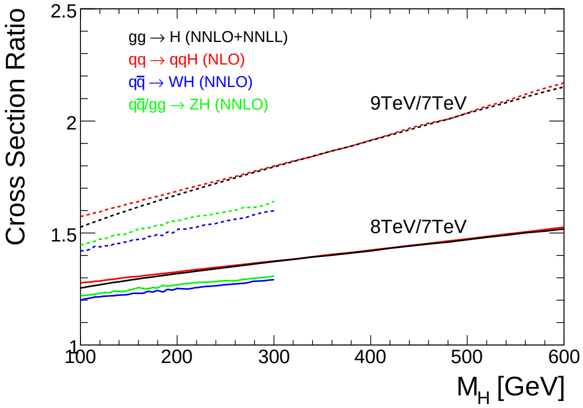

Figure 4: The ratio of the Higgs boson cross-section at 8 or 9 TeV to that at 7 TeV as a function of mass.

Table 3: Higgs mass range coverage at 8 TeV.

Mode	**2 fb^{-1}**	**5 fb^{-1}**	**10 fb^{-1}**
95% C.L.	Any	Any	Any
3σ	118-500+ GeV	Any	Any
5σ	130-200 GeV	120-500 GeV	Any

The Tevatron will continue to run through 2011 and produce new results. In the area of Higgs searches it will remain competitive for some while. The aim is to have 2.4 σ sensitivity for Higgs boson masses below 185 GeV. This is similar to the minimum sensitivity of the combined

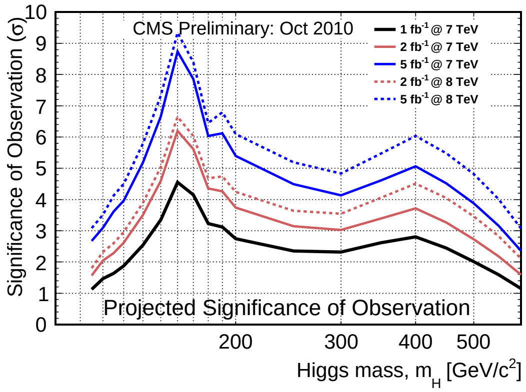

Figure 5: The significance of the expected observation of the Standard Model Higgs boson at 7 or 8 TeV for various assumed luminosity scenarios.

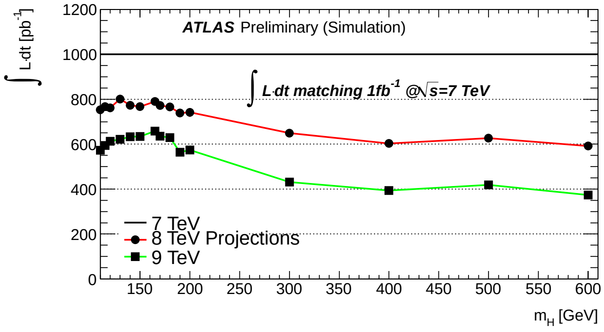

Figure 6: Effective luminosity, (see text)

LHC experiments given 2.5 fb^{-1} at 7 TeV each, however the LHC experiments would be more powerful everywhere other 115 GeV.

CONCLUSIONS

The LHC physics programme has got off to an excellent start in 2010, and we thank all the LHC team that have made it possible. There is an extremely exciting programme awaiting the LHC in 2011, in which we envisage two orders of magnitude more data and significant possibilities for a breakthrough in many areas. If the beam energy can be raised to 4 TeV there are important gains to be made. Some of these are itemised in Table 4.

Table 4: Gain from raising the E_{CMS} to 8 TeV for various analyses.

	Gain
SUSY	Needs 60% as much data
W′, Z′	Half the data needed
Black holes	Factor 5 increase in production
top	40% more top quarks
Higgs	Needs 80% as much data

It must be stressed that these projections have many assumptions. Typically the effects of pileup have not been completely included, which will degrade the results. However, the analyses used are generally rather simple and robust, and it is likely that the combined work of many highly motivated people will produced more finally-honed results.

Assuming 3.5 TeV beam energy, with about 2.5 fb^{-1} ATLAS and CMS can each independently exclude at 95% CL or more the Standard Model (SM) Higgs with every mass. With about 6 fb^{-1} ATLAS and CMS can each independently obtain at least a 3σ observation from the LEP bound at 114.4 GeV to about 500 GeV.

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PROBABILITY OF BURN-THROUGH OF DEFECTIVE 13 KA SPLICES AT INCREASED ENERGIE LEVELS

A.P. Verweij, CERN, Geneva, Switzerland

Abstract

In many 13 kA splices in the machine there is a lack of bonding between the superconducting cable and the stabilising copper along with a bad contact between the bus stabiliser and the splice stabiliser. In case of a quench of such a defective splice, the current cannot bypass the cable through the copper, hence leading to excessive local heating of the cable. This may result in a thermal runaway and burn-through of the cable in a time smaller than the time constant of the circuit. Since it is not possible to protect against this fast thermal run-away, one has to limit the current to a level that is small enough so that a burn-through cannot occur. Prompt quenching of the joint, and quenching due to heat propagation through the bus and through the helium are considered. Probabilities for joint burn-through are given for the RB circuit for beam energies of 3.5, 4 and 4.5 TeV, and a decay time constant of the RB circuit of 50 and 68 s.

INTRODUCTION

At the Chamonix 2009 workshop [1] a quench scenario of the 13 kA joints was presented that could not be protected and that could lead to burn-through and arcing between the two cables of the splice, similar to the incident on 19 Sept. 2008 [2]. Such an unprotectable burn-through could occur in case of a quench in a joint having a lack of bonding between the superconducting cable and the copper stabiliser, coinciding with a longitudinal interruption of the bus stabiliser. Fig. 1 shows various ways causing a quench of a joint and the probabilities of a burn-out. Note that steady-state resistive losses in the splices are detected with the new QPS bus protection ***before*** they could lead to a quench of the joint.

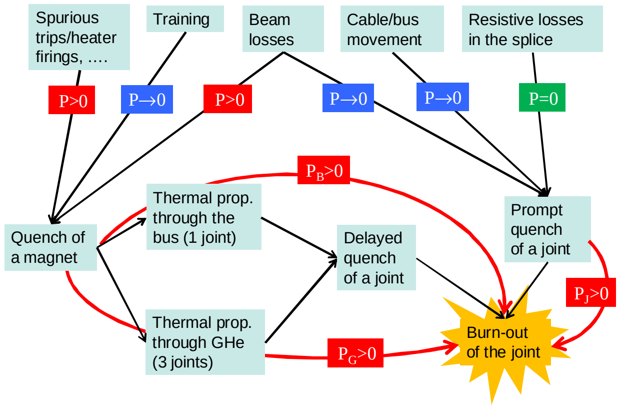

Figure 1: Probability flow chart for currents up to 9 kA.

Up to 9 kA the most likely scenario for quenching a joint is by means of thermal propagation from an adjacent quenching magnet.

In this paper the probabilities P_B, P_G and P_J will be discussed and estimated, for beam energies of 3.5, 4 and 4.5 TeV.

P_G: The probability that a joint burns through due to the propagation of gaseous helium if an adjacent magnet quenches.

P_B: The probability that a joint burns through due to the heat propagation from an adjacent quenching magnet, including the diode and its lead, through the bus towards the interconnect.

P_J: The probability that a joint burns through when it promptly quenches, e.g. due to beam losses.

The probability per year (P_Y) that a joint burns through can then be written as:

$$P_Y=N_M(3P_G+P_B)+N_JP_J$$

With N_M the number of magnet quenches per year and N_J the number of prompt joint quenches per year. Note that each dipole magnet quench affects 4 joints: 1 joint quenches through thermal propagation through the bus, while 3 joints quench through warm gaseous helium. The probability P_G is therefore multiplied by a factor 3.

All calculations have been performed using the computer code QP3 [3].

ASSUMPTIONS

The calculation of possible quench scenario's and hence the probabilities P_G, P_B, and P_J depend not only on the operating current and the decay time constant τ, but also on several other parameters, such as:

- Defect size (represented by R_{addit}).
- RRR of the bus, the diode lead, and the cable.
- "Dipole-Bus-Diode" geometry.
- Heating up of the magnet coil.
- Heating up of the diode.
- Heat transfer to helium (for the bus, diode lead, and joint area).
- Resistance of the 'half moons'.
- GHe propagation time.

Assuming a worst case value for all these parameters would result in an unrealistically low safe current. Therefore, most parameters will be fixed to best-known (but somewhat conservative) values, as given below:

Defect size:

The distribution of defects around the machine is taken from an analysis based on a few hundred so called R16 measurements [4]. The number of defects larger than a certain limiting value R_{lim} is shown in Fig. 2. The percentage is calculated based on the total number of about 10000 joints in the machine.

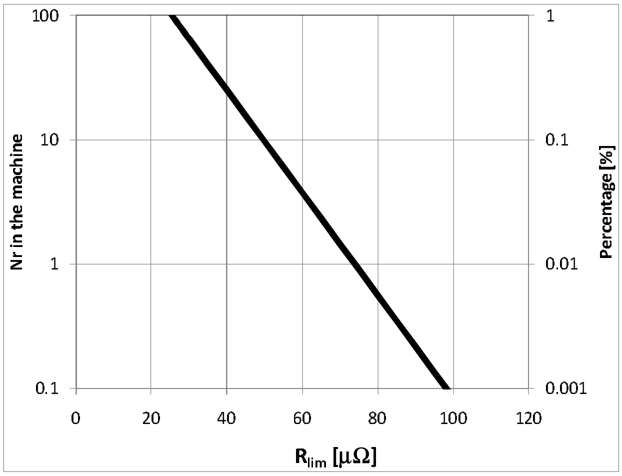

Figure 2: The cumulative distribution of all available measured R16 resistance data.

RRR:

Recent measurements [5] show that the bus bars have a RRR of 250±50. A value of 200 is therefore used for the RRR of the bus, the wedge, the U-profile and the diode leads. The RRR of the cable is assumed to be 80, similar to the value after cable production [6]. The magneto-resistivity of copper is also taken into account.

Geometry magnet - bus – diode:

Four slightly different geometries are studied (see Fig. 3), which have different lengths of the diode lead and the bus between magnet and joint. The most critical geometry (namely type B connected to the upper heat sink) is used as default case.

The calculations performed with QP3 are done in such a way that only the bus bars are simulated (including the half moon and the joint), and not the diode heat sink and the magnet itself. This approach requires a time-dependent boundary temperature at the interface between bus bar and magnet and at the interface between bus bar and diode. These temperature profiles are discussed in the next two sub-sections. In the model, the main bus bar with standard bus insulation (i.e. on the left of the joint in Fig. 3) is taken long enough so that the temperature gradient equals 0 at the end of the bus.

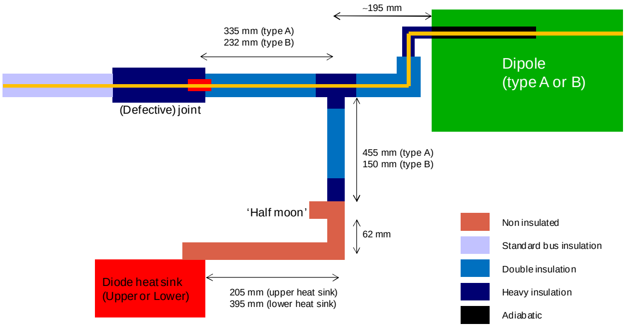

Figure 3: Schematic view of the dipole, bus, diode, diode lead and joint. Only one connection is shown. Lengths vary among the 4 possible geometries.

Heating up of the magnet coil:

Immediately after quench detection, the heaters in the magnet are fired, the magnet resistance and voltage increase, and the current deviates into the by-pass diode as soon as the magnet voltage reaches the diode opening voltage of 6 V. The exact shape of the current decay in the magnet is not very important for the simulation, and for simplicity an exponential function (with decay time τ_{mag}) is assumed, although in reality it is not. During this process the magnet coil heats up, especially in those parts of the coils where the field is high. The bus is connected to the cable entering the mid-plane of the outer coil. This part of the coil is in low field and not in direct contact with the heaters, and warming up is therefore limited [7,8]. For all calculations I have used the following maximum temperatures and times τ_{mag}:

- 20 K and 1.3 s (for 3.5 TeV)
- 22 K and 1.1 s (for 4 TeV)
- 26 K and 1.0 s (for 4.5 TeV)

Heating up of the diode:

As soon as the current bypasses the quenching magnet, the diode starts to warm up. Of course the rate of warm-up depends on the current and on the decay time constant of the circuit. Experimental data are shown in Fig. 4 [9],[10].

All calculations are performed with an approximate temperature increase equal to: $T=T_0+At^B$ with the constants A and B equal to:

- 18.55 and 0.384 (for 3.5 TeV)
- 18.62 and 0.396 (for 4 TeV)
- 18.69 and 0.408 (for 4.5 TeV)

Heat transfer to liquid helium:

The heat transfer (in W/m^2) from the non-insulated bus (between the diode heat sink and the half moon) to the helium is given by Kapitza cooling equal $180(T_{\mathrm{bus}}^4-T_{\mathrm{He}}^4)$ up to a maximum of 35000 W/m^2. Above this value film boiling is assumed equal to $1250(T_{\mathrm{bus}}-T_{\mathrm{He}})$.

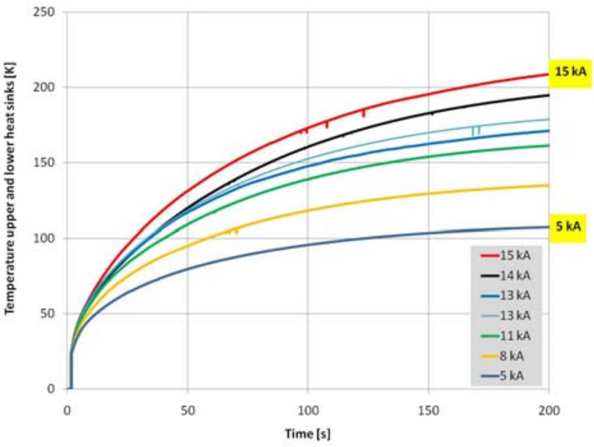

Figure 4: Experimental data of the temperature increase of the heat sink of a dipole by-pass diode for currents between 5 and 13 kA.

The heat transfer from a kapton insulated bus to the helium is given by a series transfer through solid kapton (using the NIST data for kapton) and film boiling, using 1250(T_{ins}-T_{He}) with T_{ins} the temperature of the outer surface of the kapton. This approach gives a good fit to heat transfer measurements performed on a bus bar sample [11], and is qualitatively and quantitatively similar to the analysis given in [12]. The thickness of the kapton layer used in the above given approach equals 0.29 mm (for a standard bus insulation), 0.6 mm (for a double insulation), 1 mm (for a heavily insulated bus), and 2 mm (for the joint area over a length of 24 cm), see also Fig. 3.

Resistance of the half moons:

The resistance of the so-called half moons (connecting the diode lead with the internal bus of the diode) is based on measurements performed in SM18 during a current discharge from 3 kA, see Fig. 5.

Calculations of the probability for joint burn-out are performed for a resistance of 2.5 μΩ.

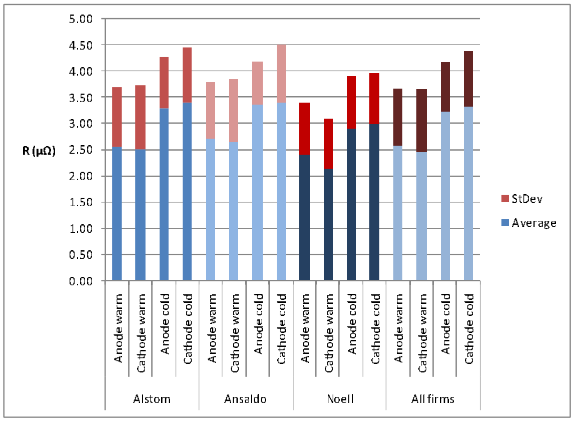

Figure 5: Overview of the 'half moon' resistance values, as deduced during the magnet reception tests in SM18.

Gaseous helium propagation time:

All calculations assume that warm gaseous helium reaches the joint 20 s after the quench in an adjacent magnet, independent of the current in the magnet. This somewhat conservative value is based on data from the HWC 2008 campaign [13], see Fig. 6.

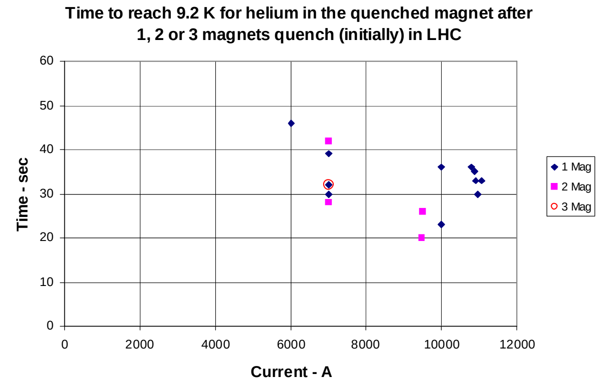

Figure 6: Calculated time to quench the joint in the M3 line after a quench in an adjacent dipole magnet for various currents between 6 and 11 kA.

PROBABILITY P_G

Fig. 7 shows the burn-out current versus the defect size for a joint quench initiated by gaseous helium from an adjacent magnet. Data are given for initial currents of 6, 6.8, and 7.6 kA, corresponding to about 3.5, 4, and 4.5 TeV (with an additional margin of about 100 A).

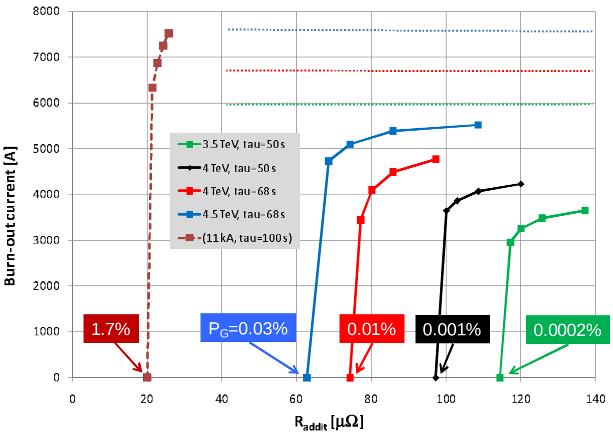

Figure 7: Burn-out current vs defect size for several operating currents, and the probability P_G (in % per magnet quench) using Fig. 2.

The 6.8 kA case is calculated for τ=50 and τ=68 s, since it was not yet completely sure which time constant has to be used (depending on possible limitations from QPS, power converters, and energy extraction). For comparison, also the 11 kA, τ=100 s case is plotted. Using the estimated defect distribution in the machine (see Fig. 2), the probability P_G is calculated that a defective joint burns through. P_G equals 0.0002% per magnet quench for 3.5 TeV, up to 0.03% per magnet quench for 4.5 TeV.

PROBABILITY P_B

Fig. 8 shows the burn-out current versus the defect size for a joint quench initiated by thermal propagation through the bus from the warm magnet, diode and diode lead (including the half moon). Data are given for the same currents as previously. Using the estimated defect distribution in the machine (see Fig. 2), the probability P_B is calculated that a defective joint burns through. P_B equals 0.002% per magnet quench for 3.5 TeV, up to 0.1% per magnet quench for 4.5 TeV.

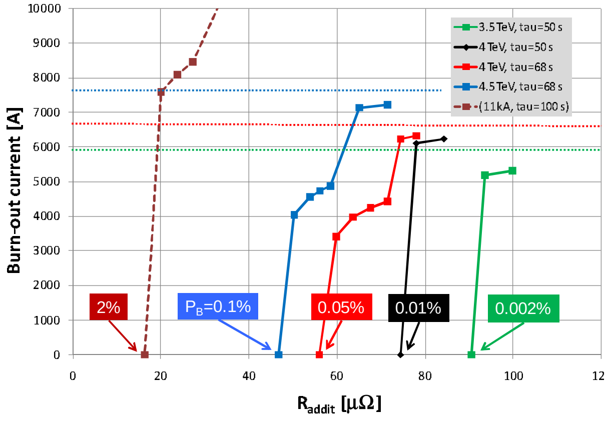

Figure 8: Burn-out current vs defect size for several operating currents, and the probability P_B (in % per magnet quench) using Fig. 2.

PROBABILITY P_J

Fig. 9 shows the burn-out current versus the defect size assuming that the joint quenches promptly, e.g. due to excessive beam losses. Data are given for the same currents as previously. Using the estimated defect distribution in the machine (see Fig. 2), the probability P_J is calculated that a defective joint burns through. P_J equals 0.003% per prompt joint quench for 3.5 TeV, up to 0.12% per magnet quench for 4.5 TeV.

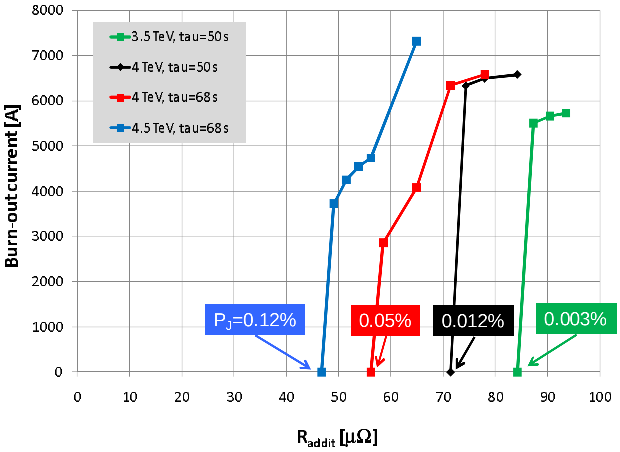

Figure 9: Burn-out current vs defect size for several operating currents, and the probability P_J (in % per prompt joint quench) using Fig. 2.

PROBABILITY OVERVIEW

Table 1 summarizes the probabilities P_G, P_B and P_J as given in Figs. 7-9. Note that each magnet quench affects 4 joints: 1 joint quenches through thermal propagation through the bus, while 3 joints quench through warm gaseous helium. The probability P_G is therefore multiplied by a factor 3.

As written in the introduction the probability of a burn-through of a joint during one year of operation can be summarised by $P_Y=N_M(3P_G+P_B)+N_JP_J$ with N_M the number of magnet quenches per year and N_J the number of prompt joint quenches per year.

Table 1: Overview of the probabilities for 4 operation scenario's. Note that P_G and P_B are given in % per MB quench, and that P_J is given in % per prompt joint quench.

Beam energy [TeV]	τ [s]	$I^2τ$ [10^6A^2s]	P_G	P_B	$3P_G+P_B$	P_J
3.5	50	1800	0.0002	0.002	0.0026	0.003
4	50	2300	0.001	0.01	0.013	0.012
4	68	3150	0.01	0.05	0.08	0.05
4.5	68	3900	0.03	0.1	0.19	0.12

Considering that N_M>>N_J, and that P_J and ($3P_G+P_B$) are similar, the previous formula can be reduced to: $P_Y=N_M(3P_G+P_B)$. This relation is visualized in Fig. 10. Note that a possible asynchronous beam dump may cause prompt quenching in many interconnects, so that in this case also the probability P_J should be taken into account. Experience of operation in 2010 showed almost no dipole quenches, so for the risk evaluation, a number of about 10 quenches per year seems reasonable.

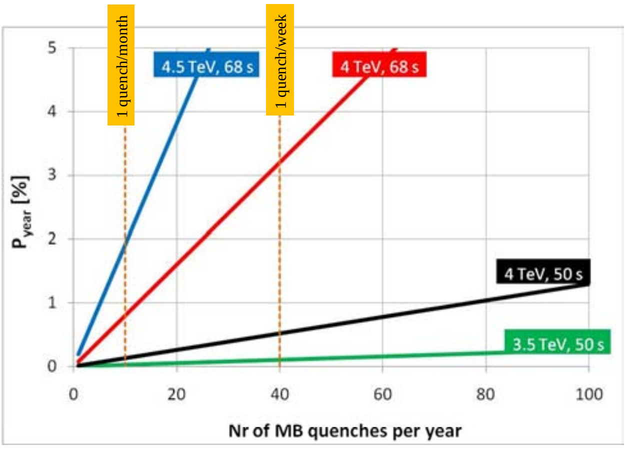

Figure 10: The probability per year of a joint burn-out as a function of the number of MB quenches, for 4 operating scenario's.

Note that the probability figures hold under the assumptions that:

- the R_{addit} measurements are representative for the entire machine, and hence the R_{addit} distribution in Fig. 2 is correct.
- the joints did not deteriorate over the last 2 years.

Up to now, only the RB circuit is analysed. The RQD/F circuits are safer, due to:

- the small decay time constant (9-15 s), also implying that P_G=0,
- the slightly smaller current,
- the longer distances between the magnet and the joint, and between the diode and the joint,

Sensitivity studies show that especially the GHe propagation and the thermal propagation from the diode & half moons to the joint have a large impact. Also the resistance of the 'half moon' plays an important role.

Bus signals can be measured with the nQPS after quenching one or a few dipoles in the machine. This will give accurate values of a few 'half moon' resistances, and might give some insight in the thermal propagation through the bus as well as the GHe propagation. However, a good understanding will be difficult due to limitations in current, external noise, limited number of voltage taps, and lack of useful temperature sensors.

Alternatively, a test in SM18 can improve our understanding of the thermal propagation through the bus. The advantages of such a test are that it can be performed up to high current, and that several temperature sensors and voltage taps can be connected to the diode and the bus. However, the test will not give relevant information on the GHe propagation, because the cryogenic system in SM18 is completely different from the tunnel.

A 'thermal amplifier test' in all sectors could qualify the safe operating current in situ (see [5]).

ACKNOWLEDGMENT

I would like to thank many colleagues from the TE department for valuable input and discussion.

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CURRENT STATE OF COPPER STABILIZERS AND METHODOLOGY TOWARDS CALCULATING RISK

M. Koratzinos, CERN, Geneva, Switzerland

Abstract

This paper attempts to review the factors that limit the maximum safe energy of the LHC. It concentrates on improvements on knowledge gained since the author gave a similar talk in Chamonix 2010 last year [2]. A way of defining risk at different beam energies is also put forward, as well as a proposal for a qualification tool that might allow to run at higher energies in the future.

CHANGES SINCE LAST YEAR

There have been two major improvements to our knowledge that affects the maximum safe energy of the LHC: the first comes from an improved simulation of burnout limits [1] that includes a detailed study of the case of interconnect quenches due to heat conduction through the busbar ("busbar propagation" quenches). This mode of quenching an interconnect had not been studied in detail before (instead a very crude model of quench propagation through the busbar was used) and leads to somewhat lower limits for the maximum allowed excess resistance of a joint.

The second improvement comes from an increase in the knowledge of the busbar segments themselves: an important quantity (related to the quality of the copper stabilizer), namely the residual resistivity ratio (RRR) has been measured for all sectors of the machine, and for both the RB and RQ circuits. The RRR measured is higher than the conservative number used last year and therefore leads to somewhat higher limits for the maximum allowed excess resistance.

Another important development is that the idea behind a complete qualification tool, the so-called 'thermal amplifier' was for the first time tested in the lab ("proof of principle studies") giving good agreement between simulation and actual measurements. This idea is important as it might be the only qualification tool that might allow us to run safely at an energy higher than last year's.

RRR MEASUREMENTS

The burnout limit of a joint of the main circuits of the LHC depends on the RRR of the copper stabilizer of the circuit. Measuring the RRR of the busbar stabilizer *in situ* in the tunnel is not an easy task, and previous attempts to measure it were not very successful. For this reason, a conservative value (of 100) was used up to now for the determination of burnout limits. If the RRR would be 200 instead of 100, the safe energy of the LHC would increase by a good fraction of a TeV.

It was therefore decided to measure the RRR in all sectors. A type test was performed exactly a year ago and a campaign for measuring the RRR was performed between 10/12/2010 and 27/1/2011. This is a combined effort between the EPC, CRG and MPE groups of TE – without the help of all these groups the measurement would not have been possible. The campaign took only two days per sector thanks to the efficiency of the cryogenics and power converter groups, but necessitated many hours of work in the LHC tunnel, designing and installing patches, etc.

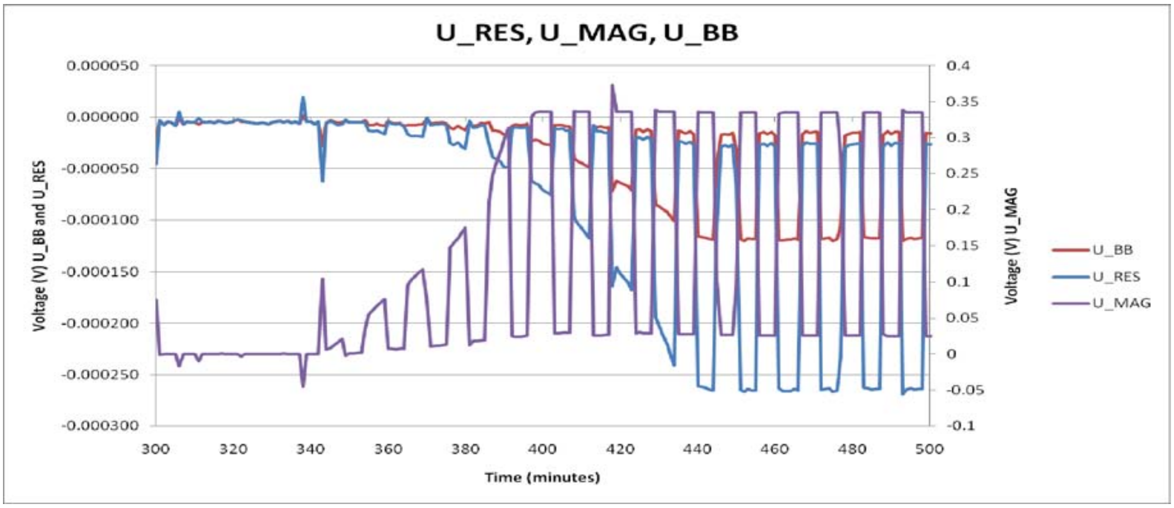


Figure 1: *Traces of four relevant signals close to magnet B12L6 during a superconducting to normal transition: U_MAG is the voltage across the magnet (right scale). U_RES is the raw signal of a bus bar segment and U_BB is the actual voltage across a bus bar segment after corrections for the voltage drop of the QPS cable.*

The voltage of all busbar segments in a sector (leading to the determination of resistance) is measured using the nQPS system. However, the nQPS system was not designed for this kind of measurements – corrections are necessary and are large. For this reason, apart from the measurement proper, an extra “calibration” step was taken.

Calibration is needed due the complex corrections necessary, amounting to more than 50% of the raw signal measured – see Figure 1. More than half the voltage recorded by the nQPS system is not due to a voltage drop in the bus bar segment, but due to a drop in the nQPS cables that take the signal to the voltage measuring device. This voltage drop is proportional to the cable lengths and their resistivity.

The calibration was performed by installing a series of ‘patches’ in about 10% of the bus bar segments of a sector that eliminated the voltage drops in the nQPS cables. This calibration gave a value for the resistivity per meter of the nQPS cables of 87mΩ/m with a preliminary uncertainty of 5%. The analysis presented here, still preliminary, uses one value for the resistivity per meter of the nQPS cables and thus does not take into account differences in the ambient temperature of the tunnel between different sectors. This (complex) analysis will be published in due time, but we can here present the results with systematic errors that will eventually be reduced. The results are shown in Figure 2. RRR values between sectors and between circuits are consistent and in the range 200-300.

The mean RRR of the copper busbar of the machine was found to be **250±50** (50 being the systematic error, taken as the maximum difference between RB and RQ circuits in one sector (40) and the maximum difference between different sectors (50) and is expected to be reduced in the final publication).

Therefore we can safely assume that the RRR for the whole machine is larger than **200**. The improvement on safe energy going from RRR=100 to RRR=200 is 0.2TeV per beam for “busbar propagation” quenches and 0.5TeV per beam for “gaseous He propagation” quenches.

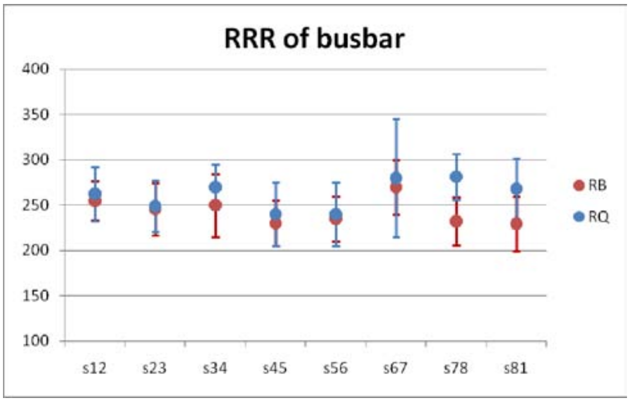


Figure 2: *The RRR values of the copper stabilizer measured for all sectors. The dot is the mean value and the spread the standard deviation of the measurements*

MAXIMUM SAFE ENERGY

The maximum safe energy of the LHC depends on:

1. The condition of the soldering of the superconducting cables of the interconnects. As we shall see, this does not pose a problem for LHC operation.
2. The condition of the copper stabilizer joints …
3. …coupled to a quench of the joint

Points (2) or (3) alone are not sufficient to produce a serious incident. A bad copper stabilizer joint will not run away if there is no nearby quench. But the combination of (2) and (3) will produce a thermal runaway if the condition of the copper stabilizer joint is worse than the limits calculated in [1].

[The burnout limit depends (amongst other things) on the RRR of the main busbars, as already discussed.]

Condition of superconducting cable joints

Superconducting joints are measured by estimating the resistance of a busbar segment at cold. The largest resistance seen is ~3nΩ which poses no problem for operation (compared with 300nΩ of the joint responsible for the accident of 19 September 2008). However, a question remains: do they deteriorate with time? Monitoring the resistances for a year has shown that no deterioration of cold resistances has been seen during 2010 (Figure 3) [3].

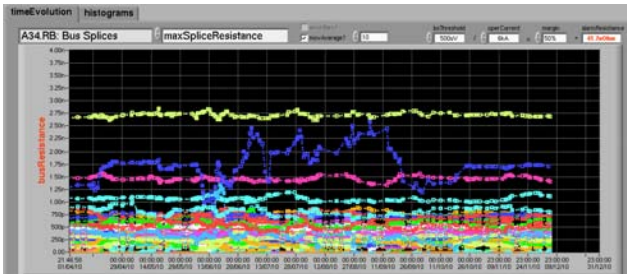


Figure 3: *Evolution of bus bar segment resistances at cold during 2010.No deterioration is seen. The blue trace belongs to a noisy QPS measuring board.*

Condition of copper stabilizer joints

The maximum safe energy of the LHC critically depends on the condition of copper stabilizer joints [1]. Unfortunately, our knowledge of the condition of these joints comes from a small and most probably biased sample of 134 joints (out of 10000 total in the machine) measured accurately in 2009. Out of these, 23 are above 20μOhms. The analysis fits a functional form on the distribution of these 23 values and this functional form is used to estimate the number of joints exceeding a specific threshold in all subsequent discussions on maximum safe energy of the LHC. The distribution and the fit are shown in Figure 4. The sample of the aforementioned 23 joints is from the RB bus only, and from 5 out of 8 sectors. We have no measurement of the stability of these joints with time (indeed there are scenarios where a joint resistance can deteriorate). This analysis is unchanged since last year [2].

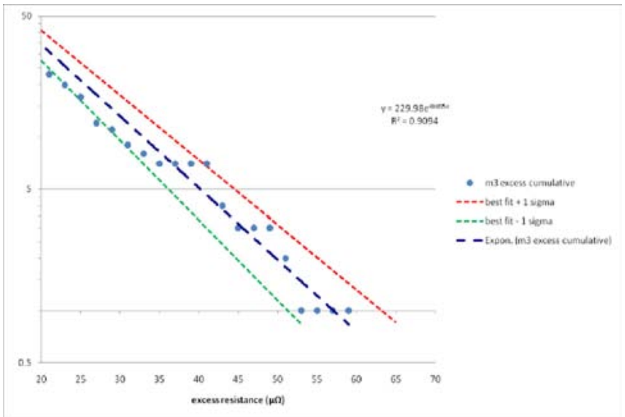


Figure 4: *The tail of the cumulative distribution of excess resistances measured accurately in 2009 (values larger than 20uOhms). An exponential function fits the distribution well (blue line). The ±1 sigma fit (red and green lines) is also shown.*

Quenches in 2010

One of the pleasant outcomes of this year's running, is that we have observed zero unintentional beam-induced quenches. This was mainly due to a well behaving, reproducible machine and a BLM system that intervened in time and prevented magnet quenches due to beam losses.

If we were sure that we will get zero quenches next year, running at ANY energy would be safe from the splices point of view. However, non-beam-induced quenches have been seen in 2010.

Quench statistics

A quick attempt has been made to look at how many quenches happened in 2010 (thanks to H. Reymond): The PM system is interrogated for cases where a/ there was a QPS signal present in the post-mortem files denoting a quench and b/ there was high current it the sector at the time (>5000A).

This gave a total of 27 events. Manual inspection of those revealed that 9 were not real quenches (no heaters fired). Three more quenches were identified manually that were missed by the automatic analysis. The categories identified were:

- Trip during PGC1: 11 quenches
- Provoked quench: 3 quenches
- Power cut: 5 quenches
- Other: 2 quenches

In conclusion, in 2010 we had about 20 quenches of the RB circuits above 5000A, due to various reasons.

For next year, we simply do not know how many quenches we are going to get. Therefore in what follows, the number of quenches is left as a free parameter.

SUGGESTED STRATEGY

As the probability of an accident, and hence the risk, is a function of both the condition of the copper stabilizer joints and the number of quenches (which is largely an unknown quantity for the year(s) to come), we found that the best way to present how safe it is to run at a specific energy is to calculate how many quenches we need per year before reaching a pre-defined incident probability level.

I have used 0.1% as the acceptable incident probability level (one incident every 1000 years), but the reader can easily translate the conclusions presented here to his favoured level.

In this framework, if the number of quenches we can "afford" is large, then operation is safe, and we would only need to re-assess the situation when this number of quenches is reached. If, however, the number of quenches we can "afford" is less than one, getting a single quench would put us above our pre-defined 'risk' level.

Types of events

Quench events can be broadly divided in two categories:

Prompt quenches, where the interconnect quenches first or at the same time as an adjacent magnet, are the most serious as they happen at the highest current. However, they are also the most unlikely (we had zero prompt quenches in 2010).

The other category is quench events where the magnet quenches first and the quench is propagated to the interconnect either through the busbar connecting the (rapidly heated) diode to the main busbar, or through the propagation of warm gaseous Helium. The gaseous Helium propagation speed has not been measured accurately, so a conservative value of 20 seconds is taken.

Quenching a quadrupole magnet has less severe consequences than quenching a dipole magnet due to the longer distances between the diode and the main busbar and due to the fact that less energy stored. A quench of a dipole or quadrupole magnet affects both the RB and the RQ circuits but it is important to note that the time constant of the energy extraction of the two circuits is very different: currently around 50 seconds for the RB and 10 seconds for the RQ.

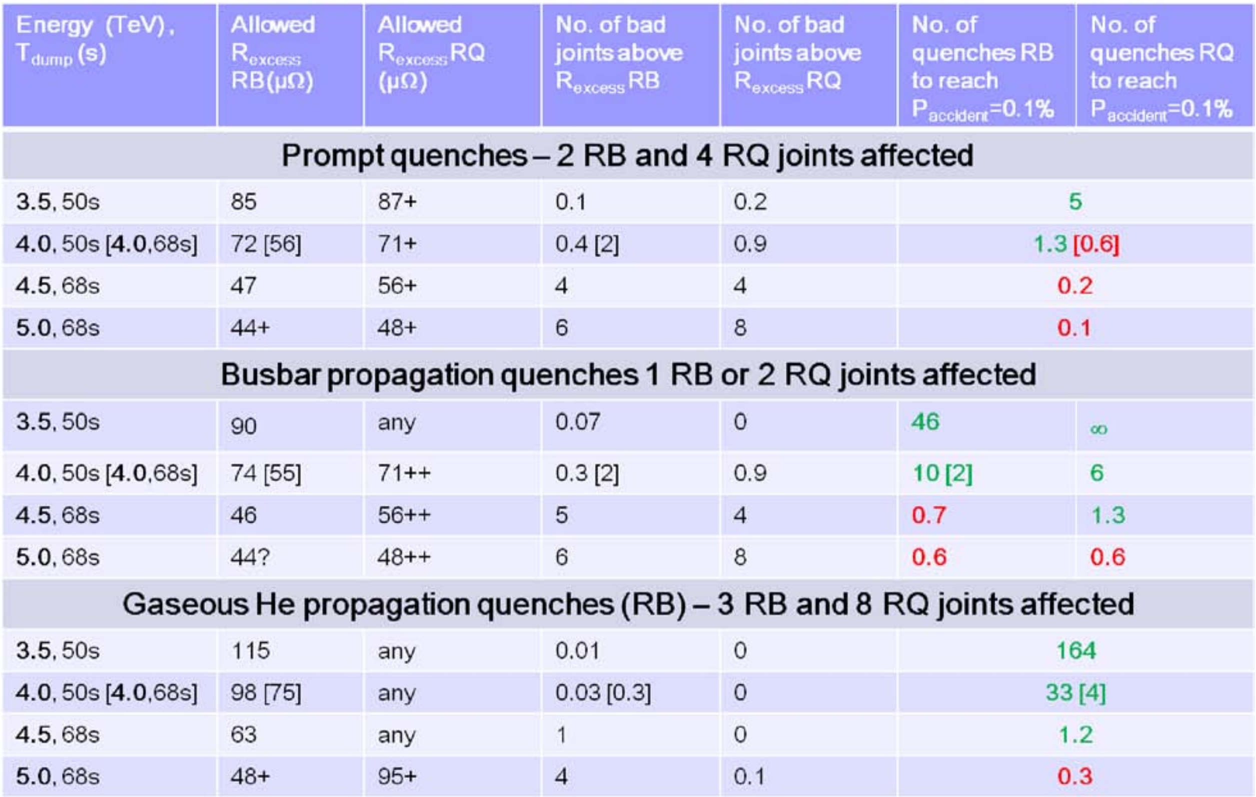
In summary, the types of quench events and their corresponding consequences are:

- **Prompt quench** of the interconnect region (beam induced). This is very unlikely since calculations show that the adjacent magnet has a quench sensitivity which is a factor 10^5 higher. The number of interconnects that will quench in such an event are 2 RB interconnects and 4 RQ interconnects.

- **Magnet quench** of a dipole magnet:
    - 1 RB interconnect will quench first from heat propagation through the busbar from the diode. This calculation is new this year and leads to more strict limits than the simpler calculation of last year's [1].
    - 3 RB and 8RQ interconnects will quench ~20 seconds later from heat transferred through gaseous Helium [this is only relevant for the RB circuit, as the RQ circuit will have most of its energy extracted in 20 seconds]
- **Magnet quench** of a quadrupole magnet:
    - 2 RQ interconnects will quench first from heat propagation through the busbar from the diodes. This calculation has not been performed yet in detail, but it is believed that it is less important than the RB case.
    - 4 RB and 6 RQ interconnects will quench in much more than 20 seconds later from heat transferred through gaseous Helium i.e. this failure mode is safe at the energies we are considering.

The table below shows in summary the maximum allowed defect at different energies depending on the failure more, the number of joints affected per quench event, the number of joints above the limit using the best knowledge of the state of interconnects taken from the fitted function of Figure 4, and finally the number of quenches to reach a predefined accident probability level of 0.1%. Some numbers presented in the second and third columns are taken from last year and have not been recomputed with the new values of RRR measured in the machine. Therefore they are conservative (denoted by a plus sign next to the number). For 4TeV operation, the numbers corresponding to two energy extraction constants are shown, 50 and 67 seconds [in square brackets]. The colour code of the last two columns is as follows: if one quench already takes us above the predefined accident probability, the number is green. If not (and therefore operation at this energy is risky after one quench) the number is red. In the case of prompt quenches or gaseous helium propagation quenches, it makes no sense to talk separately about the RB and RQ buses, so the last two columns are combined. Busbar propagation quench calculations in the case of the RQ circuit have not been performed, but the limits are believed to be much larger than the equivalent prompt quench cases (denoted by a ++).

Table 1: *Maximum excess resistance allowed, number of bad joints and number of quenches to reach an accident probability of 0.1%*



Energy (TeV), T_{dump} (s)	Allowed R_{excess} RB(μΩ)	Allowed R_{excess}RQ (μΩ)	No. of bad joints above R_{excess}RB	No. of bad joints above R_{excess}RQ	No. of quenches RB to reach $P_{accident}$=0.1%	No. of quenches RQ to reach $P_{accident}$=0.1%
Prompt quenches – 2 RB and 4 RQ joints affected						
3.5, 50s	85	87+	0.1	0.2	5	
4.0, 50s [**4.0**,68s]	72 [56]	71+	0.4 [2]	0.9	1.3 [0.6]	
4.5, 68s	47	56+	4	4	0.2	
5.0, 68s	44+	48+	6	8	0.1	
Busbar propagation quenches 1 RB or 2 RQ joints affected						
3.5, 50s	90	any	0.07	0	46	∞
4.0, 50s [**4.0**,68s]	74 [55]	71++	0.3 [2]	0.9	10 [2]	6
4.5, 68s	46	56++	5	4	0.7	1.3
5.0, 68s	44?	48++	6	8	0.6	0.6
Gaseous He propagation quenches (RB) – 3 RB and 8 RQ joints affected						
3.5, 50s	115	any	0.01	0	164	
4.0, 50s [**4.0**,68s]	98 [75]	any	0.03 [0.3]	0	33 [4]	
4.5, 68s	63	any	1	0	1.2	
5.0, 68s	48+	95+	4	0.1	0.3	

In conclusion, regarding the maximum safe energy of the LHC for 2011:

- The most stringent limits come from prompt, beam induced, quenches, considered unlikely. If we are confident we will get no prompt quenches, we can ignore the ‘prompt’ quench category.
- The most relevant limits come from the ‘bus propagation’ quenches, whose calculations are new this year.
- Some calculations (for 5TeV or for the RQ) have not been updated with the latest information (higher RRR) and will become less stringent.
- 4TeV operation with an extraction time of 50 seconds gives us some margin for all types of quenches, therefore 4TeV operation cannot be ruled out from the information we have about the state of the machine.
- However, 4TeV limits are more stringent than for 3.5TeV operation. Therefore, running at a higher energy needs to be balanced against pushing for higher luminosity this year, something that might result in a larger number of quenches than in 2010.

THE “THERMAL AMPLIFIER”

The need for a qualification tool

Up to now, with the splice consolidation campaign to take place in 2012, it was clearly not high priority to investigate ways of increasing the safe energy of the LHC. However, if 2012 will be a year of LHC operation, it makes sense to try and see if a test that fits in a period of (an expended perhaps) shutdown can be performed which might allow us to run at a substantially higher energy in 2012, say 5TeV.

The main reason for not being able to go higher in energy this year is that our current knowledge of the state of the copper stabilizer joints in the main circuits is very poor since:

- Not all sectors have been measured
- Different sectors that have been measured seem to have very different joint quality.
- Time degradation has not been studied and is a worry.

For this reason, the current safe energy analysis is based on (mostly) pessimistic assumptions, to counterbalance the above lack of knowledge.

A promising possibility is the ‘Thermal Amplifier’ [provisional name]. It is a qualification tool that can qualify a sector to the maximum current it can safely withstand. Since the idea was first conceived (by Howie Pfeffer and others), a lot of conceptual work has taken place (with a lot of input from A. Verweij), that has simplified the original idea considerably making it easier to implement. There are still a series of engineering challenges to be solved before we can put such a method into production, necessitating close collaboration of many different groups (EPC, CRG, MPE, etc.). Also, the very first ‘proof of principle’ test of the idea was performed – so this now is not simply an idea on paper.

Thermal amplifier principle

The thermal amplifier applies a pulse of high current (of order 3000A at 40K or 6000A at 20K) for about 10 to 20 seconds in a sector which is kept at non-superconducting temperatures (tests can be dome between 20K and 40K). Any bad splices selectively warm up, whereas good splices remain cold. A joint that warms up from 20K to around 200-300K, has its resistance increased by a large amount (order 100), hence it is easy to detect. What makes the operation safe and an important ingredient of the principle is that the current flows through the diodes, so very little energy is stored in the circuit. The other big advantage of the method is that it is a direct measurement of a thermal runaway at the exact conditions of a joint so no further assumptions are needed.

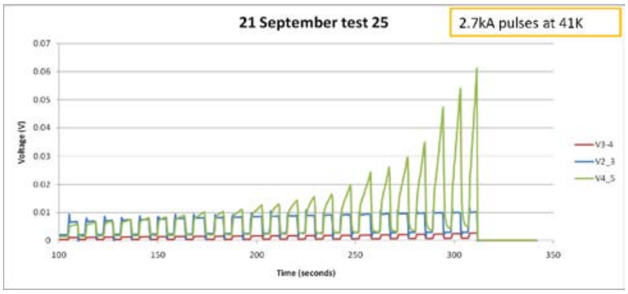


Figure 5: *Voltages across busbar segments during a number of 7s long pulses (every 10s) of 2.7kA at 41K. The green voltage contains a 50uOhm defect and runs away after about 30 pulses. The blue and red voltages are across perfect joints.*

The block 4 tests

A series of tests were performed in September 2010 in the Block 4 test facility (special thanks to M. Bajko, C. Giloux, J. Feuvrier). A defective joint (about 50µOhms) and a series of perfect joints were monitored as high current (2000A to 6000A) passed through the copper at temperatures varying from 20K to 40K. What was measured agreed with simulations (Figure 7) and valuable experience was gained.

Figure 6: *A picture of the defect machined out of a solid copper bar for the Thermal Amplifier tests in Block 4. This represents a defect of about 50uOhms at room temperature.*

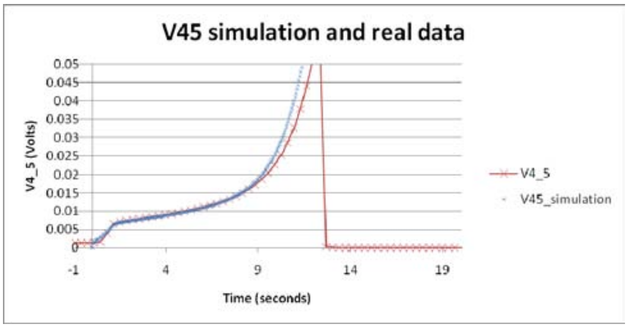


Figure 7 *Comparison of simulation (blue) and real data (red). The single current pulse in this test was 3200A. Initial temperature was 42K.*

A second test at Block 4 had to do with another important ingredient of the Thermal Amplifier idea: the diode turn-on voltage. For the RB, the total voltage budget of the power converter is 190V for 154 diodes (this corresponds to 1.23V per diode). The diode turn-on voltage has been measured extensively in the past, but not at the temperatures we are interested in. For this reason four diodes were tested in Block 4 at temperatures between 20K and 40K. The four diodes exhibited slightly different characteristics, with the maximum diode turn-on voltage at a specific temperature varying by as much as 0.5V depending on the diode (see for instance Figure 9 showing the voltage across the four diodes during a test performed at 35K.).

The diode test was inconclusive due to the large spread of values of turn-on voltages seen by the four diodes tested. If they are a representative sample of the diodes installed in the machine, then at 40K the current RB power converter might just be sufficient to ignite the diodes, simplifying the setup considerably. For operation at 20K, more measurements will be needed to determine if the power converter needs to be modified or boosted by an ‘igniter’ power supply.

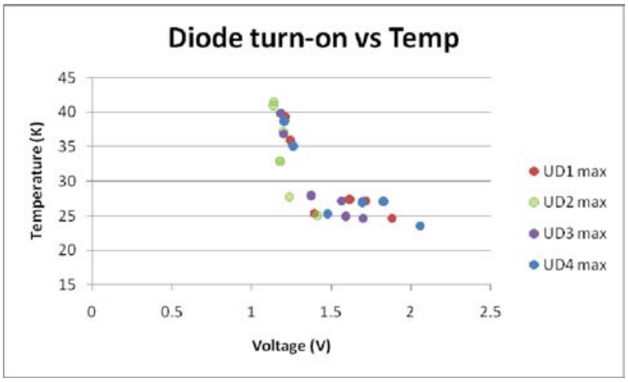


Figure 8: *diode turn-on voltage (max.) versus the temperature during the time of the highest voltage. At 40K, diode turn on is around 1.1V whereas at 25K 1.5 to 2V.*

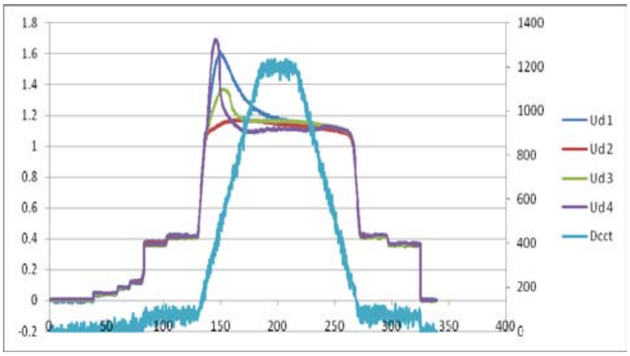


Figure 9: A typical diode test. *Diodes start conducting at 1.1V, their voltage initially rising before it finally drops to 1.1V after they heat up (left scale). The average maximum turn-on voltage is 1.4V. Right scale: current flowing through the diodes (in blue). Horizontal scale is time in seconds. This test was performed at 32K.*

Engineering challenges

As we have mentioned, there are a series of engineering challenges that need to be met in order to be able to implement the thermal amplifier concept, some of them briefly discussed in the previous section. For completeness, the challenges we need to solve before this idea goes to production are the following:

- The DFBs might need to be cooled to a different temperature than the rest of the arc (CRG group)
- The voltage budget of the power converters to be used needs to be sufficient (EPC group).
- Safety should be ensured either with a very robust procedure or with an interlock (MPE group)

It is worth mentioning here the worst case scenario, if for any reason the safety systems should fail and thermal runaway ensues during a Thermal Amplifier test:

- The joint that run away will be destroyed
- The energy stored in the circuit is minimal, so no other damage will take place

- The vicinity of the joint (a cryogenic subsector) would have to be warmed up, opened up and repaired

Although such a scenario is clearly undesirable, the fact that the test is performed with such small energy stored in the magnets means that the consequences are not catastrophic.

Resources and time estimate of a possible project

If such a project is approved with the intention to perform tests on all sectors during the 2011-2012 Christmas shutdown, a series of milestones would first need to be achieved. Such milestones include:

- Proof of principle. This is already done.
- Verification of the voltage budget; what is available now with no modification might just be sufficient, but some more tests are needed.
- An interlocking scheme needs to be defined.
- The best temperature to perform the test would need to be defined. This will be between 20 and 40K.

Here we should also mention that the RRR measurements performed during the 2010-2011 Christmas technical stop have good synergies with an eventual thermal amplifier test, as many components are the same (nQPS, etc.). For this reason, the experience gained during the RRR tests will be very useful to the project.

Regarding the time estimate for performing such a test, we estimate we need ~4 weeks for a type test (the first sector) and then ~3 weeks for all other sectors, with the possibility of sector overlap. From the point that cryogenic conditions have been established and after a type test has taught us how to use the system, we believe we can perform the measurements of two sectors in parallel in one week (the figure of two sectors comes from the assumption that special QPS cards for the interlock will be manufactured for two sectors).

The project could possibly be divided into three phases: an in-depth study (about 3-4 months); preparation (about 3-4 months); and production (~ 3 months). After phase 1, an external review would be desirable. Manpower resources estimate for phase 1: a minimum of 1.5FTE of an engineer. For phase 2: 1.5FTE of an engineer plus 1.5FTE of a technician. The production phase will take more resources (but for a shorter period).

CONCLUSIONS

Recent RRR measurements indicate that we can safely assume an RRR of 200 for the copper stabilizer of the main circuits of the LHC.

Given the (lack of) knowledge of the excess resistance of the copper stabilizer joints, running at any energy carries a certain risk.

The maximum number of quenches before we reach a pre-determined level of accident probability has been presented as a function of energy.

A qualification method (the thermal amplifier) has been presented that will allow us to run at the highest possible energy with very little risk.

A thermal amplifier campaign can fit in the 2011-2012 shutdown.

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IMPLICATION OF INCREASED BEAM ENERGY ON QPS, EE, TIME CONSTANTS

J. Steckert, CERN, Geneva, Switzerland.

Abstract

Increasing the beam energy of LHC is coupled with an increase in current in the main dipole and quadrupole circuits. This paper will show the implications of increased beam energy on the circuit protection (CP) systems. Relevant system details and their limits will be discussed for several operational scenarios. The main focus lays on the system's behavior during the fast power abort (FPA) which is the most challenging mode of operation. Furthermore measures to mitigate the EM-transients during FPAs are shown.

CURRENT SITUATION

During the 2010 run, LHC was operated at an energy of 3.5 TeV. The main bending dipoles as well as the quadrupole magnets had been commissioned up to a current of 6kA. This is half of the nominal current. Minimizing the risk for the magnet interconnects, the energy extraction (EE) time constants had been reduced to τ=52s for the main dipoles and τ=10s for the main quadrupole circuits [1]. Operating with half the current but also half the time constant during EE the voltages in the systems are equivalent to nominal settings (12kA/104s). The 2010 run period had shown that the most challenging situation for the quench protection (QPS) and EE systems is the fast power abort. During this event high inductive and resistive voltages as well as electromagnetic transients and interferences are present. At the same time the QPS system should operate reliably with rather low detection thresholds. Hence the main focus of the next paragraphs will be on energy extractions and their effects on the circuit protection.

SYSTEM OVERVIEW

The picture below shows a schematic layout of a LHC 13kA dipole circuit. 154 bending dipoles are connected in series with two energy extraction systems at both sides of the arc. The power converter is in series with the even-point extraction system. All the relevant voltages which occur during a fast power abort are marked in the drawing.

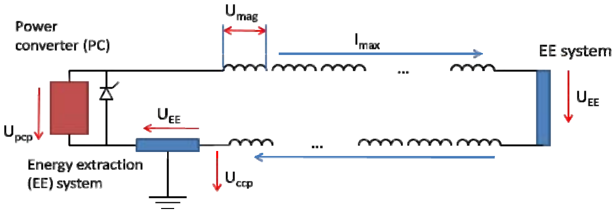

Figure 1 Main circuit schematic

U_{mag} is the voltage drop over a single super conducting magnet. The symmetric quench detection board of the nQPS measures this voltage and compares it to the adjacent magnets to detect a symmetric quench. U_{mag} at the beginning of a fast power abort can be calculated with (1)

$$U_{mag} = \frac{(2*R_{dump}*I + m*U_{diode})}{154 - m} \tag{1}$$

where R_{dump} is the resistance of the energy extraction resistor, U_{diode} is the forward voltage of the cold diode parallel to each resistor and m is the number of quenching magnets. Given this equation, the magnet voltage is primarily dependent on resistance and current and in second order dependent of the number of quenched magnets ~100mV per quenched magnet.

U_{EEmax} is the voltage drop over the energy extraction resistor. As shown in (2) U_{EEmax} is determined by the value of the resistor and the current in the circuit at the moment of the EE switch opening.

$$U_{EEmax} = R_{dump} * I \tag{2}$$

Another important parameter is the time constant of the circuit during EE. It can be calculated with (3)

$$\tau = \frac{L}{2*R_{dump}} \tag{3}$$

Where L is the inductance of the circuit and R_{dump} is the energy extraction resistor value. Since L is fixed, the dump resistor value is the only way to change the time constant of the circuit. Connected to the time constant is maximum di/dt during the EE. It is

$$dI/dt = I/\tau \tag{4}$$

where I is the Current in the circuit at the beginning of the energy extraction

The following table shows the limits of the parameters introduced above

System	Main Dipoles	Main Quadrupoles
Cold circuit peak voltage U_{ccp}	< 1900V (1600V*)	< 240V
Energy Extraction U_{EE}	< 1300V	< 200V
Common mode power converter U_{pcp}	< 1000 V	< 420V
Max di/dt magnets	120 A/s	350 A/s
oQPS max di/dt	< 150 A/s	<1000 A/s
nQPS SymQ U_{mag}	< |14.5V|	< |14.5 V|

Table 1: General system Limits

SYSTEM DETAILS

The following subsections will briefly describe the relevant system details which lead to the values in shown in Table 1.

Energy Extraction System

The main limit of the EE system is the maximum voltage over the EE switch. Dedicated tests had shown that a voltage up to 1300V for the dipole switches is tolerable. Beyond that point the arc shuts of the switch cannot extinguish the electrical arc anymore. For the quadrupole circuits this limit is at 200V due to a modified arc shut. For all dipole configurations shown in Table 2 the switch voltage is not a limiting factor. However the rating of the quadrupole switch starts to be an issue from beam energies beyond 4TeV. To reduce the electrical arc during switch opening and hence the resulting EM transients, snubber capacitors can be installed in parallel to the switch. Tests had been shown that the arcing is reduced considerably. The figure below shows the snubber capacitors installed inside a 13kA switch sonic cabinet.

Figure 2 Snubber capacitors installed on a 13kA switch

Another integral part of the EE system is the energy extraction resistor which absorbs the energy stored in the circuit. The configuration of the dump resistors is the only way to vary the time constants of the main circuits. Given the actual design of the resistors time constants of 104s, 68s, 52s, and 34s are possible for the dipole circuits. The quadrupole circuits can be configured to 10, 12 or 15s time constant.

Old QPS system

This system is the primary quench protection of both, dipole and quadrupole circuits. Based on analogue measurement bridges, one of the limiting parameters is the change in current. Above a di/dt of 150A/s the difference in inductance between the apertures of the magnet will unbalance the measurement up to the quench detection threshold of 100mV. This effect as well as the EM transient caused by the arcing switches can lead to spurious heater firing. While the di/dt limit gets critical around 4.5TeV/52s operation, the EM transients caused by the arcing switches is already an issue for 6kA operation. Fig3 shows the signal of all oQPS detectors of one sector during a fast power abort

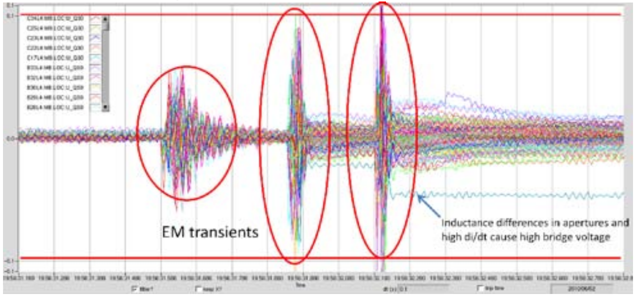

Figure 3: oQPS bridge signal during FPA

As shown above the electrical arc during switch opening is clearly visible in the aperture difference signal of the oQPS detectors. As mentioned above, snubber capacitors will mitigate the arcing and hence the EM transients.

New QPS system

The nQPS system consists of the bus-bar splice protection board and the symmetric quench detection system. Since the bus-bar supervision board is not active during EE, the remaining system is the symmetric quench detection board (SymQ). The symmetric quench detection board is measuring the voltage across four electrically adjacent magnets and compares them. If any of the differences between these voltages is exceeding the threshold the respecting heater is fired. The limiting factor of this component is the maximum input voltage. The ADC of this system is saturating at a voltage across a single magnet of |15.5V|, hence the protection is not assured beyond that value. Given some margin the limit for normal operation is |14.5V|. According to (1) each quenching magnet increases the voltage load on the other magnets. Therefore the operational parameters have to be chosen with an additional margin allowing a number of simultaneous quenching magnets without exceeding the voltage limits. Another important parameter of the symmetric quench detection is the threshold. In the actual setting the threshold was calculated for a current of 6kA, any operation beyond that current requires a new (lower) detection threshold. Figure 4 shows the difference signal of one SymQ board during an energy extraction from 5.8kA. As shown, the biggest differences in U_{mag} appear during the switch opening.

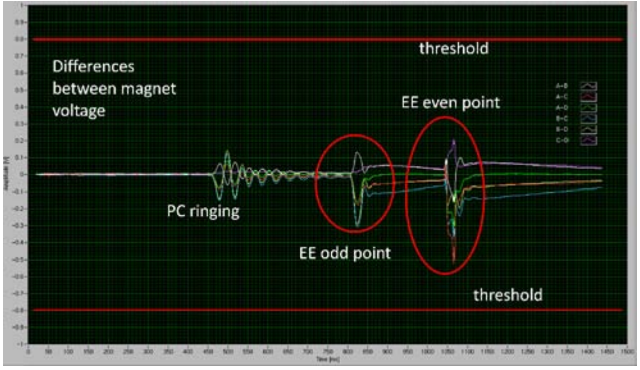

Figure 4: dUmag of SymQ during FPA from 5.8kA

SYSTEM LIMITS VS OPERATIONAL PARAMETERS

Given the system limits defined by the properties of the various system elements it is possible to crosscheck these limits with the operational parameters for several beam energies. As mentioned above, the two variables are the beam energy and the time constant. Table 2 shows the operational parameters and highlights violations of system limits.

	τ[s]	I_{RBc} [A]	U_{EE} [V]	U_{mag} [V]	di/dt [A/s]	τ [s]	I_{RQc} [A]	U_{EE} [V]	U_{mag} [V]	di/dt [A/s]
Circuit	**RB**					**RQ**				
3.5 TeV	52	6000	882	11.5	116	10	6000	□74	2.3	609
4 TeV	52	6000	999	13*	130	10	6400	187	2.4	655
4 TeV	68	6800	768	10	100	15	6400	120	1.6	421
□.5□TeV	52	7650	1125	**14.6**	146	10	7200	**209**	2.7	731
4.5 TeV	68	7650	864	11.2	112	15	7200	135	1.7	747
5 TeV	52	8500	1250	**16.2**	**162**	10	8000	**232**	3	812
5 TeV	68	8500	961	12.5	125	15	8000	150	1.9	527

Table 2: Selected system parameters for different beam energies. The numbers in **bold** exceed one of the limits set in Table 1. Figures with light gray background are close to the limit.
*15 quenching magnets will increase this value to the limit of 14.5V

Dipole circuit

The current operational state is shown in the first line of Table 2: a beam energy of 3.5 TeV with a time constant of 52s. This setting does not violate any of the system limits. If the energy is increased to 4TeV without changing the time constant, a maximum di/dt of 130A/s is exceeding the magnets' rated di/dt. Since this rating is only slightly violated and furthermore the current is still far below the max current this should be not an issue. Another parameter which comes close to its limit is the U_{mag}. With 13 volts it is still 1.5V below the limit however, 15 quenching magnets would increase this value to 14.5V. Nevertheless operation at 4TeV with 52s time constant is still regarded to be possible. Realizing the 4TeV with a time constant of 68s relaxes all critical parameters for the CP system.

Any energy beyond 4TeV cannot be operated with 52s time constant due to the violation of at least one critical parameter. However, if a time constant of 68s is chosen the system limits would permit operation up to 5TeV.

Quadrupole circuit

As shown in Table 2 the quadrupole circuit is less critical concerning most of the parameters. The time constants can be varied between 10 and 15s. With the 10s setting as it is in the moment. Operation up to 4TeV is possible. Beyond that energy the time constant has to be increased to 15s. Overall the quadrupole circuits which are limited by the 200V switch rating are less critical than the dipoles circuits

OPERATION SCENARIOS

To further evaluate the different constraints, limits, risks and benefits. The following paragraphs show different scenarios of operation and discuss the advantages as well as the risks.

Current settings (A)

This scenario neither increases beam energy nor include any hardware changes. The following table shows the pro and contra points of this scenario.

Pro	Con
No hardware changes	No physics gain
Proven, reliable operation	Arcing on switches persist
No increased risk for BB splices	Spurious heater firing on oQPS

Current settings + snubber capacitors (B)

Snubber capacitors are a good way to reduce the overall stress to the system caused by electrical arcs in the switches. Especially the oQPS will profit from these devices.

Pro	Con
Reduced switch arcing	No physics gain
Less system stress	Hardware modifications
No increased risk for BB splices	

4TeV, no hardware changes (C)

This scenario leaves the hardware of the circuit untouched and just increases beam energy.

Pro	Con
Physics gain	Increased EM transients
No hardware changes	Increased BB splice risk (higher current)
	Higher probability for spurious QPS triggers

4TeV, snubber capacitors (D)

This scenario leaves the time constant at 52s but snubber capacitors are installed across the dipole switches. The table below shows the risks and benefits.

Pro	Con
Physics gain	Increased BB splice risk (higher current)
Reduced switch arcing	Hardware modifications

4TeV, increased time constant (68s), snubber capacitors (E)

This scenario is the best for the CP systems as it greatly reduces the overall system load during EE which would lead to reduced false triggering.

Pro	Con
Physics gain	Further increased risk for BB splices (higher current and time constant)
Reduced switch arcing	Hardware modifications
Less system stress	

4.5TeC, increased time constant (68s), snubber capacitors (F)

Another scenario which is possible from CP point of view is the operation at a current equivalent to 4.5TeV beam energy and a time constant of 68s. While these settings are not violating any limits of the circuit protection systems, the additional risk for the splices makes this scenario rather unlikely

Conclusion

As it can be clearly seen in the scenarios above, the benefit of longer time constants for the CP system are contradictory for the bus-bar splice risk. A good balance between the risks has to be found to operate the circuits in an optimal way. The following graph shows the beam energy versus the time constants versus the CP systems' limits and the risk for the bus-bar splices. The points of operation for the different scenarios are marked.

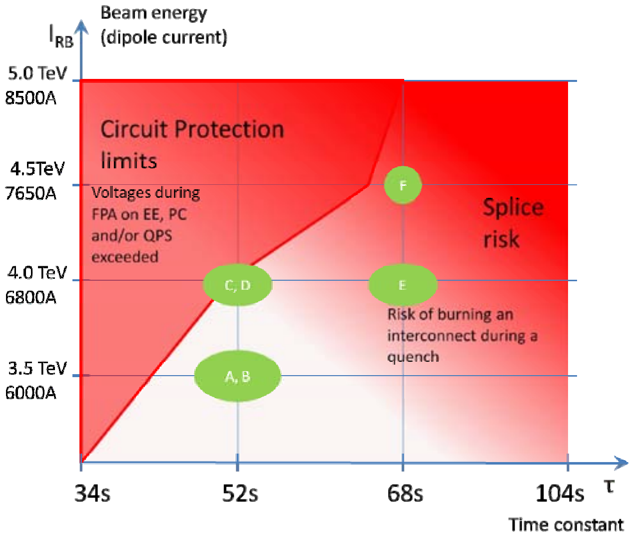

Figure 5 System limits vs. beam energy, time constant an possible points of operation

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WHAT NEEDS TO BE DONE TO REACH BEAM ENERGY ABOVE 3.5TEV? COMMISSIONING OF ESSENTIAL MAGNET POWERING AND MACHINE PROTECTION SYSTEMS.

N. Catalan Lasheras CERN, Geneva, Switzerland.

Abstract

After the initial plans in 2007 to run the LHC at 7 TeV, a number of unexpected events, and the extended knowledge of the machine that came after them, have convinced us to gradually reduce the beam energy to the current 3.5 TeV. As a consequence of this, some circuits have been commissioned to different energy levels. Some systems, as the quench protection system, are working at a reduced level of accuracy based on less demanding conditions. Non-conformities that were unacceptable for higher energy have no consequences at the current energy and are thus accepted. In this contribution, we will review the current status of commissioning of all the circuits and estimate the time and effort necessary to make all circuits operational at higher energies. All existing nonconformities that need to be solved before increasing the energy will be reviewed.

INTRODUCTION

During the different stages of installation and commissioning, a number of non-conformities or performance issues have been revealed since 2007. The paper will be divided between the most critical non-conformities revealed during the electrical quality assurance (ElQA) campaigns, and the performance issues revealed during both ElQA and hardware commissioning. While the first two cases limit very clearly the current in the circuits and thus the beam energy, performance issues, unsolved mostly in corrector circuits, have a less clear impact on the beam energy.

The last part of this review deals with a series of measurements that have not yet been done in the superconducting circuits, but that are deemed necessary to go to higher energies. The energy to which we can go without them is not defined precisely.

ELECTRICAL NON CONFORMITIES

During the first phase of hardware commissioning, a campaign of electrical qualification of all LHC superconducting circuits is done in the tunnel [1]. At this stage, the continuity of circuits, the proper functioning of the current leads and the insulation of each circuit and of the quench heater circuits are checked. The most serious electrical problems are revealed at this time. Two main non-conformities have been found that limit the use of circuits during operation:

MQXA quench heater insulation [2]. The insulation of one out of the two quench heater circuits inside the RQX1.R1 did not fulfil the acceptance criteria. It broke down consistently around 1100V which is the qualification voltage for this component. As the maximum voltage is defined by the quench heater discharge capacitor, this value is independent from the beam energy. For operation at 3.5 TeV, working with the remaining quench heater circuit was judged sufficient and the faulty circuit was simply disconnected. For increasing the energy, the full protection has to be restored. Two solutions were discussed:

1. Limit the charging voltage of the capacitor to 400V. The energy delivered to the magnet during a quench will be lower and the protection less effective. However, simulations and extrapolation from prototype measurements done in KEK indicate that this situation would be sufficient even for nominal beam energy [3].
2. Increase the capacitor value in order to lower the charging voltage by discharging the same energy into the quench heaters. This solution is the preferred option and will require a rather simple change of hardware. The lead time for the procurement of the capacitor is however rather long and this cannot be implemented during the present Christmas break.

Both solutions will allow going to nominal current and energy. The required intervention can be done at any time as soon as the hardware is ready.

B30R7 insulation weakness [4]. During the qualification of the RB.A78 circuit, a breakdown appeared around 1.6 kV instead of the nominal qualification voltage of 1.9 kV. The insulation breakdown was localized inside the B30R7 dipole (MB1007) by the use of oscilloscopes [5]. The fault being inside the cold mass, there is no possibility to repair in-situ.

The qualification voltage is defined as the maximum operating voltage that the circuit might experience and has, for the case of the dipole circuit, two components. The first part (600 V) comes from the energy extraction resistance and the common mode voltage in the converter in case of short. This contribution is not energy dependent and cannot be reduced. Only a change in the energy extraction resistors and thus in the decay time for the RB circuit during a fast power abort will decrease the maximum voltage. This solution is however not considered safe until the splice consolidation has been done. The second part (1300 V) comes from the quench development inside the coil and scales down with current and beam energy.

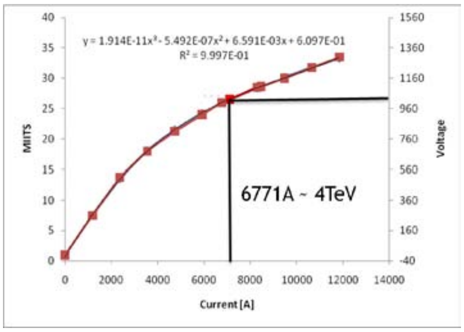

Figure 1: Simulated MIITS (A. Verweij) for the main arc dipole in LHC against current and the equivalent voltage developed in the coil.

Extrapolating from MIITS measurements in the main dipole (see Figure 1), a reduction of 300V in the voltage developed during a quench will mean a reduction of 3TeV. The maximum beam energy for which the use of this magnet is still safe is 4 TeV. Above that energy, the magnet should be replaced.

PERFORMANCE ISSUES

During the hardware commissioning, a number of NC have been revealed during the years [6]. These problems affect mostly the performance of the circuit and the maximum current at which it can be routinely operated. As they affect mostly corrector circuits, the performance loss did not impact the operation in 2010. Their impact at higher energies should nevertheless be taken into account.

Training non-conformities. A number of circuits have experienced quenches during hardware commissioning. At the time of commissioning in 2009/2010, the training was stopped and the nominal current decreased to save time. There is however no reason why the circuits will not go to higher currents. Figure 2 shows the training of RCD circuits both in 2008 and 2009. In this particular case, every circuit containing 77 magnets experienced one to seven training quenches before reaching 550A. Still all of them reached nominal during the 2008 campaign.

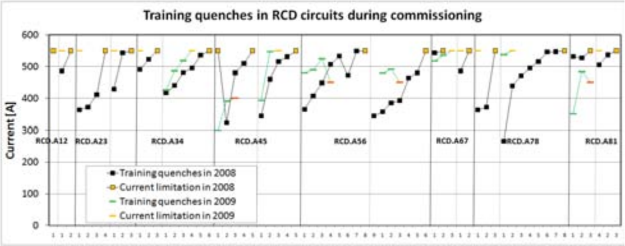

Figure 2 Quench history of all RCD circuits during the hardware campaigns 2008 and 2009. (S. Le Naour)

Similar results were observed for RQT/RQTL circuits in which several training quenches should be needed before reaching nominal current. Only the case of RQTL8.L7B1 should be considered anomalous as the circuit is showing detraining (quenches at 300 A, 245 A in 2008 and 240 A and 257 A in 2009). The circuit is currently limited to 200A and further studies will be necessary if this limit is insufficient.

Inner triplet 600 A corrector circuits. For these circuits, the present cooling scheme of the current leads may become unstable at current higher than 400A [7]. There are plans to consolidate the cooling procedure during the last long shutdown but, until then, the current in the circuits is limited to 400 A. Besides, the horizontal and vertical orbit corrector of the same module are nested which means that the voltage developed in one coil, while the other is ramping, will trigger the QPS detector. As a consequence, even if single circuits have been commissioned to 400A, the synchronous powering of the horizontal and vertical corrector in the same module cannot exceed 300 A.

RSD/RSF circuits. The QPS protection is unable to distinguish between a resistive transition and an inductive voltage in very short time. This limits the maximum ramp rate for circuits with high inductance like RSD/RSF circuits or RQ6 in IP3 and IP7. Future development of the QPS detectors and software will improve the situation but for the moment, the ramp rate of RSD/RSF circuits is limited to 0.15A/s.

Orbit corrector problem. It affects mostly MCBY and fewer MCBC magnets. The problem shows as instability on the control by the power converter. A parallel resistance needs to be added to the model of the load in order to stabilize the current. However, some of these circuits quench when decreasing the absolute current in the circuit. In other cases, they sustain the nominal cycle but quench as soon as a fast power abort is started. The limiting current stays constant without apparent degradation.

Table 1: Orbit dipole circuits affected by a performance problem. The parameters at which they were commissioned and the NC number in EDMS.

Circuit name	Commissioned parameters	NC number
RCBYHS5.R8B1	20A. 0.6A/s	1063839
RCBYV5.L4B2	50A, 0.5A/s	1049055
RCBYH4.R8B1	50 A, 0.67A/s	1051795
RCBYHS4.L5B1	50 A, 0.67A/s	1053709
RCBCV8.L1B2	-	NA
RCBCV8.L1B2	-	NA
RCBYH4.L2B2	-	NA
RCBCV7.L2B2	-	1084849
RCBYHS4.R2B1	-	1028324

The full list of affected magnets is shown in Table 1. The first four circuits are limited either in current or in ramp rate and five more show this behaviour only after a fast power abort, which generates very high ramp rates.

Two more circuits have recently been identified as showing similar behaviour and are presently under investigation.

A possible explanation for this observation is a resistive short circuit between two layers in the coil. Figure 3 shows the schematic shorted circuit. Simulations with such model seem to confirm the observed behaviour. A test using a modified magnet with a set of extended instrumentation is scheduled for April in the new SM18 vertical cryostat facility. This will allow verifying this hypothesis.

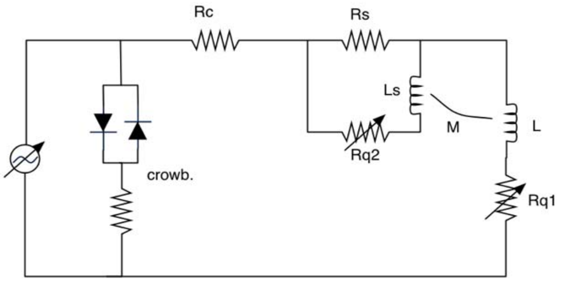

Figure 3: Electrical schematic of a dipole corrector in which one group of coils will be short-circuited. The final configuration would include two independent coils with a mutual inductance.

Unfortunately, the current in these circuits cannot be raised. If stronger correction is needed at any beam energy, new cryo-magnets should be put in the machine or additional warm correctors should be added. Both solutions will only be possible during a long shut-down period.

Open or resistive circuits. A number of circuits have been condemned during the ElQA and hardware commissioning campaigns (see Table 2). In the first two cases, the circuit is open. For RCO.A81B2 circuit, the discontinuity was localized by the ElQA team in the tunnel between B12L1 and B11L1. The last two circuits in Table 2 were found too resistive during ElQA and powering tests and have been condemned and the converter removed. Localization of the resistive segment for the RCO circuit should be possible using high precision voltmeters in the tunnel.

Table 2: Condemned superconducting circuits in the LHC due to serious non conformities.

Circuit name	NC number	Comment
RCOSX3.L1	948545	Open circuit
RCO.A81B2	955048	Open circuit
RCO.A78B2	1029807	Resistive splice
RCBH31.R7B1	1017094	1 mOhm

Reconfigured QPS protection. Quench heaters are a very important element for the integrity of the magnet. If the QH circuit is damaged, the activation of the heater stripe and protection of the magnet against quench cannot be ensured. Besides, if the QH strip itself is damaged, discharging the capacitors in it could damage the magnet itself and have serious consequences. For this reason, quench heaters integrity is evaluated often during operation. During the ElQA campaign and during individual system tests of the QPS, a number of QH circuits have been found defective, (bad insulation, too resistive, open or not discharging smoothly). In these cases, after verification of the insulation between heater and coil, the protection scheme has been reconfigured in order to use the available spare quench heaters. Up to now, the QPS protection has been reconfigured in eight dipole magnets, and two insertion quadrupoles. The new protection scheme is redundant in all cases, except the RQX1 mentioned earlier, and allows operating the magnet up to nominal current of 7 TeV equivalent. Nevertheless, some of these magnets, for which the QH circuit fault is suspected to be inside the cold mass, will be changed during the next long technical stop for in-depth investigation. No case has been revealed yet during operation.

ADDITIONAL DIAGNOSTICS

In addition to the faults found during the standard electrical and powering tests, a number of potential risks have been identified for which additional or modified tests will be required. The energy at which we can drive the LHC beam is not clearly defined in this case, but the measurements should be done as soon as possible or, at the latest, before the next long technical shutdown to have the chance to repair in case of confirmed fault.

Bus-Bar resistance measurements in the insertion magnets. During the international reviews following the 2008 incident, it was recommended to measure all the splices in the machine done during interconnection. A new QPS system was deployed in 2009 to monitor and protect the main quadrupoles and dipoles in the arc. The insertion magnets individually powered are not as critical because the bus-bar and interconnection splices are protected at the same level as the internal coil by the current QPS system. However, no monitoring of the bus-bar resistance is done, as for the arc magnets. A campaign of electrical measurements started in 2010 to characterise every bus-bar of the individual powered quadrupoles in the dispersion suppressor and matching section. Up to now, all the circuits in the continuous cryostat have been measured and no evidence of a resistive splice has been found. The measurements are done during technical stops using mobile equipment and the test in one circuit takes about one hour. The rest of the circuits in the matching section, separation dipoles, and inner triplet, need to be measured before the beginning of the long shutdown so that eventual faults can be repaired. Measuring them all during technical stops in the next two years seems feasible.

Improved high voltage testing. During the recent investigations of the splice consolidation task force [8], it was noticed that the withstand voltage at which every circuit is tested in the tunnel during electrical qualification, might not be adapted to the real conditions in the machine. Indeed, this voltage had been defined for individual testing of the insulation of each circuit versus ground [9]. However, the worse voltage conditions happen simultaneously for all the circuits in a powering sector during a global power abort triggered by an emergency dump. In theses conditions, the relative voltage between circuits is, in some cases, higher than the specified one. The reference documents used for the electrical quality assurance are being updated. However, stressing the circuits to new values has a certain risk and should be avoided. A campaign of testing at this new voltage values should be planned at the end of the present run or before the long shutdown, in order to identify possible weakness of the insulation and have a chance to repair them. The time required to perform this campaign together with the localization of faults already known is estimated to two weeks.

CONCLUSIONS

Two electrical non-conformities limit the current beam energy in LHC. While the quench heater systems in RQX1.R1 can be recovered quite quickly, the voltage breakdown in dipole B30R7 is more serious and no other solution than changing the magnet seems feasible to go above 4TeV. Several performance issues in corrector magnets have been described and their limitation given in terms of current in the circuit. The impact on the beam energy has to be evaluated by the BE/ABP group.

Finally, some diagnostics are recommended before increasing the beam energy. The list is not exhaustive and will be improved before the next long shutdown. However, they do not seem to be limiting the energy bellow 4TeV.

ACKNOWLEDGEMENTS

This work was made possible thanks to the joint effort of all the MP3, ElQA, and hardware commissioning teams working jointly in the CCC and the tunnel to make sure the LHC superconducting circuits perform better than expected and needed.

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CONSEQUENCES OF A HYPOTHETICAL INCIDENT FOR DIFFERENT SECTORS

F. Bertinelli, S. Claudet, C. Garion, J.M. Jimenez, V. Parma, A. Perin, R. Schmidt,
L. Tavian, J.P. Tock & R. van Weelderen, CERN, Geneva, Switzerland.

Abstract

During the 2009 long shutdown, the LHC machine has been partially consolidated by adding safety relief devices in order to better protect the cryostats against large helium release and consequently to mitigate the risks of collateral damages. After recalling the present relief valve implementation and other mitigations related to the collateral damages, this paper describes the damage process of a hypothetical incident, presents its consequences for the different sectors and for beam energies up to 5 TeV with emphasis on the induced downtime.

INTRODUCTION

The 19th September 2008 incident of LHC [1] has created heavy wide-spread damages and collateral damages of the machine like:

- He vessel and beam pipe perforation,
- mechanical damage of MLI,
- contamination by soot of MLI and beam pipes,
- contamination by MLI of vacuum enclosure and beam pipes,
- buckling of bellows,
- rupture of supports and ground anchors,
- damage to tunnel floor,
- mechanical damage to interconnects,
- secondary electrical arcs.

Following this incident, the machine has been repaired and partially consolidated in 2009 in order to restart the operation of the machine at reduced beam energy of 3.5 TeV, i.e. at reduced currents in the main magnets. The new protection scheme of the vacuum enclosure implemented to prevent or limit the pressure build-up in case of large helium release is defined [2]. The long straight sections are fully consolidated, except two Q6 quadrupoles (in R2 and L8). The continuous cryostat of sectors S1-2, S3-4, S5-6 and S6-7 are fully consolidated, as well as the most critical subsectors of the continuous cryostat of the sector S4-5. The remaining parts of the machine are partially consolidated.

A hypothetical electrical arc could appear in a cryo-magnet interconnect like during the September 2008 incident or in a cryo-magnet coil like during the Noell 4 incident in SM18. The corresponding consequences on the machine damages are different and are developed here after for beam energies varying from 3.5 to 5 TeV.

MAXIMUM CREDIBLE INCIDENT UP TO 5 TeV IN CASE OF AN ELECTRICAL ARC IN A MAGNET INTERCONNECT

In case of an electrical arc in a cryo-manget interconnect, up to 3 interconnect lines containing main electrical bus bars can be damaged. However, the corresponding discharged helium flow from the cold-mass circuit to the vacuum enclosure is limited by the free cross-section of the cold-mass laminations which corresponds to 2 x 60 cm^2 [3]. This total cross-section can be created already at a main magnet current of 6 kA corresponding to a beam energy of 3.5 TeV. For the continuous cryostat of LHC, the discharge mass-flow through this breach corresponds to 30 kg/s.

Leaving the cold-mass, the discharged helium is then heated by the power dissipated by the electrical arc. The temperature of the helium heated by the electrical arc power and which has to be discharged through the safety devices protecting the vacuum enclosure depends on:

- the stored magnetic energy,
- the current discharge time constant,
- the heat transferred by convection from the environment.

Figure 1 shows the stored magnetic energy and the discharged helium temperature as a function of the beam energy for the continuous cryostat.

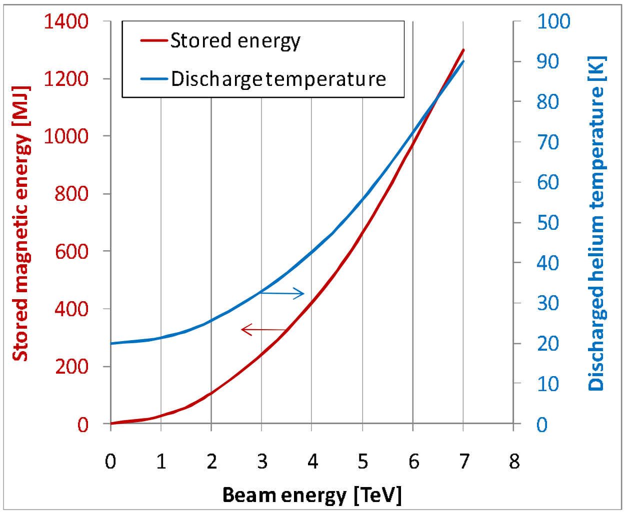

Figure 1: Stored magnetic energy and the discharged helium temperature versus beam energy.

The 19th September 2008 incident occurred at a main current of 8.7 kA which corresponds to a equivalent beam energy of 5 TeV. Figure 2 shows the footprint of the incident electrical arc as well as possible smaller ones. With “smaller” electrical arc (i.e. lower magnetic stored energy and/or lower discharge time constant), perforation of the beam pipe cannot be excluded with the present consolidation status (electrical insulation of the beam pipe interconnects foreseen in the next long shutdown).

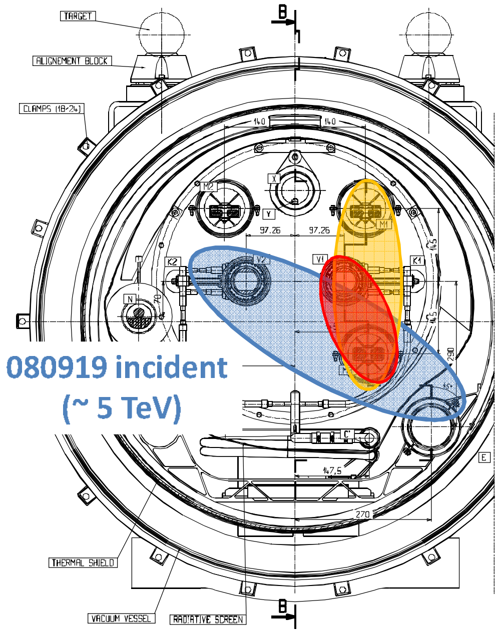

Figure 2: Footprint of electrical arcs.

With the present consolidation status the maximum pressure appearing during a hypothetical incident is shown in Figure 3 for beam energy of 3.5 and 5 TeV.

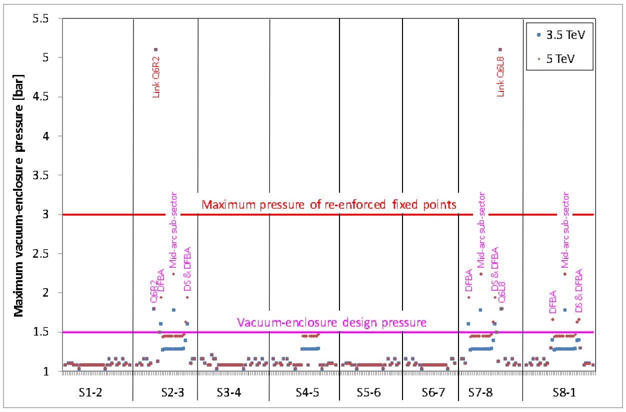

Figure 3: Maximum vacuum enclosure pressure.

Two links of Q6 cryo-magnets (see Table 1) are pressurized above the threshold corresponding to the maximum pressure which can be handled by the reinforced fixed-points (3 bar). These links which have an external diameter of 200 mm can withstand this overpressure.

Other sub-sector vacuum enclosures exceed slightly their design pressure threshold of 1.5 bar (see Table 1). However, the overpressures remain compatible with the design margins of vacuum enclosures. Above 1.9 bar, plastic deformations could occur in the vacuum barriers of the short straight sections; consequently, at 5 TeV, the vacuum barriers of the mid-arc sub-sectors in S2-3, S7-8 and S8-1 could be affected (see Table 1).

Table 1: Maximum pressure in off-design cases

Vacuum sub-sector	**Pmax [bar]**	
	3.5 TeV	5 TeV
Link Q6R2 & Q6	5.1	5.1
Q6R2 & Q6L8	1.8	1.8
Mid-arc S2-3, S7-8 & S8-1	1.8	2.3
DFBA HCM R2, L3, R7 & L8	1.6	2.0
DFBA HCM R8 & L1	1.4	1.7
DS L3, L8 & L1	1.4	1.6

In conclusion, mechanical collateral damages are no longer expected up to beam energy of 5 TeV. Figure 4 shows the updated fault tree of an electrical arc in a cryo-magnet interconnect up to 5 TeV. Nevertheless remaining damages are:

- He vessel and beam pipe perforation,
- mechanical damage of MLI,
- contamination by soot of MLI and beam pipes,
- contamination by MLI of vacuum enclosure and beam pipes,
- mechanical damage of instrumentation cabling.

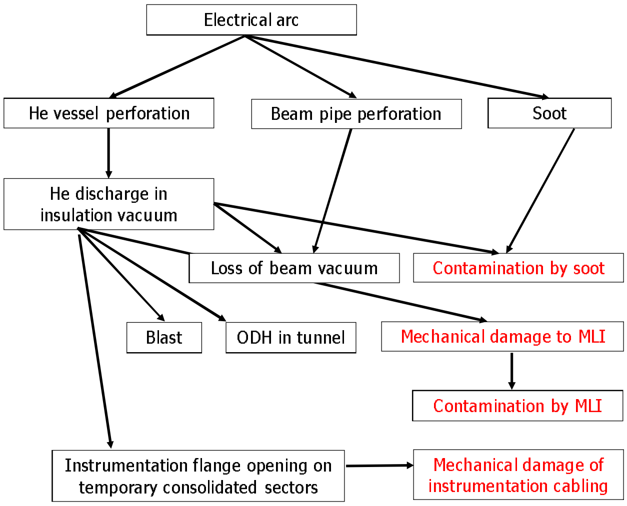

Figure 4: Updated fault tree of an electrical arc in a cryo-magnet interconnect up to 5 TeV.

Contamination by soot of MLI and contamination by MLI of vacuum enclosure will be propagated all over the sub-sector vacuum enclosure, i.e. over a length up to 214 m. These contaminations will affect the thermal performance of the sub-sector cryo-magnets. However, the existing overcapacity margin existing on the cryogenic system could allow postponing the repair to the next scheduled long shutdown.

Helium vessel and beam pipe perforation by the electrical arc will require the immediate removal of the two adjacent cryo-magnets.

The mechanical damage of instrumentation cabling mainly for beam position monitors must be in situ repaired on the four short straight sections of the concerned sub-sector before operation restart.

Concerning the mechanical damage of the MLI, the affected length can be scaled from the 19th September 2008 incident taking into account the frictional pressure drop and the discharge valve distribution. In case of a new incident up to 5 TeV, the affected length is scaled to about 130 m, i.e. about 10 cryo-magnets (2/3 of a standard sub-sector). MLI plays an important role in protection of the cold-mass enclosure in case of catastrophic break of the insulation vacuum by air or by helium. Without MLI, the heat flux entering the cold-mass increase up to a factor 10 (from 5 kW/m^2 to 50 kW/m^2) and the pressure relief system protecting the cold-mass enclosure is definitely undersized. Consequently the mechanical damage of MLI in the cryo-magnets by the high helium flow-rate is critical and need to be repaired before operation restart.

Concerning the contamination by soot of the beam pipe, the affected length can be scaled from the 19th September 2008 incident taking into account the quantity of soot introduced during the beam pipe pressurization. During the September 2008 incident, the V1 beam pipe was pressurized to 3.5 bar (without rupture disk opening) and the corresponding contaminated length was 600 m. In case of a new incident, the beam pipe pressurization is limited to 1.1-1.5 bar, i.e. a factor 2.3 to 3 lower. The new expected affected length will be from 200 to 250 m. The contaminated beam pipes cannot be cleaned in situ and the corresponding cryo-magnet must be transported at ground level for cleaning or must be exchanged before operation restart.

Concerning the contamination by MLI of the beam pipes, the full continuous cryostat (~2900 m) will be affected and must be in situ cleaned before operation restart.

All together up to 14 cryo-dipoles and 4 short straight sections will have to be removed and re-installed. The corresponding repair downtime is estimated to about 8 months. This repair downtime could be extended up to about one year if critical components like current feed boxes are affected.

MAXIMUM CREDIBLE INCIDENT UP TO 5 TeV IN CASE OF AN ELECTRICAL ARC IN A CRYO-MAGNET COIL

In case of an electrical arc in a cryo-magnet coil, the beam pipe is directly perforated. This electrical arc will also create a resistive transition of the magnet producing a pressure increase inside the cold-mass enclosure and the beam pipe. Figure 5 shows the corresponding fault tree and the resulting damages:

- mechanical damage of nested and PIM bellows of the beam pipe,
- contamination by soot of the beam pipe.

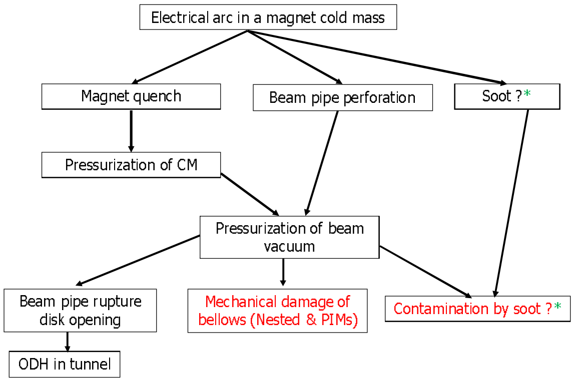

Figure 5: Fault tree of an electrical arc in a cryo-magnet coil.

The mechanical damage of the beam pipe bellows occurs when the pressure reaches the buckling pressure of 3.5 and 5 bar respectively for the PIM and nested bellows. Figure 6 shows the maximum pressure developed in the cold-mass following a dipole resistive transition for two current discharge time constants (tc=100 and 50 s). To remain below the buckling pressure of the PIM bellows, the beam energy has to be limited to 3.5 TeV with a current discharge time constant of 50 s. At 5 TeV, the driving pressure inside the cold mass could reach 17 bar corresponding to the quench-valve setting pressure. The beam pipes are presently protected against pressure build-up by only two rupture disks located at the continuous cryostat extremities. Figure 7 shows the pressure profile of the beam pipes for driving pressures of 10 and 17 bar. In both case, more than 600 m of beam pipe could be affected by the buckling of bellows.

Above a beam energy of 3.5 TeV, a large fraction of the continuous cryostat can be affected by the buckling of bellows. The PIM bellows can be exchanged in situ; the exchange of the nested bellows requires the removal of cryo-magnets.

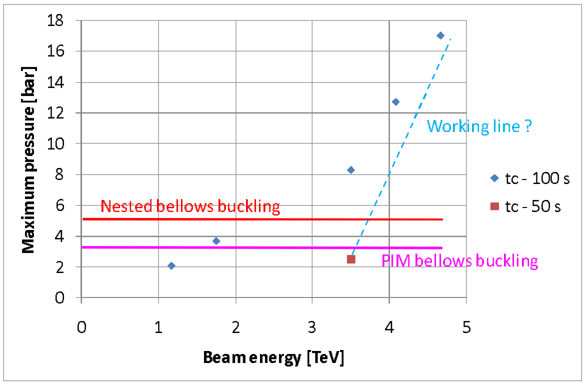

Figure 6: Maximum cold-mass pressure following a dipole resistive transition.

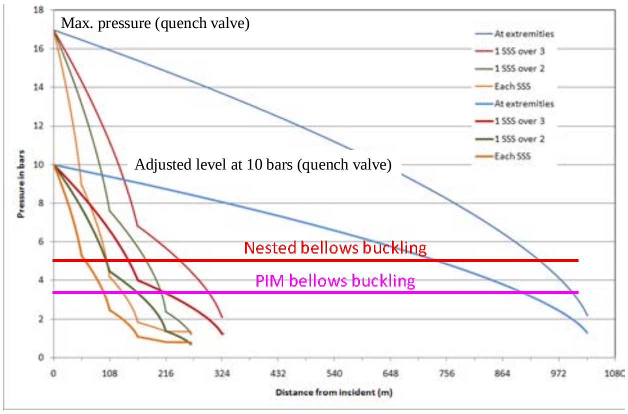

Figure 7: Pressure profile of beam pipes.

CONCLUSION

In case of an electrical arc in a cryo-magnet interconnect, the present consolidation, up to 5 TeV, will suppress mechanical collateral damages in adjacent sub-sectors. Nevertheless, mechanical damage of the MLI in the concerned sub-sector as well as contamination of the beam pipe(s) could require heavy repair work. With the present consolidation status, a new incident will still have big impact on the machine downtime (8 to 12 months).

In case of an electrical arc in a cryo-magnet coil, a limited impact at 3.5 TeV is assumed with only one magnet to be exchanged requiring at least 4 months of downtime. The impact could be more critical above 3.5 TeV with the additional damage of bellows over several sub-sectors.

In conclusion, a hypothetical incident caused by an electrical arc during the 2011/12 operation could seriously impact the LHC physics program. Consequently, corresponding risks must be carefully assessed.

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OPERATIONAL OVERHEAD OF MOVING TO HIGHER ENERGIES

M. Lamont, CERN, Geneva, Switzerland

Abstract

The operational overheads of moving above 3.5 TeV are examined. The costs of performing such a move at the start, or during, the 2011 run are evaluated. The impact of operation with beams above 3.5 TeV on machine protection systems is briefly reviewed, and any potential limitations are enumerated. Finally the possible benefits of increasing the beam energy on the luminosity are discussed.

PREAMBLE

A potential increase of the LHC beam energy is under consideration. In 2011 this potential increase is limited to a step up to 4 TeV from 3.5 TeV [1].

Clearly consideration of the risks coming from the splices dominates the decision of which energy to go to. However other system also have limits that must, in time, be lifted. The BLMs have a limitation in energy between 4 and 5 TeV due to noise on cables. The beam dump system has breakdown along the switches of the MKDs resulting in asynchronous dumps. The team is awaiting isolators to be installed and the present limit is 4.5 TeV.

It is assumed here that the snubber capacitors, energy extraction reconfiguration, QPS tests, IPQ tests, HWC are or will be done to fully qualify any increase in energy. These issues are fully covered elsewhere in these proceedings [1].

The temporal options in respect of an energy increase in 2011 are:

- start 2011 operations at the new energy;
- switch to the new energy during the year;
- leave any energy increase until 2012 or later;
- or possibly perform limited tests in a machine development environment.

RE-COMMISSIONING IN 2011

The re-commissioning in 2011 will see new settings for the ramp & squeeze (to 1.5 m). Relevant experience will be cut and pasted in and the ensemble re-commissioned from scratch. There will be full revalidation of LBDS with beam with specific tests for 4 to 4.5 TeV (BETS, protection) if required. There will be full re-setup of collimation and re-validation. Machine protection tests with beam will take place as usual. There will be configuration and tests of feedbacks, transverse damper, RF and other beam based systems.

If we start at a higher energy, the squeeze will be fully optimized and commissioned for said energy with optimum beta*. [2].

Given this approach, and give or take some details outline below, starting 2011 at a new energy would be almost cost free. Assuming, of course, the readiness of the magnetic circuits, QPS etc.

Machine Protection

Most machine protection systems are energy independent. These include the PIC, BIS, PIC, WIC, and SIS. The FMCM becomes more efficient at higher energy (greater current swing) and a quick verification of, say, a D1 would suffice to re-qualify the system. The BLM threshold tables are used at a higher energy but are already well qualified. The LBDS is OK to go to 4.5 TeV and standard tests at a higher energy would be sufficient. In summary, the MPS teams are fairly relaxed about 0.5 to 1 TeV increase in energy.

Pre-cycle

The precycle and ramp-down precycle combination works with 3.5 TeV values for the MBs, MQs, IPQs, ITs, and IPDs. The settings would clearly take these main circuits up to 4 TeV values. There would be a slightly longer pre-cycle/ramp-down combination but nothing dramatic.

There would be some minor effect on decay at injection and snapback, which could dealt with the usual tools. Diligent off-line preparation would be required as always.

Ramp

The optics do not change in the ramp and the normalized magnet strengths remain constant. The momentum function is a carefully optimized parabolic-exponential-linear-parabolic function of time and is essential function driving the calculation of all strengths to field or gradient. The magnet 'calibration curves' then provide look-up tables to given the required current in a given circuit.

Snapback, tune and chromaticity evolution at the start of the ramp - give or take effects of different the precycle – will be same. Standard procedure would copy in: tune, chromaticity, coupling, orbit, knobs, beating trims, landau damping, separation, crossing angles, non-closure knobs. Offline generation of collimator settings, transverse damper, RF would also be standard and be a natural extension of the lower energy settings.

In summary, a higher than 3.5 TeV ramp should be straightforward. The magnets would be pushing a bit further into magnet transfer functions but one would not expect any surprises. The orbit corrections can be extended at constant kick. The collimator functions can be extended to track emittance reduction with energy. The feedbacks, RF and transverse dampers are still expected to be comfortable.

Low intensity trials to flat-top would be required along with optics checks, validation dumps and loss maps.

Squeeze

The squeeze stitches together matched optics. Parabolic round in and round off over fixed time period of the current functions between match optics ensures smooth, coherent current changes. These current changes respect the time constraints from current decreases in the single quadrant power converters.

The tunes move to collisions tunes during first tens of seconds and operations generally worry about tune feedback, orbit feedback's change of references, chromaticity, coupling, optics corrections and the position of tertiary collimators.

Squeeze reuse

With an increase in energy the MAD optics/strengths remain the same, and the currents more-or-less scaled up with energy, give or take non-linear components in the magnet calibration curves.

If it is possible to use the same squeeze skeleton, we could use the same strength functions and simply re-scale with a new momentum function. This would sacrifice fully optimized timings and a few seconds and a small potential reduction of beta* (for example: 1.6 m to 1.5 m going from 3.5 TeV to 4 TeV (approx. 7% in luminosity)[2]). The orbit corrections could also be scaled up and one might hope that the 3.5 TeV reference orbit holds good. Tune, chromaticity and coupling corrections can be folded over, similarly beating corrections.

The hope here is that if beating and orbit are within limits that re-setup of collimators would not be required. (The reduction in emittance with energy would give slightly smaller beam sizes at collimators). The scenario could be tested in MD before making the definitive step up in energy. If the scenario doesn't work, collimator setup would be required.

Stepping up during the year: summary

The required time for re-establishing collision after an energy increase is summarized in table 1. This would amount to around 1 week with 50% machine availability Another week would be required if full collimator set-up were to be required.

Table 1: Estimate of time required to re-establish colliding beams at 4 TeV for a step-up during the year.

Phase	**Task**	**Shifts**
Ramp	Low intensity trials, test beam dump.	1
Flat-top	Orbit and optics checks	1
Flat-top	LBDS – asynchronous dump	0.5
Flat-top	Betatron loss maps & positive off-momentum, negative off-momentum	1
Squeeze	Q, Q', coupling, orbit checks, feedbacks	2
Squeeze	Beating & local coupling checks	1
Collision	Test, test luminosity scans	0.5
1.5 m separated	Betatron loss maps & positive off-momentum, negative off-momentum	1
1.5 m separated	Asynchronous dumps	0.5
1.5 m collisions	Betatron loss maps & positive off-momentum, negative off-momentum	1
1.5 m collisions	Asynchronous dumps	0.5
Total		**10**

Intensity ramp-back up

Following successful commissioning and validation of ramp, squeeze etc. with low intensities some circumspection might be appropriate before going back up to full intensity. A fairly aggressive, staged ramp back up intensity would seem appropriate with validation checks and the normal cross-system checklist. One week would seem reasonable.

BEAM

The effects of increasing energy on the relevant beam parameters are summarized in table 2.

Table 2: variation of key parameters with energy. The last two rows illustrate the change in beam size at the primary collimators.

	3.5 TeV	**4 TeV**	**4.5 TeV**
Gamma	3730.26	4263.16	4796.05
Normalized emittance [mm.mrad]	2.5		
Emittance [nm]	.67	.586	.521
Beta*[m]	1.5		
Beam size at IP [micron]	31.7	29.7	28.0
Number of bunches	930		
Luminosity [$cm^{-2}s^{-1}$]	1.03×10^{33}	1.15×10^{33}	1.28×10^{33}
Beam energy [MJ]	59.9	68.5	77.0
Beam size at beta = 145 m	368.9	345.0	325.3
Beam size at beta = 85 m	282.4	264.2	249.1

- There is a corresponding increase in energy density with energy if the normalized emittance stays the same. Note that with the decrease in assumed normalized emittance, the geometrical emittance approaches the nominal 7 TeV value.
- The decrease in beam size brings some increase in minimum beta* reach [2].

Trade-off

In simple terms, if the increase in energy:

- brings an increase in sensitivity for a given process of x% (choose your channel) [3];
- and brings an increase in luminosity of y%;
- and takes N days to re-commission;
- and takes R days to ramp up back up in intensity;

then we will have run at the increased energy for around (N + R/2)/(x + y) days to make up the time used for the energy step-up. For example to go to 4 TeV with N = 7, R = 7, x = 0.25 (low mass Higgs), y = 0.13, it will take around 4 weeks to catch up lost time. The message here is that if the step-up is to be done during the year, it should be done sooner rather than later,

CONCLUSIONS

Given any HWC/QPS/MP3 overheads, starting a new year at a new energy 0.5 to 1.0 TeV above 3.5 TeV is almost cost free from an operational perspective. Full setup from scratch is planned anyway and any additional machine protection tests can be absorbed into normal re-commissioning.

An increase in energy during the year, with successful squeeze re-scaling, would require around 1 week re-commissioning. Without squeeze re-scaling, the additional collimator setup and verification would bring the total up to around 2 weeks. To be able to make up for time lost to re-commissioning, any energy step-up should be made in good time.

The final option is to run the whole of 2011 at 3.5 TeV, which is clearly easiest from an operational perspective. Here we would rely on squeezing harder and an increased number of bunches to lift performance.

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LHC COLLIMATION – TOO GOOD OR TOO BAD?

R.W. Aβmann and D. Wollmann, CERN, Geneva, Switzerland

Abstract

The LHC beam operation at 3.5 TeV has seen a rapid and quite worry-free increase of beam intensity. The energy stored in the proton beams quickly reached more than 10 times the values achieved in other colliders and was not perturbed by quenches of super-conducting magnets from stored beam. Losses were reliably and efficiently intercepted by the phase 1 of the LHC collimation system. The success of the collimation system has triggered the questions whether collimation performance is already sufficient and whether the foreseen completion and upgrade of the system is justified. These questions are addressed in view of the first beam experience.

INTRODUCTION

The LHC collimation system was conceived and approved in 2003 as a phased system [1,2]. The phase 1 system was completed for the LHC start-up in 2009 and is being used for the beam commissioning and operation at 3.5 TeV. Selected parameters of the initial 3.5 TeV run of the LHC are compared in Table 1 to the design parameters.

Stored energies and energy densities are compared in Fig. 1 and Fig. 2 for various accelerators and designs. It is seen that the parameters achieved in the LHC during the 2010 run are already well beyond the achievements in other accelerators (a factor 10 or higher beyond previous records). A stored energy of 28 MJ was reached in the LHC without a single quench of the sensitive super-conducting magnets (limits: 10-30 mJ/cm^3), once stored beam was established. It is noted that the intensity increase in Tevatron and HERA was limited by quenches of super-conducting magnets. The rapid and quite worry-free increase of LHC beam intensity was possible due to the highly efficient first phase of the LHC collimation system [2].

At the same time, predicted system limitations have been measured with beam [2]. Several improvements are under development since 2009 to complete the system and to guarantee that nominal and ultimate beam intensities can be achieved [3]:

- The LHC dispersion suppressors must be equipped with collimators [4] to reduce losses into the super-conducting magnets in this area with the associated risks of quenches and long-term magnet damage.
- Second-generation collimators for faster and more flexible setup must be constructed and installed into the already equipped phase 2 collimator slots. This will also allow achieving the smallest β^* values.
- Remote handling, measures to reduce radiation to electronics and measures for lower environmental impact must be constructed and installed.

This paper reviews a few selected topics of LHC collimation in the light of the first LHC beam experience.

Table 1: Collimation and Protection Relevant Parameters Compared between 3.5 TeV (up to April 2011) and the Nominal LHC at 7 TeV

Parameter	**2010/2011**	**Nominal**
E	3.5 TeV	7 TeV
γ	3,730	7,461
$\varepsilon_{x,y}$	0.5 nm	0.5 nm
N_p	0.56×10^{14}	3.00×10^{14}
E_{stored} (total)	31 MJ	362 MJ
ρ_e (tot)	248 MJ/mm^2	2.9 GJ/mm^2
E_{stored} (1bunch)	72 kJ	128 kJ
ρ_e (1bunch)	0.6 MJ/mm^2	1.0 MJ/mm^2

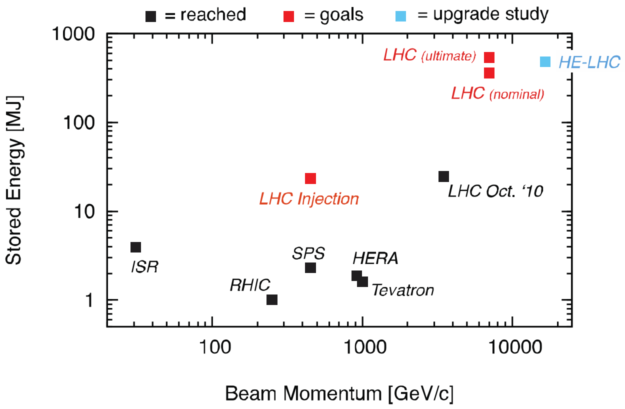

Figure 1: Stored energy per beam versus beam momentum for various accelerators. Filled black squares indicate achieved values, red squares show design values and the blue square represents an upgrade study.

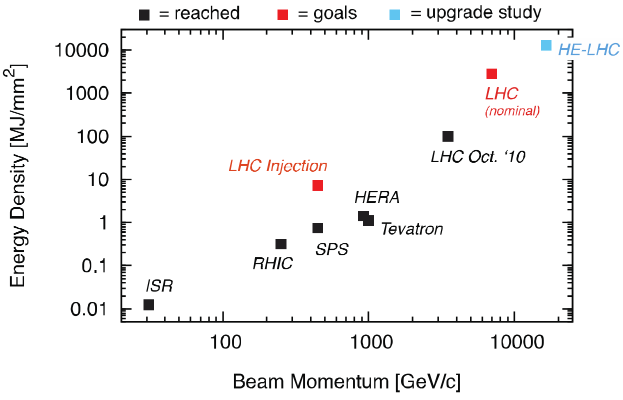

Figure 2: Energy density versus beam momentum.

LIMITS IN DISPERSION SUPPRESSORS OF BETATRON COLLIMATION

The cleaning inefficiency describes the leakage from the collimation systems into critical machine elements, for example all super-conducting magnets. We define a local cleaning inefficiency as the maximum leakage to one meter of critical super-conducting magnets [5]:

$$\tilde{\eta}_{in} = \max_i \left(\frac{\Delta N_i / L_i}{N_{impact}} \right) \tag{1}$$

Here, ΔN_i is the number of lost protons in the super-conducting magnet number i of length L_i. N_{impact} gives the number of protons that impact on the primary collimators.

Intensity reach from cleaning efficiency

The maximum intensity N_{max} in the LHC is a function of the local cleaning inefficiency, the minimum beam lifetime τ_{min} during the fill and the quench limit R_q [5]:

$$N_{\max} \approx \frac{\tau_{\min} \cdot R_q}{\tilde{\eta}_{in}} \tag{2}$$

Ideal Performance Reach of LHC Collimation

Simulations have shown during the design phase that the efficiency of the LHC collimation system will be limited by losses in the dispersion-suppressors of the LHC. The leakage (cleaning inefficiency) gets worse with increased beam energy in the range from 1 TeV to 7 TeV. This is due to smaller multiple Coulomb scattering angles at higher beam energies and an increased probability of single-diffractive scattering.

Single diffractive scattering generates off-energy protons that cannot be intercepted by collimators in the straight sections of the cleaning insertions (lack of dispersive dipole kicks). These off-momentum protons are then lost in the dispersion suppressors downstream of the cleaning insertions. The higher is the beam energy, the higher is the fraction of single-diffractively scattered protons and the higher is the leakage (or inefficiency).

The past performance reach estimates were based on Equation 1. Past assumptions (before beam commissioning) for 7 TeV are listed [6,7]:

• Quench limit R_q (steady state):	7.8×10^{6}	p/m/s
• Ideal cleaning inefficiency η_{in}:	4.63×10^{-5}	m^{-1}
• Minimum beam lifetime τ_{min}:	720	s

With this input we obtain a maximum beam intensity of **1.2 × 10^{14} protons or 40% of nominal design intensity** (nominal design is 3e14 protons). This is the well-known **ideal performance reach** of phase 1 of LHC collimation. In addition, imperfections were simulated to reduce efficiency by a factor 11 to a realistic performance reach of 3.6% of nominal intensity. This was presented in various committees and published in PhD's and elsewhere.

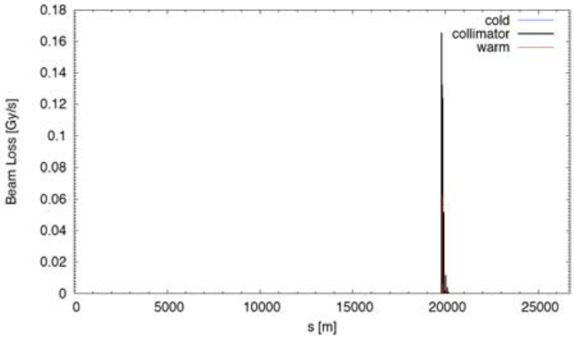

Figure 3: Measurement of proton losses in the betatron cleaning insertion IR7 and around the ring, performed at 3.5 TeV beam energy. Losses are shown in linear scale. The beam runs in direction of s.

2010/11 Measurements and Raw Cleaning Inefficiency for Protons

Generating beam losses at primary collimators (achieved by moving a selected machine tune onto the 1/3 resonance) assesses the efficiency of the LHC collimation system. Data for 3.5 TeV, as recorded with the LHC beam loss measurement (BLM) system, are shown in Figures 3 and 4 for 2010 conditions ($\beta^* = 3.5$ m). The proton losses are intercepted, as designed, at the primary collimators. The overall efficiency can be assessed roughly by looking into integrated losses appearing in characteristic regions of the ring:

• Losses in cleaning insertions	99.93 %
• Losses in super-conducting magnets	0.07 %

Excellent global collimation efficiency was found. From primary collimators onwards, losses are reduced with additional collimators by about four orders of magnitude. Details can only be assessed on a logarithmic scale, as shown in Fig. 4. There it is seen that single diffractive protons are lost in two characteristic, super-conducting magnets.

The raw cleaning inefficiency is defined as the ratio of two BLM measurements R, namely of (1) the measured peak loss rate $R_{DS,i}$ at any magnet i in the dispersion suppressor and (2) the peak loss rate R_{TCP} at the primary collimator:

$$\eta_{in,raw} \approx \max\left(\frac{R_{DS,i}}{R_{TCP}} \right) \tag{3}$$

This quantity is used to assess the quench risk of super-conducting magnets, which depends on the local distribution of beam losses and related heating in the magnet. The raw cleaning inefficiency has been monitored over four months in 2010 for the different planes and beams in the LHC [8]. The measured data is shown in Fig. 5. The data is used to define an average performance and a worst case (over the 6 measurements), as summarized in Table 2.

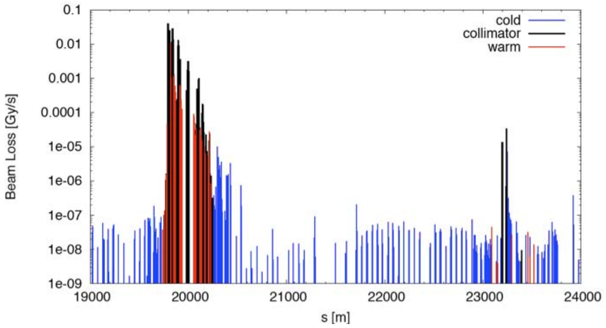

Figure 4: Measurement of proton losses in the betatron cleaning insertion IR7 and through the downstream arc into IR8, performed at 3.5 TeV beam energy. The losses are shown in logarithmic scale. Black bars indicate losses at collimators, red bars at warm machine elements (not critical) and blue bars at superconducting magnets (critical). The beam runs in direction of s.

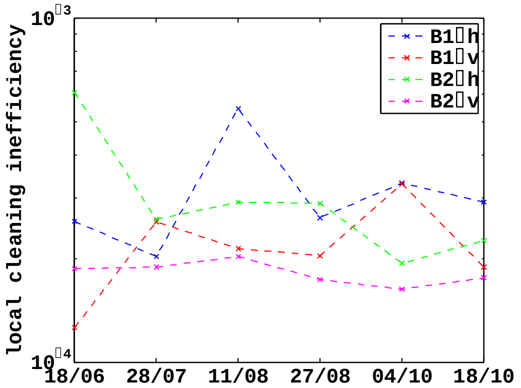

Figure 5: Measured “raw” **cleaning inefficiencies $\eta_{in,raw}$ at 3.5 TeV** during the 2010 run. This data was used to determine an average cleaning inefficiency and the worst case (over 6 measurements). From [8].

Table 2: “Raw” values for cleaning inefficiency at 3.5 TeV. This is the ratio of the peak BLM measurement at a SC magnet (leakage rate) over the BLM measurement at a primary collimator (primary loss rate).

Case	**“Raw” cleaning inefficiency (3.5 TeV)**
Average 2010	2.6×10^{-4}
Worst measured (out of 6)	6.1×10^{-4}

2010/11 Measurements and Raw Cleaning Inefficiency for Heavy Ions

The collimation performance was assessed for heavy ions and is quickly shown. A measurement of betatron collimation performance is shown in Fig. 6. Again estimating global efficiency in characteristic regions we find:

• Losses in cleaning insertions	98.1 %
• Losses in super-conducting magnets	1.9 %

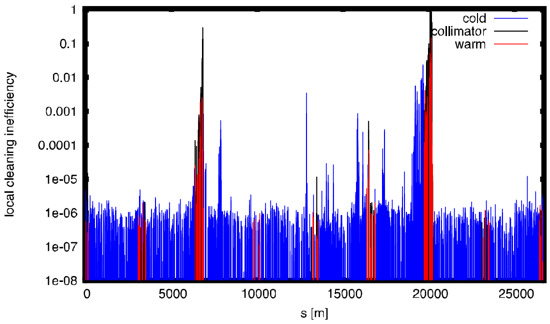

Figure 6: “Raw” cleaning inefficiency for betatron collimation of heavy ion beams in the LHC. The losses are shown in logarithmic scale. Black bars indicate losses at collimators, red bars at warm machine elements (not critical) and blue bars at superconducting magnets (critical). Here, the beam runs in opposite direction of s (“beam 2”).

The integrated leakage into SC magnets is 27 times worse for heavy ions than for protons. Essentially all losses impact again on the two exposed SC magnets in the IR7 dispersion suppressor. In addition, leakage up to a few per mille hits some isolated magnets around the ring, many km’s away from the collimation insertion.

It is noted that the increased leakage for heavy ions has been predicted and simulated during the design phase of the collimation system. It is caused by particular physics processes of dissociation and fragmentation of ions. Affected ions behave essentially as off-momentum particles and are lost in the same characteristic locations as single-diffractive protons.

Corrected Cleaning Inefficiency for Protons

The response of BLM’s at super-conducting magnets in the IR7 dispersion suppressors and IR7 primary collimators can be very different. The relative response was assessed with a special measurement method [9]:

1. A closed orbit bump is implemented in the Q9 magnet of the IR7 dispersion suppressor, such that the LHC aperture bottleneck is in the Q9 of IR7.
2. The beam is injected and stored at 450 GeV.
3. The primary collimator is set to some number of normalized beam sigmas, initially open and then closed further and further.
4. The stored beam is blown up horizontally by passage through the 1/3 tune resonance, while the BLM responses at the Q9 magnet and the primary collimator are measured simultaneously.
5. The BLM signals to the grazing beam loss are normalized to the amount of intensity loss, yielding values in Gy/s/p.
6. The beam is dumped and the procedure continues from step 2, taking a measurement for a different collimator setting.

As a result one obtains the relative beam loss measurements at the Q9 and the primary collimator as a function of collimator setting. Two such measurements are shown in Figure 7 for the right and left sides of IR7. It is seen that the beam loss occurs at the primary collimator for small collimation gaps and at the Q9 for large gaps. The two asymptotic values give the difference in BLM response to the same beam loss. This measurement is only possible at 450 GeV and it must be assumed that the response is the same at 3.5 TeV. It is noted that the point of equal losses in the Q9 and the primary collimator is a measure of the magnet aperture (after subtraction of the known bump amplitude). This method is used very successfully for aperture measurements in the LHC.

A consistent difference in BLM response is seen for both beams (Fig. 7). It is probably due to features in material and geometry, but also details in beam loss distribution. A correction factor $C_{BLM,TCP}/C_{BLM,SC}$ is defined in order to take the measured response into account. The data suggest $C_{BLM,TCP}/C_{BLM,SC} = 2$. For the same number of protons lost a BLM at the super-conducting magnet in the IR7 dispersion-suppressor measures about half the signal of the BLM at the primary collimator. The inefficiency is therefore under-estimated and needs to be corrected:

$$\eta_{in,corr} = \frac{C_{BLM,TCP}}{C_{BLM,SC}} \eta_{in,raw} \tag{4}$$

The "corrected" values of cleaning inefficiency are summarized in Table 3. It is seen that the peak leakage to a dispersion suppressor magnets can in worst case reach the 1.2 per mille and on average the 0.5 per mille level.

Local Cleaning Inefficiency

The risk of magnet quenches depends on the longitudinal distribution of losses inside the magnet. The BLM measurements contain no direct information about this. It was seen that proton losses, different by a factor 10, can produce the same BLM signal. A longitudinal dilution length L_{dil} must therefore be assumed from preliminary simulations and FLUKA studies. A value L_{dil} = 3.5 m is taken. The local cleaning inefficiency is then given by:

$$\tilde{\eta}_{in} = \frac{C_{BLM,TCP}}{C_{BLM,SC}} \cdot \frac{\eta_{in,raw}}{L_{dil}} \tag{5}$$

The resulting values for local cleaning inefficiency from 3.5 TeV data are summarized in Table 4. A comparison with the simulation results for the ideal setup is included and shows that imperfections reduce the performance by a factor 4 – 10, in good consistency with expected effects.

It is noted that this estimate of local cleaning inefficiency can be affected by significant errors. The appropriate value of L_{dil} depends on details of beam loss and imperfections. The quoted value of 3.5 m must be taken as a rough estimate with large uncertainties that can reach a factor 5. It must be assessed by special experiments with LHC beam.

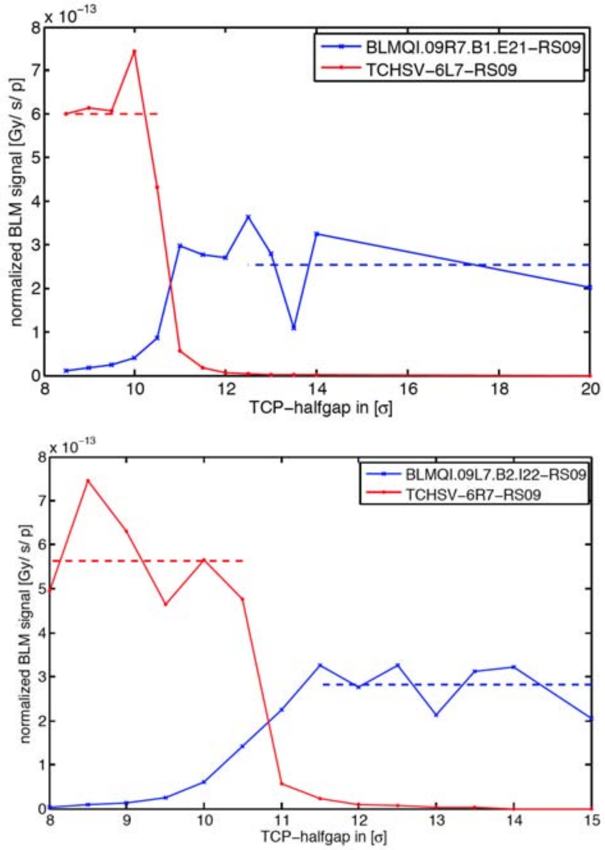

Figure 7: Measurements of relative response of BLM's from primary collimators (here TCHSV) to a cold magnet in the IR7 dispersion suppressor (Q9R7/L7). Shown are beam 1 (top) and beam 2 (bottom). The data have been corrected for intensity fluctuations in the beam. The data suggest $C_{BLM,TCP}/C_{BLM,SC} = 2.4$ (2.0) for beam 1 (beam 2).

Table 3: "Corrected" values for cleaning inefficiency at 3.5 TeV.

Case	**"Corrected" cleaning inefficiency (3.5 TeV)**
Average 2010	5.2×10^{-4}
Worst measured (out of 6)	12.2×10^{-4}

Table 4: Estimates of **local cleaning inefficiency** at 3.5 TeV.

Case	**Estimated local cleaning inefficiency (3.5 TeV)**
Average 2010	1.5×10^{-4} m^{-1}
Worst measured (out of 6)	3.5×10^{-4} m^{-1}
Simulation (ideal setup)	0.4×10^{-4} m^{-1}

Extrapolation of Cleaning Inefficiency to 7 TeV

The energy dependence of the simulated local cleaning inefficiency [5] is shown in Fig. 8 with two possible settings for collimators (“tight” and “intermediate”). It is seen that the LHC cleaning inefficiency gets worse with increased beam energy. The existing simulation data [7] in the range from 1 TeV to 7 TeV can be fitted as a function of beam energy E, here expressed in units of TeV:

$$\frac{\tilde{\eta}_{ineff}}{10^{-4}} = 0.0276\frac{1}{m} + 0.0231\frac{1}{m}E + 0.0051\frac{1}{m}E^{2} \qquad (6)$$

This relationship is valid for so-called “tight” collimator settings, referring to nominal settings with primary collimators at 6 σ, secondary collimators at 7 σ, tertiary collimators at 8.4 σ and absorbing collimators at 10 σ.

The local cleaning inefficiency can be extrapolated to 7 TeV and to nominal collimator settings using the simulated data shown in Fig. 8.

$$\tilde{\eta}_{in}[7\ \mathrm{TeV}] \approx 2.5 \times \tilde{\eta}_{in}[3.5\ \mathrm{TeV}] \qquad (7)$$

$$\tilde{\eta}_{in}[tight] \approx 0.43 \times \tilde{\eta}_{in}[\mathrm{intermediate}] \qquad (8)$$

These relationships are used to extrapolate to 7 TeV.

Calculated Quench Limit

The calculated quench limit R_q of a standard LHC super-conducting magnet is shown in Figure 9 as a function of the beam energy. A concentrated and slow, continuous beam loss is assumed. The following quench limits R_q are used in the context of this study:

$$R_q[.45\ \mathrm{TeV}] = 70.0 \times 10^{7}\ \ p/m/s \qquad (9)$$

$$R_q[3.5\ \mathrm{TeV}] = 2.40 \times 10^{7}\ \ p/m/s \qquad (10)$$

$$R_q[6.5\ \mathrm{TeV}] = 0.88 \times 10^{7}\ \ p/m/s \qquad (11)$$

$$R_q[7.0\ \mathrm{TeV}] = 0.78 \times 10^{7}\ \ p/m/s \qquad (12)$$

It is seen that the slow quench limit at 7 TeV is a factor ~3 tighter than at 3.5 TeV and a factor ~90 tighter than at 450 GeV.

The LHC cannot be run just to the quench limit. Instead a margin must be taken into account that is used to set a BLM threshold R_{lim} below the actual quench limit. Once the measured beam loss reaches this limit the beam is dumped before any magnets can quench. The following beam loss limit R_{lim} must therefore be respected:

$$R_{\mathrm{lim}} = {R_q}/{3} \qquad (13)$$

The limiting beam loss rates then become:

$$R_{\mathrm{lim}}[.45\ \mathrm{TeV}] = 23.3 \times 10^{7}\ \ p/m/s \qquad (14)$$

$$R_{\mathrm{lim}}[3.5\ \mathrm{TeV}] = 0.80 \times 10^{7}\ \ p/m/s \qquad (15)$$

$$R_{\mathrm{lim}}[6.5\ \mathrm{TeV}] = 0.29 \times 10^{7}\ \ p/m/s \qquad (16)$$

$$R_{\mathrm{lim}}[7.0\ \mathrm{TeV}] = 0.26 \times 10^{7}\ \ p/m/s \qquad (17)$$

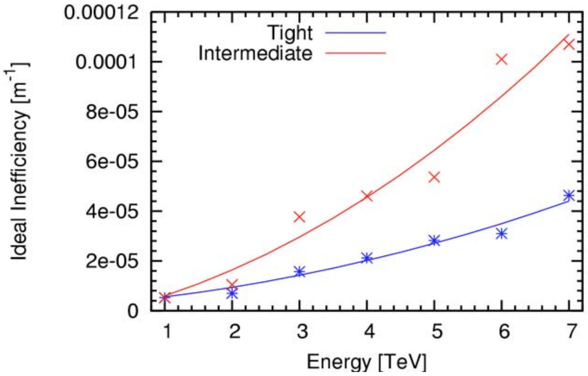

Figure 8: Simulated cleaning inefficiency of the LHC multi-stage collimation system. The two curves show two different settings of collimators. The lines show a fit to the data (see text). The data is from [7].

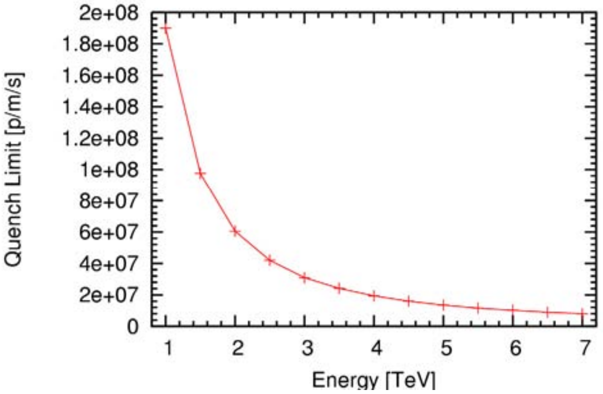

Figure 9: Calculated quench limit R_q of a standard LHC super-conducting magnet versus beam energy for concentrated, continuous beam losses [7]. No relevant experimental data was obtained during 2010/11 operations.

Table 5: Minimum beam lifetimes as found during 5 fills with 368 bunches and high luminosity in 2010. The BLM calibration factor used is 4.8×10^{11} p/Gy.

Integration time	**Minimum lifetime [h]**
10.24 ms	0.52
1.3 s	0.64

Peak Loss Rate and Minimum Beam Lifetime

The minimum lifetime of LHC beams was determined by analysing beam loss rates at primary collimators during five LHC fills in 2010 with highest beam intensity [8]. The measured BLM values were converted into proton loss rates with a calibration factor of 4.8×10^{11} p/Gy. The results are summarized in Table 5. It is assumed that high beam intensities have the same beam stability as observed in 2010. An example of beam loss rate versus time is shown in Fig. 10.

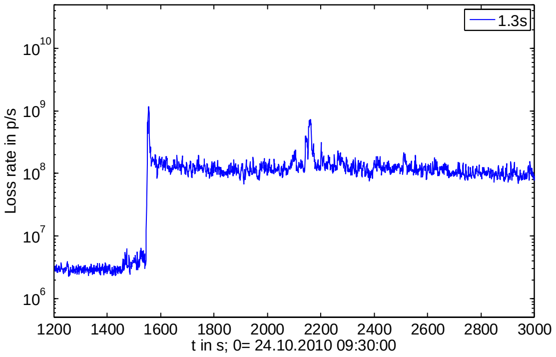

Figure 10: Example of loss rates at primary collimators during a physics fill in 2010. Collisions create beam diffusion and higher loss rates at collimators. The peak loss is encountered when bringing the beams into collision.

PERFORMANCE REACH ESTIMATES

Intensity Reach

All parameters for predicting the intensity reach in the LHC have now been introduced and discussed. Using a slightly modified version of Eq. 2

$$N_{\max} \approx \frac{\tau_{\min} \cdot R_{\lim}}{\tilde{\eta}_{in}} \tag{18}$$

the intensity reach of the LHC can now be calculated. A minimum beam lifetime of 0.64 h and a local cleaning inefficiency of 1.5×10^{-4} m^{-1} are used. Results are summarized in Table 6.

It is noted that nominal beam intensity could be possible with the present betatron collimation system ("phase 1") if the beam lifetime at primary collimators can be kept above 12.8 hours at any time during high energy. A beam lifetime of 5.3 hours would make this possible if tight collimation settings can be used.

The predicted and observed loss limitation of the LHC collimation system ("phase 1") will be overcome by the proposed installation of collimators into the dispersion suppressors of the LHC.

Table 6: Performance reach in LHC intensity, calculated with a minimum beam lifetime of 0.64 hours and average measured cleaning inefficiency in 2010. It is noted that significant uncertainties may affect these predictions.

Beam energy	**Reach (intermediate coll. settings)**	**Reach (tight coll. settings)**
3.5 TeV	41 %	95 %
6.5 TeV	6 %	15 %
7.0 TeV	5 %	12 %

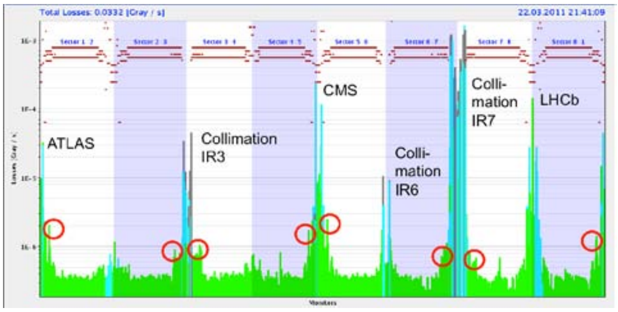

Figure 11: Beam losses around the LHC ring in a 2011 physics run with peak luminosity of 2.5×10^{32} cm^{-2} s^{-1} (fill #1645, 200 bunches, 2.4×10^{13} p per beam). Leakage into the dispersion suppressors of IR1/3/5/7 are indicated by circles.

Emittance Reach

The LHC collimators and protection devices have been designed for nominal and ultimate intensities. We assume that all these elements are robust for ultimate bunch intensity and nominal emittance at 7 TeV beam energy. Then we can establish the following brightness limit [10]:

$$\frac{N_p}{\varepsilon} \leq 3.4 \times 10^{20} m^{-1} \tag{19}$$

Here N_p is the maximum number of protons in a bunch and ε is the geometric emittance. Further experimental studies on damage limits or more robust collimator materials might relax this limit.

It is interesting that the luminosity reach at the robustness limit is:

$$L \leq \frac{10^{40} (cm\ s)^{-1}}{\gamma \cdot \beta^*} \cdot \frac{E_{stored}}{500\ MJ} \tag{20}$$

It is an easy function of the stored energy, the β^* and γ. The geometric correction factor F from the crossing angle is neglected here.

β* Reach

The β^* reach from collimation involves questions of machine protection, collimator hierarchy and operational tolerances. A complete study has been performed and published [11]. The arguments are not repeated here. However, it is noted that the proposed upgrade of LHC collimators with in-situ beam position pickup buttons will significantly improve the β^* reach from collimation. Tight collimation settings could be achieved with much less demanding requirements on operational stability and tolerances.

Luminosity Reach

Colliding beams generate off-energy protons during the beam-beam collisions. Some of these protons escape the long straight section and are lost in the same characteristic dispersion suppressor locations as in IR7 and IR3. This is illustrated in Fig. 11 for a high luminosity fill at 3.5 TeV.

Simple scaling shows that these losses in super-conducting magnets will reach several kGy per year at 7 TeV and can come close to or reach the BLM limits on these magnets. Risks for long-term operation and quenches must be calculated in detail.

The proposed installation of collimators into the dispersion suppressors will safely intercept these losses and protect the super-conducting magnets.

CONCLUSION

The LHC has seen a quick and worry-free increase of beam intensity at 3.5 TeV. The state-of-the-art in stored energy was quickly surpassed by more than a factor of 10, reaching by now more than 30 MJ. This was achieved without a single quench of a super-conducting magnet due to losses of stored beam. Other colliders were limited with much less stored beam due to beam losses, collimation efficiency and magnet quenches.

The rapid and worry-free increase of LHC beam intensity relies on the “phase 1” of the LHC collimation system that intercepts beam losses reliably and with high efficiency. The collimation performance is helped significantly by the lower beam energy, which results in better efficiency, much larger quench margins, lower collimator-induced impedance and relaxed operational tolerances.

A detailed analysis of performance shows that the “phase 1” of the LHC collimation system performs in fact as designed. The observed cleaning efficiency is fully compatible with detailed design simulations. The predicted residual leakage of protons and ions into the LHC dispersion-suppressors was fully confirmed in location and magnitude. The system behaves as expected.

An attempt was made to extrapolate the performance at 3.5 TeV to higher beam energies. The same model as used for system design and optimization was used. In this model, losses in the LHC dispersion suppressors are predicted to limit the LHC intensity at 7 TeV to something between 5% and 12% of nominal intensity. It is noted that large uncertainties affect these values. They should be taken as indications and cannot serve as firm predictions. Several studies are underway to improve the accuracy of predictions.

The LHC collimation system was the last major LHC sub-system that entered into serious design and construction, as late as 2003. For this reason it was conceived and approved as a phased system. Its “phase 1” was completed in 2009 for initial commissioning and operation. Preparations for the completion of the LHC collimation system started in 2008 and are well advanced by now [12]. The installation of collimators into the dispersion suppressors and second-generation collimators with relaxed operational tolerances will ensure that nominal and ultimate beam intensities and small β^* values can be achieved without facing limitations from collimation.

In summary, the collimation system is neither too good nor too bad. It is the best system that CERN could design, build and install within a very limited time span of 6 years. It performs much better than any such system did before but it has its long-predicted weaknesses. These weaknesses should be addressed and eliminated to ensure that LHC can continue its quick and worry-free increase of beam intensity.

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LIMITS FOR BEAM INDUCED DAMAGE: RECKLESS OR TOO CAUTIOUS?

A. Bertarelli, V. Boccone, F. Carra, F. Cerutti, A. Dallocchio, N. Mariani,
CERN, Geneva, Switzerland
L. Peroni, M. Scapin, Politecnico di Torino, Turin, Italy

Abstract

Accidental events implying direct beam impacts on collimators are of the utmost importance as they may lead to serious limitations of the overall LHC Performance. In order to assess damage threshold of components impacted by high energy density beams, entailing changes of phase and extreme pressures, state-of-the-art numerical simulation methods are required.

In this paper, a review of the different dynamic response regimes induced by particle beams is given along with an indication of the most suited tools to treat each regime. Particular attention is paid to the most critical case, that of shock waves, for which standard Finite Element codes are totally unfit. A novel category of numerical tools, named Hydrocodes, has been adapted and used to analyse the consequences of an asynchronous beam abort on Phase 1 Tertiary Collimators (TCT).

A number of simulations has been carried out with varying beam energy, number of bunches and bunch sizes allowing to identify different damage levels for the TCT up to catastrophic failure.

THERMALLY INDUCED DYNAMIC PHENOMENA

The rapid interaction of highly energetic particle beams with matter induces dynamic responses in the impacted structure [1]. The intensity and the time scale of the response can be divided in different categories depending on several parameters, mainly deposited energy, maximum energy density, interaction duration and strength of the impacted material.

Three dynamic regimes can be identified at increasing deposited energy, namely Elastic Stress Waves, Plastic Stress Waves and Shock Waves.

Stress Waves in Elastic Domain

This regime is encountered in case of relatively low energetic impacts, when induced dynamic stresses do not exceed the material yield strength. Changes of density are negligible and pressure waves propagate at the elastic sound speed (C_0) without plastic deformation. These phenomena can be very well treated with standard implicit FEM codes (e.g. Ansys Multiphysics) [2] or even with analytical tools [3].

Stress Waves in Plastic Domain

When the dynamic stresses exceed the material yield strength, plastic stress waves appear propagating at velocities slower than elastic sound speed ($C < C_0$). The affected component is permanently deformed. Changes of density can still be considered negligible. These dynamic responses can be treated at an acceptable degree of approximation with standard implicit FEM codes [4].

Shock Waves

When the deposited energy is high enough to provoke strains and stresses exceeding a critical threshold (ε_c , σ_c), an energetic shock wave is formed propagating at a velocity higher than C_0 potentially leading to severe damages in the affected component. A shock wave is characterized by a sharp discontinuity in pressure, density and temperature across its front.

It can be shown that for metal-based material, shock waves do not appear unless changes of phase occur: if one assumes uniaxial strains, critical strains required to generate shock waves are in the range of 15% for Tungsten and 7.5% for Copper, whereas the total deformation at the melting point is in the range of 2% for both metals.

HYDROCODES

When dealing with changes of phase and significant changes of density one has to resort to a new class of wave propagation codes, called Hydrocodes. These are highly non-linear Finite Element tools, using explicit time integration schemes, developed to study very fast and intense loading on materials and structures. Hydrocodes are capable of managing very high plastic deformations at elevated strain rates, encountered in such phenomena as projectile impacts on structures, explosions or, as in our case, very short and energetic particle impacts leading to material melting. They take their name from the original assumption of pure hydrodynamic behaviour of the impacted solids; nowadays the deviatoric behaviour (responsible for material ‘strength’) is also taken into account, however the original name is still widely used.

As opposed to a standard, implicit FEM code, hydrocodes usually rely on complex material constitutive models, as these must be able to encompass a much larger range of densities and temperatures, including changes of phase. Strength and failure models are also more complicated as they must take into account the effects of strain rate, temperature, density change etc.

Equations of State

The Equation of State (EOS) is integrated in the hydrocode to model the behaviour of materials under any state and condition. It provides the evolution of pressure as a function of density, temperature and energy. Most used analytical EOS are Shock, Tillotson and Mie-Gruneisen, however their application is limited since analytical modelling can describe only a single phase region of the EOS [5]. A tabular EOS can be employed to appreciate material behaviour over different phases without loss in precision. Additionally, polynomial EOS can be interpolated from tabular ones. In this work a tabular EOS has been used for Tungsten, while a polynomial EOS has been assigned to Copper.

Strength Models

To model the behaviour of materials in the extreme conditions due to shock wave propagation, an advanced yielding criterion is needed. The model must take into account, in addition to strain, the strain rate (which in case of shock waves can be as high as 10^6 s^{-1}) and the temperature (above melting point the material loses its deviatoric strength and behaves as a fluid). Most used models are Johnson-Cook, Steinberg-Guinan and Johnson-Holmquist. In the present work Johnson-Cook model has been chosen for both Tungsten and Copper.

Failure Models

On the same basis, dynamic failure models must take into account many factors such as strain, strain rate, temperature, maximum and minimum pressure, fracture toughness. In addition, failure criteria also depend on the type of failure and on the mesh used for the simulation. In our work we used Maximum Plastic Strain Failure Criterion and minimum Hydrostatic Pressure Failure Criterion (Pmin) to model the behaviour of Tungsten, while the maximum Plastic Strain Criterion was used for Copper.

Validity of Results

Hydrocodes are extremely powerful tools with capabilities steadily growing; however results must be carefully analyzed. As shown in previous paragraphs, a large set of parameters is required to correctly model the material behaviour.

Unfortunately literature data providing properties of materials of interest under extreme conditions are very scarce; besides, most of the existing information is often classified as it is drawn from military research. In addition, very few data are available for metal alloys: in this study, EOS data of pure Tungsten were used instead of Inermet 180 (95% W, 3.5% Ni and 1.5% Cu alloy) [6].

Consequently presented results are affected by uncertainties that can be fully mastered only once data obtained by direct material characterization through in-house experimental testing (e.g. in the HiRadMat facility) become available.

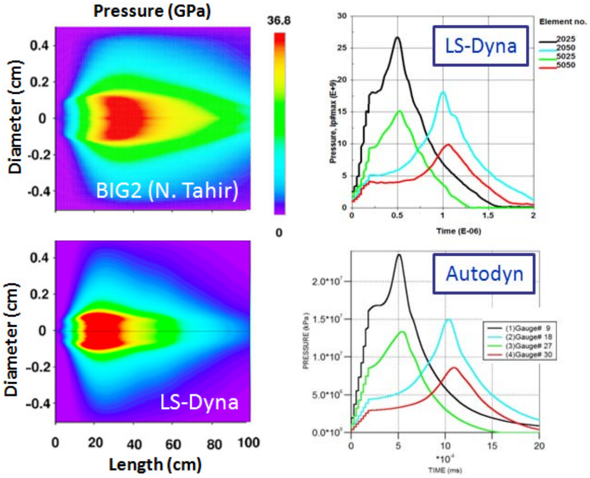
An example of comparison between numerical and experimental results, in the case of a well known material such as pure Copper, was carried out by H. Richter et al. [7].

Benchmarking between different Hydrocodes

In this work Autodyn by Ansys was extensively used, making use both of Lagrangian and Smoothed-Particle Hydrodynamics (SPH) techniques [8].

A preliminary benchmarking with other two Hydrocodes (LSDyna by LSTC, BIG-2 developed by GSI) was performed, comparing the results obtained by simulations of a cylindrical Copper sample impacted by nominal LHC bunches [9].

The good agreement between the three codes is shown in Figures 1 – 4.



Figures 1 – 4: Comparison between LSDyna, BIG-2 and Autodyn

NUMERICAL ANALYSIS OF TCT

The layout of a TCT jaw assembly is presented in Figure 5. The part of the jaw directly interacting with the beam is essentially composed of five Inermet 180 blocks, each 200 mm long. These are fixed with stainless steel screws to a support made of OFE-Cu. The Copper support is in turn brazed to cooling pipes made of Copper-Nickel alloy (90% Cu – 10%Ni), while these are brazed to a back-stiffener (made of Glidcop, a Dispersion Strengthened Copper).

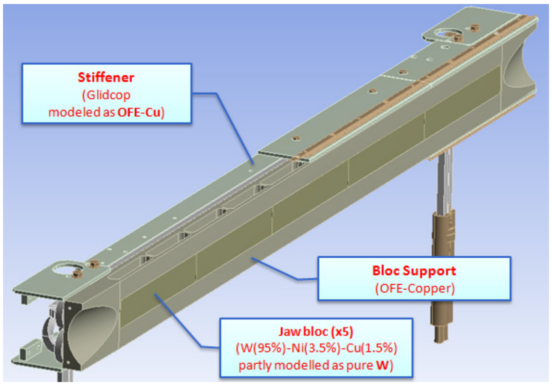


Figure 5: Jaw assembly of a TCT Collimator

Table 1 provides details about the constitutive models used for each of the relevant materials. It is worth noting that water in the cooling pipes was also included in the analysis.

Table 1: Materials models

Material	EOS	Strength model	Failure model
Tungsten [10], [11]	Tabular (SESAME)	Johnson-Cook	Plastic strain/ Hydro (Pmin)
Copper OFE [9], [10]	Polynomial	Johnson-Cook	Johnson-Cook
Stainless Steel AISI 316 [12]	Shock	Johnson-Cook	Plastic strain
Water	Shock	-	Hydro (Pmin)

Two 3D models were implemented in Autodyn:

- Full jaw with Lagrangian mesh, to study the shock-wave propagation and assess possible damage in each element of the jaw assembly;
- A short model of a single Tungsten block (200 mm) with its Copper support, along with a portion of the opposite jaw and of the stainless-steel tank cover. The Tungsten block was modelled by the SPH technique, in order to study the high-speed ejection of W particles and their impact on the tank and on the opposite jaw.

Accident scenarios

Two possible accident scenarios were identified with different degrees of severity and probability. Both scenarios are based on an asynchronous beam abort event [13].

- Single Bunch Set-Up: less severe but with higher probability. This event may occur during collimation set-up if the set-up bunch is accidentally steered at the correct phase.
- Standard multi-bunch operation: less likely with more severe consequences. In this case a series of unfortunate events must sum up:
  - Asynchronous beam abort.
  - Margin between TCDQ and TCT completely eaten up (wrong hierarchy).
  - One or more bunches steered at correct phase.

Seven cases were derived from these scenarios, with varying beam energies, intensities and emittances, conservatively assuming that all bunches have the same impact parameter (2 mm) as well as same charge (1.3 x 10^{11} p) and optical functions at TCTH.4R5B2.

It is worth noting that for multi-bunch cases, we have implicitly assumed that the density variation caused by preceding bunches is negligible: this only holds for a limited number of bunches (up to 8), before density changes become too large to be disregarded.

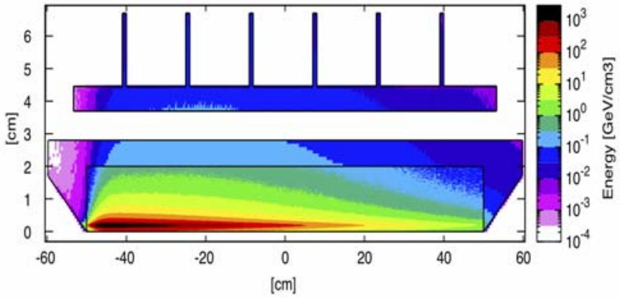
Relevant parameters for the studied cases are provided in Table 2 (note that energy is not scaling exactly with bunch number because of small mesh distortion during the deposition).

A complete FLUKA [14], [15] model of the TCT collimator was set up and full shower simulations were carried out providing the energy deposition distribution for each case (Figure 6). These 3D maps were then loaded in the Autodyn 3D model through dedicated subroutines.

Table 2: List of accident cases.

Case	Beam Energy [TeV]	Norm. Emittance [μm rad]	N. of Impacting Bunches	Energy on Jaw [kJ]	TNT Eqv. [g]
1	3.5	3.50	1	38.6	9.2
2	5	7	1	56.2	13.4
3	5	3.5	1	56.5	13.5
4	5	1.75	1	56.6	13.5
5	5	1.75	2	111.3	26.6
6	5	1.75	4	216.1	51.6
7	5	1.75	8	429.8	**102.7**

A first, preliminary, assessment of damaged area extension can be roughly done by evaluating the molten region dimension on the Tungsten block from FLUKA maps [16].



Figures 6: Slice of the energy deposition distribution on the impacted jaw and support for Case 4 (not to scale).

In order to determine the consequence on the collimator and machine operation, three different damage levels were defined:

- Level 1 – The collimator need not be replaced. The jaw damage is limited so that an intact spare surface can be found relying on the 5th axis movement (+/-10 mm). Permanent jaw deformation is limited.
- Level 2 - Collimator must be replaced. Damage to the collimator jaw is incompatible with 5th axis travel (damaged area diameter higher than 8 mm). Other components may also be damaged (e.g. Screws).
- Level 3 - Long down time of the LHC. Very severe damage to the collimator leading to water leakage into beam vacuum (pipe crushing, tank water circuit drilling ...).

Results

All the single-bunch cases, both at 3.5 and 5 TeV, at all emittances, fall within damage level 1. A grove is created on the two first Tungsten blocks with an extension roughly proportional to the bunch energy. The size of the damaged region is already much larger than the beam size so that no sensible difference is found when varying the beam emittance (Figure 7).

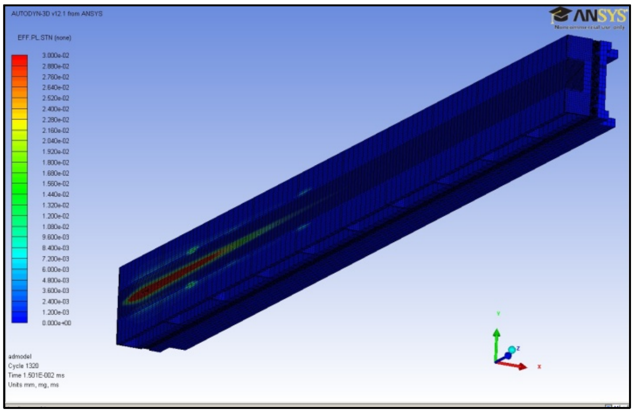
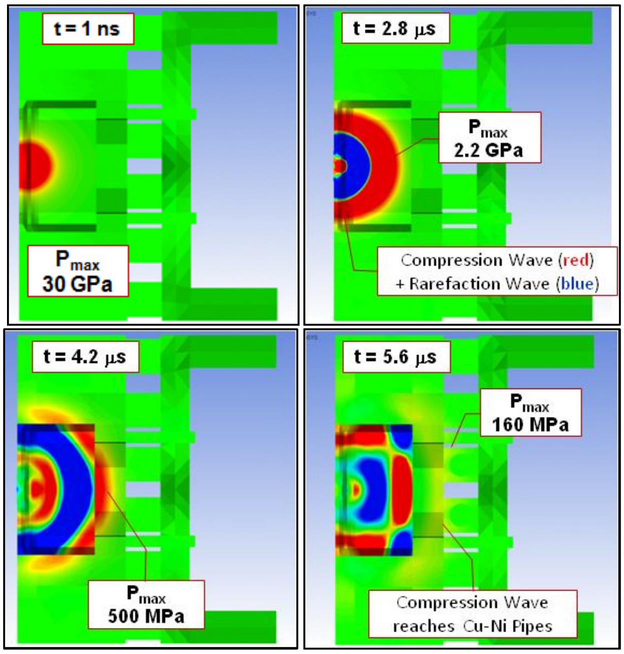


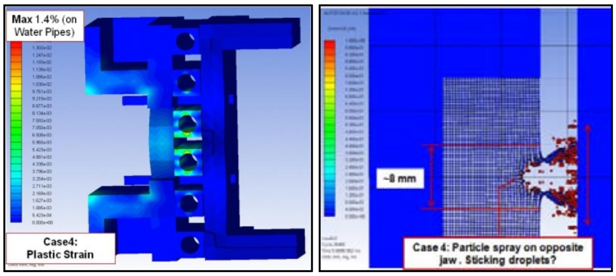
Figure 7: Extent of the damage ($\varepsilon_p > 3\%$) on Tungsten blocks (Case 4)

It is important to note that the so-called shock impedance between W and Cu, defined as $Z = \rho_0 U_s$ (with ρ_0 initial density and U_s sound speed) [17] plays a key role in limiting the damage as it confines most of the wave energy inside the Tungsten block (Figures 8-11).

It can also be observed that the jaw damage extension at 5 TeV (Case 4) is at the limit of Damage Level 2; plastic deformations on cooling pipes and screws remain limited (Figure 12); Tungsten particles are sprayed on a larger area of the opposite jaw (Figure 13): this jaw is not directly damaged; however its final flatness may be affected by possible re-solidified droplets stuck on its surface.



Figures 8–11: Case 4. Propagation of the shock wave in the jaw assembly. Note the wave is mostly reflected at the W-Cu interface, only partially transmitted to Cu Support.



Figures 12-13: Case 4. Residual Plastic strain on Cu and damage extension on W. Note particles sprayed on opposite jaw.

Cases 5 and 6 (2 and 4 bunches at 5 TeV) belong to Damage Level 2. In this case, the jaw damage extension is much larger than 8 mm and severe plastic deformations can be observed on cooling pipes ($\varepsilon_{p,max}$~12%) and screws, although visible failures are not detected. The SPH simulations show in these cases a permanent damage on the opposite jaw, provoked by the Tungsten particles impacting at elevated velocity (Figure 14).

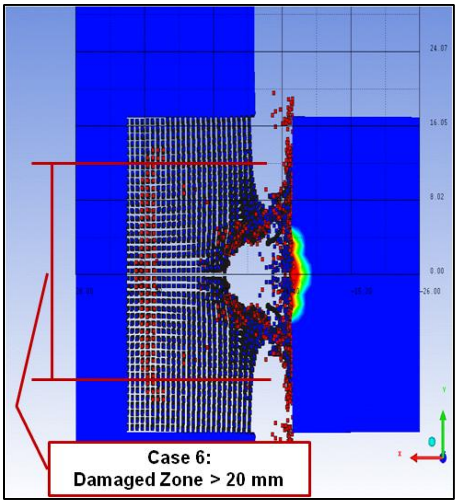


Figure 14: Case 6. High speed particle spray provoking an extended damage on the opposite jaw.

The only studied case leading to catastrophic damage (level 3) is case 7 (8 bunches at 5 TeV).

The consequences of this event are:

- High probability of water leakage due to very severe plastic deformation on pipes ($\varepsilon_{p,max}$~21%, Figure 15).
- Extended eroded and deformed zone on the W jaw.
- Projections of hot and fast solid Tungsten bullets (T ~ 2000K, V_{max}~1 km/s) towards opposite jaw. Slower particles hit tank covers (at velocities just below ballistic limit, Figure 17);
- Risk of permanent bonding betweeen the two jaws due to the projected re-solidified material (Figure 16).

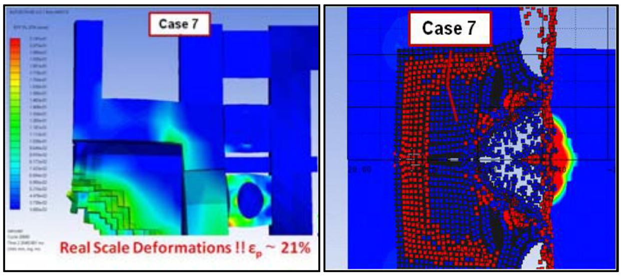


Figure 15-16: Case 7. Plastic strain and Damage extension on the two jaws (possible jaw bonding).

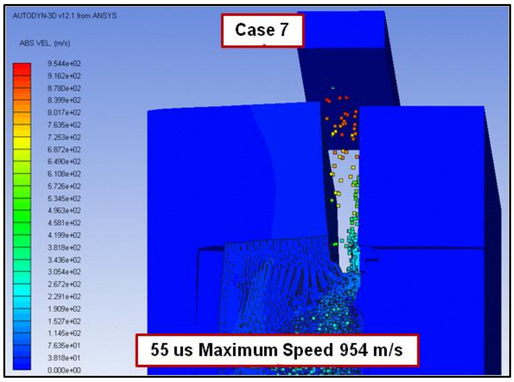


Figure 17: Particles projected towards the stainless steel tank.

CONCLUSIONS

While thermally-induced dynamic phenomena up to the melting point of metals can be reasonably well treated with standard FEM codes, advanced wave propagation codes (Hydrocodes) become necessary when changes of phase and density occur. In this paper a thorough numerical analysis of a Tertiary Collimator was carried out, relying on advanced simulation techniques applied to a complex 3D model. Several asynchronous beam abort cases were studied with different values of beam emittance, energy and intensity.

- Single-bunch accidents at 3.5 and 5 TeV induce jaw damage which does not require collimator replacement as in-situ spare surface can be found by shifting the full collimator (relying on the 5th axis).
- Multi-bunch accidents always require collimator replacement.
- Risk of very severe damage leading to long LHC downtime above four bunches (risk of water leakage detected at 8 bunches).

The most important simulation issue concerns the reliability of constitutive material models, as they are beyond commonly available data. Only specific tests in dedicated facilities (such as HiRadMat) can provide this information.

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RADIATION TO ELECTRONICS: REALITY OR FATA MORGANA?

V. Boccone, M. Brugger, M. Calviani, A. Ferrari, D. Kramer, R. Losito, K. Røed,
S. Roesler, G. Spiezia, A. Thornton, Y. Thurel
for the R2E Mitigation Project, www.cern.ch/r2e
CERN, Geneva, Switzerland

Abstract

A first year of successful LHC operation has passed reaching about 50pb^{-1} of integrated luminosity (1‰ of nominal, 5% of 1fb^{-1}) and more than 1% of peak luminosity, as well as a successful ion run. It is thus time having a first look on the observed radiation levels around LHC critical areas and to compare them to available simulation results. In spite of the still very low integrated intensities and cumulative luminosities, this paper summarizes the failure rate predictions by evaluating the observed radiation levels and early electronics failures, as well as the additional results from 2010 CNRAD radiation tests. Upcoming possibly in early 2011, electron cloud and scrubbing issues and their impact on radiation levels are also briefly discussed. Based on this, updated predictions for 2011 operation and beyond will be deduced, on the base of the envisaged LHC intensity, energy and luminosity reach. Starting from these estimates, priorities for short-term improvements and beam tests are presented, as well as a brief overview of upcoming 'Radiation To Electronics (R2E)' driven mitigation actions.

INTRODUCTION

As studied and documented in detail over the past years, there is a relevant risk of occurrence of radiation damage to electronics at the LHC. A dedicated strategy is required to reduce it to a level that will allow for smooth LHC operation and maximum performance. Mitigation measures to be performed "in the shadow" of increasing LHC intensity, energy and luminosity require the thorough analysis, optimization and coordination of all related activities, the most important being:

- A thorough analysis of available monitoring data and their comparison with expected radiation levels, based on detailed simulation results and taking into account most accurate detector calibrations. This requires a detailed review of existing and required Monte-Carlo calculations together with the development of efficient monitoring tools and the constant improvement of monitor locations. For all LHC critical areas radiation levels have to be reviewed on a regular basis, assuring full monitoring coverage and the best possible understanding of their results.
- A close collaboration with the equipment groups for the assessment of radiation tolerance of presently installed (and future) electronic equipment in radiation exposed areas. Common design practices and appropriate radiation tests have to be discussed and reviewed in detail. In addition, observed radiation induced failures have to be carefully analyzed and used as direct input for (a) failure rate estimates, (b) the development of required patch-solutions, as well as (c) for the development of radiation tolerant equipment. To support (b) and (c), radiation test campaigns have to be organized on a regular basis within CERN (CNRAD, H4Irrad test areas) and at external facilities (PSI, etc.).
- The technical integration study and detailed implementation of medium-term mitigation measures such as the installation of shielding and relocation campaigns of sensitive equipment.

This paper summarizes our understanding of radiation levels, their development during the coming years of LHC operation and the consequences for electronics installed in critical areas. Finally, past and ongoing mitigation measures are briefly described and follow-up actions are identified.

RADIATION TESTS AT CNRAD

To estimate the possible implication of radiation induced failures of electronics in the LHC, three groups of information have to be known: (1) the failure mode(s) of the device, (2) the failure cross section (probability) or level at which it occurs in case of cumulative effects and (3) the expected radiation level at the point of installation. Most of the electronics systems located in the LHC tunnel, but only a few systems from the LHC shielded areas were actually tested in the CNRAD (CNGS TSG4) test area, but partly also in external facilities in 2009 [1] and earlier.

For the large number of commercial systems being installed in the shielded areas, only a representative selection of devices could be tested in 2010 and it is important to note that even for this selection no guarantee can be given that equal devices (same manufacturer and type) will also behave in an equal manner when exposed to radiation. The latter is due to fact that for 'Components of the Shelf (COTS)' no guarantee nor information is provided from the producer that in all devices the same components (manufacturer, process, batch) are used, thus variations on their behaviour under radiation have to be expected.

However, to provide a global estimate for the LHC, the test results provide the only information on the sensitivities of the devices as well as their likely failure modes. These results are then combined with the information available in the equipment inventories of the LHC (see [2-5]) which were performed in 2010 in order to allow for a detailed analysis of all types of exposed equipment, their working principle and their impact on LHC operation in case of failures.

Numerous radiation tests were performed during 2010 with a significant fraction focusing on COTS components. For the latter, the following representative electronic systems have been selected and were available to be installed at CNRAD (equipment details provided in brackets):

- Timing and Remote Reset (custom built system as installed in the LHC)
- Cooling and Ventilation Control (Siemens S7-300, S7-200, Schneider Telemecanique Premium)
- Fire Detection (detectors of different types based on commercial components/systems)
- Control equipment of electrical installations located in LHC safe-rooms (RTU CLP500E, Ethernet Switch, DAU MAP3200, 48/24VDC, Pt100/20mA, RS232/RS485, etc.)
- Ethernet Distribution (Ethernet Switches 3Com 4400)
- Interlock Controller (PLC 315F 2 DP, Ethernet controller, 24 DI safety input modules, 2 x DO Relay modules, 2 x 32 DO module, IM153.1 - ET 200M, Boolean Processor - FM 352-5)
- Collimation (Drivers, I/O RIO, National Instruments PXI MDC + PRS, ADC, DAC, FPGA card, power supply)
- Europa crate (custom electronic for LVDTs and Resolvers excitation/acquisition, power supply)

Table 1: Equipment failure cross-sections as obtained during the 2010 CNRAD radiation test campaign on COTS systems.

Device Type	Failure Mode	Failure Cross-Section [cm^2]
PLC-S7-200	Profibus lost, reset needed	$1.8x10^{-7}$
24V DC Power Supply	Destructive failure (burned-out chip)	$1.1x10^{-8}$
PLC-S7-300	blocked, reset needed	$7.8x10^{-8}$
PLC-Schneider	PS burned	$1.1x10^{-7}$
PLC S7-300 + FM352-5	beam dump and access	$1.1x10^{-7}$
Fire Detectors	power cycle	$1.0x10^{-9}$
Ethernet Switch	blocked, reset needed	$1.4x10^{-8}$

The systems were closely monitored during the irradiation period and failures were classified into soft failures (reset allowed to continue the operation of a device) and hard failures (device was not recoverable). A selection of respective failure cross-section is provided in Table 1 with more details provided in the various radiation test reports (partly still in work) of the responsible equipment groups as collected on the RadWG website (www.cern.ch/radwg).

To illustrate the stated failure cross sections (representing the probability of failure per unit high-energy radiation fluence), one can take the result for the PLC-S7-200 and put it into perspective with the radiation levels at its installed LHC locations:

- failure cross-section: $1.8x10^{-7}cm^2$
- expected annual radiation levels in the UJ14: ~ $1x10^9cm^{-2}y^{-1}$ (in case no shielding/relocation is applied)
- this device would faile ~200 time per year at nominal LHC operation, leading to a beam-stop and required access

The failure cross sections obtained during the CNRAD irradiation tests can then be used together with the information collected through the equipment inventories [2-5] and can be also applied for similar electronics installed in the various areas to provide failure rate estimates (see respective chapter in this publication). However, due to the large number of different equipment types, manufacturers and components being used around the LHC critical areas, an overall uncertainty of one order of magnitude should be considered even in case when equipment types similar to the tested ones are used.

Table 1 further shows that large differences can be observed between the various equipment and depending on the failure mode. An overall suggested ‘rule of thumb’ for unknown equipment failure cross sections is:

- soft failures (reset required): 1 failure per equipment and a cumulated high-energy radiation fluence of 10^6-10^9cm^{-2}.
- hard failures (device not usable anymore): 1 failure per equipment and a cumulated high-energy radiation fluence of 10^7-$10^{10}cm^{-2}$.

FLUKA BENCHMARK MEASUREMENTS

Radiation levels to be expected around the LHC during nominal and ultimate LHC intensities are predominantly based on detailed and partly very complex FLUKA Monte-Carlo calculations [6, 7]. Their respective results were analyzed, updated and evaluated during the past years [8] and provided together with the equipment sensitivities the starting point for the mitigation analysis.

In order to investigate the accuracy one can obtain with Monte-Carlo calculations, it is important to distinguish between three main sources of possible uncertainties:

- level of details included in the calculation (geometry, materials)

- physics models included in the Monte-Carlo code
- operational and loss assumptions leading to the final normalisation of the results

The validity of the discrete physical models implemented in FLUKA has been benchmarked against a variety of experimental data over a wide energy range, from accelerator data to cosmic ray showers in the Earth atmosphere (see [6, 7] and references therein). LHC operation and the complexity of the final radiation field around LHC critical areas require for 'Radiation To Electronics (R2E)' purposes a detailed analysis of different levels of benchmark experiments, globally summarized in three categories:

1. dedicated experiments with LHC representative radiation fields allowing for a controlled comparison between simulations and measurements
2. controlled beam-losses and respective radiation fields in the LHC environment
3. complex beam losses and large scale simulations compared to measurements performed over an extended operation period

(1) Benchmark Measurements at the CERF Facility

In order to obtain measurements in a radiation environment similar to the LHC, however still within a well controlled setup, a set of measurements was performed at the CERF benchmark facility [9]. A layout of the CERF experimental area is shown in Figure 1. A pulsed, 120 GeV/c mixed hadron beam (60.7% π+, 34,8% p, 4.5% K+), from the Super Proton Synchrotron (SPS) accelerator, is aimed at a 50 cm long copper target creating a radiation field similar to what can be expected in the beam loss regions in the LHC tunnel. The CERF facility can therefore be used as reference field for calibrating and testing of equipment monitoring damage to electronics in a mixed radiation field. Variation in this radiation field can be achieved by placing the equipment at different positions around the copper target. These positions are indicated by labels ranging from 1 through 6, where the downstream positions (4-6) are representative for the LHC tunnel regions, whereas the other positions (1-3) are very similar to shielded areas close to the accelerator tunnel.

RadMon detectors [10, 11] were used for the benchmark at the CERF facility as the RadMon provides online measurements of the Total Ionizing Dose (TID as measured with a RadFET), the 1 MeV neutron equivalent fluence (measured with a PIN-diode) and the high-energy (> 20 MeV) hadron fluence (measured by "counting" SEUs in a memory). Each RadMon can be operated at 5V or 3V where the lower voltage effectively increases its Single Event Upset (SEU) sensitivity. During the past years and in view of their high importance for the LHC, a significant effort was made in order to improve their calibration for the various radiation components representative to the LHC radiation environment.

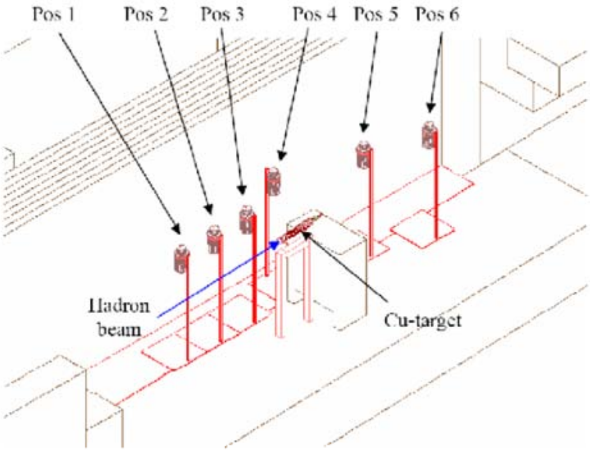


Figure 1: CERF layout with the copper target and the six measurement positions as used for the measurements.

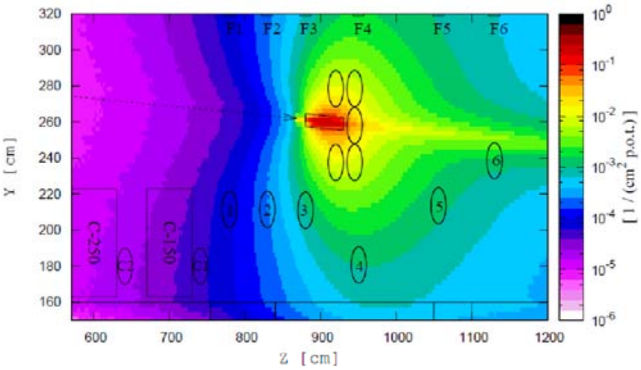


Figure 2: High-energy hadron fluence normalized per primary particle of the 120 GeV/c mixed hadron beam particle (60.7% π+, 34.8% p, 4.5% K+) impinging on the copper target.

Table 2: Comparison between FLUKA simulation and RadMon (set to 5V) measurements as performed during the CERF benchmark measurements. Results are given as high-energy hadron fluence per primary proton impinging on the CERF target. Stated errors are based on counts and calibration uncertainties for the RadMon values, as well as statistical uncertainties for the FLUKA calculations.

Location	**RadMon [Error]**	**FLUKA [Error]**	**Ratio (R/F)**
Pos1	3.77 x 10^{-4} [20.0%]	4.17 x 10^{-4} [5.1%]	0.90
Pos2	5.76 x 10^{-4} [20.0%]	5.76 x 10^{-4} [4.6%]	1.00
Pos3	1.99 x 10^{-3} [20.0%]	1.97 x 10^{-3} [2.8%]	1.04
Pos4	1.75 x 10^{-3} [20.0%]	1.71 x 10^{-3} [3.4%]	1.02
Pos5	1.53 x 10^{-3} [20.0%]	1.67 x 10^{-3} [3.2%]	0.92
Pos6	2.19 x 10^{-3} [20.0%]	2.19 x 10^{-3} [2.9%]	1.00

During the CERF experiment these RadMons were displaced between the different measurement positions to study their response in the various mixed radiation field which are representative for the LHC. For the same setup FLUKA simulations were performed including all relevant details (geometry, materials, source term, etc…). For all measurement locations the total ionizing dose, 1 MeV neutron equivalent and high-energy hadron fluence, as well as the particle energy spectra for the various types of particles were calculated. A horizontal cut through the layout and its respective high-energy hadron (>20 MeV) radiation field can be seen in Figures 1 and 2. The measured data and the FLUKA calculations at the different measurement positions were compared as shown in Table 2 and a very good agreement was obtained.

(2) LHC Application Benchmark during Injection Tests

Profiting from the controlled and known particle losses during LHC injection tests, monitor readings of RadMon detectors were analyzed and compared to respective FLUKA simulation results. The complex layout (see Figure 3) of this injection section into the LHC (more than 100m long) allowed for a detailed practical benchmark in order to verify the FLUKA predictions made for dedicated measurements.

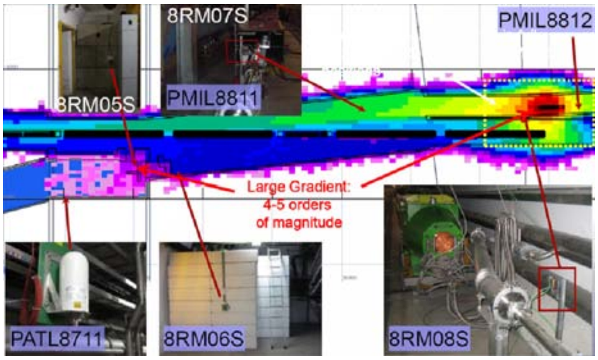


Figure 3: Layout of the LHC injection line where it enters the LHC tunnel and as implemented in FLUKA. In addition, the various monitor locations are shown.

During the first benchmark the RadMon was placed directly behind the injection dump (TED) which is situated at the end of the LHC injection line. The TED can be moved into the beam in order to allow for setup and tuning studies to be carried out in the injection line without bringing beam into the LHC. This allows for an ideal benchmarking setup where the loss term (number of protons impinging on the TED) is known in all details. The high-energy hadron fluence distribution as well as the successful comparison between measurements and simulations are shown in Figure 4 and Table 3.

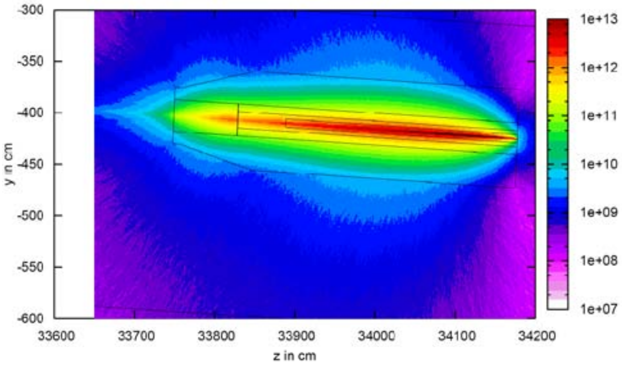


Figure 4: Horizontal high-energy hadron fluence distribution around the TI8 beam stopper (TED) for 6.8x10^{12} 450GeV/c protons impinging on the TED. The color code refers to number of particles per square-centimeter above 20 MeV [cm-2].

Table 3: Comparison between FLUKA simulation and RadMon (set to 5V) measurements performed during the injection test with direct dump on the TI8 beam stopper (TED). Stated errors are based on counts and calibration uncertainties for the RadMon values, as well as statistical uncertainties for the FLUKA calculations.

Quantity	**RadMon [Error]**	**FLUKA [Error]**	**Ratio (R/F)**
High-energy hadrons (cm^{-2})	1.2 x 10^{10} [20.0%]	0.96 x 10^{10} [3.2%]	0.80
1 MeV neutron equiv. (cm^{-2})	2 x 10^{10} [20.0%]	2.1 x 10^{10} [2.5%]	1.05
Dose (Gy)	4.73 [20.0%]	5.0 [10%]	1.06

Beam losses occur not only on the TED (during injection line setup) but also during injection when fractions of the injected beam will be lost on the injection collimator (TCDI). Electronics near the shielded area has therefore to be sufficiently protected and respective shielding improvements were already performed in 2009 [8]. Figure 5 shows the radiation field distribution in case of a beam loss on the TCDI, as well as the two monitor locations of interest.

During a setup of the TCDI collimator with a known number of protons impinging on its jaw, the two monitor locations (8RM05S and 8RM06S, see Fig.4) then served as application benchmark in order to compare the FLUKA simulations and the detector readings. The good agreement is shown in Table 4, where the results are expressed as high-energy hadron fluence per primary particle interaction on the collimator jaw.

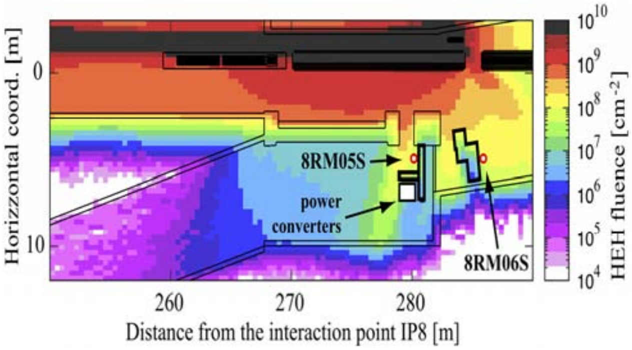


Figure 5: High-energy hadron fluence distribution around the collimator (TCDI) location originating from losses of 450GeV/c protons injected into the LHC. Fluences are normalized for an estimated cumulative annual loss on the respective collimator.

Table 4: High-energy hadron fluence (cm^{-2}) for two RadMon measurement positions close to the shielded area. Results are given as fluence per primary proton impinging on the injection collimator (TCDI). Stated errors are based on counts and calibration uncertainties for the RadMon values, as well as statistical uncertainties for the FLUKA calculations.

Location	**RadMon [Error]**	**FLUKA [Error]**	**Ratio (R/F)**
8RM05S (3V)	6.97. x 10^{-5} [20.0%]	7.75 x 10^{-5} [5.7%]	0.9
8RM06S (5V)	6.36 x 10^{-6} [20.0%]	6.10 x 10^{-6} [6.8%]	1.05

(3) 2010 operation and comparison of monitor readings with FLUKA simulations results

Proton losses occur distributed on the collimators during all phases of accelerator operation. During the collimation study phase and their respective design and implementation into the LHC, detailed calculations were carried out based on SixTrack [12] for particle tracking and FLUKA [6, 7] for various applications ranging from the characterisation of the radiation field, radiation protection issues and energy deposition studies. This led to a very detailed FLUKA implementation of the collimation areas (IR3 and 7) [13], which is in the following used to compare the radiation levels as predicted by the particle loss distribution based on the tracking code and the subsequent detailed FLUKA calculations with RadMon measurements as obtained during 2010 3.5TeV LHC operation.

Based on the loss distribution between the various collimators the actual loss location of the primary protons is sampled as source term in the FLUKA calculations. The secondary particle distribution is then tracked in detail along the more than 500m long geometry of the long straight section and for about half a million of primary particles in order to allow for reasonable statistics at the monitor locations (the DS/ARC sections are disabled in the case of these simulations). Strong radiation gradients exist in IR7 between the area of the primary collimators and the downstream critical areas (UJ76 or RR77) as can be seen in Figure 6 where the FLUKA results for beam-1 induced losses are shown.

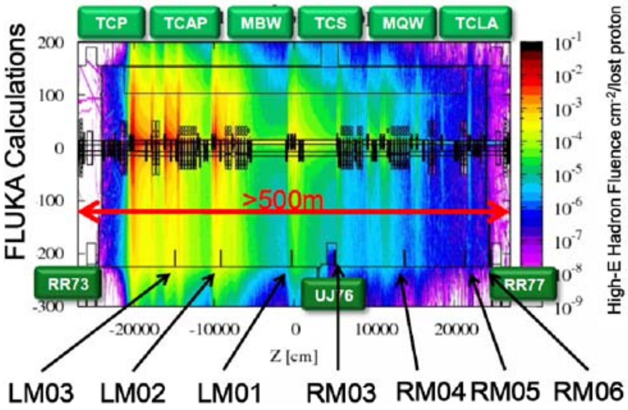


Figure 6: High-energy hadron fluence distribution along the full long-straight-section of IR7 and for primary losses occurring for beam-1 only.

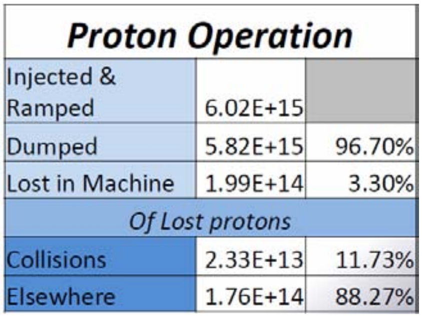
In a first approximation and for the location of the RadMon detectors (see Figure 6 and detectors numbered as LM01-03, RM03-06) the particle losses between beam-1 and beam-2 can be considered as symmetric, thus allowing to mirror the radiation levels against the IP providing this way a complete radiation map for all monitor locations expressed as high-energy hadron fluence per primary lost particle.

To normalize the calculation results to the absolute values, in a next step the total number of particles lost in IR7 during 2010 LHC operation has to be determined in order to correctly compare the obtained high-energy hadron fluence to the respective cumulative monitor readings. The particle losses at the collimators being distributed and changing between the various phases of beam operation (*e.g.* ramp, squeeze, physics), together with the fact that there is no direct measurement providing the detailed number of lost particles for each collimator, the following procedure has been applied to determine the total number of protons lost in IR7 during 2010 operation (see Tables 5 and 6):

- based on the LHC BCTs as logged in TIMBER for each fill the highest intensity in the machine is considered as ‘injected intensity’ (see Table 5)
- right before the dump of the beam the last intensity value is considered as ‘dumped intensity’ (see Table 5)
- the difference between the two values is assumed to be ‘lost’ in the machine mainly between collisions at the experiments and collimators
- for the number of interactions in the experiments, their total luminosity is used together with an assumed total inelastic cross section of 80mb.

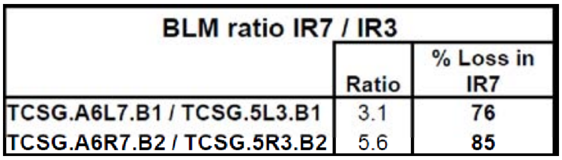
- the remaining intensity mainly refers to the collimators in the two collimation insertions (IR3 and IR7), and to determine the fraction of protons being lost in IR7 the BLM signals close to the collimators are used, in particular the cumulative dose at the first secondary collimator (see Table 6)

Table 5: Summary on injected, dumped and lost protons during 2010 LHC operation.



Proton Operation		
Injected & Ramped	6.02E+15	
Dumped	5.82E+15	96.70%
Lost in Machine	1.99E+14	3.30%
Of Lost protons		
Collisions	2.33E+13	11.73%
Elsewhere	1.76E+14	88.27%

Table 6: Ratio of cumulative BLM readings at the first secondary collimator in IR3 and IR7. The ratio is used to determine the fraction of the total losses as accumulated in IR7 during 2010 LHC operation.



BLM ratio IR7 / IR3	Ratio	% Loss in IR7
TCSG.A6L7.B1 / TCSG.5L3.B1	3.1	76
TCSG.A6R7.B2 / TCSG.5R3.B2	5.6	85

The RadMon detectors measure number of upsets in their SRAM memory which is proportional to the particle fluence. For charged particles the memory is sensitive to high energy particles (>20MeV) only, while for neutrons also intermediate energies (5-20MeV) and thermal neutrons (<0.5eV) have to be considered. In order to allow for a complete response analysis of the RadMon memory, a series of calibration measurements were carried out at CERN (CERF, CNRAD) as well as at dedicated mono-energetic facilities (PTB, NRI) [14, 15]. The particle energy spectra as obtained by the FLUKA simulation in combination with the measured thermal neutron component at a few representative locations in IR7 (based on combined 3V and 5V RadMon measurements, as well as dedicated TLD detectors) allow to predict the number of memory upsets based on the FLUKA simulations and compare them with the 2010 measurements as shown in Table 7.

As can be seen in Table 7, a very good agreement between measurements and simulations can be obtained even in situations with a very complex geometry, varying beam loss conditions and difficult particle energy fields where the calibration of detectors has to be carefully looked at.

Table 7: Comparison between FLUKA simulation and RadMon measurements for the IR7 tunnel locations. The number of measured and calculated memory upsets are compared and the contributing beams are listed.

RadMon	#SEUs Measured	Beam Contr.	#SEUs FLUKA	Ratio (M/F)
7LM03S	14401	B1	15015	1.04
7LM02S	5253	B1	9765	1.86
7LM01S	2689	B1+B2	3116	1.16
7RM03S	950	B1+B2	401	0.42
7RM04S	18727	B2	13032	0.70
7RM05S	303	B2	962	3.17
7RM06S	13	B1+B2	17	1.33

RADIATION LEVELS AROUND THE LHC

Based on the multitude of successful benchmark and ‘application benchmark’ measurements (a few of them briefly described in the previous chapter), it can be concluded that depending on the complexity and reproducibility of particle losses around the LHC, respective radiation levels can be very well predicted with the FLUKA Monte-Carlo code. In the following, we thus review the predictions of radiation levels for 2010 LHC operation, compare them to the predicted radiation levels and provide an outlook to the coming years of operation as well as nominal and ultimate LHC conditions.

2010 Operation

In order to provide an evaluation of the radiation levels as observed during 2010 LHC operation, all details like particle losses and distributions, operational conditions as well as monitor calibrations were carefully included in the calculation analysis and the following steps have been taken in order to obtain both, measured radiation levels around LHC critical areas, as well as correctly updated FLUKA results to be compared with:

- FLUKA predictions as based on the various source terms (*e.g.* collisions at the experiments, loss distribution in collimators, etc.) were rescaled to the actual operational conditions during 2010 (*e.g.* number of protons in the machine, accumulated luminosity for each experiment, etc.)
- RadMon monitor readings were converted into high-energy hadron fluence (>20MeV) applying updated calibration factors (this is particularly important for areas where the RadMons were operated at 3V, thus have a significant sensitivity on thermal neutrons
- To determine the thermal neutron contribution at the various measurement locations, either dedicated RadMon measurements at two voltages were used (see measurement procedure as described in [14]), or the results of dedicated TLD samples were applied (TLDs are thermo-

luminescence detectors allowing through the use of ^{6}Li and ^{7}Li to determine the dose contribution from thermal neutrons; they were further calibrated at CERF in order to improve their absolute response to mixed-radiation fields, thus allowing to determine the total thermal neutron fluence as compared to the high-energy hadron fluence (>20MeV).

Applying the above procedure to all critical areas where RadMon detectors showed a signal (at least a few counts over the LHC operation period in order to provide minimal statistics), Table 8 compares the measured radiation levels to the predicted ones.

Table 8: Radiation levels (high-energy hadron fluence above 20MeV) as predicted by FLUKA and measured at the end of 2010 LHC operation.

Critical Area	**Predicted Fluence [cm^{-2}]**	**Measured Fluence [cm^{-2}]**	**Ratio (M/P)**
UJ14/16	1.3E+06	1.1E+06	0.84
RR13/17	2.5E+05	6.2E+05	2.50
UJ56	1.3E+06	2.5E+05	0.20
RR53/57	2.5E+05	6.2E+05	2.50
UJ76	1.2E+06	2.1E+06	1.86
RR73/77	5.7E+05	3.1E+06	5.44
UX85b	1.3E+07	1.0E+07	0.82
US85	6.3E+06	2.9E+06	0.47
UJ23	5.6E+05	3.9E+06	6.97
UJ87	5.6E+05	2.0E+06	3.62

A generally good agreement between the predictions and the actual measurements is obtained, especially when considering the partly low radiation levels (leading to low statistics of the observed memory upsets in the RadMon where one can consider radiation levels of ~ 10^{7}cm-2 as ‘good statistics’), the high dependency on LHC operation (*e.g.* higher injection losses as can be seen for the UJ23/87) and the fact that partly strong radiation gradients exist.

Prediction for 2011/2012 and Nominal Operation

Based on the before described FLUKA results we can then combine them with the predicted LHC operation parameters for 2011/2012 as well as nominal and ultimate conditions. Based on this, and again only for the selected critical areas (a full summary can be found on the R2E website [16]) Table 9 provides for the most critical areas the expected radiation levels for the coming years of LHC operation.

Table 8 and 9 nicely show that while radiation levels were generally low during the 2010 operation period (lower intensity/luminosity and beam availability), they will reach significant levels already in 2011/12 and high levels during nominal and ultimate operation if no mitigation measures are taken.

Table 9: Predicted annual radiation levels (high-energy hadron fluence in [cm^{-2}] above 20MeV) for the coming years of LHC operation. Predictions take into account the measured radiation levels as given in Table 8.

Critical Area	**2011 [cm^{-2}]**	**2012 [cm^{-2}]**	**Nominal [cm^{-2}]**	**Ultimate [cm^{-2}]**
UJ14/16	7.2E+07	1.2E+08	2.1E+09	4.2E+09
RR13/17	4.3E+07	7.1E+07	1.2E+09	2.5E+09
UJ56	1.7E+07	2.9E+07	5.0E+08	1.0E+09
RR53/57	4.3E+07	7.1E+07	1.2E+09	2.5E+09
UJ76	4.7E+07	8.0E+07	7.4E+08	8.3E+08
RR73/77	6.9E+07	1.2E+08	1.1E+09	1.2E+09
UX85b	9.4E+07	1.9E+08	3.3E+08	3.3E+09
US85	2.7E+07	5.4E+07	9.4E+07	9.4E+08
UJ23	7.2E+07	1.2E+08	2.1E+09	4.2E+09
UJ87	4.3E+07	7.1E+07	1.2E+09	2.5E+09

It shall be noted that underlying uncertainties of the here presented estimates are not insignificant and mainly connected to the actual behaviour of the LHC accelerator.

OBSERVED EQUIPMENT FAILURES DURING 2010 LHC OPERATION

As discussed in the previous chapters, radiation levels were relatively low during 2010 LHC operation. Furthermore, expected failure cross-sections for unknown equipment can range several orders of magnitudes, where an annual high-energy hadron fluence of 10^7cm^{-2}y^{-1} is considered as a reasonable ‘threshold’ level [17] where radiation induced failures start becoming visible above their standard failure modes (leading to a comparable equipment MTBF without radiation; *e.g.* without radiation the current power-converters aim for an MTBF of about 10^{5}h per equipment).

Especially during the period of early LHC operation, and respective low radiation levels, it is thus very difficult to distinguish a radiation induced equipment failure from another one which is a standard equipment failure mode. This can be further illustrated by the fact that one is observing a very large sample of electronic components in the LHC with all of them having non-radiation induced failure modes and respective probabilities. Based on partly measured failure cross sections and assuming 10^{-7}cm^2 as conservative cross-section for unknown equipment only a few radiation induced failures were expected during the 2010 operation period [18]. It would thus be necessary analyzing in detail all occurring failures, which is not entirely possible.

R2E has thus setup a procedure where failures leading to beam-stop (as discussed during the LHC 8:30h meeting) were checked if they fulfil the following criteria:

- did the problem happen together with high radiation levels occurring in the area at the same time (radiation spike, higher losses)
- is the failure occurring in a critical area and on a possibly radiation sensitive equipment
- is the error linked to a communication problem and was resolved by a reset/power-cycle
- is the failure mode recurrent and increasing in frequency with higher radiation levels

All failure candidates were then discussed in detail with the responsible equipment groups and through the "Radiation Working Group (RadWG) [19]" in order to identify possible radiation induced failure candidates (see also the respective database available in the news section of the RAdWG website [19]). This analysis process is obviously not complete and with only a few failure candidates especially the above mentioned last criteria on the frequency of occurrence can hardly be applied.

However, the following few failures were successfully analyzed and confirmed as being very likely radiation induced:

- WIC crate failure in TI8: this failure was already observed in 2009 and is due to a communication problem of the PLC which was also tested in CNGS reproducing the same behaviour [20].
- QPS tunnel card failures: problem with a digital isolator chip (ISO150) leading to a permanent PM trigger; occurred many times and at high-loss locations (injection TCDIs, adjacent to collimation regions); was in the beginning difficult to identify as SEE induced as a similar EMC induced failure mode exists. This device was actually tested with radiation, however is used in a different way in its final implementation, thus making the electronics more vulnerable to the failure. Mitigation actions were already successfully developed in form of a firmware upgrade and partly integrated (the remaining locations will be continuously updated during the 2011 technical stops and accesses) [21] .
- µFIP communication problem: the existing controller chip is radiation tolerant, however the high number of exposed components as well as a possible batch-to-batch variation (with a possible different failure cross-section) led to three observed failures in 2010 (two on QPS equipment, one on CRYO). It shall be noted that the same failure mode was also observed during CNRAD tests.
- TE/EPC power supply: a power supply of a power converter rack situated in the UA87 close to the maze towards the TDI suffered from a burnout. The failure occurred at the same time when high injection losses at the TDI where observed. During a test at CNRAD, the same destructive failure mode was observed [22].

We can thus conclude that already a few radiation induced failures were observed, despite the relatively low radiation levels in the machine: 10^5-10^7cm^{-2} in critical areas (~10^8cm^{-2} in the tunnel) where electronics is exposed. It shall be noted that the respective LHC operation parameter correspond to only about 0.1% of nominal integrated annual luminosity, up to 2% of peak luminosity and about 1% of nominal lost beam.

Previsions provided in 2010 expected a number of radiation induced problems for the reached LHC intensities and luminosities, also in critical areas. As listed before, in the LHC tunnel 5-10 SEE events were already observed in 2010 causing the stop of the accelerator and requiring an intervention (a mitigation procedure exists for the QPS problem and is currently implemented). For the shielded areas only one failure could so far be confirmed.

Three lessons can be learned from this:

- it is (and remains) very difficult to identify radiation induced failures and quantify their risk as long as radiation levels are relatively low;
- also radiation tolerant equipment has certain weaknesses and is exposed to increasing radiation levels, thus detailed monitoring and constant analysis from all concerned equipment groups is of high importance;
- lower and higher failure rates than predicted can not be excluded as unknown equipment can be more or less sensitive (*e.g.* QPS case of the digital isolator chip ISO150), but radiation levels can also be lower or higher than expected (*e.g.* electron cloud, injection losses, life-time for ions)

Strong team efforts are required from all equipment groups and the RadWG, as no big safety margins can be taken for the R2E mitigation project and all activities have to be strongly optimized with respect to LHC operation and shutdown planning, considering the impact on installed equipment, LHC performance and final costs.

FAILURE RATE PREDICTION AND DISCUSSION ON 2011/2012 OPERATION

Based on the before presented results of radiation tests and obtained failure cross sections, as well as the expected radiation levels for LHC critical areas during 2011/2012 but also nominal and ultimate intensities, in the following we try to deduce a global radiation induced failure rate for the LHC. While performed benchmark experiments and early measurements during 2010 operation have shown that the radiation levels can be predicted with sufficient accuracy, it is important to bear in mind that strong uncertainties still remain on both, the actual sensitivity of the COTS equipment, as well as the operational behaviour of the accelerator (especially at high-loss locations or during the scrubbing period). The following estimate is thus intended to illustrate the order of magnitude, but not the detailed number of failures to the last digit.

Based on the performed equipment inventories [2-5] and in iteration with the respective equipment responsible, the following four general failure categories were identified and included in the analysis process:

a) a failure leading to a dump of the beam and requiring access prior restart of the machine
b) as (a) but not requiring immediate access
c) a failure requiring an access which can be scheduled in the next technical stop or other access
d) other failures

Furthermore, the following procedure has been applied to determine the best possible estimate of the collective number of failures for the coming years of LHC operation:

- Based on the measured radiation levels in the various critical areas, the expected radiation levels were revised and updated as much as possible (see previous chapter).
- Wherever possible, equipment failure cross sections are based on measurements and the same are applied to similar equipments in case their sensitivity is unknown.
- For complex equipment like power-converters the expected failure cross-sections are based on the feedback as provided by the power-converter review [23].
- For unknown components a "guessed" failure cross-section is applied according to the complexity of the device and ranges from 10^{-7}cm^2 to 10^{-9}cm^2.
- An intermediate iteration used the 2010 measured and calculated radiation levels and the respective cross sections to deduce a first collective number of failures. This resulted in a higher number of failures as actually observed during the 2010 operation period (see previous chapter), thus the "guessed" failure cross sections were down-scaled accordingly to match the observed number of failures in critical areas.
- The next step is to scale the expected radiation field with the operational parameters for 2011, 2012, nominal and ultimate LHC operation. During this conference and update was provided for 2011 and 2012 [24], with nominal and ultimate conditions remaining unchanged from the original design values [25], leading to the annual radiation levels as listed for a few representative critical areas in Table 9.
- A last step then considers the total number of components/systems per area and for each equipment type their failure cross section and the expected radiation level to calculate the number of annual failures for the respective equipment. Grouping these failures by the four general failure modes (a-d) allows providing an estimate of the total number of annual failures of all equipment being installed around LHC critical areas.

Table 10 summarizes the obtained annual number of failures for the respective failure types and expresses them as mean-time between failures (MTBF).

Table 10: Predicted MTBF due to radiation induced problems in LHC electronics for the coming years of LHC operation. Levels lower than one failure per day are not realistically reachable due to machine turn-around, however listed as theoretical failure rates only.

Failure Mode	2011 [days]	2012 [days]	Nominal [days]	Ultimate [days]
Immediate Dump and Access	4	2	0.2	0.1
Immediate Dump	19	11	0.8	0.4
Scheduled Access	10	6	0.5	0.3
Other	12	7	0.5	0.3

The dominant uncertainty in the above estimate is the actual behaviour of the installed electronics. As outlined before, only a minor fraction of the equipment could be tested and partly strong assumptions had to be made on the other equipment and its failure probability. In addition, as explained in a previous chapter, the radiation levels being mainly based on measurements require a detailed evaluation of the radiation field as this impacts the monitor calibration, thus the final measured value. In order to quantify the respective uncertainty of the predicted MTBF, a sensitivity analysis has been performed on the two independent parameters:

- increasing and decreasing the failure cross-section of not tested equipment (x-axis in Figure 6);
- varying the thermal neutron contribution to the RadMon reading at the location of the radiation monitors, thus changing their calibration factors (shaded areas in Figure 6);

Combining both sensitivity studies leads to the results shown in Figure 6 which states the total MTBF as a function of the assumed failure cross-section. The shaded areas illustrate the sensitivity on the monitor calibration in the respective radiation field. It is important to note, that Figure 6 does not illustrate the other uncertainties as listed earlier (operational behaviour of the LHC or batch to batch variations of measured components/systems).

However, it is clearly shown that aiming for a MTBF of one week for ultimate LHC conditions, requires an improvement of at least two orders of magnitudes, thus considered to be outside the reach of additional uncertainties. A combination of shielding and relocation activities, as well as radiation tolerant developments are thus required as presented in the following chapter.

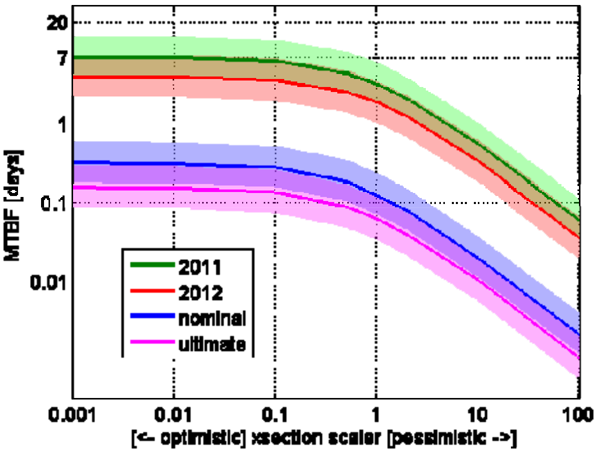


Figure 6: Sensitivity analysis of failure rate prediction as a function of the assumed failure cross sections for untested equipment, as well as the radiation field at the monitor locations.

R2E MITIGATION APPROACH AND ONGOING STUDIES

As shown in the previous chapters, estimating the detailed MTBF due to radiation damage of electronics for the entire LHC machine and all individual equipments is very difficult due to the fact that too many electronic systems are installed in areas exposed to radiation and that it will be impossible to measure the respective radiation sensitivity of all of them.

During the past almost three years the R2E study group has thus put the focus on quantifying the risk, assign priorities, propose a mid-and long-term mitigation plan and perform identified urgent actions to improve the situation and reduce the risk of radiation induced failures as much as possible already during the first years of operation.

The already implemented mitigation actions include:

- closure of holes in shielding: numerous ducts/holes in various UJs, shielding of ducts between the UAs and RAs in Point-6 (next to the TCDQ)
- installation of additional shielding in the injection areas (UJ22, UJ88) to protect adjacent power-converters; safe-room shielding in the US85 and for the UJ76; shielding of the RRs in P7;
- relocation of safety related equipment: Fire/ODH control racks in P5 and P7; UPS in P7; fire detectors in P8;
- relocation of equipment known to be very sensitive and of areas where high radiation levels are reached earliest: relocation of remaining cryo-equipment in the UX85b and the installation of remote valve controllers; relocation of RTUs from the safe-rooms at Point-5 and 7.

It shall be noted that these actions have already mitigated a certain risk of radiation induced failures, however are only a first step towards a complete long-term solution. For the study and development of the latter, the following main constraints have to be considered and are briefly described in the following with their impact on the long-term mitigation approach:

a) the definition of a design criteria for acceptable annual high-energy hadron fluences and the classification of critical areas
b) an acceptable global equipment failure rate induced by radiation
c) the available time windows for mitigation actions

For (a) a design limit of 10^7cm^{-2}y^{-1} high-energy hadrons is not intended to be used as an absolute value below which there is no risk of occurrence of SEE, but rather as the upper value for which normally a single non radiation tolerant electronic device, either COTS or a custom designed has good chances to have an MTBF above one year. This way it cannot be excluded that very sensitive electronics may present dramatic failures already at this level, but the R2E study group considered that the number of equipments presenting this risk is rather limited and a workaround in case of problems can be found in a reasonable time. Reducing this limit further to come close to the yearly value normally registered at ground level (~<10^5 high-energy hadrons/cm^2) would represent an investment (costs and time) well beyond what is reasonable and achievable in the given project constraints.

To reach this design goal the R2E mitigation project thus aims at minimising the number of equipment exposed to higher radiation by:

- installing additional shielding
- relocation into properly shielded areas
- directly reducing the source term of the radiation levels which is an option currently in preparation for IR7 where the installation of additional collimators in IR3 will allow to significantly reduce the radiation levels in IR7 (it remains however to be studied if this can be considered as a long-term solution or if at a certain point IR7 will again have to be used as betatron collimation area)

Unfortunately, shielding is not a sufficient option for all critical areas, thus the remaining equipment has to fulfil the second criteria (b) which was defined together with beam operation as a collective acceptable failure rate of one weekly radiation induced equipment failure under ultimate LHC conditions (intensity/luminosity/losses). This requires that for equipment not possible to be replaced and remaining in not sufficiently shielded areas alternative solutions have to be found and requiring radiation tolerant developments. The latter mainly impacts the power-converters as they have strong relocation limitations (*e.g.* cable lengths making it impossible to relocate them from the RRs with standard cables), as well as certain tunnel components which are already known to be not sufficiently radiation tolerant in the long-term (*e.g.* µFIP). Basically two mitigation options exist:

- a new radiation tolerant design to replace the existing power-converters in the critical areas remaining after relocation and shielding mitigations
- the development of new long-distance and vertical super-conducting links allowing to relocate the power-converters to the surface without having the constraint of cable lengths

Only the thorough study of all options can allow for an effective and efficient optimisation of the mid/long-term solutions to be implemented.

However, perhaps the biggest constraint in this endeavour remains (c) which significantly restricts the time windows (short stops during Christmas, long-shutdowns) available for the mitigation actions to be implemented. Furthermore, (c) has a further strong impact on the actual mitigation strategy in the sense that foreseen long operation periods between long shut-downs limit the possibilities where R2E related mitigation work can be performed in the LHC. The electronics will thus be exposed to higher radiation levels before the actual mitigation measures could be implemented. This is a particular problem for the power-converters where the development phase will be longer than the time available until the next long-shutdown.

Based on the results of the R2E study group two workshops were organised in 2010:

- ‘LHC Power-Converters Workshop’ [26]
- ‘R2E Workshop’ [27]

The first workshop studied the problematic of the existing power-converters, confirmed the high operational risk, proposed a combination of radiation tests and pointed out the importance to study immediately the possibility of a long-term radiation tolerant development. The second workshop focused on the available mid-term mitigation actions (shielding and relocation) and what actions have to be taken in order to assure a long-term mitigation plan, as well as their integration into the LHC operational schedule. The current proposal is illustrated in Figure 7.

This study and the conclusion of the R2E Workshop [27] led to the creation of the R2E mitigation project with the mandate to optimize the mitigation plan and implement all corresponding actions.

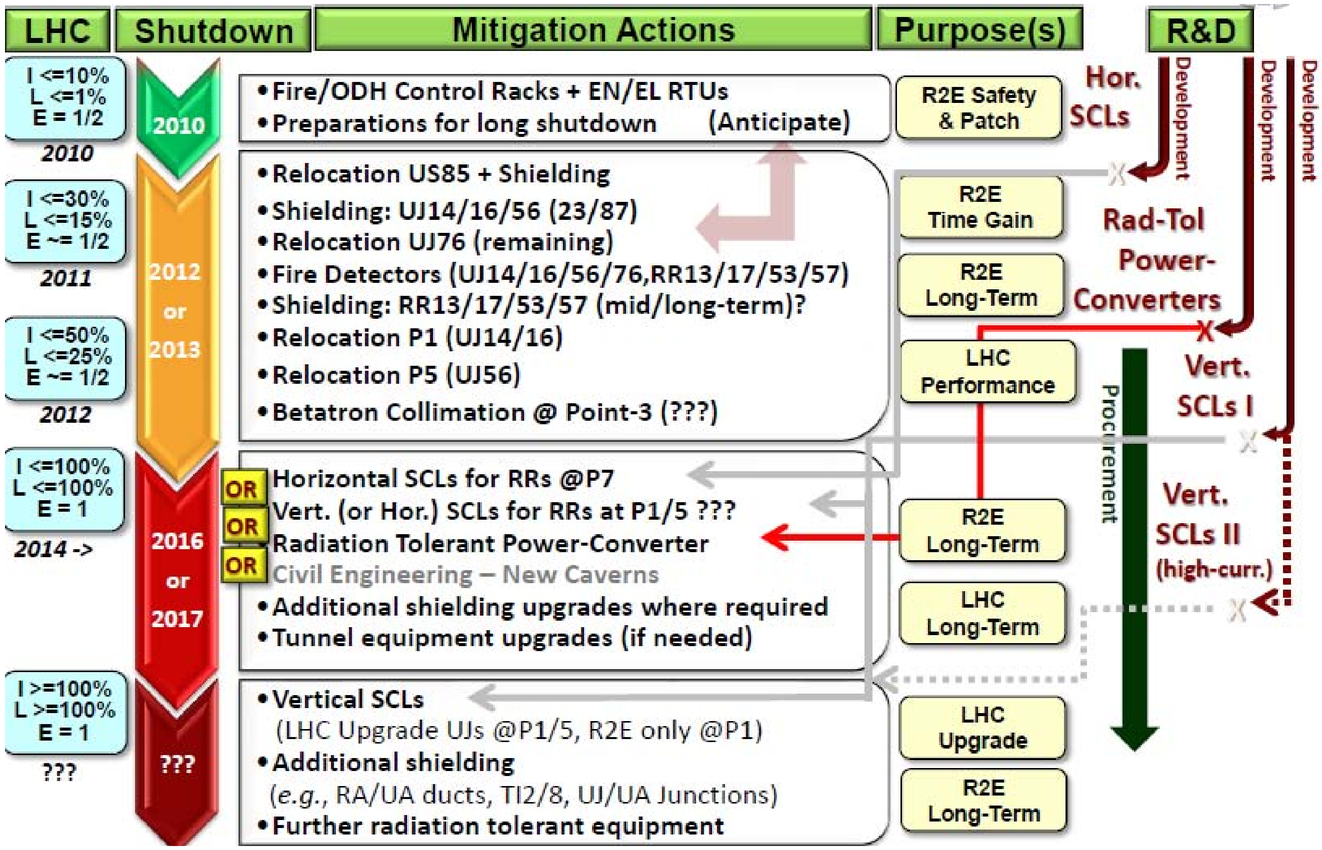


Figure 7: Proposed R2E mitigation approach including studies and actions following the LHC operation and shutdown planning.

Figure 7 illustrates that according to the available time-windows the first long-shutdown will focus on relocation and shielding actions, while the started R&D activities for the development of radiation tolerant power-converters and the design and study of super-conducting links will allow to optimize the long-term solution. In addition, civil engineering actions are kept as backup solution, knowing that such activities would most probably exceed the available length during a shutdown and also be significantly higher in total costs.

The R2E mitigation project has the mandate to minimize (avoid) any risk of radiation induced failure to electronics. It studies a detailed mitigation plan fitting into the planned shutdown periods and optimizes it with respect to planning and costs. This requires a strategy to monitor and benchmark the radiation around all critical areas, constantly review the equipment behaviour and follow-up on radiation induced problems to further refine the required mitigation actions and their respective planning. In parallel, so-called "Patch-Solutions" have to be studied and prepared wherever available. The next long shutdown will focus on shielding and relocation options, anticipating certain work already during the preceeding short stops during Christmas (*e.g.* cabling work during the 2010/11, Fire/ODH and RTU relocations). In parallel, all major long-term solutions (R&D for Superconducting Links and Radiation Tolerant Power-Converters, as well as Civil Engineering) are followed in parallel.

Besides the ongoing R&D work, implementation studies and preparations, the following questions are identified as key points to be answered towards a finalized long-term mitigation program for LHC electronics:

- what are the long-term radiation levels in the dispersion suppressors and in the arc and what does that imply for the respectively installed equipment (*e.g.* higher radiation levels during scrubbing periods);
- how can the large workload related to shielding and relocation activities be reduced and possibly fit into a shutdown of around one year [28];
- what implementation solution can be found for the safe-room equipment in Point-5 and Point-7;
- what is the radiation sensitivity of the currently installed power-converters and how does this translate into equipment failure risk once shielding and relocation measures have been applied;
- given the operation period of several years after the next long-shutdown, what intermediate solution can be found for the power-converters in accordance with the new radiation tolerant development and what is the best corresponding long-term approach;
- what additional weak-links exist in the installed tunnel-equipment and what mitigation measures can be considered.

CONCLUSION AND FOLLOW-UPS

Starting with the two questions to be answered during the 2011 Chamonix workshop, from the R2E point-of-view we can conclude that there is only a minor impact on the expected radiation levels in case the LHC energy is increased from 3.5TeV [29] to higher values, thus this is not considered as an issue for R2E.

However, shifting the long shutdown to 2013 will lead to a delay of the before described R2E mitigation measures (shielding/relocation), thus leading to a higher exposure of the installed electronics. Given the expected radiation levels and equipment sensitivities, an impact on 2012 operation can not to be excluded, however, is expected to be close to acceptable limits (MTBF >= 1 week). It is important to note that the risk of destructive failures must not be forgotten (especially for power devices) and can not be further quantified with the existing radiation test results.

For 2011, the R2E mitigation project thus puts the focus on additional radiation tests (*e.g.* full power-converter tests in the new H4IRRAD facility with representative radiation environments) and the preparation of shielding and relocation measures. The launched development for radiation tolerant power-converters will start working on the conceptual design as well as the component study and respective radiation tests.

The 2011 operational experience together with detailed monitoring and scheduled radiation tests will then allow for a further optimization step of the long-term strategy. In addition, equipment groups and the RadWG study patch solutions to be applied in case certain equipment specific failures are observed and require an early work-around.

The following related follow-up actions have been discussed and agreed upon during this workshop:

1) Prepare as much improvement as possible for 2011/12 shutdown:
   - this requires a frozen layout for all points and the input from radiation tests/operation in order to select what equipment can be prioritized. The relocation work will be anticipated as much as possible (one example: the WIC crate in P8 will most likely be moved already during one of the early technical stops).
2) Change the dispersion setup of B2 (IR7 left): shorten region in the dispersion suppressor where particle losses appear due to ion beam cleaning in IR7 (ions):
   - this will significantly reduce the ion induced radiation losses next to the collimation areas making the radiation levels during one month of ion operation comparable with the remaining year of proton operation.

3) Continue efforts to reduce uncertainty in equipment sensitivity:
   - the new facility H4IRRAD and respective radiation tests are in preparation and will involve in 2011 multiple power-converters as installed in critical areas, EN/EL safe-room equipment and GTOs as used in Point-6.
4) Perform beam tests to improve radiation field calibration:
   - two test locations (quench test location + injection region) are proposed to LHC operation and respective MD shifts are to be scheduled.

The above points together with the R&D program for power-converters, the radiation tolerant development of tunnel equipment (*e.g.* nanoFIP), the radiation test campaigns and RadWG activities shall ensure the required flexibility from the equipment point-of-view. The preparation of shielding and relocation measures

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RADIATION PROTECTION: HOW (RADIO)ACTIVE ARE WE GOING TO BE?

C. Adorisio, D. Forkel-Wirth, S. Roesler#, CERN, Geneva, Switzerland

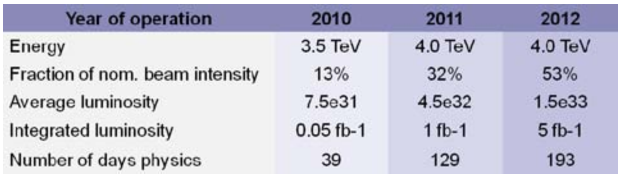
Abstract

Operation in 2010 has caused the first components to become radioactive. An overview of the present residual dose rates around the machine is given. It shows that measurable activation is presently limited to a few components only, such as collimators and absorbers. The procedures to be applied for maintenance and repair work in the tunnel and/or workshops reflect the low radiological risk. However, the comparison to calculated residual dose rates also confirms results of studies and adds confidence in predictions for operation in 2011/12. The latter are given assuming operation at 4 TeV with up to 53% of nominal beam intensity. At the same time, predictions by pure simulation have limitations which are outlined. In order to overcome them, assessments combined with measurements are planned and will be summarized. Finally, the implications of the envisaged operational scenarios for 2011/12 on maintenance and consolidation work as well as on the validity of compensatory measures are detailed.

OPERATIONAL PARAMETERS AND DERIVED SCALING FACTORS

During the year 2010 the LHC has stored beams of up to 368 bunches and a total intensity of 4.3×10^{11} protons at 3.5TeV. Peak luminosities reached values of about $1\times10^{32}/\mathrm{cm}^2/\mathrm{s}$. Predictions for operational conditions which might be achieved in the coming two years are summarized in Table 1 [1].

Table 1: Operational parameters [1].



Year of operation	2010	2011	2012
Energy	3.5 TeV	4.0 TeV	4.0 TeV
Fraction of nom. beam intensity	13%	32%	53%
Average luminosity	7.5e31	4.5e32	1.5e33
Integrated luminosity	0.05 fb-1	1 fb-1	5 fb-1
Number of days physics	39	129	193

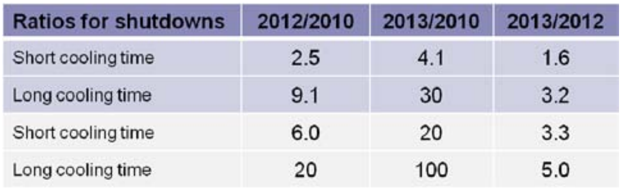
It is assumed that beam intensities will gradually increase up to about 1/3rd of nominal intensity in 2011 and about ½ of nominal intensity in 2012. Similarly, peak luminosities are expected to increase by factors of six and 20, respectively, as compared to last year. With these values, integrated luminosities of 1/fb in 2011 and 5/fb in 2012 can be obtained. Assuming that the luminosity is on average 75% of its peak value and an operational efficiency of 20%, about 129 days of physics operation would be required in 2011 to achieve the goal of 1/fb and 193 days in 2012 to reach 5/fb.

These parameters can serve as basis of a first rough estimate of the evolution of induced radioactivity. The activation in the arcs and collimation regions is determined by the beam intensity. At a certain cooling period, nuclides dominate which have half-lives of about the cooling time. Thus, residual dose rates at short cooling times (few hours to days) are determined by short-lived nuclides (of which the activities have most likely reached saturation), *i.e.*, they reflect the operational parameters of the week preceding the beam stop and roughly scale with the average beam intensity. For example, if the intensity was 32% at the end of the run in 2011 and 53% at the end of 2012, the residual dose rates at short cooling times will be higher by about a factor of 0.53/0.32=1.6. On the contrary, at cooling times of several months long-lived nuclides, that may not yet have reached saturation, dominate the dose rates. In this case, the total number of beam particles lost in the area preceding the given moment matters for dose rate estimates. Assuming that losses scale roughly with beam intensity the residual dose rates at long cooling times increase with the integrated number of circulating protons, which yields, for example, a factor of 3.2 after the run in 2012 as compared to the situation after the 2011 run.

With similar arguments, the evolution of activation around the experiments (detectors, inner triplets, *etc*.), which is dominated by secondary particles from the interaction points, can be estimated. In this case, the average luminosity of the week preceding the beam stop determines the dose rates at short cooling time while the dose rates after several months of cooling reflect the integrated luminosity.

Table 2 summarizes the scaling factors obtained with the arguments discussed above. For example, the 2011 run will increase the residual dose rates in the arcs by factors between 2.5 and 9.1 (depending on the cooling time) and operation in 2012 will cause a further increase by factors between 1.6 and 3.2. Around the inner triplets at Points 2 and 5 a stronger increase is expected, by factors between 20 and 100 until the end of 2012.

Table 2: Scaling factors derived from the operational parameters. The first two lines give the factors for areas where losses scale with beam intensity, the latter two lines show those where activation is caused by p-p collisions.



Ratios for shutdowns	2012/2010	2013/2010	2013/2012
Short cooling time	2.5	4.1	1.6
Long cooling time	9.1	30	3.2
Short cooling time	6.0	20	3.3
Long cooling time	20	100	5.0

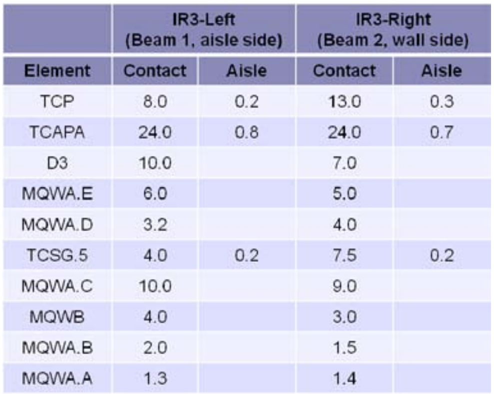
Stefan.Roesler@cern.ch

PRESENT RADIOLOGICAL SITUATION

At present (technical stop 2010/11) all LHC underground areas are classified as Supervised Radiation Areas [2], mostly not because of the residual dose rate levels but due to the fact that accelerator components are potentially radioactive. Residual dose rates at cooling times of about two months after the proton run are at background level, except for a few localised areas in the collimation regions of Points 3 and 7, the TAS absorbers at Points 1 and 5 and the beam dumps.

Tables 3 and 4 list residual dose rates measured with an AD6 detector on contact to the most radioactive components as well as in the aisles at Points 3 and 7, respectively. The date of the measurements (early January 2011) corresponds to about two months of cooling time after the proton run. The ion run is assumed to give a negligible overall contribution to the activation due to the much lower intensities (number of accelerated nucleons) as compared to proton operation, except for a few spots in the dispersion suppressor regions where no beam protons but ion fragments of certain rigidities are lost.

Table 3: Residual dose equivalent rates (in μSv/h) in the momentum cleaning insertion at Point 3 as measured on 1/10/2011.



	IR3-Left (Beam 1, aisle side)		IR3-Right (Beam 2, wall side)	
Element	**Contact**	**Aisle**	**Contact**	**Aisle**
TCP	8.0	0.2	13.0	0.3
TCAPA	24.0	0.8	24.0	0.7
D3	10.0		7.0	
MQWA.E	6.0		5.0	
MQWA.D	3.2		4.0	
TCSG.5	4.0	0.2	7.5	0.2
MQWA.C	10.0		9.0	
MQWB	4.0		3.0	
MQWA.B	2.0		1.5	
MQWA.A	1.3		1.4	

Table 4: Residual dose equivalent rates (in μSv/h) in the betatron cleaning insertion at Point 7 as measured on 1/7/2011.

	IR7-Left (Beam 1, wall side)		IR7-Right (Beam 2, aisle side)	
Element	**Contact**	**Aisle**	**Contact**	**Aisle**
TCP.D6	5.0	0.5	10.0	1.2
TCP.C6	14.0	1.5	18.0	2.5
TCP.B6	31.0	2.6	31.0	3.1
TCAPA	70.0	1.4	70.0	3.0
TCAPB	8.0	0.4	13.0	1.2
TCSG.A6	19.0	2.0	8.0	1.5
TCAPC	45.0	1.2	65.0	2.5

The tables show that presently the most radioactive components are the passive absorbers (TCAPA/B/C), followed by the primary (TCP) and first secondary collimators (TCSG). Dose rates on contact are of the order of tens of μSv/h, in the aisle they do not exceed 3μSv/h. The latter values justify that also the collimation regions are classified as Supervised Radiation Areas.

It should be mentioned, that systematic checks proved the absence of contamination.

GENERIC STUDY

In order to obtain more realistic scaling factors, *i.e.*, factors which take into account the actual irradiation pattern for the years 2010-12 (see Table 1) a generic study was performed with the FLUKA Monte Carlo code [3,4]. The calculations utilized a generic collimator geometry that had been used previously to assess the influence of different material choices, beam energies and particle types on residual dose rates [5]. It consists of two rectangular, vertical jaws of a length of 120 cm made of carbon. The cooling system is approximated by two copper plates with an artificially reduced density, in order to account for its actual design based on water-cooled pipes, fixed to the jaws with stainless steel clamps. The entire assembly is finally placed into a stainless steel tank. Figure 1 shows a cross sectional view through the geometry. The geometry also includes a tunnel wall which, however, is of minor importance due to its small contribution to the dose rate close to the absorber.

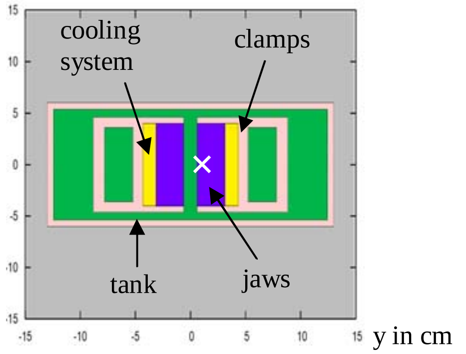


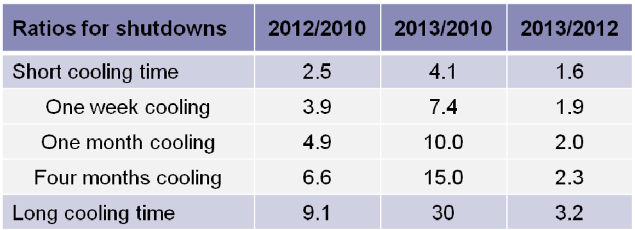
Figure 1: Cross sectional view of the absorber geometry. The beam impact point is indicated with a white cross.

For the calculations, a pencil beam of 4TeV protons was assumed to hit one of the jaws at a distance of 4mm to its edge (see Figure 1). Residual dose rates, scored in a one-dimensional, longitudinal binning (*i.e.*, in beam-direction) at 2cm above the absorber, were calculated for the operational cycle between 2010 and 2012 and cooling times between one week and four months using the parameters given in Table 1.

The scaling factors obtained from this calculation are shown in Table 5 together with those estimated by scaling beam intensities (Table 2). As expected, the values calculated for the generic absorber between one week and four months of cooling are within the ranges for short and long cooling times. Moreover, using the operational scenarios of Table 1 the run in 2012 will increase the dose rates only by about a factor of two in the arcs and at Point 3, where significant consolidation and upgrade works are planned for the next long shutdown. Thus, pre-cautions to be taken during the work to limit the radiological risks will not depend on the year of the shutdown, *i.e.*, whether it is in 2012 or 2013.

The calculations also yield the cooling time dependence of the residual dose rates which is given in Table 6 relative to one month cooling. Consequently, the dose rates drop by about a factor of two between one week and one month cooling and by another factor of 2-3 between one and four months of cooling.

Table 5: Scaling factors derived from operational parameters for short and long cooling times (first and last line, taken from Table 2) as well as obtained with the generic study.



Ratios for shutdowns	2012/2010	2013/2010	2013/2012
Short cooling time	2.5	4.1	1.6
One week cooling	3.9	7.4	1.9
One month cooling	4.9	10.0	2.0
Four months cooling	6.6	15.0	2.3
Long cooling time	9.1	30	3.2

Table 6: Ratios of residual dose equivalent rates at a certain cooling time and at one month cooling.

Dose rate relative to one month cooling	2011	2012	2013
One week cooling	2.3	1.9	1.7
One month cooling	1.0	1.0	1.0
Four months cooling	0.3	0.4	0.4

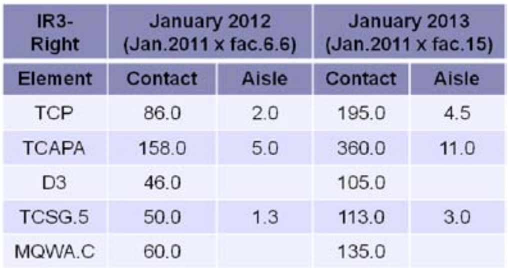
RESIDUAL DOSE RATE ESTIMATES FOR THE NEXT LONG SHUTDOWN

The above scaling factors allow one to predict residual dose rates for the next long shutdown based on the present measurements. The resulting values are given for some of the components in Points 3 and 7 in Tables 7 and 8, respectively. As can be seen, dose rates on contact to some of the passive absorbers at Point 7 may reach 1mSv/h, the dose rates in the aisle are in general of the order of tens of µSv/h. For this reason the tunnel sections at Points 3 and 7 containing the collimators will have to be classified as Controlled Radiation Areas [2] where job and dose planning becomes obligatory.

Of course, these estimates carry significant uncertainties, also due to the underlying assumptions such as scaling with beam intensity, the identical collimator settings until 2013, *etc*.

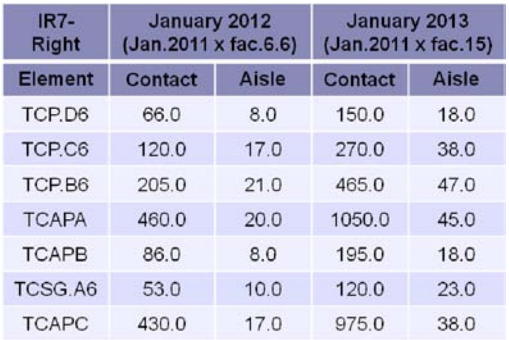
All radiological studies for the collimation system are based on nominal performance parameters of the LHC. In order to compare to residual dose rates predicted for nominal conditions a further scaling in intensity (factor of two) and beam energy (factor of $(7.0/3.5)^{0.8} = 1.7$) has to be applied to the values given in Table 8 for January 2013. For example, this would result in a dose rate on contact to the first passive absorber (TCAPA) of 3.6mSv/h (1mSv/h see Table 8). This agrees approximately with the FLUKA results for nominal LHC parameters presented in Ref. [6] (see values inside the black circle in Figure 2).

Table 7: Estimated residual dose equivalent rates (in µSv/h) in the momentum cleaning insertion at Point 3 for January 2012 and January 2013.



IR3-Right	January 2012 (Jan.2011 x fac.6.6)		January 2013 (Jan.2011 x fac.15)	
Element	Contact	Aisle	Contact	Aisle
TCP	86.0	2.0	195.0	4.5
TCAPA	158.0	5.0	360.0	11.0
D3	46.0		105.0	
TCSG.5	50.0	1.3	113.0	3.0
MQWA.C	60.0		135.0	

Table 8: As in Table 7, here for the betatron cleaning insertion (Point 7).



IR7-Right	January 2012 (Jan.2011 x fac.6.6)		January 2013 (Jan.2011 x fac.15)	
Element	Contact	Aisle	Contact	Aisle
TCP.D6	66.0	8.0	150.0	18.0
TCP.C6	120.0	17.0	270.0	38.0
TCP.B6	205.0	21.0	465.0	47.0
TCAPA	460.0	20.0	1050.0	45.0
TCAPB	86.0	8.0	195.0	18.0
TCSG.A6	53.0	10.0	120.0	23.0
TCAPC	430.0	17.0	975.0	38.0

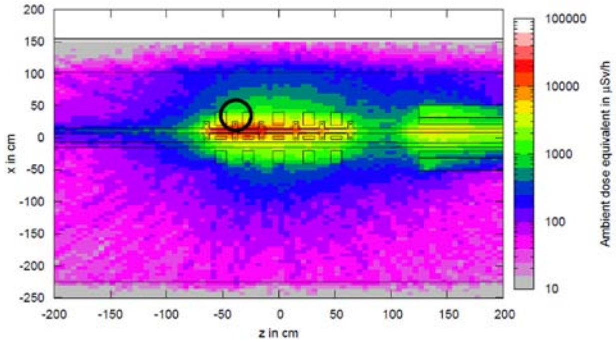


Figure 2: Ambient dose equivalent rate distribution around the passive absorber TCAPA at Point 7 (in µSv/h) for losses at nominal LHC energy and intensity [6]. The location of the measurement performed in January 2011 is indicated with a black circle.

In order to predict induced radioactivity in more detail around interconnects between cold arc magnets dedicated FLUKA studies were performed. Here, activation is dominated by beam-gas interactions. In the calculations a residual gas density of $10^{15}$$H_2$-equivalent/m^3 is used; results can be easily re-scaled to any other measured value. The studies are based on a sophisticated FLUKA geometry and input of the collimation and dispersion suppressor region at Point 7 developed by the FLUKA team [7].

Figures 3 and 4 show the residual dose rate distributions in the area between magnets MQ11 and MQ13 due to beam-gas interactions of beam 1 one month after the runs in 2011 and 2012, respectively. Only on contact to the innermost parts (*e.g.*, beam pipe) values exceed 1µSv/h. At locations accessible for a human body dose rates are well below that value indicating that risks due to external irradiation in the arcs should in general be low.

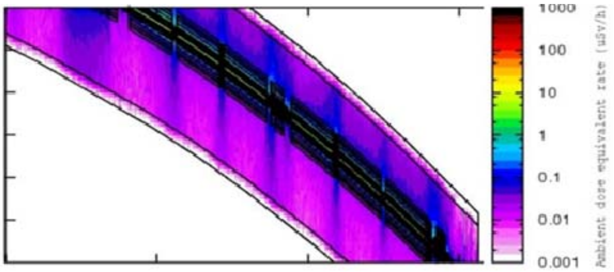


Figure 3: Ambient dose equivalent rate distribution (in µSv/h) due to beam gas interactions at Point 7 between magnets MQ11 and MQ13 one month after the run in 2011.

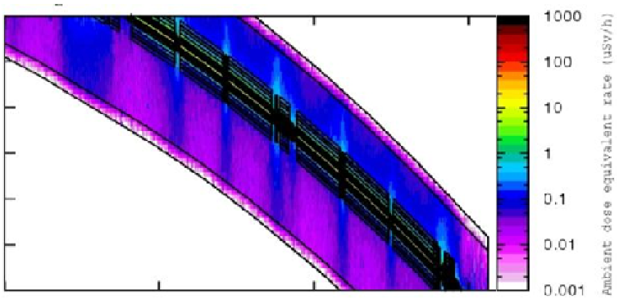


Figure 4: As in Figure 3, here one month after the run in 2012.

In addition to activation by beam gas interactions, localised areas of increased radioactivity exist where protons diffractively scattered in primary collimators or ion fragments are lost. Results of related studies were presented elsewhere [8] and showed that contact dose rates of the order of 10µSv/h can be expected in these locations after one month of cooling. Due to the limited number of such spots, the risk due to external irradiation during consolidation work still remains low.

CONSOLIDATION OF INTERCONNECTS

The consolidation of the LHC interconnects also involves machining and soldering with the associated risk of releasing radioactivity as dust, in fumes, *etc*. Thus, a risk analysis is imperative based on an estimate of the nuclide inventory. At present, the latter can only be obtained by means of FLUKA calculations; later on (prior to the work) measurements will add further information.

Figure 5 shows the FLUKA geometry of the simulated interconnect between two dipole magnets. It includes a detailed representation of the M-lines taking into account the actual material compositions [9].

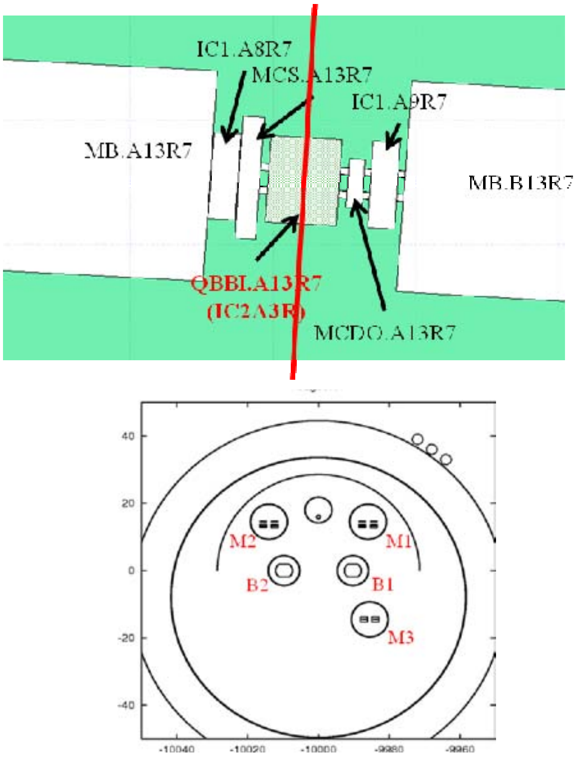


Figure 5: Top view of the FLUKA geometry of the interconnect between the dipole magnets MB.A13R7 and MB.B13R7 (top) and transverse section (bottom) at the position of the red line indicated in the top panel.

In each of the components the specific activity due to beam-gas interactions in beam 1 was scored and divided, for each nuclide, by the CERN exemption limit for radioactive material [10]. By definition, if the sum of these ratios over all nuclides exceeds unity for both total and specific activities the component is classified as radioactive material. It is also radioactive if the residual dose rate at 10cm distance is larger than 100nSv/h after subtraction of the background. Assuming a residual gas density of $10^{15}$$H_2$-equivalent/m^3 the above mentioned sum-rule for specific activity yields for both the M1-pipe (stainless steel) and the super-conduction cable (copper), see Figure 5, a value of 0.3 one month after the run in 2012. The contribution of trace elements and solder is difficult to assess with reasonable statistical significance.

However, generic studies showed that, for example, for silver this value is about a factor of 20 higher. Taking into account the small amount of such elements they should not add a significant contribution.

Thus, the study indicates very low activation of the interconnects in the arcs and, consequently, a low risk of contamination and internal exposure should the radioactive nuclides be released during the consolidation work. Nevertheless, the ALARA principle requests precautions to be taken that contain any released particles or dust and avoid spreading it, *e.g.*, vacuum cleaners, plastic foils to protect the work-site *etc*.

Unfortunately, the estimates of specific activities in the interconnects carry large uncertainties of various sources, such as

- beam-gas pressure,
- activation by so-called scrubbing runs,
- loss assumptions (sharing of losses between IR3 and IR7, losses in heavy ion runs),
- differences between actual and simulated geometries (collimator settings, imperfections, *etc*.),
- statistical uncertainties,
- models for predicting induced activity.

Thus, verification by measurement becomes essential. This includes systematic RP-survey measurements during technical stops in order to monitor the evolution of residual dose rates as well as the analysis of BLM-readings, integrated over the year, in order to identify loss points. Furthermore, samples of materials, especially those which have to be machined during the consolidation works (copper, stainless steel, tin, silver), will be placed outside of the interconnects (see Figure 6). Gamma-spectroscopy measurements together with FLUKA simulations (providing the gradient in activation between bus-bar and sample location) would then allow a verification of the present estimates and the assessment of the actual risks well before the work starts.

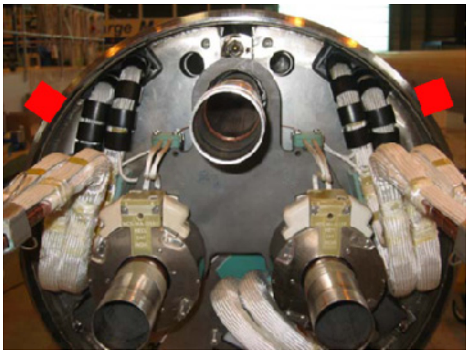


Figure **6**: Position of material samples to be placed outside of the interconnects (red boxes).

CONFINEMENT OF ACTIVATED AIR

At Point 7, air venting Sectors 6-7 and 7-8 is extracted and released into the environment. In order to reduce the annual dose to the reference group of population below the optimization goal of 10µSv it was decided to enclose the areas with the highest particle losses at Point 7 by ventilation doors such that the release of short-lived nuclides is minimized [11]. Up to now, bypass ducts, guiding the air from the adjacent sectors through the loss areas, are installed and the ducts in the TZ76 gallery have been removed. As outlined in Ref.[12] the optimized ventilation scheme must be fully functional as soon as losses exceed one half of the value predicted for nominal operation. Thus, the installation must be completed in the next long shutdown or latest in 2013. Of course, in order to minimize job doses time-consuming modifications close to radioactive components (installation of door frames, *etc*.) should be implemented as soon as possible.

Furthermore, a complete separation of the air volumes in service areas and machine tunnel should be achieved during the next long shutdown [13]. This concerns mainly the re-installation of ventilation doors in the UP galleries (*e.g.*, UP63/67), which had been removed to provide a path for an accidental helium release, and the sealing of the ducts between UA galleries and machine tunnel.

CONCLUSIONS

Based on the operational scenarios for the LHC during the years 2011/12, beam-intensity-dependent activation and residual dose rates are expected to increase by about a factor of 4-7 during the 2011 run and by another factor of two during 2012. Thus, radiation protection constraints and recommendations for shutdowns in 2012 and 2013 are quite similar. Of course, it assumes that losses scale linearly with beam intensity and neglects the contributions from scrubbing or ion runs. The luminosity-dependent activation (mainly the detectors and inner triplets) will increase by a factor of 20-100 until 2013.

Presently the entire LHC is classified as Supervised Radiation Area with low activation and dose rate levels (January 2011: maximum dose rate in the aisle: 3µSv/h, maximum dose rate on contact to a passive absorber in Point 7: 70 µSv/h). During technical stops and shutdowns in 2012 and 2013 a few limited areas (*e.g.*, IR3/7) will have to be classified as Controlled Radiation Areas where job and dose planning is obligatory.

Residual dose rates in the arcs after the 2012 run are estimated to be very low (no limitation in duration of work). A few localised areas in the dispersion suppressor regions (loss points of protons or heavy fragments “leaking” from the straight section) might show measurable residual dose rates (<10 µSv/h). Despite low residual dose rates in these areas, components might become “radioactive” according to CERN regulations and dissipation or incorporation of this radioactivity must be prevented (ALARA principle).

Due to significant uncertainties it is important to continuously monitor the evolution of activation (*e.g.*, survey measurements, material samples) to be able to further optimise work plans and schedules. In areas where civil engineering will be required (*e.g.*, dispersion suppressor regions in IR3) concrete samples should be placed in order to demonstrate absence of activation prior to the work.

The full functionality of the ventilation bypass in IR7 has to be established in the next long shutdown. The separation of the LHC tunnel and service area air volumes has been improved and additional monitoring at Point 4 and 6 is being added. However, a full sealing between service areas and machine tunnel has to be established in the next long shutdown.

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COLLIMATOR IMPROVEMENTS 2011 AND UPGRADE 2012: WHAT DO WE PLAN?

S. Redaelli for the LHC Collimation Team, CERN, Geneva, Switzerland

Abstract

The LHC collimation system has provided an outstanding performance during the first year of high-intensity beam operation. The complete Phase I system was commissioned with beam and delivered routinely a cleaning efficiency close to the nominal performance with relaxed collimator settings. On the other hand, the first commissioning experience has also provided first indications of system limitations alongside of hints for possible improvements. In particular, the expected performance limitations from losses in the cold dispersion suppressors (DSs) at either side of the warm cleaning insertions have been confirmed. While some improvements of the system can already be implemented during the 2010 shutdown, the major performance limitation from losses in the DSs require a change of the machine layout that will be addresses in the long shutdown. In this papers, the proposed improvements of the system are presented. The expected gains and the implication of the proposed changes on the system recommissioning are discussed.

INTRODUCTION

The performance of the LHC collimation system at 3.5 TeV was very good [1]. Together with the other machine protection systems, this is one of the key ingredients that allowed a safe operation in 2010 without a single beam-induced quench with circulating beams, with stored beam energies up to 30 MJ. The collimation experience accumulated in 2010 is very valuable and must be used to critically assess the collimator design choices, to collect feedback on various operational aspects and to project the achievable cleaning performance to larger intensities and energies. While there is essentially no time for any hardware modification during the short 2010-2011 shutdown, the experience gained can provide very valuable inputs to steer the design choices of the system upgrade scenarios foreseen for the first long shutdown.

In this paper, after a brief introduction of a few relevant aspects of the Phase I collimation system, the highlights of the 2010 operational experience are presented, with a particular emphasis on the possible areas of improvement. Then, the changes foreseen to improve the system in 2011 are discussed in detail. This consist essentially on software improvements that do not require modifications of the hardware. The possible system upgrades that are presently considered for an implementation in the first long shutdown are then outlined. Finally, some conclusions are drawn.

Table 1: List of Phase I Movable LHC Collimators

Functional type	Name	Plane	Num.	Material
Primary IR3	TCP	H	2	CFC
Secondary IR3	TCSG	H	8	CFC
Absorbers IR3	TCLA	H,V	8	W
Primary IR7	TCP	H,V,S	6	CFC
Secondary IR7	TCSG	H,V,S	22	CFC
Absorbers IR7	TCLA	H,V	10	W
Tertiary IR1/2/5/8	TCT	H,V	16	W/Cu
Physics debris absor.	TCL	H	4	Cu
Dump protection	TCSG	H	2	CFC
	TCDQ	H	2	C
Inj. prot. (lines)	TCDI	H,V	13	CFC
Inj. prot. (ring)	TDI	V	2	C
	TCLI	V	4	CFC
	TCDD	V	1	CFC

PHASE I COLLIMATION

Brief recap. of collimation layout

The complete Phase I collimation system was installed in 2009 and has been operational throughout 2010. The system includes a total of 100 movable collimators for the ring (87) and transfer lines (13) [2], including injection and dump protection elements. The list of Phase I collimator types, including information on collimation plane, number of installed devices and material, is given in Tab. 1. Collimators are installed in all interaction regions (IRs) except IR4 (RF insertion). The back-bone of the system is given by the momentum (IR3) and betatron (IR7) cleaning collimators (28 devices per beam). Local protection of superconducting triplet and experiment is provided by tertiary collimators in all the interaction points (IPs). Injection protection and dump collimators are installed in the transfer lines and in IR2, IR8 and IR6.

Controls and machine protection aspects

With the exception of the one-sided TCDQ collimators, all the LHC collimators have 2 jaws that are controlled by 4 independent stepping motors. Motors can be moved in discrete steps at a constant velocity of 2 mm/s or following arbitrary functions of time [3], which is a specific feature of the LHC. This ensures optimum settings during ramp and betatron squeeze. Each collimator has a highly redundant survey system for jaw positions and collimator gaps to ensure correct settings for each operational phase. Six direct position measurements (4 motor axes and 2 upstream and downstream gaps) are interlocked for a total of 2750 independent interlocks [4]:

(1) 12 position interlocks as a function of time are used to interlock inner and outer reading of each LVDT is all conditions;

(2) 2 maximum allowed gap limits as a function of energy are used to ensure that the collimator gaps are reduced during the energy ramp.

In addition, 5 interlocked temperature sensors per collimator can dump the beam if temperatures above safe limits are detected.

For the position interlocks (1), a different set of settings is available for the different machine phases (injection, ramp, squeeze, collision, physics data taking). The limit and the position settings can be expressed as discrete values (injection, flat-top, physics) or as functions of time (ramp, squeeze, collision function) and triggered synchronously with power converters and RF system. The energy limits remain the same for all machine phases and are designed to catch the failure that a collimator does not move during the energy ramp and remains at injection settings within the injection limits, which can happen e.g. in case of problems with the start-of-ramp trigger.

The squeeze is done at 3.5 TeV when the energy limits remain constant. Therefore, the movements of tertiary collimators during the squeeze are presently relying on time-dependent limits only (no redundancy in addition the the time interlocks). In addition, energy limits are not operational for the injection protection collimators in the ring.

Recap. of beam-based setup

Collimator settings are calculated in local beam sigma units around the local orbit position. These parameters must be calculated with “beam-based” techniques [5] because one cannot rely of the absolute positioning between beam position monitor (BPM) measurements and collimator centre, e.g. in presence of electronics BPM offsets.

The determination of the beam position at the collimators is most critical for the establishment of the operational settings (the nominal optics can be used for the beam size calculations with acceptable errors due to the excellent optics quality [6]). The beam position at the collimator is established with beam-based techniques relying on the beam loss monitor (BLM) response. Collimator jaws must therefore be moved into the beam until they “touch” the halo particles. This becomes critical with large stored energies.

The BLM-based alignment proved to be sufficiently precise up to 3.5 TeV but is lengthy and requires dedicated machine fills with a few nominal bunches. Reduced intensities are needed to allow masking BLM interlocks that might be otherwise triggered during the alignment of metallic collimators. Good settings of the system rely therefore on machine stability and collimator position reproducibility. Dedicated fills for loss maps must then be performed regularly to validate the system settings. See details in [7].

2010 OPERATIONAL FEEDBACK

The collimation cleaning in 2010 has essentially confirmed the predictions of simulations. At an energy of 3.5 TeV and β^* of 3.5 m in all IPs, with relaxed collimator settings, the local inefficiency in cold magnets was below a few 1e-4. No beam-induced magnet quenches were experienced in 2010 with circulating beams. The LHC has profited from this good cleaning performance also in term of operation efficiency as the machine was tolerant to beam losses well above specifications. No intensity limitations are expected with the 2011 parameters from collimation aspects. See [1] for more details.

From hardware and controls view points, all the main design choices of the system have been confirmed and there are so far no indications of problems. The operational performance of the system has been addressed in [9]. Appropriate software tools were established to handle the complex setting parameter space in all operational phases. Note that about 14000 different settings - functions or discrete - were needed in 2010 for each operational cycle.

On the other hand, also some limitations and areas of improvements could be identified during the 2010 operation:

- for protons, the cleaning inefficiency is limited by the cold magnets in the dispersion suppressors at either side of the cleaning insertions [7]; no additional bottlenecks are found[1]; these losses can eventually limit the total LHC intensity;
- for ions, the cleaning performance is worst due to ion fragmentation and dissociation that induce larger effective momentum offsets after the first ion interaction with the primary collimators. The overall performance is still limited by losses in the cold region downstream of the cleaning insertions [7];
- we cannot extrapolate reliably the beam life time to higher intensities, higher energies and smaller β^* values. This is presently the main uncertainty for the final performance reach estimates [8];
- the interlock strategy in some critical phases like the injection and the squeeze are not redundant and rely still on manual execution of operational sequences;
- the system setup is manual and lengthy (average of about 15 minutes per collimator) and has to be repeated in several machine phase; the setups at top energy are particularly risky because they require to work close to the dump limits of beam loss monitors;
- the system setup depends critically on the stability and fill-to-fill reproducibility of the closed orbit; this uncertainty limits the achievable β^* and in general is a concern for the collimation hierarchy;

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[1] Other cold magnets in IP3, IP6 and IP7 or some triplet magnet showed occasionally larger losses than the DS magnets. It is believed that these losses are generated by showed from the collimators close-by and hence do not represent an issue for the magnet quenches. These losses have to be handled with appropriate choices of BLM thresholds.

- collimation and machine protection matters related to setup of movable devices constrain in some case the operational flexibility, e.g. during changes of crossing angle configurations, or extended luminosity scans.

- nominal collimator settings, required at 7 TeV with minimum nominal β^* remain to be demonstrated with beam at the LHC; the corresponding impedance estimate only rely on simulations;

- even if with limited statistics, we had first indications of radiation induced effects on the electronics, e.g. in the cold region downstream of IP7 during ion operation [10][2]. There were no indications yet of single event upset in the electronics racks of the cleaning insertions.

- The recovery of the system in case of power cuts is quite cumbersome. The auto-retraction mechanisms designed to take the jaws out of the beam in case of motor powering failure [11] can cause a violation of the maximum allowed jaw tilt angle tolerance. This requires (1) a lengthy remote procedure to carefully move the jaws within tolerance and (2) a new verification of the collimator positions.

IMPROVEMENTS FOR 2011

Updated interlock strategy

No significant hardware changes have been carried out during the short 2010-2011 shutdown beyond standard hardware maintenance (e.g., replacement of isolated faulty components that caused problems in 2010). The hardware design choices (mechanics, sensors, motors, drivers, etc.) have shown no issues and a very good reliability [1].

Important improvements of the collimator controls software have been implemented to increase the safety role of the system [12]:

1. New gap limits versus β^* functions in the IPs:

   Previous implementation:
   This functionality was foreseen [13] but not yet implemented due to the missing β^* information. After initial successful tests that showed that β^* can be calculated from the current measurements of selected quadrupoles used during the squeeze [14], the β^* values in each IP will be available in 2011 and distributed through the timing system.
   New implementation:
   Additional "inner" and "outer" limits as a function of β^* will be added for upstream and downstream gap measurements (4 new limits per collimator). Different collimators will use β^* values from different IPs (e.g. TCTs in different points) or the minimum value from all IPs (e.g. for IP7 collimators). This new functionality will be available for all collimators in the ring except for the TCDQs (to be implemented) and for the TDI (not necessary). An example of gap settings and β^* versus time and of the corresponding calculated gap limits versus β^* are given in Figs. 1 and 2, respectively.

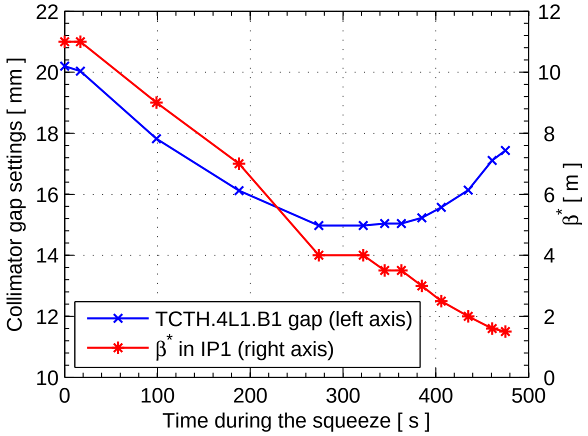

Figure 1: Collimator gap settings (blue, left axis) and β^* in IP1 (red, right axis) versus time during the squeeze. Gap settings are calculated for a normalized collimator aperture of 11.8 σ [8] by taking into account the variation of local optics at the collimator.

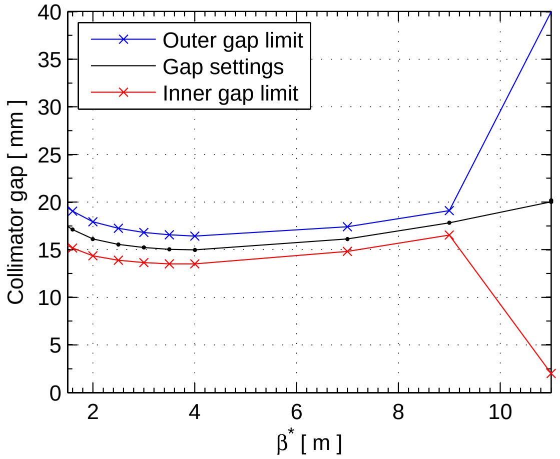

Figure 2: Example of inner (red) and outer (blue) collimator gap limit as a function of β^* calculated from the gap settings of Fig. 1 (here shown in black). The limits are open at the β^* value of the injection optics (11 m for IP1) in order to allow larger gaps at injection. In this example, if the TCT did not move, the beams would be dumped less than 90 s after the beginning of the squeeze.

2. New gap limits as a function of energy for the injection protection collimators in the ring (TDI's, TCLI's, TCDD):

   Previous implementation:
   Limits were implemented for TCLI's and TCDD but

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[2] It is noted that this effects were related to local losses caused by the poorer cleaning performance with ion beams. The radiation effects in the tunnel service areas - which are addressed by the combined momentum-betatron cleaning system discussed later - are not yet been observed.

with the same logic as for the ring cleaning collimators, i.e. they generated an interlock for the circulating beam if the measured gap was larger than the limit. Nothing had been foreseen for the TDI's (no direct gap measurements are available). Note that the energy limits are instead fully operational and active for the TCDI's in the transfer lines (injection interlock generated if maximum allowed gap is exceeded).
New implementation:
The new limits as a function of energy generate an injection interlock that prevents injection if the gaps of the injection collimators are larger than safe values. For the TDI that does not have direct gap measurements, the gap values are inferred from the position measurements of the jaw corners and limits are set on these calculated gap values.

3. Updated logic of the mechanism that stop the collimator motors if the position limits are exceeded:
Previous implementation:
For all collimators, the motors were stopped upon reaching the time dependent limits (discrete or functions).
New implementation:
For injection protection, it will be possible to move across the limits: the transfer line TCDI's can move across inner and outer limits whereas the injection protection collimators in the ring can only move across the outer limits (inner limits still stop the motor to prevent the jaws from running into the beam).

It is noted that in all cases, the proposed improvements provide additional redundancy to a system that proved already to be quite safe.

At the time of this workshop, the required changes are being addressed with high priority at all controls levels. The schedule is tight but there is not indication that the new implementations should not be available and tested for the start-up. Two weeks of remote commissioning and tests from the CCC are planned before the start of beam operation. In particular, the machine protection functionality of the system will have to be fully re-validated after the modifications proposed above [12].

Semi-automated beam-based alignment

A new software application for semi-automated collimator setup is being prepared and will be tested in the collimator alignment campaigns in 2011 [15]. This new software is designed to help the collimator setup in various ways: (1) define software limits for the maximum BLM signal to minimise the risks of beam dumps due to aggressive collimator movements; (2) automatize the setup/configuration of repetition of collimator movements in small steps, with reduced risk of human errors; (3) automatize the collection of data for settings generation that is presently done manually. In addition, the software will also help making the alignment procedure faster. On the other hand, in the first version, the 1 Hz BLM data will be used and this will still limit the overall alignment time.

CHANGES BEYOND 2011

Combined momentum-betatron cleaning in IP3 with DS collimators in the cold region

A combined momentum and betatron cleaning system in IP3 was initially proposed [16] to mitigate the effects of radiation to electronics. The main motivation is that the locations of the electronics racks are expected to receive up to 100 times less radiation than the IP7 ones for the same number of proton lost according to simulations [17, 18]. This proposal relies on adding vertical collimators in IP3, re-using existing installation slots with minimum layout impact, to provide a vertical cleaning in the momentum insertion that otherwise contains only horizontal primary and secondary collimators and shower absorbers. The cleaning of such a system [16] would however be about a factor 2 worst than what is provided by the present betatron insertion (without skew cleaning and with less collimators).

The cleaning limitations of the combined system are removed by adding dispersion suppressor (DS) collimators originally conceived a possible improvement for IP7 [19]. In fact, preliminary simulations without imperfections [20] show that with DS collimators, a cleaning performance compatible with the LHC nominal and ultimate beam intensities at 7 TeV can be achieved. Collimator impedance remains an issue but can be kept under control [21].

The combined momentum-betatron cleaning in IP3 with DS collimators is therefore the baseline for the system upgrade in the first long technical stop. The new DS layout is based on a warm technology for the DS-collimators and on a cryogenic by-pass in the region of the missing dipole [21]. The Phase I collimators will remain installed on operational. System readiness, implication on the schedule and required activities in the cryogenic regions are being been addressed, as reported in companion papers [22, 23].

BLM-integrated design

In order to speed up the alignment procedure, BPM buttons could be integrated into the collimator jaws (see Fig. 3) for a direct measurement of the local beam orbit [24]. This concept enables (1) a fast alignment by equalizing the signal on the two buttons (expected time is 10-20 seconds); (2) a constant monitoring of beam drifts with operational gap values, without need to touch the beam. In principle, mounting BPMs on both upstream and downstream collimator sides also allows determining the orbit angle at the collimator location. Note that the centring (1) is expected to be independent of systematics in the BPM electronics. These advantages are particularly interesting for the TCT collimators next to the experiments that presently require a new setup campaign for every crossing scheme configuration.

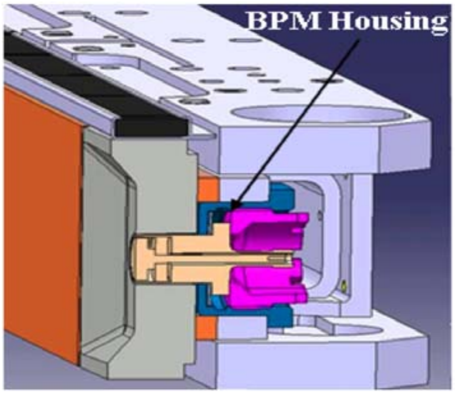

Figure 3: Illustrative drawing of the collimator jaw with BPM integrated at the end of the jaw, close to the tapered part. Courtesy of A. Dallocchio [24].

The feasibility of this BPM-integrated design has been addressed in 2010 by dedicated beam tests at the SPS that gave very promising results. For example, in Fig. 4 the BPM signal is shown as a function of the jaw position during an asymmetric scan. When one jaw only is moved, the BPM measurements shows deltas corresponding to half of the jaw movements, as expected because the total centre shifts by half of the movement of one jaw. The SPS tests have very preliminarily assessed that:

- the standard BLM-based and the BPM-based methods are in good agreement;
- showers induced by an upstream SPS collimator or by the collimator jaw itself did not affect the BPM signal. This suggests that acquisitions are possible also with small collimator gaps (operational settings) in presence of losses;
- scans of the collimator gap position showed that the BPM signals scales correctly;
- BPM measurements can be performed for a broad variety of collimator gap values (from a few mm up to above 40 mm), which covers the LHC operational range;
- the linearity of the signal seems acceptable [25];
- detailed estimates of the BPM-based setup time were not possible due to the still manual BPM acquisition chain used in the beam tests. By looking on-line at the scope, we could equalized the signals from the two bottoms within a few minutes.

The collimator prototype equipped with BPM-integrated jaws will remain in the SPS in 2011 and beam tests will continue to confirm these preliminary results.

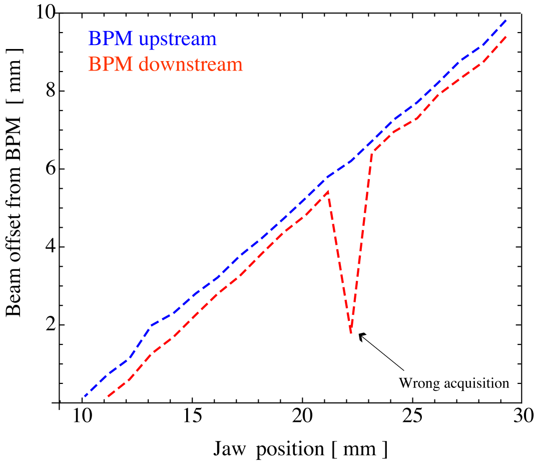

Figure 4: Beam centre measured by the up- and downstream BPMs versus jaw position during SPS beam tests. Moving one jaw at a time gives an relative shift of the beam centre that is half of the jaw movement. Courtesy of M. Gasior (BE/BI) and D. Wollmann (BE/ABP).

Modified TCT layout in IP2

A new layout of the interaction point 2 [26] was proposed to remove a conflict between the ALICE zero degree calorimeter (ZDC) and the TCTV collimators installed between the ZDC and IP2. Depending on the TCTV settings, part of the spectator nucleons are caught by the collimator jaws before reaching the ZDC. This introduced a systematic error that depends on machine parameters. During the 2010 ion operation, this issue was partly avoided by opening the TCTV's: risks were considered acceptable with a limited number of ion bunches because asynchronous dump failures affect only the horizontal plane [28]. The situation could be avoided if the TCTV were installed downstream of the ZDC with respect to the IP.

A technical solution has been found for an updated LSS2 layout that provides the same protection/cleaning functionality of the system without shadowing the ALICE ZDC. With a limited modification of the vacuum layout, space can be made upstream of the ZDC to fit the TCTV collimator in the region with separated vacuum chambers for B1 and B2 (i.e. close to the present location of the TCTH). This solution has implications for the vacuum layout, for the bake-out of the LSS2 and for the collimator production (two more collimators are required). The time line is being followed-up by the LMC [29]. This takes into account the possibility to perform the change in a short 2011 shutdown.

DS collimators in other IPs

The possibility to add additional "cryo" collimators in dispersion suppressor of other interaction points (IR7 or experiments), possible combined with a new design for short dispersion suppressor dipoles, in not considered viable for the first long shutdown and is not the subject of this paper.

CONCLUSIONS

The good performance of the LHC collimation system allowed a safe and efficient operation at 3.5 TeV. There are no expected intensity limitation at this energy for 2011 if the beam life time will remain as in 2010. The collimator controls have been extended in order provide more redundancy for machine protection and a faster beam-based alignment. In particular, additional limits as a function of β^* will enforce correct collimator movements during the betatron squeeze and an improved interlock strategy for injection protection will make injection safer.

The first operational experience has also confirmed the expected limitations, like the locations of the highest losses from halo leakage out of the cleaning insertions and like the long setup time from manual setup procedures. Other expected limitations, like radiation to the electronics in the tunnel service areas or like the impedance with small gaps, did not see yet a firm experimental confirmation but remain critical for achieving higher intensities. For example, the LHC efficiency has already been affected by radiation. New aspects were also identified, like the many constraints that collimation puts on the LHC operation (lengthy loss maps, constraints on separation and crossing schemes and on the luminosity scans, etc.). The operational experience is essential to guide the choice of system upgrades.

The upgrade scenarios for the first long shutdown have been reviewed. This includes a combined momentum and betatron cleaning in IP3, a new dispersion suppressor layout with warm DS collimators, a new design with BPM integrated in the jaw for faster beam-based setup. The present estimates indicate that these proposals can address satisfactorily the system limitations towards LHC nominal intensities at 7 TeV. The project resource must now be prioritized in order to maximise what can be done in the first long shutdown. The feasibility of the various options in the given time constraints are being addressed. A project review is schedule for mid-2011 to establish a final strategy, which will also take into account the feedback from the 2011 experience at 3.5 TeV, with higher intensities and smaller β^*.

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The content of this paper is presented on behalf of the many people who contributed over many years to the collimation project. The author has tried to document properly the different contributions with an extended list of reference. In addition, O. Aberle, R. Assmann, R. Bruce, C. Boccard, M. Gasior, R. Losito, D. Macina, A. Masi, A. Rossi, G. Valentino, D. Wollmann, are kindly acknowledged used in this contribution. The LHC operation (in particular M. Lamont and J. Wenninger), injection (C. Bracco, B. Goddard, V. Kain), interlock and the BE/CO teams (G. Kruk) are also kindly acknowledged.

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THE LHC RF: IS IT WORKING WELL ENOUGH?

Reported by P. Baudrenghien, CERN, Geneva, Switzerland
for the LHC RF Team*

Abstract

We first briefly review the RF setting-up and operation in 2010. The issue of RF noise is developed in details, identifying the major noise sources and explaining why it did not lead to significant beam diffusion effects. A figure is given for its contribution to the bunch lengthening in physics, that is well below the effect of Intra-Beam Scattering. Capture losses were low in 2010 (below the 1% level) but still made filling troublesome due to the very large sensitivity of the Beam Loss monitors. The choice of voltage at injection is revisited and it is proposed to mismatch the capture in 2011 to reduce loss. We then present the longitudinal damper that will also reduce capture loss in multi-batch injection. The issue of surviving a klystron trip during physics is studied. Finally, the longitudinal 2011 parameters are presented.

PROTON RF OPERATION 2010

This section presents a very brief review of the proton RF operation. It is presented in much more details in [1].

The single bunch pilot (5 10^9 p) was ramped to 3.5 TeV on March 26th for the first time. The emittance at injection was 0.2 eVs. The bunch was captured with 8 MV (synchrotron frequency f_{s0}=65.3 Hz). The voltage was increased to 12 MV before the ramp (f_{s0}=80 Hz), then kept constant (f_{s0}=28.9 Hz @ 3.5 TeV). Bunch lengthening was as expected from adiabatic evolution in the ramp and nothing dramatic was observed when crossing the much feared 50 Hz synchrotron frequency.

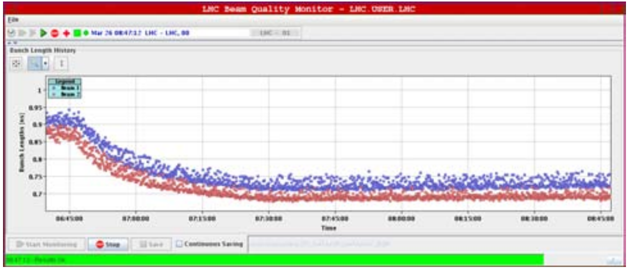

Figure 1: 4σ bunch length during the ramp. March 26th. Single bunch pilot in both rings, ~ 0.2 eVs.

Figure 1 shows the 4σ bunch length evolution. The measurement was not calibrated at the time. The bunch on the flat top is actually shorter than the indicated 700-750 ps. The lifetime was very good: with single bunch pilots, the bunch lengthening (4σ lenght) was around 30 ps/hour at the 450 GeV injection energy (8 MV) and 6 ps/hour at 3.5 TeV (12 MV).

Bunch intensity was increased in the coming months to reach the nominal 1.1 10^{11} p/bunch intensity. At injection, the nominal bunch was 1.2-1.3 ns long (4σ), with 0.3-0.4 eVs longitudinal emittance. The matched voltage is around 2.3-3 MV and we decided to capture with 5 MV. We then raised the voltage to 8 MV before the start of the ramp. Ramping was done with a constant 8 MV. The bunch was violently unstable. During the ramp it shrank down below 500 ps resulting in loss of Landau damping (figure 2).

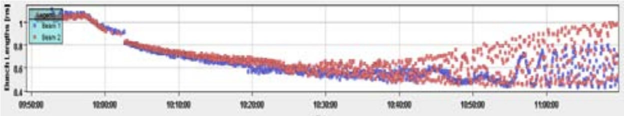

Figure 2: May 15th. First attempt to ramp nominal intensity single bunch. Bunch length during ramp. The longitudinal emittance is too low (< 0.4 eVs). The bunch becomes unstable when the length falls below 550 ps.

At the time longitudinal emittance blow-up was not available yet in the LHC but it was possible in the SPS [2]. So we decided to blow-up in the SPS to a 4σ length of 1.7 ns, maximum for injection in the LHC 400 MHz bucket. The longitudinal emittance became 0.6-0.7 eVs. We revised the voltage function in the LHC to better match the capture in order to preserve bunch length. After capture with 3.5 MV, the bunch would be 1.5-1.7 ns long. We raised the voltage linearly to 5.5 MV in the parabolic part of the momentum ramp, then kept it constant for the rest of the ramp and during physics. On May 28th a nominal intensity single bunch reached 3.5 TeV, with a length of 0.8-0.9 ns providing Landau damping sufficient to preserve stability (figure3).

Figure 3: Single bunch nominal intensity. Fast Beam Current Transformer (BCT) and 4σ bunch length through the ramp. The bunch shrinks from 1.5-1.7 ns on the flat bottom to 0.8-0.9 ns at 3.5 TeV.

Maximal blow-up in the SPS is not a lasting solution as it creates long bunches and results in capture loss at injection. Emittance blow-up in the LHC ramp is preferable. It is also needed for longitudinal stability at

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* **LHC RF Project Leader**: E. Ciapala; **Longitudinal beam dynamics:** E. Shaposhnikova, J. Tuckmantel; **LLRF and RF Control team:** M.E.Angoletta, L. Arnaudon, P. Baudrenghien, T. Bohl, A. Butterworth, F. Dubouchet, J. Ferreira-Bento, G. Hagmann, W. Hofle, M. Jaussi, S. Kouzue, D. Landre, J. Lollierou, T. Mastoridis, J. Molendijk, J. Noirjean, A. Pashnin, J. Sanchez-Quesada, M. Shokker, D. Stellfeld, D. Valuch, U. Wehrle, F. Weierud; **Klystron and ACS cavities team:** O. Brunner, D. Glenat, P. Maesen, P. Martinez Yanez, C. Nicou, G. Pechaud, J. Pradier; **BE-OP :** D. Jacquet, G. Papotti; **US-LARP collaboration:** J. Fox, C. Rivetta, D. Van Winkle, SLAC

nominal intensity [3]. Longitudinal emittance blow-up became operational in the LHC on June 15th. We could then reduce the SPS bunch length to 1.5 ns (~ 0.5 eVs) at transfer to the LHC and capture the bunch with 3.5-4 MV. The voltage was increased linearly through the momentum ramp, to reach 8 MV on flat top. The LHC blow-up was active through the ramp, and adjusted to keep the bunch length at 1.5 ns [1]. This figure was reduced to 1.2 ns in September to prepare for bunch trains, resulting in a 1.6 eVs emittance on flat top. The LHC RF was operated with these longitudinal parameters (voltage and bunch length) for the rest of the year.

In the beginning of September we reconfigured the RF hardware for higher intensity (batch of bunches with 150 ns spacing) and faster ramp (15 minutes long): without active feedback a cavity presents a very large impedance to the beam and that can drive Coupled-Bunch instabilities. We therefore switched all klystrons on. The 150 ns bunch spacing did not cause any problem. The proton run came to an end in October with 368 nominal bunches at 150 ns spacing (12% nominal ring intensity). However, with the increased number of injections, the injection dump would fire on occasion, triggered by radiation measured by the Beam Loss Monitors (BLM) and found above threshold. The problem was traced to a small amount of beam, un-captured at each injection, and slowly drifting in the machine. See [1] for more details.

At 3.5 TeV the Synchrotron Radiation damping time is about two hundred hours. The target for longitudinal emittance blow-up growth time caused by RF noise was 13 hours minimum at 7 TeV (equal to the synchrotron radiation damping time at that energy). RF noise was a major concern during LHC design: klystrons convert HV ripples in phase modulation whose frequencies are harmonics of 50 Hz, extending to 600 Hz in the LHC. During acceleration the synchrotron frequency crosses the 50 Hz line and problems were expected. The LLRF was therefore designed to reduce noise sources and minimize their impact on the beam. Figure 4 shows the bunch length evolution during fill 1444. Observe the fast bunch lengthening during the first 60 minutes at 450 GeV (250 ps/hour), the reduction caused by the 15 minutes long acceleration ramp with controlled emittance blow-up, and the slow 15 ps/hour 4σ lengthening during physics.

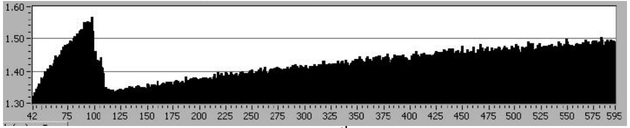


Figure 4: Fill 1444, Oct 26th, 150 ns spacing, 368 bunches. Horizontal axis in minutes. Vertical: 4σ bunch length in ns. The above data have not been corrected for the bandwidth of the measurement chain. The bunch length is over-estimated by 100-200 ps.

RF NOISE AND BEAM DIFFUSION

Beam diffusion caused by RF noise is a very important issue in hadron colliders. The observed intensity lifetime was very good in 2010. Still the RF team made a series of measurements and studies to better understand the sources of RF phase noise in the LHC and its effect on the beam. The LHC LLRF has a two-levels hierarchy [4],[5]:

- We have one **Beam Control** per ring, located on the surface. It uses beam-based measurements (phase averaged over all bunches), updates once per turn (11 kHz rate) and generates a fixed amplitude RF reference (VCXO) sent to all eight Cavity Controllers.
- Each cavity has its private **Cavity Controller**. It uses klystron and cavity field measurements, updates at the bunch frequency (40 MHz) and generates the klystron drive. It includes a Klystron loop to reduce klystron amplitude and phase ripples, and a strong RF feedback loop.

Figure 5 shows the Single Side-band (SSB) phase noise (in dBc/Hz) of the Vector Sum of the eight cavities B2 (green) compared to the RF reference generated by the Beam Control (blue), with no beam in the machine. The RF feedback closed loop bandwidth is 300 kHz (single sided). The noise in the Beam Control reference RF (VCXO) dominates at low frequencies (below 200 Hz). Imperfect compensation of the driver and klystron noise is responsible for the 200 Hz to 20 kHz range. From 20 kHz to the 300 kHz closed-loop BW, the spectrum is flat, dominated by the measurement noise (noise added by the cavity antenna demodulator).

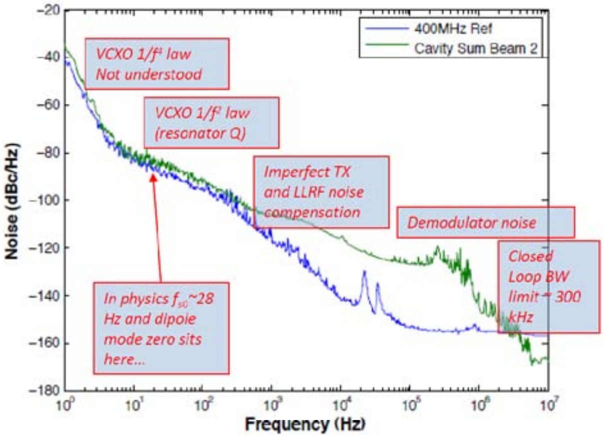


Figure 5: SSB phase noise *L(f)* (in dBc/Hz) of the Vector Sum of the eight cavities B2 (green) compared to the RF reference (blue). No beam.

If the beams were to sample the phase noise as represented in figure 5, the intensity lifetime would be less than one hour. The problem is the very low synchrotron frequency (28 Hz) that samples a large level of phase noise Power Spectral Density (PSD) caused by the 1/f^2 phase noise characteristic of the VCXO. The LHC RF profited from the experience of SPS p-pbar RF operation. The Beam Control system was designed with a strong Beam Phase Loop (BPL) that compares the beam phase (averaged over all bunches of a given ring) with the cavity field Vector Sum and minimizes the error by acting on the VCXO input. Figure 6 shows the SSB phase noise of the Vector Sum with and without BPL.

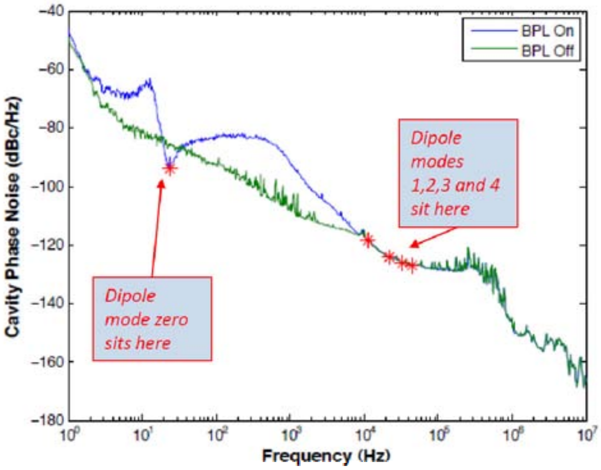


Figure 6: SSB Phase noise *L(f)* (in dBc/Hz) of the Vector Sum of the eight cavities B2 with Beam Phase Loop OFF (green) and ON (blue). Circulating beam at 3.5 TeV

The BPL reduces the noise on the dipole mode 0 synchrotron sidebands (f_{s0} ~ 28 Hz). Without it the phase noise at f_{s0} leads to 300-400 ps/hour bunch 4σ lengthening [6]. Notice how the Phase Loop actually increases the noise PSD outside the synchrotron band, below 10 kHz, but the beam does not react. As a bunch crosses the cavity at every turn, the revolution frequency sidebands are aliased into baseband and the RF noise in the bands $\pm n f_{rev} \pm f_{s0}$ will also excite the beam. As the BPL is clocked at the revolution frequency, it has no effect on the higher sidebands ($n \neq 0$).

By changing the BPL gain, we can modify the level of the phase noise PSD at the synchrotron frequency and observe the effect on beam diffusion. Figure 7 shows the 4σ bunch length of a bunch (1 10^{10} p, 3.5 Tev, 8 MV RF) as the BPL gain is being varied. Without phase loop we get 400 ps/h for a SSB phase noise PSD of -85 dBc/Hz in a single synchrotron band. Bunch lengthening is proportional to the PSD sampled by the beam at the synchrotron frequency

$$\frac{d\sigma_{\phi}^{2}}{dt} = \frac{\Omega_{s}^{2}}{4} S_{\phi\phi}(f) \qquad (1)$$

Where $S_{\phi\phi}(f)$ is the Phase Noise PSD in rad²/Hz. Neglecting amplitude noise we have

$$S_{\phi\phi}(f) = 2.10^{\frac{L(f)}{10}} \qquad (2)$$

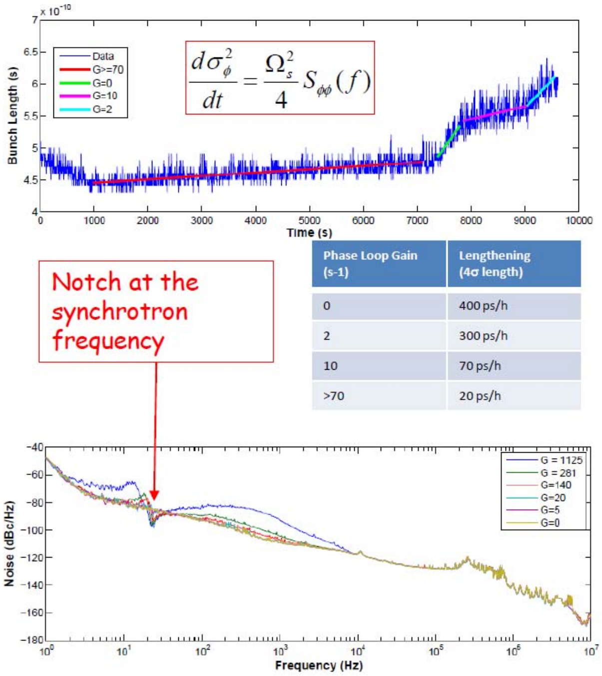
To achieve 10 ps/h 4σ–lengthening, the SSB PSD must therefore be below

$$-85 - 10\log[40] = -101\,\text{dBc/Hz} \qquad (3)$$

In the 300 kHz of the noise BW we have 60 such bands (figures 5 and 6). The noise floor PSD for 10 ps/h is therefore

$$-101 - 10\log[60] = -119\,\text{dBc/Hz} \qquad (4)$$

As we measure a noise level of ~ -125 dBc/Hz from 10 kHz to 300 kHz, the 4σ bunch lengthening caused by RF noise can be estimated around 2.5 ps/h. Please consult [6] for more details. More measurements on Beam Diffusion were done in Nov. 2010 while operating as Lead ion collider [7]. The results fit very well with the above figures.



Phase Loop Gain (s-1)	Lengthening (4σ length)
0	400 ps/h
2	300 ps/h
10	70 ps/h
>70	20 ps/h

Figure 7. Top: 4σ bunch length while varying BPL gain. Bottom: SSB Phase Noise *L(f)* in dBc/Hz in one cavity. The synchrotron frequency is ~ 28 Hz

CAPTURE REVISITED

With 7.2 MV RF at 200 MHz, the SPS bucket has a 3.0 eVs area and $\pm 10^{-3}$ Δp/p momentum half height. After longitudinal blow-up in the SPS ramp the bunch has a 1.5 ns 4σ-length and ±4.5 10^{-4} Δp/p, resulting in 0.51 eVs emittance. The matched capture voltage in the LHC is between 2.5 MV and 3 MV at 400 MHz. In 2010 we have captured with 3.5 MV, resulting in a 0.94 eVs bucket area and ±6 10^{-4} Δp/p bucket half height (figure 8).

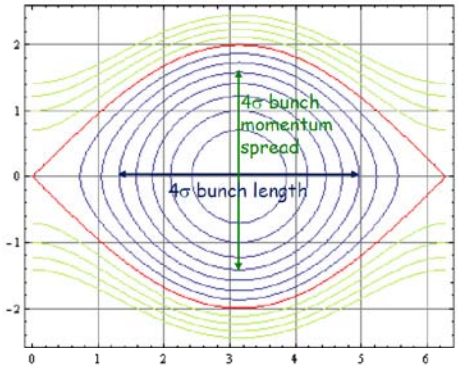


Figure 8: Trajectories in normalized phase space (ϕ, $1/\Omega_s$ dϕ/dt) at capture in the LHC with 3.5 MV RF. The separatrix is marked in red. The 4σ length and momentum spread of the injected bunch are marked in blue and green respectively.

Losses are small (< 1 %) but cannot be zero because a significant portion of the bunch (13.5 % for a pure two-dimensional Gaussian distribution) is outside the marked 4σ boundary. The SPS bucket being much larger than the LHC bucket (twice longer, 70% taller and more than three times the area), part of the injected bunch falls outside the LHC bucket. Reducing the SPS bunch length is not a long-term solution as shorter bunches will not be stable in the SPS at nominal intensity (25 ns spacing). What we can do is to increase the LHC RF voltage at injection to capture more off-momentum particles. In 2011 we will experiment with a strongly mismatched voltage (5-6 MV) during filling. Calculations are being done, taking the exact SPS conditions, to predict the LHC capture loss for varying LHC injection voltages [11].

LONGITUDINAL DAMPER

The Beam Phase Loop minimizes the phase error averaged over all bunches. For the first injected batch it will efficiently damp any phase or energy error (if common over all bunches of the batch) via a proper modulation of the RF frequency. As more batches are injected, the injection error is given less and less importance in the average as it competes with the contributions from the quiet circulating bunches. That results in capture loss increasing with the number of injections.

The LHC does not have a dedicated longitudinal kicker. Unlike in the transverse plane, Landau damping is sufficient to keep the nominal intensity beam stable in the longitudinal plane. But some damping of the longitudinal errors would be highly desirable at each batch injection to minimize capture loss. With the strong RF feedback, we can precisely control the field in the RF cavities. In the LHC, small-signal field change is possible in ~1 μs [5], which is the time separation between the successive batches at injection. By quickly modulating the phase of the cavity field between the batches, we can give momentum kicks to the incoming batch only, while keeping the field quiet for the circulating bunches. PEPII used a similar system that they nicknamed the Sub-Woofer as it would take care of the lower frequency part of the damping bandwidth. (The high frequency part was sent to a real longitudinal wideband kicker).

The efficiency depends on the amplitude of the quadrature voltage step that the klystron can create in the cavity in 1 μs. We have measured 70 kV on a test stand [5]. As the klystron DC power has been since reduced from 300 kW to 200 kW, we will take the more conservative figure of 50 kV per cavity. With eight cavities the maximum momentum kick is therefore 0.4 MeV/c per turn, or 90 MeV/c per synchrotron period (f_{s0}~50 Hz). At injection the 2σ bunch energy spread is 202.5 MeV/c (±4.5 10^{-4} Δp/p). Our damper could reduce the energy error by 1σ bunch energy spread in a synchrotron period. That should be fast enough to avoid filamentation and to reduce capture loss significantly. It will be commissioned in 2011.

The longitudinal damper acting by modulation of the RF field phase looks promising for damping batch-per-batch injection errors but it does not have sufficient bandwidth to act on the bunch-per-bunch phase error in a given batch.

RF PROBLEMS IN 2010

The problems found with the RF power and the cavity conditioning are presented in a companion paper [8].

In operation we had problems with two cavities:

- RF noise on Cav4B1 was first observed towards the end of a physics fill on early morning Sept 26th. It was visible on the bunch length monitoring (the trace became a bit more noisy) but did not affect the luminosity. Later re-filling became impossible however as debunching was very fast at 450 GeV. The cavity was not operational for the rest of the run. We have replaced all modules in the LLRF and several suspicious cables and connectors. The cavity is in operation and being monitored closely.
- Cav7B2 became noisy at high current levels (48 bunches per batch) during the 75 ns scrubbing run (Nov 18th-19th). There was a clear correlation between the injections and the cavity field ripples. No problem was observed with the 150 ns spacing or with the injection of 24 bunches batches at 75 ns spacing.

All LLRF electronics worked perfect: we have more than 50 VME crates installed with ~400 VME modules of 36 different makes, all custom-designed. The only faults were caused by damaged cables and connectors: all SMC cables in the Cavity Controllers will be replaced with higher-quality during the 2011 technical stops.

SURVIVING A KLYSTRON TRIP

This section is concerned with the longitudinal Coupled-Bunch Instability caused by the impedance of the RF cavity at the fundamental. The growth rate and tune shift of coupled-bunch mode l (dipole only) can be computed from the cavity impedance. With I_0 the DC current and f_b the bunching factor (≤ 1).

$$\sigma_l + j\Delta\omega_l = -\frac{\eta\, q\, I_0 f_b}{2\,\beta^2\,\Omega_s\, E\, T_{rev}} \sum_{p=-\infty}^{\infty} \omega\, Z(\omega) \qquad (5)$$

With

$$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_t^2} \qquad (6)$$

and

$$\omega = (p.h + l)\omega_{rev} + \Omega_s \qquad (7)$$

For a cavity at the fundamental, only two terms in the above infinite sum are not negligible: p=1 and p=-1. The impedance $Z(\omega)$ is modified much by the LLRF feedback. The above equation can be used to analyze different configurations. The exercise was done independently by the author (using a simple linear model for the RF feedback loop and with a conservative bunching factor equal to one) and by the US-LARP collaboration (with a complex model including klystron non-linearity, finite bunch length and the exact configuration of the LLRF loops as recorded during the winter 2010 setting-up). Both results will be listed, with the one from the simple model first and the prediction from the more complex model between brackets. Stability is preserved if the growth rate is significantly smaller than the tune spread [9]

$$\sigma_l < \frac{\Delta\Omega_s}{4} \tag{8}$$

With tune spread function of the 4σ bunch length L

$$\Delta\Omega_s = \Omega_s \frac{\pi^2}{16}\left(\frac{hL}{2\pi R}\right)^2 \tag{9}$$

3.5 TeV conditions

We consider the following nominal cavity and longitudinal parameters: 14 MV total RF, cavities at half detuning (3 kHz), main coupler at position Q_L=60000, 1.2 ns bunch length (4σ) and nominal beam current 0.58 A DC. The synchrotron frequency is 31 Hz.

Configuration	Detuning (kHz)	Growth rate simple model σ (s^{-1})	Growth rate exact model σ (s^{-1})	Tune shift Δω/2π (Hz)	Tune spread Δf_s (Hz)	$\Delta\Omega_s/4$ (s^{-1})
1 cav with fdbk	3	0.013	0.005	0.07	4.4	7
1 cav fdbk off	3	1	0.87	1	4.4	7
8 cav with fdbk	3	0.1	0.04	0.56	4.4	7
7 cav with fdbk + 1 cav fdbk off	3	**1.1**	**0.91**	**1.49**	**4.4**	**7**

Figure 9: 3.5 TeV conditions with nominal beam and RF. Maximal growth rate for various configurations.

With RF feedback only, the maximum growth rate is $0.013 s^{-1}$ per cavity ($0.005 s^{-1}$ predicted with the more complex LLRF model) and the max tune shift 0.07 Hz/cavity while the tune spread is 4.4 Hz. The corresponding most unstable mode number is $l \approx -12$ (figure 10).

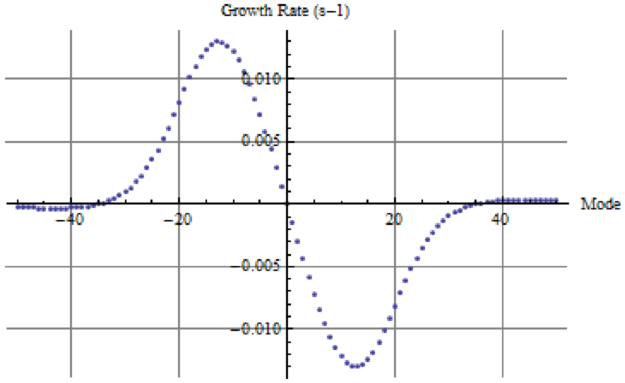


Figure 10: 3.5 TeV conditions with nominal beam and 14 MV total RF. Growth rates as a function of mode index l (dipole mode). Computed with the simple linear model.

So the 8 cavities will give a total growth rate of $0.1 s^{-1}$ ($0.04 s^{-1}$), that is two orders of magnitude below the $7 s^{-1}$ Landau damping.

If a cavity trips during physics, it sits, without impedance reduction, at the 3 kHz detuning. Its contribution to the growth rate jumps to $1 s^{-1}$ ($0.87 s^{-1}$), with 1 Hz tune shift, still OK given the $7 s^{-1}$ damping. From the stability point of view we can survive several klystrons tripping during physics. But the numbers are so good that further analysis is required: with Q_L=60000, the cavity single-sided -3 dB BW is 3.5 kHz. The 3 kHz detuning (very small for a high intensity machine) combined with the effective impedance flattened by the strong RF feedback over a 600 kHz two-sided BW explain the very low growth rates: the terms p=-1 and p=1 cancel out in equation (5). But a small asymmetry in the feedback response will have a big effect on the growth rates. Figure 11 compares the effective cavity impedance with near-perfect adjustment of the RF feedback and with a five degrees alignment error. Figure 12 shows the respective growth rates. The largest rate is increased from $0.013 s^{-1}$ to $0.06 s^{-1}$. Phase drifts are likely to happen in operation, caused by either aging or uncompensated klystron saturation effects. In the coming years we will study the feasibility of on-line optimization: we will measure feedback response, with circulating beam, by injecting noise with no Power Spectral Density in the synchrotron bands.

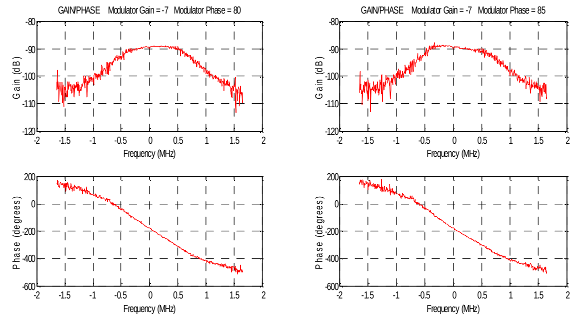


Figure 11: Effective cavity Impedance with near-perfect RF feedback adjustment (left) and 5 degrees offset (right). Simple linear model.

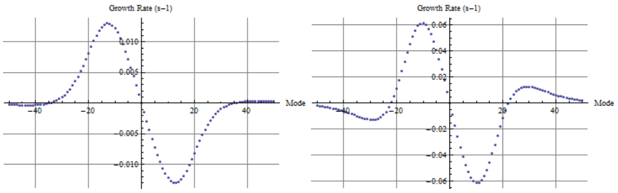


Figure 12: Growth rates corresponding to the situations of figure 11. Notice the different vertical scales.

When a klystron trips at nominal intensity, the beam induced voltage in the idling cavity will much exceed the safe 2 MV cavity voltage and the RF power dissipated in the load will exceed 300 kW [10]. Above half nominal, the RF will trigger the beam dump when one klystron trips to protect the idling cavity and its circulator load.

Another concern is the population of the abort gap with debunched beam following the abrupt voltage reduction caused by a klystron trip. In 2010 we have survived a trip of 3 out of 7 cavities during physics at 12% nominal current. This resulted in only 0.5 % debunched beam. The abort gap got populated but it cleaned naturally after ~18 minutes as the unbunched beam lost energy through synchrotron radiation and finally ended up on the momentum collimators [1]. Calculations are being done to compute the amount of unbunched beam expected to populate the abort gap following a klystron trip [11]. The 2010 precedent is very reassuring but the figure strongly depends on the actual bunch distribution. Both calculations and Machine Developments sessions (intentional klystron trip) are needed in 2011 to define the beam intensity at which a klystron trip is considered as safe. On the longer term, the solution is a compensation for a klystron trip by quickly increasing the voltage demanded from the remaining 7 cavities. This scheme is being studied.

450 GeV conditions

We now consider the situation during filling: 4 MV total RF, cavities at half detuning (10 kHz), main coupler at position Q_L=20000, 1.5 ns bunch length (4σ) and nominal beam current 0.58 A DC. The synchrotron frequency is 46 Hz. The Landau damping $\Delta\Omega_s/4=16s^{-1}$.

Configuration	Detuning (kHz)	Growth rate simple model σ (s^{-1})	Growth rate exact model σ (s^{-1})	Tune shift $\Delta\omega/2\pi$ (Hz)	Tune spread Δf_s (Hz)	$\Delta\Omega_s/4$ (s^{-1})
1 cav with fdbk	10	0.2	0.19	0.3	10	16
1 cav with fdbk	5	0.1	0.135	0.15	10	16
1 cav fdbk off	10	15		2.4	10	16
1 cav fdbk off	5	8.5		3	10	16
1 cav parked	100	15-20	7.5		10	16

Figure 13: 450 GeV conditions with nominal beam and 4 MV total RF. Maximal growth rate for various configurations. Contribution per cavity.

With RF feedback only, the maximum growth rate is $0.2s^{-1}$ ($0.19s^{-1}$) per cavity and the tune shift 0.3 Hz/cavity, to be compared to a 10 Hz tune spread. The corresponding mode number is $l \approx$-12. The large growth rate (compared to the 3.5 TeV situation) is due to the large detuning that is not strictly needed with only 4 MV. Deviating from a strict half-detuning policy, and with 5 kHz detuning only, the growth rate drops to $0.1s^{-1}$ ($0.135s^{-1}$) per cavity.

So the 8 cavities will give a total growth rate of $1.6s^{-1}$ ($1.53s^{-1}$) or $0.8s^{-1}$ ($1.08s^{-1}$) for 10 kHz and 5 kHz detuning respectively. That is still comfortably below the $16s^{-1}$ Landau damping. Notice however that the margin is reduced compared to the 3.5 TeV case. The 1-T feedback would help at injection.

If a cavity trips towards the end of the filling, its contribution to the growth rate and tune shift jumps to $15s^{-1}$ and 2.4 Hz (10 kHz detuning) or $8.5s^{-1}$ and 3 Hz (5 kHz detuning). With the larger detuning we probably loose the beam on mode l=-1, while it should remain stable with the smaller detuning.

We conclude that a cavity trip towards the end of filling will make the beam unstable at nominal intensity with half detuning. It could be survived at half nominal.

Filling with one klystron off

If one klystron or cavity is off, we would “park” the cavity, that is detune it maximally (100 kHz detuning) and enter the coupler to reduce its Q_L to 20000. In the conditions considered above (4 MV total from the remaining seven cavities and nominal beam current 0.58 A DC) the growth rate caused by the un-damped cavity would be $20s^{-1}$ if its tune happens to be on a revolution frequency line and $15s^{-1}$ ($7.45s^{-1}$) if its tune is just in between two revolution frequency lines. Recalling the $16s^{-1}$ Landau damping at injection, we conclude that re-fill with one line off will not be possible much above half nominal.

Higher order Coupled-Bunch modes

In the above analysis we have considered dipole modes only. Following Sacherer’s formalism [9] we can compute a Form Factor F_m for each mode. With a 4σ bunch length in the 1-1.5 ns range and a resonator at 400 MHz, the dipole mode is excited much more than the higher order modes, validating the restriction of the above analysis to the dipole mode only.

LONGITUDINAL PARAMETERS FOR 2011

In 2011 it is intended to start physics with 75 ns bunch spacing, increasing the number of bunches to ~ 300. This would be followed by a short scrubbing run with 50 ns bunch spacing, then physics, reverting to 75 ns spacing, and further intensity increase to ~900 bunches (about one third nominal).

We keep the SPS longitudinal parameters unchanged: 7.2 MV RF @ 200 MHz and longitudinal blow-up to 1.5 ns (4σ) at transfer (0.51 eVs). While we have used 3.5-4 MV RF @ 400 MHz for capture in the LHC, we will experiment with higher voltages this year (5-6 MV). The voltage will be raised linearly during the momentum ramp to reach 12-14 MV at 3.5 TeV (we have used 8 MV in 2010), then kept at this level during physics. In 2010 the longitudinal blow-up during the ramp set the bunch length at 1.2 ns. We will experiment with settings in the 1ns range in 2011, resulting in a 1.5 eVs longitudinal emittance in a 5 eVs bucket (14 MV, 3.5 TeV).

CONCLUSIONS

In 2010 the LHC has made physics with 12% nominal intensity: 368 bunches with 150 ns spacing. The bunch lengthening (4σ-length) observed in physics was 15 ps/hour, probably mainly caused by IBS. There has been no visible effect of the RF noise. Neither did we find any problem related to the intensity increase until e-cloud effects put a stop to the raise.

RF reliability has been very good in 2010. The beam stability considerations presented above indicate that we can survive a klystron trip and operate with one klystron off, up to half nominal intensity. The RF should not be responsible for much down time in 2011 either. We do not expect big problems from the reduced bunch spacing (75 ns vs. 150 ns). The only clouds in this very bright picture are the problems observed with Cav4B1 (intermittent RF noise observed with and without beam) and Cav7B2 (RF noise observed with the injection of 48 bunches at 75 ns spacing). These two cavities are being monitored closely at start-up.

The longitudinal parameters will be optimized in 2011: the higher (mismatched) voltage at injection should reduce the capture loss. The higher voltage in physics allows for a smaller bunch length, and therefore better intensity lifetime, while keeping the longitudinal emittance about constant. Of course the overall effect on the luminosity must be evaluated.

A series of hardware upgrades will be commissioned through the year: the longitudinal damper is meant to reduce capture loss in multi-batch injection. The 1-Turn feedback will reduce transient beam loading. Depending on the optimal voltage for filling, we may implement operation of klystrons with varying DC parameters through the machine cycle [1].

We will continue the studies to identify the sources of RF noise and evaluate their effect on the beam. We will start investigating the longitudinal impedance of the machine.

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EXPERIENCE WITH MPS DURING THE 2010 RUN

J. Wenninger, CERN, Geneva

Abstract

In 2010 the LHC stored beam energy was pushed to 25 MJ, ten times above TEVATRON, in little over 6 months. No machine protection issues were recorded, and the reliability of the machine protection system (MPS) did not impact beam operation in a significant way. After an initial phase of low intensity beam operation that was used among other things for the commissioning of the MPS, the intensity was increased in steps of a factor 2 up to 2 MJ. Following a stability run at 2 MJ, the intensity was increased in steps of around 3 MJs every few days during train operation. The intensity steps and upcoming MP issues were approved and discussed in the restricted Machine Protection Panel (MPPr) composed of representatives from the main MP sub-systems. Two reviews of the MPS were organized in 2010, one internal and one external review. This presentation will discuss the performance of the MPS, the experience from the MPPr and of the intensity increase and the outcomes of the reviews.

INTRODUCTION

March and parts of April 2010 were largely devoted to commissioning with beam of the LHC MPS following the predefined procedures. The test plans where uploaded on WEB pages and the test results were filled by the MPS experts. The MPP chairman checked the results and ensured that no steps were skipped or forgotten. The discipline for filling in test results was good and the plans were followed. No major issues or availability problems encountered in this phase.

The same period saw the first collimator setups, including validations with loss maps and de-bunched beams (asynchronous beam dump simulations). The setups were verified periodically, but not at the predefined rate of once per week. The alignment (or at least retraction) of TCT collimators was verified by a MPP responsible for each fill of the high intensity period using the post-mortem data. The performance of collimation and protection systems was stable along the year, outlining the excellent stability of the machine (orbit, optics and collimator positioning). But it must be noted that the stability is not yet sufficient for nominal tolerances.

STEERING THE INTENSITY INCREASE

The intensity increase was steered in 2010 through the restricted Machine Protection Panel (MPPr). It was composed of MPS experts from the main MP sub-systems, the head of the LHC OP group and the LHC physics coordinator (R. Assmann, B. Goddard, J. Uythoven, B. Dehning, M. Zerlauth, A. Siemko, R. Schmidt, J. Wenninger, M. Lamont, M. Ferro-Luzzi). The MPPr provided recommendations on the MPS envelope (maximum intensity) to be approved by the LMC. From the beginning the plan foresaw 3 phases:

- Low intensity for commissioning and early experience.
- Ramp up to 1-2 MJ followed by a stable operation period of around 4 weeks that intensity.
- Breaking the World record of stored beam intensity and move into 10s of MJ regime.

The actual intensity ramp up in 2010 is shown in Fig 1, and the three phases are clearly visible.

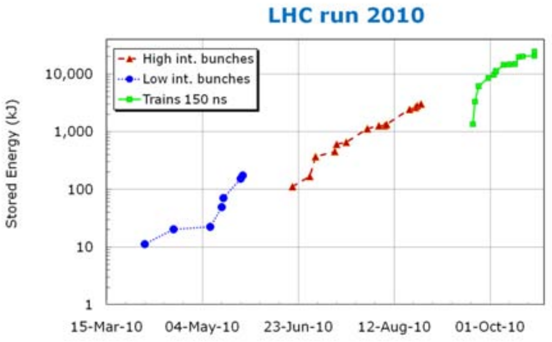

Figure 1: Evolution of the peak stored beam energy in stable beams in 2010.

Figure 2 compares the intensity ramp up plan approved by the LMC in February 2010 with the achieved ramp up. There are a number of notable differences. The plan assumed that commissioning for the different phases (for example single bunches to trains) would be performed in the shadow of physics operation. Train operation was assumed to be run with 50 ns trains of 8×10^{10} p/bunch. The reality turned out to be rather different:

- Commissioning was not transparent and could not be done in parallel to physics operation. Dedicated periods were devoted to commissioning of higher bunch charge (June) and trains (September).
- Higher bunch charges were eventually used (up to 1.2×10^{11} p/bunch).

- In the last phase the intensity followed a much steeped slope than anticipated because no problems were encountered, see also Fig. 3.

In the final phase the slope was four times steeper than what had been planned: this was possible thanks to the excellent performance of the entire machine and in particular of the collimation [1] and MPS.

Figure 2: Evolution of the peak stored beam energy in stable beams in 2010 compared to the plan outlined at the LMC in February 2010.

Figure 3: Evolution of the peak stored beam energy in stable beams in 2010 compared to the plan outlined at the LMC in February 2010 on a linear scale. In the last high intensity phase the achieved slope is 4 times steeper than the planned slope.

Too fast or too slow?

When everything went well it is easy to conclude (a posteriori) that we could have progressed faster! We tend to forget that we had a steep but also sometimes rocky learning curve (OP + MPS) in parallel to the intensity increase . MPPr recommendations were the outcome of agreements (or compromises) among ALL MPPr members some more conservative, some more aggressive. In many cases operational issues played a significant role (QFB versus damper, orbit stability). Afterglow of the TT40 incident was still on some minds. More aggressive colleagues and coordinators were a bit frustrated

The intensity increase in the last phase corresponded to stored energy steps of 3 MJ every 3 fills + 20 hours collisions. Within a factor 2 of a super-aggressive rate: 1 fill of 10 hours. Issue of controlling UFOs in this phase: BLM threshold increase first by a factor 3, towards the end even by a factor 5. We could have considered larger steps towards the end when the fractional increase became rather small.

The intensity increase plan was reasonable given that we were in a commissioning year. Overall the progress followed recommendations of MPPr. MPPr was over-ruled twice. Intensity within factor 2 of recommendations.

REVIEWS

Two reviews of the LHC MPS were organized in 2010, first an internal review [2] in June 2010, and later an external review [3] in September 2010. The internal review was help before increasing the intensity towards one MJ, and it also served as a preparation for the external review. The external review took place after the longer operation period in the range of 1-2 MJ and before ramping up the stored beam intensities to new World records. The external review committee was composed of MPS and operation experts from FNAL, BNL, GSI, DESY, SNS and CERN. It was chaired by R. Bacher of DESY. The external review provided a detailed snapshot of the MPS state. The review committee made 11 recommendations:

- None of the recommendations was a show stopper for the intensity increase.
- The committee expressed strong concerns around configuration and sequencing. As a consequence a major sequencer clean-up was made by the OP group under the super-vision of L Ponce [4].
- All points have been (or will be) addressed.

In parallel to those main reviews, two sub-system reviews have been organized:

- BLM system FPGA code review.
- LBDS TSU review (Trigger Synchronization Unit).

SURPRISES

Quench and damage

A real surprise of the 2010 run was the absence of ACCIDENTAL beam induced quench was with circulating beam. This outlines the excellent performance of BLM and collimation systems.

The only (known) damage to an LHC machine component is the beam2 wire-scanner that almost evaporated during a quench test, when the wire speed had to be reduced to 5 cm/s (from 1 m/s) in order to quench the D4 separation dipole [5]. This test was almost fatal to the wire: the Carbon wire diameter was reduced from 30 to 17 μm over a length corresponding to size of the beam.

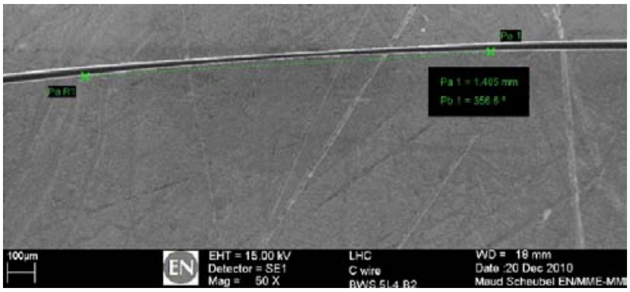

Figure 4: Damaged beam2 wire. Over a length corresponding to the width of the beam, the wire thickness is reduced to 17 μm (nominal 30 μm).

UFOs

The very fast beam loss events (time scale of 1 ms) in cold regions of the machine have been **THE other surprise** of the 2010 run, see Fig. 5. Those events have been nicknamed UFOs (an acronym borrowed from nuclear fusion community where similar events are observed in plasmas). 18 dumps were triggered by UFO-type events, and more than 100 events that remained below the BLM dump threshold have been found in the logging data. The most likely cause of the UFOs are small μm sized objects (dust) entering the beam. Some events were correlated in time and space to roman pot movements. Depending on the mass, it is possible that the particles charge up by ionization and are re-expelled from the beam. More details can be found in Reference [5].

Figure 6 shows the correlation of the number of UFOs that dumped the beams and the integrated circulating beam intensity. After the increase of the BLM threholds by a factor of 3, the number of UFO triggered beam dumps per integrated intensity decreased by a factor 4.1. A simple extrapolation for the 2011 run with 950 bunches leads to one UFO induced dump every 10 hours

Asynchronous dumps

The first asynchronous dump was recorded for beam1 on Friday November 19th at 450 GeV with a circulating pilot bunch. The event therefore occurred in rather favorable conditions as seen from MP. The event was initiated by a fault on a trigger fan out unit. Both diagnostics and reactions to the event were correct:

- The faults were detected by the LBDS IPOC and XPOC systems.
- A test dump revealed a missing trigger (reduced redundancy).
- Access to repair followed by revalidation.

The dump was however doubly asynchronous since it involved 2 MKD kickers and not one as expected. This was due to a change in the trigger fan out signal distribution (with respect to the initial design) following a reliability analysis. The cabling of the trigger fan outs will be restored in 2011 to the nominal specifications.

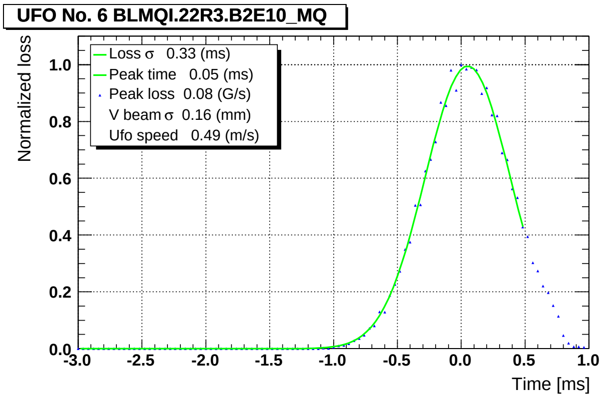

Figure 5: Time evolution of the losses for a UFO that dumped the beam. One bin corresponds to a 40 μs time interval.

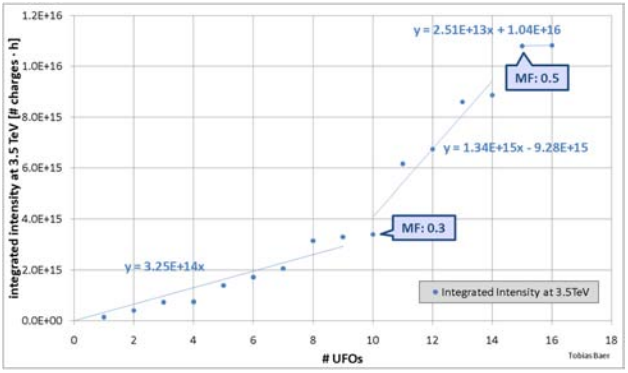

Figure 6: Correlation between the number of UFOs and the integrated circulating beam intensity. The slope change occurred after an increase of the BLM thresholds by a factor 3.

STATISTICS

A detailed analysis of the protection dumps was performed by M. Zerlauth at the Evian Workshop in December 2010 [6]. We present here only some selected points.

Above injection energy 47 of 370 (13%) of protection dumps were triggered by the BLMs. Most of the dumps occurred prior to the increase of the BLM thresholds on various cold and warm elements. The causes of the BLM dumps are shown in Fig. 7: the UFOs were dominant, other triggers occurred mostly during MPS tests and setups such as loss maps, wire scans and quench tests. All failures were captured by the BLMs before quenching any magnet (the QPS providing the ultimate redundancy).

The dependability and availability of the machine protection systems has been a major design criteria. It was subject to extensive studies using the FMECA approach (Failure mode, effects and criticality analysis). The MPS dependability studies were confirmed in 2010, see Table 1.

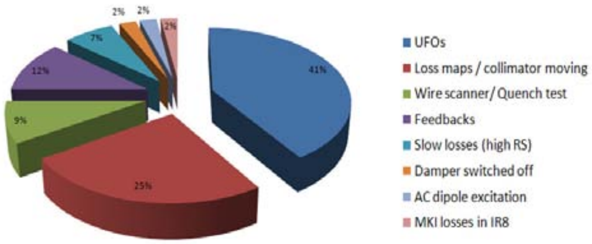

Figure 7: Initiating events for the protection dumps triggered by the BLM system.

CONCLUSION

The LHC Machine Protection Systems have been working extremely well during 2010 run thanks to the commitment and rigor of operation crews and MPS experts. Most failures are captured before effects on the beams are seen, no quenches occurred with circulating beam.

Controlling (and understanding) UFOs could become a main issue in 2011. The BLM thresholds may have to be adjusted and possibly increased to probe the limit of the quench.

Steering of the intensity increase through MPPr should be pursued in 2011. The intensity increase plan for 2011 must be be defined, and the experience of 2010 should be integrate to optimize the plan.

An improved tracking system for ALL MPS changes must be put in place for 2011, in particular in view of the MD periods: a safe recovery and pre-flight MP compatibility checks will become essential.

System	Expected	Observed
LBDS	4	9
BIC	0.5	0.5
BLM	17	3
PIC	1.5	2
QPS	16	11
SIS	–	4.5
Total	41 ± 6	31

Table 1: Expected and observed number of ’false’ (internally triggered) dumps for each of the main MPS subsystems. One event is shared and BIC and SIS. The observed dumps correspond all to energies above 450 GeV.

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CAN OPERATIONS PUT THE MPS INTO AN UNSAFE STATE?

L. Ponce

Abstract

During the 2010 run, the MPS have been additionally stressed by the commissioning of operational procedures and systems tests. As requested by the MPS external review committee, human factors have to be further minimized and discipline reinforced when increasing the stored beam energies towards and beyond the 2010 target of 30 MJ. This talk will present a synthesis of the Evian discussion on MPS and human factors, with an emphasis on the tools and procedures to be put in place for the 2011 run in order to ensure the machine safety during standard beam operation and after periods of machine developments or technical stops.

PREPARING THE MACHINE PROTECTION SYSTEM FOR THE 2011 RUN

J. Uythoven, CERN, Geneva, Switzerland.

Abstract

The expected performance of the Machine Protection System for 2011 is presented. An overview of the foreseen modifications to the machine protection system components during the Christmas stop and the required time for recommissioning is given. The possible impact of the MPS on the operational parameters of the LHC, like beam intensity, beta*, emittance and maximum beam energy, are discussed

INTRODUCTION

During the 2010/2011 Christmas Technical stop interventions have taken place on many different systems which form the heart of the LHC Machine Protection System (MPS). This paper concentrates on the modification to the main players of the MPS: the Beam Interlock System (BIS), the Safe Machine Parameters (SMP), The Quench Protection System (QPS), the collimation system, the Beam Loss Monitoring System (BLM), the Power Interlock Controlling System (PIC for the cold magnets and WIC for the warm magnets), the Fast Magnet Current change Monitoring system (FMCM), the Software Interlock System (SIS), the injection and the beam dumping systems. For each of these systems the changes and the required re-commissioning time are given, together with any possible impact on the operational parameters for 2011, like maximum beam energy and beam intensity.

THE BEAM INTERLOCK SYSTEM

Changes to the system

The LHC BIS has not been touched during this Technical Stop. Changes have been made to the SPS Extraction BIS to allow for extraction to the new TT66 extraction line towards HiRadMat. Consequently the Master BIC managing Beam 1 will be updated.

Time required for re-commissioning

Prior to beam operation a few hours of commissioning time is required. No commissioning time with beam is required

Limitation on operational parameters

There should be no limitation to the LHC operational parameters due to the BIS system

SAFE MACHINE PARAMETERS

Changes to the system

Important changes are taken place to the SMP for 2011 operation: two Beam Energy sources are now required, instead of the single source so far. Both sources are from the beam dumping system, but coming from different octants. Also for the Beam Intensity two sources are required for 2011 operation instead of a single source. Both the BCTF-A and BCTF-B will be required by the SMP system during the year.

At start in 2011 up for the energy and beam intensity the largest of the two values will be used for the SMP but in the future the system will be configured to create a beam dump in case of disagreement of the signals.

For the Beam Presence Flag dedicated hardware is used from a BPM in addition to the Fast BCT, using a voting strategy. The Movable Device Flags will have next to the existing modes Stable Beams and Unstable Beams a new mode Beam Dump. The Setup Beam Flag will have next to the status of Normal and Relaxed two new statuses Very Relaxed and Ion.

Time required for re-commissioning

Commissioning without beam should be finished during the hardware commissioning period. Several tests will need to take place with beam, but this should be in the shadow of other work. Test ramps with different beam intensities are required.

Limitation on operational parameters

There should be no limitation to the LHC operational parameters due to the SMP system.

BEAM LOSS MONITORING SYSTEM

Changes to the system

Several upgrades in the FPGA firmware have taken place together with preventive actions on the tunnel installations.

Time required for re-commissioning

Commissioning without beam should take place in the shadow of other activities. About one shift with beam at injection will be required for testing the BLM system.

Limitation on operational parameters

Due to noise on some BLM signal cables the operational energy is limited between 4 and 5 TeV. Tests with double shielded cables for future operation are foreseen.

QUENCH PROTECTION SYSTEM

Changes to the system

An important number of changes has taken place on the Quench Protection System: Installation of snubber capacitors on the 16 extraction switches of all Main Dipoles; removal of ‘old’ global busbar protection (replaced everywhere by simplified detector and nQPS);

replacement of input power switches of all quadrupole quench heater power supplies: 900 units & broken ones on dipoles; QPS of all Q8, Q9 and Q10: modified to be less sensitive to noise pick-up: change of voltage dividers & firmware modification.

Time required for re-commissioning

During the Chamonix workshop it was decided that the snubber capacitors will be commissioned for all octants, requiring approximately one week of additional hardware commissioning. The busbar detector protection can be tested parasitically on the first ramps. The new quench heater will be tested during the Individual System Tests, independent of the Hardware Commissioning Tests. The QPS changes will be tested parasitically during the first ramps.

No tests are required with beam.

Limitation on operational parameters

There should be no limitation to the LHC operational parameters due to the QPS system.

COLLIMATION SYSTEM

Changes to the system

For 2011 operation the collimation settings will depend on the distributed squeeze factor parameter. Changes have been made to the internal logic of the collimation system and a recalibration of the sensors has taken place. Details can be found in [1].

Time required for re-commissioning

Commissioning without beam should take place in the shadow of other activities. Set-up and qualification with beam needs to be done at injection energy, about 4 shifts, and at full energy for about 5 shifts. Approximately 6 to 10 additional ramps will be required. In 2010 about 12 shifts were spent setting up collimators.

Limitation on operational parameters

The limitation on the $\beta^* \approx 1.5$ m, foreseen for 2011, is closely linked to the expected collimation system performance [2]. No limits on beam energy, beam intensity or emittances are imposed by the collimation system on operation during 2011.

PIC/WIC/FMCM

Changes to the system

During the Christmas stop an upgrade of the PIC PLCs has taken place, with the aim of improving the diagnostics in the case a PLC gets stuck. A WIC at point 8 has been moved from UA83 to US85 following the results of Radiation to Electronics studies (R2E). A WIC in TI8 has been moved away from the collimator position following a unique SEU in 2009.

Time required for re-commissioning

Most of the re-commissioning can take place during the hardware commissioning period. The re-commissioning of the PIC-BIS interface is expected to take 6 hours. Possible tests with beam include FMCM checks for D1 and the MSD with the newly applied β^* for 2011, which can normally be done as an ‘end-of-fill study’. When increasing the beam intensities checks on the reaction time of the different systems are required.

Limitation on operational parameters

No limits are imposed on the operational parameters by the PIC/WIC/FMCM systems, assuming that the tests with beam mentioned above are passed successfully.

SOFTWARE INTERLOCK SYSTEM

Changes to the system

For 2011 the SIS will produce the β^* values, which will transit through the SMP and it is subsequently transmitted over the timing system. A new injection oscillation interlock will be in place and the intermediate beam intensity during injection will be enforced. The SIS will include a more performing, and more complex, orbit interlocking to handle special conditions like special optics and Van der Meer scans. There is an improvement of the settings management for special conditions.

Time required for re-commissioning

Most testing without beam can be done parasitically. About 1 – 2 shifts dedicated time for testing with beam are required.

Limitation on operational parameters

The SIS imposes no limitations on the operational parameters.

INJECTION SYSTEM

Changes to the system

Many changes to the injection system are made for the 2011 start-up. On the hardware side it can be noted that one MKI injection kicker magnet (B point 2) has been replaced because it showed some occasional break-downs during 2010 operation. Improved diagnostics and controls and improved interlocking of MKIs has been implemented. Fine synchronisation of kicker modules and AGK will be performed for 2011. New TI2 BPMs with dual acquisition has been installed. Diamond BLMs in IP2 and IP8 for bunch by bunch diagnostics are installed.

Modifications are made to the Injection Quality Check program (IQC), including interlock on injection oscillations, the checks on B1 and B2 will be independent and change in functionalities and latching philosophy are made (see Evian follow-up meeting 19/01). The MKI operational settings will have an envelope to only allow limited trims. New injection procedures with intermediate beam intensity will be enforced. New TCDI interlock logic will be applied at start-up and automatic set-up procedures are foreseen for later during the year. Shielding of ring BLMs from TCDI showers is being installed in different phases. The BLM interlock thresholds on TDI and TCLI are under discussion and possible TDI shielding is being studied. Also BLM 'sunglasses' which will temporarily disable the interlock from some BLMs at the moment of injection is being studied and could possibly be implemented after the summer. 'Sunglasses' for the LHCb and ALICE experiments, temporarily increasing the thresholds of the BCMs, will be available from start-up. Abort gap cleaning and injection gap cleaning to limit the beam losses on the TDI during injection will be commissioned.

Time required for re-commissioning

About 1 shift without beam, but the BIS loop closed, is required for setting up and machine protection tests. With beam approximately 3.5 shifts are required for setting up the injection protection plus 1.5 shifts for general machine protection tests with beam, totalling in 5 shifts of tests with beam. During the year another 3 shifts are expected to be required during the injection intensity increase and another shift every 2 – 4 weeks for maintenance of injection protection.

Limitation on operational parameters

During 2010 operation injection of 48 nominal bunches per injection took place successfully. Taking into account the BLM signals during these injections, it is expected that in the configuration at start-up the injection is limited to 144 nominal bunches per injection [3, 4]. For higher injected intensities the measures discussed above (shielding, sunglasses etc.) are required.

BEAM DUMPING SYSTEM

Changes to the system

The extraction kicker MKD Trigger Fan Out (TFO) system is re-cabled to minimise the probability of obtaining and asynchronous dump with multiple MKD kickers. The MKD generators will be working at a higher thermal working point of 26 °C, instead of the 23 °C during 2010, to obtain experience for future higher energy operation. The TCDQ has undergone several controls and diagnostics improvements. The TCDQ sequences will be separated from the collimator sequences. The extraction septum MSD will have corrected settings for 2011, following a recalibration of one of the MSD magnets at CERN, and degauss cycles of the MSD magnets will be performed during machine cycling. The eXternal Operational Check (XPOC) will include an additional module with compares the position of the TCDQ with measured beam position at the TCDQ. The BLM limits used by XPOC will be calculated in a different manner, relative to reference BLMs with the largest losses, it will include the BLMs at the TCTs and generally the limits will be lower for higher beam intensities which were not very effective during 2010 operation, see fig.1.

Other modifications to the beam dumping system include the replacement of 2 MKD and 2 MKB generators, following the program to counteract contact erosion. As a result all kicker settings and references will be regenerated. The Trigger Synchronisation Unit (TSU) will undergo a firmware upgrade following the recommendations of the external audit. The BEM firmware will be updated to correct communication errors between BETS and PLC. The development of abort gap population monitoring and cleaning will continue during 2011.

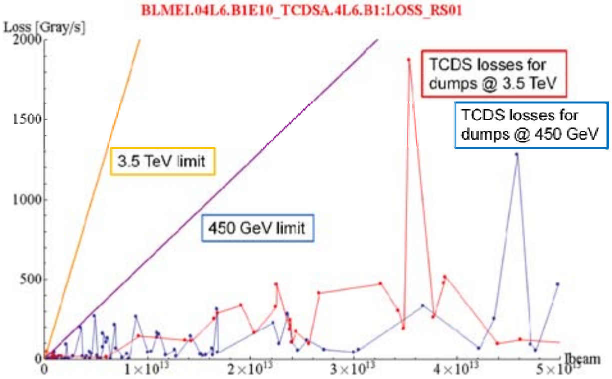

Figure 1: Measured beam losses on BLM at the TCDS during 2010 operation at 450 GeV and 3.5 TeV together with the XPOC limits used. This clearly shows that the XPOC BLM limits were not very effective for higher beam intensities.

Time required for re-commissioning

About 4 shifts are required for commissioning the beam dumping system without beam and about 10 shifts with beam of which 3 shifts for basic checks, 3 shifts for setting up the TCDQ/TCT protection, including ramps up to full energy, and 4 shifts for abort gap cleaning and monitoring.

Regular simulations with beam of asynchronous dumps will need to be performed at injection and at full energy to test the protection set-up. During the intensity increase and the change of filling patterns the BPMS interlock system needs to be verified, requiring about 30 minutes at injection for each test.

Limitation on operational parameters

The beam energy is limited to 4.5 TeV due to the increased risk of a HV break down alongside the MKD kicker switch for higher operating voltages. The switch is waiting for new isolators to be installed before the 2012 start-up.

Detailed calculations of the maximum load of the TCDQ absorber are ongoing. Rough calculation indicate an operational limit of a bunch intensity between $7 \cdot 10^9$ and $7 \cdot 10^{10}$ protons, assuming 28 bunches with 25 ns spacing and 7 TeV energy impinging on the collimator. This is only important in the case of an asynchronous dump and spare TCDQs exist. Precise loss measurements are required as a reference to be able to check on any possible damage. The effect of small emittances on any possible TCDQ damage is unknown.

The presently installed number of MKB diluters, still 2 magnets missing per beam, is sufficient for nominal beam intensity.

COMMISSIONING AND OPERATIONAL LIMITS

Adding up the different system commissioning times mentioned above, the time required for machine protection tests during the cold check out is about 8 shifts, plus one week for testing the QPS snubber capacitors. Machine protection tests with beam will require an estimated 28 shifts, which means about 10 days, before the beam intensity can be increased. During the intensity increase on average a few shifts per week will be required for system set-up and maintenance.

The maximum beam energy is limited between 4 to 5 TeV due to noise on some BLM cables and to 4.5 TeV due to HV breakdowns in the generators of the beam dump extraction kicker magnets MKD.

There is no explicit limit on maximum beam intensity, although the TCDQs risk to be damaged in case of an asynchronous dump with high beam intensities. The number of bunches per injection is limited to 144 in the present configuration.

The β^* at the interaction points is limited to about 1.5 m due to collimation, taking into account orbit stability, beta-beat etc.

PERFORMANCE OF THE MPS

The performance of the Machine Protection System has to be evaluated considering safety and availability. During 2010 operation the safety of the MPS was good: no damage and no beam induced quenches above 450 GeV occurred. Procedures remain the weak point considering safety. The ‘2010 Safety Events’ include the MKD erratic with two magnets, for which the TFO logic is modified for 2011 operation. Injection took place onto a moving TCDQ. As a measure the TCDQ controls will be made more conform to the other collimators and work on the sequences is performed. Other 2010 safety issues concern mainly the operational procedures and the sequencer and don’t affect the MPS as such [5].

The availability of the MPS during 2010 was basically as expected. It is shown [6] that as expected most of the ‘down time’ is coming from the large MPS systems: QPS, Power Converters and Injection. In all these fields important improvements are foreseen for 2011 operations, as is detailed in this paper.

The impressive amount of changes to the Machine Protection System in the Technical Stop are shown to focus on known weaknesses of the system, as experienced during 2010 operation, and affect both Safety and Availability. Taking into account the already good performance of the MPS during 2010, one can expect a Safe and Available LHC in 2011.

CONCLUSIONS

The commissioning of the Machine Protection system for 2011 operation will require about 10 days during the cold check out without beam and another 10 days with beam before the beam intensity can be increased. During the intensity increase a few shifts per week will be required for machine protection system set-up and maintenance.

The energy for 2011 operation is limited to 4.0 TeV due to noise on some BLM cables. The maximum injected number of bunches under the present configuration of the injection system is 144. The β^* at the interaction points is limited to about 1.5 m.

A large number of machine protection system modifications has taken place during the Christmas technical stop. This should further improve the performance of the machine protection system compared to the already good safety and availability performance in 2010.

ACKNOWLEDGEMENTS

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Is the BLM system ready to go to higher intensities?

M. Sapinski, F. Cerutti, B. Dehning, E. Effinger, J. Emery, B. Goddard, A. Guerrero, S. Grishin,
E. B. Holzer, S. Jackson, Ch. Kurfuerst, A. Lechner, A. Marsili, M. Misiowiec, E. Nebot, A. Nordt,
A. Priebe, Ch. Roderick, R. Schmidt, A. Verweij, J. Wenninger, Ch. Zamantzas, F. Zimmermann
CERN, Geneva, Switzerland

Abstract

The higher beam intensities will enhance the effects of the beam losses observed during 2010 run. In particular beam losses due to so called UFO events are discussed, but also other beam loss phenomena like luminosity losses, injection losses and the leakage from the collimation system are considered. The current understanding of the quench limits reflected in the BLM thresholds on the cold magnets is presented. The thresholds for possible increased beam energy are reviewed.

INTRODUCTION

The 2010 LHC beam, despite of its record-breaking stored energy of 30 MJ, has not induced any unintentional quenches of superconducting magnets nor other equipment damage. Nevertheless, a number of unexpected phenomena have been observed, some of them affecting machine operation.

This paper concentrates on understanding of beam losses, with emphasis on UFO phenomena and on accuracy of the present knowledge of the Beam Loss Monitor beam-abort thresholds. It attempts to foresee the problems during LHC run in 2011 and 2012, when intensity, and maybe the energy of the beam, will be significantly increased.

DO WE UNDERSTAND ALL LOSSES?

The loss pattern observed by the BLM monitors around the LHC ring is, in most cases, well understood. Nevertheless, there are special cases of losses which occurred in 2010 run and which need to be further studied in order to understand their mechanism and the BLM signals which they generate.

The important beam losses, generating large signals in the BLMs, have been usually noticed during the operation because they were very visible on fixed displays, they affected the beam lifetime or even initiated the beam dump. Examples of such losses are discussed first. A systematic search of nominal loss level variation has also been performed in order to look for loss variations, which have been unnoticed during operation.

Examples of unexplained losses

One example of unexplained loss has been reported already a year ago [1]. The difference in the loss pattern at overinjection between IR2, where beam 1 is injected, and IR8 where beam 2 injection takes place is illustrated in Figure 1. It has been explained only partly by a presence of a chicane in IP8 which is responsible for significant decrease of the signal in monitors installed on Q1 magnet (first from left) in IP8. Another feature, the signal in the monitor on MBX magnet which is about 3-5 times higher in case of IP8, remains unexplained. Some observations considering the difference in location of the monitors have been done [2], but a simulation has to be performed to evaluate if these differences explain the difference in signal. The beam-abort thresholds for this monitor in IP8 have been temporarily increased in order to allow overinjection without dumping the beam.

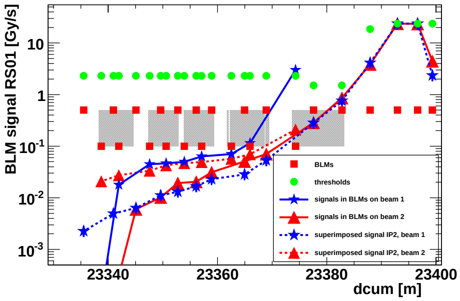

Figure 1: Asymmetry in the BLM signals at injection of beam 1 and beam 2. The MBX magnet is the first dark box from the right. The irregular signal on one of the monitors installed on this magnet is visible.

Another example has a different nature. On the 3rd of October 2010 at 20:28 a sudden increase of BLM signal on the triplet magnets in IP1 led to a beam dump issued by `BLMQI.02R1.B1E23_MQXB` monitor. Signal averaged over long integration times 0.655 - 20.9 s exceeded the beam-abort threshold. Other monitors on the same tunnel card presented behaviour suggesting a very high loss event, but the monitors which are expected to be sensitive to such large loss (BLMs on collimators, ATLAS Beam Condition Monitors) have not confirmed it. The reason of this event, which has been observed only once, remains unclear.

Systematic studies

A method of systematic studies leading to a detection of abnormal losses has been proposed. The method uses the integrated dose measurement by the BLMs during stable beams periods, normalized to integrated luminosity. As the beam conditions during these fills were identical, small variations are awaited. Large fill-to-fill variations indicate the unexpected loss rate change and their should be investigated in order to understand loss rate variations.

Figure 2 presents such a variation analysis for high-intensity proton fills. Monitors with the largest variations are located in the Long Straight Sections. Understanding of these variations need further investigation, but they will probably not affect the running of the machine in 2011 and 2012. Details of this study can be found in [3].

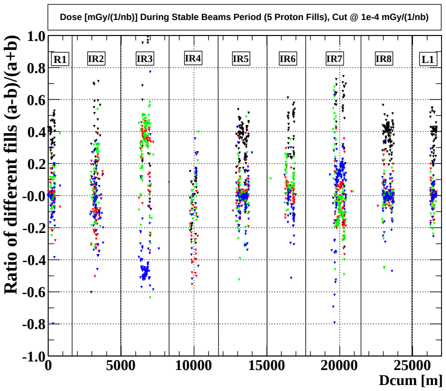

Figure 2: Study of fill-to-fill variation of beam losses: **a** and **b** are the total doses normalized to the luminosity integrated during the fill. Every point depicts ratio $(\mathbf{a}-\mathbf{b})/(\mathbf{a}+\mathbf{b})$ for one monitor (and for two fills).

WHAT DO WE KNOW ABOUT UFO?

The term ”UFO” has been adopted from the plasma physics community, where a phenomena of dust particles falling into plasma has been observed. In LHC, this name is used for the sudden losses with a millisecond-scale duration appearing in any part of the accelerator ring. The properties of these events suggest that they are generated by small objects (dust) falling into the beam or being attracted by the beam electromagnetic fields.

The first UFO event has been observed on July 7th, 2010 as it triggered a beam dump, because of losses observed by the BLM system. The post-mortem data [4] of this event, presented in Figure 3, show a complex time structure with 6 peaks separated by 70 or 100 μs . For a detailed analysis see [5].

Sub-thresholds analysis

A systematic search for sub-threshold UFO events (i.e. events which have not initiated beam dump) has been launched after July 7th. A collection of 111 such events has been gathered in 2010 data during the periods when beams were declared stable [6]. The data have been extracted from the Logging Database using the following criteria:

- Signal is observed on primary collimators (TCP).

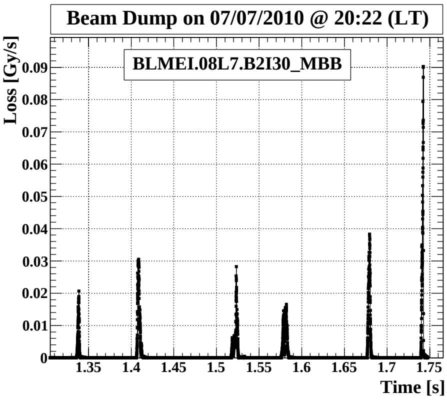

Figure 3: The post-mortem data of the first UFO event which caused a beam dump.

- Signal is observed in at least three neighbouring BLM monitors.
- Loss duration is in the millisecond scale.

Additional analyses with loosen conditions are ongoing.

The analysis of this sample revealed the following properties of the UFO events:

- The UFO event rate increases linearly with the beam intensity, as shown in Figure 4; the rate expected at beam of 1000 bunches, extrapolated from the linear tendency, is about 1 event every half hour.

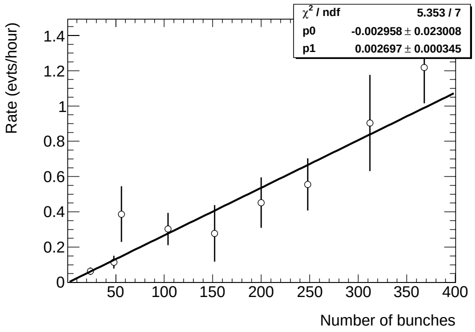

Figure 4: Dependence of the UFO event rate on the beam intensity.

- The observed signal length becomes shorter with increasing beam intensity, as shown in Figure 5.
- The BLM signal amplitude, measured as a signal accumulated in 40 μs integration time, is independent on the beam intensity, as shown in Figure 6.

Model of dust particle

A model describing a dust particle falling into a beam has been developed [7]. The model includes the effect of change of the particle charge due to interaction with the beam. The movement of the particle is guided by forces

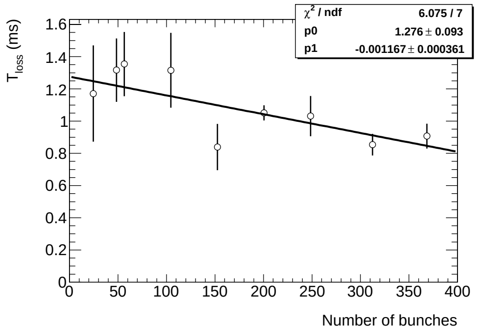

Figure 5: Dependence of duration of the UFO event signal on the beam intensity.

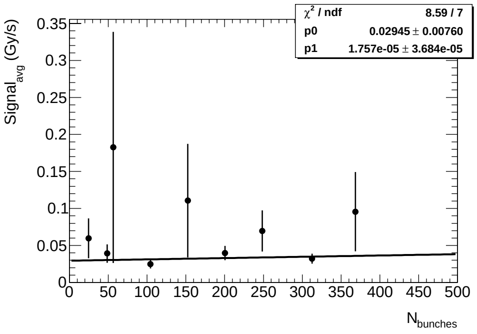

Figure 6: Dependence of the amplitude of the UFO event signal on the beam intensity.

due to the electric fields of the beam charge and of the image charge at the chamber wall and by gravity. Interestingly the model predicts the signal shortening with increasing beam intensity and lack of dependence of the signal amplitude on the beam intensity (see Figure 7). It also predicts the existence of UFO events with a precursor loss. Such type of events has been observed (see Figure 3 for event with multiple precursors), however in most cases the losses have only one peak.

FLUKA simulations

The effect of the LHC beam interactions with the obstacles has been also investigated using particle shower simulations in [8]. This study does not take into account the additional forces acting on an object due to electromagnetic interactions with the beam, which modifies the object trajectory. The outcome of the study is a relation between the beam intensity needed to quench the LHC magnets and the size of the object itself. For beam energy of 3.5 TeV, a nominal bunch intensity and assuming a metallic object of size x (expressed in μm), the quench should occur if the beam intensity exceeds $220/\mathrm{x}$ bunches. For a plastic object the size must be almost 10 times larger to generate a quench. According to this results, the lack of UFO-generated quenches during the 2010 run suggests that the size of the falling objects is smaller than $0.3\ \mu\mathrm{m}$ if the object is metallic or $3\ \mu\mathrm{m}$ in case of plastic one.

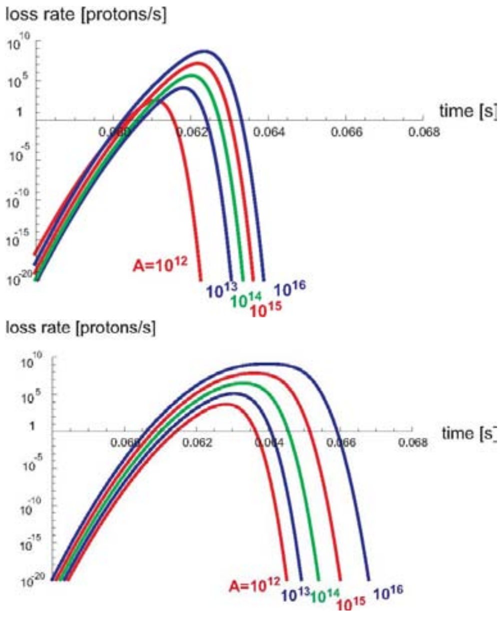

Figure 7: Model predictions of UFO loss rate for nominal (upper plot, $3.2 \cdot 10^{14}$ protons) and low (bottom plot, $2.3 \cdot 10^{12}$ protons) intensities.

UFO speed

In case of UFO events which dumped the beam, the high-time-resolution post-mortem data [4] are saved. In 2010 there were 18 beam dumps due to UFO events. Out of these 10 events had a signal shape which can be well fitted with gaussian, reminding a signal shape obtained during the wire scan. An example of such data is shown in Figure 8.

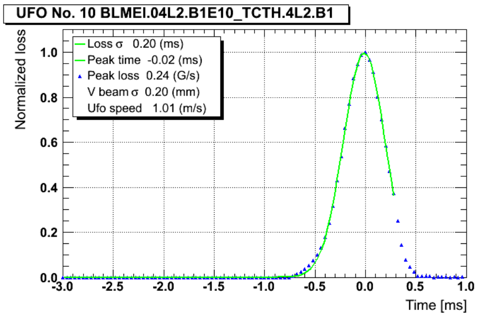

Figure 8: BLM Post-Mortem data generated by a UFO event which dumped the beam.

Assuming that the size of the UFO particle is much smaller than the beam size one can calculate the speed of the particle passing through the beam. The speeds found in this analysis vary from 0.4 to 4.5 m/s, what supports the idea that the electromagnetic forces have dominant contribution to the movement of the UFO objects.

Remedy to UFOs

The study of UFO events will continue during the 2011 run. As the frequency of these events is expected to increase, a strategy to avoid spurious beam dumps must be developed.

One possibility is so called scrubbing run foreseen during the first weeks of 2011 operation. During the scrubbing a high intensity beam at injection energy is circulating in the machine in order to enhance outgassing from the internal surfaces of the beam chamber. It is possible that the scrubbing will also enhance the release rate of the dust particles therefore suppressing the rate of UFO events in the following physics runs. The UFO activity before, during and after scrubbing run will be carefully monitored.

The second possibility relies on the lack of UFO-induced quenches during 2010 run. The BLM thresholds at the end of the run have been already increased to about 60% above the originally estimated quench level. This modification allowed to avoid spurious beam dumps which would have been generated by the BLM system if lower thresholds had still been applied.

The signals observed during the UFO events have exceeded the expected BLM signal at quench. The reason can be two-fold:

- The BLM thresholds have been set assuming the beam loss due to orbit deviation and therefore the beam hitting directly the beam screen; UFO events correspond to different loss scenario.
- For the losses in the millisecond-scale the cooling contribution of helium it is not well established.

In order to investigate the impact of these two unknowns, a simulation study has started and a special quench test has been performed.

It must be stressed that, in case of the beam energy increase, the amplitude of the loss generated by UFO will increase (as in case of BLM signal during the wire scan, see Figure 9). Together with the reduced quench level, this might lead to a significant increase of the quench probability when running the LHC with energies above 3.5 TeV.

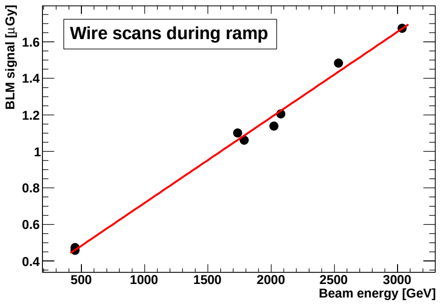

Figure 9: BLM signals registered during the wire scans when beam energy has been ramped.

Quench test at millisecond timescale

In order to investigate the quench margin at the millisecond timescale a loss of this duration must be generated. Such a loss is generated by the wire scanner during its normal operation. Therefore a quench test using this device has been performed.

The test conditions were the following: beam with energy 3.5 TeV and intensity of $1.53 \cdot 10^{13}$ protons. The MBRB magnet is situated 32 meters downstream the wire scanner. The magnet quenched when the wire speed reached $5\ \mathrm{cm/s}$. The overlapped post-mortem data from the BLM monitor and QPS system are shown in Figure 10. The irregular BLM signal (blue points) shows that the carbon fiber was vibrating during this scan. The electron microscope picture of the fiber made after the test has shown that about 50% of the wire diameter sublimated due to heating from the beam.

The raise of the QPS signal started about 10 ms after the start of the beam scan seen by the BLM system. Therefore the probed time scale was longer than the one characteristic for UFO events (about 1 ms).

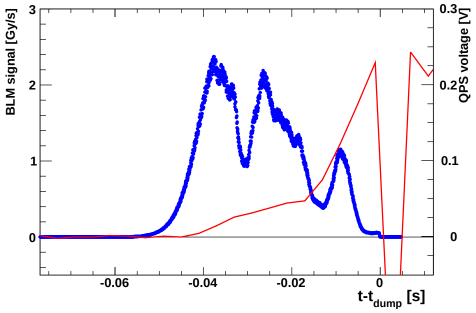

Figure 10: BLM post-mortem signals (blue) overlapped with QPS voltage readout (red) during the wire scan which led to quench of MBRB magnet.

The preliminary results of the quench analysis using the QPS and BLM post-mortem data [9] and QP3 code [10] suggest that the quench limit for the 10-ms perturbation is in the range $35 - 42\ \mathrm{mJ/cm^3}$. The preliminary results of FLUKA simulations have been presented [11], and the final conclusions from this experiment are expected soon.

A repetition of this test during 2011 run is strongly suggested. The conditions should be modified, especially the beam intensity should be increased by about factor of 4.

HOW CORRECT ARE THRESHOLDS?

The BLMs are protecting various machine elements against beam losses. The beam-abort thresholds have been computed differently depending on type of protected element. For cold magnets the methods of thresholds computation are described in [12, 13, 14]. In case of collimators the relevant document is [15] and in case of warm magnets the present strategy is documented in [16, 19].

Two aspects of threshold correctness are discussed here:

- The locations where the observed losses were close to beam-abort thresholds.
- The accuracy of the threshold values.

The major modification to cold magnet thresholds, which has been done before 2011 run, is presented.

Low margin locations

The threshold setting is based on two threshold tables called master and applied [17]. The master table is the one which assures protection of the accelerator components against damage. The thresholds which are actually used in the electronics (applied thresholds) must be below the master table. The following convention is used: in the normal situation the applied thresholds are 10 times below or equal the master thresholds. This allows the operators to raise, fast and safely, the thresholds up to factor 10, when needed. This method has been found very useful in 2010 run, when UFO events became an important thread to the beam availability.

The weakness of this approach is seen for the short signal integration times. The upper bound of the dynamic range of the BLM channels (with standard ionisation chamber) is about $23\ \mathrm{Gy/s}$. According to the convention the applied threshold values must be set to maximum $2.3\ \mathrm{Gy/s}$. In case of short signal integration times this value is often much lower than the estimation of the physical threshold. Therefore the BLM system is often overprotective for short losses.

The above arguments should be kept in mind when looking at the results of the systematic search for channels where signals are close to the thresholds. Figure 11 illustrates the results of such search. Every point depicts a maximum registered ratio of signal to applied threshold for every monitor. The red line represents the dump level, and the green line 10% of the dump level. Higher beam intensities and higher luminosity expected in 2011 run will increase the losses, while higher beam energy will decrease the thresholds, so factor 10 between loss and threshold as observed last year might not be enough during 2011 run. More details on this analysis can be found in [3], where also a lists of monitors with low margin to thresholds (above green line) are published.

Threshold changes

The changes of thresholds which took place in 2010 were due to hardware modifications (for instance filter installations) as well as due to debugging of the threshold generation code. These changes are described in [3, 18, 19].

The most important change, affecting almost all monitors on superconducting magnets, follows the better understanding of the quench limits due to lack of quench induced by UFO event (millisecond scale, described before) and as a conclusion of quench test for long losses (1-5 second scale).

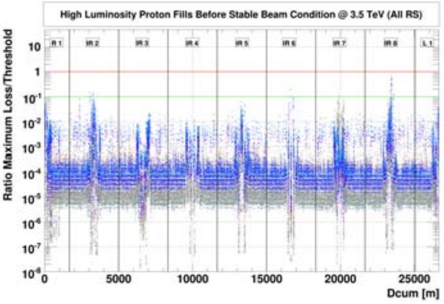

Figure 11: Ratio of maximum signal to the applied threshold registered during the stable beam period, as a function of monitor location, for 5 high luminosity proton fills.

The quench tests performed before Autumn 2010 were testing only MB magnets at injection energy and for very short losses, where the quench limit can be easily calculated as an enthalpy limit of a dry superconducting cable [13]. A series of tests performed in September and October 2010 used orbital bump technique to provoke slow losses on arc MQ magnet for injection energy and at 3.5 TeV. An example of the loss signals observed during the quench test at 3.5 TeV are shown in Figure 12. The small blue and red squares mark the positions of the BLM monitors observing beam 1 and beam 2 respectively. The beam direction was from right to left (beam 2). The green line shows the signals expected in the second and the third monitor in the moment of quench. The red line connects the signal actually registered by the BLMs during the quench. The existing threshold was overestimated by factor 2 to 3 [20].

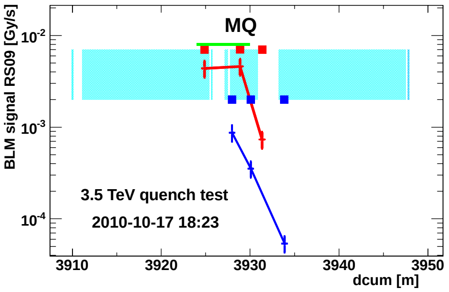

Figure 12: Signals registered in the BLM system during the quench test of MQ magnet at 3.5 TeV.

Corrections to BLM thresholds on cold magnets have been applied before the start of 2011 run. They are depicted in Figure 13, where the solid line is an example of old 3.5 TeV quench thresholds, and dashed line shows the new thresholds.

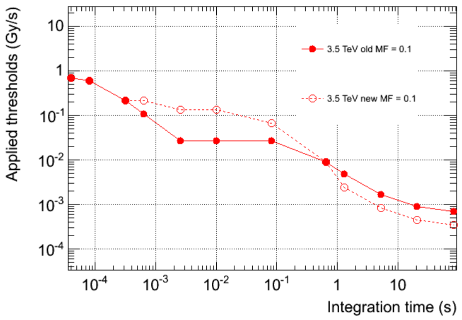

Figure 13: Example of BLM thresholds for beam energy 3.5 TeV.

CONCLUSIONS

The beam losses as observed by the Beam Loss Monitoring system, are generally understood, but a few specific cases need more study or a follow-up. A systematic study of the fill-to-fill variations of the total dose registered by the BLMs gives a hint about variation of small losses, which will probably not affect the operation of the machine, but which are not understood yet.

The UFO events, which are millisecond-scale losses provoked probably by small objects falling into the beam, are feared to affect the operation in 2011 and 2012. The analysis of sub-threshold UFOs reveal lack of dependence of UFO amplitude from beam intensity, what should allow to keep the dump rate due to UFOs under control.

The analysis of the UFO events and the results of quench tests with circulating beam lead to massive upgrade of BLM thresholds on cold magnets. A list of monitors where the observed signals were close to the beam-abort thresholds has been extracted from 2010 data.

The BLM system is well prepared to high intensities expected during 2011 run but a careful follow up on UFO events and signals close to the thresholds is necessary.

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POTENTIAL ISSUES WITH INJECTING UNSAFE BEAM INTO THE LHC

C. Bracco, W. Bartmann, B. Dehning, B. Goddard, V. Kain,
M. Meddahi, V. Mertens, A. Nordt, J. Uythoven, CERN, Geneva, Switzerland

Abstract

Nominal LHC operation foresees to inject four batches of 72 bunches at the time. Injection of up to 48 bunches per batch has been tested in 2010 and possible intensity limitation and machine protection issues have been highlighted, in view of 2011 run. Beam leakage at LHCb and ALICE during injection and qualification of the provided protection are evaluated. Encountered and potential failures of the injection system are presented together with existing and required redundancy of the injection interlocks. Possible modifications of injection procedure and implication for filling schemes are discussed.

INTRODUCTION

Proton beams are injected into the LHC, at 450 GeV, via the transfer lines TI 2 and TI 8, in the combined experimental and injection insertions IR2 and IR8. The injection system comprises 5 horizontally deflecting septum magnets (MSI) and 4 vertically deflecting kicker modules (MKI) per beam. Any failure of the injection system causes the loss of the beam in a single turn. Typical examples are: wrong machine settings during injection, failures in the extraction from the SPS or in the transfer lines, MKI failures (i.e. BETS [1], erratic or missing kicks, wrong length and timing of the kick, magnet sparks, terminating resistor breakdowns, etc.). A robust interlock system has been put in place to protect the machine in case of injection failures. Tighter interlock thresholds and tolerances are needed when increasing beam intensity. Further passive protection is ensured by the collimators in the transfer lines (TCDI) and in the ring (TDI and TCLI). In particular, the TDI has been designed to withstand the impact of a nominal injection batch (288 bunches). This collimator must be set up correctly to intercept mis-kicked beams that could hit and seriously damage the machine. The TCLIs act as a complement and have to absorb any eventual leakage from the TDI.

2010 OPERATION

The “unsafe beam” limit for the LHC corresponds to $>10^{12}$ protons (10 nominal bunches). A maximum of 48 bunches has been injected during 2010 operation: a factor of 5 above safety. Two examples of failures, when injecting unsafe beam, are presented in the following.

Missing MKI Kick

The protection system prevents the MKI from firing, in case of any fault during extraction from the SPS. On October the 23^{rd}, the Abort Gap Keeper (AGK) stopped the MKI while injecting 32 bunches which, then, impacted on the upper jaw of the TDI. The showers of particles from the TDI induced high losses in IP2 and the dump of the circulating beam.

ALICE experiment is installed in IR2 and LHCb is in IR8. Dedicated simulations were performed, by people from the experiments, to evaluate possible dangers for the detectors when dumping 288 bunches at the TDI. The event presented provided ALICE with an important set of benchmarking data. Further tests were carried out, both for ALICE and LHCb, by changing the delay of the MKI kick, so that the injected beam was grazing on the TDI jaws, and evaluating the leakage at the experiments [2]. According to simulations and test results, no limit is expected on the intensity of the injected beam provided that the TDI is properly set up.

Wrong TCDQ Settings

LHC collimators are movable objects which have to be set up according to rigorous hierarchic rules in order to provide beam cleaning and machine protection. They have to define the smallest machine aperture (6σ = primary collimators half aperture) and follow the adiabatic beam damping during acceleration. One extraction protection collimator (TCDQ) was accidentally moved, trough the ramp function, to the 3.5 TeV settings while still at injection (TCDQ at $\sim 4\sigma$). The interlock system did not record any nonconformity since the thresholds were also changed according to the ramp function. Moreover, no visible loss was observed in the extraction region due to the slowness of the movement and the low intensity of the circulating beam (pilot bunch). The beam was dumped by the losses at the TCDQ when injecting 24 bunches. This incident highlighted the possibility of injecting unsafe beam in a mis-set up machine generating downtime and damage (for example of the tungsten tertiary collimators). Possible solutions to this problem are:

- Implementation of an energy interlock on the minimum allowed gap for collimators. At present, this interlock checks the collimator gap as a function of the energy and gives a fault only if it is bigger than a certain threshold [3].

- On line aperture measurements. This would allow to identify the minimum aperture and highlight eventual anomalies.
- State machine. This function should check any machine component and compare it with well defined references depending on operational conditions, beam process, etc.
- Compulsory re-injection of a pilot bunch after any change in the machine.

In general, the injection system worked as expected. Few failures occurred when injecting unsafe beam and they did not cause any machine damage. These incidents allowed to identify weak points and possible further upgrades of the system and of the injection process. The crucial role played by TDI correct setup in providing the very last protection, in case of any failure, has been highlighted.

INTENSITY LIMITATIONS DURING INJECTION AND POSSIBLE SOLUTIONS

Two main sources of losses were observed which could limit the intensity of the injected beam. Showers of particles, which are generated by the TCDI intercepting the beam tails in the transfer lines, are detected by the ring Beam Loss Monitors (BLM). These showers come from outside the magnet cryostat and do not constitute a danger for the machine, however, they would trigger a beam dump if above BLM thresholds. Losses from TCDI increase linearly with the intensity of the injected beam. A second source of losses is represented by the un-captured beam, from the SPS and the LHC, that is spread onto the TDI jaws. In this case the loss rate depends both on the intensity and the time between two consecutive injections. In both cases any limit in beam intensity is due to operation and not to machine protection issues. It is expected to be able to operate the machine, in 2011, with 108 bunches and to inject up to 144 bunches without mitigation [4]. Possible solutions to mitigate losses from TCDI cross-talks and un-captured beam are presented.

Non Critical

Some mitigation solutions do not present any drawback from the point of view of machine protection. For example, losses from un-captured beam can be reduced with abort gap and injection cleaning, as presented in [5], and by improving diagnostic and beam quality in the injectors. Moreover, the installation of shielding blocks close to the critical regions can help in reducing significantly particles showers. Energy deposition studies showed that an appropriate shielding close to the TDI could reduce the signal at the BLM triplet magnets, in IP2 and IP8, by a factor of 10. Three TCDIs (2 for Beam 1 and 1 for Beam 2) have been identified as critical. Shielding has already been installed in TI2, as illustrated in Fig 1, and is is expected to improve the signal at the ring BLMs by up to a factor of 8. Shielding is more complicated in TI8, due to the small available space, and requires a special support. A factor of 4 gain was calculated for this location.

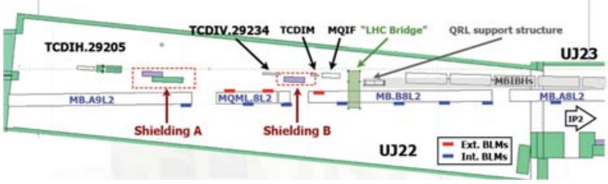

Figure 1: Shielding installed in TI2 to reduce the signal at the BLM in the common region of LHC and transfer line tunnels.

Critical

Supplementary techniques, which could provide a further improvement but might also have an impact on machine protection, are under study.

The TCDIs define a generic single pass protection system and have to provide a full phase space coverage. Due to optics and space constraints, there are only three collimators (double jawed) per plane installed at the end of each transfer line close to the LHC. The settings of these collimators depend on the aperture available for the injected beam. Nominally, the TCDIs are set at 4.5σ to protect a theoretical aperture of 7.5σ. It was shown that a factor of 4 reduction in cross-talks can be obtained by opening the TCDIs by 0.5σ. Moreover, measurements showed that the available aperture is about 10σ but an additional tolerance margin for orbit (2 mm), injection oscillations (1.5-2 mm) and energy offset has to be taken into account. Machine protection validation tests have been performed and showed that the required phase space coverage is obtained with the TCDIs at 5σ. Operation with higher intensity seems feasible with this setting. Further checks are anyhow necessary at the start-up in 2011 and when changing the filling pattern to re-validate the system.

Another promising option consists in the BLM sunglasses. The aim, in this case, is to temporary mask the BLM interlocks affected by cross-talks and un-captured beam losses during injection. A fourth crate should be added to the existing ones and, when receiving the injection pulse event, blind the affected BLMs for a fixed time. This is a critical procedure since the BLMs will be also blind to eventual dangerous losses. Requirements for this system are:

- SIL level equivalent to both BLM and BIS systems
- Fail safe design
- Fixed time-out duration (hard-coded, no remote way to modify it)
- RF pulsed period: maximum repetition rate fixed by hardware

- Cross-check with the energy value
- Remote monitoring of the input and output signals

The definition of the blinding time is crucial since it has to allow the distinction between good and bad injections without compromising machine safety. An example of good injection is shown in Fig. 2 for 36 bunches. The blue line represents the ratio between the losses (black line) and the BLM thresholds (red line) as a function of the integration time. A factor of ten margin between losses and thresholds is required in order to be able to inject a full intensity batch (i.e. blue curve below green line). The signal of the presented BLM should be masked over 80 μs; this is an acceptable time-out since it corresponds to less than 1 turn and the system could not provide any protection for these losses. A full data analysis is ongoing to evaluate if, in case of good injection, the BLM signal stays above thresholds for longer running sums. An acceptable limit for the blinding time has to be defined (320 μs ?). A bad injection is shown in Fig. 3 for a not filtered (top) and a filtered monitor (bottom). A high level of de-bunched beam was in the machine due to an abnormally long waiting time between two consecutive injections. As expected in case of bad injection, the factor of 10 margin is obtained after a considerably long integration time: 655 ms. Filtered monitors need a longer period for collecting the charges and they should not be connected to the sunglasses crate since they would increase the required blinding time.

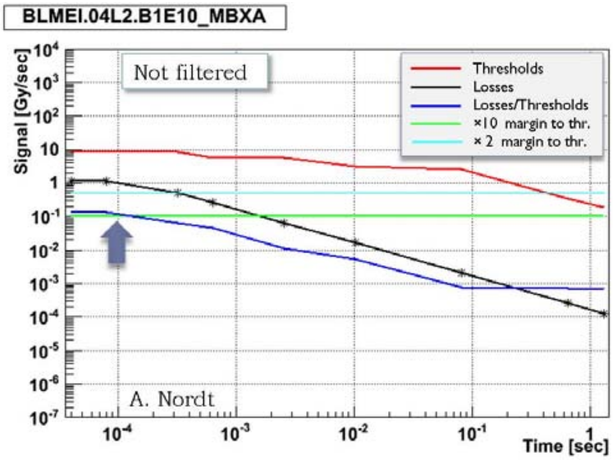

Figure 2: An example of good injection of 36 bunches is shown.

In total one expects that about 20-30 BLMs should be connected to the new crate (BLM families: TCTVB, MQX, MBX, TCLI, TDI, MQ6, MQ7, MQ8, MSIA and MSIB). The question if it is possible to profit of redundancy from other BLMs, located nearby the masked ones or in the cleaning insertions, to guarantee the required protection in case of losses is addressed. In addition, the possibility of increasing the BLM thresholds for short running sums is considered. The studies presented are very preliminary and effectiveness and reliability of this solution have to be fully probed. A machine protection review will be made after the completion of these studies before eventual implementation and commissioning of the sunglasses (middle/late 2011).

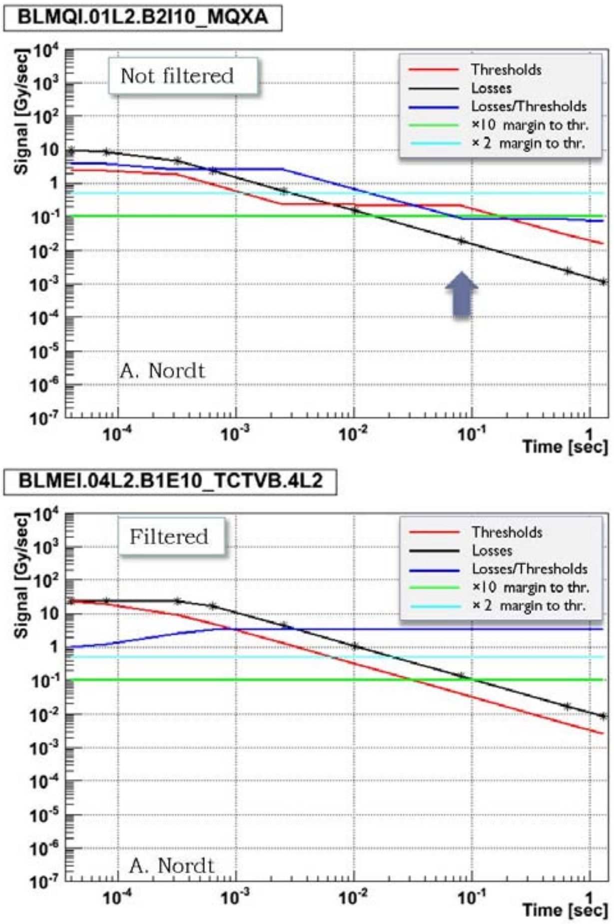

Figure 3: An example of bad injection of 32 bunches is shown for a not filtered (top) and a filtered (bottom) monitor.

INJECTION SYSTEM UPGRADE

The main change applied to the injection system, during the Christmas technical stop, concerned the position interlocks logic for the injection protection collimators. According to the old logic, common to all the LHC collimators, any jaw movement outside position thresholds would have been stopped inducing an injection inhibit (for TDI, TCLI and TCDI). The collimators have to be moved, for mechanical and operational reasons, during the nominal machine cycle. In particular, TDI and TCLI have to be open to parking position after injection, before the start-up of the energy ramp. This action required to open also the position thresholds to parking with the consequent risk of injecting the beam with the injection protection collimators not correctly set up. The new logic allows to move these collimators outside thresholds, but it prevents the movement of TDI and TCLI into the circulating beam. In this way, thresholds can be kept at injection setting, collimators can be moved according to the operational needs and any injection will be inhibit in case of wrong setup. Moreover, an energy interlock has been implemented, for TDI and TCLI, that forbids injection if the measured gap is bigger than defined thresholds. A software interlock has been introduced that force the MKI to standby before opening the TDI and TCLI. This ensures that the beam is dumped at the TDI in case of an erratic MKI kick.

A new interlock will be added to control injection oscillations when injecting high intensity beams. In particular, in case of bad injection oscillations, it will be possible only to inject an intermediate intensity. A new high intensity injection will then be allowed as soon as good oscillations will be recorded. The implementation of this interlock requires testing and stability of the Injection Quality Check (IQC) module and beam commissioning time.

CONCLUSIONS

The fundamental importance of a correct machine status during injection has been discussed in this paper. In particular, injection protection collimators have to be properly set up to provide the required passive protection also in case of failures of other systems (for example MKI). The LHC ran already with unsafe beam in 2010, and a limit of 144 bunches is expected for 2011 operation. No limitation in intensity is foreseen to come from LHCb and Alice, which are ready for 288 bunches dumped on the TDI. Predicted intensity limitations come mainly from operational more than machine protection related issues. Possible uncritical an critical solutions to go to higher intensity have been presented. The upgraded and safer logic applied for the operation of injection protection collimators has been described. The principles for an interlock on injection oscillations have been introduced.

ACKNOWLEDGMENTS

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IS THERE A LIMITATION TO THE STORED BEAM ENERGY FOR 2011 AND BEYOND?

R.Schmidt, CERN, Geneva, Switzerland

Abstract

The machine protection systems have been designed to ultimately operate with beams of a stored energy of 360 MJ. This presentation will address if there is an intermediate limit and what upgrades are required to permit operation with 360 MJ. A failure in one of the protection systems (BLM, BIC, LBDS, …) could have catastrophic consequences for LHC. Considering the operational experience, the most critical failure modes are reviewed, their probability is estimated and methods for mitigation are discussed. Ideas for reducing the risk include additional interlocks (DIDT interlock, abort gap cleaning/monitoring, fast BLMs, additional BPMs as HW interlock, aperture measurements,…), operational procedures and upgrades of hardware systems. There are also examples when the beams should NOT be dumped immediately.

LIMITATION TO THE STORED BEAM ENERGY?

For the run in 2011 and 2012 there should be no limitation for the stored energy with 75 ns or 50 ns filling schemes.

- Beam Interlock System: no dependence on the stored beam energy
- Beam Dumping System: No dependence on stored beam energy, but on energy [1]
- Beam Loss Monitors: No dependence on stored beam energy, but on energy [1]
- Beam Absorbers and Collimators: dependence on stored beam energy for the TCDQ that needs an upgrade for operation with nominal beam and 7 TeV. Assuming operating at 3.5…4.0 TeV with up to 900 bunches there should be no limitation. The exact limit is being assessed and an upgrade is being studied.

SAFE FOR THE FUTURE?

In the following the question is addressed if operation is expected to be safe in the long run and what improvement are recommended. The most critical mechanisms for failures are considered, and the risks at injection and with stored beam are analysed, for the principle protection systems: Beam Dumping Systems, Beam Interlock System, Safe Machine Parameter Systems, Injection Systems, Beam Loss Monitor System and Collimators / Beam Absorbers. Failures in other systems are not discussed here (SIS, FMCM, PIC, WIC, QPS, …).

FAILURE SCENARIOS

There are only very few mechanisms for single turn failures where the beam is deflected into the aperture within a single turn. This can happen at injection energy:

- the beam is not correctly injected
- the circulating beam is deflected because of a failure in the injection kickers system

This can also happen after start of the energy ramp:

- the injection kicker might fire
- there could be a failure when dumping the beams

There are no other known failure mechanisms that would lead to a single turn failure.

For multi turn failures many mechanisms cause a loss of beam. There is a lot of experience from 2010. The machine protection was designed with the fastest failures anticipated after a trip of a power converter for normal conducting magnets (typically D1). Such trips are detected with the FMCM (Fast Magnet Current Change Monitor) that worked very well in 2011. Another mechanism for fast beam losses was not predicted: UFOs lead to a loss of a small part of the beam within <1ms – 10ms [2]. It is assumed that these losses are caused by small particles inside the beam pipe.

RISKS

At 7 TeV with nominal beam parameters the energy stored in the beam is 360 MJ, and at 450 GeV about 28 MJ. Other parameters important for the assessment of damage is beam emittance and bunch pattern (although less relevant for major damage). The repair of damage after a serious failure will take a few days to many months. It cannot be excluded that there is damage beyond (reasonable) repair.

Occasional magnet quenches should be avoided, but are normally not considered as a major risk for LHC. However, before the interconnections of main magnets are consolidated, quenches at collision energy are critical. A quench close to a splice with insufficient copper stabilisation could lead to a thermal runaway, and an opening of the splice.

Failures of machine protection systems have been addressed several times [3,4,5]. Here a fresh look is presented, in light of the experience gained during 2009 and 2010 and new tools and simulation results.

INJECTION FAILURES

The duration of an injection kicker pulse is such to deflect maximum one batch with 288 bunches. The maximum number of injected bunches is 288. The energy of one batch (288 bunches) injected into LHC with nominal beam parameters is 3 MJ. With 3 MJ, damage beyond repair is unlikely. This is shown with data from a SPS failure during extraction at 450 GeV on 25th of October 2004: the septum magnet power supply tripped during high intensity extraction. This caused damage of the beam pipe and a quadrupole magnet, when extracting one full nominal batch $3{\cdot}10^{13}$ (grazing incidence). This was very annoying, but not catastrophic. In LHC such incident would be more serious if this happens in superconducting section, but not lead to damage beyond repair.

However, after such incident the availability of spares could be an issue, depending on what is damaged by beam impact. Two questions:

- What are the most likely failure scenarios?
- If equipment is damaged, do we have spares?

CRITICAL FAILURES

The criticality of the different systems is addressed by considering the most likely serious failures and consequences.

- Most critical are failures of the Beam Dumping Systems and Beam Interlock System that could lead in the worst case to damage of LHC equipment and experiments beyond repair.
- Failures of the Injection Systems, the Beam Loss Monitor System, the Safe Machine Parameter System, Collimation and Beam Absorbers for injection and beam dump protection could lead to damage that requires repair for many month (damage similar to the 19/9/2008 accident).
- For other collimators, failures would most likely lead to damage that take days to a few weeks to repair.
- Systems like SIS and FMCM: failures critical in combination with other failures are critical and could lead to serious damage.

DETECTING FAILURES WITH CIRCULATING BEAM

The detection of failures and dumping the circulating beams worked very well during the past year(s). The detection of beam losses with BLMs showed high level of redundancy. In general, after beam loss, several BLMs trigger a beam dump and protection does not rely on the correct operation of a single BLM. Very fast failures (UFOs) were detected in time and beam losses remained below quench limit. There was no accidental quench with circulating beams.

Failures in the electrical distribution were efficiently detected by Fast Magnet Current Change monitors (FMCM). In case of a failure the beams were always dumped before the beam was affected.

In some cases failures other monitors detected the failure before any beam loss occurred (e.g. BPMs, …).

SERIOUS FAILURE IN A PROTECTION SYSTEM

Beam Loss Monitor System

A complete failure of the BLM system is very unlikely but not impossible, since the correct functioning relies on complex programming in FPGA and all monitors having the same code.

The thresholds for BLMs could be too high, e.g. due to a wrong transmission of the energy or due to a major problem in the threshold tables. This is not expected to be catastrophic, since many thresholds are independent of energy, for other thresholds the change with energy is not very large. Still, all efforts should be done set the thresholds correctly.

In all cases when the beam was dumped by BLMs, beam losses are also visible at the primary collimators in IR7 (TCP) and/or at the secondary collimators in IR (TCSG). If the beam would not be dumped and losses would further increase, the threshold of these monitors would be exceeded.

If the beam loss monitor would not detect the failure, beam losses would quench a magnet and the QPS would dump the beam via the Powering Interlocks (PIC) and Beam Interlocks (BIC). This takes about 10 ms and would dump the beam in time for most failures, but not all.

Beam Interlock System

The most serious failure mode is if the system does not transmit the beam dump request to the beam dumping system (despite two/four fold redundancy). Beam would be lost due to orbit movement at collimators, possibly destroying the entire collimation system and leading to massive magnet quenches. It cannot be excluded that the LHC would be damaged beyond repair. The mitigation for such failure is to trigger the beam dump using a link to the beam dumping system that does not use the Beam Interlock System.

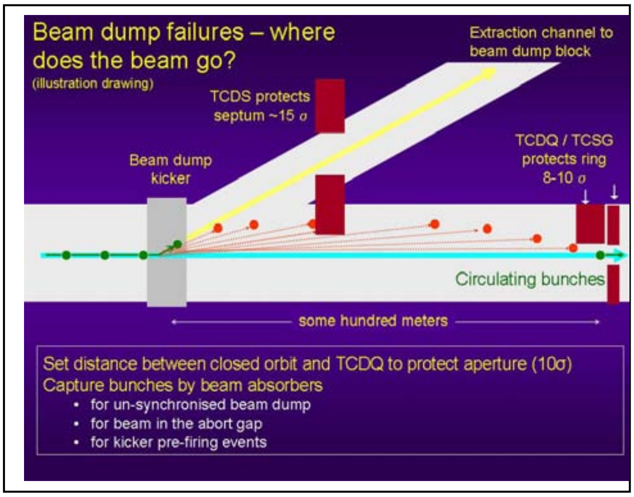
Mitigation

It is proposed to commission the already installed “direct BLMs” in IR6. These beam loss monitors are installed close to TCDQ / TCSG and have a direct link to the Beam Dumping System. From 2009 data, it should be possible to derive the thresholds.

The interface between Beam Interlock System and Beam Dumping System is highly critical. A redundant triggering of kicker magnets by the Beam Interlock System via an additional channel is considered. The signal would enter into the retriggering branch of the TSU unit and result in an asynchronous beam dump. Such signal must be delayed in order to ensure that the normal trigger comes first.

The time between the interlock generated by the Beam Interlock System and the beam dump should be measured with high accuracy.

Fast Beam Current change Monitor will become operational during this year. Such monitors were used successfully for many years during HERA operation. In case the beam loss monitors do not detect significant loss of beam, these monitors would trigger a beam dump.



Beam dump failures – where does the beam go?

(illustration drawing)

Set distance between closed orbit and TCDQ to protect aperture (10σ)

Capture bunches by beam absorbers

- for un-synchronised beam dump
- for beam in the abort gap
- for kicker pre-firing events

BEAM DUMP KICKER FAILURES

Beam Dump Kicker not firing

In Chamonix 2009 B.Goddard addressed two questions [6]:

"What do we do if the dump doesn't react to a programmed request?" In the case of a dump requested by operation, there is still time to react, and it is suggested to work out a procedure for operation what to do in some case.

"If dump fails to fire after an interlock, beam will probably already be long gone. How much of LHC machine will also be gone?" Depending on the stored beam energy, massive damage is expected.

With the operational experience, progress in simulation work and the future tests at HiRadMat it should be possible to address this problem quantitatively. The simulation studies require the coupling of programs such as FLUKA (for calculating the energy deposition into material) and BIG2 (or possibly ANSYS-AUTODYN) to calculate the hydrodynamic response of the target, as already done in the past [7]. Code validation experiments at HiRadMat (interaction of SPS beam with targets, such as collimators) are planned.

Other risks during beam abort

One of the failure modes that should not lead to any damage is an asynchronous beam dump with high intensity beams. There are several conditions required for a correct beam dump, in order of importance:

- The Beam dump kickers must deflect the beam with the correct angle. This is the most serious failure.
- The TCDQ / TCS absorbers must be at the correct position and beam must be centred between TCS jaws.
- Large orbit bumps around the LHC must be avoided.
- Other collimators must be at the correct position.

Most bunches will hit the TCDQ. Although this absorber was designed for such impact, a procedure should be developed to validate the integrity of this object. The correct position of the TCDQ / TCS assembly with respect to the orbit is of the utmost importance for LHC machine protection.

The closer the TCDQ is to the beam orbit, the better for protection in case of serious failure, but also for asynchronous beam dumps. The control of the horizontal beam position in the TCQD / TCS is very important. However, the TCDQ should not violate the collimation hierarchy for keeping the required cleaning efficiency.

Can The CDQ / TCSG absorbers move closer to the beam? A test is suggested. An interlock of the TCDQ position with respect to the beam using a solution based on hardware and the BETS (energy information) is proposed.

Beam dump kicker deflects beam with wrong angle

A deflection of the beam by a small angle is most dangerous (deflection by 5-10 σ), since the deflected beam can affect equipment in the entire machine. It could lead damage of the collimation system and to damage of other equipment.

Such wrong deflection could be due to a failure of the energy tracking system, e.g. the beam is deflected with a strength corresponding to 450 GeV, instead of, say, to 3.5 TeV or 7 TeV.

Another failure mode is a fault of the retriggering system and only one kicker magnet fires. An improved automatic test system is under development.

The TCDQ / TCSG absorbers could help to mitigate the consequences in case of such serious failures of the beam dumping system. In a future upgrade of the TCDQ the robustness of this absorber might be increased.

Massive beam impact

In the worst case, all bunches would be deflected into equipment. The challenge is to calculate the impact of 2808 bunches as function of time. During the impact, the material vaporises. Simulation results show that a 7 TeV nominal beam would tunnel through 25-30 m of copper. In the case of a graphite target, most of particles would be stopped by a graphite absorber of about 10 m length. The validation of the codes is planned with an impact experiment at HiRadMat.

OTHER SHOWSTOPPERS FOR HIGH STORED BEAM ENERGY?

When increasing the stored beam energy there are several effects to be watched out for:

- Single event upsets
- EMC effects might appear with more bunches / other bunch patterns
- UFOs: it might be required to increase the thresholds of the beam loss monitors and this could

increase the number of quenches. A compromise has to be found since a quench has a (small) risk of triggering a thermal runaway of a high current splice and lead to rupture.

- Beam instabilities: how fast can the beam become unstable? Is the phase coverage by collimators for losses that happen in a few turns sufficient? For the time being, there is no indication that we must worry…

Reviews on machine protection were very useful. From past reviews in general the recommendations were followed, sometime later than recommended by the reviewers. Later this year another review might be organised.

PROPOSALS

1. Mitigation of serious failure modes of BLM and BIC: direct BLM to be connected to Beam Dumping System using BLMs close to TCSG in IR6. This can be done soon. Later, possibly BLMs close to TCP in IR7 could be linked directly to the beam dump in the future.
2. Fast Beam Current Change Monitor should be made operational soon.
3. Mitigation of serious failures of Beam Dumping System: write procedure for CCC, what to do if an operators requests a beam dump, and it does not work.
4. A redundant triggering interface between BIC and LBDS should be considered.
5. TCDQ / TCS positioning to be improved (e.g. energy tracking).
6. Buttons to measure the beam position should be directly installed in beam absorbers would increase the level of protection, ensuring that the beam is always centred. The TCSG and TDI are prime candidates to be equipped with buttons.
7. The TCDQ consolidation should takes into account studies of beam tunnelling simulations (can the TCDQ stop the full beam with minimum consequences?)
8. Study consequences of catastrophic failures with simulation programs (MAD, SIXTRACK, FLUKA, AUTODYN).
9. Do we have sufficient pares for possible damage due to the most likely failure modes?
10. It possible, software interlocks should move towards hardware interlocks.
11. Injection: make sure that TDI is at the correct position.

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EXPERIMENTS’ EXPECTATIONS

M. Ferro-Luzzi, CERN, Geneva, Switzerland

Abstract

An overview of the requests from the experiments for 2011 will be given. This will include integrated luminosity considerations, special runs and special beam conditions. The 2011 run schedule is discussed.

INTRODUCTION

The LHC 2010 physics run was presented in details elsewhere [1]. In brief, the LHC produced first pp physics collisions at $\sqrt{s} = 7$ TeV in March 2010, starting with a luminosity of about $8 \cdot 10^{26}$ $\mathrm{Hz/cm^2}$ and finally reached $2{\cdot}10^{32}$ $\mathrm{Hz/cm^2}$ in October 2010, thus brilliantly surpassing the target. The experiments took advantage of the gradual luminosity increase to step through (i) calibration of the detectors, (ii) “re-discovery” of particle physics (quarkonia, weak bosons, top quarks, ...), thus gauging the level of understanding of their detectors, and finally (iii) to actually produce physics results [2]. The integrated delivered luminosities (2010 totals) were approximately $48\ \mathrm{pb}^{-1}$ (IP1), $0.5\ \mathrm{pb}^{-1}$ (IP2), $47\ \mathrm{pb}^{-1}$ (IP5) and $42\ \mathrm{pb}^{-1}$ (IP8).

The end of 2010 was devoted to a first Pb run (with LHCb switched off). In this case, the luminosity was increased from $3{\cdot}10^{23}$ $\mathrm{Hz/cm^2}$ to $3{\cdot}10^{25}$ $\mathrm{Hz/cm^2}$. The integrated delivered luminosities were approximately $9.9\ \mu\mathrm{b}^{-1}$ (IP1), $9.3\ \mu\mathrm{b}^{-1}$ (IP2) and $9\ \mu\mathrm{b}^{-1}$ (IP5).

In total, the LHC operated 1074 hours in `STABLE BEAMS` (851 hours with p and 223 hours with Pb) out of about 6600 hours. There were 147 fills with `STABLE BEAMS` (110 with p and 37 with Pb). Yearly summary plots for peak luminosity and integrated luminosity are available at the LHC Programme Coordination web site [3].

An important parameter for 2011 projections is the overall efficiency of the machine for luminosity delivery. Figure 1 shows that, when operation was dedicated to luminosity delivery (like in August and November 2010), about 30% of the scheduled time was actually spent in physics collisions. In 2011, approximately 135 ± 10 days will be dedicated to 3.5 TeV high luminosity physics operation [4]. Thus, for 2011 projections, one could expect at least 970 ± 70 h of `STABLE BEAMS` in the proton run (and 190 h in the Pb run).

Next, we discuss the main expectations from the experiments for proton operation, the special requests for proton operation, and the expectations for the heavy ion (HI) run.

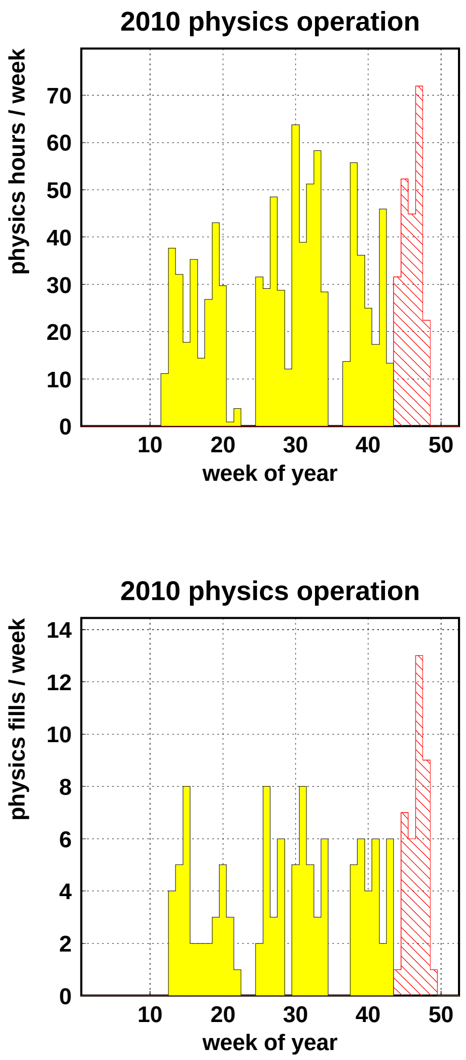

Figure 1: Overview of 2010 proton run. The top (bottom) graph shows the number of fills (hours) of `STABLE BEAMS` per week. Shaded (yellow) histogram: proton run. Hatched (red) histogram: ion run.

PROTON RUN: 2011 EXPECTATIONS

The goals for 2011 proton running have been set a year ago, namely to deliver an integrated luminosity of at least $1\ \mathrm{fb}^{-1}$ to each of IP1, IP5 and IP8. Given the excellent results obtained in 2010, a substantially larger integrated luminosity can probably be achieved for IP1 and IP5. However, for IP8 the task is more challenging, as will be discussed below.

Highlights of the ATLAS and CMS physics potential, in particular concerning the Higgs discovery reach or exclusion limits, have been updated by the experiments and presented elsewhere [5]. Assuming 3.5 TeV beam energy, with about $2.5\ \mathrm{fb}^{-1}$ ATLAS and CMS can each independently exclude at 95% CL the Standard Model (SM) Higgs with any mass. With about $6\ \mathrm{fb}^{-1}$ ATLAS and CMS can each independently obtain a 3σ observation from the LEP bound (≈ 115 GeV) to about 500 GeV.

The LHCb potential was also reminded [5]. Illustratively, with $1\ \mathrm{fb}^{-1}$ LHCb can exclude at 95% CL the FCNC[1] rare decay $B_s \to \mu^+\mu^-$ branching ratio down to about $6\cdot10^{-9}$, leaving little room for hypothetical enhancements of this decay by New Physics, such as supersymmetry. A signal above the SM value ($5 \cdot 10^{-9}$) and below the current Tevatron limit ($\sim 37 \cdot 10^{-9}$) could also be discovered by LHCb and open a door on New Physics territory.

Naturally, the main wish of ATLAS, CMS and LHCb is to obtain the largest possible integrated luminosity. For ATLAS and CMS, this can be planned without any limitation on pile-up other than the design values (which are probably beyond reach for 2011), while for LHCb the pile-up should be limited, as discussed below. In general, for the same reach in integrated luminosity, acquiring physics data with less pile-up is more favorable. This statement is valid for all experiments. Therefore, once good conditions with trains have been established (with the maximum number of long-range encounters for the chosen bunch spacing), a rapid increase of the number of bunches to the maximum possible is desirable (to about 900 for 75 ns spacing or about 1400 for 50 ns spacing).

As a reminder, the luminosity and average number of interactions per crossing are given by

$$\begin{aligned} L &= n\ f_{\mathrm{rev}}\ \frac{N^2\ S\ \gamma}{4\pi\ \varepsilon_N\ \beta^*} \\ \mu &= \sigma_{\mathrm{inel}}\ \frac{N^2\ S\ \gamma}{4\pi\ \varepsilon_N\ \beta^*} \end{aligned} \tag{1}$$

where N is the bunch population, n the number of bunch pairs colliding at the given IP per LHC turn, ε_N the normalised transverse emittance, $\gamma = 3.5\ \mathrm{TeV}/0.938\ \mathrm{GeV} \approx 3730$ is the Lorentz factor, β^* the optics function at the given IP, $f_{\mathrm{rev}} = 11245$ Hz is the LHC revolution frequency, σ_{inel} is the inelastic cross section and S is a reduction factor which includes effects due to the local geometric parameters: the crossing half-angle α, the ratio of the longitudinal and transverse beam sizes (in the local crossing plane), and a possible transverse separation d_w along the transverse axis $w = x$ or y.

In October 2010, the LHC was routinely operated with 368 bunches of nominal bunch population ($1.15 \cdot 10^{11}$) and low emittance ($\sim 2.5\ \mu$m). In 2011, a factor 2.3 from the lower β^* (1.5 m) in IP1 and IP5 can be expected, and a factor of 2.6 or more from the increased number of colliding pairs (900 or more, as opposed to 348). Therefore, from the 2010 experience, and if e-cloud scrubbing facilitates 75 ns operation with 900 bunches or more [6], a peak luminosity of $L = 10^{33}\ \mathrm{Hz/cm^2}$ in IP1 and IP5 seems within reach. The average number of inelastic interactions per crossing would be $\mu \approx 7.3$, a value still perfectly acceptable for ATLAS and CMS which were designed for $\mu = 25$ to 30. With such luminosity, one can expect delivering $26\ \mathrm{pb}^{-1}/10$ h (this includes a factor of 0.7 for luminosity decay) and $2.5\ \mathrm{fb}^{-1}$ in 970 h. A rapid L increase to the "reasonably expectable" value is important, since every week lost for intensity ramp-up will imply a loss of integrated luminosity at the end of the year (when peak luminosity will be maximal, perhaps even in excess of $10^{33}\ \mathrm{Hz/cm^2}$). This could be a loss of as much as $0.2\ \mathrm{fb}^{-1}$ per week.

An important difference with 2010 operation is that the high luminosity LHC experiments have already recorded more than $45\ \mathrm{pb}^{-1}$ of data at $\sqrt{s} = 7$ TeV. Therefore, any operation at a luminosity of less than $\sim 2 \cdot 10^{32}\ \mathrm{Hz/cm^2}$ will contribute negligibly to the total integrated luminosity. For illustration, operation with 100 bunches (i.e. $1.1\cdot10^{32}\ \mathrm{Hz/cm^2}$) would deliver $2\ \mathrm{pb}^{-1}$/day (this includes a factor 0.7 for luminosity decay and 0.3 for the time fraction in `STABLE BEAMS`). Under the same assumptions but with 900 bunches, luminosity delivery would go at a pace of $18\ \mathrm{pb}^{-1}$/day. These numbers are to be compared with $\sim 45\ \mathrm{pb}^{-1}$ (on tape) and $\geq 1000\ \mathrm{pb}^{-1}$ (2011 base target).

Thus, there is no request for physics operation with 50 to $\lesssim 300$ bunches. Ideally, the 2011 intensity ramp-up should be reduced to the minimum required for safe machine operation (i.e. recommissioning and machine protection validation).

The case of IP8 - LHCb

LHCb has been designed for a luminosity of around $2 \cdot 10^{32}\ \mathrm{Hz/cm^2}$ and an average number of inelastic interactions per crossing μ of 0.4 to 0.5. In 2010, the LHCb Collaboration (successfully) deployed important efforts to cope with an increased pile-up, in order to maximize the recorded luminosity. A peak luminosity close to the LHCb design luminosity was achieved with 344 colliding pairs, instead of the nominal 2622 colliding pairs. This means that LHCb was able to take good data with $\mu \approx 2.5$ to 3, i.e. a factor 6 beyond the original design value. For 2011, not much further "stretching" of the LHCb detector capability can reasonably be expected.

For 2011, LHCb wishes to have the following luminosity and maximum average number of interactions per crossing

$$L_{\mathrm{lhcb}} \approx 3 \cdot 10^{32}\ \mathrm{Hz/cm^2} \tag{2}$$

$$\mu_{\mathrm{lhcb}} \lesssim 2.5\ . \tag{3}$$

The luminosity limit is probably a softer limit than the pile-up limit and could slightly increase with experience. From these requirements, and assuming an inelastic cross section of $\sigma_{\mathrm{inel}} = 72$ mb, one can derive

$$n_{\mathrm{thr}} = \frac{L_{\mathrm{lhcb}}\ \sigma_{\mathrm{inel}}}{\mu_{\mathrm{lhcb}}\ f_{\mathrm{rev}}} \approx 770 \tag{4}$$

---

[1] Flavor changing neutral current.

where $n_{\rm thr}$ is the "threshold" value of the number n_8 of bunch pairs colliding in IP8 below which it is not possible to deliver a constant luminosity $L = L_{\rm lhcb}$ without exceeding the pile-up limit (3).

Assuming 970 hours of `STABLE BEAMS`, a start-of-fill luminosity of $L_{\rm lhcb}$, and *no* luminosity leveling, one obtains an integrated luminosity of at most $0.73\ {\rm fb}^{-1}$ (an overall factor of 0.7 was applied to take into account the luminosity decay). With luminosity leveling, an integrated luminosity of just about $1\ {\rm fb}^{-1}$ is possible.

Two methods of luminosity leveling were considered. The first one would use a range of (decreasing) values of β^* during an LHC fill, with beams colliding head-on. The second one would use a sufficiently small β^* and adjust the vertical beam separation during the fill (reducing the separation as the value of N^2/ε_N decays). The first method seems a more favorable solution for long term, but requires substantial developments and involves a number of machine protection issues. The second method is operationally much simpler and was already successfully applied in 2010 to IP2 (ALICE, horizontal separation) from July to October. It was also tested in two occasions at IP8 (with 150 ns and 50 ns) and implicitly tested at each luminosity optimisation or Van der Meer scan at all IPs. No significant instability or beam loss associated with beam separation could be evidenced in 2010, despite the nominal bunch intensity and the lower than nominal transverse emittances. The interpretation of this "robustness" of the LHC beams was discussed elsewhere [7], where it was also recommended to study further beam-beam effects (and the beam-beam limit) in the presence of long-range encounters.

Based on the above arguments, it is proposed to use the beam separation method in 2011 to level the luminosity in IP2 and IP8. The β^* for IP8 is to be chosen small enough that leveling to constant luminosity $L = L_{\rm lhcb}$ is possible throughout a full fill once sufficient bunches are colliding at IP8 ($n_8 \geq n_{\rm thr}$). Early beam-beam tests in 2011 should clarify the validity range of the beam separation method for luminosity leveling, a topic also important for future operation of LHC (HL-LHC).

We will use the approximation

$$S = \left(1 + (\frac{\sigma_z}{\sigma_x}\ \tan\alpha)^2\right)^{-1/2} \cdot e^{-\frac{d_y^2}{4\sigma_y^2}} \tag{5}$$

where σ_z and $\sigma_{x,y}$ are the longitudinal and transverse beam sizes, which are each assumed here to be identical for the two beams ($\sigma_{z,1} = \sigma_{z,2}$, $\sigma_{x,1} = \sigma_{x,2}$ and $\sigma_{y,1} = \sigma_{y,2}$), and a crossing in the x-z plane was assumed (like in IP8). For a crossing in the y-z plane (like in IP2), the x and y indices should be exchanged.

Figure 2 shows the required separation d_y in IP8 (in units of the local beam size σ_y) as a function of N^2/ε_N for two example values of β_8^*. As long as the number n_8 of colliding pairs in IP8 is less than $n_{\rm thr} \approx 770$, the pile-up requirement (3) limits the luminosity at LHCb. Luminosity leveling by y-separation can be used to keep $\mu \leq 2.5$.

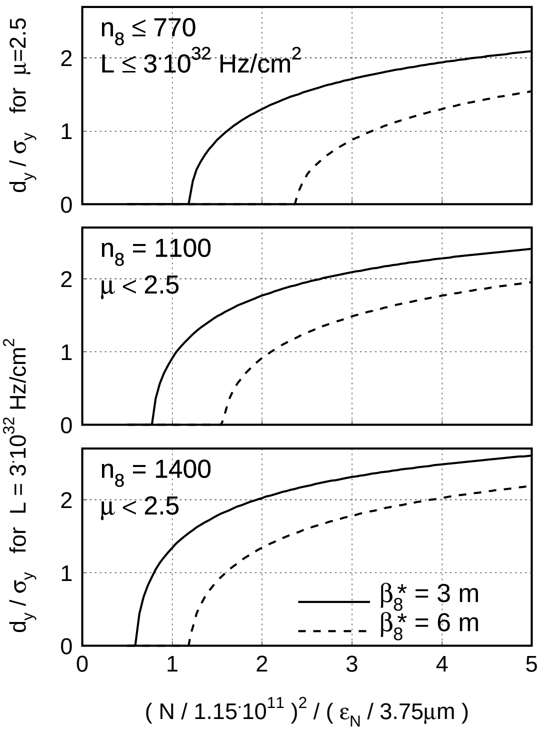

Figure 2: The top graph shows, as a function of N^2/ε_N, the required beam separation at IP8 for the initial phase of 2011 ($n_8 \leq 770$) with constant pile-up and a luminosity still below what LHCb can operate with. The middle (bottom) graph shows the required beam separation at IP8 when $n_8 = 1100$ (1400) with constant luminosity and reduced pile-up.

When n_8 exceeds $n_{\rm thr}$, the luminosity can be kept as close as possible to the LHCb requirement (2). Note that the luminosity is sub-optimal (i.e. $L < L_{\rm lhcb}$) whenever N^2/ε_N is smaller than the value for which $d_y = 0$. The 2011 start-up value for N^2/ε_N is expected to be 2 times larger than nominal ($N \approx 1.2 \cdot 10^{11}$ and $\varepsilon \approx 2.5\ \mu$m [4]) and will be further pushed up during the year. Assuming that the parameter N^2/ε_N decays by a factor 2 during a fill, one should ideally choose a β_8^* value such that the required separation never falls to zero. From figure 2, the choice $\beta_8^* \approx 3$ m seems appropriate.

The strategic choice to use luminosity leveling by beam separation at IP8 relies on the assumption that this technique will function for the values of bunch population, tranverse emittance and fill patterns that can reasonably be foreseen for 2011. If the limits of this leveling technique were to be found in the course of 2011, a fall-back solution would have to be considered (like β^* leveling).

Hereabove, it was argued that $1\ {\rm fb}^{-1}$ could be delivered to IP8 if luminosity leveling is efficiently used. This estimation assumes 970 hours of physics collisions at $3{\cdot}10^{32}\ {\rm Hz/cm}^2$. This luminosity can only be reached once the LHC machine collides at least 770 bunches at IP8. Before this point, the luminosity will be limited by the pile-up constraint. Therefore, utilization of luminosity leveling and a rapid increase of the number of bunches are crucial for meeting the target of $1\ \mathrm{fb}^{-1}$ delivered to IP8.

The case of IP2 - ALICE

It is reminded that pp physics is an integral part of the ALICE physics programme. Similar to last year, the ALICE Collaboration would like to operate at a luminosity L_{alice} ranging from $5 \cdot 10^{29}\ \mathrm{Hz/cm^2}$ to $5 \cdot 10^{30}\ \mathrm{Hz/cm^2}$ and with $\mu \leq 0.05$. This will be achieved by not squeezing IP2 ($\beta_2^* = 10$ m) and separating the beams in the horizontal direction. With 75 ns operation most bunches collide in IP2. With 50 ns (and 150 ns) operation, a few bunches are specially arranged to give collisions in IP2. For $L_{\mathrm{alice}} = 5 \cdot 10^{30}\ \mathrm{Hz/cm^2}$, the required separation d_x will generally be driven by the pile-up constraint and will range from 3.2 to $3.8\ \sigma_x$. Such luminosity can be achieved with 75 ns spacing and several hundreds of bunch pairs colliding in IP2 ($n_2 \geq 640$) while keeping $\mu \leq 0.05$. For $L_{\mathrm{alice}} = 5 \cdot 10^{29}\ \mathrm{Hz/cm^2}$ and many bunch pairs colliding at IP2 (e.g. 900), the required d_x may be as high as $\sim 4.8\ \sigma_x$.

Spectrometer magnets

The ATLAS and CMS magnets will be operated with the same (fixed) value and sign as in 2010. For LHCb, the external angle will be kept constant and the internal angle is fully compensated by corrector magnets. Only one set of TCT positions needs to be prepared and validated. In the case of ALICE, since the external angle sign will change when the internal angle is reversed, the TCTs must be set up and validated for each polarity independently. In addition, in IR2 the combined effect of the solenoid and dipole cannot be fully compensated by the dipole correctors. This effect needs to be taken into account and, ideally, its impact on ease of polarity reversal should be minimized.

The ALICE and LHCb Collaboration would like to collect the same amount of data with each spectrometer polarity for each set of physics conditions. Therefore, minimizing the number of changes in physics conditions will reduce the number of requested reversals. During 3.5 TeV high luminosity LHC operation, the frequency of polarity reversal is expected to be of the order of once per month.

It was pointed out that, if the emittance is adequately chosen, a mode of operation can be found which allows one to constantly keep the LHCb spectrometer magnet at nominal value [8]. LHCb would much prefer such a solution, since it minimizes the fatigue imposed on the magnet and increases its life time.

Non-colliding bunches

Experiments are generally interested in having at least one bunch per beam that does not collide at their IP. This allows them to monitor background conditions and, possibly, disentangle different sources of background. The collisionless time around the arrival of the non-colliding bunch needs to be long enough (exact time yet to be specified, but typically from 0.1 to 1 μs). Such a feature can be incorporated by shifting one or two SPS batches, or by adding an isolated bunch.

PROTON OPERATION: SPECIAL REQUESTS

A “special request” means here a request for operation outside the 2011 parameter envelope that will be used for luminosity production at a center-of-mass energy $\sqrt{s} =$ 7 TeV. Here, all special requests from the experiments are outlined.

Intermediate energy run

A pp center-of-mass energy $\sqrt{s} = 2.76$ TeV corresponds to the nucleon-nucleon equivalent of Pb-Pb collisions at $\sqrt{s} = 7\ Z$ TeV, and is of particular interest for the HI community. The ALICE Collaboration has requested a proton run at $E = 1.38$ TeV to be scheduled as soon as possible, in order to allow them a combined analysis of the 2010 Pb data and $\sqrt{s} = 2.76$ TeV pp data. This request was strongly supported by the LHCC and approved by the Research Board. ALICE requires 35 h of `STABLE BEAMS` at an inelastic interaction rate at IP2 $R = \mu\ n_2\ f_{\mathrm{rev}}$ of 3 to 10 kHz. This will allow them to collect the requested 50 million events. The average number of interactions per crossing should not exceed 0.05. From this, one can derive that the number of colliding bunch pairs at IP2 should be larger than 5.

The setup time for this run was estimated to be about three 8 h shifts [9]. The main steps are: a test ramp and dump with a probe bunch, and 2 or 3 fills for loss maps (collimator settings validation and asynchronous dump test).

The other experiments will also take data during this special physics run. The physics programme of ATLAS and CMS concentrates on hard probes (“rare” events). For this reason, ATLAS and CMS would like to run at the maximum possible luminosity achievable without extra setup time. For CMS the physics programme would be well covered with about $300\ \mathrm{nb}^{-1}$ (at this level, the statistical uncertainties would match those of the 2010 Pb data sample). Similarly, ATLAS would like to record at least $100\ \mathrm{nb}^{-1}$ and take a small data sample with low pile-up ($\mu < 0.01$), which could be arranged either by keeping a probe bunch or by separating the beams in IP1 for part of the running time. The LHCb Collaboration wishes to record at least $25\ \mathrm{nb}^{-1}$, if possible with both polarities (provided this does not cost extra setup time). The detailed aperture (crossing angle) and collimator settings in these runs may influence the choice of the VELO gap that LHCb will adopt fro operation. This needs to be followed up.

The ALICE requirements can be fulfilled with un-squeezed optics and a number of bunches still compatible with zero crossing angle. If beams are colliding head-on at IP2, the parameter N^2/ε_N should be $\leq 7.8 \cdot 10^{20}$ $\mu\mathrm{m}^{-1}$, e.g. $N \leq 4 \cdot 10^{10}$ for $\varepsilon_N = 2$ μm. However, to maximize luminosity at IP1 and IP5 it would be preferable to use nominal bunch population, the smallest possible emittance ($\varepsilon_N = 1.5$ μm ?) and the largest possible number of bunches (156 bunches ?). In this case, a transverse separation of 2 to 3 $\sigma_{\rm beam}$ should be applied at IP2.

The choice of the crossing schemes needs to be finalized and should be mainly driven by ease of operation and minimisation of setup time.

All experiments will request a Van der Meer scan during one of the $E = 1.38$ TeV physics fills. This may limit the acceptable value of N/ε_N (but only for that particular fill). In particular, ALICE needs to be able to operate its trigger detectors during the van der Meer scan, i.e. the maximum pile-up in IP2 should not exceed $\mu \simeq 0.3$ during the scan. This is important for ALICE to obtain a reliable cross section normalisation. Length scale calibrations will also be required.

The operational envelope for this intermediate energy run and associated luminosity calibration measurements needs to be defined.

TOTEM / ALFA special requests

The physics programme of TOTEM and ATLAS/ALFA foresees operation during bulk high luminosity physics and in special conditions.

TOTEM and ATLAS/ALFA request their Roman Pots (RPs) to be aligned with beam as soon as possible in squeezed β^* conditions, such as to be able to take data during 2011 luminosity production with the RPs moved into "squeezed physics" position (likely between 10 to 15$\sigma_{\rm beam}$ from the beam orbit). This will allow them to collect data at large values of the four-momentum transfer squared $|t|$. The alignment exercise was performed for TOTEM in 2010 for 3.5 m squeeze (with a single nominal bunch) and took about 4 hours (for 12 RPs). This year TOTEM will utilize 24 RPs and ATLAS/ALFA 8 RPs. Such an alignment will be needed after each collimator re-alignment. TOTEM also asks to be able to take data for a few hours, for example (but not necessarily) at the end of the alignment exercise, with the RPs set at about 5 $\sigma_{\rm beam}$ from the beam orbit in order to reach lower $|t|$ values (down to around $0.2\ \mathrm{GeV}^2$). This would require modest total beam intensity ($\lesssim 5 \cdot 10^{11}\ p$) in the machine.

TOTEM would like to collect diffractive physics data ($\mathcal{L} \geq 10\ \mathrm{nb}^{-1}$) with low pile-up ($\mu = 0.01...0.05$) to fully profit from the now complete detector system (RPs, T2 and T1). The T1 detectors were successfully installed during the 2010-2011 winter stop. Taking $\mathcal{L} \approx L \cdot 0.7 \cdot T = n_5\,(\mu/\sigma_{\rm inel})\,f_{\rm rev}\,0.7 \cdot T$ one obtains that TOTEM needs a running time T of the order of 500 h with a single bunch. Therefore, this could be delivered without any beam time cost by adding four probe bunches during the first physics fills (e.g $4 \times 1.15 \cdot 10^{10}$ at nominal emittance of 3.75 μm), if a running time of about 125 h is achieved in these conditions. This would not limit luminosity production for the other experiments, as long as the machine is not fully occupied with bunch trains. It is therefore important that the TOTEM RPs be ready for taking data before the intensity ramp-up.

With the dedicated $\beta^* = 90$ m optics [10] a first measurement of the total cross section and of luminosity with the Optical Theorem would be possible (at $\sqrt{s} = 7$ TeV). TOTEM and ATLAS/ALFA request such optics to be developed and used in 2011.

The time for machine developments has been estimated to be about 5 shifts (with a large uncertainty) [10, 11]. For TOTEM, 4 fills of about 8 h with the 90 m optics would be enough to cover the physics programme at 3.5 TeV. The desired conditions are summarized in table 1 (the table was composed for $E = 4$ TeV; hence, the numbers are indicative) [12]. The distance $d_{\rm RP}$ of the RPs relative to the beam are given in units of transverse beam size $\sigma_{\rm beam}$ at the RPs (one expects transverse sizes of the order of 0.5 mm). The quantity $|t_{50}|$ denotes the low edge of the four-momentum transfer squared $|t|$ for which the acceptance falls to 50%. The lower the reach in $|t|$, the more precise the extrapolation of the elastic cross section at $|t| = 0$. The statistical error $\delta\sigma_{\rm el}(|t| = 0)$ of the extrapolated elastic cross section is given in the table. It should be small enough that the total error be dominated by systematic uncertainties. These will be affected, in particular, by uncertainties on the local optics. For example, for TOTEM, the proton transport matrix elements and hence the betatron functions β_x and β_y at the RP positions have to be known within an uncertainty of the order of 1%. The same level of precision is required for the dispersion D_x and D_y, which is needed to reconstruct the proton momentum loss in diffractive events. The detailed requirements on local optics measurements for TOTEM and ATLAS/ALFA will need special attention.

We note that ATLAS/ALFA would like to have two 90 m physics runs in the second half of 2011, possibly one in September and one shortly before the heavy ion run.

Table 1: Indicative TOTEM requirements for the four runs with 90 m optics. Details explained in the text.

run	1	2	3	4
ε_N	3	3	1	1
$d_{\rm RP}/\sigma_{\rm beam}$	8	6	8	6
$N/10^{10}$	7	7	6	6
$L/(\mathrm{Hz/mb})$	6.9	6.9	15	15
μ	0.05	0.05	0.1	0.1
$\|t_{50}\|/\mathrm{GeV}^2$	0.019	0.011	0.0070	0.0043
$\mathcal{L}/(\mathrm{nb}^{-1}/8\ \mathrm{h})$	0.2	0.2	0.4	0.4
$\delta\sigma_{\rm el}(\|t\| = 0)$	$\sim 1.5\%$	$\sim 1\%$	$< 1\%$	$< 1\%$

The 90 m optics run should accomodate $\beta^* = 90$ m at IP1 and IP5. In addition, ALICE and LHCb will also take data during these runs, profiting from the small pile-up to collect reference data. Therefore, it is likely that more than one bunch will be used. LHCb will also perform beam-gas luminosity calibration measurements. The optics at IP2 and IP8 can be either "injection optics" (10 m) or defocused optics ($\beta^* > 10$ m).

Luminosity calibration

A series of luminosity calibration measurements was carried out in 2010 at $\sqrt{s} = 7$ TeV. A total accuracy of around 5% was achieved [13]. Assuming the beam energy will not be changed in 2011, there is no urgent request to improve on this accuracy. However, an accuracy of 2% with the Van der Meer scan method and the beam-gas imaging method seems possible. The physics motivation for such an accurate measurement was discussed elsewhere [13]. For example, such a precise absolute measurement of the top quark production cross section could approach the top mass sensitivity of the method based on kinematic distributions. A precision of 2% in weak boson production cross sections would allow one to constrain parton distribution functions.

To reach such a level of precision, a number of systematic studies would be required and dedicated luminosity calibration fills would be needed [10]. The importance of such studies and dedicated fills will have to be balanced against the associated loss of integrated luminosity.

ION RUN: 2011 EXPECTATIONS

In 2010 Pb operation, a peak luminosity of $3 \cdot 10^{25}$ $\mathrm{Hz/cm^2}$ was achieved. The β^* value was 3.5 m, the number bunches was 137 and their population was up to $1.2 \cdot 10^8$ Pb ions. Transverse emittances around 1.5 μm were obtained. The bunch spacing was 500 ns, long enough to facilitate usage of a zero crossing angle scheme.

For 2011 several improvements are being considered. A factor 2.3 or more in peak luminosity could come from the squeeze (3.5 m versus $\beta^* \leq 1.5$ m ?). The 2011 proton experience will help deciding on the β^* targets for the ion run. A factor 4.5 could be gained from the number of bunches, using the "nominal" scheme with 100 ns spacing and 592 bunches [14]. However, it is currently unclear whether higher-than-nominal bunch populations with small emittances can also be obtained for the nominal scheme. So far, populations of $1 \cdot 10^8$ Pb have been achieved in the injector with about twice nominal emittance [15]. Intermediate schemes (200 ns spacing ?) are being investigated and an optimum between the 2010 scheme and the nominal scheme might be found [16]. Realistically, a peak luminosity 4 to 5 times larger than in 2010 could be expected. Following this, a delivered integrated luminosity of 30 $\mu\mathrm{b}^{-1}$ per IP in 2011 seems a target within reach. It would quadruple the total integrated luminosity.

The main request from the experiments is a maximisation of the delivered integrated luminosity. In addition, the ALICE Collaboration would like to operate with no shadowing of the ZDC by the TCTVB collimators and they would like to collect approximately the same amount of data with the two magnetic field polarities. An additional preference is a zero net crossing angle (unless there is a substantial gain in luminosity with a bunch separation and/or β^* value that is/are incompatible with a zero net crossing angle). In any case, a small net crossing angle is generally preferable for all experiments.

Finally, it has been noted that, if the prospects for a substantial increase of the total delivered Pb-Pb luminosity in 2012 were modest, a first p-Pb run in 2012 may become scientifically more pertinent than a third Pb-Pb run. In such a case, ALICE would support p-Pb exploratory studies during the 2011 ion run.

SCHEDULING

A draft LHC operation schedule was proposed in this workshop [4]. Beam operation starts on February 21 with 20 to 30 days of recommissioning and continues with proton operation until November 6, followed by heavy ion operation until December 12. Six 4-day technical stops are planned, each followed by one day of machine operation recovery. All but the first stop are preceded by a 4-day block of machine developments (MDs). Approximately 10 days have been reserved for e-cloud scrubbing. This leaves approximately 145 ± 10 days of physics operation. Assuming that about 10 days can be devoted to special requests, then 135 ± 10 days would be dedicated to high luminosity physics operation (with $n \geq 900$ bunches).

The intermediate energy run is scheduled to start with setting up on April 2, and will be followed by the LHC scrubbing run. However, depending on progress with machine recommissioning, this run might be moved to just before the first technical stop.

Machine developments for the 90 m optics could start in the first MD block. However, 90 m physics operation will not take place in the first half of 2011.

Dedicated physics fills for luminosity calibration measurements at 3.5 TeV will also not be scheduled in the first half of 2011.

The top priority for the first half of 2011 will be to rapidly establish efficient luminosity delivery with a luminosity in excess of 10^{33} $\mathrm{Hz/cm^2}$ in IP1/IP5 and stabilized around $3 \cdot 10^{32}$ $\mathrm{Hz/cm^2}$ in IP8.

CONCLUSION

A number of special requests and desiderata from the LHC experiments have been presented. The main (and most time-consuming) of these requests are reminded here:

- Intermediate energy run ($E = 1.38$ TeV): 3 shifts to set up and 35 h in `STABLE BEAMS`,

- 90 m optics: about 5 shifts to set up and 4×8 h fills for physics,

- Accurate luminosity calibration: several systematic studies and 2 dedicated fills for the actual luminosity calibration measurements.

The implementation of these special activities will have to be balanced with the loss of integrated luminosity for the mainstream physics programme.

The target of $1\ \mathrm{fb}^{-1}$ for IP8 will be challenging, but seems possible if continuous luminosity leveling by beam separation is successfully applied throughout 2011 and if a rapid increase of the number of bunches (770 and beyond) is achieved. This would allow LHCb to explore uncharted particle physics territory. The target of $1\ \mathrm{fb}^{-1}$ for IP1 and IP5 seems well within reach and more could be hoped for. With $6\ \mathrm{fb}^{-1}$ ATLAS and CMS would be able to (each independently) close the question of the SM Higgs!

The experiments, impressed by 2010 LHC performance results, are looking forward to a prosperous data collection in 2011. 2010 will remain as the memorable year when the LHC machine started to deliver. 2011 could become “une année charnière” for physics.

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PUSHING THE LIMITS: BEAM

E. Métral (for the ABP/ICE section)

Abstract

Many collective effects were observed in 2010, first when the intensity per bunch was increased and subsequently when the number of bunches was pushed up and the bunch spacing was reduced. After a review of the LHC performance during the 2010 run, with a particular emphasis on impedances and related single-beam coherent instabilities, but mentioning also beam-beam and electron cloud issues, the potential of the LHC for 2011 will be discussed. More specifically, the maximum bunch/beam intensity and the maximum beam brightness the LHC should be able to swallow will be compared to what the injectors can provide.

INTRODUCTION

The highest LHC peak luminosity (~ 2.07 10^{32} $cm^{-2}s^{-1}$) was achieved on Monday 25/10/10 on the fill number 1440 with a total intensity per beam of ~ 4.35 10^{13} p and beam parameters given in Table 1 [1]. The missing factor 50 to reach the nominal peak luminosity can be explained by the missing number of bunches (~ 8) and the missing factor for the β* (~ 6), realizing that the loss by a factor 2 from the beam energy was compensated by transverse emittances which were about two times smaller than nominal.

Parameter	Achieved	Nominal	Missing factor
Bunch population [p/b]	1.15 10^{11}	1.15 10^{11}	1
Number of bunches / beam	368	2808	
Bunch spacing [ns]	150	25	
Colliding bunch pairs	348	2808	8.07
Beam energy [TeV]	3.5	7	*2*
β* [m]	3.5	0.55	6.36
Norm. trans. emittance [μm]	~ 2.1	3.75	*~ 0.56*
Full crossing angle [μrad]	200	285	
Rms bunch length [cm]	9	7.55	
Peak luminosity [$cm^{-2}s^{-1}$]	2.07 10^{32}	10^{34}	50

Table 1: Parameters used for the LHC maximum peak luminosity performance in 2010.

The integrated luminosity goal for 2011 is 1 fb^{-1} (even if the experiments are now asking for few fb^{-1}). Assuming the same peak luminosity as the maximum reached in 2010 (see Table 1), a total of ~ 100 operational days (see [2] where ~ 120 days are anticipated, i.e. about half of the total run length) and a Hubner (overall run) factor of 0.2 would lead to an integrated luminosity of ~ 1/3 of the 2011 goal. This means that one should aim at least at gaining a factor ~ 3 in peak luminosity, meaning that one should reach at least ~ 6 10^{32} $cm^{-2}s^{-1}$. To have some margin one should therefore aim for ~ 10^{33} $cm^{-2}s^{-1}$, which was also said in the past to be a goal for 2011. Hence, a factor 5 should be gained compared to last year.

Many collective effects were observed in 2010. The first in spring when the bunch intensity was increased to the nominal value. Accelerating a single-bunch, an horizontal single-bunch coherent instability from the machine impedance was observed and stabilized with Landau octupoles. The second collective effect appeared in summer when the number of bunches was increased and the crossing angle was scanned. First analyses revealed that the Head-On (HO) beam-beam effects alone seem to be fine, but the Long Range (LR) effects remain to be studied in detail [3]. Furthermore, when the transverse feedback was removed at top energy in the presence of many bunches (and small chromaticities, i.e. few units), the beam was lost which seems to indicate that a transverse coupled-bunch instability was stabilized by the transverse feedback, but this instability was not studied in detail yet. Finally, the third collective effect occurred in autumn when the batch spacing was reduced to 150 ns, 75 ns and finally 50 ns, which revealed some electron cloud effects (the smaller the batch spacing the more significant the electron cloud effects) [4-6]. In these conditions, which parameters can therefore be realistically used in 2011 to increase the peak luminosity by a factor 5 and reach the goals? A reduction of the β* from 3.5 m down to 2 m seems a reasonable assumption, and this value will be assumed for the rest of this paper (in fact 1.5 m is also contemplated at the moment) [7,8]. Furthermore, the energy is assumed to increase from 3.5 TeV to 4 TeV (even if the final decision will only be taken after the Chamonix2011 workshop), as the effect is rather small (14% increase in luminosity). These two effects would already increase the peak luminosity to ~ 4 10^{32} $cm^{-2}s^{-1}$. This means that "only" a factor ~ 2.5 remains to be gained, playing with the beam intensity and/or beam brightness, i.e. with 3 parameters: the bunch population, the number of bunches and the transverse beam emittance.

This paper is structured as follows. In Section 1, the predictions for the LHC impedances and single-beam instabilities are compared to the observations made in 2010. As the particular item of the Landau octupoles was raised on the Monday morning of the workshop, some more information are given to try and explain why the Landau octupoles had to be used already with a single nominal bunch. In Sections 2 and 3, the electron cloud and beam-beam predictions are compared to the observations made in 2010. Finally, a scenario is proposed in Section 4 to reach the goals for 2011 together with a fallback plan.

IMPEDANCES AND SINGLE-BEAM INSTABILITIES

It is worth reminding that when we discuss "the impedance of a machine", we speak in fact of (at least) 5 impedances, which are needed to correctly describe the beam dynamics, and these 5 impedances are all complex functions of frequency: (1) the longitudinal impedance, (2) the horizontal dipolar (or driving) impedance, (3) the horizontal quadrupolar (or detuning) impedance, (4) the vertical dipolar (or driving) impedance, and (5) the vertical quadrupolar (or detuning) impedance. Nevertheless, two interesting quantities (numbers) are given by taking the imaginary part of the effective impedance (i.e. the impedance weighted by the bunch spectrum) in both longitudinal and transverse (most critical of the horizontal and vertical) planes. These numbers are referred to as the longitudinal and transverse (sum of the dipolar and quadrupolar impedances) imaginary effective impedances and the predictions were the following: ~ 0.09 Ω in the longitudinal plane at both injection and 7 TeV/c and for the transverse plane, ~ 3.5 MΩ/m at 450 GeV/c, ~ 7.5 MΩ/m at 3.5 TeV/c and ~ 30 MΩ/m at 7 TeV/c (i.e. a value larger than in the SPS, where ~ 20 MΩ/m are now obtained [9], and which comes from the numerous collimators with very small gaps [10]). First measurements in 2010 revealed that in the longitudinal plane, a value very similar to the predicted one (i.e. ~ 0.09 Ω) was measured from the loss of Landau damping leading to undamped bunch oscillations at the beginning of the run with small longitudinal emittance [11]. The imaginary part of the effective transverse impedance has been evaluated from tune shift measurements vs. intensity and revealed that it was within less than 40% compared to theoretical predictions. Furthermore, moving all the collimators of IR7 only, an even better agreement was obtained (as was already obtained in 2004 and 2006 in the SPS with a LHC collimator prototype [12]): closing all the collimators from 15 σ to 5 σ a transverse coherent tune shift of - 2.4 10^{-4} was measured while - 2.0 10^{-4} was predicted (with an about nominal bunch). The real part of the transverse effective impedance was measured through the instability rise-time of an instability studied at 3.5 TeV/c (see below) and it seems to be very close to expectations. All these measurements reveal therefore a good agreement with predictions. There was only one exception recorded so far, which concerns the TDI and the two TCLIs (all of them used only at injection): it seems that their induced tune shift is a factor ~ 2 - 2.5 larger than expected. This issue is followed up [13]. No measurements of the imaginary part of the effective transverse impedance at high energy (3.5 TeV/c) are available yet. One should try and have an estimate of it in 2011, even if no big surprise is anticipated (to be confirmed!), as it should be dominated by the collimators, for which our impedance model is the more precise. But, what could happen if the impedance is larger than expected (or if more critical beam parameters are used)? The answer is: (i) in the longitudinal plane, we could observe a loss of Landau damping leading to undamped bunch oscillations (as observed at the beginning of the run with small longitudinal emittance) [11]; (ii) in the transverse plane, this could lead to a Transverse Mode Coupling Instability (TMCI). From Fig. 1, which depicts the predicted (in 2006) real and imaginary parts of the transverse complex tune shifts (due to the machine impedance and for nominal beam parameters) at 7 TeV/c for the first head-tail modes, for both single-bunch and coupled-bunch instabilities and vs. chromaticity, it can be seen that for 0 chromaticity the single-bunch (SB) real tune shift for mode 0 is ~ - 5 10^{-4}. Assuming that the TMCI intensity threshold is reached when the tune shift of the mode 0 is ~ equal to - Q_s (the synchrotron tune, whose value is ~ 2 10^{-3} at 3.5 TeV/c), one can deduce that the intensity threshold should be a factor ~ 4 higher than nominal. This is confirmed by recent HEADTAIL simulations, as can be seen from Fig. 2, where an intensity threshold of ~ 3.5 10^{11} p/b is obtained, i.e. a factor ~ 3 higher than nominal.

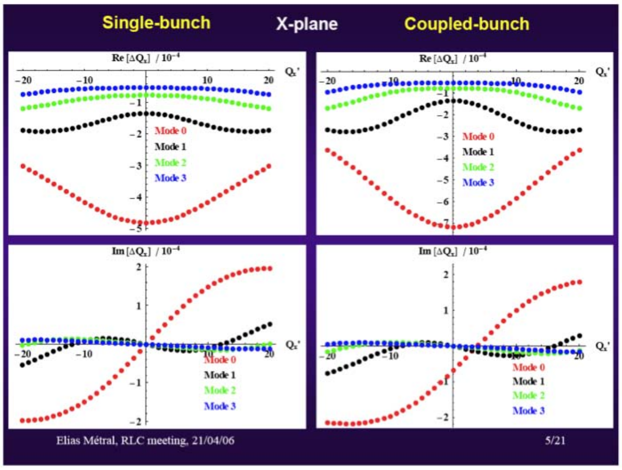


Figure 1: Predicted (in 2006) real and imaginary parts of the transverse complex tune shifts (due to the machine impedance and for nominal beam parameters) at 7 TeV/c for the first head-tail modes, for both single-bunch and coupled-bunch instabilities and vs. chromaticity (without any Landau damping mechanism).

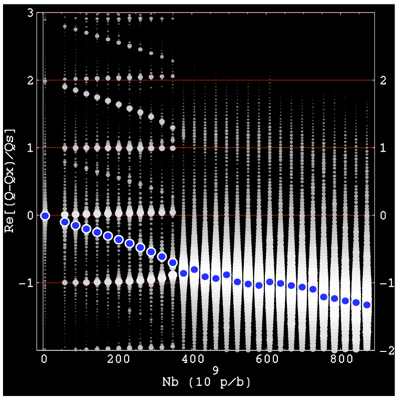


Figure 2: Horizontal modes vs. bunch intensity for 0 chromaticity and TMCI intensity threshold (when modes 0 and -1 couple).

It is worth mentioning that contrary to other machines, the TMCI is more critical at top energy than at injection energy (factor ~ 7 there) due to the fact that the transverse impedance increases with energy (collimators!). Furthermore, with many bunches the coupled-bunch (CB) TMCI intensity threshold could be lower [14], as can already be anticipated by looking at Fig. 1, where the coupled-bunch tune shift for mode 0 and 0 chromaticity is ~ - 7 10^{-4} instead of ~ - 5 10^{-4} for a single-bunch. This mechanism will be studied in detail soon, with the HEADTAIL code which was recently extended to multi-bunch operation by N. Mounet, but the intensity threshold should be higher than nominal.

However, chromaticity is never 0 in a real machine and a single bunch is always potentially unstable (for any beam parameter!) as can be seen on Fig. 3, where the single-bunch (and coupled-bunch) instability rise-times vs. chromaticity (computed in 2006) are shown for the case at 7 TeV/c (same case as the one shown in Fig. 1). A rise-time of less than 1 s is predicted (with nominal beam parameters and Q' ~ 6), with neither intrinsic nonlinearities nor Landau octupoles (i.e. without any Landau damping mechanism). The solution is to reduce the chromaticity as much as possible (but still positive, if not using a transverse feedback) and use Landau octupoles (if the "unknown" intrinsic nonlinearities are not sufficient). The latter are "unknown" and therefore this is why we could not answer (precisely) in the past to the following two questions: (1) for which bunch current do we need to put some octupoles?; (2) for which number of bunches do we need to put the transverse feedback on (related here to the coupled-bunch instability)? The "unknown" intrinsic nonlinearities depend on the machine and it is therefore also very difficult to compare between different machines. What will make the beam stable or not is: (i) the natural (uncontrolled) lattice nonlinearities; (ii) the fact that the bunch is kept in the machine for a time with is shorter than ~ the instability rise-time; (iii) external (controlled) nonlinearities through (Landau) octupoles to provide Landau damping; (iv) other spreads could help: internal (i.e. from space charge, nonlinear synchrotron motion, etc.), from impedances etc; (v) linear coupling between the transverse planes (as e.g. in the PS where this method replaced the octupoles). Examples of head-tail instabilities are shown in Fig. 4, where several superimposed consecutive traces are depicted to reveal the (absolute value of the) head-tail mode number equal to the number of nodes: mode 0 in the PSB in ~ 1974 and mode 6 in the PS in 1999. A simple visualization of the Landau damping mechanism is shown on Fig. 5, explaining why above a certain "unknown" (at least before detailed studies) intensity, Landau octupoles are needed to keep the transverse coherent (i.e. of the whole bunch) tune inside the incoherent (i.e. of the individual particles) tune spread to absorb (incoherently) the energy and stabilize the beam through Landau damping. It is said in the LHC Design report [15, pages 103 and 104] that the higher order head-tail modes have to be stabilized by Landau damping or (slightly) negative chromaticity and that all the single-bunch head-tail modes at injection should be Landau damped by the lattice nonlinearities (space charge can also help under some conditions). The fact that at higher energy the situation is more critical is due to the fact that the lattice nonlinearities are smaller (the beam size is smaller) and the space charge tune spread reduces. For the nominal bunch intensity, the bunch will become unstable (without Landau octupoles) at the energy where the incoherent tune spread will become ~ smaller than the transverse coherent tune shift. Detailed analyses will continue on this subject in 2011.

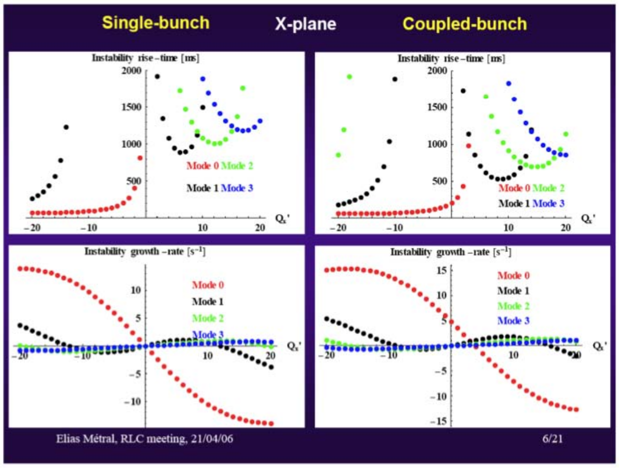


Figure 3: Predicted (in 2006) instability rise-times and growth rates corresponding to the case of Fig. 1.

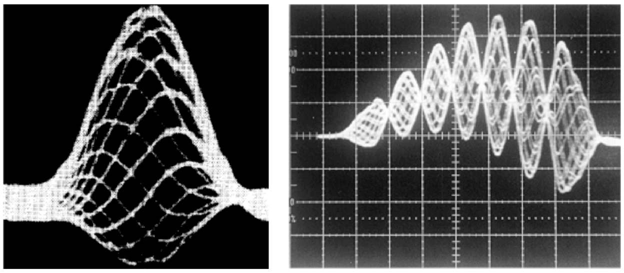


Figure 4: Example of head-tail modes: (left) in the PSB in ~ 1974 by Gareyte and Sacherer; (right) in the PS in 1999.

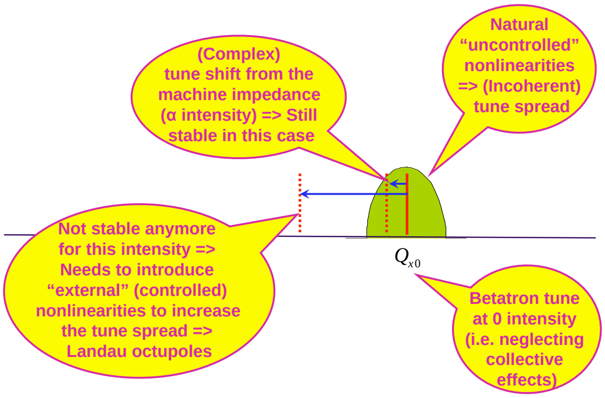
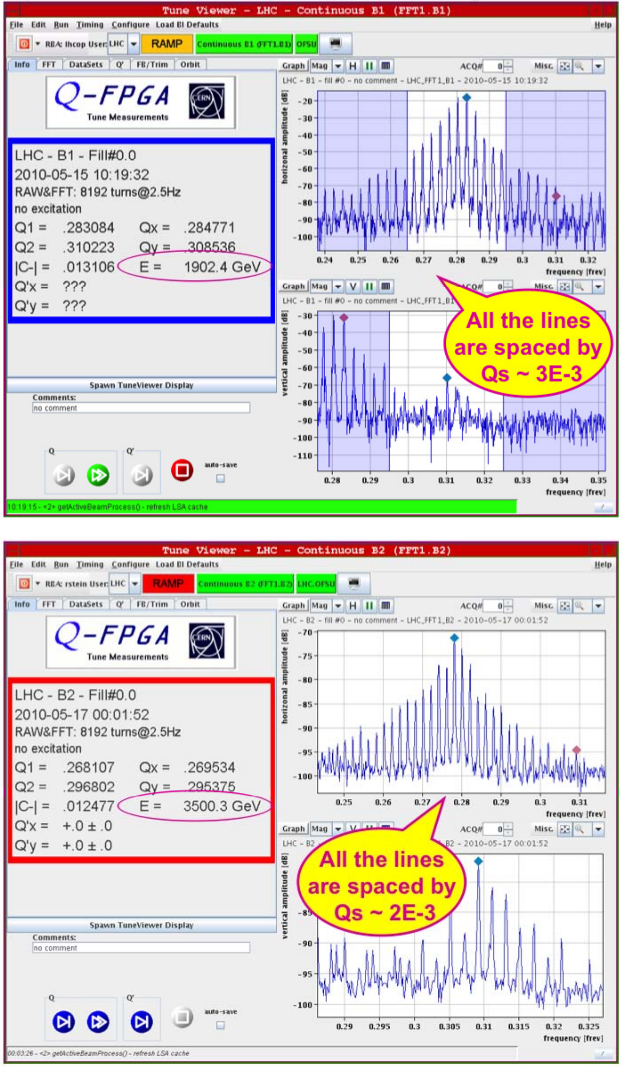


Figure 5: Visualization of the transverse Landau damping mechanism.

A first ramp was tried with a single bunch of ~ 10^{11} p/b (on both beams B1 and B2) on Saturday 15/05/2010 without Landau octupoles. The bunch was unstable at ~ 1.8 TeV/c for B1 and ~ 2.1 TeV/c for B2. This led to the famous "Christmas tree" (see Fig. 6) together with beam losses in IR7: can we explain it?



LHC - B1 - Fill#0.0
2010-05-15 10:19:32
RAW&FFT: 8192 turns@2.5Hz
no excitation
Q1 = .283084 Qx = .284771
Q2 = .310223 Qy = .308536
|C-| = .013106 E = 1902.4 GeV
Q'x = ???
Q'y = ???

LHC - B1 - fill #0 - no comment - LHC_FFT1_B1 - 2010-05-15 10:19:32

Comments: no comment

10:19:15 - <2> getActiveBeamProcess() - refresh LSA cache

LHC - B2 - Fill#0.0
2010-05-17 00:01:52
RAW&FFT: 8192 turns@2.5Hz
no excitation
Q1 = .268107 Qx = .269534
Q2 = .296802 Qy = .295375
|C-| = .012477 E = 3500.3 GeV
Q'x = +.0 ± .0
Q'y = +.0 ± .0

LHC - B2 - fill #0 - no comment - LHC_FFT1_B2 - 2010-05-17 00:01:52

Comments: no comment

00:03:26 - <2> getActiveBeamProcess() - refresh LSA cache

Figure 6: "Christmas tree" observed on 15/05/2010 at 1.9 TeV/c (upper) and on 17/05/2010 at 3.5 TeV/c (lower).

A detailed study was performed on Monday 17/05/10 at 3.5 TeV/c (the acceleration was done with some octupole current equal to - 200 A at 3.5 TeV/c corresponding to a K_3 = - 12 m^{-4}). The bunch was stable and then the octupole current was reduced by steps (see Fig. 7). The bunch was still stable for I_{oct} = - 20 A (may be we could redo this measurement by waiting longer) and became unstable for I_{oct} = - 10 A, for which a rise-time of ~ 10 s (with Q' ~ 6 and a transverse emittance of ~ 5 μm, but there are some doubts on this measurement) was measured (see Fig. 8, upper). The stabilizing octupole current seems therefore to be between - 20 A and - 10 A.

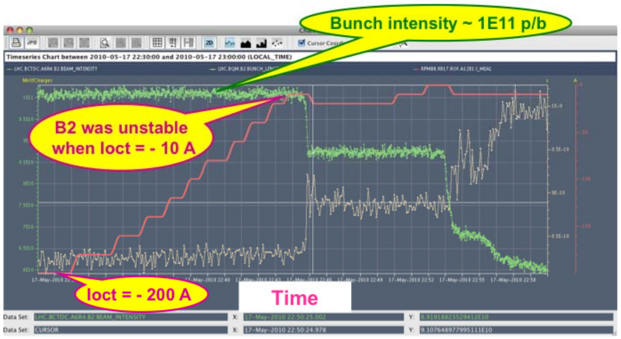
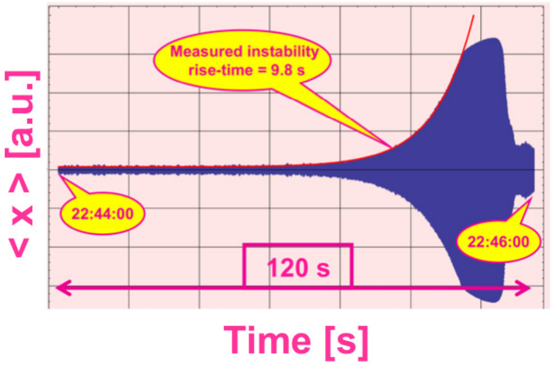


Figure 7: Correlation between the octupole current which was reduced by steps, from - 200 A to - 10 A (red curve) and the bunch intensity (green curve).

MEASUREMENTS

(17/05/2010 at 3.5 TeV)



SIMULATIONS

Scan in octupole current

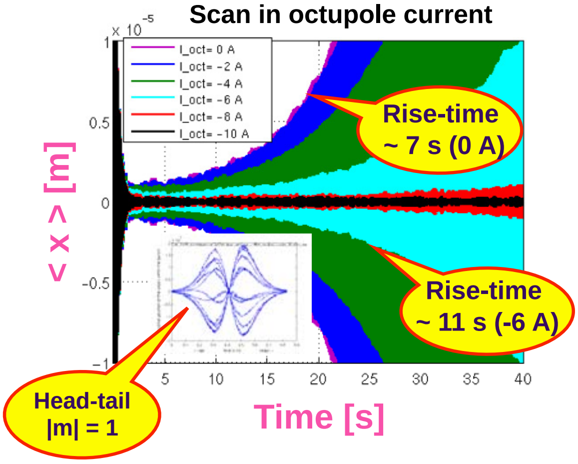


Figure 8: (Upper) Measured horizontal single-bunch instability for a current in the octupoles of - 10 A for a chromaticity Q' of ~ 6 and an emittance of ~ 5 μm (however there are some doubts about this value as the transverse emittances were overestimated at the beginning of the 2010 run. To be checked…). (Lower) Corresponding HEADTAIL simulations assuming the nominal horizontal emittance of 3.75 μm.

HEADTAIL simulations (see Fig. 8, lower) predict an unstable bunch (with Q’ ~ 6 and a nominal transverse emittance of 3.75 µm) for $I_{oct} > -10$ A, with a rise-time of ~ 11 s for $I_{oct} = -6$ A. Therefore, a similar rise-time (of ~ 10 s) is observed in both cases, for $I_{oct} = -6$ A in the simulations and for $I_{oct} = -10$ A in the measurements (here again with some doubts on the transverse emittance value). Furthermore, bunch stability is obtained in the measurements for a current in the octupoles between - 20 A and - 10 A, whereas HEADTAIL simulations predict bunch stability for ~ - 10 A. Therefore, we can say that a good agreement between measurements and HEADTAIL simulations is obtained. Looking at the frequency domain, Fig. 9 was measured. It can be seen there that the mode m = - 1 (at - Q_s from the tune) clearly grows up alone ($Q_s \sim 2\ 10^{-3}$) and the other head-tail modes follow afterwards. Note that the instability rise-time can also be estimated from these pictures in the frequency domain [16]: the instability rise-time is given by the time needed for the amplitude of the unstable line to be increased by ~ 9 dB. We see from Fig. 9 that it is increased by ~ 24 dB in 24 s, i.e. by ~ 9 dB in ~ 9 s. Therefore, the instability rise-time is ~ 9 s, as found in the time domain (see Fig. 8, upper).

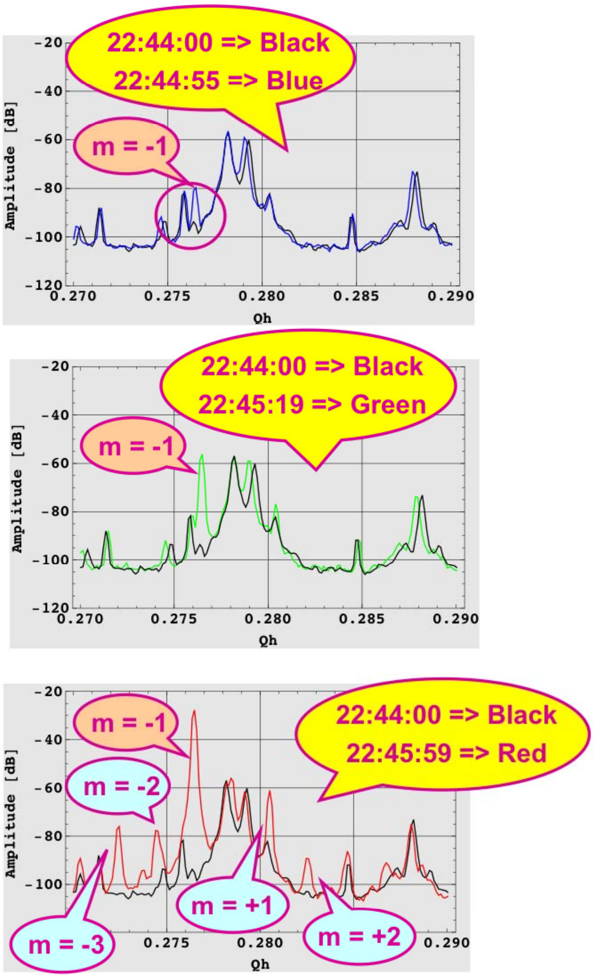


Figure 9: Frequency analysis of the measured Fig. 8.

Everything seems therefore to be consistent with a head-tail instability of mode m = - 1. HEADTAIL simulations were nevertheless performed to try and see if we could reproduce two observations linked to this instability: (i) the famous “Christmas tree” (see Fig. 6) and (ii) a bunch length increase. To study the “Christmas tree”, HEADTAIL simulations were performed for the case of the nominal bunch at 7 TeV/c (as the instability is faster there…) and it is found that the “Christmas tree” appears when the beam losses are included (see Fig. 10). The exact mechanism still needs to be understood to have a full understanding but it is only a consequence and not the cause of the instability.

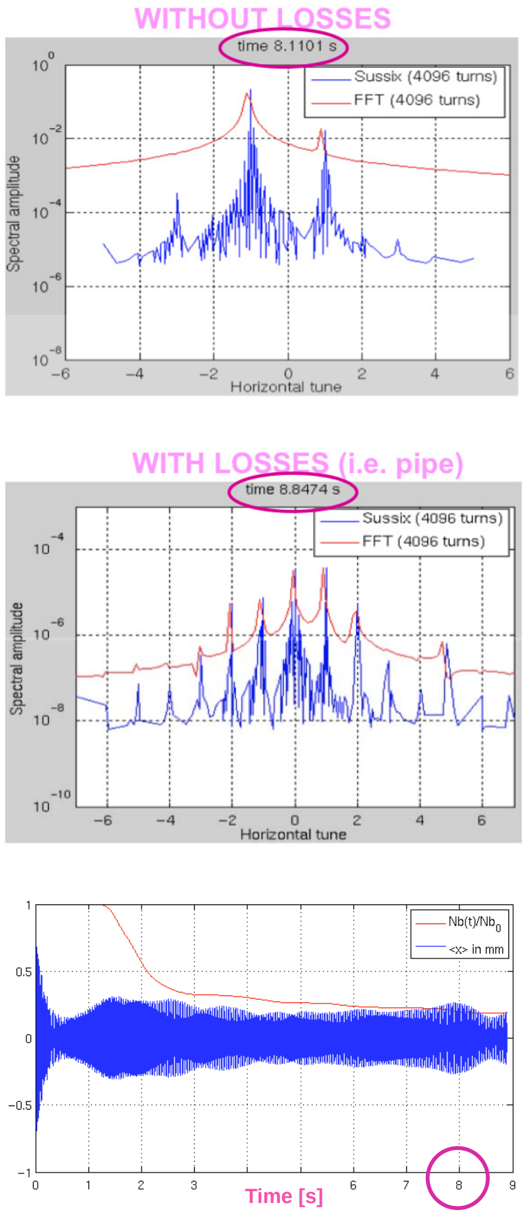


Figure 10: HEADTAIL simulations for the case of the nominal bunch at 7 TeV/c without and with beam losses (i.e. including the beam pipe in the simulations).

The bunch length increase appearing during the instability was studied with the bunch parameters of Fig. 8 (lower) without octupole current (see Fig. 11). It is seen that when beam losses start to appear (after ~ 40 s of simulation) the rms bunch length increases from ~ 0.06 m to ~ 0.09 m. In the measurements, the rms bunch length increased from ~ 0.06 m to ~ 0.07 m (see Fig. 12). Therefore, a similar behavior is observed. The exact mechanism still needs to be understood to have a full understanding but it is, again, only a consequence and not the cause of the instability.

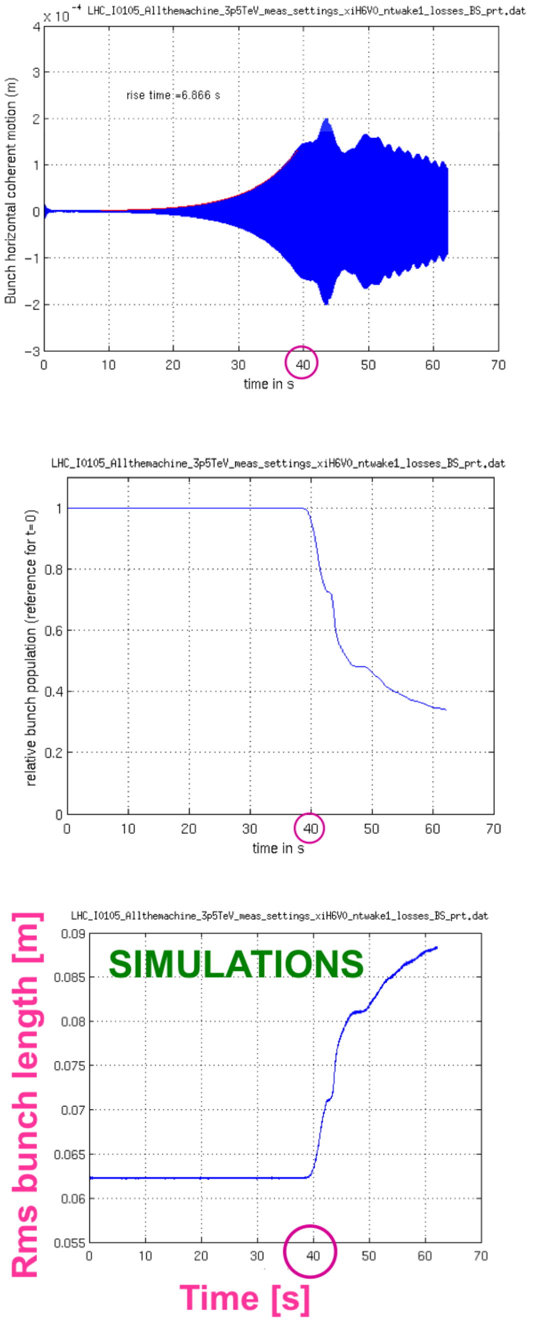


Figure 11: HEADTAIL simulations for the case of Fig. 8 (lower) without octupole current including beam losses (i.e. with a beam pipe).

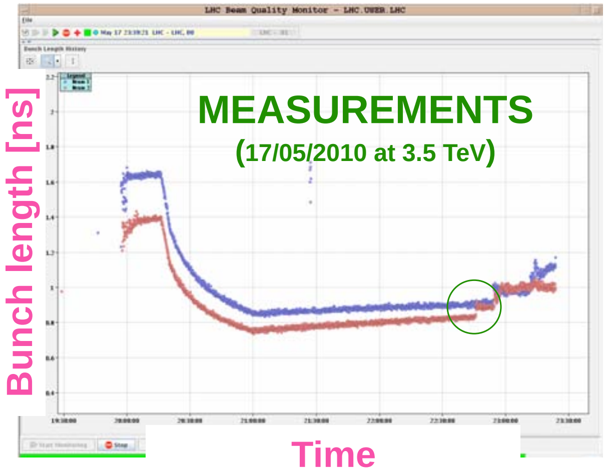
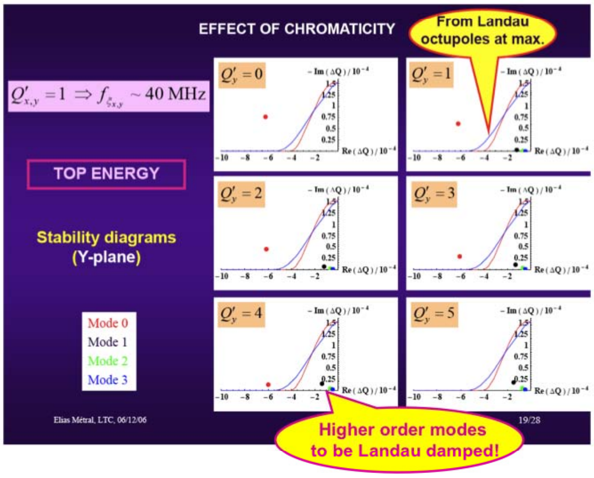


Figure 12: Measurements of bunch length increase during the instability studies performed on Monday 17/05/10.

In summary, we "believe" we understand this instability because it was predicted: Head-Tail instability m = - 1 with a rise-time of ~ 10 s (note that it should be close to 1 s at 7 TeV). The Christmas tree and the bunch length increase seem to be consequences of the beam loss: the exact mechanisms still need to be understood to have a full understanding but they are not essential as they are consequences of the instability and not causes. The intrinsic nonlinearities of the LHC are not sufficient to provide Landau damping (i.e. the field quality is too good!) and external ("controlled", i.e. coming from the Landau octupoles) nonlinearities need to be introduced to stabilize the beam. It is worth mentioning at this point that transverse coupled-bunch instabilities are also predicted in the absence of Landau damping and transverse feedback. The transverse feedback should be able to damp the mode 0. However, (as already mentioned above), the higher order head-tail modes have to be Landau damped by natural nonlinearities or Landau octupoles, otherwise the beam will be unstable (see Fig. 13).


EFFECT OF CHROMATICITY

From Landau octupoles at max.

$Q'_{x,y} = 1 \Rightarrow f_{\xi_{x,y}} \sim 40$ MHz

TOP ENERGY

Stability diagrams (Y-plane)

Mode 0
Mode 1
Mode 2
Mode 3

Higher order modes to be Landau damped!

Elias Métral, LTC, 06/12/06

19/28

Figure 13: Apparition of higher order head-tail modes for the transverse coupled-bunch instability when chromaticity is increased (computation in 2006).

ELECTRON CLOUD

Electron cloud effects were expected in the LHC but the 2010 observations came may be earlier than anticipated because most of the time a Secondary Emission Yield (SEY) smaller than 1.7 was considered. The legitimate question to ask would then be: why did we make our electron cloud estimates for SEY between 1.1 and 1.7, as (i) for unbaked copper tube, ~ 2 < SEY < ~ 2.5 (see Fig. 14) and (ii) using ~ 2 < SEY < ~ 2.5, the electron cloud team can reproduce some of the observations [17]? As already mentioned at the beginning of the workshop [5], a huge simulation campaign has restarted. Our best estimate for the moment is an initial SEY between 2 and 2.5 (which would be compatible with an unbaked copper tube) to explain the 2010 measurements, but many other parameters play also an important role (more news soon…).

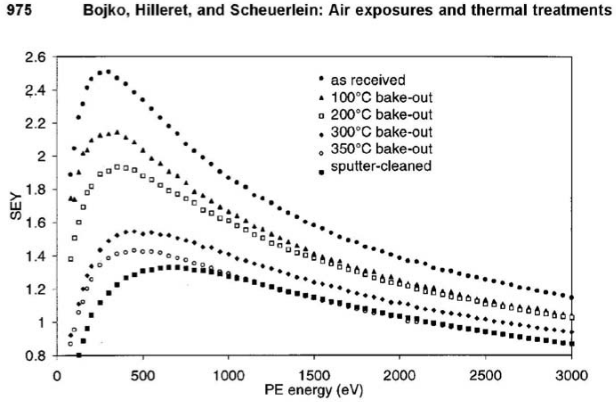


Figure 14: Influence of 24 h bakeouts at various temperatures on the SEY of technical copper [18].

It is worth mentioning that the LHC design has adopted a fourfold strategy for suppressing the formation of an electron cloud [15, page 116]: (i) NEG coating in the warm sections (i.e. ~ 10% of the total circumference) to have a SEY of ~ 1.1; (ii) sawtooth surface in the arcs to reduce the forward reflectivity from ~ 80% to 2%; (iii) the pumping slots in the beam screen are shielded by baffles to avoid, in dipoles, a direct electron path along the magnetic lines between the beam region and the cold bore; (iv) scrubbing (i.e. surface conditioning) to reduce the SEY.

For the predicted coherent and incoherent effects, the 2010 observations and for the scrubbing run proposal in 2011, see Refs. [5] and [6], which were devoted to these subjects.

BEAM-BEAM

Many predictions were made in the past (see for instance Refs. [3] and [15, page 117]. Did we have some surprises in 2010? The answer is no: the good results obtained with a HO tune shift about 2 times larger than nominal can be explained by smaller lattice nonlinearities than expected (as confirmed also from the observed single-bunch instability from the machine impedance). In Ref. [3], it is mentioned that a typical tune shift per collision of 0.006 to 0.007 imposed no lifetime problems in the SPS (with p-pbar operation) and that similar numbers are reported from the Tevatron. Therefore, it should be expected that similar values can be reached in the LHC. It is worth reminding that the nominal HO tune shift was derived from the SPS experience, taking into account possible contributions from the lattice nonlinearities and significant LR contributions. The nominal value of the beam-beam parameter $\xi = 0.0037$ was defined to provide a coherent set of parameters to reach the target luminosity of 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. It should be considered as conservative and not as an expected upper limit, in particular in the absence of strong LR interactions. In the presence of strong LR interactions, the situation is more involved as the tune footprint (i.e. the area occupied in the tune diagram by all the particles due to the nonlinear beam-beam force) is much bigger (see Fig. 15) and there are thus more possibilities of interaction with lattice resonances and subsequent beam lifetime problems [3].

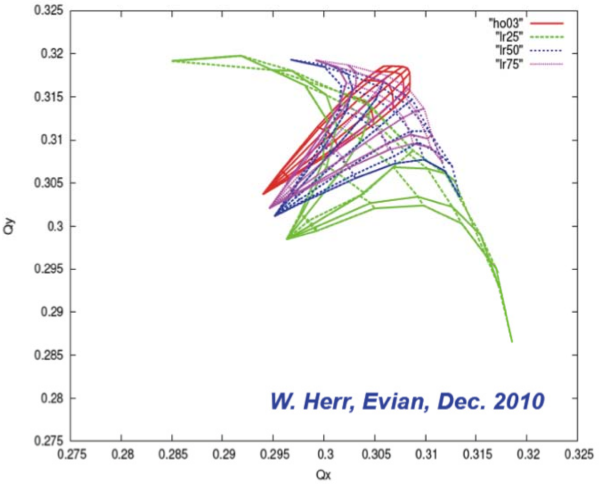


Figure 15: Beam-beam tune footprints (for HO collisions only and both HO and LR) for different bunch spacings at 3.5 TeV/c and β* = 3.5 m.

The optimization strategy for 2011 depends on the first beam-beam limit which will be reached, i.e. HO or LR. The HO tune shift is proportional to the beam brightness, i.e. the intensity to emittance ratio, and is independent of β* and the energy as can be seen from Eq. (1), while the LR tune shift depends on β*, the crossing angle and energy, as can be seen from Eq. (2)

$$\Delta Q_{\mathrm{HO}} \propto \frac{N_b}{\varepsilon_n} , \tag{1}$$

$$\Delta Q_{\mathrm{LR}} \propto \frac{N_b}{d_{sep}^2} = \frac{N_b \, \varepsilon_n}{\alpha^2 \, \beta^* \, \gamma} , \tag{2}$$

where N_b is the number of protons per bunch, ε_n the normalized transverse emittance, α the crossing angle and γ the relativistic mass factor. If the HO interaction is the beam-beam limit, it is therefore advantageous to increase the bunch intensity together with the transverse emittance since this would keep the HO tune shift unaffected, but increases the luminosity proportionally to the intensity. The luminosity is further increased by a reduction of β*, without affecting the beam-beam parameter ξ. The situation is very different for the contribution of LR interactions where the tune shift is still proportional to the bunch intensity but is inversely proportional to the square of the beam separation d_{sep} (see Eq. (2)). This means that any change of β* or the energy requires to adjust the crossing angle to keep the LR tune shift constant.

PROPOSED SCENARIOS FOR 2011

As already discussed in Introduction, a factor 5 needs to be gained in 2011 to reach the goal luminosity of 10^{33} cm^{-2}s^{-1}. Assuming a beam energy of 4 TeV (instead of 3.5 in 2010, even if the final decision will only be taken after the Chamonix2011 workshop), as the effect is rather small (14% increase in luminosity), a β* of 2 m (whereas 1.5 m is even currently discussed), leads already to a gain of a factor 2 (~ 4 10^{32} cm^{-2}s^{-1}). A factor ~ 2.5 remains to be gained, playing with the beam intensity and/or beam brightness. Figure 16 shows the link between the number of bunches, the intensity per bunch and the transverse normalized emittance to reach 10^{33} cm^{-2}s^{-1}, together with what the SPS can provide [1,19,20]. Based on Fig. 16 and on the 2010 experience, the proposed scenario (plan A) and the fallback solution (plan B) are given in Table 2. The idea is essentially to multiply the number of bunches by ~ 3 (after the re-commissioning, scrubbing run etc., i.e. in production mode).

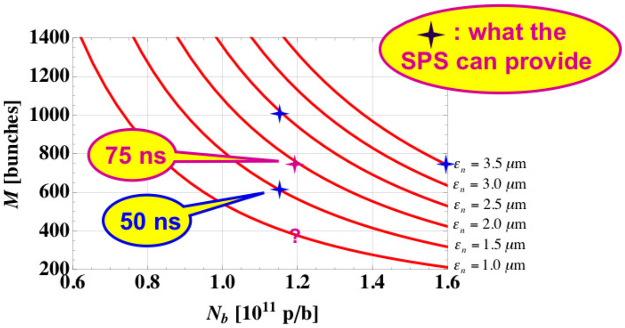


Figure 16: Relation between the bunch population, the number of bunches and the transverse normalized beam emittance to reach a peak luminosity of 10^{33} cm^{-2}s^{-1}, assuming a beam energy of 4 TeV and a β* of 2 m. The blue star is used for the 50 ns beam while the red one is for the 75 ns beam.

Parameter	PLAN A	PLAN B
Bunch population [p/b]	1.15e11	1.15e11
Number of bunches / beam		936 (max)
Bunch spacing [ns]	50 ns	75 ns
Colliding bunch pairs	1000 (max = 1404)	936 (max)
Beam energy [TeV]	4	4
β* [m]	2	2
Norm. trans. emittance [μm]	2.3	2.2
Full crossing angle [μrad]	285	285
Rms bunch length [cm]	9	9

Table 2: Proposed scenarios for 2011: Plan A is more challenging but it has more potential and 108 bunches were already accelerated in 2010; Plan B is less challenging (824 bunches were already injected in 2010) but it has also less potential.

SUMMARY AND OUTLOOK

The small lattice nonlinearities have one “detrimental” and one beneficial effect: (i) Landau octupoles are needed to stabilize the single-bunch instability from the transverse impedance; (ii) the HO tune shift can be ~ 2 times larger than nominal (without strong LR interactions). All the observations made so far are in good agreement with predictions and more detailed measurements will be done in 2011 to try and fully understand the single-bunch instability observed around ~ 2 TeV without Landau octupoles (i.e. the effect of the smaller transverse beam size, smaller lattice nonlinearities, smaller space charge tune spread, etc.). Nevertheless, most of it seems to be already understood and recommendations were already given in Ref. [1], in particular for the use of chromaticity. The next steps should consist in: (i) trying to fully understand the single-bunch instability, i.e. why (quantitatively, see above) it develops around 2 TeV; (ii) measuring the transverse coherent tune shift at 3.5 TeV/c to try and estimate the TMCI intensity threshold (the prediction for the single-bunch TMCI is around 3.5 10^{11} p/b); (iii) measuring the coupled-bunch complex tune shifts at both injection and top energy without transverse feedback; (iv) identifying the beam-beam limits which are very important for the LHC performance and which are vital ingredients for the LHC upgrade studies.

The electron cloud observations in 2010 are certainly due to ~ 2 < SEY < ~ 2.5, whereas 1.7 was usually the maximum value studied in the past. A huge simulation campaign has restarted and our best estimate for the moment is an initial SEY between 2 and 2.5 (which would be compatible with an unbaked copper tube) to explain the 2010 measurements, but many other parameters play also an important role (more news soon…). Detailed studies should be performed during the 2011 LHC scrubbing run.

ACKNOWLEDGEMENTS

After this first year of LHC commissioning and first impedance and induced instability measurements, I would like to thank to all the people who worked on impedances in the past, in particular F. Ruggiero, L. Vos, F. Caspers, A. Grudiev, all the vacuum people etc. I would like also to thank in particular B. Salvant and N. Mounet for the recent studies on impedances and single-beam coherent instabilities. Many thanks also to all the people who

worked in the past on electron cloud (F. Zimmermann et al., all the vacuum people etc.) and beam-beam (W. Herr et al.), and thanks also to many people from different groups (ABP, OP, BI, RF etc.) for fruitful discussions and help in the 2010 measurements. Finally, I would like to express my gratitude to Lyn Evans for having put Landau octupoles in the LHC (despite some budget crises) and having hence provided us with a machine in very good shape for hopefully outstanding future performances.

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Pushing the limits: crossing angles, aperture and β^*

W. Herr, CERN, Geneva, Switzerland

Abstract

First experiences with colliding beams have been collected during the 2010 LHC run. These will be critically examined and serve as input to define strategies for operation with more bunches and higher luminosities in 2011. The proposed strategies include running scenarios for proton operation in ALICE and LHCb.

INTRODUCTION - WHERE ARE THE LIMITS

Running the LHC at lower energy, the possible β^* and the crossing angles are limited by the available mechanical aperture. At the same time a minimum crossing angle is required to avoid a reduction of the dynamic aperture due to long range beam-beam effects. For a low-β insertion (i.e. not at injection), the normalized separation for a given crossing angle α is a function of β^* as well as the emittance and can be written as [1]:

$$d_{sep} = \sqrt{\frac{\alpha^2 \cdot \beta^* \cdot \gamma}{\epsilon_n}}$$

The corresponding long range beam-beam tune shift can be approximated by:

$$\Delta Q_{lr} \propto \frac{N}{d_{sep}^2} = \frac{N \cdot \epsilon_n}{\alpha^2 \cdot \beta^* \cdot \gamma}$$

Given the desired separation (12 σ, [2]), we can define the necessary crossing angle as:

$$\alpha = \sqrt{\frac{d_{sep}^2 \cdot \epsilon_n}{\beta^* \cdot \gamma}}$$

However, the mechanical aperture imposes a maximum crossing angle [3, 4].

CONFIGURATION IN IP1 AND IP5

To obtain maximum luminosity in IP1 and IP5, it is desirable to operate with the smallest possible β^*. Furthermore, the proposed scenario should work for any bunch spacing foreseen for running the LHC in 2011 and 2012. Both conditions defined above are summarized and superimposed in Fig.1. The required crossing angle as defined above is plotted for different emittances and the constraints from the mechanical aperture are superimposed [5]. The latter are slightly pessimistic since the nominal emittance is assumed for the calculation. The two curves represent different assumptions on the quality of the orbit control.

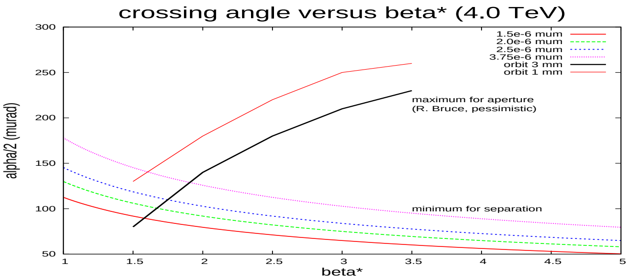

Figure 1: Required crossing angle versus β^* for different emittances. Also shown are limits from mechanical aperture [5].

Realistically, the curve for orbits of 1 mm should be used. The crossing points of the curves define the lower limit for β^* and give the required crossing angle.

The result of this is summarized in Tab.1 assuming different values for the normalized transverse emittance and the energy of the machine.

ϵ_n Energy	β^* 3.5 TeV	β^* 4.0 TeV	α (μrad) 3.5 TeV	α (μrad) 4.0 TeV
1.5 μm	1.4 m	1.4 m	± 120	± 120
2.0 μm	1.5 m	1.4 m	± 120	± 120
2.5 μm	1.6 m	1.5 m	± 120	± 120
3.75 μm	1.8 m	1.6 m	± 140	± 140

Table 1: Crossing angle versus β^* for different emittances.

Recommendations IP1 and IP5

Following the results from Tab.1, a scenario for interaction points 1 and 5 is proposed as (assuming an emittance of ϵ_n = 2.5 μm [7]):

- Operating with β^* = 1.5 m
- Half crossing angle of ± 120 μrad.
- Works for bunch spacings of 50 ns and 75 ns.

For emittances larger than ϵ_n = 2.5 μm the numbers must be modified (see Tab.1).

A question that may be raised is the minimum β^* in case of a substantial emittance growth during a physics fill. While the aperture at the beginning of a fill may be sufficient it may not be towards the end, leading to a limit for β^*. So far it was not yet attempted to optimize the machine working point for collision and it can be hoped that a possile emittance growth can be controlled. In particular for future running with more substantial long range encounters the search for a good working point becomes important and should be pursued as an operational procedure.

CONFIGURATION IN IP2

The operation in IP2 is complicated by two requirements:

- Moderate luminosity, levelled with adjustable transverse separation [8].
- Spectrometer magnet, producing an antisymmetric bump and a rather large crossing angle [8].

It is requested to change the polarity of the spectrometer on a regular basis, i.e. the sign of the crossing angle changes. To avoid parasitic encounters, an additional, external crossing angle must be applied and it is assumed that this angle has the same sign as the internal angle, i.e. it must be inverted when the polarity of the spectrometer is changed. Both angles are in the vertical plane and can be chosen freely since no interference with the exchange of aperture between the separate vacuum chambers is expected.

Choosing the external and internal angles with opposite sign allows a small effective crossing angle, but at the expense of additional crossings, depending on the bunch spacing [8]. When the bunch spacing is large enough, such a scenario, including to reduce the effective angle to zero, is possible.

Recommendations IP2

The proposed parameter set for the operation in IP2 is:

- Internal crossing angle at 3.5 TeV is ± 140 μrad.
- External crossing angle at 3.5 TeV is ± 80 μrad, leading to a net crossing angle of ± 220 μrad.
- Operation with β^* = 10 m.

To avoid additional crossings and the implied complications it is highly recommended to choose the external and internal crossing angles with the same sign.

CONFIGURATION IN IP8

Like IP2, in IP8 a moderate luminosity is wanted and can be provided with a small separation. The full feasibility of this separation in the presence of long range beam-beam encounters remains to be verified [1].

Unlike IP2, the crossing plane in IP8 is horizontal and in order to avoid multiple crossings, the sign of the external angle is fixed [8], i.e. beam 1 crosses the interaction point with a negative angle. This is shown in Fig.2 where the orbits of the two beams are shown for the external crossing angle only. Shown are also the positions of beam-beam encounters for different bunch spacings. This configuration (sign) is the only one allowed for IP8.

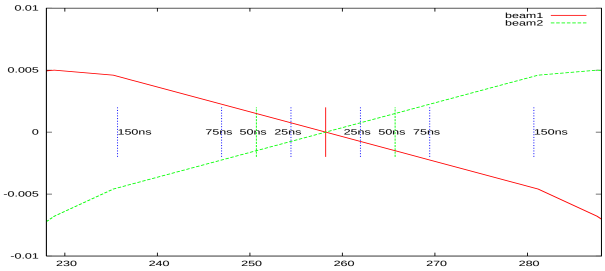

Figure 2: Geometry of external crossing angle in IP8. Shown are also the positions of beam-beam encounters for different bunch spacing.

The Figs.3 and 4 show the orbits of the two beams produced by the spectrometer magnets together with its compensators [8]. It is assumed [6, 9] that the spectrometer is always operated with full field during physics data taking, independent of the machine energy. At the energy of 3.5 TeV this produces a half crossing angle of ± 270 μrad (Figs.3 and 4). It is clearly visible that the orbits of the two beams change signs when the polarity of the spectrometer is inverted. The bunch spacing used during 2010, i.e. 150 ns, has the advantage that the first parasitic encounter is outside this bump and a change of the polarity does not affect the separation. This spacing was chosen considering

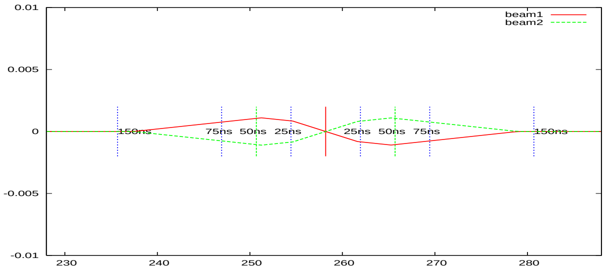

Figure 3: Geometry of internal crossing angle in IP8. Picture shows the preferred polarity. Shown are also the positions of beam-beam encounters for different bunch spacing.

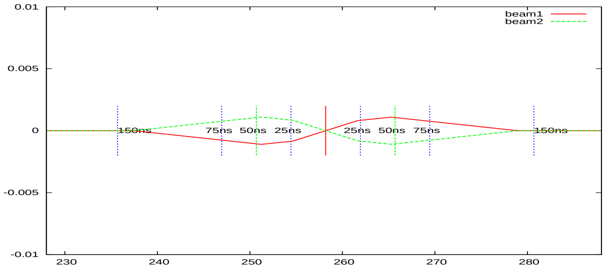

Figure 4: Geometry of internal crossing angle in IP8. Picture shows the less preferred polarity. Shown are also the positions of beam-beam encounters for different bunch spacing.

this feature.

Collisions in IP8

When beams are colliding, both, internal and external crossing angles must be present to avoid parasitic encounters. Since the sign of the external angle is fixed, the combined orbits in the two cases are rather different. The Fig.5 shows the external angle superimposed on the internal angle for the preferred polarity. Both angles add and provide sufficient separation for all possible encounter. This configuration is operational for all β^* allowed by the mechanical aperture [3, 4] and the foreseen bunch spacings. The situation is very different for the case depicted in Fig.6 where the polarity of the spectrometer is switched, while the external angle is the same as in Fig.5. Since the two signs are opposite, the separation for the encounters inside the antisymmetric bump are very small and insufficient for operation. The situation depends on the bunch spacing and the situation is more critical for 50 ns than for the 75 ns case. The crossing angle must therefore be increased to separate the beams sufficiently. Due to aperture considerations and the requirement of a minimum beam separation the available β^* is limited. To find the required set of parameters, an optimization similar to the one for IP1 and IP5 was done for IP8. This is shown in Fig.7. In this case the minimum required angle is shown as a function of β^* for the two options for the bunch spacing, i.e. 50 ns and 75 ns. The emittance in this figure is assumed to be 2.0 μm, but the evaluation was done also for other values.

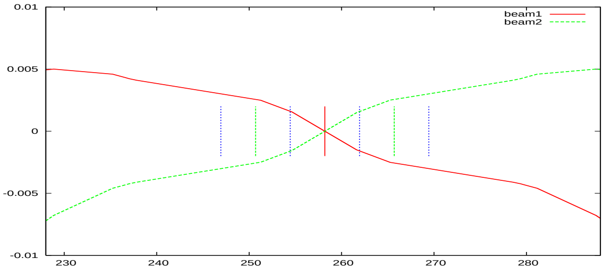

Figure 5: Geometry of external and spectrometer crossing angle in IP8 for the preferred polarity. Shown are also the positions of beam-beam encounters for different bunch spacing.

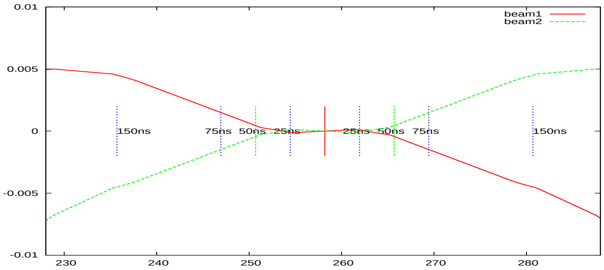

Figure 6: Geometry of external and spectrometer crossing angle in IP8 for the less preferred polarity. Shown are also the positions of beam-beam encounters for different bunch spacing.

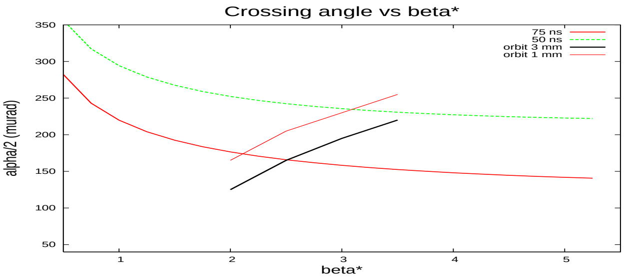

Figure 7: Required crossing angle versus β^* in IP8 for 50 ns and 75 ns spacing. Superimposed constraints from mechanical aperture.

Recommendations IP8

The results of this procedure are summarized in Tab.2 where the recommended β^* together with the proposed crossing angles are shown. As expected, the required configuration depends on the bunch spacing. It appears, that a scenario with:

spacing	ϵ_n	β^*	α
50 ns	2.0 μm	3.0 m	$\mp$ 235 μrad
50 ns	2.5 μm	3.2 m	$\mp$ 250 μrad
50 ns	3.75 μm	3.6 m	$\mp$ 270 μrad
75 ns	2.0 μm	2.0 m	$\mp$ 160 μrad
75 ns	2.5 μm	2.2 m	$\mp$ 170 μrad
75 ns	3.75 μm	2.5 m	$\mp$ 210 μrad

Table 2: Possible operational parameters for IP8, less preferred polarity of spectrometer.

- ϵ_n = 2.5 μm
- $\beta^* \geq 3.0$ m
- $\alpha \approx \mp$ 250 μrad

is possible for both bunch spacings. This reduces the possible β^* reach for 75 ns, but allows a common setup for all considered bunch spacings, simplifying the operation of the machine, inparticular if it can be adopted also for the preferred polarity.

However, it should be noted that an operation with a bunch spacing of 25 ns is excluded unless a different configuration is used [10].

Injection in IP8

At injection, the operation of the spectrometers can impose additional complications. If it is desired to have the fields at full strength already at injection energy, the amplitude of the antisymmetric bump and the associated crossing angle are very large (approximately ± 2.1 mrad in the case of IP8). It is therefore excluded that the external angle can be chosen large enough to compensate for such an angle in case the signs are opposite. The two cases with full field of the spectrometer in the case of IP8 are shown in Figs.8 and 9. The additional crossing points in Fig.9 cannot be avoided. During the energy ramp the bump amplitude decreases and the unwanted crossing points move longitudinally, thus always sampling the potential encounters for any bunch spacing.

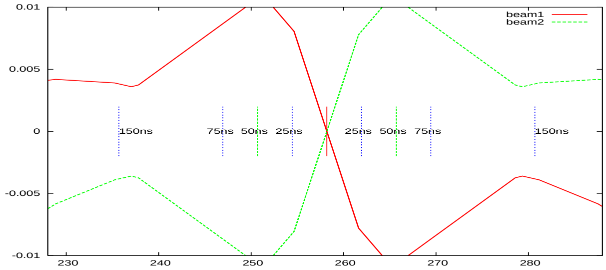

Figure 8: Crossing scheme at injection energy for IP8, full field of the spectrometer with preferred polarity of spectrometer.

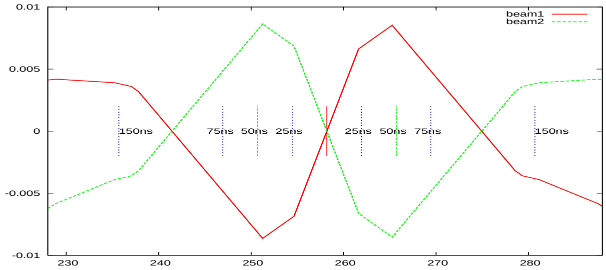

Figure 9: Crossing scheme at injection energy for IP8, full field of the spectrometer with less preferred polarity of spectrometer.

To solve this problem, two possible solutions are proposed:

- Run the spectrometer at a lower field at injection and ramp up with energy.
- Try to separate all encounters with the parallel separation bump.

It can be shown that setting the magnetic field of the IP8 spectrometer to about 10% or less provides sufficient separation.

The second option relies on the separation in the other plane. Originally [8], the parallel separation is designed to separate the central collision point only, while all parasitic encounters are separated by the crossing angle bump. To test whether the parallel bump is sufficient to also separate the first few parasitic encounters, the normalized separation provided by this bump is shown in Fig.10. Three curves are shown computed with different normalized transverse emittances between 2.0 μm and the nominal emittance.

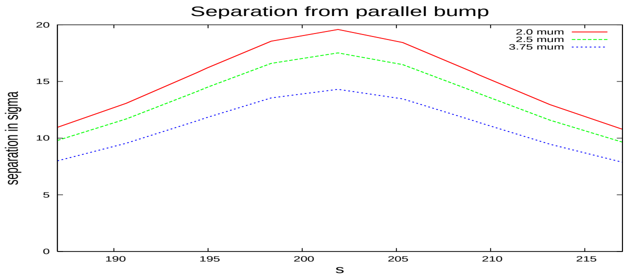

Figure 10: Normalized beam separation provided by parallel separation bump around IP8. Numbers given for 3 different emittances.

Using the criterion for a sufficient separation one comes to the conclusion that the separation provided is sufficient under the condition that the emittance is not larger than 2.5 μm. In that case the IP8 spectrometer can be operated at full field at injection energy for both polarities and all bunch spacings.

Finally, it is desired to keep the luminosity in IP8 approximately constant at a moderate value. To this purpose the beams are separated transversely and this was tested in 2010. It remains to be demonstrated that such a separation (of the order of 1 σ) can be used also in the presence of many additional long range encounters, a configuration not yet used.

SUMMARY

The main results of this study can be summarized as:

- Given the boundary conditions from mechanical aperture and required beam-beam separation, the collision points in IP1 and IP5 can be operated with a β^* = 1.5 m and a crossing angle around ± 120 μrad.
- The external angle in IP2 proposed is ± 80 μrad.
- The minimum β^* in IP8 depends on the bunch spacing and the spectrometer polarity and will be between 2 m and 3.5 m. The corresponding crossing angles are specified.
- For emittances smaller than 2.5 μm at injection, the separation provided by the parallel bump is sufficient for both polarities and bunch spacings when the spectrometer is at full field.

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LUMINOSITY ANALYSIS

G. Papotti, CERN, Geneva, Switzerland

Abstract

The first year of LHC operation was very successful regarding the peak and integrated luminosity targets, but the luminosity lifetime could probably have been better. For this reason, the luminosity evolution during physics fills is studied and correlated to single beam lifetimes and emittance growth in order to try and understand possible causes of luminosity lifetime decrease, e.g. IBS, beam-beam related phenomena, electron-cloud and possibly the “hump”.

INTRODUCTION

The instantaneous luminosity can be calculated from the machine parameters according to the well known formula:

$$L = \frac{I_{b1} I_{b2} f_{rev} n_b}{2\pi\sqrt{(\sigma_{1x}^2 + \sigma_{2x}^2)(\sigma_{1y}^2 + \sigma_{2y}^2)}} \qquad (1)$$

The revolution frequency f_{rev} and the relativistic γ factor that goes into the beam size σ are fixed. The β function at the interaction point (β^*, which also contributes to the beam sizes) was 3.5 m in the period of interest for this analysis. The number of bunches n_b changed often, in particular during the month of October when the main aim of the machine commissioning was an intensity ramp up to reach a peak instantaneous luminosity of $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, the target for the year. The bunch intensity (I_{b1} and I_{b2}) and horizontal and vertical emittance change both from fill to fill and within a fill.

In particular the intensity decrease and the emittance growth (e.g. see [1]) are the main causes for the instantaneous luminosity decay over the fill duration. Examples of causes of intensity loss are luminosity production itself and losses on collimators from tails or due to emittance growth. The emittance increases e.g. due to IntraBeam Scattering (IBS) or scattering on residual gas, due to noise on power converters or RF cavities, due to electron cloud etc. To be noted that also orbit drifts can affect the luminosity by diminishing the overlap region between the two beams, but this effect seems to be negligible at the LHC.

In this paper the analysis is restricted to the period between end of July and end of October 2010, that is proton physics fills from 25 bunches up to bunch trains. The bunch trains consisted mostly of 150 ns spaced bunches (up to 368 bunches per ring), plus one physics fill with 50 ns spaced beams (fill 1459). Only luminosity data gathered from the ATLAS and CMS experiments are used; as the two see collisions from the same pairs of bunches, thus allowing a direct comparison of the results.

2010 LUMINOSITY EVOLUTION

The rapid progress of the LHC machine in 2010 is often summarized by plots that show the fill peak luminosity (L_{pk}) versus fill number for the high luminosity experiments ATLAS and CMS (e.g. [2], reported here in the first subplot in Figure 1). Fill 1251 marked the beginning of a stable running period (3 weeks in August) with 25 nominal bunches per ring, which finished with a few fills at 48-50 bunches per ring. The steep peak luminosity increase after fill 1364 (the first one with bunch train injections) corresponds to the intensity ramp up period (October), where the number of bunches per ring was increased by about 50 bunches every 3 fills. It is clear how luminosity production with 25 or 50 nominal bunches was rather negligible compared to the last physics fills were 368 bunches per ring produced up to the record $2 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (fill 1440).

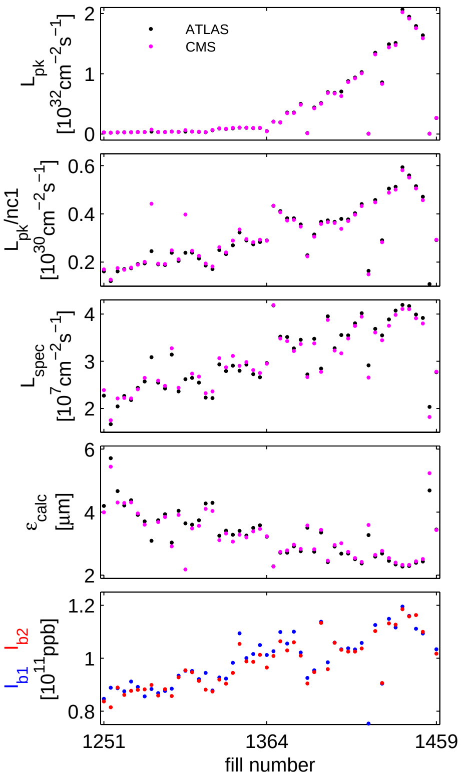

Figure 1: 2010 proton physics fills summaries from fill 1251 to fill 1459.

The second subplot in Figure 1 shows the total peak luminosity divided by the number of bunches (nc1) colliding at the Interaction Point (IP), or "peak luminosity per colliding bunch": a factor three improvement was reached in the period under study. By folding in the intensity per bunch from the fast Beam Current Transformer (fBCT) system, one can derive the specific luminosity and calculate the emittance at the start of the physics fill (assuming equal and round beams). The specific luminosity (L_{spec}) and the calculated emittance (ϵ_{calc}) are shown in the third and fourth subplots, while the average bunch intensity per ring (I_{b1}, I_{b2}) is shown in the fifth subplot of Figure 1. It becomes then clear how the peak luminosity per bunch was increased by a factor three over a few months. First, the intensity per bunch was slowly increased from 0.8×10^{11} ppb to 1.2×10^{11} ppb. Second, the emittance was slowly decreased from 4-5 μm (above the 3.5 μm nominal size, [3]) to just above 2 μm at the start of physics.

LUMINOSITY LIFETIME COMPARISONS

The luminosity evolution at the Tevatron was described as a fractional power law [4] according to:

$$L = \frac{L_0}{(1+t/\tau/b)^b} \qquad (2)$$

This description worked well also for a selection of LHC physics fills, and the resulting fit parameters τ and b are plotted in Figure 2 for most long fills with bunch trains. The calculated fit parameters vary quite across fills: the time constant τ is generally between 10 and 15 hours, but can be as low as 5 hours or above 20 hours; the parameter b is generally between 0.5 and 0.8, but in a few fills it is above 1. It is rather difficult to trace back the reasons of such differences a posteriori, in particular as the configuration of the machine was often changed, as for example the fill pattern. This situation should improve in 2011 when the main aim will be physics running for luminosity production, leading to stable operations and much reduced periods of machine commissioning. This analysis should then be repeated, recalculating τ and b for many 2011 physics fills, to verify their reproducibility and understand the causes behind the behaviour.

The emittance growth rates were estimated from the luminous region size published by the experiments. A horizontal lifetime τ_ϵ of about 30 hours was derived from simple exponential fits (e^{-t/τ_ϵ}). The measured lifetime though is lower than the expected IBS lifetime (about 38 hours, see for example [5], or [3] scaled for 3.5 TeV and the smaller emittance). This indicates that possibly other phenomena than IBS should be taken into account in order to explain the horizontal growth. The vertical emittance lifetime varies also quite heavily among fills, dropping sometimes below 20 hours, probably when the "hump" happens to coincide with the tune for a long time, causing emittance blow up (more details later, in the paragraph on fill 1372).

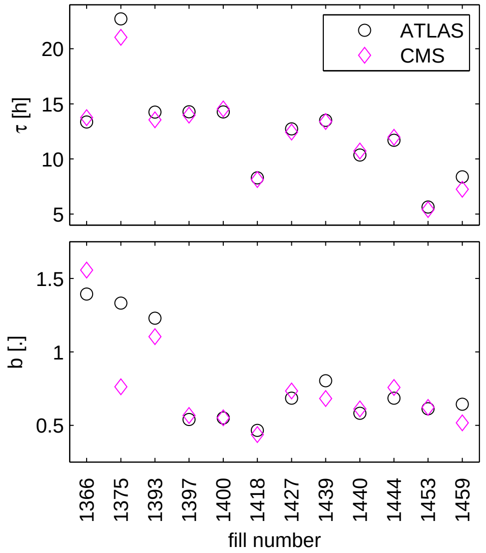

Figure 2: Fit parameters (τ, b) for different fills, fitting equation (2) to the total luminosity from ATLAS and CMS.

The single beam lifetime was in general excellent (above 100 hours), but it is unfortunately difficult to quantify it precisely. On one side, above a few hundred hours it cannot be measured precisely by the fBCT algorithm used for the displays in the control room [6]. On the other side, squeezed but not colliding beams were never kept for a long enough time to measure such good lifetimes precisely with an offline algorithm.

The losses then increase when the beams are put into collisions (e.g. see Figure 4 in the section concerning fill 1459). The intensity lifetime in collisions ($\tau_{b_{1,2}}$) varies between 50 and 120 hours depending on the fill. A parallel sum law relates the intensity lifetime to the lifetimes from all the relevant phenomena, i.e.:

$$\frac{1}{\tau_{b_{1,2}}} = \frac{1}{\tau_{lumi}} + \frac{1}{\tau_{coll}} + \frac{1}{\tau_{gas}} + \ldots \qquad (3)$$

The luminosity burnoff can be quantified assuming an average luminosity per collision of $0.4\times10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (see Figure 1), 3 collisions per bunch and a cross section of 100 mb, resulting in $1.2\times10^5 p/s$ lost or $\tau_{lumi} \cong 230$ hours. The losses on the collimators increase by about two orders of magnitude once the beams are put into collisions, a worst case lifetime was quantified to $\tau_{coll} \cong 120$ hours [7]. The losses due to the presence of residual gas were expected to give about $\tau_{gas} \cong 100$ hours in [3], but were not yet carefully measured at 3.5 TeV. Consequently, a controlled experiment to measure effective growth rates and losses with squeezed but not colliding beams is strongly encouraged in order to have clear indications on single beam parameter evolution.

BUNCH-BY-BUNCH ANALYSIS

The same functional description in equation (2) can be applied to the single bunch luminosity. The two fit parameters (τ,b) are plotted in Figure 3 for every bunch pair colliding in CMS. The colors are chosen to highlight the head-on collision schedule: red is used for bunches colliding in IP 1 and 5; blue for IP 1, 2 and 5; green for IP 1, 5 and 8; grey for IP 1, 2, 5 and 8. While the "separated" collisions in IP 2 seem to have little impact on lifetime parameters (e.g. no difference between green and grey circles), full head-on collisions in IP 8 modify the luminosity decay sensibly (e.g. red versus green circles).

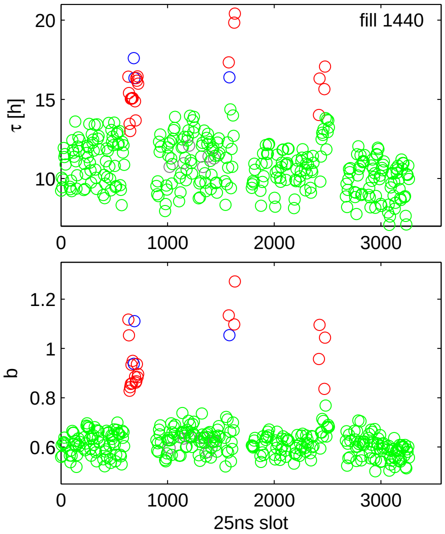

Figure 3: Fit parameters (τ, b) per colliding bunch pair (fill 1440), using equation (2). Color coding to highlight the head-on collision characteristics: grey circles are used for bunch pairs colliding in all IPs; green for IP 1, 5 and 8; blue for IP 1, 5 and 2; red for IP 1 and 5.

The experimental luminosity curves can also be described phenomenologically well by the sum of two exponential functions, even though this description does not reflect the physical processes behind the phenomena. This description divides the behaviour in a fast and a slow component (time constants of about 3 and 30 hours), and it can be seen that while the fast component shows a dependence on the collision pattern, the slow component does not. This is a reminder of how the beam-beam effect is strongest at the beginning of the collision phase, where the beams are the most intense and the emittances are the smallest.

SPECIAL FILLS

Fill 1459: trains with 50 ns spaced bunches

In 2010 there has been only one physics fill with 50 ns bunch spaced beams (fill 1459), which consisted of 108 bunches per ring, injected in 9 trains of 12 bunches. With 50 ns spaced bunches clear evidence of electron cloud phenomena was observed already at injection energy: pressure rise, emittance growth, bunch shortening, possibly instabilities especially towards the end of SPS batches [8].

Luminosity lifetimes for this fill were particularly bad, mostly due to the high losses observed. Two plots of bunch-by-bunch losses are shown in Figure 4, for beam 1 and beam 2. In order to derive these plots, the intensities measured by the fBCT are analysed from a few minutes before going into collisions until the end of the physics fill. In Figure 4, the initial 75 minutes are shown and the zero of the time axis corresponds to the moment the beams start colliding. The fBCT intensity before collisions is taken as a reference and the intensity lost from then on is plot as loss in per cent, one curve per bunch. The line colors are chosen so to highlight three different families of bunches. In red, bunches which experience sudden losses (limited by the fBCT data being logged in 1 vector per minute). In blue, bunches for which the total losses are important (up to about 30% after one hour from collisions), but develop continuously over time. In green all other bunches.

A more detailed study shows that red bunches were sitting at the end of SPS batches, hinting a possible e-cloud related phenomenon. Blue bunches instead correspond to mid-batch positions, hinting beam-beam related issues. Unfortunately, the lack of statistics for this configuration (only one fill) does not allow to generalize further the conclusions. More information should be available in the 2011 run, when the aim is for running at either 75 ns or 50 ns spaced bunches.

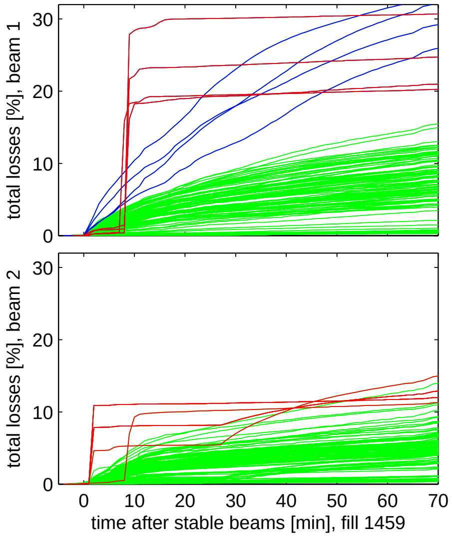

Figure 4: Bunch-by-bunch losses for fill 1459, top plot beam 1, bottom plot beam 2. Color coding: red bunches suffer sudden losses; blue bunches suffer rather big losses which are spread over longer periods of time; all other bunches are plotted in green.

Fill 1372: hump on the tune

The so called "hump" [9] is the manifestation in the tune diagram of an unidentified source of noise, visible in the tune measurement as a higher noise floor in a limited range of frequencies. While the hump is always active, its frequency changes and its effect on the beam (mostly emittance blow up) is visible only when the hump frequency overlaps with the tune. The hump has been observed to be most active on the vertical beam 2 tune.

While looking through luminosity data, one fill (fill 1372) was found to have a particularly "wavy" instantaneous luminosity curve, which was recorded by both ATLAS and CMS and is shown in the first subplot in Figure 5. Looking at the horizontal and vertical emittance derived from luminous region size from the experiments (see Figure 5, second subplot), it seems to be rather evident how the different growth rates in vertical beam size correspond to the different slopes in instantaneous luminosity. Given that the extra emittance growth is observed mostly in the vertical plane, a correlation to the hump activity seemed likely and was later proven by snapshots of the "Hump Buster", an application which shows the tune spectrum as a function of time (e.g. see [9]).

A simple estimation of how much integrated luminosity was lost due to the extra vertical emittance blow up for this fill can be done by recalculating the instantaneous luminosity profile while substituting the vertical emittance with the horizontal emittance, and then integrating over time. The difference in integrated luminosity is around 20%, making the hump rather costly in terms of performance.

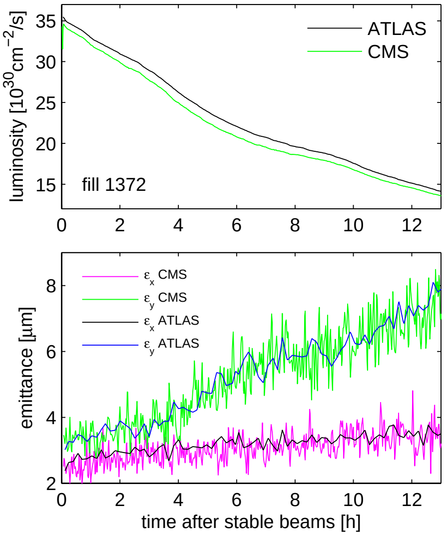

Figure 5: Fill 1372: instantaneous luminosity, top plot, and horizontal and vertical emittance from luminous region, bottom subplot. Changes of slope at about 3, 6 and 9 hours in the luminosity decay correspond to changes of slope in vertical emittance growth.

CONCLUSIONS AND FUTURE WORK

In this paper a first analysis of the LHC luminosity was set up. The peak luminosity and main beam parameters evolution was looked at for proton physics fills from 25 nominal bunches fills to bunch trains. This showed how the luminosity per bunch was increased by a factor three over time by slowly increasing the bunch intensity and decreasing the emittance. The luminosity lifetime for different fills was characterized with a parametric law (rational of fractional power), highlighting differences between different fills. In order to quantify the impact of different phenomena, dedicated measurements are strongly encouraged, e.g. the evaluation of beam parameters (losses, emittance increase) for squeezed but not colliding beams. A similar analysis was presented for a single fill, looking at bunch-by-bunch differences, confirming that beam-beam related phenomena are stronger in the beginning of the physics period. A couple of fills were looked into a bit more detail, to show the impact of 50 ns bunch spacing and of the hump. All this analysis should be repeated in the future, promptly and on a fill-to-fill basis, so to better correlate observed variations with possible causes.

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LUMINOSITY CALIBRATION

S. M. White, Geneva, Switzerland

Abstract

The experiments do not only require high collision rates and integrated luminosity, but also an absolute normalization of the observed cross sections. This normalization can be derived from theoretical predictions or the determination of the absolute luminosity. During the 2010 proton run, the Van Der Meer scan method was used to provide a first measurement of the absolute luminosity from machine parameters. Based on the outcome of the Lumi Days workshop [1], future requirements, prospects and alternative methods (vertex, high-β) will be summarized. Implications on machine operation and protection will be discussed.

INTRODUCTION

For particle colliders, the most important performance parameters are the beam energy and the luminosity. High energies allow the particle physics experiments to study and observe new effects and the luminosity is used as a measure of the number of collisions. It is defined as the proportionality factor between the event rate, measured by the experiments, and the cross section of the process observed.

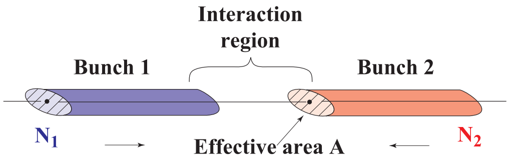

Figure 1: Luminosity from particles flux and geometry.

We consider two bunches of N_1 and N_2 particles colliding in an interaction region as shown in Figure 1. For bunches crossing head-on at a frequency f (revolution frequency in the case of a circular collider) the luminosity $\mathcal{L}_0$ is expressed as:

$$\mathcal{L}_0 = \frac{N_1\, N_2\, f}{A_{\mathrm{eff}}} = \frac{\dot{N}}{\sigma}. \tag{1}$$

$\dot{N}$ is the event rate observed by the experiments. σ is a visible cross section which depends on the energy, the physics process and the acceptance and efficiency of the detector. A_{eff} which is the effective transverse area within which the collisions take place is determined by the overlap integral and depends on the beam shape, crossing angle and offsets. For Gaussian beams colliding head-on without crossing angle we have:

$$A_{\mathrm{eff}} = 2\,\pi\,\sqrt{\sigma_{1x}^2 + \sigma_{2x}^2}\,\sqrt{\sigma_{1y}^2 + \sigma_{2y}^2}, \tag{2}$$

where σ_{iu} ($i = 1, 2$ and $u = x, y$) are the individual beam sizes.

MOTIVATION AND TARGET PRECISION

An essential ingredient in the characterization of a particle physics process is the knowledge of the absolute cross section. Recalling Equation 1 we have:

$$\mathcal{L}_0 = \frac{\dot{N}}{\sigma}. \tag{3}$$

The determination of the absolute luminosity therefore allows the particle physics experiments to normalize their data. In addition, for particle colliders the most important performance parameters are the beam energy and the luminosity. The absolute knowledge of these quantities is therefore very important to understand the performance of the machine.

The target precision for luminosity calibration is driven by the accuracy of the particle physics theoretical predictions. As of today, the W and Z production cross section is the most accurately known elementary cross section which could be determined with a precision of 2% [3]. While a measurement to better than 5% would already start challenging the models, this naturally defines the ultimate target for absolute luminosity determination.

METHODS

In e$^+$ e$^-$ colliders, the theoretically well known Bhabha scattering is generally used for this purpose. In the LHC the W and Z production which cross section could be calculated to a few percents could be used for such purpose. These normalizations however rely on the fragmentation model and it is desirable to cross check the theoretical expectations with an independent measurement.

The methods used in 2010 for luminosity calibration are based on the measurement of the effective area A_{eff} defined in Equation 1.

Van Der Meer Method

The Van Der Meer method is the main source of luminosity calibration used in 2010 and measurements were performed at the four interaction points. It was pioneered by S. Van Der Meer at the ISR [4] and uses the dependency of the luminosity on transverse offsets:

$$\mathcal{L} = \mathcal{L}_0 \exp\left[-\frac{\delta x^2}{2(\sigma_{1x}^2 + \sigma_{2x}^2)} - \frac{\delta y^2}{2(\sigma_{1y}^2 + \sigma_{2y}^2)}\right], \quad (4)$$

where δx and δy are the transverse offsets in the horizontal and vertical planes. Integrating under the curve obtained by measuring interaction rates as function of the separation will therefore allow to determine the effective beam size as well as the maximum achievable collision rate.

The main potential sources of uncertainty for this method are:

- **Bunch intensity measurements**: the LHC is a bunched beam machine and the total luminosity is given by the sum of the bunch luminosities. A precise bunch by bunch analysis is therefore required and an uncertainty on the intensity measurement would directly apply to the luminosity.
- **Beam displacement**: the knowledge of the absolute beam displacement is essential for the measurement of the beam size. Any uncertainty or error on the scale factor will directly translate in an error on the beam size.
- **Non stable beam conditions**: the precision of the method relies on the fact the beam parameters remain constant during the measurement. Emittance or orbit drifts could affect the measurement.

Other effects such as coupling or the hourglass effect could also have an impact on the measurement but are small in the LHC or could easily be minimized [5]. Generally speaking the Van Der Meer scans are best performed in the simplest possible configuration regarding beam dynamics i.e. with small beam-beam parameter.

Beam-gas Imaging

This method was initially introduced by LHCb [6] and uses the beam-gas vertices to reconstruct the individual beam sizes. The luminosity measurement using beam gas imaging does not require transverse scans and can therefore be performed parasitically. Only LHCb uses this method.

The main potential sources of uncertainty for this method are:

- **Bunch intensity measurements**: for the same reasons as for the Van Der Meer scans.
- **Non stable beam conditions**: this condition is even more relevant for this method due to the low rate of beam gas events. It is foreseen to introduce a pressure bump in order to increase the beam gas rates and reduce the time required to reconstruct the profile. The residual gas profile could also contribute to the uncertainty.
- **Vertex resolution**: the vertex resolution limits the precision with which the beam sizes can be reconstructed. This uncertainty can be decreased by increasing the IP beam sizes.

A low beam-beam parameter would also be desirable but the requirement for large beam sizes and high rates makes it difficult to accommodate. The only source of systematic uncertainty shared with the Van Der Meer scans is the beam intensity measurement. It would therefore be interesting to combine these two methods in the same fill in order to cross check the results.

An alternative to this method, also taken by CMS, is to use the proton-proton vertices during the separation scans. The same uncertainties as for the Van Der Meer scans therefore apply. The Van Der Meer method gives a direct measurement of the overlap area while this method requires to reconstruct it from the individual beam sizes which might introduce some bias in the analysis. It should therefore be seen as a complementary analysis of the Van Der Meer scans but not a primary calibration source.

Optical Theorem

This technique has been used since ISR in a number of machines and consists of determining the luminosity via an extrapolation to zero scattering angles in combination with a measurement of the total inelastic rate using the optical theorem:

$$\frac{1}{\mathcal{L}} = \frac{1}{16\,\pi}\frac{\sigma_{tot}^2\,(1+\rho^2)}{dR_{el}/dt|_{t=0}}, \quad (5)$$

where

$$\rho = \left.\frac{Re\, f_{el}(t)}{Im\, f_{el}(t)}\right|_{t=0}. \quad (6)$$

R_{tot} is the total interaction rate and R_{el} the elastic rate and f_{el} is the scattering amplitude. It is foreseen to use this method in TOTEM [7] and ATLAS [8] using dedicated high-β^* optics.

2010 MEASUREMENTS AND RESULTS

Calibration scans were performed in the four LHC interaction points [9]. The experiments first published results and latest offline analysis can be found in [11, 10], [12], [13, 14] and [15, 16]. Two sets of measurements were performed. The first measurements, in spring 2010, were performed early in the commissioning phase of the LHC and the beam conditions and instrumentation were not optimal. The final uncertainty on the measurement was found to be of 11% from which 10% came from the preliminary determination of the beam intensity [19]. A more detailed offline analysis of the beam current data improved the overall uncertainty to about 6 %. The earlier measurements also suffered from a larger emittance blow-up due related to instrumental noise picked-up by the beam [17]. The second set of measurements was performed in October 2010. Significant progress in the calibration of the LHC instrumentation and better beam conditions and stability helped reducing the overall systematic uncertainty to about 5% for these measurements. An excellent agreement was found between the different methods. The precision of 5% obtained during the first year of operation of a machine as complex as the LHC represents a significant achievement and could be further improved with dedicated beam conditions.

An example of a scan performed in CMS is shown in Figure 2.

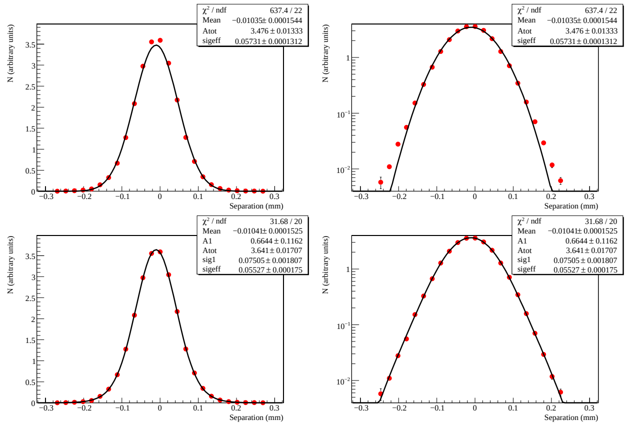

Figure 2: Example of a scan performed in CMS in the horizontal plane. The four plots show the same data, displayed with linear scale on the right, logarithmic scale on the left and single Gaussian in the top and double Gaussian in the bottom plots. A small excess of non-Gaussian tails is visible with logarithmic scale in the top right plot, which is well taken into account by the double Gaussian fit shown on the bottom.

In order to extract the correct beam size from the overlap profile it is important to know the absolute displacement generated with the closed orbit bump. An error on the relative scale of the beam position would directly translate in an uncertainty on the fitted beam size. A measurement of this error was done at the four interaction points by displacing the two beams transversally in the same direction, which results in a displacement of the luminous region, and compare the values given by the magnet settings with the position of the luminous region reconstructed by the experiments.

An excellent agreement of the order of 1% was observed between the theoretical value as given by the magnet settings and the measured luminous region centroid given by the experiments as shown in Figure 3. Different methods were used to perform this measurement in 2010. All were performed fully manually. In 2011, it would be desirable to agree on a standard procedure and implement it in an automated routine in order to avoid errors such as wrongly trimmed magnets. This measurement needs to be performed only once for the optics that are used for the scans. Using different optics for the calibration scans will result in overhead due to the requirement to perform new scale calibration measurements.

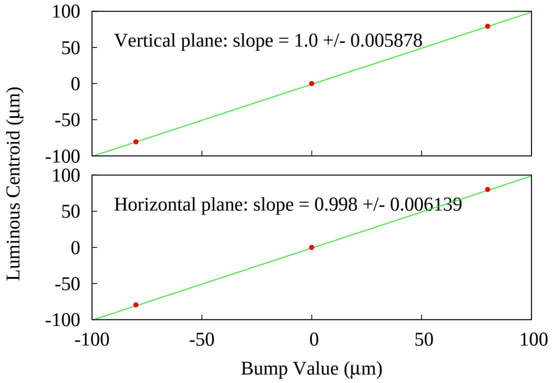

Figure 3: Bump calibration measurement done in IP5. Each scan consists of three acquisition points at -100 μm, 0 μm and +100 μm. The bump value is in excellent agreement with the vertex position.

INSTRUMENTATION

The most important observable for luminosity calibration is the intensity measurement done with Beam Current Transformers (BCT) as it directly enters the luminosity formula. They are are capable of integrating the charge of each LHC bunch. The precision of these measurements for the nominal LHC beams is expected to be of the order of 1% [18]. An additional uncertainty could come from the longitudinal bunch distribution; unbunched particles or non colliding bunches would be counted in the average beam intensity while not fully contributing to the luminosity. A careful bunch by bunch analysis combined with an intensity calibration at the end of the ramp where no unbunched beam component exists, provides a good monitoring of this uncertainty. The first measurements were performed in the early stage of the commissioning of the LHC at very low intensity (2 bunches of 2.0×10^{10} p /bunch per beam). In these conditions, an initial 10% uncertainty was derived for the determination of the beam intensity. This error was later decreased to about 3 % as the understanding of the system and the knowledge of the related systematic uncertainties was improved [19]. Increasing the overall beam intensity while keeping the bunch intensity relatively small to avoid other effects such as beam-beam and pile-up to become significant, should ultimately allow to reduce this uncertainty to 1 % per beam in the current configuration [20].

The challenge for 2011 is to reduce this error to the specifications of 1% per beam. This requires a better understanding of the satellite bunches and unbunched components which could be provided by the Longitudinal Density Monitor (LDM).

Other instruments such as the BPM system or the emittance measurements devices were used during luminosity calibration runs for verification purposes. They are not essential but proved to be very useful especially in the case of the emittance measurements. Providing automated bunch to bunch emittance acquisition and logging would help in the analysis of the calibration scan data.

MACHINE PROTECTION

The beams are displaced at the IP via a closed orbit bump that consists of four magnets and allows to control the beams independently.

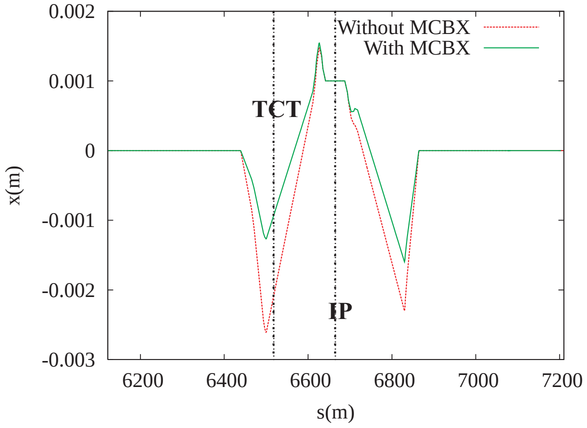

Figure 4: Example of closed orbit bumps using different orbit correctors at IP5. Displacing the beam at the IP also changes the orbit at the tertiary collimator location.

One can see in Figure 4 that a four magnet separation bump extends over a large fraction of the straight section around the IP. More specifically, displacing the beams at the IP will result in a change of orbit at the tertiary collimators (TCT). Given the non-negligible offset at the TCT introduced by the bumps, one has to ensure that while performing a separation scan the beams remain far enough from the aperture set by the collimators and that the displacement does not compromise the machine protection. In 2010, the displacement at the TCT was minimized by splitting the amplitude of the corrections required to find the optimum collision point between the two beams. In addition a re-qualification of the collimation system was done with the TCTs closed by 2σ with respect to their nominal settings to ensure that the margins were sufficient to safely perform the full scan.

In 2011, it was decided to move the TCTs together with the beam [21] in order to provide more flexibility and operation efficiency and ensure that the aperture margin between the dump protection and the TCTs remains large enough. It does not guarantee, that the safety margin between the TCTs and the triplet magnets is always respected. A complete assessment of the aperture reduction due the scans, especially in the crossing angle plane, should therefore be performed in order to ensure safe operation.

2011 SPECIAL FILLS FOR CALIBRATION SCANS

A dedicated joint machine experiments workshop was held at CERN in January 2011 [1]. The details of the discussion and proposal from the experiments can be found in [22]. The four experiments have different wishes in terms of beam conditions which can be summarized as follows:

- **ATLAS**: $\mu \approx 1.5 - 2$ driven by low acceptance detector.
- **ALICE**: $\mu \approx 0.1 - 0.5$.
- **CMS**: $\mu \approx 1$ and large beam sizes to use the proton - proton beam imaging method.
- **LHCb**: $\mu \approx 1$ and large beam sizes to use the beam - gas imaging method.

μ is the number of events per bunch crossing. It was generally agreed that these special measurements should be performed with the crossing angle on and no bunch trains. The knobs to accommodate these condition are β^*, the emittance and the bunch intensity. Some limitations apply both from the machine and operation overhead:

- Use standard optics, either physics or injection.
- Stay below or well above the BPM calibration switch to avoid crossing during the fill.

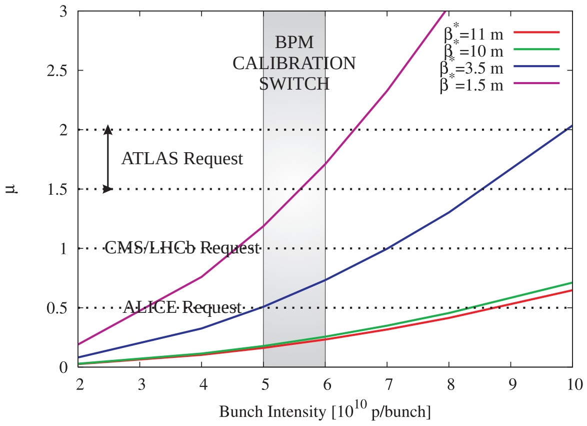

Figure 5: μ as a function of the bunch intensity for different β^* and an emittance of 3.0 μm. The experiments request are illustrated by the dashed lines.

Figure 5 shows the evolution of μ as a function of the bunch intensity for different β^* and an emittance of 3.0 μm. It is clearly seen on this picture that all the experiments requests cannot be fulfilled in a single fill unless the LHC is operated in a non-standard configuration i.e. intermediate β^*, different bunches with different intensities or emittances. This would result in significant operation overhead which could become unreasonable with respect to the time required for the measurements. It is however possible to accommodate almost all the requests in two fills using standard configuration:

- **High Precision**: optimal conditions for Van Der Meer scans. Physics optics with low bunch intensity $< 5.0 \times 10^{10}$ p/bunch. Minimal setup time.
- **Beam Imaging**: large beam sizes and high rates. Use injection optics with highest possible μ. Van Der Meer analysis could still be performed even if the conditions are not optimal. Need to assess the time required to qualify the injection optics for STABLE BEAM.
- **Reproducibility**: a few end of fill scans could be performed almost parasitically.

Given the excellent results obtained in 2010 at an energy of 3.5 TeV an early luminosity calibration is not necessary as long as the energy is not changed.

HIGH-β^* EXPERIMENTS

Two experiments, TOTEM [7] and ATLAS [8], are foreseen to study diffractive and elastic scattering at the LHC in the very forward region. They use dedicated movable detector, the Roman Pots (RP), situated on each of the IP. Ultimately these experiments should provide a cross section measurement with a precision of about 1%. The TOTEM experiment started commissioning in 2010 and is now ready for physics and expects to reach a precision of 3% on the cross section in 2011 [23]. The ATLAS experiment finished installing the RP during the 2010 winter shutdown and expects to be ready for physics in summer 2011 and to reach a precision of 5-7% on the cross section [24]. About 4 fills were requested for physics.

Both experiments require special high-β^* optics with a phase advance of $\pi/2$ in at least one plane between the IP and a roman pot detector. The details of the implementation of these optics can be found in [25].

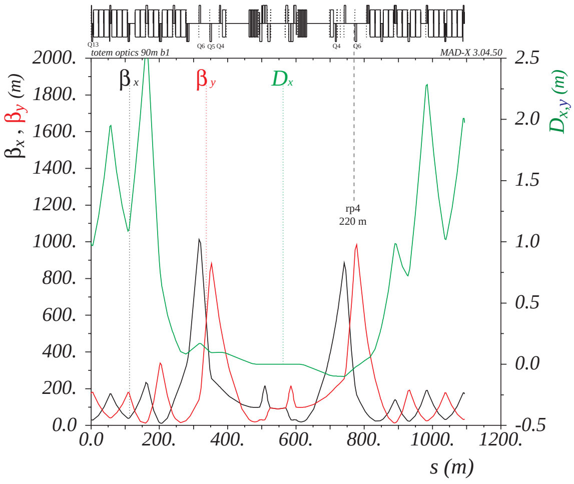

Figure 6: 90 m TOTEM optics for beam 1.

The nominal high-β^* optics have β^* of 1540 m for IP5 and 2632 m in IP1. These optics are not compatible with the actual LHC configuration. An intermediate optics solution has been found with β^* of 90 m which is illustrated in Figure 6. This optics is fully compatible with the actual LHC and is ready for commissioning in 2011 [26].

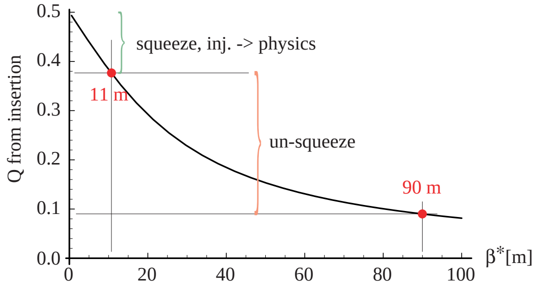

Figure 7: Tune contribution from the insertion ± 26 m from the IP as relevant for the LHC.

A low-β insertion with $\beta^* \ll \ell$, where ℓ is the distance from the IP to the triplets, contributes with a phase advance of π and tune of 0.5. For $\beta^* \gg \ell$ instead, the phase advance and tune contribution drops to zero. This is illustrated in Figure 7. We see that the local tune change from the IR for the squeeze from 11 m to 0.55 m is approximately +0.1 and about -0.3 for the un-squeeze from 11 m to 90 m. The tune changes in the un-squeeze are too large to be fully compensated internally.

Other constraints such as maintaining a phase advance of $\pi/2$ between the IP and a roman pot detector and high precision optics measurement ($\Delta\beta/\beta \approx 1\%$) make this optics very challenging for operation and the commissioning should start as soon as possible. The following strategy was discussed at the LHC Lumi Days workshop:

- Cold check-out, drive the magnets without beams
- MDs: first try to un-squeeze IP1 and IP5 at the same time, tune compensation done with the arc quadrupoles
- Beam conditions: 1 bunch per beam at low intensity, measure optics during the un-squeeze

If no major issues are found a total of 5 shifts are expected to fully commission these optics including machine protection qualification.

SUMMARY

The luminosity calibration measurements done in 2010 were very successful and a precision of 5% is expected in view of the latest results. Several methods have been developed and used which show an excellent agreement. The precision could be improved to below 5% providing dedicated beam conditions.

- **Separation Scans**: two fills are required to fulfill all the experiments wishes. As long as the energy remains at 3.5 TeV, the measurements done in 2010 remain valid and no early calibration is necessary. New developments were requested by the experiments [27] out of which the priority should be set on improving the knowledge of the bunch current normalization (BCT and LDM) and developing an automated procedure for the scale calibration. Time could be gained by performing the scans simultaneously at the four interaction points, but it remains to be demonstrated that this can be done without increase in systematic uncertainties due to beam-beam effects and leakage from the closed orbit bumps.

- **High-β^* Experiments**: TOTEM is ready for physics and ATLAS expects to be ready in summer 2011. About 4 fills were requested for physics. The 90 m optics is ready commissioning. The constraints and requirements in terms of precision represent a real challenge for LHC operation and the high-β^* goes in opposite direction with respect to the squeezed optics. Commissioning should start as soon as possible to be able to react in case of problems.

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HEAVY IONS IN 2011 AND BEYOND

John M. Jowett, Philippe Baudrenghien, Roderik Bruce, Christian Carli,
Django Manglunki,Tom Mertens, Daniel Wollmann,
CERN, Geneva, Switzerland

Abstract

The LHC's first heavy ion run set - and tested - the operational pattern for 2011 and later years: a rapid commissioning strategy intended to ensure delivery of integrated luminosity despite the risks associated with the short time-frame. It also gave us hard data to test our understanding of the beam physics that will limit performance.

The 2010 experience is fed into the commissioning plan, parameter choices and projected performance for 2011.

The prospects for future stages of the LHC ion program, Pb-Pb collisions at higher energy and luminosity, hybrid collisions and other species, depend critically on the scheduling of certain hardware upgrades.

INTRODUCTION

This talk is part of a session on the LHC luminosity in 2011. To understand what we can expect in 2011, we shall first review some aspects of the 2010 run. Given the limited time, we can only touch on a few highlights of the many things we learned from this first experience of nucleus-nucleus collisions in the LHC. We shall then discuss expectations and strategy for 2011, the possibility of hybrid proton-nucleus collisions in 2012 and recall what upgrades are needed in the coming years to explore the three dimensions of the LHC's performance parameter space (energy, luminosity, beam species).

THE 2010 LEAD-LEAD RUN

The principles of the commissioning plan for the first Pb-Pb run have evolved over the years and were summarised at the 2009 workshop [1]. A key idea in the plan was to recognise that, with a Pb beam of the same magnetic rigidity as the protons, minimising the changes to the magnetic configuration would reduce the time taken for the initial commissioning steps (achieving circulating beam, ramp, squeeze) and allow us to move quickly on to dealing with the substantial differences in beam physics between heavy ions and protons. In order to take account of the operational state of the machine and the accumulated experience with protons, final details of the plan were worked out in the weeks immediately preceding the start of the run and updated in real time on the Web [2] as they were executed.

Following the first injection of Beam 1 at 20:00 on 4 November 2010, the RF frequency was adjusted to the new value to obtain circulating beams. First collisions were obtained 54.5 h (including 11 h down time on 6 November) later at 00:28 on 7 November. Stable Beams were declared for physics at 11:20 on 7 November. In the following days, the number of bunches per beam changed on every single fill, through $k_b = 2, 5, 17, 69, 121$, injecting single bunches or batches of 4 from the SPS in variants of the “Early” filling scheme [3]. In the last few days of the run, injection of batches of 8 bunches allowed $k_b = 137$.

The integrated luminosity went up very quickly and exceeded expectations. Figure **1** compares Pb-Pb and p-p luminosities, showing clearly that the strategy allowed us to move quickly past the usual initial commissioning steps and produce luminosity useful for physics.

In practice, some care was needed to reproduce the same orbit and injection optics because of the much lower charge per bunch of the Pb beam as compared to the recent p beams. The beam position monitors had to be used in their lower dynamic range and it was necessary to transfer the reference orbit data by injecting a low intensity p beam before the species switch. Since p-p physics had been done with $\beta^* = 3.5\ \mathrm{m}$ at IP2, it was not necessary to change the optics but the crossing angle had to be adjusted so that the the large angle induced by the ALICE spectrometer bump was cancelled and collisions were head-on. The vertical tertiary collimators in IR2 were then fully opened to allow the spectator neutrons to pass unimpeded from the colliding nuclei to the Zero-Degree Calorimeter (ZDC) of the ALICE experiment.

At the other two experiments, ATLAS and CMS, the crossing angles were reduced to zero.

In addition. the beam sizes, though equal in the nominal parameter lists, were not so in practice (see the section on *Emittance Growth* below). As usual, a significant fraction of the commissioning time was devoted to collimator set-up.

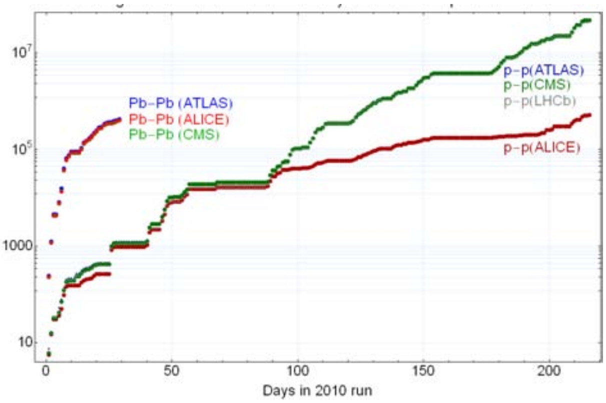


Figure 1 Integrated nucleon-nucleon luminosity ($A^2 L$, for comparison between species) in 2010 as a function of days since the start of the proton and lead runs.

There were no beam- or luminosity-induced quenches so far.

Overall, the strategy of scheduling the heavy-ion run just before the end-of-year stop, with a magnetic configuration kept as close as possible to the one used in the preceding p-p operation, seems to be a good one. It sets the pattern for future years.

Performance of Injectors

The injectors performed very well in the “Early Scheme” mode [3]. Indeed, despite the fact that the source was providing only 50% or less of design intensity, the Early mode of operation of the injector chain, without the bunch-splitting in the PS, was able to deliver bunch intensities about 70% beyond design. This was also thanks to very efficient transfer between the accelerators in the chain.

For the last fill of the year, 17 batches of 8 bunches were injected into each LHC ring from the SPS. Despite a shorted intermediate electrode in the source and thanks to the double injection into LEIR, the single bunch intensity was then 1.15×10^{8} ions/bunch , some 64% above design. The normalised emittances at injection were

$$\varepsilon_{xn} = 0.5\,\mu\text{m}, \quad \varepsilon_{yn} = 1.1\,\mu\text{m} \qquad (1)$$

substantially less than the design value of $\varepsilon_{xn} = \varepsilon_{yn} = 1.4\ \mu$m [3]; see also Figure **2**.

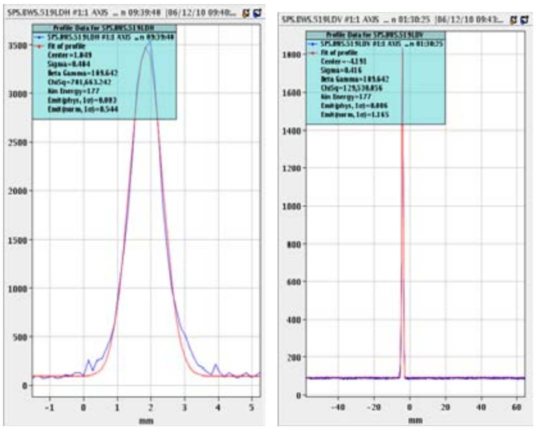


Figure 2 Wire scanner measurement of the injected Pb emittance on the last fill of 2010.

While peak performance was reached quickly, luminosity accumulation was interrupted twice for source refills. The first of these was expected (about 3 weeks uninterrupted operation expected between refills) scheduled, but grew into 5 days of “parasitic” electron cloud studies with proton beams. The second source refill had to be done unexpectedly near the end of the run. Unfortunately it turned out that it extended another interruption for cryogenics. To avoid such delays in future, it has been decided to refill the source whenever there is any kind of stop expected to last more than 24 h or so.

Beam instrumentation

In the past, concerns were often expressed that the commissioning of Pb ion beams would be slow and difficult because the initial bunch intensities would barely be visible on the beam position monitors (BPMs). This was not the case because the BPMs performed well and the injectors were able to deliver the design bunch intensities immediately. In the event, we never once had to dump beams because they fell below the threshold of visibility on the BPMs.

Emittance measurements were certainly more difficult than for protons. To avoid the risk of quenches, the wire scanners, considered to provide the best absolute calibration, could only be used at injection energy and low intensity (a few bunches).

The BSRT (synchrotron light monitors) provided the world’s first image using synchrotron light from nuclei. On the first occasion, this appeared on the screens at around 1 Z TeV but was later just visible at injection. The bunch-by-bunch capability of this device was important in revealing the differences in IBS growth rates according to individual bunch intensity. However the calibration and point-image corrections to be applied to the measurements leads to some uncertainty in absolute calibration.

The beam-gas ionisation monitors (BGI) were originally expected to be the main source of emittance data for Pb beams. They appear to provide a good continuous relative measurement but again absolute calibration is difficult and certainly changed a number of times during the ion run.

We are presently analysing the data, comparing the recommended calibrations of the instruments and attempting to achieve a consistent picture of the transverse and longitudinal emittance growth in correspondence with our simulations.

Vacuum

During the run, pressures were recovering all around the ring (following the run with protons) and the only pressure rise observed with ions were in the injections at the TDI and linked to losses [13].

Emittance growth and de-bunching

Bunch-lengthening, emittance growth (longitudinal and transverse) and de-bunching (loss of ions from the RF buckets) from intra-beam scattering (IBS) at injection were significant, as expected [4]. However the higher-than-nominal single-bunch intensity increased their importance. This subject deserves a much more extensive analysis than I have time for here but let me briefly summarise the experience and our understanding of it.

Manipulations of the RF voltage were proposed to mitigate the de-bunching. The initial value of 3.5 MV, corresponding to matched injection might be expected to best preserve the initial longitudinal emittance. However a small longitudinal emittance increases the transverse IBS, leading to loss of particles from the tails. Applying the simulation described in [4] (which includes a detailed model of IBS, going beyond the usual calculation of the emittance growth rate for a Gaussian distribution), we find results like those shown in

Figure 3. The initial mismatch blows up the longitudinal emittance and reduces the intensity loss from the transverse beam tails.

A first attempt to reduce the effects of IBS is shown in **Figure 4**. The 7 MV voltage is linearly reduced to 3.5 MV in 1 s just before injection, kept at 3.5 MV for the 3 seconds following the injection, then raised back to 7 MV in 1 s. This greatly reduced the intensity of the uncaptured beam, revealed by the difference between the DCCT (DC current monitor) and FBCT (fast current monitor for individual bunches) being suddenly reduced at the start of the ramp. However, the RF modulation creates so-called ghost bunches: there is debunching at each voltage reduction followed by recapture in nearby buckets when the voltage returns to 7 MV.

Finally it was found best to maintain the voltage at a constant 7 MV, as simulated in Figure 3. The unmatched injection produced an initial increase in longitudinal emittance from filamentation which was of overall benefit in reducing losses and, to some extent, the transverse emittance growth.

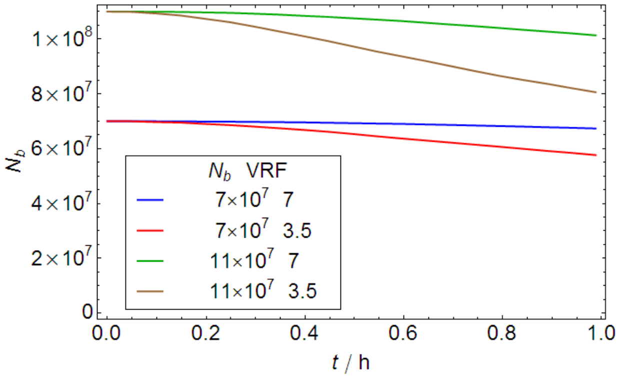
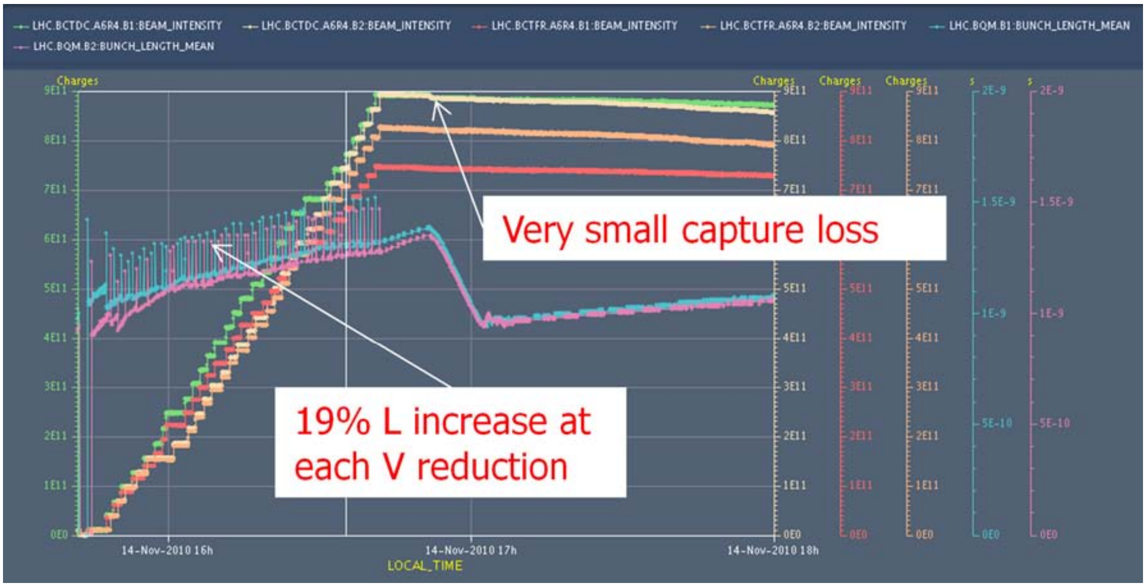


Figure 3 Simulation of the effect of doubling the RF voltage on the intensity decay of a single Pb bunch due to IBS, at nominal intensity and the higher intensity typically injected in 2010. In both cases, the higher voltage reduces the intensity decay.



Very small capture loss

19% L increase at each V reduction

Figure 4 RF voltage manipulations and their effects. These data from the logging system in a fill (12-13 Nov 2011) show the total beam charge during accumulation and the bunch length (called L here) which jumps up at each voltage reduction for injection. The capture losses at the beginning of the subsequent ramp were reduced as compared to injection with the constant $V_{\mathrm{RF}} = 3.5\ \mathrm{MV}$. The bunch length is reduced adiabatically in the ramp before starting to grow again by IBS at top energy.

Comparing simulations to the logged data is complicated by the fact that the injection process took about an hour. The bunches injected first have much more time to grow by IBS. We can see this in the individual bunch lengths. However at injection we can only measure averages of the transverse emittance so we can only try to use the simulation of a single bunch evolution as a "Green function" to fold together with the logged intensity history to predict it (the BSRTs do not work at injection for Pb beams). And there are the calibration questions and threshold intensities for operation of the BGI, maximum allowed intensities for the very few wire scans, etc.

Figure 5 shows an example of an attempt to simulate the emittance evolution during injection. The BGI provides the only continuous data on the emittances and is calibrated in this case using fits to the longitudinal IBS growth rate. This gives initial transverse emittances consistent with those estimated by other means. Note that the raw data is also smoothed using moving averages. The BGI data only appears when the intensity reaches a threshold. While the example mainly serves to illustrate the difficulty of the procedure, it also seems clear that there is an emittance growth effect beyond those (mainly IBS) included in the simulation. This is, presumably, the so-called "hump" [14] and is particularly strong in the vertical plane.

Work continues to improve these results and we hope also to apply the technique to protons.

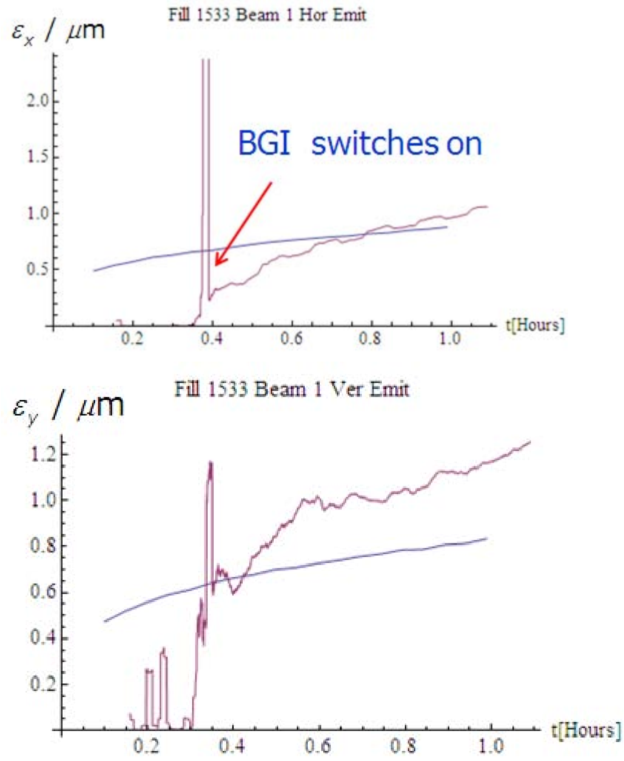


Figure 5 Simulation (blue) vs BGI data (purple) on transverse emittances at injection.

Beam losses

Beam losses have been a major focus of the studies of heavy ion beams for several years and will be discussed in more detail elsewhere.

Generally speaking the measured collimation loss maps corresponded quite well to what was expected [17,6] although some so-far-unidentified peaks have been seen in the loss maps measured during collimation set-up, particularly for the case of momentum cleaning.

Note that for ion beams, we expect the loss distribution in physics to contain peaks corresponding to the products ultraperipheral interactions such as bound-free pair production (BFPP) [16,7]. The analysis of these losses is not yet complete but will be important in estimating the ultimate luminosity reach until "cryo-collimators" are installed around experimental IPs.

Figure 6 is an example of a passive loss map measured in the highest luminosity conditions with an interpretation of the various measured peaks. Note, in particular, that the BFPP peaks occur exactly in the predicted locations and their intensity is very well correlated with luminosity.

Global cleaning with Pb beams

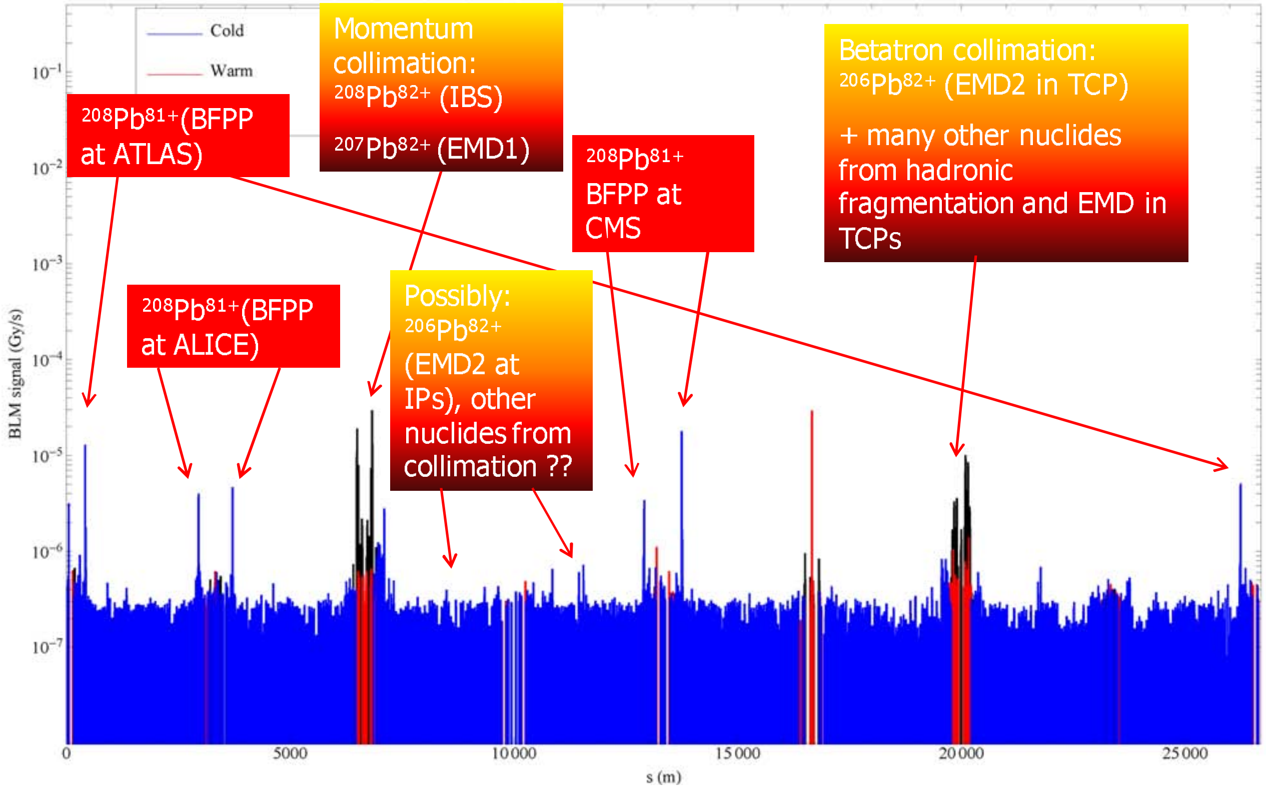
Following the same approach and notations as for protons at the Evian workshop [15], an analysis has been carried out for qualification measurements on 7-8/11/2010 at 3.5 *Z* TeV physics conditions. The highest global leakage into the cold aperture was found for Beam 2 in the vertical plane but the other planes are comparable.

$$\frac{\sum L_{\mathrm{coll}}}{\sum L_{\mathrm{all}}} = 0.948 \tag{2}$$

$$\frac{\sum L_{\mathrm{coll}} + \sum L_{\mathrm{warm}}}{\sum L_{\mathrm{all}}} = 0.981 \tag{3}$$

$$\frac{\sum L_{\mathrm{cold}}}{\sum L_{\mathrm{all}}} = 0.0186 \tag{4}$$

An overview of the leakage into specific regions is given in Table 1 [15].



$^{208}Pb^{81+}$(BFPP at ATLAS)

Momentum collimation: $^{208}Pb^{82+}$ (IBS)

$^{207}Pb^{82+}$ (EMD1)

$^{208}Pb^{81+}$ BFPP at CMS

Betatron collimation: $^{206}Pb^{82+}$ (EMD2 in TCP)

+ many other nuclides from hadronic fragmentation and EMD in TCPs

$^{208}Pb^{81+}$(BFPP at ALICE)

Possibly: $^{206}Pb^{82+}$ (EMD2 at IPs), other nuclides from collimation ??

Figure 6 Global view of losses with Pb-Pb stable beams, in the last fill of the year which provided record luminosity. The identification of the loss peaks is done according to long-standing expectations. It is of course not possible to identify the lost isotopes from the BLM data.

Intensity limit from collimation

We can derive a first estimate of the ultimate intensity limit for Pb beams

$$N_{\text{tot}}^{q} = \frac{\tau_{\min} R_q}{\eta_{\text{corr}}} c_{\text{BLM}}\, c_{\text{FLUKA}} \qquad (5)$$

It was assumed that the measured cleaning inefficiency is diluted over the length of one metre, i.e. $\eta_{\text{corr}} = \eta_{\text{meas}} / (1\text{ m})$. As the BLM response for the same losses is different for a collimator and a superconducting magnet the measured cleaning inefficiency had to be corrected by a factor of 0.36. This factor was achieved during an aperture measurement experiment earlier. The assumed quench limits R_q were taken from C. Bracco's thesis (see quotation in [15]). The minimum life time for steady state losses was derived from the data. Two ion runs have been analysed (with BLM integration times of 80 µs, 640 µs, 10.24 ms and 1.3 s):

- 20/11/2010, 121 bunches, $N_{\text{tot}} \approx 8.3\times10^{11} / Z$
- 22/11/2010, 121 bunches, $N_{\text{tot}} \approx 8.5\times10^{11} / Z$

The lowest steady state life time (1.5 h) was found in the run of the 20/11/2010 for 10.24 ms BLM integration time. Table 2 shows the parameters of the calculations for the intensity limits.

loss cases	DS	COLD	TCT
B1h	0.02	0.006	1.0e-4
B1v	0.027	0.005	0.001
B2h	0.03	0.011	8.0e-5
B2v	0.025	0.006	1.4e-4
B1+B2 pos. off momentum	0.045	8.0e-4	0.06
B1+B2 neg. off momentum	0.007	2.0e-4	0.005

Table 1 Highest leakage in local cleaning inefficiency η_{meas}, of ions into specific regions (DS = dispersion suppressor, COLD= cold aperture excluding DS, TCT = tertiary collimators).

The nominal intensity is 4.1×10^{10} ions (592 bunches, $N_b \approx 7\times10^{7}$ ions per bunch), i.e. $N_{\text{tot}} \approx 3.4\times10^{12} / Z$ (in terms of measured charges). Assuming the same performance and stability suggests that we are ready for nominal intensity with ions, even at $7\,Z$ TeV/c. At

3.5 Z TeV/c the intensity can be increased by a factor 17.5 compared to the maximum achieved in 2010.

These estimates are preliminary and do not take into account a possible reduction of the collimation inefficiency between the present and future energies (a factor 2 reduction was found for protons in simulations).

	with measured proton life time	with measured ion life time
η_c [1/m]	3e-2	3e-2
BLM response	0.36	0.36
η_{corr} [1/m]	1.08e-2	1.08e-2
τ_{min} [s]	4680	5667
R_q [p/m/s] @3.5 TeV	2.4e7	-
R_q [p/m/s] @4 TeV	1.9e7	-
R_q [p/m/s] @7 TeV	7.8e6	-
BLM factor	0.33	0.33
FLUKA factor	3.5	3.5
N_{tot}^q [charges] @3.5 TeV/c	1.20e13	**1.45e13**
N_{tot}^q [ions] @3.5 TeV/c	1.47e11	1.77e11
N_{tot}^q [charges] @4 TeV/c	9.52e12	**1.152e13**
N_{tot}^q [ions] @4 TeV/c	1.16e11	1.4e11
N_{tot}^q [charges] @7 TeV/c	3.9e12	**4.73e12**
N_{tot}^q [ions] @7 TeV/c	4.76e10	5.76e10

Table 2 Overview of measured parameters for Pb ions and the results of calculating the total intensity limit. For this analysis the lowest life time of the proton runs and the lowest life time of the 2 analyzed ion runs was used. For protons this fill took place on 26/10/2010 and had 368 bunches per beam with 150 ns bunch spacing. For ions the fill was on 20/11/2010 with 121 bunches per beam and 500 ns bunch spacing.

THE 2011 LEAD-LEAD RUN

Some of the physics conditions, such as the β^* values, will be determined by what is already in place for p-p. All details will be finalised by the time of the run, taking account of the experience gained with protons.

Orbits and optics

As for protons, we assume $\beta^* = 1.5$ m which will already be implemented for ATLAS and CMS. Since p-p running in 2011 will be done with $\beta^* = 10$ m in ALICE, some additional commissioning time, about 2 days, will be needed to implement this additional squeeze. If lower values have been implemented, we will of course take them over.

As in 2010, it is highly desirable to operate with the smallest possible crossing angle in ALICE to avoid problems for the ZDC due to the present location of the TCTVs. This point is further illustrated in the slides of this talk

We will likely also reduce crossing angles for ATLAS and CMS as this was done quickly in 2010.

The TCTVBs should be kept fully open in IR2. This caused on problems in 2010. At present we are awaiting the green light from Machine Protection to do this at higher intensity.

Filling scheme

We are considering two types of filling scheme, based either on the Nominal (100 ns bunch spacing, about 540 bunches, reduced from the 592 of [3] by the present abort gap keeper restriction) or a variation of the Early beam (called Intermediate, 200 ns spacing, about 340 bunches) in the injectors. The choice will depend on the bunch intensity that can be achieved. We expect up to 70% higher values with the Intermediate scheme for several reasons.

With the Intermediate scheme, there will be two bunches spaced at 200 ns in the PS but no splitting, a configuration that can be set up rather quickly. One would then inject up to 15 times into the SPS. Work on the injection kicker should allow us to achieve a constant spacing of 200 ns [20] (this improvement is potentially of interest for the Nominal scheme as well). Batches of up to 30 bunches can then be sent to the LHC.

In either of the currently envisage schemes, it should be possible to obtain

$$L = 1 - 1.4 \times 10^{26}\ \text{cm}^{-2}\text{s}^{-1} \qquad (6)$$

$$\text{Integrated luminosity 30-50 } \mu\text{b}^{-1}$$

in the 2011 run, with the number of days presently foreseen, and there are some prospects for doing better.

Nonetheless we should always remember that a short run is very sensitive to time lost for whatever reason (MDs, down time, …).

Luminosity evolution from simulation

The choice of filling scheme also depends on how the luminosity evolves during a fill.

Figure 7 shows some predictions based on the simulation program described in [4]. There are 4 different combinations of initial bunch intensity and emittance as indicated in the captions. The higher intensities correspond to a bunch number $k_b = 340$ and the lower to $k_b = 540$. The lower initial emittances are more likely obtained with lower bunch intensity of course.

The three plots show the bunch intensity, transverse emittance and the resulting luminosity. The emittance is growing due to IBS but no "hump" effect is included in the present simulation. The further two plots show in Figure 9 are two components of the losses, first that from de-bunching, ie, particles being lost from the tails or the RF bucket due to IBS effects, second that from luminosity burn-off due to the extremely large electromagnetic cross sections (we have calculated values appropriate to the beam energy of 4 Z TeV, a value still envisaged at the time this talk was given). Initially the luminosity losses dominate but as time goes on, the IBS losses take over.

Simulations like this can predict the integrated luminosity and will be used to decide between the filling schemes. The experiments have indicated that either scheme would be acceptable.

At present, the choice is essentially between the two cases shown as blue and brown curves and the choice is not clear. Further studies and the performance of the injectors should make the choice clearer in the coming months.

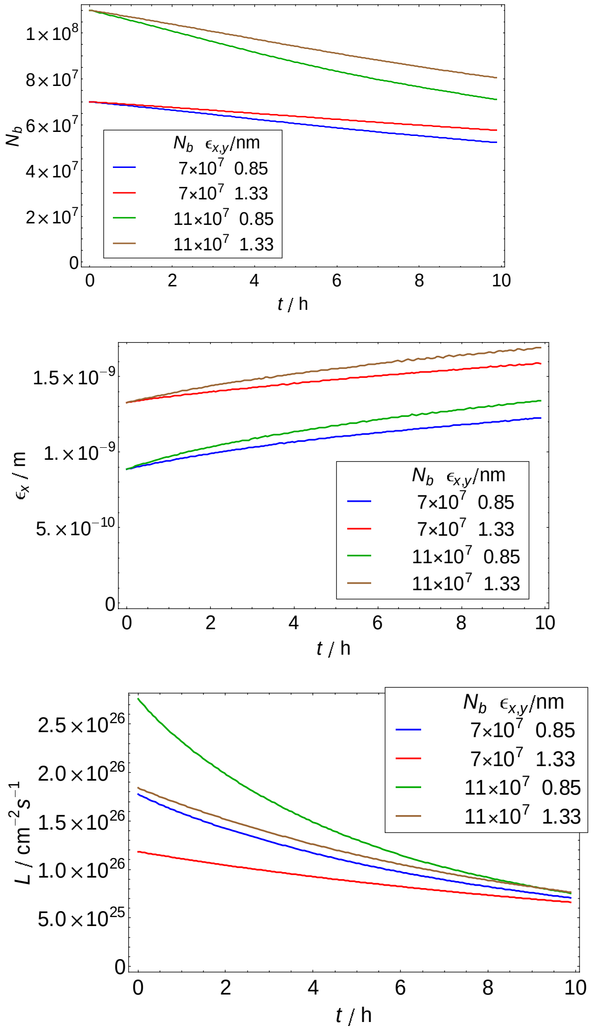


Figure 7 Simulation of luminosity evolution for various combinations of initial emittance and intensity in 2011.

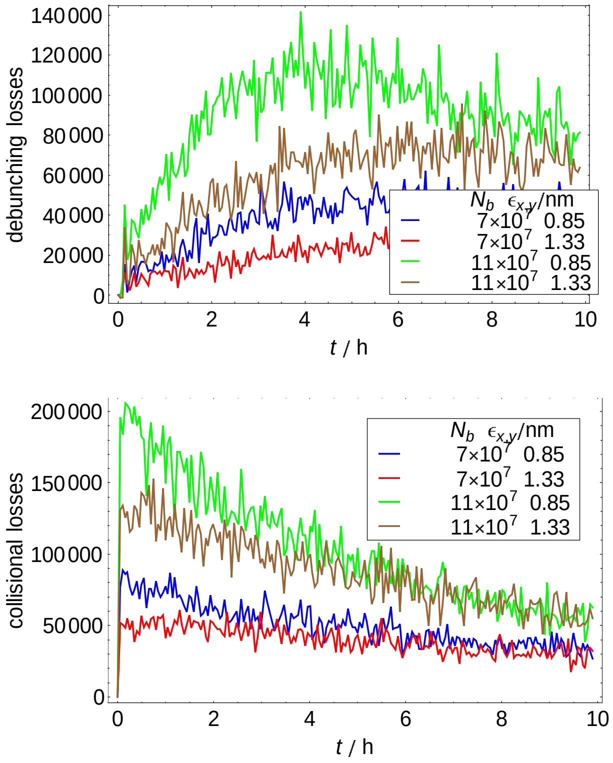


Figure 8 Losses of different physical origins (debunching and luminosity) from the same simulation as Figure 9.

THE 2012 X-LEAD RUN

The ALICE experiment has asked us to consider two possibilities for the 2012 run.

Pb-Pb collisions

The obvious possibility is to continue to accumulate luminosity since we will still be far short of the initial goal of 1 nb^{-1}. Since the beam energy is unlikely to increase (much) in 2012 there are, at present, no obvious ways to provide a significant increase in peak luminosity over 2011. However this should certainly be reviewed after the 2011 run and there is little point in discussing it further today.

p-Pb (and Pb-p) collisions

We might also consider a first attempt at providing hybrid collisions of protons with lead nuclei. Although this mode of operation of the LHC was not mentioned in [3], a first workshop was held a few years ago [9], an executive summary of the accelerator aspects was approved for inclusion in a report describing the physics case and experiments' performance [10] and a short paper was published [11].

Thanks to this preliminary work, many aspects of p-Pb operation are already clear:

- We have a clear prescription for operating the injectors: how to construct a proton beam with a 100 ns filling scheme to match that of the Pb beam (there are some concerns because of the lack of spare 80 MHz cavities in the PS).

- We have an outline of the operational cycle of LHC when operated with two beams of different mass.
- We know that no significant changes of the LHC hardware are required. In particular, the RF systems of the two rings can be operated at different frequencies during the injection and ramp. With a small upgrade to the low-level RF (to be made in 2012), it will become possible to equalise the frequencies at top energy and "cog" the beams so that collisions take place at the proper interaction points. At that point the central momentum shifts required will be [9,11]

$$\delta_{\mathrm{p}} = -\delta_{\mathrm{Pb}} = \frac{c^2\gamma_T^{\ 2}}{4p_{\mathrm{p}}^2}\left(\frac{m_{\mathrm{Pb}}^2}{Z_{\mathrm{Pb}}^2} - m_{\mathrm{p}}^2\right) \approx 3\times10^{-4} \qquad (7)$$

  at 3.5 Z TeV and the displacements of the central orbits in the arcs will be a fraction of a mm.
- The beam instrumentation is not expected to have any special difficulties.
- The BFPP problem will disappear.
- The collimation setup should be as for each beam individually.
- Although the preferred initial configuration for ALICE will be protons in Beam 1 (nucleon-nucleon centre-of-mass moving towards the spectrometer), there should be no difficult in switching beams between the rings (p-Pb to Pb-p). At [9] no preference was apparent for ATLAS and CMS.

The principal uncertainty related to this mode of operation is whether the modulation of the long-range beam-beam effects due to the moving parasitic encounter points at injection and during the ramp can lead to intensity loss or unacceptable emittance blow-up. These effects were certainly seen at RHIC in early attempts to accelerate deuteron and gold beams with equal magnetic field in the two rings [9]. However the magnitudes of the modulated beam-beam kicks and "tune-shifts" will be small at the LHC [9,11] thanks to the large separation and high beam rigidity. In addition, some local cancellation of the effects will occur because each Pb bunch will encounter a few p bunches at different betatron phase advances within each experimental straight section where the two beams can interact.

Note also that the present tentative parameter list [9,11] provides an acceptable luminosity at 7 Z TeV with only 10% of the nominal proton bunch intensity against the Nominal Pb beam.

Nevertheless, at present, a good quantitative understanding of these effects is lacking and we cannot consider the feasibility of the p-Pb mode as established.

For this reason, further studies are essential. An *experimental test* could be envisaged around the start-up of the 2011 ion run, when *both beam species are available* from the injectors. There is unlikely to be time prepare the 100 ns proton beam in the injectors but a test of injection of one or a few Pb bunches against one of the available proton beams (say, a 75 ns beam), followed by a ramp with the appropriate independent frequencies for the two beams, should be sufficient to demonstrate feasibility. If difficulties were encountered it would give us some opportunity to try mitigation strategies with present hardware.

Whatever the outcome, the information obtained would clear up the uncertainties and allow better planning for the future. This proposed experiment needs to be planned in detail but should not cost too much beam time.

A further reason for scheduling a p-Pb run in 2012 is that the centre-of-mass energy per colliding nucleon pair

$$\sqrt{s_{NN}} \approx 2E_p\sqrt{\frac{Z_1Z_2}{A_1A_2}} \qquad (8)$$

at the present proton energy, $E_p = 3.5\,\mathrm{TeV}$, would be close to that obtained in later Pb-Pb collisions, and may be useful as comparison data, as shown in Figure 9.

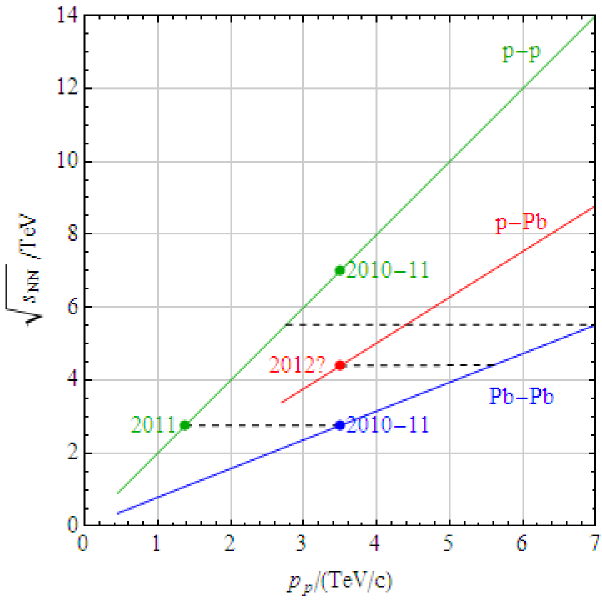


Figure 9 Nucleon-nucleon centre-of-mass energy, given by (8), for different combinations of beam species, shown as a function of the equivalent proton momentum, throughout the operating range of the LHC. The horizontal dashed lines indicate some possible correspondences of $\sqrt{s_{NN}}$ between runs of different species. These include p-Pb collisions in 2012 and Pb-Pb at a later, higher energy and the so-called "intermediate energy" p-p run requested for early this year. Note the lower limit for p-Pb collisions, as derived in [9,11].

CRITICAL UPGRADES

The following upgrades are important for the heavy-ion programme:

LLRF

For the p-Pb collision mode, as mentioned above, a small upgrade to the low-level RF will be necessary to equalise the revolution frequencies of the two beams and move the collision points to their proper positions. This will be available in 2012.

TCTVs in IR2

As discussed above, the present installation of vertical tertiary collimators (TCTVBs) in IR2 needs to be replaced to avoid interference with an essential physics signal, the spectator neutrons on the ZDCs. This involves moving the recombination chambers towards the IP and installing new TCTVs behind the ZDCs [12].

DS collimators in IR2

With our present knowledge of the performance limits, the most important upgrade would be to install dispersion suppressor collimators around IR2 to raise the peak luminosity limit (from BFPP) for ALICE. This modification is comparable to that discussed for IR3 [5] although only half as many “cryo-collimators” need to be installed.

DS collimators in IR3

This installation has been discussed in detail for protons [5] but is expected to also be very effective in raising the intensity limit due to collimation inefficiency for ion beams. Simulations of the effect of DS collimators in IR7 [6] strongly suggest that the IR3 DS collimators will be beneficial in raising the intensity of Pb beams. However simulations of the proposed combined betatron and momentum collimation in IR3 for ion beams have still to be carried out.

DS collimators in IR7

In the event that combined betatron-momentum collimation in IR3 is insufficient, it may also be necessary to install such collimators in IR7.

Note that a preliminary study of the collimation of Ar^{40+} beams [6] suggested that this might be the most demanding collimation scenario out of all beam species (including high-intensity protons) envisaged for the LHC. However almost no resources have yet been devoted to studies of light ion beams in the LHC and it is not yet possible to make meaningful estimates of beam parameters or performance.

CONCLUSIONS

The 2010 Pb-Pb run demonstrated that the LHC performs very well as a heavy-ion collider, producing physics results at energies exceeding those available elsewhere by a factor 13. The strategy for species-switch and subsequent operation were extremely efficient in terms of use of beam time.

Nevertheless the physics of heavy nuclear beams is complex and quite different from that of protons, previewing, in some ways, what we can expect with future proton-proton luminosity and energy upgrades. We now have a substantial amount of data which, when further analysed, should provide much better information on the ultimate performance limits for Pb-Pb.

The so-called “hump” [14] has a significant impact on Pb-Pb performance as well as p-p. Curing it is a high priority.

A substantial factor in peak and integrated luminosity appears possible for the 2011 run. Options for filling will be clarified in discussions over the coming months and in the injector commissioning. The experiments are flexible enough to accommodate variations of the bunch spacing.

Depending on the integrated luminosity accumulated by the end of 2011 and other physics considerations, the first p-Pb collision run may be requested in 2012. Otherwise, with present planning, first experience with hybrid collisions—and the resolution of the uncertainties related to their feasibility—would not be obtained until much later. A feasibility test can and, in my opinion, should be carried out in 2011 and need not cost much beam time.

Looking further ahead, the main focus of the LHC heavy-ion programme will always be to accumulate the maximum possible luminosity in Pb-Pb collisions. At higher beam energies we can expect gains due to smaller beams, the onset of significant synchrotron radiation damping and reduced importance of IBS in physics. However other performance limits, particularly BFPP [7]—already a prominent signal on the BLMs—will come into play. The luminosity lifetime will be shorter, particularly if there are three experiments taking collisions with low values of β^*.

As with protons, certain modifications and upgrades will be critical to maintain a steady ramp-up of luminosity in the coming years.

From the point of view of the ALICE heavy-ion programme, the priority would be to install dispersion suppressor collimators (one on each side of IR2) in the 2013 shutdown (although IR3 is of higher priority for protons and also very beneficial for ions). The idea of doing *no such installation in 2013*, followed by IR3 only in 2017, could severely limit the Pb-Pb luminosity for many years to come.

Similar modifications would ultimately be required in IR1 and IR5 to raise the Pb-Pb luminosity for ATLAS and CMS.

Acknowledgements

The success of the first Heavy Ion run of the LHC was built on the efforts of all those who contributed to the “Ions for LHC” project over many years until its recent dissolution. Many others were involved in the 2010 operation itself. My personal thanks are due to several colleagues who provided information for the present talk, in particular: R. Assmann, G. Bellodi, O. Berrig, T. Bohl, E. Carlier, H. Damerau, S. Hancock, B. Holzer, M. Jimenez, D. Kuchler, S. Maury, A. Nordt, T.

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OPERATIONAL SCHEDULE 2011 AND POTENTIAL PERFORMANCE

Malika Meddahi, CERN, Geneva, Switzerland

Abstract

The assumed LHC beam parameters for 2011 are summarised. The overview of the 2011 schedule is presented and including hardware commissioning, beams re-commissioning, re-validation, scrubbing, technical stops, MD, ions and special physics run requests. A strategy for stepping up in intensity is proposed and potential issues are described together with possible actions. Finally, the potential peak and integrated luminosity are given.

ASSUMPTIONS MADE FOR THE LUMINOSITY ESTIMATES

Luminosity calculations

The luminosity estimates presented here are calculated taking some assumptions on beam energy, β^* values at the interaction points (thereafter IPs), beam separation and crossing angles at the IPs, bunch intensity, maximum number of bunches, beam emittances, number of physics days. In the following, the choice made for these parameters are explained.

The Hübner factor [1] is an approximation used in order to estimate the integrated luminosity for a given period. This approximation takes into account the machine turnaround, the unplanned interventions, the luminosity lifetime and the fill length. It was extensively used during the LEP collider era and was indeed proven to be a very good estimate in the calculation of the integrated luminosity estimates. The product of the scheduled physics time and the peak luminosity, multiplied by the Hübner factor, gives an estimated integrated luminosity for a given period. During the LEP operation, a Hübner factor of 0.2 was reflecting very closely the machine availability in Physics mode.

From the first year of LHC operation, it was shown [2] that about 60% machine availability can be expected, together with shorter turnaround time (~3 hrs) and longer fills and luminosity lifetime, than during the LEP time. The corresponding Hübner factor would be ~0.3 for dedicated LHC Physics periods. However, a Hübner factor of 0.2 has been chosen for the 2011 luminosity calculation, as it was felt that 0.3 remains very optimistic for a prolonged Physics period (failure rate of injector chain, cryogenics systems…).

Beam parameters

From the LHC injectors, the following beam parameters (Table 1) have been achieved and can therefore be chosen for the 2011 LHC beam operation.

Table 1: Beam parameters at flat bottom

Bunch spacing [ns]	**150**	**75**	**50**
Bunch intensity **[e11 p/b]**	1.2	1.2 (1-batch) 1.2 (2-batch)	1.2 (1-batch) 1.6 (1-batch) 1.2 (2-batch)
Normalised Emittance [μm]	2	2 (1-batch) ~1 to 1.5 (2-batch)	2 (1-batch) 3.5 (1-batch) ~1.5 (2-batch)
Colliding bunches	368	936	1404

In 2010 the LHC physics operation was performed with 150 ns bunch spacing and the following beam parameters achieved for the record peak luminosity fill: bunch intensity of 1.15e11p, normalised transverse emittance of 1.6 μm, with 368 bunches per beam. In terms of number of bunches with 150 ns bunch spacing, operation should be possible with 424 bunches per beam. Concerning the bunch intensity, the average during the stable beam operation was about 1e11p going into physics, reaching 1.1e11p for the last week of proton operation. Therefore assuming for 2011 an average bunch intensity of 1.2e11p remains a step up from the 2010 values.

In Table 2, the beam parameters assumed in physics operation (when beams are brought into collisions) are summarised.

Table 2: Beam parameters at top energy

Parameter	**Value**
Energy	3.5 – 4 TeV
Bunch intensity	1.2e11 p
Normalised emittance	2.5 μm (H &V)
β^* @ IP1 – 5 – 2 - 8	1.5 – 1.5 – 10 – 3 m
Beam separation	± 170 μrad (all IPs)
B1 ½ external crossing angle	± 120 μrad (IP 1 and 5)
B1 ½ external crossing angle	± 80 μrad (IP 2)
B1 ½ external crossing angle	-235 μrad (IP8)

The reasons behind the chosen values of the external crossing angles, expressed in Table 2, for beam 1 convention, are explained in [3]. During the 2011 operation, these values will be sufficient to guarantee enough separation at all parasitic encounters.

In addition, it is assumed that the beta-beating will be corrected to about 10% and stable, as measured in 2010 [4]. The same orbit control as last year is also supposed, being better than ± 0.2 mm [5].

It is also stressed that the proposed minimum β^* values will be qualified by loss maps, after the protection device setting-up [6]. Also the aperture measurements at top energy will allow assessing the possible margin (of lack of) at the IPs and tuning accordingly the β^* values.

The squeeze will then be prepared to go to ultimate values in order to allow for "easy" squeeze extend when needed and nonstop squeeze will be used in regular operation after the beam re-commissioning [7]. Finally, corresponding matched optics will be prepared [8].

OVERHEAD FOR 4 TEV OPERATION

The duration of the 2011 LHC beam commissioning was estimated to about 3 weeks [9]. New optics will be introduced, the configuration and tests of all feedback systems will be done, together with setting-up of the transverse damper, RF systems and beam instrumentation. A virgin ramp and squeeze will be generated and fully re-commissioned. The full revalidation of the LHC Beam Dump System will be performed with beam. The collimators will be re-set-up and this will be followed by full revalidation. Finally, the mandatory extensive tests with beams for machine protection will be done. Concerning a possible run at 4 TeV, if the LHC is commissioned from the beginning of the 2011 operation straight ahead at said energy, the squeeze will be fully optimised and commissioned with optimum optical values. So there would not be any overheard in operating at 4 TeV. However, switching the energy at mid-run would cost an extra 2-3 weeks of re-commissioning.

STRATEGY FOR INTENSITY RAMP-UP

The 2010 strategy for intensity ramp-up was proven to be operationally very efficient [10]. Identical strategy is proposed for the 2011 operation, with two different periods: Before the scrubbing run, during a period of about two week time, intensity steps of about 50 bunches will be performed together with close monitoring of the vacuum pressure and beam behaviour (coherent and incoherent instabilities). This intensity ramp-up strategy is to be kept until about 300 bunches per beam are achieved. After the scrubbing run, during a period of about 2-3 week time, step of 100 bunches is proposed (300 to 400 bunches), moving on to 200 bunches (400, 600, 800 and finally 900 bunches). Again, progress will all depend on machine and beam observations made during the intensity ramp-up process (instabilities, UFO, R2E, vacuum, electron clouds….).

ESTIMATE OF THE PHYSICS OPERATION DAYS

In order to optimise the machine recovery after Technical Stops (TS), Machine Developments (MD) and special physics modes of operation, it is proposed to join such periods. Therefore, a period of 4 days of MD would immediately be followed by 4 days of TS and then 1 day of machine and beam recovery and revalidation. Also, during the 2011 Chamonix workshop, it was as well suggested that, as far as possible, the special runs for Physics [11] are grouped together allowing for a reduced number of "1-day" machine and beam recovery.

Table 3: Days for luminosity operation

Item	**Days**
Total proton operation	264
5 MDs (4 days)	~ 20
6 TS (4+1 days)	~ 30
Special requests	~ 10
Commissioning	~ 20-30
Intensity ramp up	~ 30-40
Scrubbing run	~ 10
Total High Intensity	124 – 144

From Table 3, 135 days have been taken into account for the 2011 integrated luminosity estimation. It was stressed as well that during the 2010 winter shutdown, an impressive list of system changes have been performed and consequently machine protection system checks with beams will require about ~ 10 days [12]. This mainly concerns the injection, the collimator and the beam dump systems.

START UP SCENARI

The following start-up scenario is proposed:

- Beam re-commissioning with 75 ns bunch spacing - ~3 weeks
- Increase bunch number (~300b?) – ~2 weeks
- Scrub when needed with 50 ns bunch spacing – ~1.5 weeks
- Resume 75 ns operation and increase bunch number in steps for machine protection and operation qualifications – ~2.5 weeks

Other scenarios, which were not retained, are:

- 150 ns bunch spacing beam re-commissioning, scrub with 50 ns bunch spacing and perform Physics operation with 75 ns bunch spacing. This scenario would have the advantage to re-commission the LHC in a very well known mode of operation – being the one of 2010- but was discarded as it would yet be another mode of operation to set-up (injectors chain, injection, MPS revalidation while restoring a second time 300 bunches) leading at the end to more days of beam recommissioning.
- 50 ns bunch spacing re-commissioning, scrub with 50 ns and operate with 50 ns. This mode was as well discarded as the 50 ns bunch spacing is even

more critical in terms of e-clouds build-up. Also, the scrubbing run will be very demanding on the injection set-up (nominal emittance, nominal intensity, 144 bunches) and it will be much more efficient to perform this set-up along with the beam commissioning weeks, while experience and beam parameters optimisation are accumulated.

ESTIMATED PEAK AND INTEGRATED LUMINOSITIES

In Table 4, the peak and integrated luminosities are estimated, for β* of 1.5 m. In Table 5, the estimates were given for a reduced β* of 1.3 m. In both tables, the luminosity and the stored energy are calculated for 4 TeV while the integrated luminosities are given for both 3.5 and 4 TeV. The Hübner factor was varied depending on the complexity of the mode of operation: the 2010 experience of running with 150 ns led to a choice of 0.3 for the Hübner factor, while with 75 ns, 0.2 was assumed and with the demanding 50 ns bunch spacing, 0.15 is supposed.

It can be noted that what can be gained in luminosity at 4 TeV is also at reach at 3.5 TeV, with a reduced β*. The latter was felt to be a less risky exercise than increasing the energy [13-14]. These luminosity estimates at different β* and energies, provide an additional information for the choice of the 2011 operational energy.

Table 4: Estimated peak and integrated luminosities for β* of 1.5 m

Days	H.F.	Bunch Spacing ns	Bunch number	Bunch intensity e11p/b	Emittance μm	ξ/IP	L Hz/cm^2	Stored energy MJ	L Int. fb^{-1} @ 4 TeV	L Int. fb^{-1} @ 3.5 TeV
160	0.3	150	368	1.2	2.5	0.006	~5.2e32	~30	~2.1	~1.9
135	0.2	75	936	1.2	2.5 2 1.8	0.006 0.007 0.008	~1.3e33 ~1.6e33 ~1.8e33	~75	~3 ~3.8 ~4.2	~2.7 ~3.3 ~3.7
125	0.15	50	1404	1.2	2.5	0.006	~2e33	~110	~3.2	~2.8

Table 5: Estimated peak and integrated luminosities for β* of 1.5 and 1.3 m and 75 ns bunch spacing

Days	H.F.	Bunch number	β*	Bunch intensity e11p/b	Emittance μm	ξ/IP	L Hz/cm^2	Stored energy MJ	L Int. fb^{-1} @ 4 TeV	L Int. fb^{-1} @ 3.5 TeV
135	0.2	936	1.5	1.2	2.5 2 1.8	0.006 0.007 0.008	~1.3e33 ~1.6e33 ~1.8e33	~75	~3 ~3.8 ~4.2	~2.7 ~3.3 ~3.7
135	0.2	936	1.3	1.2	2.5 2 1.8	0.006 0.007 0.008	~1.5e33 ~1.9e33 ~2e33	~75	~3.5 ~4.4 ~4.9	~3.1 ~3.9 ~4.3

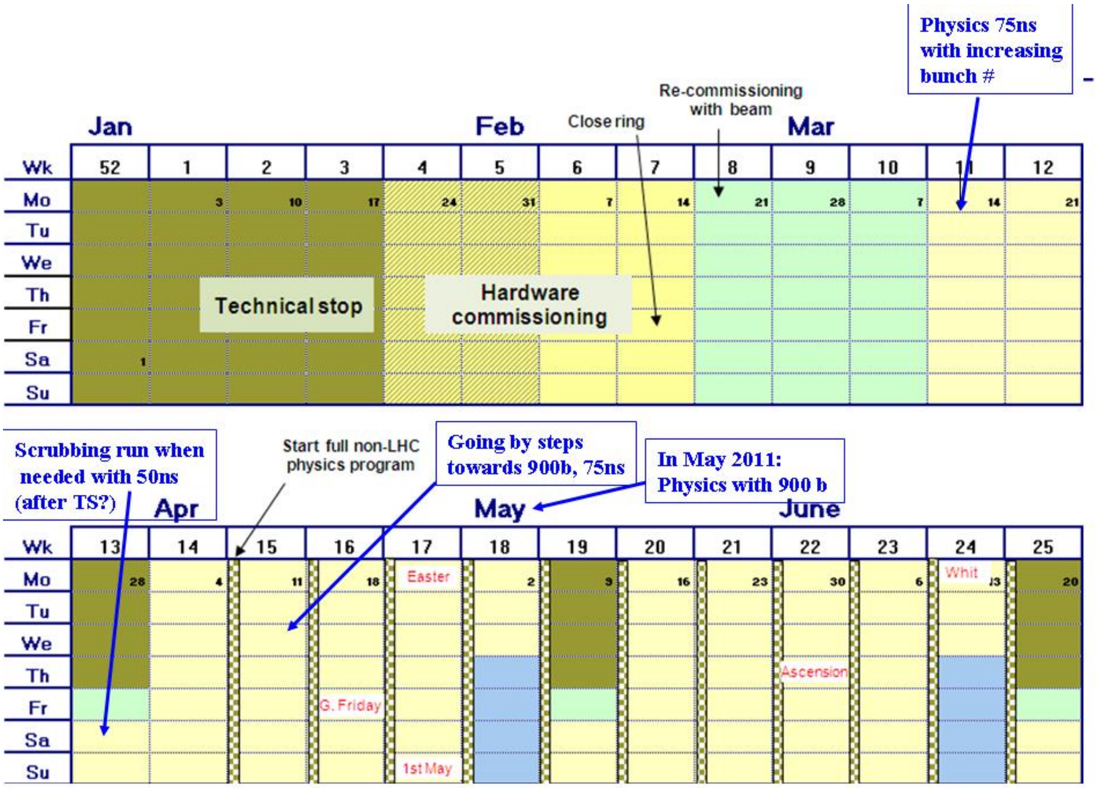

Figure 1: 2011 LHC beam commissioning schedule

2011 LHC SCHEDULE

In Figure 1, the LHC operational schedule for 2011 is presented. 3 weeks of beam re-commissioning are scheduled, followed by 2 weeks of intensity ramp-up to reach about 200-300 bunches per beam. It should be noted that the first 3 weeks of beam commissioning will mostly be performed with low number of bunches, while performing initial commissioning with bunch trains. During this period, almost certainly no 75 ns physics can be envisaged.

A technical stop is then scheduled in week 13 and would be followed by a scrubbing run with 50 ns bunch spacing beams, before increasing the bunch number progressively to 936 bunches per beam, with the 75 ns bunch spacing configuration. An intermediate energy run could possibly take place after the first technical stop, when the machine is commissioned and before the scrubbing run starts. If everything goes as expected, the machine will be ready for 936 bunch operation in May 2011.

OUTLOOK

The LHC accelerator will be re-commissioned during a period of about 3 weeks. It is proposed to use from the start of the beam operation the 75 ns bunch spacing configuration, allowing to gain right away experience with the injectors, find as early as possible any possible problems with this 2011 Physics mode of operation and have one less set-up and beam qualification for a given bunch spacing.

The scrubbing run with 50 ns bunch spacing will be performed when needed, most probably when ~300 bunches per beam are reached with 75 ns bunch spacing. Luminosity of 10^{33} cm^{-2} s^{-1} is at reach, providing possible integrated luminosity between 2-3 fb^{-1}, assuming 135 days of Physics operation.

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Do we really need the LHC luminosity upgrade?

O.S. Brüning, CERN, Geneva, Switzerland

Abstract

This paper looks at the potential performance reach for the LHC and its upgrade projects based on first observations from the LHC 2010 operation and discusses options for pushing the LHC performance beyond the nominal design values at 7 TeV beam energy.

LHC PERFORMANCE

The LHC performance can be characterized by three main parameters:

- The center of mass collision energy E_{CM} (in the following we will assume two beams with equal beam energies $\rightarrow E_{CM} = 2 \cdot E_{beam}$),
- The instantaneous luminosity specifying the rate at which certain events are generated in the beam collisions (number of events per second $= L(t) \cdot \sigma_{event}$ with σ_{event} being the cross section of the event of interest),
- The integrated luminosity specifying the total number of events that are produced over a time interval $t - t_0$.

The instantaneous luminosity is given by

$$L = \frac{f_{rev} \cdot n_b \cdot N_1 \cdot N_2}{2\pi\sqrt{(\sigma_{x,1}^2 + \sigma_{x,2}^2)} \cdot \sqrt{(\sigma_{y,1}^2 + \sigma_{y,2}^2)}} \cdot F \cdot H, \quad (1)$$

where f_{rev} is the revolution frequency, n_b the number of bunches colliding at the Interaction Point (IP), $N_{1,2}$ are the particles per bunch and $\sigma_{x,1,2}$ and $\sigma_{y,1,2}$ the horizontal and vertical beam sizes of the two colliding beams. F is the geometric luminosity reduction factor due to collisions with a transverse offset or crossing angle at the IP and H is the reduction factor for the Hour glass effect that becomes relevant when the bunch length is comparable or larger than the beta functions at the IP ($\rightarrow$ the transverse beta function varies over the luminous region where the two beams interact with each other). We neglect the hour glass effect assuming that H is close to one for all parameter sets under consideration.

The geometric reduction factor due to a crossing angle is given by

$$F = 1/\sqrt{1 + \left(\frac{\sigma_s}{\sigma_t}\frac{\phi}{2}\right)^2}, \quad (2)$$

where σ_s is the longitudinal bunch length, σ_t the transverse bunch size in the plane of the crossing angle and ϕ the total crossing angle.

In the following we assume that all bunches of both beams have equal intensities ($N_1 = N_2 = N_b$) and the same size at the IP. The transverse beam sizes at the IP are given by

$$\sigma_{x,y} = \sqrt{(\beta_{x,y}^* \cdot \epsilon_{x,y}) + D_{x,y}^2 \cdot \delta_p^2}, \quad (3)$$

where δ_p is the relative rms momentum spread ($\delta_p = \frac{\Delta p}{p_0}$) of the particles within a bunch, $\beta_{x,y}^*$ and $D_{x,y}$ are the horizontal and vertical beta and dispersion functions at the IP and $\epsilon_{x,y}$ the horizontal and vertical emittances of the two beams.

Because the bunch intensities and beam sizes of a collider vary over time, the instantaneous luminosity is implicitly a function of time.

The integrated luminosity is defined by

$$\hat{L}(t - t_0) = \int_{t_0}^{t} L(\tau) d\tau, \quad (4)$$

where t_0 is an arbitrary starting point, $L(\tau)$ the instantaneous luminosity at a given time and $t - t_0$ the time period of interest.

The HL-LHC upgrade project aims at achieving a peak luminosity of $L = 5 \cdot 10^{34} cm^{-2} s^{-1}$ with leveling such that the peak luminosity can be sustained over a significant fraction of the run time and at a integrated luminosity of ca. 250 fb^{-1} per year.

Maximizing the instantaneous luminosity implies (in order of priority):

- Maximize the number of particles per bunch (enters quadratically into the luminosity).
- Minimize the beam size at the interaction points (does not imply a 'cost' in terms of total beam power but might require special large aperture focusing quadrupoles near the experiment and tighter settings for the collimation system).
- Maximize the number of bunches in the collider.
- Optimize the overlap of the two beams at the IP (for example, this could be achieved with the use of CRAB cavities for aligning the bunches of the two beams for an optimum overlap).

The single bunch intensity is limited by collective effects and by the strength of the non-linear beam-beam interaction that the particles experience when the bunches of both beams collide with each other at the IP. The total beam current is eventually limited by hardware limitations and collective effects (e.g. multi bunch instabilities). The maximum instantaneous luminosity might be limited by the existing hardware in the machine (e.g. the cooling capacity

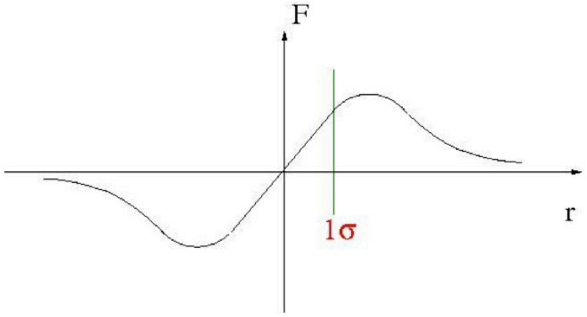


Figure 1: Schematic dependence of the beam-beam force on the particle oscillation amplitude at the IP.

for the superconducting magnets of the triplet assembly) and by the detector performance (e.g. maximum permissible event pileup per bunch crossing).

MAXIMIZING THE SINGLE BUNCH INTENSITY AND THE BEAM-BEAM LIMIT

The single bunch limitation for the Transverse Mode Coupling (TMCI) instability is estimated to be of the order of $3.5 \cdot 10^{11}$ particles per bunch [1].

The strength of the beam-beam interaction can be characterized by the linear head-on beam-beam parameter which specifies the maximum tune shift due to the beam-beam interaction per IP that a particle at the center of a bunch experiences when the two bunches collide without a crossing angle and transverse offset. The beam-beam parameter is given by

$$\xi_{x,y} = \frac{N_b \cdot r_p \cdot \beta^*_{x,y}}{2\pi \cdot \gamma \cdot \sigma_{x,y} \cdot (\sigma_x + \sigma_y)}, \tag{5}$$

where γ is the relativistic gamma factor and r_p the classical proton radius $r_p = e^2/(4\pi\epsilon_0 mc^2)$.

For round beams with equal beam emittances in both planes the beam-beam force is independent of the transverse beta-functions at the IP and depends only on the normalized beam emittance. For such round beams the beam-beam parameter can be written

$$\xi = \frac{N_b r_p}{4\pi\epsilon\gamma}, \tag{6}$$

where $\epsilon\gamma$ is the normalized emittance ϵ_n in a hadron storage ring.

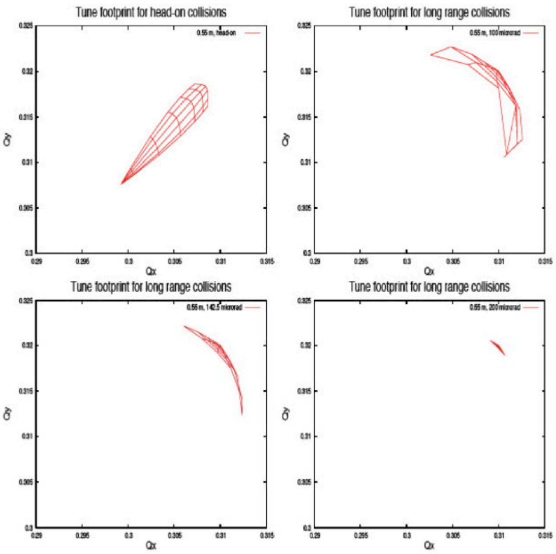


Figure 2: The tune spread due to the head-on beam-beam collisions (top left corner) together with the the tune spread from long-range beam-beam encounters for different crossing angles and beam separations for the nominal LHC configuration with $\beta^* = 0.55\ m$ (top right corner: crossing angle of 200 μrad and a beam separation of approximately 7 σ, bottom left corner: crossing angle of 285 μrad and a beam separation of approximately 10 σ, bottom right corner: crossing angle of 400 μrad and a beam separation of approximately 13 σ) [2].

Figure 1 shows a schematic picture for the dependence of the beam-beam force on the particle oscillation amplitude. While the beam-beam force in the LHC acts like a linear defocusing element (quadrupole), the force becomes strongly non-linear for particle amplitudes around 1.5 σ of the beam size and changes it's slope for large amplitude particles (long range beam-beam encounters) where the beam-beam force corresponds to the force generated by a charged wire. The nominal LHC features approximately 30 long range beam-beam encounters per Interaction Region (IR) and three head on collisions in the ATLAS, CMS and LHCb experiments (ALICE does not feature head on proton beam collisions for the nominal configuration). The tune spread due to the long-range beam-beam interactions depends on the crossing angle and the resulting beam separation at the parasitic beam encounters in the IRs. Figure 2 shows the tune spread due to the head-on beam-beam collisions (top left corner) together with the the tune spread from long-range beam-beam encounters for different crossing angles and beam separations for the nominal LHC configuration with $\beta^* = 0.55\ m$ (top right corner: crossing angle of 200 μrad and a beam separation of approximately 7 σ, bottom left corner: crossing angle of 285 μrad and a beam separation of approximately 10 σ, bottom right corner: crossing angle of 400 μrad and a beam separation of approximately 13 σ) [2].

The combined effect of head-on and long-range beam-beam collisions in the LHC results in a tune spread of the particles within the LHC beams. Figure 3 shows the resulting tune foot print for the nominal LHC collisions covering particle amplitudes from 0 to 6 σ (the particles with zero amplitudes are located at the tip of the tune foot print [near the lower left corner of the tune diagram]). The total tune spread for the nominal LHC configuration is approximately

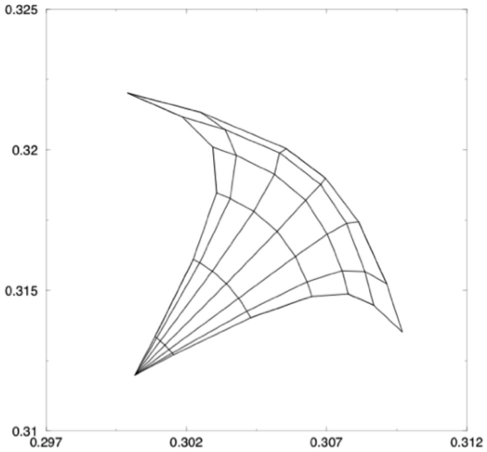


Figure 3: Tune foot print for the nominal LHC collisions covering oscillation amplitudes from 0 to 6 σ [3].

$\Delta Q = 0.01$ in both transverse planes.

The beam-beam limit in Hadron colliders without strong synchrotron radiation damping is loosely referred to as the maximum acceptable total tune spread that can still be accommodated in the tune diagram without exposing particles of the beam to too strong resonances. Experience of previous colliders have shown that resonances of order 12 or lower are detrimental to the beam distributions and the beam-beam limit can therefore be estimated as the maximum tune spread that can be accommodated in the tune diagram without exposing particles within the beam to resonances of order 12 or lower. The LHC working point is placed between the $1/3^{rd}$ and $3/10^{th}$ resonance and particles can experience the $4/13^{th}$ and $5/16^{th}$ or higher order resonances. Figure 4 shows schematically the LHC working point and beam-beam tune spread of the LHC in the tune diagram. Depending on the required distance to the coupling resonance, the total resonance-free space (up to 10^{th} order or lower) in the tune space varies between 0.01 and 0.02. The nominal LHC parameters feature a total beam-beam tune spread of $\Delta Q = 0.01$ and are compatible with conservative margins for coupling strength and additional sources for tune spread in the LHC. The beam-beam limit in the SppS collider was approximately $\Delta Q = 0.018$ and the beam-beam limit in the Tevatron collider is approximately $\Delta Q = 0.02$ for the anti-proton beam. Higher values are achievable for the total beam-beam related tune spread in the Tevatron (values of $\Delta Q = 0.03$ have been reached) but the experimental conditions and beam performance degrade quickly in the Tevatron for beam-beam tune shifts larger than $\Delta Q = 0.02$ [4].

Figure 5 shows the proton and anti-proton tune spread of the Tevatron beams in the tune diagram [5]. The red and green lines indicate resonance lines in the tune diagram. The yellow crosses are the average bunch tunes for each anti-proton bunch from Schottky measurements and the blue dots are the calculated tune distributions for the anti-proton bunches based on the measured bunch emittances and intensities (the orange dots are the calculated tune distributions for the proton bunches). Operating the machine with beam-beam tune shifts larger than $\Delta Q = 0.02$ results in some particles either hitting with low amplitudes the $3/5^{th}$ resonances or with large amplitudes the $7/12^{th}$ resonances. Having the tune of particles with large amplitudes too close to the $7/12^{th}$ resonances results in the Tevatron to the loss of halo particles (no net loss of performance as these particles do not significantly contribute to the luminosity productions). Having the tune of particles with small amplitudes too close to the $7/12^{th}$ resonances results in the Tevatron in emittance growth (varying from bunch to bunch). Both sets of resonances therefore need to be avoided during operation.

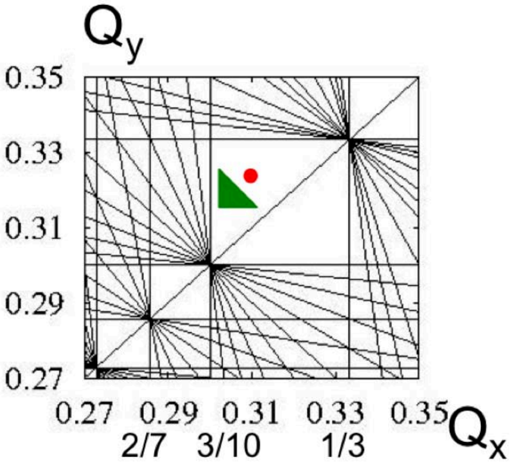


Figure 4: The LHC working point and schematic beam-beam tune spread of the LHC in the tune diagram.

ESTIMATES FOR THE BEAM-BEAM LIMIT IN THE LHC

Figure 6 shows the simulated dynamic aperture (maximum stable particle amplitudes over 10^6 turns in the LHC) for various angles for the starting conditions in the transverse plane (0 degrees equal to a purely horizontal motion and 90 degrees to a purely vertical motion) with beam-beam interactions as a function of the horizontal tune. The distance between the horizontal and vertical tunes has been kept constant at the nominal value of $Q_x - Q_y = 5.01$ [2]. The green vertical line indicates the nominal tune value for the LHC without beam-beam interaction, the blue line the tune value in the LHC with beam-beam interactions on (the defocusing force of the beam-beam interactions shifts the LHC tunes to lower values) and the red lines indicate the locations of the $3/10^{th}$, $4/13^{th}$, $5/16^{th}$ and $1/3^{rd}$ resonances. The simulations clearly indicate a reduction of the dynamic aperture for tune values close to any of the

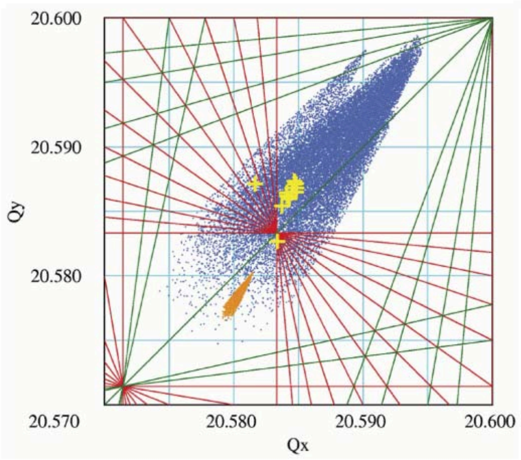


Figure 5: The Tevatron working point and beam-beam tune spread in the tune diagram. The beam-beam tune spread in the Tevatron is limited by the $3/5^{th}$ and $7/12^{th}$ resonances.

above resonances. However, the dynamic aperture does not fall below 8 σ for tune values close to the $4/13^{th}$ and $5/16^{th}$ order resonances. The $3/10^{th}$ order resonances result in dynamic aperture values down to 4 σ indicating that the $3/10^{th}$ order resonances are potentially detrimental for the LHC performance and should therefore be avoided in the LHC operation. The simulations seem to indicate that larger than nominal beam-beam tune shifts could be accommodated in the LHC if the nominal tune values are shifted to higher values closer to the $1/3^{rd}$ resonances.

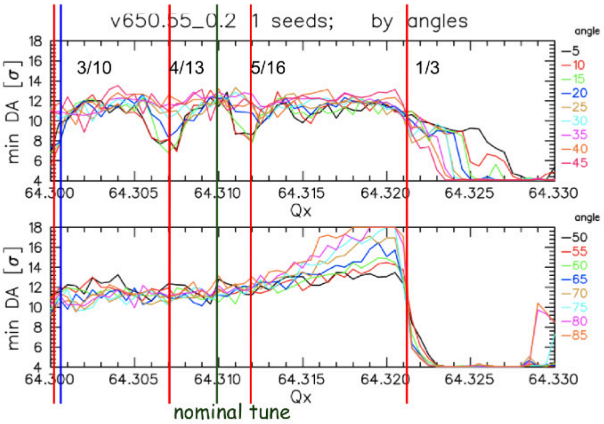
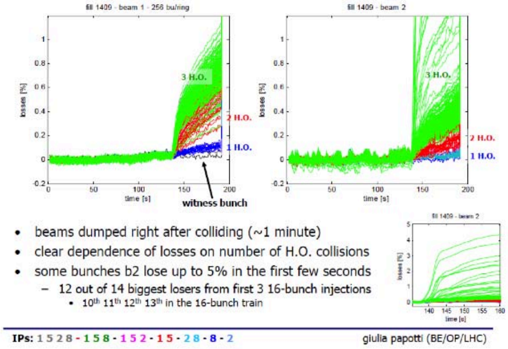


Figure 6: The Dynamic Aperture in the LHC with beam-beam interactions as a function of the horizontal tune in the machine.

Operation experience in 2010 has furthermore given indications that even resonance of 10^{th} order might be tolerable for the LHC operation and that beam-beam parameters of more than $\Delta Q = 0.02$ might be feasible even for the nominal LHC tune values. For example, Fill 1409 featured 256 bunches with a normalized transverse emittance of $\epsilon_n \approx 1.4 \mu$m and nominal bunch intensities of 10^{11} particles per bunch yielding a beam-beam parameter of $\xi = 7.7 \ 10^{-3}$ and a total beam-beam tune shift of $\Delta Q = 0.0231$ for bunches with three head-on collisions. Figure 7 shows the losses of the beams during Fill 1409 as a function of time for the different bunch classes with one, two and three head-on beam-beam collisions (blue, red and green lines respectively) [6]. While one clearly observes higher losses for bunches that have three head-on collisions as compared to bunches with one or two head-on collisions, the overall losses still seem to be acceptable.



- beams dumped right after colliding (~1 minute)
- clear dependence of losses on number of H.O. collisions
- some bunches b2 lose up to 5% in the first few seconds
  - 12 out of 14 biggest losers from first 3 16-bunch injections
    - 10th 11th 12th 13th in the 16-bunch train

Figure 7: The losses of the beams during Fill 1409 as a function of time for the different bunch classes with one, two and three head-on beam-beam collisions. While one clearly observes higher losses for bunches that have three head-on collisions as compared to bunches with one or two head-on collisions, the overall losses still seem to be acceptable [6].

Figure 8 shows the LHC tunes for the different collision classes of Fill 1409 superimposed onto the dynamic aperture simulations for the LHC with beam-beam interactions as a function of the horizontal tune in the machine. The red lines indicate the different resonances and the blue lines the tune values of the three bunch classes with one, two and three head-on beam-beam collisions. One observes that the tune of the bunches with three head-on beam-beam encounters falls right above the $2/7^{th}$ resonances, the tune of the bunches with two head-on beam-beam encounters falls between the $2/7^{th}$ and $3/10^{th}$ resonances, and the tune of the bunches with one head-on beam-beam encounter falls right above the $3/10^{th}$ resonances.

So far, the tune in physics operation has not been optimized during the 2010 operation and was fixed at the nominal design values that were optimized for a total beam-beam tune-spread of $\Delta Q = 0.01$. In order to optimize the machine operation for beam-beam parameters higher than $\Delta Q = 0.01$ the actual working point in the LHC should be optimized for a given beam-beam parameter and could be varied over a physics fill when the beam-beam parameter decreases due to the reduction in beam intensities and increase in beam emittances. One strategy for a further optimization of the LHC tunes for large beam-beam parame-

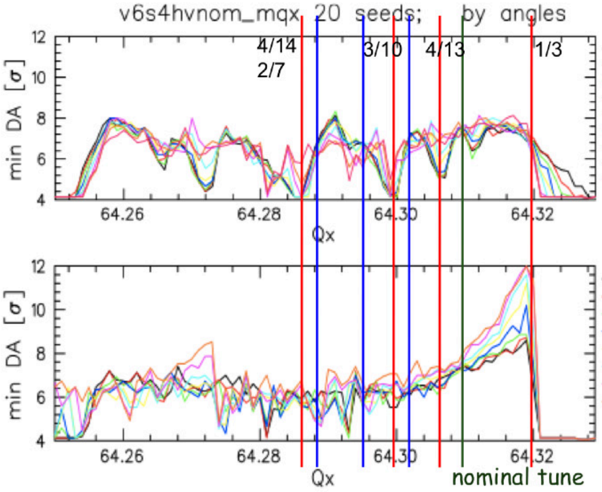


Figure 8: The LHC tunes for the different collision classes of Fill 1409 superimposed onto the Dynamic Aperture simulations for the LHC with beam-beam interactions as a function of the horizontal tune in the machine.

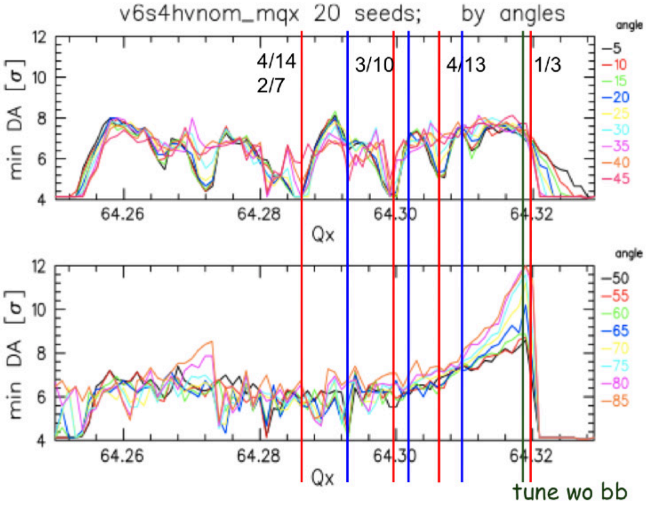


Figure 9: The LHC tunes for the different collision classes with a maximum beam-beam induced tune spread of $\Delta Q = 0.03$ superimposed onto the Dynamic Aperture simulations for the LHC with beam-beam interactions as a function of the horizontal tune in the machine.

ters could be to adjust the tunes in the LHC such that the tune of bunches with one head-on beam-beam encounter only lie right above the $4/13^{th}$ resonances, the tunes of bunches with two head-on beam-beam encounter lie right above the $3/10^{th}$ resonances and the tunes of bunches with three head-on beam-beam collisions lie between the $2/7^{th}$ and $3/10^{th}$ resonances. This strategy might imply an adjustment of the tunes as the beams are brought into collisions. Figure 9 illustrates this setup for a total beam-beam tune shift of $\Delta Q = 0.03$.

From the above observations and considerations one can conclude that a total beam-beam tune shift of $\Delta Q = 0.03$ might be in reach for the LHC operation. Based on the operational experience from the Tevatron we adopt in the following discussion of the performance reach of the LHC a slightly more conservative beam-beam limit of

$$\Delta Q_{beam-beam-limit} = 0.023, \tag{7}$$

which has already been achieved in the LHC operation in Fill 1409 (albeit without long-range beam-beam encounters). The corresponding beam-beam parameter of $\xi_{beam-beam} = 7.7\ 10^{-3}$ corresponds to a maximum bunch intensity of $N_b = 2\ 10^{11}$ to $N_b = 3.3\ 10^{11}$ depending on the assumed bunch length and crossing angle (see Tables 1 to 6 for more details) which is consistent with the assumed single bunch intensity limit from TMCI. The actual beam-beam limit in the LHC as a function of number of long-range collisions and separation is certainly a vital ingredient for estimating the LHC performance and identifying an optimum set of beam parameters for the HL-LHC. Its experimental identification should therefore be pursued with high priority in the upcoming MD sessions for the LHC.

LHC PERFORMANCE IN TERMS OF β^* VALUES

Aperture measurements in the LHC during the 2010 operation [7] indicate a better than specified mechanical aperture in the LHC. The resulting additional aperture could be used for a further squeeze of the optics at the Interaction Points (IPs) and could be compatible with β^* values between 0.3m and 0.4m (neglecting other constraints than aperture [e.g. off momentum beta-beat] for the moment that might impose larger limits on the minimum attainable β^* values).

The ATS optics scheme [8] brings β^* values of 0.15 m (for round beam) and $0.3\ m/0.075\ m$ (for flat beam operation) within reach for the HL-LHC project even for NbTi technology provided new matching section elements can be built for the corresponding larger aperture specifications.

For the estimation of the beam-beam limit in the LHC we ignored sofar the effect of long-range beam-beam interactions, assuming that the added tune spread due to the long-range collisions is small compared to the tune spread of the head-on collisions and that the non-linear forces generated by the long-range interactions are small. These assumptions on the long-range beam-beam interactions can be satisfied provided the beam separation is sufficiently large (see Figures 1 and 2). A large long-range beam-beam separation can either be achieved by increasing the crossing angle (requiring additional aperture and reducing the luminosity via the geometric reduction factor) or by increasing slightly the β^* values for a constant crossing angle (reducing slightly the luminosity via β^* and increasing the geometric reduction factor). In the following discussion we introduce additional operation margins for coping with the long-rage beam-beam effects and justifying their omission for our estimate of the LHC beam-beam limit by assuming an operational β^* value which is 15 % larger than the theoretical minimum attainable values yielding:

$$\beta^* = 0.5 \text{ m, for the nominal LHC machine} \quad (8)$$
$$\beta^* = 0.2 \text{ m, for the HL-LHC (round beams).} \quad (9)$$

LHC INJECTOR COMPLEX PERFORMANCE

A detailed discussion of the injector complex performance can be found in the proceedings of this workshop under the injector complex session. For the discussion of the LHC performance reach I used the following estimates.

Existing Injector Complex

For operation with 50 ns bunch spacing the existing LHC injector complex can provide:

$$1.2 \cdot 10^{11}\text{ppb}; \qquad \epsilon_n = 2.5\,\mu m - 3\,\mu m \text{ SB} \quad (10)$$
$$1.2 \cdot 10^{11}\text{ppb}; \qquad \epsilon_n = 1.5\,\mu m \text{ DB} \quad (11)$$
$$1.7 \cdot 10^{11}\text{ppb}; \qquad \epsilon_n = 3\,\mu m - 4\,\mu m \text{ SB}, \quad (12)$$

where SB indicates Single Batch and DB indicates double batch injection into the PS. The performance in (10) has been reached in the 2010 operation. The performance in (11) has been achieved in MD studies in 2008 [9]. And the performance in (12) is limited by single bunch effects in the SPS.

For operation with 25 ns bunch spacing the existing LHC injector complex can provide:

$$1.2 \cdot 10^{11}\text{ppb}; \qquad \epsilon_n = 3\,\mu m - 4\,\mu m \quad (13)$$
$$1.4 \cdot 10^{11}\text{ppb}; \qquad \epsilon_n = 4\,\mu m - 10\,\mu m. \quad (14)$$

The performance in (13) has been reached in the 2010 operation and the performance in (14) is limited by instabilities in the SPS.

Existing Injector Complex with LINAC4

In order to estimate the potential performance reach of the injector complex with LINAC4 and operation with 50 ns bunch spacing we take the reached performance in (11) and scale it up to the performance reach of the LINAC4 with constant brightness, assuming that the resulting beam is not limited by electron cloud effects in the PS and SPS and relying on the lower gamma-t lattice in the SPS in order to increase the single bunch instability limits in the SPS. Under these assumptions a performance reach of

$$2.5 \cdot 10^{11}\text{ppb}; \qquad \epsilon_n = 3.5\,\mu m \text{ SB} \quad (15)$$

seems to be within reach for 50 ns bunch spacing and LINAC4. The performance estimate for 25 ns does not change with the LINAC4 operation as the limit in (14) is given by bottle necks in the SPS.

Full Injector Complex Upgrade

Assuming a Laslett space charge limit of $\Delta Q = -0.3$ in the PS one can hope to reach the following performance reach for operation with 50 ns bunch spacing [10] [11]

$$2.7 \cdot 10^{11} - 3.5 \cdot 10^{11}\text{ppb}; \qquad \epsilon_n = 1.1 - 1.5\,\mu m. \quad (16)$$

For the operation with 25 ns bunch spacing one can hope to reach with a Laslett space charge limit of $\Delta Q = -0.3$ in the PS a performance of

$$1.7 \cdot 10^{11} - 2.0 \cdot 10^{11}\text{ppb}; \qquad \epsilon_n = 1.5 - 1.8\,\mu m. \quad (17)$$

SPS Space charge limit

The above performance reach for operation with 50 ns bunch spacing might be slightly lower if one assumes a space charge tune spread limit of $\Delta Q = -0.13$ in the SPS [12]

$$3.3 \cdot 10^{11}\text{ppb}; \qquad \epsilon_n = 3.75\,\mu m. \quad (18)$$

For the operation with 25 ns bunch spacing one can hope to reach with a Laslett space charge limit of $\Delta Q = -0.13$ in the SPS a performance of

$$2.0 \cdot 10^{11}\text{ppb}; \qquad \epsilon_n = 2.5\,\mu m. \quad (19)$$

The actual space charge limit in the SPS and the PS is certainly a vital ingredient for the performance estimate of the LHC injector complex and its identification should get a high priority in the upcoming MD sessions for the LHC injector complex.

TOTAL INTENSITY LIMITATION IN THE LHC

In addition to limitations coming from single bunch effects such as the beam-beam interaction and the TMCI, the total beam intensity in the LHC is limited by electron cloud effects and hardware limitations of the existing machine. A first analysis of potential hardware limitation has been performed by Ralph Assmann for the Chamonix 2010 discussions [13]. These estimates indicated a maximum total beam current of approximately 0.85 A corresponding to 2808 bunches with ultimate bunch intensities. The findings given in [13] only provide first estimates and identifications of the maximum acceptable beam intensities in the LHC. A thorough estimate of the maximum beam intensities and an analysis of ways and implications for increasing it in the framework of the LHC upgrade program should clearly be part of the upcoming HL-LHC studies.

ESTIMATES OF THE PERFORMANCE REACH FOR LHC MACHINE

Performance Estimate for the nominal LHC machine for operation at 7 TeV beam energy with the existing injector complex

First operation experience with the LHC in 2010 showed that the LHC can be operated with smaller than nominal beam emittances and larger than nominal values for the beam-beam parameters. Table 1 summarizes the resulting maximum performance reach for the nominal LHC machine when considering these larger values for the beam-beam limit and bunch intensities. The table shows the nominal design parameters together with two distinct sets of parameters: a set for operation with nominal beam emittances for operation with 25 ns and 50 ns and one set for operation with 50 ns bunch spacing and smaller than nominal transverse beam emittances.[1] It is interesting to note, that with the revised assumption on the beam-beam limit in the LHC the two options with 50 ns bunch spacing can provide with the existing injector complex a larger than nominal LHC performance with smaller than nominal total beam currents (and thus with smaller than nominal stored beam power). The total beam-beam tune shift remains for all cases below $\Delta Q = 0.02$ if one assumes three IPs with head-on collisions and that the tune shift arising from the long-range beam-beam interactions is much smaller than the tune shift coming from the head-on collisions.

Table 1: LHC Performance Reach for Nominal Configuration at 7 TeV with the existing injector complex.

Parameter	**nominal**	**25 ns**	**50 ns**	**50 ns**
$N_b[10^{11}]$	1.15	1.2	1.7	1.7
n_b	2808	2808	1404	1404
I [A]	0.58	0.61	0.43	0.43
x-ing $[\mu rad]$	300	320	320	270
b-b sep. $[\sigma]$	10	10	10	10
β^* [m]	0.55	0.5	0.5	0.5
$\epsilon_n[\mu m]$	3.75	3.75	3.75	2.5
ϵ_s [eVs]	2.51	2.5	2.5	2.5
E spread	10^{-4}	10^{-4}	10^{-4}	10^{-4}
σ_s [cm]	7.5	7.5	7.5	7.5
IBS h [h]	106	101	71	29
IBS l [h]	60	58	41	25
Piwinski	0.68	0.76	0.76	0.78
R	0.83	0.8	0.8	0.79
b-b $[10^{-3}]$	3.1	3.1	4.4	6.6
event pileup	19	19	46	65
L $[cm^{-2}s^{-1}]$	$1\ 10^{34}$	$1\ 10^{34}$	$1.2\ 10^{34}$	$1.7\ 10^{34}$

Performance Estimate for the nominal LHC machine for operation at 7 TeV beam energy with existing injector complex and LINAC4

Table 2 summarizes the resulting maximum performance reach for the nominal LHC machine when considering the increased beam brightness from LINAC4 and operation with nominal beam emittance. The table shows the nominal design parameters together with two sets of parameters: one for operation with 25 ns and one for operation with 50 ns. It is interesting to note, that for both options with larger than nominal bunch intensities the total beam-beam tune shift remains below $\Delta Q = 0.02$ if one assumes three IPs with head-on collisions and that the tune shift arising from the long-range beam-beam interactions is much smaller than the tune shift coming from the head-on collisions. The total beam current remains in all cases below the ultimate LHC beam current (2808 bunches with $1.7\ 10^{11}$ particles per bunch correspond to a total beam current of 0.85 A).

However, none of the parameter sets given in Table 2 can reach the design goal for the peak luminosity of the HL-LHC project ($L = 5\ 10^{34} cm^{-2}s^{-1}$) not to mention the requirement to reach such a peak luminosity with margins for leveling (e.g. with a virtual peak performance in excess of $L = 5\ 10^{34} cm^{-2}s^{-1}$).

Table 2: LHC Performance Reach for Nominal Configuration at 7 TeV beam energy with the existing PS and PSB and LINAC4.

Parameter	**nominal**	**25 ns**	**50 ns**
$N_b[10^{11}]$	1.15	1.4	2.5
n_b	2808	2808	1404
I [A]	0.58	0.71	0.64
x-ing $[\mu rad]$	300	320	320
b-b sep. $[\sigma]$	10	10	10
β^* [m]	0.55	0.5	0.5
$\epsilon_n[\mu m]$	3.75	3.75	3.75
ϵ_s [eVs]	2.51	2.5	2.5
E spread	10^{-4}	10^{-4}	10^{-4}
σ_s [cm]	7.5	7.5	7.5
IBS h [h]	106	80	45
IBS l [h]	60	41	23
Piwinski	0.68	0.76	0.76
R	0.83	0.8	0.8
b-b $[10^{-3}]$	3.1	3.6	6.5
event pileup	19	30	95
L $[cm^{-2}s^{-1}]$	$1\ 10^{34}$	$1.6\ 10^{34}$	$2.5\ 10^{34}$

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[1] The IBS growth rates in all tables have been calculated by John Jowett

Performance Estimate for the nominal LHC machine for operation at 7 TeV beam energy with a full injector complex upgrade

Table 3 summarizes the resulting maximum performance reach for the LHC machine when considering the increased beam brightness from a complete injector complex upgrade and operation with nominal β^* values. The table shows the nominal design parameters together with two sets of parameters: one for operation with 25 ns and one for operation with 50 ns.

Both options with larger than nominal bunch intensities feature a total beam-beam tune shift that is larger than $\Delta Q = 0.02$ if one assumes three IPs but stay below $\Delta Q = 0.023$ (the value achieved in Fill 1409 during the 2010 operation). The total beam current for the operation with 50 ns bunch spacing remains below the 'ultimate' beam current of 0.85 A. But the beam current for the 25 ns option exceeds this assumed maximum value by approximately 20%.

Both parameter sets given in Table 3 remain slightly ($\approx$ 10%) short of the design goal for the peak luminosity of the HL-LHC project ($L = 5\ 10^{34} cm^{-2} s^{-1}$) but do provide 20% to 10% margins for leveling (e.g. via Crab cavities or beam-beam long-range wire compensators that allow operation with smaller crossing angles).

Table 3: LHC Performance Reach for Nominal Configuration at 7 TeV with a full injector complex upgrade.

Parameter	nominal	25 ns	50 ns
$N_b[10^{11}]$	1.15	2.0	3.3
n_b	2808	2808	1404
I [A]	0.58	1.02	0.84
x-ing $[\mu rad]$	300	270	320
b-b sep. $[\sigma]$	10	10	10
β^* [m]	0.55	0.5	0.5
$\epsilon_n[\mu m]$	3.75	2.5	3.75
ϵ_s [eVs]	2.51	2.5	2.5
E spread	10^{-4}	10^{-4}	10^{-4}
σ_s [cm]	7.5	7.5	7.5
IBS h [h]	106	25	37
IBS l [h]	60	21	21
Piwinski	0.68	0.78	0.76
R	0.83	0.79	0.8
b-b $[10^{-3}]$	3.1	7.7	8.6
event pileup	19	91	167
L $[cm^{-2}s^{-1}]$	$1\ 10^{34}$	$4.8\ 10^{34}$	$4.4\ 10^{34}$

Performance Estimate for the HL-LHC machine for operation at 7 TeV beam energy with a full injector complex upgrade

Table 4 summarizes the resulting maximum performance reach for the LHC machine when considering the increased beam brightness from a complete injector complex upgrade and operation with small β^* values [8]. The table shows the nominal design parameters together with two sets of parameters: one for operation with 25 ns and one for operation with 50 ns.

Both upgrade parameter sets given in Table 4 clearly exceed the design goal for the peak luminosity of the HL-LHC project ($L = 5\ 10^{34} cm^{-2} s^{-1}$) (by ca. 15% to 20%) and almost a factor two margin for leveling (geometric reduction factor $R < 0.5$) (e.g. leveling via Crab cavities or beam-beam long-range wire compensators that allow operation with smaller crossing angles).

It is interesting to note, that for both options with larger than nominal bunch intensities the total beam-beam tune shift remains well below $\Delta Q = 0.02$ if one assumes three IPs and assumes that the tune shift arising from the long-range beam-beam interactions is much smaller than the tune shift coming from the head-on collisions. The total beam current for the operation with 50 ns bunch spacing remains below the 'ultimate' beam current of 0.85 A. But the beam current for the 25 ns option exceeds this assumed maximum value by approximately 20%.

Table 4: LHC Performance Reach at 7 TeV with HL-LHC and a full injector complex upgrade.

Parameter	nominal	25 ns	50 ns
$N_b[10^{11}]$	1.15	2.0	3.3
n_b	2808	2808	1404
I [A]	0.58	1.02	0.84
x-ing $[\mu rad]$	300	420	520
b-b sep. $[\sigma]$	10	10	10
β^* [m]	0.55	0.2	0.2
$\epsilon_n[\mu m]$	3.75	2.5	3.75
ϵ_s [eVs]	2.51	2.5	2.5
E spread	10^{-4}	10^{-4}	10^{-4}
σ_s [cm]	7.5	7.5	7.5
IBS h [h]	106	25	37
IBS l [h]	60	21	21
Piwinski	0.68	1.92	1.95
R	0.83	0.46	0.46
b-b $[10^{-3}]$	3.1	4.5	4.9
event pileup	19	133	239
L $[cm^{-2}s^{-1}]$	$1\ 10^{34}$	$7.0\ 10^{34}$	$6.3\ 10^{34}$

Performance Estimate for the HL-LHC machine for operation at 7 TeV beam energy with a full injector complex upgrade and operation with long bunches

The IBS growth rates given in Tables 3 and 4 reach rather small values which are comparable with the radiation damping times of the LHC at 7 TeV (ca. 25 h and 12.5 h in the transverse and longitudinal planes). In order to maximize the net luminosity lifetime it might be desirable to reduce the IBS growth rates by operating the machine with larger longitudinal emittances.

Table 5 shows one option for such an operation scenario for the full injector upgrade and operation with small β^* values. The resulting IBS growth rates are almost a factor two smaller than those for the operation with the nominal bunch length.

Both upgrade parameter sets for operation with 25 ns and 50 ns bunch spacing are still capable of reaching the design goal for the peak luminosity of the HL-LHC project ($L = 5\ 10^{34} cm^{-2} s^{-1}$) and provide more than a factor two margin for leveling (geometric reduction factor $R < 0.4$) (e.g. leveling via Crab cavities or beam-beam long-range wire compensators that allow operation with smaller crossing angles).

The total beam-beam tune shift still remains well below $\Delta Q = 0.02$ (if one assumes three IPs and assumes that the tune shift arising from the long-range beam-beam interactions is much smaller than the tune shift coming from the head-on collisions) and the total beam current for the operation with 50 ns bunch spacing remains still below the 'ultimate' beam current of 0.85 A while the beam current for the 25 ns option exceeds this assumed maximum value by approximately 20 %.

Table 6 a similar option for a operation with long bunches for the full injector upgrade and operation with nominal β^* values ($\beta^* = 0.5$ m). Both upgrade parameter sets for operation with 25 ns and 50 ns bunch spacing fall slightly short (by ca. 15% to 20%) of the design goal for the peak luminosity of the HL-LHC project ($L = 5\ 10^{34} cm^{-2} s^{-1}$) but still provide a significant margin for leveling (geometric reduction factor $R < 0.7$) (e.g. for leveling via Crab cavities or beam-beam long-range wire compensators that allow operation with smaller crossing angles).

The total beam-beam tune shift exceeds $\Delta Q = 0.02$ but still remains below $\Delta Q = 0.023$, the value that has been achieved in Fill 1409 during the 2010 operation (if one assumes three IPs and assumes that the tune shift arising from the long-range beam-beam interactions is much smaller than the tune shift coming from the head-on collisions). The total beam current for the operation with 50 ns bunch spacing remains below the 'ultimate' beam current of 0.85 A while the beam current for the 25 ns option exceeds this assumed maximum value by approximately 20%.

Table 5: LHC Performance Reach at 7 TeV with HL-LHC and a full injector complex upgrade and operation with long bunches.

Parameter	**nominal**	**25 ns**	**50 ns**
$N_b [10^{11}]$	1.15	2.0	3.3
n_b	2808	2808	1404
I [A]	0.58	1.02	0.84
x-ing $[\mu rad]$	300	420	520
b-b sep. $[\sigma]$	10	10	10
β^* [m]	0.55	0.2	0.2
$\epsilon_n [\mu m]$	3.75	2.5	3.75
ϵ_s [eVs]	2.51	3.0	3.0
E spread	10^{-4}	10^{-4}	10^{-4}
σ_s [cm]	7.5	10	10
IBS h [h]	106	39	56
IBS l [h]	60	58	56
Piwinski	0.68	2.57	2.59
R	0.83	0.36	0.36
b-b $[10^{-3}]$	3.1	3.6	4.9
event pileup	19	105	186
L $[cm^{-2} s^{-1}]$	$1\ 10^{34}$	$5.5\ 10^{34}$	$4.9\ 10^{34}$

SUMMARY

The above performance evaluations show that the design goal of the HL-LHC project can only be achieved with a full upgrade of the injector complex and the operation with β^* values below 0.5 m. Significant margins for leveling can only be achieved for β^* values close to 0.2 m. However, these margins can only be harvested during the HL-LHC operation if the required leveling techniques have been demonstrated in operation. Options for leveling include:

- The use of Crab cavities (not yet demonstrated for operation of hadron storage rings).
- The use of wire compensators for compensating the long-range beam-beam interaction. While it has been experimentally demonstrated that wires have a measurable effect on the stability of halo particles it has not yet been demonstrated that wires can compensate beam-beam induced long-range collisions in operation. It is therefore desirable to install LRBB wire compensators during the first long shutdown of the LHC (currently scheduled for 2013 to 2014) so that their applicability can be experimentally investigated in the LHC before the implementation of the HL-LHC upgrade (currently planned at the earliest for 2020).
- Dynamic squeeze of the optic functions at the IP during luminosity operation. Feasibility of such a procedure has never been demonstrated during operation of an existing machine, not to mention for a machine

Table 6: LHC Performance Reach at 7 TeV with nominal β^* values and a full Injector Complex upgrade and operation with long bunches.

Parameter	**nominal**	**25 ns**	**50 ns**
$N_b[10^{11}]$	1.15	2.0	3.3
n_b	2808	2808	1404
I [A]	0.58	1.02	0.84
x-ing $[\mu rad]$	300	270	320
b-b sep. $[\sigma]$	10	10	10
β^* [m]	0.55	0.5	0.5
$\epsilon_n[\mu m]$	3.75	2.5	3.75
ϵ_s [eVs]	2.51	3.0	3.0
E spread	10^{-4}	10^{-4}	10^{-4}
σ_s [cm]	7.5	10	10
IBS h [h]	106	39	56
IBS l [h]	60	58	56
Piwinski	0.68	1.04	1.0
R	0.83	0.69	0.7
b-b $[10^{-3}]$	3.1	6.8	7.6
event pileup	19	80	148
L $[cm^{-2}s^{-1}]$	1 10^{34}	4.2 10^{34}	3.9 10^{34}

like the LHC with unprecedented stored beam energies and small margins for losses during operation. An experimental validation of this option would be very interesting for the planning of the HL-LHC upgrade.

- Luminosity leveling via transverse offsets of the beams at the IPs. While first operation experience in the LHC has shown that the operation with beam offsets at the IP is in principle possible, the feasibility of such a procedure has never been demonstrated during operation with many long range beam-beam interactions. An experimental evaluation of this option would be very interesting for the planning of the HL-LHC upgrade.

In addition to the validation of the above leveling options, the final parameters of the HL-LHC upgrade depend also on the replies to the following points that, where applicable, should be addressed with high priority during the Machine Development periods of the LHC and the injector complex:

- Need to verify the LHC beam-beam limit as function of beam separation and number of long-range collisions.
- Need for identifying the maximum achievable bunch intensities for operation with 25 ns and 50 ns in the LHC injector complex.
- Need for identifying the smallest achievable transverse emittance for nominal and ultimate bunch currents for operation with 25 ns and 50 ns in the LHC injector complex.
- Need for identifying the maximum acceptable total beam current in the LHC. The presentation by Frank Zimmermann [14] highlights that the maximum attainable beam lifetime in the LHC is directly proportional to the maximum acceptable beam current.
- Interest in testing the ATS scheme in the existing LHC during MD studies.

Assuming a maximum limit for the total beam current in the LHC, the performance can clearly be maximized by putting the beam current in the smallest number of bunches. This gives a preference for operation with 50 ns bunch spacing. In all the scenarios discussed above, the 50 ns bunch spacing scenarios are the only options that can provide the HL-LHC design goals with less than 'ultimate' total beam currents. The operation scenarios with 25 ns bunch spacing imply approximately 20% larger total beam currents. Formulated the other way around, in case the beam current in the LHC is really limited to 'ultimate' beam currents, the performance of the 25 ns operation scenarios will be approximately 35% smaller than quoted in the above discussions.

However, the operation with 50 ns bunch spacing also implies larger bunch luminosities and therefore a larger event pile up per interaction. While the event pileup is approximately 100 for the operation scenarios with 25 ns bunch spacing (approximately a factor fife larger than the nominal pileup), the maximum event pileup varies between 150 and 240 events per bunch crossing for the operation scenarios with 50 ns bunch spacing corresponding approximately to a tenfold increase with respect to the nominal LHC configuration. It still remains to be demonstrated that such high pile up rates are acceptable for the experiments.

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BREACHING THE PHASE I OPTICS LIMITATIONS FOR THE HL-LHC

Stéphane Fartoukh, CERN, Geneva, Switzerland

Abstract

This paper scrutinizes the performance goal of the HL-LHC Project and proposes a solution to reach it. This solution is based on an Achromatic Telescopic Squeezing (ATS) principle which can push β^* well below the limits which were identified in the context of the so-called Phase I Upgrade studies. The novel optics scheme is described, with its main weak points, possible mitigation measures and hardware modifications needed in the LHC ring in order to implement it. Other implications or by-products are also highlighted. Some of them are rather exotic and are worth to be mentioned in the abstract even if not completely developed in the paper: the possibility to run with a third low-β experiment installed in IR3 or IR7 (which is an interesting direction for a smooth co-habitation between the HL-LHC and the LHeC), a notable reduction of the IBS growth rate in the longitudinal plane (generally the most critical plane), or a boost by more than one order of magnitude for the efficiency of the Landau octupoles, making them strong enough to shape the head-on beam-beam tune footprint (but without yet any demonstration of the possible benefits) or, at least, to relax the constraints on the transverse impedance budget of the LHC at 7 TeV.

INTRODUCTION

One key ingredient to push the performance of a collider is a reduction of the transverse beam sizes at the interaction point (IP), which are directly given by the transverse emittances of the beam and by the value of the β-functions at the IP, i.e. β^*_x and β^*_y. Intrinsic limitations obviously exist for each of these quantities, driven by the performance of the injector for the first one and by a series of optics and aperture related constraints for β^* in the LHC.

Using the usual concept of a circular collider where low-β insertions (IR) with "squeezable" optics are interleaved with passive arcs used to transport the beam at constant optics, and counting already on a very sophisticated scheme for the correction of the chromatic aberrations induced by the final quadrupoles of the experimental IR's [1], the limit on β^* was clearly identified for the LHC (see [2] and reference therein). This limit was found to be in the range of $\beta^* \approx 30$ cm for an inner triplet (IT) based on the NbTi technology, possibly reduced to $\beta^* \approx 24$ cm (i.e. $\sim 25\%$ gain) assuming the availability of Nb3Sn quadrupoles at the horizon of the LHC Upgrade. Those two numbers did not include any provision for operational margins and were driven by the chromatic correct-ability of the new triplet within the nominal strength budget of the lattice sextupoles (with two sectors of sextupoles needed for the chromatic correction of one single triplet, and an extremely rigid overall optics due to a series of phase advance constraints imposed all around the machine). In addition other limitations were also analysed, related to the mechanical acceptance of the existing matching section and to the optics flexibility of the low-β insertions, and found just in the shadow of the above limit. In view of these severe limitations and following the decision to cancel the Phase I project and to combine it with a single Upgrade project at the horizon 2020-2021, the so-called HL-LHC project, a novel optics concept was then mandatory in order to satisfy the very ambitious performance target of this new project.

The HL-LHC performance target will be discussed in the next section and the potential of flat collision optics (i.e. with a β^* aspect ratio different from unity) will be introduced at this occasion. Then will follow a short reminder of the Phase I optics limitations and a brief description of the new optics scheme in order to breach them (see [3] for more details). The latter is based on a "Achromatic Telescopic Squeezing" (ATS) principle as we will understand it a bit latter. The main weak points of the ATS scheme will then be presented, with possible mitigation measures and the hardware changes needed in the LHC ring in order to implement it. Finally in order to demonstrate the powerfulness of the novel approach, the ATS scheme will be used in order to propose and analyze a complete solution for the Upgrade of the LHC, even in a worst case where the crab-cavity technology would not be available on time for the HL-LHC. In this scenario, the crossing angle seems then to be the most promising tool for luminosity leveling (see e.g. [4]), which is one of the keystones of the new project. This alternative has however the reputation of being very demanding in terms of triplet aperture (except in the case of the so-called "early separation scheme" which assumes the installation of orbit corrector inside the detector [5]). We will see that this is not really the case for a flat collision optics where the crossing angle is chosen in the plane of largest β^*.

PERFORMANCE TARGET OF THE HL-LHC

The performance goal of the HL-LHC is to integrate a luminosity of 3000 fb^{-1} over the full life time of the machine (see e.g. [6]), that is typically 25 years for a large hadron machine taking as (unique) example the Tevatron. Then counting on an unique upgrade of the machine at the horizon of 2020-2021, followed by a few years to recommission the machine and ramp it up to its maximum performance, the above target corresponds to an integrated lu-

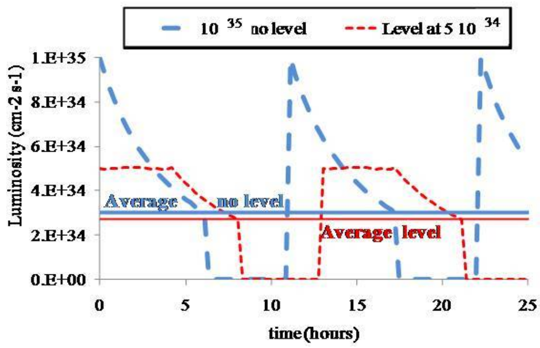


Figure 1: *Typical pattern targeted for the luminosity production in the HL-LHC (courtesy of E. Todesco)*

minosity of 250-300 fb^{-1}/year. Finally, assuming as usual two third of the year (240 days) dedicated to operation and a bit more than one good physics fill achieved in average per day, the HL-LHC target can be transposed into an integrated luminosity of about **1 fb^{-1} per fill**.

In agreement with the experiments, the general consensus is to run with an instantaneous luminosity not exceeding 5×10^{34}cm^{-2}s^{-1} [7], which will have to be sustained during a couple of hours using some leveling techniques not yet decided and never tested so far in any other machine (using crab-cavities, if available, the crossing-angle or β^*, see e.g. [4]). After this first period, a second period of typically 3 hours will follow where the peak luminosity will decay up to a point where, depending on the average turn around time, it will be advisable to dump the beam and refill the machine in order to maximize the daily integrated luminosity.

As illustrated in Fig. 1 assuming some upgrade scenario, the typical coast duration is not expected to exceed one third of the daily operation time of the HL-LHC, i.e. not more than one shift. This confirms a posteriori the above (possibly conservative) assumption of about one good physics fill delivered in average per day, keeping a realistic margin reserved for the machine turn around time, possible delays due to machine unavailability and short technical stops. The other very important information contained in Fig. 1 is that the potential peak luminosity which is available or, let say, "stored" in the machine shall be typically a factor of 2 higher than the target specified for the leveled luminosity. In this respect, the effective target of the HL-LHC is not really relaxed with respect to the one initially defined in the framework the sLHC project, at least in the sens of a "virtual" peak luminosity of 10^{35}cm^{-2}s^{-1}, but which is not usable in practice due to various limitations, either coming from the machine (e.g. beam-beam) or from the detectors (e.g. so-called "pile-up"). As a result, from the injector and HL-LHC designer point of view, the HL-LHC target will then require to push both the beam parameters and the LHC optics, and in particular β^* well beyond the limits identified for Phase I.

In order to already give some orders of magnitude but also to introduce the potential of flat collision optics (i.e. with $\beta^*_x \neq \beta^*_y$), Fig. 2 shows the peak luminosity as a function of $\beta^*_{\rm X}$ in the crossing plane for different value of β^*, namely $\beta^*_{||}$, in the other plane, choosing a typical normalised crossing angle of $10\,\sigma$ and assuming the nominal 25 ns bunch spacing (2808 bunches) at ultimate intensity ($1.7\,E11$ proton/bunch), nominal emittances ($\gamma\epsilon = 3.75\,\mu$m in both transverse planes) and bunch length ($\sigma_z = 7.5$ cm). On the same figure, the case of a round optics (i.e. with the same β^* in both planes) is superimposed. Contrary to the case of a round collision optics where, due to the well-known geometric loss factor, the luminosity saturates rather quickly below a β^* of the order of 30 cm, flat optics possess two interesting features. First of all, for any value $\beta^*_{||}$ chosen in the plane perpendicular to the crossing plane, the luminosity shows an optimum for a specific value chosen for $\beta^*_{\rm X}$ in the crossing plane. This β^* can be called the Piwinski β^* since, neglecting the hour glass effect, it corresponds to a Piwinski angle of exactly 1 rad (see [3] for an analytical proof):

$$\frac{\partial \mathcal{L}}{\partial \beta^*_{\rm X}} = 0 \text{ for } \beta^*_{\rm X} \sim \beta^*_w \equiv \alpha\sigma_z\,, \tag{1}$$

with α denoting the half normalised crossing angle, that is typically 5 for the LHC, which corresponds to an optimum β^*_X of about 30-35 cm. Then sticking to the Piwinski β^* in the crossing plane, and reducing $\beta^*_{||}$ in the other plane, the luminosity still increases with $1/\sqrt{\beta^*_{||}}$, till saturating due to the hour glass effect. Consequently a natural choice for a flat collision optics is a target β^* of the order of

$$\beta^*_{||} \sim \sigma_z = 7.5\,\text{cm} \tag{2}$$

in the plane perpendicular to the crossing plane. This then

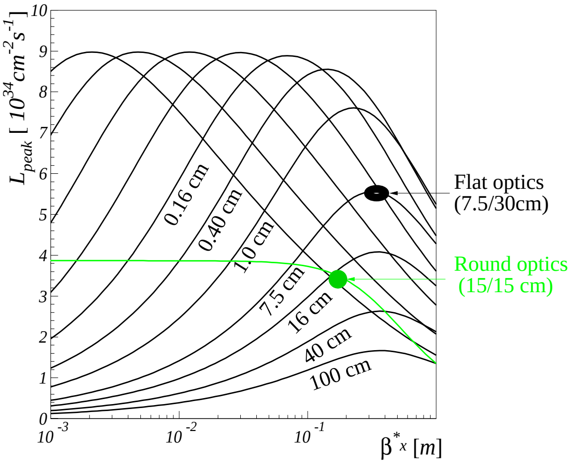


Figure 2: *Peak Luminosity as a function of β^* in the crossing plane for different values of β^* in the other plane (full crossing angle of $10\,\sigma$, so-called "ultimate" beam parameters with 25 ns bunch spacing, 1.7E11 p/bunch, $\gamma\epsilon = 3.75\,\mu m$, $\sigma_z = 7.5\,cm$). The green line stands for the case of round collision optics ($\beta^*_x = \beta^*_y$).*

corresponds to a Piwinski β^* of the order of

$$\beta_X^* \sim \beta_w^* = 30\,\mathrm{cm} \qquad (3)$$

in the crossing plane, assuming a typical full crossing angle of 10σ. Under these conditions, the peak luminosity calculated with the so-called "ultimate" LHC beam parameters reminded above, is equal to $5.6\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This is still a factor of about 2 less than a "virtual" luminosity target of 1E35, but substantially higher than the peak luminosity of $3.5\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ which would be obtained with an equivalent round optics, i.e. with $\beta_X^* \equiv \beta_{||}^* = \sqrt{7.5\times30} =$ 15 cm (see Fig. 2).

Assuming the presence of crab-cavities with ideal performance, the round and the flat optics would give a similar virtual luminosity of the order $8-9\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, with of course a clear preference for the round optics in this case. In the contrary case, the beam parameters would have to be pushed beyond or well beyond their design values, in terms of bunch charge and/or emittance, in order to find the factor of 2 (for the flat optics) to 3 (for the round optics) still missing in order to meet the effective target of the HL-LHC. In any case, with or without crab-cavity, a novel optics scheme is then hardly needed for the HL-LHC, in order to push β^* below or far below the hard limit of $\beta^* = 30$ cm which was identified in the context of Phase I Upgrade, that is to open a new β^* territory that new Nb3Sn triplets, alone, can certainly not reach.

THE ACHROMATIC TELESCOPIC SQUEEZING (ATS) SCHEME

Phase I optics limitations.

As soon as the triplet is equipped with new low-β quadrupoles of sufficiently large aperture (e.g. 120 mm for Phase I instead of 70 mm for the existing MQX type magnets), severe optics limitations coming from the "non-IT side" of the machine have been identified in the context of the Phase I Upgrade project [2]. While of different nature, all these limitations can be quantified and ranked with the maximum possible peak β-function which is reached in the inner triplet, namely β^{max}, and then can be matched to the regular optics of the arcs, within the aperture and the gradient limits of the IR magnets, but also "chromatically correctable" (in terms of Q' but also off-momentum β-beating) within the strength budget of the sextupole scheme. This β^{max} limit is therefore not influenced by the technology of the inner triplet triplet (Nb-Ti or Nb3Sn) but only depends on constraints coming from the "non-IT side" of the machine. This limit then corresponds to an optimum aperture for the new triplet (with some basic assumptions concerning the beam emittance, the crossing angle and the tolerance budget). Finally, depending on the technology, the IT aperture obtained hereabove fixes the length and the operational gradient of the low-β quadrupoles, which ultimately gives a minimum possible β^* (see Tab. 1 in the case of the Phase I upgrade).

Limitation	β_{Ring}^{max} [km]	β_{min}^* [cm] (for Nb-Ti)
Matching section aperture	~ 13	26
Optics flexibility	~ 17	21
Chromatic aberration	~ 11	30

Table 1: *Phase I optics limitations expressed in terms in maximum possible peak β-function reached in the inner triplet and corresponding minimum possible β^* for an Nb-Ti triplet [2]. The Nb3Sn technology can push all these limits by 25%. The aperture related limit stands for the existing D2, Q4 and Q5 of the matching section. The so-called optics flexibility limit is reached when at least one quadrupole magnet (in practice several) runs below 3% or above 100% of its nominal gradient. The chromatic limit stands for the nominal current of 550A in the lattice sextupoles, and assumes that two sectors of sextupoles are used for the chromatic correction of one single triplet.*

Within a good approximation, this minimum β^* is constrained by the following scaling law [2]:

$$\beta_{min}^* \propto \frac{1}{\left(\beta_{Ring}^{max}\right)^{3/4}\sqrt{B_{\rm peak}}}\,, \qquad (4)$$

where, on one hand, the β_{Ring}^{max} limit depends only on the optics limitations imposed by the "non-IT side" of the machine and, on the other hand, the critical field $B_{\rm peak}$ is given by the triplet technology. Passing from the Nb-Ti to the Nb3Sn technology for the new triplet should give a jump by 50% for $B_{\rm peak}$, therefore corresponding to a reduction of β_{min}^* by 25%. This gain looks quite modest compared to the factor of 2 to 4 which are needed to operate the HL-LHC with a β^* of 15 cm or even twice below for a flat collision optics (see previous section). A much more promising approach therefore consists in elaborating a global optics scheme which would be able to relax the constraints imposed by the "non-IT side" of the machine, that is to increase by a big factor the β_{Ring}^{max} limit occurring in the previous scaling law.

The ATS scheme

The idea of this novel scheme was imagined a few years ago by the author when realizing the severe optics limitations of the Phase I project. Only its name and corresponding acronym was very recently invented. This new concept and its implications in terms of hardware changes in the LHC ring have been already documented in 2010 [3] together with its effective implementation in terms of optics and layout and first analysis [8, 9]. Hereafter, the basic principle and a few illustrations are given for the optics and its fundamental chromatic properties.

Motivations and basic idea. As shown in Tab. 1, the Phase I optics limitations were given by

- the mechanical acceptance of the matching section,
- the gradient limits of the IR quadrupoles,
- the strength limits of the arc sextupoles.

Concerning the first limitation, the only solution is to rebuild new two-in-one magnets of larger aperture, in particular to replace the existing D2, Q4 and Q5 (see later), with of course some limits still to be clearly specified in this case (i.e. taking into account the nominal separation of 194 mm between the two beams at D2 and beyond). Concerning the very poor optics flexibility of the experimental insertions IR1 and IR5 observed at low β^*, where some quadrupoles of the matching section (Q5 and/or Q6) shall operate a very low gradient and other magnets belonging to the dispersion suppressor (Q7 and QT12/13) tend to run out of strength, one possibility is to allow floating matching conditions at the boundaries of these insertions in order to relax the internal constraints. More precisely the idea is to maintain the dispersion matching constraints at the entry and exit of the low-β insertions (from Q13.L to Q13.R) but to allow the "auxiliary" insertions on either side (IR8/2 for IR1 and IR4/6 for IR5) to contribute to the matching of the β-functions, at least below a certain β^*. As a result, β-beating waves will be induced in the sectors adjacent to the low-β insertions (s45/56 for IR5 and s81/12 for IR1). Assuming a phase advance per arc cell strictly matched to $\pi/2$ in these sectors, and if correctly phased with respect to the IP, these waves will reach their maximum at every other sextupoles, i.e. at the sextupoles which belong to the same electrical circuit in the LHC. Consequently, the chromatic correction efficiency of these sextupoles will drastically increase at constant strength which, de facto, will be a definite cure for the third limitation previously mentioned.

The reasons why this new scheme is particularly well-suited to the LHC are two-folds.

- Due to the large dynamic energy range of the machine from 450 GeV to 7TeV and the reduction in proportion of the transverse physical emittances of the beam, the peak β-functions in the arcs can be increased by a factor of about 16 at flat top energy without exceeding any aperture related limits.
- At flat top energy, the quadrupole magnets of the so-called "auxiliary" insertions are either moderately pushed, which is the case for the experimental insertions IR8 and IR2 assuming a β^* of a few meters in pp collision mode, or not pushed at all, in the case of IR4 and IR6 for which the injection optics is kept constant at flat top energy.

Therefore all the ingredients are already available in the existing machine in order to blow up the β-functions in the arcs 81/12/45/56 at 7 TeV and then implement the ATS scheme.

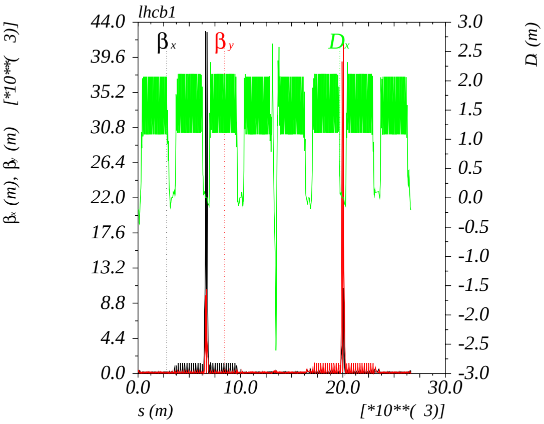


Figure 3: *Alternated flat collision optics for the HL-LHC with* $\beta^*_{x,y} = 7.5/30$ *cm at IP1 and* $\beta^*_{x,y} = 30/7.5$ *cm at IP5. Starting from a pre-squeezed optics with* $\beta^*_{x,y} = 60$ *cm,* β*-beating waves are induced in the sectors 81, 12, 45 and 56 with peak values increased by a factor of 2 or 8 with respect to the regular FODO optics.*

Implementation and illustration. A comprehensive description of this new scheme can be found in [3], in particular concerning the phase constraints imposed on the left and right side of the low-β insertions and the squeeze performed in a two stage telescopic mode. More detailed analysis and illustrations, in particular showing the variation of the optics of the "auxiliary insertions" IR8, IR2, IR4 and IR6 during the squeeze, are presented in [8]. The flat collision optics discussed in the previous section is then illustrated in Fig. 3 with $\beta^*_X = 30$ cm in the crossing plane and 7.5 cm in the other plane. In this particular case, it is assumed that the plane of smallest β^*, and therefore the crossing plane which is perpendicular, is alternated between IR1 and IR5 in order still to ensure a partial compensation of the long range beam-beam interactions between the two high luminosity insertions (see later). However any other possible combination have been successfully rematched and the corresponding collision optics implemented in the so-called SLHCV3.0 repository [9]. The round collision optics with $\beta^* = 15$ cm at IP1 and IP5 developed more recently for the fourth crab-cavity workshop [10] is also available at the same address. Within the exception of the Q5 quadrupoles of IR6 which needs to be made 20 to 25% longer (and more deeper modifications obviously needed in LSS1 and LSS5, see later), all these optics have been found fully compatible with the existing hardware and layout of the "auxiliary" insertions IR8, IR2, IR4 and IR6.

From the optics point of view, the high luminosity insertions therefore cover a much larger fraction of the machine, containing three optical modules with well-distinguished functionalities:

- the low-β insertions proper which become strictly passive below a so-called "pre-squeezed β^*". The latter is defined as being the minimum possible β^* for which the chromatic correction of each triplet can be performed by only one sector of lattice sextupoles (contrary to the Phase I scheme which counted on 2 sectors per triplet). Assuming the existing sextupole scheme of the LHC arcs and a reference gradient of 100 T/m for the new triplet (compatible with an aperture of 150 mm for the Nb-Ti technology), the pre-squeezed β^* is of the order of 60 cm.

- the "auxiliary" insertions IR8/IR2 and IR4/IR6 which plays the role of matching section in order to squeeze IR1 and IR5 further down.
- two interleaved horizontal and vertical chromatic correction sections which are supported by the lattice sextupoles of the sectors located on either side of IR1 and IR5 (s45/s56 for IR5 and s81/s12 for IR1). Due to the β-beating waves induced in the arcs, the correction efficiency of the sextupole increases with $1/\beta^*$ at constant strength, and the chromatic limit is therefore never reached in this way.

With this construction, the peak β-functions β^{max} reached in the IT can then largely exceed the Phase I limits given in Tab. 1, but paying the price of an increase of the peak β-functions in the arcs by a factor of 2 to 8 starting from a pre-squeezed optics with $\beta^* = 60$ cm.

Chromatic properties. The chromatic properties of the ATS scheme are illustrated in Fig. 4 in the case of the flat optics. The chromatic variations of the betatron tunes are almost linear over a rather large momentum window of ±1.5 permil (which basically corresponds to the opening of the momentum collimators at flat top energy). The chromatic Montague functions (giving the amplitude of the first order chromatic derivative of the β-functions) are nicely vanishing in the collimation insertions IR3 and IR7 and at IP1 and IP5. Another important feature which is not visible in the previous picture is that, in each of the two planes, the off-momentum β-beating waves induced by the lattice sextupoles are exactly in quadrature of phase with the β-functions themselves, in particular in the triplet and its neighboring magnets. Therefore, no further degradation of the off-momentum mechanical aperture is induced in the arcs, the matching section and the new triplet, except the usual one coming from the contribution of the dispersion, which remains nominal and perfectly matched in the ATS scheme. Finally an extremely important quantity to control is the spurious dispersion induced by the crossing scheme in IR1 and IR5. The latter can reach up to 10 m in the new IT, produced by one of the two high luminosity insertions and then exported in the other one. However, thanks to the specific phasing conditions imposed in the ATS scheme, very modest H or V orbit bumps of the order of 2.5-3 mm generated in the sectors adjacent to IR1 and IR5 are found to be sufficient to bring it back to a level of a few tens of centimeters (see [3] for more details).

Sextupole scheme. Before closing this section, a specific discussion is needed concerning the existing sextupole layout. In order to reach a "decent" β^* of 30 cm for Phase I, two sectors of sextupoles with specific constraints of phase advance between them and with respect to the IP, were needed for the chromatic correction of one single triplet. Below this β^*, half of the defocusing sextupole circuits were pushed above 550A. This scheme made the optics very rigid, not only by pushing the LHC IR's at the limit of their tunability range but also generating more or less strong interferences between the correction of the off-momentum β-beating proper and any tune or chromaticity trims performed in operation in the real machine. For the ATS scheme, only one sector sextupoles per triplet is foreseen for the chromatic correction of the squeezed optics. In particular, this explains why, without any additional ingredient (see later), the pre-squeezed optics is presently limited to a β^* of 60 cm (and not 30 cm). Then, in order to squeeze further down, the β-beating waves need to be engaged in the arcs. The net benefit is then to leave free of constraints the four sectors adjacent to the collimation insertions, namely s23, s34, s67 and s78, which makes the overall optics much more flexible and tunable in operation. In particular, even when the optics is squeezed in IR1 and IR5, the sextupoles belonging to the sectors 23, 34, 67 and

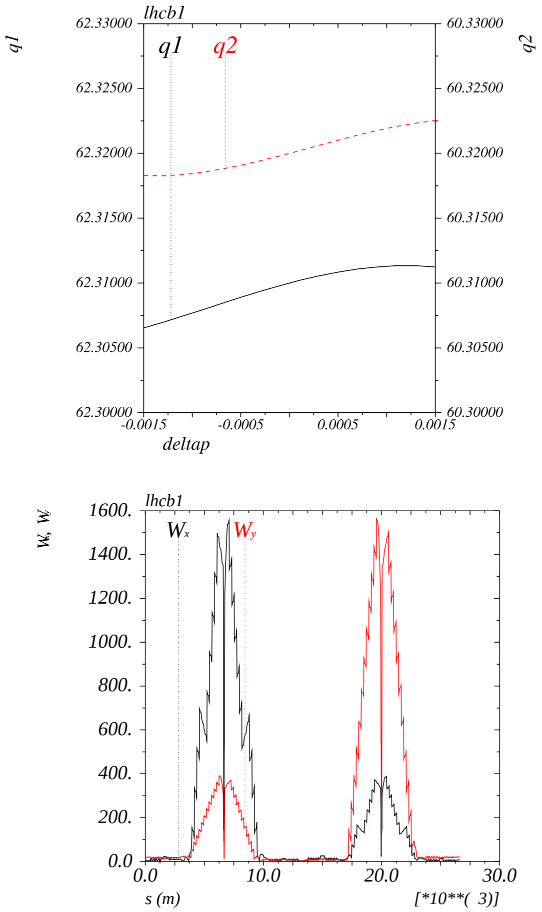


Figure 4: *Chromatic variation of the betatron tunes (top) and chromatic Montague functions along the machine starting from IP7 (bottom) for the alternated flat collision optics showed in Fig. 3.*

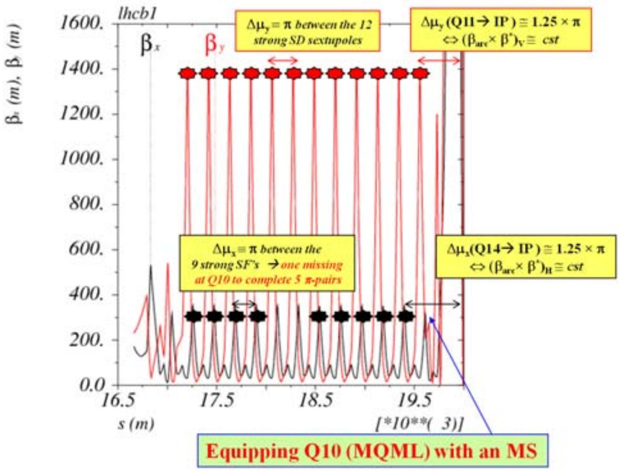


Figure 5: *Flat collision optics (beam 1) zoomed in between IP4 and IP5. The focusing and defocusing sextupoles correcting the triplet are indicated by the black and red spots (2 SF's close to mid-arc are replaced by skew sextupoles), with phase advance constraints imposed between them and with respect to the IP. Equipping Q10 with an additional sextupole warrant an almost perfect self-cancellation of the geometric aberrations induced.*

Optics	Pre-squeezed	"2222"	"4444"	"8228"
$\beta^*_{x,y}$ [cm]	60	30	15	7.5 ↔ 30
Peak $\beta^{arc}_{x/y}$ [m]	180 (nom.)	350 (H and V)	700 (H and V)	1400 ↔ 350
Min. DA [σ]	> 50	28	15	11

Table 2: *Minimum 10^5 dynamic aperture v.s. optics without including yet any field imperfection in the new IT and the new elements (D1/D2/Q4/Q5) of LSS1 and LSS5 [8].*

78 still keep their 7 TeV equivalent injection setting. This represents a huge reserve for any chromaticity trim in operation or, turned differently, for a third low-β experiments, such as for instance an e-p experiment (LHeC), but located in IR3 or IR7. On the other hand half of the sextupoles are pushed to very high field in the four sectors adjacent to IR1 and IR5 (550A for half of the defocusing sextupoles SD's and around 300 A for the SF's which are about twice more efficient due to the larger dispersion at the QF's). By construction, the β-beating waves are also maximum at the locations of these strong sextupoles. In order to avoid a sharp excitation of the third order resonances and keep under control the tune spread induced by these strong sextupoles, a natural requirement is that the sextupoles participating to the chromatic correction can be paired by π, which means in particular an even number of SF's and SD's dedicated to each triplet. However, as illustrated in Fig. 5, for a given beam and a given side of the high luminosity insertion, there is always one plane where it is not presently the case: one SF/SD is missing for beam1 on the left/right sides of IR1 and IR5, and conversely for beam2 due to the optics antisymmetry. Therefore two possibilities are offered, either removing one sextupole from each circuit under concern (e.g. at Q14) or add a new one with a preference for Q10 on the left and right sides of IR1 and IR5 (basically exchanging the long MCBC orbit corrector equipping the MQM type cold masses with a standard dipole sextupole corrector MSCB equipping the SSS's). Assuming no strength limitation in the sextupoles, the two options gives very similar improvements in terms of dynamic aperture and tune spread [8]. The first one would even be cleaner, since the β functions at Q10 differ already slightly from the ones of the regular arcs and the phase advance from Q14 to Q10 is no longer exactly π. However in the present situation where the pre-squeezed optics is already limited by the available strength of the sextupoles, the difference between the two options correspond to a difference of about 20% in terms of peak β-functions in the arcs at constant β^* in physics or, said differently, to a possible downgrade of β^* by 20% taking into account certain limits imposed on the arc optics (see next section). This 20% difference is then very similar to the possible improvement by 25% that the Nb3Sn technology could bring to the overall system. Equipping the Q10's with lattice sextupoles in IR1 and IR5 is then more than justified in this sens.

WEAK POINTS, MITIGATION MEASURES AND OTHER IMPLICATIONS

Increasing the β-functions in the arcs has obviously several implications and draw-backs. The main worry concerns the impact on the dynamic aperture (DA). This item will be addressed in the next paragraph together with a series of possible mitigation measures. Other implications will then be mentioned, some of them being particularly surprising. Finally a critical overview of the situation, not specific to the ATS scheme but concerning the triplet requirements at low β^*, will be given in the last paragraph of this section.

Optimizing the telescope to preserve the DA

A net degradation of the dynamic aperture is expected due to the increase of the β-functions in the LHC arcs, combined with the strong sextupoles involved in the chromatic correction and the field quality of the arc magnets (dipoles and quadrupoles). Without including yet any field imperfections in the new triplets and D1's, but assuming that the quadrupoles Q10 will be equipped with a lattice sextupole in IR1 and IR5 (see previous discussion), the dynamic aperture of the machine has been calculated for various collision optics, starting from the pre-squeezed optics [8]. For each optics considered, the results obtained have been quantified by one single number representing the minimum 100'000 turns dynamic aperture calculated over 5 angles of the phase space and 60 different possible configurations of the as-built machine. As shown in Tab. 2 for round optics, the dynamic aperture decreases more or less linearly with the increase of the β-functions in the LHC arcs. In the case of the flat optics, the DA is only 11σ.

At this stage, it is rather difficult to give a precise specification for this quantity, in particular because the field quality of the new triplet is not known. On the other hands, several elements are already available to justify an improvement of the situation by about 40%, i.e. a global reduction of the β-functions in the arcs by the same amount, in particular below the 1 km level for the flat optics. Indeed a dynamic aperture of 11 σ which is mainly driven by the field quality of the main dipoles and quadrupoles of the lattice corresponds exactly to the situation of the LHC at injection where it is a priori excluded to collide bunch trains (i.e. with both head-on and long-range beam-beam interactions). Then, deriving a first estimate for the field quality targets of the new triplet, and betting on a coil aperture of 150 mm, we will see later that the contribution of the triplet alone should also correspond to a dynamic aperture in the range of 11 σ and 15 σ for the 7.5/30 cm flat and the 15 cm round optics, respectively. In this respect, the dynamic aperture calculated by considering only the contribution of the arcs should be in the shadow, with a corresponding dynamic aperture of at least 20 σ and 15σ for the round and flat optics, respectively, i.e. about 40% larger than the values obtained in Tab. 2.

The mitigation measures are simple. First of all, the pre-squeezed optics with $\beta^*=60$ cm needs to be further pushed in order to reduce in the same proportion the amplitude of the β-beating waves in the arcs at a given β^* in physics. The pre-squeezed optics is presently limited by the sextupole strength available in the defocusing sextupoles SD's, with still a big margin available in the SF's. Therefore 10% can be gained operating the sextupoles at the ultimate current of 600A, which has been already validated for all of them during the cold tests of SM18, and with training quenches observed only in a few cases (see e.g. the minutes of the Magnet Evaluation Board). Another gain resulting from the installation of a lattice sextupole at Q10 (see previous section) will allow to push further down the pre-squeezed β^* by about 10%. Finally, combining the two above measures and the substantial margin still existing in the focusing sextupoles, a flat pre-squeezed optics with $\beta^*_{x/y}=30/50$ cm would be perfectly reachable, in a configuration where both the SF's and the SD's would operate at 600A and assuming a (100 T/m-150 mm) inner triplet. Should not it be sufficient to restore a decent dynamic aperture, at least for the most critical optics (i.e. the flat optics), the Nb3Sn technology, if available to build a (150 T/m-150 mm) triplet, will offer an additional reduction of the pre-squeezed β^* by 25% at constant sextupole strength, i.e. the same reduction of the β-functions in the arcs and the same relative improvement in terms of dynamic aperture at constant β^* in physics. Finally, relaxing β^* in physics from 7.5 cm to 10 cm in the plane perpendicular to the crossing plane corresponds to a Piwinski β^* of 36 cm (instead of 30 cm) in the crossing plane. With a new triplet based on the Nb-Ti technology, this ultimate measure would then restore a rather safe situation, almost identical to the one discussed above assuming Nb3Sn low-β quadrupoles and at a very modest cost in terms of luminosity: a performance loss by only 10% for an increase of $\beta^*_{x,y}$ by 20-30%, due to the small sensitivity of the luminosity v.s. β^* in the crossing plane when operating in the vicinity of the Piwinski β^*, and the saturation due to the hour-glass effect which disappears very quickly at $\beta^*=10$ cm in the other plane.

To summarise, at a maximum cost of 10% in terms of performance and counting on a modest upgrade of the sextupole scheme in the sectors 81, 12, 45 and 56, the dynamic aperture of the collision optics (flat or round) should no longer be influenced by the implementation of the ATS scheme, but only by the field quality of the new triplet and, of course, by the beam-beam effect.

Other implications specific to the ATS scheme

The ATS scheme has a series of other implications which are listed below, some of them being very surprising and all of them being relevant enough to require a detailed analysis. Most of these implications are however related to the increase of the β-functions in the arcs and therefore will be mitigated by the different measures previously discussed.

Operational aspects. A modification of the IR4 and IR6 optics during the squeeze is a clear specificity of the ATS scheme. Optics solutions can in general be found preserving as much as possible (i.e. within 20-30%) the twiss parameters in the core of these two insertions where most of the instruments and equipments are hosted. One exception however has to be kept in mind. It concerns the dispersion suppressor on the right side of IR4, which contains several BPMs presently used by the damper system, while the β-beating waves are already important in this part of the ring.

Another operational aspect which is worth to be mentioned is an increased sensitivity of the beam to the linear field imperfections located in the arcs adjacent to the high-luminosity insertions. If the correction of these imperfections is not local enough, that is at least sector by sector for a_2 and b_2, their impact on the beam will be magnified, e.g. in terms of closed orbit, coupling or β-beating, in proportion to the increase of the β-functions in the arcs during the second part of the squeeze. On the other hand, if local or sector by sector corrections are properly achieved, simulations have shown that this side-effect is a non-issue. Then, in the real machine, thank to the global orbit feed-back of the LHC and/or any feed-forward techniques which would be applied during the commissioning of the new squeeze, this aspect should represent an addtionnal complication but a priori not a real show-stopper for the ATS scheme.

Optics	T_x [h]	T_z [h]
"1111"	$78 \rightarrow 49$	$47 \rightarrow 29$
"2222"	$69 \rightarrow 44$	$49 \rightarrow 31$
"8228"	$59 \rightarrow 36$	$56 \rightarrow 35$

Table 3: *Horizontal and longitudinal emittance growth time due to IBS at 7 TeV with $N_b = 1.7$E11 p/bunch and $\gamma\epsilon = 3.75\ \mu$m (courtesy of A. Vivoli) for different optics (see Tab. 2 for the corresponding peak β-functions in the arcs), and two different possible bunch lengths: 7.5 cm (2.5 eV.s) $\rightarrow$ 6.0 cm (1.6 eV.s).*

Collimation and machine protection. With peak β-functions increased by up to a factor of 8 in the LHC arcs, the normalised aperture of the main magnets shrinks down to $n_1 \sim 10 - 11$ at 7 TeV in the sectors adjacent to the high luminosity insertions. Possible implications in terms of collimation inefficiency or machine protection need then to be addressed.

Effective impedance, Landau damping and "footprint shaping". The increase of the β-functions averaged over the eight arcs of the ring is around 60-70% in the worst case (flat optics). The effective beam-screen impedance seen by the beam will then increase in the same proportion at 7 TeV, and therefore the imaginary part of the coherent tune shift and the instability rise times. However, since only the beam-screen impedance is concerned, we should not forget that the situation at injection will always be much worst (by a factor of about 10 in terms of rise time [11]) and is already proved to be under control via the transverse damper, at least for eventual multi-bunch instabilities. Concerning possible single bunch instabilities, it is then worth noting that, as for the sextupoles, the efficiency of the Landau octupoles is widely improved by the ATS scheme, e.g. by more than one order of magnitude in both planes for the alternated flat optics. More generally speaking, this feature of the ATS scheme leads to an exceptional situation for a circular collider where non-linear corrector magnets would become efficient enough for shaping the tune spread induced by the beam-beam collisions (but at a possible cost not yet evaluated in terms of dynamic aperture and other side effects as the second order chromaticity Q'' induced by the MO circuits of the LHC arcs).

Intra-beam scattering. Last but not least, a significant sensitivity of the IBS growth rate has been observed with respect to the choice of the collision optics. This variability is again driven by the sharp modifications of the β-functions in half of the machine when the optics is squeezed. Starting form the pre-squeezed optics (with the nominal β's in the arcs), the tendency is a net degradation of the IBS growth time by 30% in the horizontal plane but a significant improvement in the longitudinal plane, which is generally the most critical plane with respect to IBS for the LHC (see Tab. 3). In the extreme case of the flat optics "8228", the horizontal and longitudinal IBS growth times are very similar, of the order of 35 hours for the ultimate charge per bunch, the nominal transverse emittances and assuming a longitudinal emittance already reduced to 1.6 eV.s (corresponding to an r.m.s. bunch length of 6 cm for the nominal 16 MV RF voltage of the LHC).

Implications for the IT when running at low β^*

Regardless of the specificities of the ATS scheme, it is worth reminding the severe requirements imposed on the new triplets when running at a very low β^*, or more precisely at a β^{max} in the range of 20 km or 40 km for the round and flat optics presently discussed.

IT stability. The tolerance of the new triplet to mechanical vibrations and PC jitter shall be improved with $1/\sqrt{\beta^*}$ and $1/\beta^*$, respectively, with respect to the existing triplet. More precisely, by requesting a control of the transverse position of the IP within one tenth of a sigma and by imposing tune ripples due to PC jitters not exceeding the 10^{-4} level per triplet, the sub-micron level is reached for the alignment control of the low-β quadrupoles, together with the sub-ppm level for the short-term stability of the power supplies feeding the triplet:

$$\begin{array}{lcl} \delta x^* \lesssim \sigma_x^*/10 & \Rightarrow & \delta x_{IT} \sim 0.75 \rightarrow 0.5\ \mu\text{m} \\ \Delta Q \lesssim 10^{-4} & \Rightarrow & \Delta I/I_{max} \sim 1 \rightarrow 0.5\ \text{ppm}\,, \end{array} \tag{5}$$

for $\beta^* = 15 \rightarrow 7.5$ cm and assuming a reduced normalised emittance of 2.75 μm (see later).

IT field quality. A preliminary target error table can be easily established for the new triplet, starting from the field quality measured in the existing MQXB type magnets and then applying a rescaling at constant non-linear kick:

$$\frac{[b_n(R_{r_{\text{new}}})]_{\text{Target}}}{[b_n(R_{r_{\text{old}}})]_{\text{MQXB}}} \equiv \left(\frac{(\beta_{IT}^{max})_{\text{old}}}{(\beta_{IT}^{max})_{\text{new}}}\right)^{n/2} \times \left(\frac{R_{r_{\text{new}}}}{R_{r_{\text{old}}}}\right)^{n-2}\ , \tag{6}$$

with $R_{r_{\text{old}}} \equiv 23.3$ mm denoting the reference radius used to define the multipole components of the existing MQXB type magnets (at 2/3 of the 70 mm aperture), which would correspond to $R_{r_{\text{new}}} = 50$ mm for a new triplet with a coil aperture of 150 mm.

Round optics with $\beta^* = 15$ cm. Taking $(\beta_{IT}^{max})_{\text{old}} \approx 4.5$ km for the peak β-function reached in the existing triplet at the nominal collision β^* of 55 cm, and $(\beta_{IT}^{max})_{\text{new}} \approx 21$ km for the round optics with $\beta^* = 15$ cm, we simply get

$$\frac{[b_n(R_{r_{\text{new}}})]_{\text{Target}}}{[b_n(R_{r_{\text{new}}})]_{\text{MQXB}}} \sim \left(\frac{R_{r_{\text{old}}}}{R_{r_{\text{old}}}}\right)^2\ . \tag{7}$$

Roughly speaking, the above relation corresponds to a fraction of a units for the low-order multipoles at two third of the aperture of the new triplet. This may well rule out the

Nb3Sn technology for the HL-LHC triplet if no big improvement is made in this direction in the coming years. Furthermore, these targets are already a factor of about 2 (more precisely a factor 150/70) more demanding than the "natural" gain expected in terms of field quality with NbTi quadrupoles of larger aperture [12]. On the other hand, the dynamic aperture of the LHC in collision is about $15\,\sigma$ for two insertions squeezed to $\beta^* = 55$ cm [13]. In addition, the triplet correction (concerning all multipoles below $n = 6$, except a_5, b_5 and a_6) looks rather inefficient to improve further the situation [13]. This means that the 15σ dynamic aperture level may be actually driven by the a_5, b_5 or a_6 field imperfections of the existing triplet, in which case equipping the new IT with such corrector coils will relax the target on these multipoles at least by the factor of 2 requested above. Then a second possibility would be that this $15\,\sigma$ DA level is in fact driven by multipoles of order larger of equal to $n = 7$. In this case, relaxing the above targets by a factor of 2 should not degrade the dynamic aperture by more than 10% (more precisely with a factor $2^{1/(n-2)}$ with $n \geq 7$). Assuming that the scaling law derived in [12] will be verified for a new NbTi triplet of 150 mm aperture, and counting eventually on new corrector coils to equip the new triplet (a_5, b_5 or a_6 in addition to the existing types), the round optics with $\beta^* = 15$ cm should then correspond to a dynamic aperture in the range of $14 - 15\sigma$.

Flat optics with $\beta^*_{x/y} = 7.5/30$ *cm.* A further degradation of the dynamic aperture by a factor $\sqrt{2}$ is expected when increasing β_{max} by a factor of 2 in one of the two transverse planes and reducing it by the same amount in the other plane. This expectation might be a bit pessimistic for a flat collision optics where the plane of smallest β^* is alternated between IR1 and IR5, and the peak orbit excursion due to the crossing angle occurs in the plane of smallest β^{max} (see e.g. [14] where several DA calculations were performed to compare the nominal LHC collision optics with possible flat optics with a β^* aspect ratio of 4). Under these conditions, the 7.5/30 cm flat optics should lead to a dynamic aperture in the range of $10\,\sigma$, probably $11\,\sigma$ but hardly more. This value is substantially less than the dynamic aperture calculated with the nominal collision optics of the LHC but remains compatible with the design value of $10\,\sigma$ which was targeted in collision in the early design of the machine [15].

As already mentioned, this last consideration fully justifies the need of further optimizing the pre-squeezed optics in order to reduce the peak β-functions reached in the arcs and therefore keep their impact on the dynamic aperture well in the shadow of that of the new triplet. Finally, this demonstrates as well that a β^* of 7.5 cm is probably at the limit of feasibility for the HL-LHC (at least at nominal transverse emittances), even if substantial margins still exist in the matching quadrupoles of IR8, IR2, IR4 and IR6 in order to squeeze even further the high luminosity insertions using the ATS techniques.

HARDWARE CHANGE REQUESTS

The implementation of the ATS scheme only requires few hardware modifications in the LHC ring, without counting of course the ones needed in the long-straight sections LSS1 and LSS5 (magnets with larger apertures). These modifications have been already defined in [3] and are reminded below.

Sextupole scheme

As already discussed, the sextupole scheme shall be upgraded in the sectors 81, 12, 45 and 56 with

- a re-commissioning of the circuits at the ultimate current of 600A.
- the implementation of an MSCB (dipole sextupole) corrector in the four Q10 quadrupoles (MQML type) located in the dispersion suppressors of IR1 and IR5.

The second measure is mandatory for minimizing the large geometric aberrations induced by the sextupole circuits participating to the chromatic correction of the triplet. Then, the two above measures, if combined together, enable a reduction by 20% of the peak β-functions reached in the arcs for a given β^* targeted in physics, and therefore the same relative improvement in terms of dynamic aperture.

"Auxiliary insertions IR8, IR2, IR4 and IR6"

Within only one exception, the existing layout of IR8, IR2, IR4 and IR6 is fully compatible with the new optics functionality requested by the ATS scheme, i.e. the generation and absorption of β-beating waves in the sectors 81, 12, 45 and 56. The only exception concerns the Q5 quadrupoles of IR6 (MQY), which would need 20 to 25% more integrated strength. A natural proposal would be to develop a longer version of the existing MQY type, namely an MQYL type, that is with a magnetic length of 4.8 m equal to that of the MQML type quadrupoles, compared to 3.4 m for the standard MQY and MQM type magnets.

LSS1 and LSS5

Inner triplet, D1 and corrector package. Reducing β^* requires obviously an inner triplet (IT) and a separation dipole (D1) of larger aperture. Considering the nominal emittance $\gamma\epsilon = 3.75\,\mu$m, the flat optics illustrated in Fig. 3 (with $\beta^*_{\mathrm{X}} = 30$ cm and $\beta^*_{||} = 7.5$ cm) and a normalised crossing angle of $\theta_c = 13\,\sigma$ in the plane of largest β^* (i.e. $535\,\mu$rad), and assuming the induced spurious dispersion to be fully corrected by the generation of orbit bumps in the arcs as already discussed, the inner dimension of the beam-screen shall be around 125 mm for the IT quadrupoles and around 135 mm for D1 (see Fig. 6). The corresponding coil apertures are then estimated to 150 mm and 160 mm respectively. These estimates do not include any dedicated shielding in Q2, Q3 and D1 but assume an overall budget of 13 mm for the manufacturing and alignment tolerances

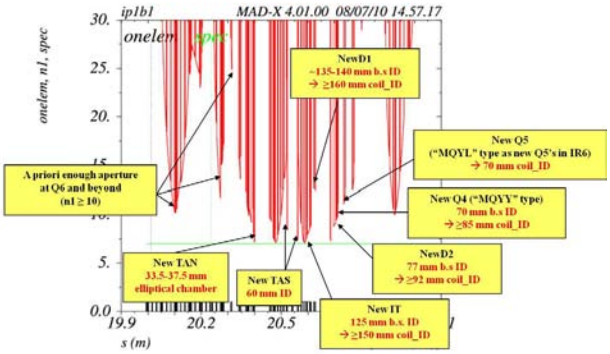


Figure 6: *Required aperture for the new TAS, IT, D1, TAN, D2, Q4 and Q5 in IR1 and IR5 and corresponding aperture plot assuming* $\beta^*_{\rm X}=30$ *cm,* $\beta^*_{||}=7.5$ *cm, a full crossing angle of* $13\,\sigma$ *and the nominal emittance (*$\gamma\epsilon=3.75$ μ*m). The numbers indicated here above have to be understood with an error bar of the order of* $\pm 5-6$ *%, depending on the technology which will be chosen for the new* ~ 150 *mm inner triplet, more precisely assuming an operating gradient of 100 T/m (if Nb-Ti) or 150 T/m (if Nb3Sn) for the inner triplet.*

of the cold bore and beam-screen (as directly rescaled from the 11 mm budget which was taken for the Phase I triplet and for which there is very likely some room for improvement). The same figures would be obtained for the round optics with $\beta^*=15$ cm and a normalised crossing angle of $10\,\sigma$ (i.e. 580 μrad at nominal emittance).

It is important to stress that the above estimates have been obtained with an intermediate gradient of 123 T/m for the inner triplet, more precisely using the IT layout developed for the Phase I IR Upgrade project [2]. For an aperture of 150 mm, this gradient lies almost exactly in between the possibilities offered by the Nb-Ti and Nb3Sn technologies (i.e. about 100 T/m and 150 T/m, respectively). Then, at constant β^* and normalised crossing angle, the beam sizes and orbit excursions reached in the inner triplet and D1 vary approximately with the fourth root of the IT operating gradient. Therefore depending on the technology of the new low-β quadrupoles, the coil apertures specified above have to be understood with an error bar of the order of 5-6%, which corresponds to an aperture range of 140–160 mm for the new triplet.

The main advantage of the Nb3Sn technology is actually elsewhere. Indeed, in all cases, the new inner triplet will have to be longer than the existing one with, consequently, a net increase of the number of parasitic beam-beam encounters in the interaction region (e.g. 21 parasitic encounters on either side of the IP for the Phase I layout [2] compared to 15 for the nominal layout of LSS1 and LSS5). In this respect, a 150 mm aperture Nb3Sn triplet operating at 150 T/m for the LHC Upgrade could eliminate about 3 parasitic encounters with respect to a Nb-Ti triplet of the same aperture.

Then in order to further optimize the layout, the D1 separation dipole shall be installed as close as possible to the inner triplet, in particular by displacing the IT-D1 feed box from the non-IP side of Q3 (as it is presently the case and was the case for the Phase I project) to the non-IP side of D1. Under these conditions the expected gain is of the order of 2 parasitic encounters on either side of the IP.

The type and number of linear and non-linear IT correctors will actually depend on the field quality achieved in the new low-β quadrupoles (and eventually D1). However based on the experience gained during the conception of the nominal LHC and the study of the Phase I project, it is worth noting that a minimal set consists in at least three double plane orbit correctors [16], a skew quadrupole corrector magnet and a b_3 and b_6 correction coil per triplet. Then, as already mentioned, other non-linear coils will certainly be needed to correct a fraction if not all the even and odd multipoles of order lower or equal to $n=6$. In all cases, nested corrector magnets, in particular combined H and V orbit correctors, will be highly desirable not only to compactify the triplet layout and therefore minimise the peak β-function β^{max} reached in the IT at a given β^*, but also to further reduce the number of parasitic encounters. Under these conditions, indeed, a gain corresponding to slightly more than one parasitic encounter is expected on either side of the IP assuming an optimized IT orbit correction scheme consisting in 3 H/V nested orbit correctors attached to Q2a, Q2b and Q3 [16].

Matching section. With a target β^* as small as the r.m.s. bunch length, new two-in-one magnets with larger aperture are also needed not only for replacing the existing matching section quadrupoles Q4 and Q5 but also the recombination dipole D2. Assuming a clearance of not more than 15 mm between the inner diameter of the coil and that of the beam-screen (including manufacturing and alignment tolerances), the required aperture of these new magnets is reported in Fig. 6. The 70 mm coil aperture of the existing MQY type magnets is perfectly suitable for the new Q5 (presently of MQML type, therefore to be replaced with the new MQYL type discussed for the new Q5's of IR6). On the other hand, Q4 and D2 require a coil aperture of the order of 85 mm and 92 mm assuming the nominal separation of 194 mm and 188 mm, respectively, between the bores of these two magnets. The integrated strength of the new Q4 and Q5 can be kept nominal, while the bending angle of the new D2 will depend on the length of the new triplet or, more precisely, on the distance which will separate the new D1 and D2.

Finally, with a full crossing angle exceeding the 0.5 mrad level, the orbit correctors equipping the new Q4's shall be made stronger than the existing ones [17], if not doubled if the crossing angle is used as the main tool for luminosity leveling (see next section). In this configuration, 50% more strength will also be needed in the orbit correctors equipping Q5 and Q6.

Absorbers The TAS and the TAN need to be rebuilt with a larger aperture (see Fig. 6 for more details). Then, due to the net reduction of the normalised aperture in the matching section ($n_1 \sim 9 - 10$ compared to $n_1 \sim 14 - 15$ for the nominal collision optics of the LHC with $\beta^* = 55$ cm), additional TCT-like absorbers will certainly be needed in order to protect Q4 and Q5 both with respect to the incoming and to the out-going beams.

A COMPLETE SOLUTION FOR THE HL-LHC

The ATS scheme can potentially give a peak luminosity of $5.6E34$ for a flat collision optics pushed to $\beta^*_{x/y} = 7.5/30$ cm and assuming the so-called ultimate parameters of the LHC beams (see Fig. 2). As already mentioned, this performance might eventually be limited at the level of $5E34$, assuming a flat optics relaxed to 10/36 cm in order to mitigate the corresponding increase of the β-functions in the arcs and preserve the dynamic aperture of the machine. Roughly speaking, a factor of approximately 2 is then still missing in order to reach the 1E35 level given for the effective target of the HL-LHC in terms of “virtual luminosity” as defined in the first section of this paper. Finally, in all cases, an efficient tool for luminosity leveling remains to be defined.

An upgrade scheme based on crab-cavities, if available and fully operational, would then bring an elegant solution for the above two problems, but still based on the ATS scheme in order to achieve a round collision optics with $\beta^* = 15$ cm. The aim of this section is however to develop and analyze a scenario without crab-cavity, in order to demonstrate that the ATS scheme is not only a necessary ingredient for any path towards to the LHC Upgrade but represents by itself a complete solution for the HL-LHC which is only based on the already existing and well-characterized LHC technology. The aim is therefore to develop a specific scenario

- relying on the generation of flat collision optics thanks to the ATS scheme,
- betting on a sizable (but not aggressive) reduction of the beam emittances, as suggested by the present behaviour of the LHC beam, in order to find the factor of about 2 missing in terms of “virtual performance”,
- and using the crossing angle as a tool for luminosity leveling.

A possible optics and beam parameter set to reach this goal will be discussed in the next paragraph, both for the 25 ns and 50 ns bunch spacing. Using the crossing angle for luminosity leveling will then be analysed in terms of triplet aperture and beam-beam effects.

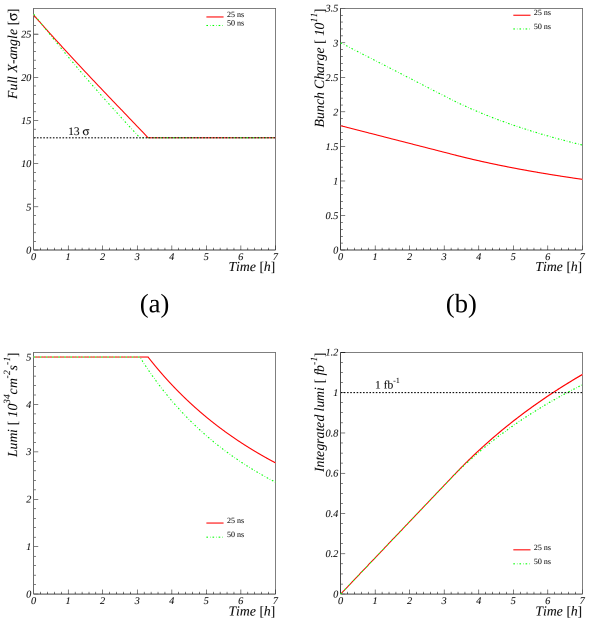
Bunch spacing [ns]	25	50
Longitudinal plane		
Number of bunches	2808	1404
Bunch charge [10^{11}]	1.8	3.0
Bunch length [cm]	6.0 (1.6 eV.s)	8.5 (3.2 eV.s)
IBS growth time [h]	~ 21	~ 25
Transverse plane		
$\gamma\epsilon [\mu\text{m}]$	2.75	
β^*_X (Xing) [cm]	30	
$\beta^*_{\|\|}$ (non-Xing) [cm]	7.5	
X-angle [μrad]	$955\ (27.2\,\sigma) \to 455\ (13.0\,\sigma)$	
IBS growth time [h]	~ 18	~ 22
Performance		
Time needed for 1 fb^{-1}	6h10min	6h30min

Table 4: *Possible parameter sets for an HL-LHC without crab-cavities.*

Target parameters for an HL-LHC without crab-cavities

Two possible parameter sets are given in Tab. 4 in order to reach the performance targets of the HL-LHC assuming a bunch spacing by 25 ns or 50 ns. The transverse parameters have been taken identical in the two cases, in terms of β^* (flat optics of Fig. 3), transverse normalised emittance (reduced by 1μm with respect to its nominal value) and dynamic range of the crossing angle for luminosity leveling. This range is limited on one side by the 150 mm aperture of the new triplet and, on the other side, by the long range beam-beam interactions (see later). Then playing with the bunch charge and the bunch length, the two cases can be made very similar in terms of IBS growth times (about 20 hours in the horizontal and longitudinal planes), beam-beam tune footprint combining both the head-on and parasitic beam-beam collisions (see later) but also in terms of performance.

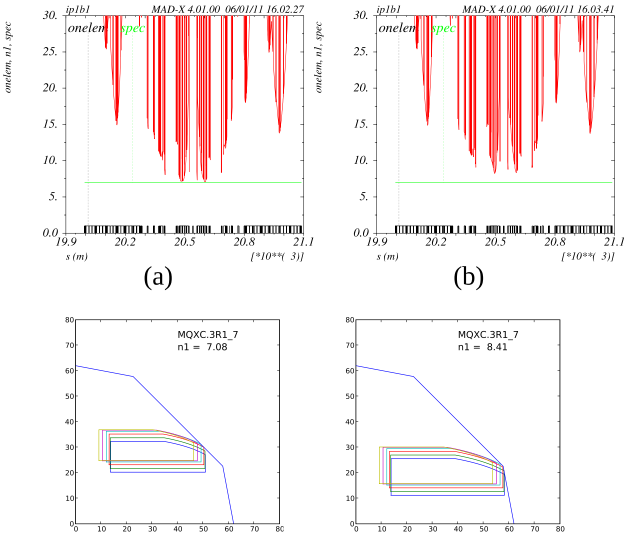
The performance is qualified by the time needed in order to integrate a luminosity of $1\,\text{fb}^{-1}$. It is of the order of 6 to 6.5 hours in the two cases, with about half of this time during which the luminosity can be sustained at the $5E34$ level at the beginning of the physics coast (see Fig. 7). It is worst noting that the beam intensity obtained in the “25 ns” case exceed the ultimate threshold by only 5%. On the other hand, the longitudinal emittance shall be reduced to 1.6 eV.s which is however perfectly reachable with the nominal RF system of the LHC and seems to be sufficient for Landau damping if extrapolating to 7 TeV the single bunch measurements which already took place in the LHC, and assuming no additional requirements imposed in multi-bunch operation [18]. The situation is not drastically different in terms of current for the other case. The total beam intensity can only be reduced by 10% with respect to the ultimate current for the 50 ns case, in order



(a) (b)

(c) (d)

Figure 7: *Time evolution of the crossing angle (a), charge per bunch (b), instantaneous luminosity (c) and integrated performance (d) during an HL-LHC physics coast assuming the parameter sets given in Tab. 4 for a bunch spacing of 25 ns (solid lines) and 50 ns (dashed-dotted lines).*



(a) (b)

(c) (d)

Figure 8: *Aperture plots of the low-β insertions (top) and extension of the secondary halo inside the octagonal beam-screen of Q3 (bottom) assuming the optics and the transverse emittance given in Tab. 4, and considering the initial and final crossing angle specified at the beginning (left) and end (right) of the physics coast.*

to stay competitive in terms of leveling time and beam life time (even if this case corresponds to a substantially larger "virtual luminosity" at the beginning of the coast).

The above estimates are based on the total hadron cross section of 100 mbarn per experiment, compared to 80 mbarn sometimes used by certain authors neglecting the elastic cross-section of 20 mbarn (see e.g. [5]). On the other hand the possible degradation of the performance due to IBS, estimated to about 10-15% in the worst case (see later), has not been taken into account because considered well inside the error bars related to the turn around time of the HL-LHC and therefore the number of $1\,\mathrm{fb}^{-1}$ fills which will be achievable in average per day at the horizon of 2020. On the other hand, in the presence of emittance growth due to IBS in the horizontal plane and emittance reduction in the vertical plane due to the radiation damping at 7TeV, a systematic luminosity unbalance is expected between the two experiments, assuming an alternated crossing scheme in IR1 and IR5 and the corresponding flat optics with $\beta^* = 30$ cm in the crossing plane. This unbalance should amount to about 10% (with the horizontal crossing configuration giving obviously the largest performance), and therefore around $300\,\mathrm{fb}^{-1}$ integrated over the full life time of the machine. This number is large enough to justify a full flexibility in the choice of the crossing angle for the HL-LHC collision optics, passing periodically from one crossing plane to another one in a given experiment, while always preserving an alternated crossing scheme for beam-beam related reasons. Sticking to the concept of an octagonal shape beam-screen to equip the new triplet (as developed for Phase I) is therefore more than justified in this case.

Luminosity leveling with crossing angle and impact on aperture and beam-beam tune footprint

Aperture. As already mentioned, using the crossing angle for luminosity leveling may be very demanding in terms of aperture, at least for round collision optics, i.e. with the same β^* in the two transverse planes. The situation is quite different when the β^* aspect ratio is substantially different from unity and the crossing plane corresponds to the plane of biggest β^* (i.e. smallest β^{max}). Using the parameter set proposed in the transverse plane in Tab. 4, in particular assuming a normalised emittance of only 2.75 μm, considering the new triplet, D1, D2, Q4 and Q5 discussed in the previous section, and applying the standard tolerance budget of the LHC in collision [19], the aperture plots of the new high luminosity insertion is showed in Fig. 8. The left and right pictures illustrate the situation at the beginning and the end of the coast, respectively, that is with an initial and final crossing angle of $27.2\,\sigma$ and $13\,\sigma$ imposed in the plane of biggest β^*. The sensitivity of the 2D normalised aperture with respect to the crossing angle is then rather moderate, corresponding to a variation of only $\delta n_1 \sim 1.3$ in the inner triplet for a modification of the crossing angle by almost $15\,\sigma$. When inspecting for instance the shape of the secondary halo inside the octagonal beam-screen of Q3.R, the reason is simple and lies in the fact that the aperture requirements are mainly driven by the plane of smaller β^*, that is the plane perpendicular to the crossing plane (see Fig.'s 8(c) and (d)).

Finally, compared to a luminosity leveling technique based on β^*, using the crossing angle goes exactly in the opposite (and in the right) direction, relaxing the aperture requirements and therefore offering a certain budget for emittance growth during the luminosity production.

Beam-beam tune footprint. The situation in terms of beam-beam tune footprint is illustrated in Fig. 9, assuming the two possible parameter sets proposed in Tab. 4 (25 ns and 50 ns), neglecting the possible contributions of IR2 and IR8 and assuming 21 long range interactions on either sides of the new high luminosity insertions. The two cases shows a very similar behaviour, both at the beginning of the physics coast (Fig. 9(a)) where the beam-beam tune footprint is very small due to the very large crossing angle, but also just before the second part of the coast when the normalised crossing angle has just reached 13 σ and the beam current is still rather high ($N_b \approx 1.4/2.2E11$ for the 25 ns and 50 ns case, respectively). While, in both cases, the total tune spread does not exceed the 0.01 (design) limit of the nominal LHC, two phenomenons can be clearly observed:

- the development of wings in the tune footprint due to the long-range beam-beam interactions, pushing some particles towards the coupling resonance (more precisely the (2,-2) resonance), especially for the 25 ns case,
- a sizable tune shift of the order of $\Delta Q_{LR} \approx -0.01$ in both planes. This effect adds up with the head-on beam-beam tune shift and comes from the fact that, for flat optics, an alternated crossing scheme can only warrant a partial compensation of the long-range beam-beam tune shift between IR1 and IR5.

A dynamic readjustment of the betatron tunes looks then mandatory during the leveling period. However, considering also the so-called pacman bunches which sample only half of the long-range interactions in the worst case, only half of the effect shall actually be corrected. This would therefore correspond to a tune correction of the order of

$$\Delta Q = -\Delta Q_{LR}/2 \approx 0.005\,. \qquad (8)$$

This tune correction is not included in Fig. 9(b) but will definitely contribute to shift the overall footprint just above the 10$^{\rm th}$ but still well below the 3$^{\rm rd}$ order resonances (i.e. $0.3 \leq Q_x < Q_y \lesssim 0.32$), which was a fundamental criteria for the choice of the nominal working point of the LHC (see e.g. [20]).

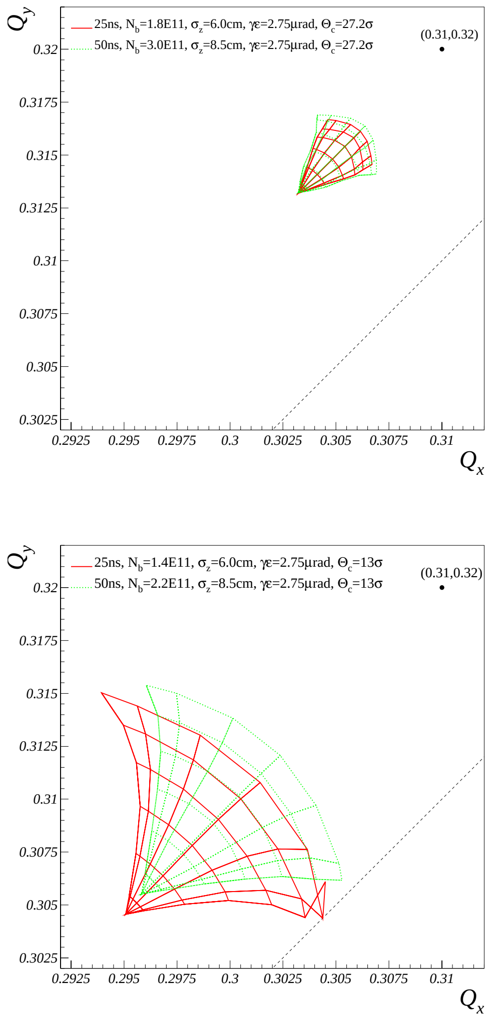


Figure 9: *Beam-beam tune footprint for particles with betatron amplitudes up to 6 σ, calculated at the beginning of the first (top) and second (bottom) period of the physics coast and based on the parameter sets defined in Tab. 4. The solid and dotted-dashed lines stand for a bunch spacing of 25 ns and 50 ns, respectively. The possible degradation due to head-on collisions at IP2 and IP8 is neglected. The number of parasitic encounters is assumed to be 21 on either side of IP1 and IP5. Only the case of nominal bunches is illustrated. The tune correction by $\Delta Q = +0.005$ is not included in the bottom picture (see Eq. 8).*

CONCLUSIONS AND OUTLOOKS

The Achromatic Telescopic Squeezing (ATS) scheme clearly opens a new β^* territory. It can squeeze by a factor of up to 4 the hard limit of $\beta^* \sim 30$ cm (resp. ~ 25 cm) which was identified in the context of the Phase I Upgrade Project for an Nb-Ti (resp. Nb3Sn) triplet with an optimum aperture of 120 mm [2]. On the other hand, for more than one decade, the scenarios proposed for the LHC Upgrade heavily relied on a β^* lower or much lower than 25 cm (see e.g. [21] for a review), or just equal to 25 cm for the most aggressive ones in terms of technology (crab-cavity, Nb3Sn triplet) and/or beam parameters (in particular bunch charge). In this respect, the ATS scheme shall then be considered as a fundamental basis for the HL-LHC project (formerly the LHC Upgrade Phase II) since it is the only optics scheme available today which enables to reach such low values of β^*.

Furthermore, by pushing so widely the β^* limits, the ATS scheme opens the route for flat collision optics, that is with a very small β^* in the plane perpendicular to the crossing plane. Flat optics shall be seen as a compromise in terms of luminosity gain at low β^*, with a gain with $1/\sqrt{\beta^*}$ without crab-cavity, which ranges exactly in between a quick saturation of the luminosity for round optics and a gain with $1/\beta^*$ assuming the availability of crab-cavities. Said differently, the ATS scheme is therefore not only a necessary ingredient for any upgrade scenario but represents by itself a novel path towards the LHC Upgrade, if used to produce flat collision optics, and therefore relying only on already existing and well-characterized technologies.

As described in details in the paper, the ATS scheme in its present stage requires however to be further optimized in order to mitigate its impact onto the dynamic aperture of the ring in collision, but the direction to follow is rather clear. In addition, contrary to any existing upgrade proposal, the ATS scheme can also be directly tested in the LHC, at least in its basic principles, and in order to analyze its limits for instance in terms of maximum allowable peak β-functions in the arcs or robustness of its fundamental chromatic properties (off-momentum β-beating, non-linear chromaticity, spurious dispersion induced by the crossing angle). One can also easily imagine that if the transverse emittance of the LHC beam is kept as small as it is found today, certain performance limitations related to the chromatic aberrations induced at low β^* may well be reached before saturating the aperture of the existing triplet. This scenario would then be at the extreme opposite of the one which motivated the Phase I project, but corresponds more or less to the present situation of the RHIC machine. In this configuration, the ATS scheme would then offer as well a efficient mean to boost the performance of the machine, at least after the long shut-down, that is after reaching an energy of 6.5-7 TeV per beam. In this case, indeed, assuming a normalised emittance of $\gamma\epsilon \sim 2.5\mu$m, a β^* of let say 35 cm would be easily achievable thank to the ATS scheme, while being fully compatible with the aperture of the existing triplet.

Finally, at a given beam brilliance, the ATS scheme is clearly in favor of a low emittance rather than a high intensity beam. The intrinsic optics limitations of the scheme are indeed only driven by mechanical and dynamic aperture related constraints. Furthermore a substantial margin exists for the head-on beam-beam tune shift due to the increase of the Piwinski angle at low β^*, even at ultimate intensity and nominal emittance, and still considering a beam-beam limit of $\Delta Q_{ho} = 0.01$ for the LHC. From the point of view of the author, the last big unknown is then related to the eventual excitation of beam-beam driven synchro-betatron resonances, operating with a Piwinski angle equal, larger or much larger than 1 (which is far from being recommended in [22]) and/or due to the hour-glass effect at low β^*. This question concerns most of the upgrade scenarios and is even more relevant for the HL-LHC since one of the key-stones of the project is based on luminosity leveling trough aggressive variations of the Piwinski angle (via crab-cavities, β^* or the crossing-angle itself). This recurrent question should therefore be answered with high priority since the output of such an analysis could drastically modify our present views and strategies for the LHC upgrade, i.e. pushing more on the bunch length side, with more RF voltage and Landau cavities, than on the β^* side.

ACKNOWLEDGMENTS

As I already did it in the primary paper [3], I would like to thank again Riccardo. He supported me in constructing an effective upgrade optics based on the ATS principles and performed a battery of exhaustive tracking studies in order to assess the performance of the scheme in terms of dynamic aperture.

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HL-LHC: PARAMETER SPACE, CONSTRAINTS & POSSIBLE OPTIONS

F. Zimmermann

CERN, Geneva, Switzerland

Abstract

This paper reviews the most promising ingredients to boost the LHC integrated luminosity, including smaller beta*, higher beam intensity, crab crossing, long-range beam-beam compensation, large Piwinski angle, flat longitudinal profile, and variations of bunch length, transverse emittance, crossing angle, and bunch spacing. It discusses how various ingredients conspire or compete, and how they pose different requirements on new LHC hardware and on the beams from the injectors, as well as their relative importance. Special emphasis is given to luminosity-levelling schemes. Finally a proposed roadmap towards HL-LHC and branching points in the research for a solution are sketched.

In particular, this paper points out that raising the beam current is important for reaching a high integrated luminosity, and that long-range beam-beam compensation should be pushed as a simple tool to boost HL-LHC luminosity performance.

INTRODUCTION

The parameter space and ingredients for an LHC luminosity upgrade have first been explored in the 2001 LHC upgrade feasibility study [1]. Later they have been refined and revisited in the frame of CARE-HHH [2], through several targeted workshops, e.g. [3.4,5,6], and, more recently, within the EuCARD-AccNet activity [7]. A review of HL-LHC parameters was presented at the 2010 Chamonix workshop [8]. The key result from Ref. [8] is reproduced in Fig. 1.

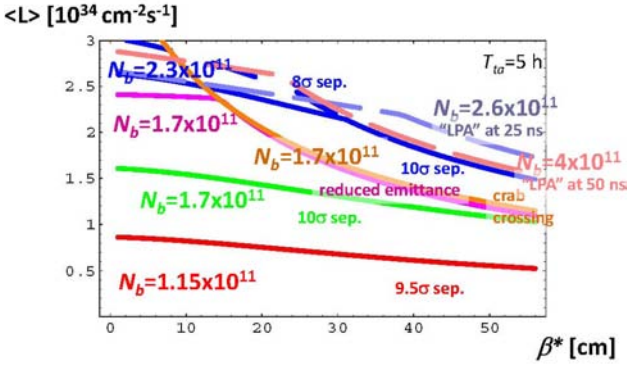


Figure 1: Average luminosity as a function of β^* for the nominal LHC and for various upgrade scenarios with 25-ns and (one with) 50-ns bunch spacing, with a long-range beam-beam separation of at least 8-10σ [8]. An average turnaround time of 5 h, a nominal normalized transverse rms emittance of 3.75 μm, and a maximum total beam-beam tune shift of 0.01 are assumed.

A number of changes have occurred since Chamonix 2010: (1) In the first year of LHC operation the head-on beam-beam limit has been found to be at least a factor of two larger than previously assumed, e.g. to correspond to a total tune shift of 0.02 or higher instead of 0.01 [9]. Though this observation still needs to be confirmed in the presence of the full number of nominal long-range collisions, the larger value of 0.02 will be taken as a new upper bound in our parameter optimization. (2) The LHC operational experience so far indicates the possibility to operate with up to two times lower emittance than nominal, or with twice the nominal beam brightness [9], at least for bunch-spacing values larger than the nominal value of 25 ns. (3) It has been defined that the HL-LHC will employ levelling techniques and run at a constant luminosity of 5x10^{34} cm^{-2}s^{-1} [10]. (4) A novel "Achromatic Telescopic Squeezing" (ATS) scheme, entailing beta-beat waves in the arcs [11-12], is a proposal, based on an effective construction and analysis of the corresponding optics [13], to achieve HL-LHC interaction-point (IP) beta functions of less than 30 cm, down to 7.5 cm. In particular, this proposal includes a so-called "flat" optics, with a beta* aspect ratio different from 1 [11-13]. Relevant chromatic aberrations are corrected, respecting the available sextupole strengths in the LHC arcs. The ATS scheme is able to match peak beta function of the order of up to 42 km reached in the triplet (for beta*=7.5cm) to a non-nominal, but regular optics in the adjacent arcs within the strength limits of the matching quadrupoles of the high luminosity insertions [11-12].

This paper is structured as follows. In the first part we discuss schemes for luminosity levelling and introduce the notion of "virtual peak luminosity". Next, the assumptions for estimating annual integrated luminosities are described. It is then shown which combinations of IP beta functions, transverse emittance, beam intensity and bunch spacing are required to reach a given integrated luminosity goal of e.g. 300 fb^{-1} per year. In the following we survey various ingredients for improving the geometric collision spot size, like crab cavities, long-range beam-beam compensators, a higher-harmonic RF system, or unequal "flat" IP beta functions, and we recall the maximal beam intensity available from the injectors (for various stages of the planned injector upgrades) as well as intensity limits in the LHC itself. At this point we are in a position to assemble the results in order to construct a number of HL-LHC parameter sets which could deliver 300 fb^{-1} per year, with varying values of β*, emittance, and bunch spacing, and to determine the beam intensity required for each of these scenarios. Finally, we draw some conclusions and, based on the earlier findings, we propose a roadmap, milestones, and branching points on the path towards the HL-LHC.

LUMINOSITY LEVELLING

The term "luminosity levelling" refers to intentionally decreasing the peak luminosity and running at approximately constant luminosity during the store. There are several motivations for such operating mode: it reduces the peak event pile up in the particle-physics detectors; it decreases the peak interaction-region (IR) power deposition; and it can maximize the integrated luminosity by potentially lowering the peak value of the beam-beam tune shift.

Around 1998, various luminosity levelling schemes including continuous beta* reduction were considered for the Tevatron Run II [14]. In 2000, luminosity levelling via beta* variation was mentioned for the LHC ion-collision programme ("e.g. squeeze of the beta function during the fill") [15]. Levelling for *pp* collisions in the context of the LHC luminosity upgrade was first proposed in 2007 [16]. Here, levelling with beta* variation or through changes of the bunch length and, thereby, of the Piwinski angle were considered for the so-called "Large Piwinski Angle" (LPA) upgrade scheme. LHC luminosity levelling by crossing-angle variation was proposed a few months later, for the alternative "Early Separation Scheme" of the LHC upgrade [17]. Soon thereafter, luminosity levelling with the crab-cavity RF voltage was suggested for the "Full Crab Crossing" upgrade scheme [18].

For a given levelled luminosity, L_{lev}, the "effective beam lifetime," $\tau_{\rm eff}$, scales with the total beam current. The effective beam lifetime is defined, and computed, by the following two equations,

$$\frac{dN_{tot}}{dt} = -\frac{N_{tot}}{\tau_{eff}} = -n_{IP}\sigma L_{lev}\,,$$

which yield

$$\tau_{eff} = \frac{N_{tot}}{n_{IP}\sigma_{tot}L_{lev}}\,,$$

where $n_{\rm IP}$ denotes the total number of high-luminosity interaction points (IPs), with $n_{\rm IP}=2$ for the LHC, and $\sigma_{\rm tot}$ the total cross section. For the LHC centre-of-mass energy the $\sigma_{\rm tot}$ is quite well known from cosmic-ray experiments to be about 100 mbarn [19].

Figure 2 shows the effective lifetime as a function of total proton intensity for the given HL-LHC target value of levelled luminosity. It is evident that, to obtain a decent proton beam lifetime at the HL-LHC target luminosity, proton intensities above nominal will be required.

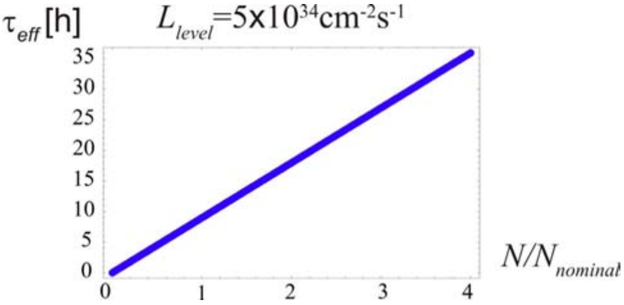


Figure 2: Effective beam lifetime at L_{lev}=5x10^{34} cm^{-2}s^{-1} as a function of total proton intensity in units of nominal intensity (2808 bunches of 1.15x10^{11} protons each).

The general luminosity formula is

$$L = \frac{f_{rev}n_b N_b^2}{4\pi\beta^*\varepsilon}F\left(\phi_{piw},\Delta x,\ldots\right) \qquad (1)$$

where F denotes a geometric reduction factor from crossing angle and/or beam-beam offset or hourglass effect.

For the luminosity with levelling we can write

$$L_{lev} = f_{lev}(t)L_{\max}(t)$$

where f_{lev} designates a time-dependent levelling factor, $f_{lev} \leq 1$, which characterizes the amount of "levelling detuning" with respect to the unlevelled maximum luminosity that would be possible at this point in time.

We define a "virtual peak luminosity" as

$$\begin{aligned}\hat{L} &\equiv L_{\max}(0)\\ &= \frac{f_{rev}n_b N_b^2(0)}{4\pi\beta^*(0)\varepsilon}F\left(\phi_{piw,\min}(0)\right)\\ &= \frac{L_{lev}}{f_{lev}(0)}\end{aligned}$$

It is equal to the levelled luminosity divided by the initial value of the levelling detuning factor. In a similar spirit we introduce a virtual peak tune shift.

Various levelling schemes can be considered for the HL-LHC:

(1) Varying the beam-beam offset Δx (successfully applied during LHC operation in 2010 [20]) , which gives rise to the following expressions

$$L_{lev} = \hat{L}\exp\left(-\left(\frac{\Delta x}{2\sigma^*}\right)^2\right);$$

$$\Delta Q_{lev} = \Delta\hat{Q}\,2\left(\begin{gathered}\left[\exp\left(-\frac{(\Delta x)^2}{2\sigma^{*2}}\right)-1\right]\frac{\sigma^{*2}}{(\Delta x)^2}\\ +\exp\left(-\frac{(\Delta x)^2}{2\sigma^{*2}}\right)\end{gathered}\right)$$

where for the tune shift we have assumed an alternating, horizontal and vertical offset at two collision points.

(2) Varying the Piwinski angle ϕ_{piw} ,that is σ_z, θ_c, or $V_{crab.}$ The characteristic equations for this case are

$$L_{lev} \approx \hat{L}\frac{1}{\sqrt{1+\phi_{piw}^2}};$$

$$\Delta Q_{lev} \approx \Delta\hat{Q}\frac{1}{\sqrt{1+\phi_{piw}^{2}}}$$

where we have assumed two IPs with alternating crossing. (3) Varying the IP beta function β* e.g. at constant ϕ_{piw}, leading to (for round beams):

$$L_{lev} \approx \hat{L}\frac{\hat{\beta}^{*}}{\beta^{*}_{lev}};$$

$$\Delta Q_{lev} \approx \Delta\hat{Q}.$$

A few typical time evolutions for these three levelling schemes may serve as an illustration.

First, we consider levelling with the offset Δx. We take the example of L_{peak}=1.0 (or 1.5) x10^{35} cm^{-2}s^{-1}, which means that the initial offset has to be chosen as Δ*x* =1.7 (or 2.1) σ^* to get L_{lev}=5x10^{34} cm^{-2}s^{-1}. Figure 3 depicts the subsequent change of Δ*x* as a function of time required to maintain a constant luminosity. Figure 4 shows the resulting evolution of the beam-beam tune shift. The maximum levelling time is 0.3 (or 0.42) $\tau_{\rm eff}$. It is interesting to observe in Fig. 4 that, with offset levelling, the tune shift changes sign during the store.

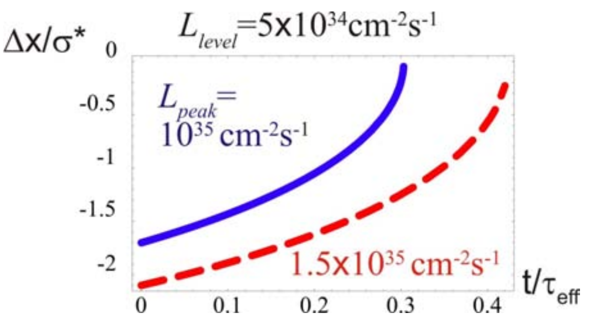


Figure 3: Transverse offset as a function of time in units of the effective beam lifetime, when levelling by offset variation, for two different values of the virtual peak luminosity (as indicated).

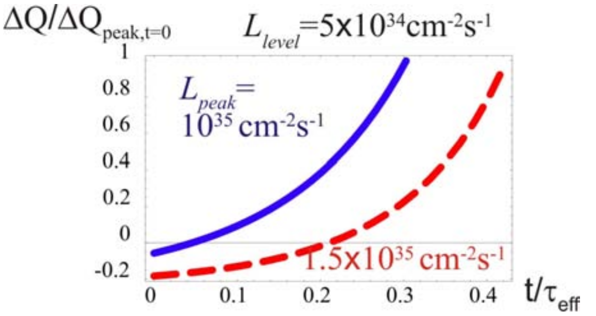


Figure 4: Total beam-beam tune shift in units of the virtual peak tune shift as a function of time in units of the effective beam lifetime, when levelling by offset variation, for two different values of the virtual peak luminosity (as indicated).

Second, we look at levelling with θ_c or V_{crab}. We take the same example values for the virtual peak luminosity as before, that is L_{peak}=1.0 (or 1.5) x10^{35} cm^{-2}s^{-1} . In this case the initial Piwinski angle has to be set to ϕ_{piw}=1.7 (or 2.8) rad in order to obtain L_{lev}=5x10^{34} cm^{-2}s^{-1}. Figure 5 shows the change of ϕ_{piw} as a function of time needed in order to keep a constant luminosity. Figure 6 displays the implied evolution of the beam-beam tune shift for levelling with the Piwinski angle. The maximum levelling time is 0.3 (0.42) $\tau_{\rm eff}$ as before. Figure 6 indicates that when levelling with the Piwinski angle, the beam-beam tune shift increases during the store, which might not always be desirable.

Third, we discuss levelling with β^*. Proceeding as before, we find that with a virtual peak luminosity of L_{peak}=1.0 (or 1.5) x10^{35} cm^{-2}s^{-1} at β^*=0.15 m, we need to increase the initial IP beta function to β^*=0.3 (or 0.45) m in order to get L_{lev}=5x10^{34} cm^{-2}s^{-1}. Figure 7 illustrates the evolution of β^* as a function of time for constant luminosity, and Fig. 6 the evolution of the beam-beam tune shift with β^* levelling. When levelling by reducing β^*, the tune shift decreases during the store (see Fig. 8). The maximum levelling time is again 0.3 (0.42) $\tau_{\rm eff}$, which is hence independent of the levelling scheme, and only depends on the value of the virtual peak luminosity and on the target levelling luminosity.

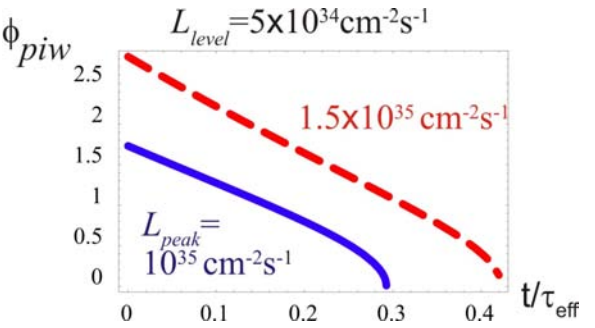


Figure 5: Piwinski angle as a function of time in units of the effective beam lifetime, when levelling by varying the Piwinski angle, for two different values of the virtual peak luminosity (as indicated).

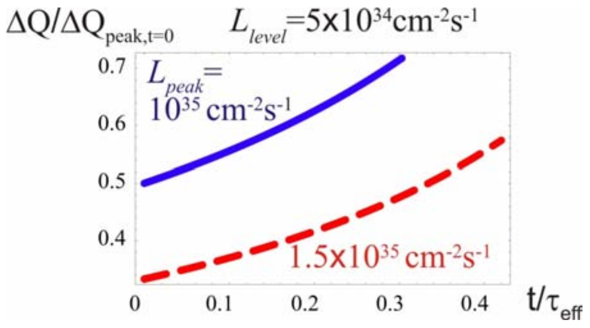


Figure 6: Total beam-beam tune shift in units of the virtual peak tune shift as a function of time in units of the effective beam lifetime, when levelling by varying the Piwinski angle, for two different values of the virtual peak luminosity (as indicated).

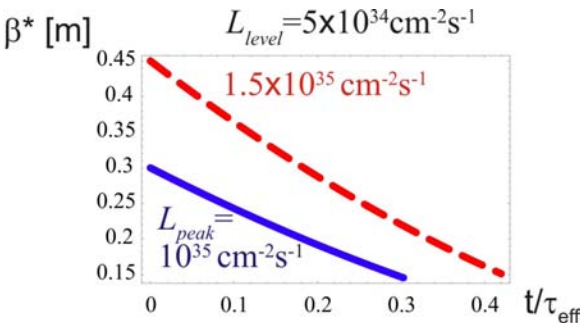


Figure 7: IP beta function as a function of time in units of the effective beam lifetime, when levelling by varying β^*, for two different values of the virtual peak luminosity (as indicated).

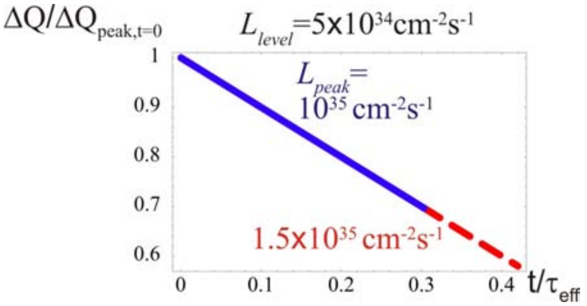


Figure 8: Total beam-beam tune shift in units of the virtual peak tune shift as a function of time in units of the effective beam lifetime, when levelling by β^* variation, for two different values of the virtual peak luminosity (as indicated).

For a given levelled luminosity, the maximum levelling time in units of $\tau_{\rm eff}$ is a function of the virtual peak luminosity according to

$$\frac{t_{lev}}{\tau_{eff}} = 1 - \sqrt{\frac{L_{lev}}{\hat{L}_{peak}}} \ ,$$

which is shown in Fig. 9.

The absolute levelling time t_{lev} also depends on the beam intensity. Figure 10 shows the absolute levelling time as a function of the virtual peak luminosity for two different proton beam intensities. The absolute levelling time scales linearly with the total beam intensity.

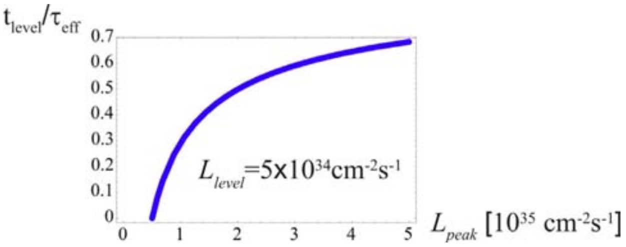


Figure 9: Maximum levelling time in units of effective beam lifetime as a function of the virtual peak luminosity. The curve is independent of the levelling scheme.

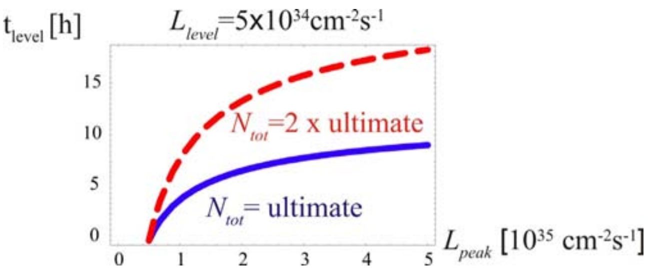


Figure 10: Maximum levelling time in units of hours as a function of the virtual peak luminosity, for two different proton beam intensities.

For estimating integrated luminosity at the HL-LHC, we make the following assumptions:

- two high-luminosity collision points;
- beam & luminosity lifetime are dominated by *p* consumption;
- 200 physics days of proton run per year (w/o restart, w/o TS's, w/o MD periods);
- 5 h turnaround time from physics to physics;
- 75% machine availability.

The last number appears conservative. In November 2010 the LHC availability has already reached 80% [21]. Many other accelerator and/or collider projects around the world have obtained higher availability numbers; see Table 1.

Table 1: Machine availability for various accelerators.

PEP-II [22]	87%
LCLS [22]	94%
Tevatron (best) [23]	97.5%
RHIC (2010-11 run) [24]	82%
LHC Nov. 2010 [21]	80%

We can then calculate the integrated luminosity with levelling at 5x10^{34} cm^{-2}s^{-1}. It depends only on the virtual peak luminosity and on the total beam current, as is illustrated in Fig. 11.

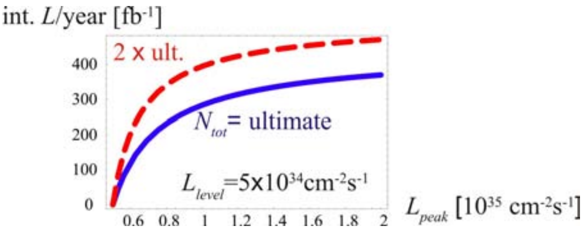


Figure 11: Annual luminosity as a function of virtual peak luminosity for two different total proton-beam intensities.

For example, getting 300 fb^{-1} per year, at ultimate intensity requires a virtual peak luminosity of L_{peak}=1.10x10^{35} cm^{-2}s^{-1}, while at two times the ultimate intensity a peak luminosity of L_{peak}=0.71x10^{35}cm^{-2}s^{-1} would be needed (and with higher beam current it would also be much easier to get this virtual peak luminosity).

As shown in Fig. 12, we can "invert" the above relation and compute the beam intensity required to obtain a given target annual luminosity as a function of the virtual peak luminosity.

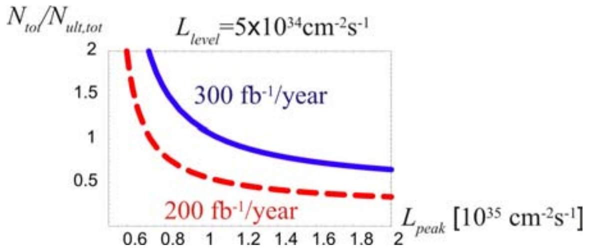


Figure 12: Total beam intensity required to reach 300 fb^{-1} or 200 fb^{-1} per year, as a function of the virtual peak luminosity.

We note that for a given bunch spacing the virtual peak luminosity on the horizontal axis of Fig. 12 scales with the square of the beam intensity, so that the beam intensity enters linearly in vertical direction and quadratically towards the right. This underlines the tremendous importance of beam intensity for reaching the HL-LHC integrated luminosity target.

How much do we need to squeeze or what is the benefit of squeezing further? To answer this question, it is straightforward to factor out the intensity from the peak luminosity and to convert Fig. 12 into a curve of geometric beam size reduction as a function of beam intensity. The result is shown in Fig. 13.

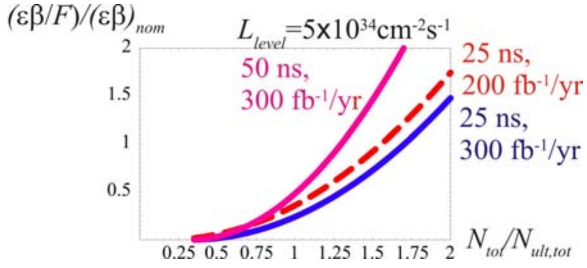


Figure 13: Geometric beam-size reduction $\beta^*\varepsilon/F$ (see Eq. (1)) needed to meet the annual integrated luminosity goal, including crossing-angle effect and normalized to the nominal value of ($\beta^*\varepsilon$), as a function of the total proton beam intensity, for two different values of bunch spacing and luminosity target.

For example, to obtain 300 fb^{-1} per year at N_b=2x10^{11} bunch population and 25 ns spacing we need to reduce ($\beta^*\varepsilon$)/F by a factor 0.38 compared with the nominal ($\beta^*\varepsilon$), while at N_b=3.4x10^{11} and 50 ns we need to reduce ($\beta^*\varepsilon$)/F only by a factor 0.48.

Holding the emittance constant, equal to nominal, and assuming a long-range beam-beam separation of 8.5σ (achieved with long-range compensators), Fig. 13 can be converted into a requirement on β^*, presented in Fig. 14.

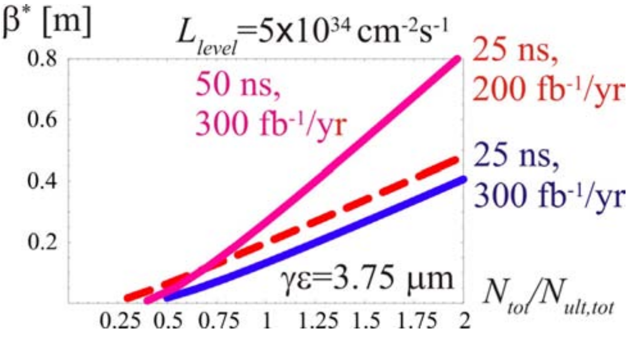


Figure 14: IP beta function needed for delivering 300 or 200 fb^{-1} per year as a function of total proton intensity in units of ultimate intensity, for two different values of bunch spacing, at a constant transverse normalized emittance equal to nominal.

Figure 14 illustrates the trade-off between proton beam intensity and β^*, for a given integrated luminosity goal and bunch spacing. For 25-ns bunch spacing the design β^* value of 55 cm would suffice at twice the ultimate intensity (that is, at 2 x 2808 x 1.7 x 10^{11} protons), while for nominal intensity β^* must be shrunk to below 20 cm. A bunch spacing of 50 ns would allow for two times larger β^* values at the same total intensity.

Instead of varying β^* we can keep it constant, equal to nominal (0.55 m), and reduce the transverse emittance to meet the integrated luminosity goal. The emittance required as a function of total beam intensity is shown in Fig. 15, again for a long-range separation of 8.5σ. With 50-ns spacing the nominal emittance would suffice at about 1.5 times the ultimate intensity

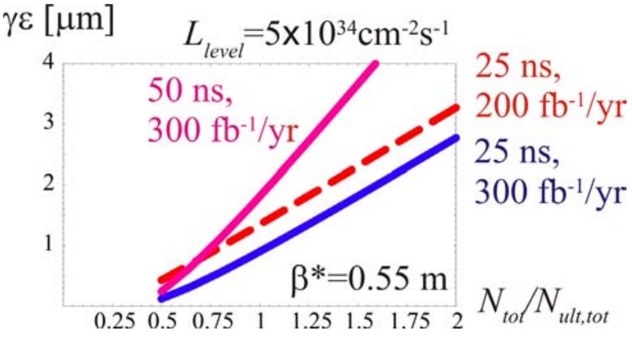


Figure 15: Transverse normalized emittance needed for delivering 300 or 200 fb^{-1} per year as a function of total proton intensity in units of ultimate intensity, for two different values of bunch spacing, at a constant IP beta function equal to nominal.

Table 2 shows (ε,β^*) combinations that would provide the target annual luminosity at a total intensity equal to the ultimate LHC intensity, for two different bunch spacings. As can be seen, the scenarios with 50-ns bunch spacing are particularly attractive and they would allow reaching the target with an IP beta function of about 30 cm and close to nominal emittance, at ultimate total proton intensity.

Table 2: ε–β* combinations that would deliver a target annual luminosity of 300 or 200 fb^{-1} per year at ultimate total proton intensity.

luminosity	spacing	norm. emittance	IP beta
300 fb^{-1}/yr	25 ns	3.75 μm	0.13 m
200 fb^{-1}/yr	25 ns	3.75 μm	0.20 m
300 fb^{-1}/yr	**50 ns**	**3.75 μm**	**0.27 m**
300 fb^{-1}/yr	25 ns	0.90 μm	0.55 m
200 fb^{-1}/yr	25 ns	1.35 μm	0.55 m
300 fb^{-1}/yr	**50 ns**	**1.81μm**	**0.55 m**
300 fb^{-1}/yr	25 ns	1.65 μm	0.30 m
200 fb^{-1}/yr	25 ns	2.47 μm	0.30 m
300 fb^{-1}/yr	**50 ns**	**3.32 μm**	**0.30 m**

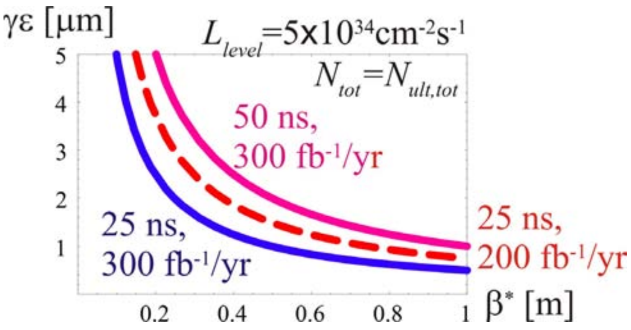


Figure 16: Normalized emittance yielding target integrated luminosity at ultimate proton beam intensity, as a function of IP beta function.

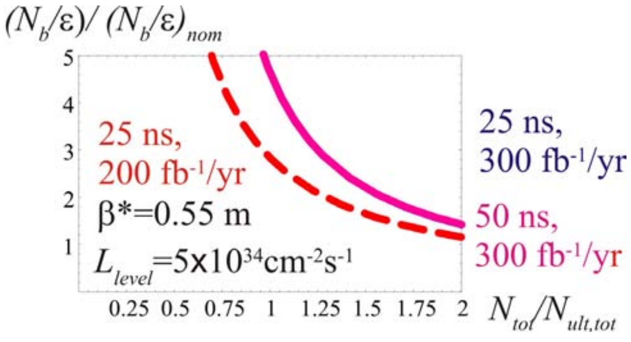


Figure 17: Beam brightness, normalized to ultimate brightness at 25 ns spacing and nominal bunch length, required for delivering 300 or 200 fb^{-1} per year as a function of total proton intensity in units of ultimate intensity, for two different values of bunch spacing, at a constant IP beta function equal to nominal (0.55 m), with emittance varying as in Fig. 16. The curve for 25-ns spacing equals the one for 50-ns spacing.

Figure 16 graphically illustrates the relation between normalized transverse emittance and IP beta function that must be met to reach the target HL-LHC integrated luminosity at ultimate proton beam intensity. Figures 17 and 18 show the bunch brightness as a function of total intensity, corresponding to the emittance variation in Fig. 15 and to the β^* variation in Fig. 14, respectively.

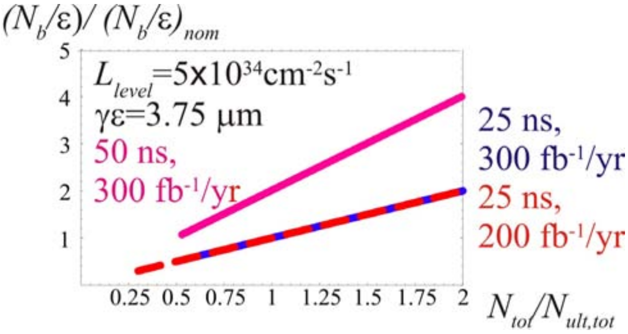


Figure 18: Beam brightness, normalized to ultimate brightness at 25 ns spacing and nominal bunch length, required for delivering 300 or 200 fb^{-1} per year as a function of total proton intensity in units of ultimate intensity, for two different values of bunch spacing, at a constant transverse normalized emittance equal to nominal (3.75 μm), with β^* varying as in Fig. 15. At a given bunch spacing and emittance, the curves are independent of the target luminosity.

APPROACHES AND INGREDIENTS TO BOOST LHC LUMINOSITY

Alternative approaches to increase the LHC intensity include the following: (1) low β* & crab cavities (a few tens of MV), (2) low β* & higher harmonic RF (e.g. 7.5 MV at 800 MHz) plus long-range compensation, and (3) operating in a regime of large Piwinski angle together with long-range beam-beam compensation. These three collision schemes are sketched in Fig. 19. Interaction-point β^* values below 30 cm could be achieved with the ATS optics [11-13,25]. In all the aforementioned scenarios the beam intensity should be pushed to the "limit" as well.

Each collision scheme could be implemented with either 25-ns or 50-ns bunch spacing, and correspondingly adjusted bunch charge. The value of β* is also a variable. In addition, for each case one can consider both round-beam collisions and collisions with different IP beta functions in the two transverse planes ($\beta_x^* \neq \beta_y^*$), in this case with alternating aspect ratio at the two primary IPs. A large (infinite) number of parameter combinations exist which can meet the target value for the HL-LHC integrated luminosity.

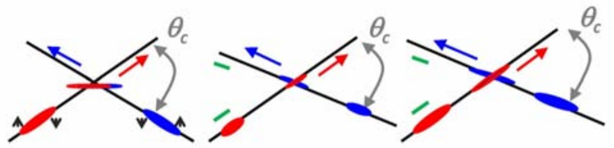


Figure 19: Alternative collisions schemes for the HL-LHC; low β* & crab cavities [left]; low β* & higher harmonic RF plus long-range compensation [center], and collisions at large Piwinski angle together with long-range beam-beam compensation [right].

Crab cavities offer the following benefits: They improve the geometric overlap for small β* and large crossing angle (which is one of the primary motivations for installing them in the LHC); they can potentially boost the beam-beam limit (a potential additional benefit); they allow for an easy and transparent luminosity levelling (another key motivation for the LHC); and they would avoid off-center collisions from beam loading (an additional benefit for the LHC); the beam loading issue was highlighted in [26]. An ATS-type optics solution accommodating crab cavities with $\beta_{x,y}^*$=15 cm has been constructed [25].

A number of points need to be addressed prior to a full crab-cavity installation in the LHC, including the emittance growth from crab-cavity RF noise, the effect of the crab-cavity impedance, the size and impact of any field nonlinearity, machine protection issues in case of a crab-cavity failure, trip rate, various technical challenges, and the time line.

There exist 4 to 5 promising designs for compact crab cavities which could be accommodated in the LHC interaction regions (see Fig. 20). The present plan is to perform SPS/LHC prototype beam tests in about 2015/16, before a final decision is taken.

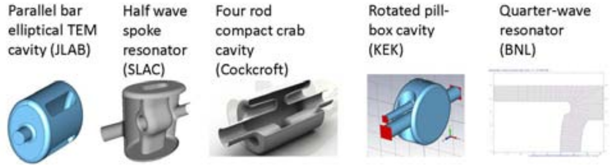


Figure 20: Candidate designs for compact HL-LHC crab cavities presented at the LHC-CC'10 workshop [27]: ODU/JLAB design by J. Delayen; SLAC design by Z. Li et al; CI design by G. Burt; KEK design by K. Nakanishi; and BNL design by I. Ben-Zvi.

A number of recent simulations studies suggest that crab-cavities can raise the LHC beam-beam limit. Figure shows results from a weak-strong beam-beam simulation by D. Shatilov and M. Zobov [28] using the Lifetrac code. A frequency map analysis of tune diffusion in the A_x-A_y normalized amplitude space (extending to 10σ) reveals that the crab crossing suppresses all important resonances which are present in case of a finite crossing angle, as is shown in Fig. 21.

Figure 22 present results from a strong-strong beam-beam simulation by K. Ohmi for a different set of LHC parameters [29], which indicate that the luminosity lifetime with crab crossing is 10 times higher than without.

Long-range beam-beam compensation using "wires" has first been proposed by Jean-Pierre Koutchouk [30]. Prototype beam-beam compensators have been built and deployed for beam studies at the SPS [31] and in RHIC [32]. At present 2x2 water-cooled units are installed in the SPS (two with remote control), and 1x2 spare units are ready for installation. The two RHIC compensators have recently been dismounted to increase the aperture for new Roman pot experiments. They have been donated for SPS and LHC studies. The 1st RHIC compensator is already stored at CERN; the 2nd is being shipped. In total 5 long-range beam-beam compensator sets will soon be available on the CERN site. Different from the SPS design, the RHIC compensators are air-cooled.

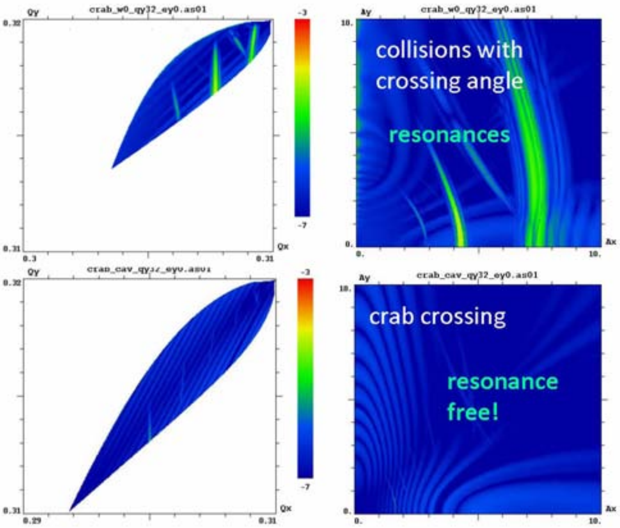


Figure 21: Frequency map analysis of weak-strong beam-beam simulations for LHC scenarios without [top] and with crab crossing [bottom] [28]. The beam parameters assumed were $\varepsilon_{x,y}$ =0.5 nm, E = 7 TeV, $\beta^*_x = 30$ cm, β^*_y = 7.5 cm, σ_z = 11.8 cm, θ_c= 315 mrad (ϕ_{piw} =1.5), N_b = 4.0x10^{11}, Q_s =0.002, $\Delta Q_{x,y}$ ~ -0.0065, and a single interaction point.

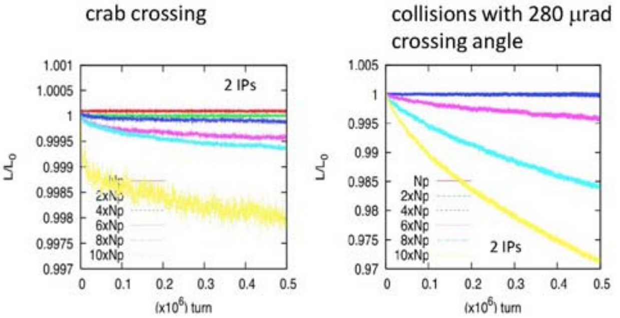


Figure 22: HL-LHC luminosity as a function of time from a strong-strong beam-beam simulation with crab crossing [left] and crossing angle [right] [29]. This simulation was performed for the nominal LHC considering 2 interaction points with alternating crossing, and a crossing angle of 280 μrad. The various curves correspond to different bunch intensities given as multiples of the nominal intensity (color code).

Figure 23 shows a photo of one of the SPS compensators, which is equipped with independent three wires in order to be able to compensate, or mimic, long-range beam-beam collisions in the horizontal plane, in the vertical plane, and at 45 degrees.

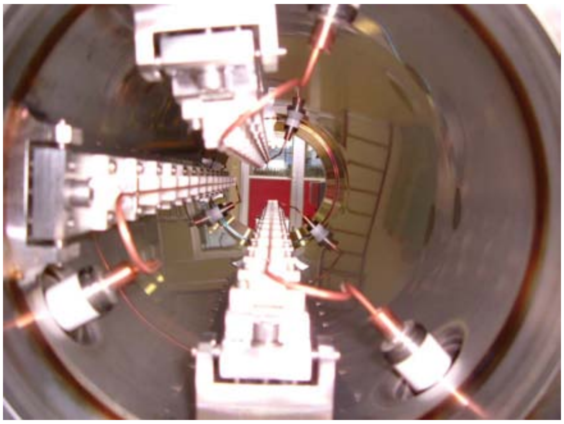


Figure 23: Photograph of a long-range beam-beam compensator prototype unit installed in the CERN SPS, with three independent wires mounted at a horizontal, vertical, and 45-degree separation from the beam (G. Burtin, J.-P. Koutchouk, F. Zimmermann et al.).

Figure 24 illustrates the potential benefit from the long-range beam-beam compensation. Shown is the normalized crossing angle as a function of bunch intensity. Without compensators the minimum norrnalized crossing angle required in the LHC increases as a function of bunch intensity N_b and spacing $T_{\rm sep}$ roughly as [33]

$$\frac{\theta_{c,\min}}{\sigma'^*} \approx 6 + 3.5\sqrt{\frac{N_b}{1.05\times 10^{11}}\,\frac{25\ \mathrm{ns}}{T_{sep}}\,\frac{n_{LR}}{72}}\ ,$$

which is represented by the two sold lines in the figure. Long-range beam-beam compensation would be effective at a separation of about 8.5σ, where the field of the other beam is well approximated by a $1/r$ law up to a betatron amplitudes of about 6σ - the nominal location of the LHC primary collimators.

Specifically, Fig. 24 demonstrates how the long-range compensators enable further increases in beam intensity while maintaining a constant crossing angle corresponding to 8.5 times the rms IP beam divergence, to be compared with a crossing angle of 9.5σ*’ for the nominal LHC design.

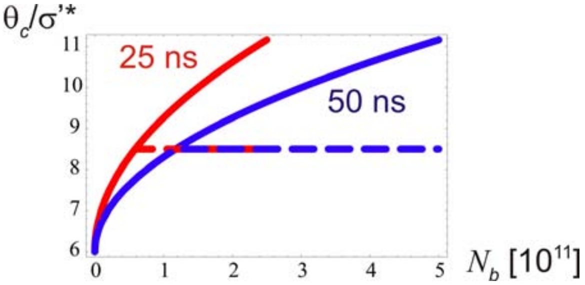


Figure 24: Normalized LHC crossing angle as a function of bunch intensity without (solid) and with long-range compensation (dashed) for 25-ns (red) and 50-ns bunch spacing (blue), according to the above formula.

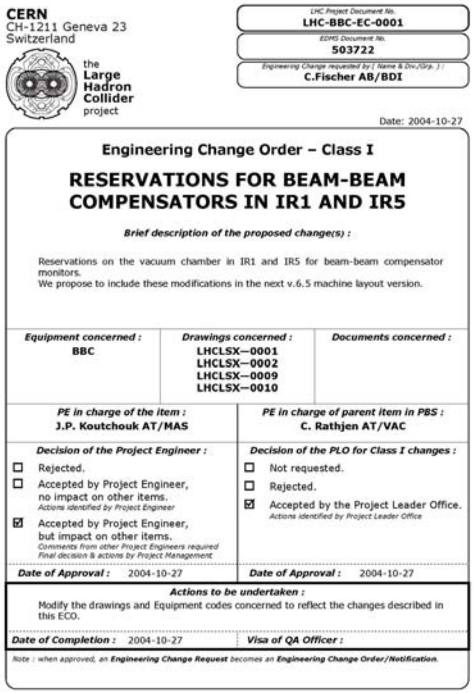
For the installation of future long-range beam-beam compensators in the LHC 3-m long sections have been reserved at 104.93 m (center position of the wire) on either side of LHC IP1 and IP5, as documented by an LHC engineering change order issued by J.-P. Koutchouk in 2004 (Fig. 25).

If the colliding beams are not round but “**flat**” **with** $\beta_x^* \neq \beta_y^*$, the minimum crossing angle may not only depend on the normalized separation in the plane of crossing, but also on the beta function in the other plane. Considering alternating crossing with $\beta_x^*>\beta_y^*$ and horizontal crossing in one IP, and $\beta_x^*<\beta_y^*$* plus vertical crossing in the second IP, and comparing the moduli of the long-range beam-beam tune shift with those for round-beam collisions, we expect that, for flat beam collisions, the minimum separation needed in the plane of crossing for an IP beta function ratio of 4 could be about 50% larger than estimated by looking only at the separation in the plane of crossing, due to the fact that the beta function is larger in the orthogonal plane. The validity of the above reasoning needs to be confirmed in tracking simulations.

Using formulae of [34] for the tune shift induced by a single centered flat-beam collision, and denoting $r=\beta_x^*/\beta_y^*$ (with $\beta_x^*>\beta_y^*$), the total “head-on” flat-beam tune shift with alternating crossing at two collision points is

$$\Delta Q_{tot,\,flat} = \frac{r_p N_b}{2\pi\gamma\varepsilon}\left(\frac{1+\sqrt{\frac{1}{r}\left(1+\phi_{piw}^2\right)}}{\left(1+\phi_{piw}^2\right)+\sqrt{\frac{1}{r}\left(1+\phi_{piw}^2\right)}}\right)$$

where the normalized emittance is assumed to be the same in the two transverse planes, i.e. $\gamma\varepsilon=\gamma\varepsilon_x=\gamma\varepsilon_y$. For r=1 the above reduces to the standard round-beam expression.



CERN
CH-1211 Geneva 23
Switzerland

the
Large
Hadron
Collider
project

LHC Project Document No.
LHC-BBC-EC-0001

EDMS Document No.
503722

Engineering Change requested by (Name & Div./Grp.) :
C.Fischer AB/BDI

Date: 2004-10-27

Engineering Change Order – Class I

RESERVATIONS FOR BEAM-BEAM COMPENSATORS IN IR1 AND IR5

Brief description of the proposed change(s) :

Reservations on the vacuum chamber in IR1 and IR5 for beam-beam compensator monitors.
We propose to include these modifications in the next v.6.5 machine layout version.

Equipment concerned :	***Drawings concerned :***	***Documents concerned :***
BBC	**LHCLSX—0001** **LHCLSX—0002** **LHCLSX—0009** **LHCLSX—0010**	

PE in charge of the item :	***PE in charge of parent item in PBS :***
J.P. Koutchouk AT/MAS	**C. Rathjen AT/VAC**
Decision of the Project Engineer :	***Decision of the PLO for Class I changes :***
☐ Rejected. ☐ Accepted by Project Engineer, no impact on other items. *Actions identified by Project Engineer* ☑ Accepted by Project Engineer, but impact on other items. *Comments from other Project Engineers required Final decision & actions by Project Management*	☐ Not requested. ☐ Rejected. ☑ Accepted by the Project Leader Office. *Actions identified by Project Leader Office*
Date of Approval : 2004-10-27	***Date of Approval :*** 2004-10-27

Actions to be undertaken :

Modify the drawings and Equipment codes concerned to reflect the changes described in this ECO.

Date of Completion : 2004-10-27 ***Visa of QA Officer :***

Note : when approved, an ***Engineering Change Request*** *becomes an* ***Engineering Change Order/Notification.***

Figure 25: Engineering change order reserving space for long-range beam-beam compensators around LHC IP1 and IP5, dating from the year 2004.

A **higher harmonic RF system** in the LHC, as proposed in [35], could help the HL-LHC performance in a number of ways. It could be used to lengthen or shorten the bunches, or for tailoring the bunch profile (creating longitudinally peaked or flat bunches), and most importantly for increasing Landau damping and enabling higher beam intensity. The higher-harmonic RF system can be thought of as a “Landau octupole” for the longitudinal plane. The report [35] discussed higher-harmonic RF systems at 1.2 GHz and 800 MHz. The presently favored system is at 800 MHz [36]. This system, with a voltage of about 7.5 MV, would raise the stability gain by at least a factor of 3, e.g. allowing for three times higher beam intensity or for lower longitudinal emittance (avoiding the controlled blow up in the LHC) and, thereby, shorter bunches.

MAXIMUM BEAM INTENSITY

The beam intensity available from the injectors increases with the proposed injector upgrades. The projected intensities in various upgrade phases, and for different values of bunch spacing and transverse emittance, are summarized in Table 3, taken from [9]. As we will show later, the last two rows correspond to “HL-LHC” class intensities, i.e. intensities needed to meet the HL-LHC design goals for integrated luminosity. We will argue that it would be helpful if the maximum intensity could still be increased by 10-20% beyond these values.

Table 3: Intensity and emittances available from the LHC injector complex for various upgrade phases.

	spacing [ns]	bunch intensity [10^{11}]	transverse norm. emittance [µm]
nominal	25	1.15	3.75
available “now”	25	1.20	3.75
available “now”	50	1.70	3.75
available “now”	50	1.70	2.50
w LINAC4	25	1.40	3.75
w LINAC4	50	2.50	3.75
w LINAC4+LIU	25	2.00	2.50
w LINAC4+LIU	50	3.30	3.75

An intensity limit in the LHC itself is imposed by the cooling capacity available for the beam screen and magnet cold bore with regard to beam-induced heat loads. The cooling capacity for the cold LHC arcs is limited both globally, by the cooling power of the cryo plants, which must also cool the interaction region quadrupoles – at high luminosity subjected to large heat from collision debris –, and locally, by the hydraulic impedance of the beam-screen cooling loops [37-39]. It is assumed that the HL-LHC will have dedicated cryoplants for the interaction region and the RF system, and that the existing cryoplants are used for the cooling of the LHC arcs only.

In the LHC arcs proper, synchrotron radiation, image currents (together with the resistive wall impedance) and electron cloud are the main sources of heat load. The heat from synchrotron radiation and impedance can be fairly accurately calculated [38,39]. Heat load due to image currents and synchrotron radiation increase with bunch intensity as shown in Figs. 26-28, for three different combinations of bunch length and bunch spacing. The figures demonstrate that the sum of these heat loads always stays below the maximum available local cooling capacity of about 2.3 W/m per aperture. Bunch intensities up to $2.5\text{x}10^{11}$at 25 ns and $5\text{x}10^{11}$ at 50 ns bunch spacing appear feasible from the point of view of these heat loads.

Another heat-load contribution is from gas scattering onto the cold bore. Nuclear beam-gas scattering at a beam lifetime of τ~100 h (32 ntorr hydrogen pressure at room temperature) contributes a beam-screen heat-load equivalent of 0.15 W/m at nominal current; see e.g. [40]. This represents a rather small additional contribution, which does not change our above conclusion.

The heat load from electron cloud is obtained from simulations [42,43]. The most optimistic simulations consider a maximum secondary emission yield below 1.3, where beam-induced multipacting is largely absent, and where the remaining electron-induced heating is dominated by the accelerated primary photo-electrons.

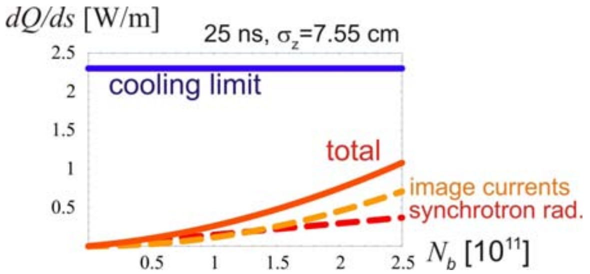


Figure 26: Heat load from synchrotron radiation and image currents, as well as their sum, as a function of bunch intensity, for a bunch spacing of 25 ns and an rms bunch length of 7.55 cm.

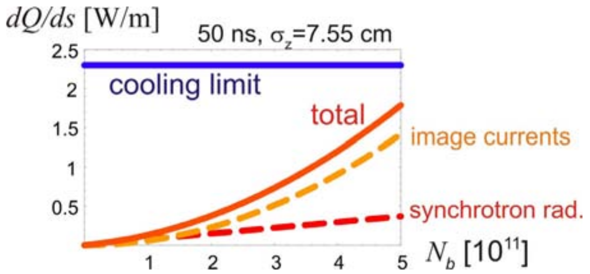


Figure 27: Heat load from synchrotron radiation and image currents, as well as their sum, as a function of bunch intensity, for a bunch spacing of 50 ns and an rms bunch length of 7.55 cm.

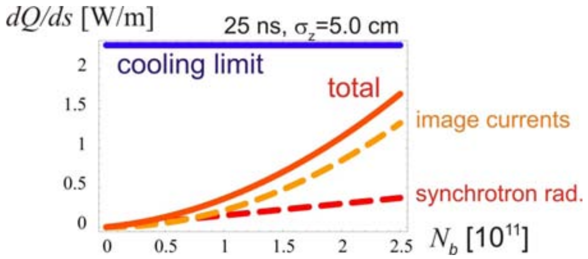


Figure 28: Heat load from synchrotron radiation and image currents, as well as their sum, as a function of bunch intensity, for a bunch spacing of 25 ns and an rms bunch length of 5.0 cm.

Figures 29 and 30 compare, for bunch-spacing values of 25 ns and 50 ns, respectively (and with different IP beta functions), the residual cooling capacity available and the simulated heat load from the electron cloud. Here, the residual (global) cooling capacity [without dedicated IR cryo-plants] was calculated by subtracting from the global limit the equivalent cooling power required for the interaction region (depending on the luminosity), and the computed heating from synchrotron radiation and image currents; by subtracting from the local limit only the latter two arc contributions; and then taking the minimum value of the remaining global and local cooling capacities so obtained.

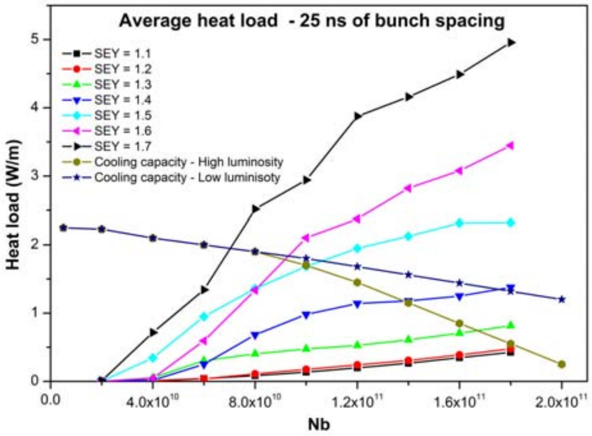


Figure 29: Residual cooling capacity for electron cloud per aperture and per meter at low and high luminosity at β*=0.55 m (or with and without dedicated IR cryo plants) as a function of bunch intensity [37-39] together with the electron cloud heat load simulated for various values of the maximum secondary emission yield and 25-ns bunch spacing, with a Gaussian bunch profile [41,42].

Figures 29 and 30 demonstrate that in order to reach any decent bunch intensity at high luminosity (actually the first is a precondition for the latter), separate dedicated cryo plants are needed for the interaction regions. More specifically, Fig. 29 shows that for 25-ns bunch spacing, going above N_b=1.7x10^{11} protons per bunch at nominal β* requires dedicated IR cryo plants; if such plants are installed the “hard” intensity limit becomes N_b~2.3x10^{11}. From Fig. 30, for 50-ns bunch spacing, dedicated IR cryo plants are required at bunch intensities above N_b=1.3x10^{11} with an upgraded β*~0.25 m; again assuming a separate IR cooling, the hard limit on the bunch intensity is pushed to N_b~5x10^{11}.

In conclusion the additional electron cloud contribution to the beam-screen heat load is acceptable if δ_{max}≤1.2.

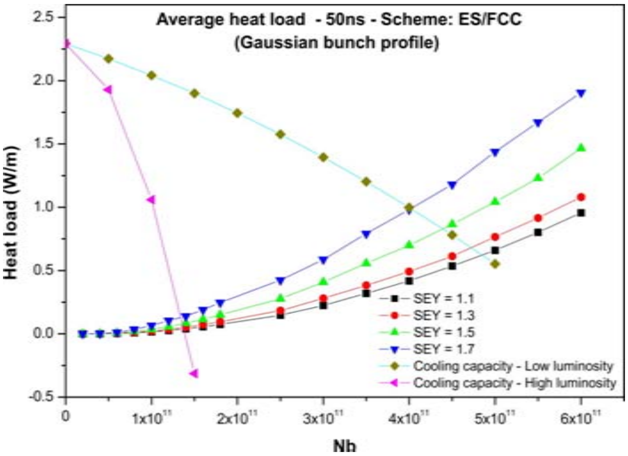


Figure 30: Residual cooling capacity for electron cloud per aperture and per meter at low and high luminosity (or with and without dedicated IR cryo plants) for a bunch spacing of 50 ns and β*=0.25 m as a function of bunch intensity [37-39] together with the electron cloud heat load simulated for various values of the maximum secondary emission yield. A longitudinally Gaussian bunch shape is assumed [41,42].

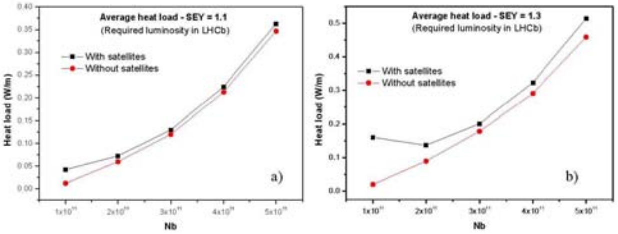


Figure 31: Simulated electron heat load as a function of main bunch intensity for 50 ns bunch spacing with (black) and without LHCb satellite bunches (red) for two different values of the maximum secondary emission yield (δ_{max}=1.1 – left, and δ_{max}=1.3 – right) [41,42]. In this simulation, the satellite bunch intensity has been varied as the inverse of the main-bunch intensity, namely as $N_{b,sat}$~1.1x10^{10} x 5x10^{11}/$N_{b,main}$, in order to obtain a constant target luminosity of about 2x10^{33} cm^{-2}s^{-1} in (S)LHCb.

Figure 31 presents simulated heat loads for the 50-ns bunch spacing of the standard 50-ns LPA scheme with and without additional dedicated LHCb satellite bunches interleaved at a distance of 25 ns from the main bunches [41,42] (see Fig. 32). Here, the satellite bunch intensity is decreased in inverse proportion to the main bunch intensity in order to provide a constant target luminosity in LHCb (determined by collisions between main bunches and satellites). Figure 31 illustrates that the heat load including the "LHCb satellite" does not show a fully monotonic dependence on the main bunch intensity, which is consistent with earlier studies of other types of LHC satellite bunches [43,44], but that the additional smaller bunches only marginally increase the (low) 50-ns heat load.

We infer that the electron-cloud heat load would also be acceptable for 50-ns spacing plus "LHCb satellites".

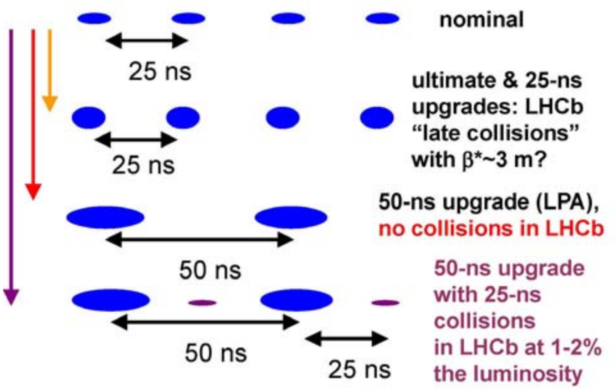


Figure 32: Bunch patterns for the LHC luminosity upgrade with and without collisions in (S)LHCb.

HL-LHC PARAMETER SETS

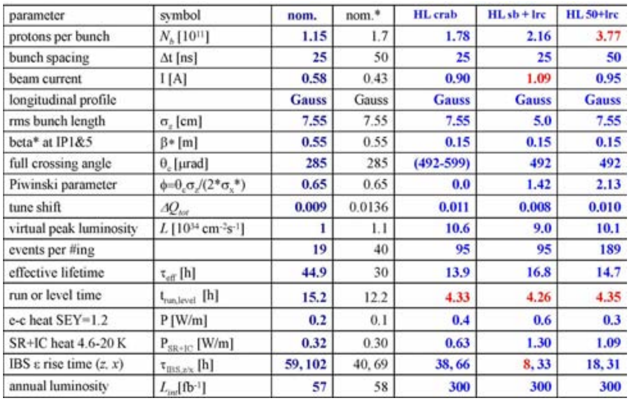
Tables 4-6 compile example parameter sets for the HLC-LHC. The three tables refer to $\beta_{x,y}^*$=15, $\beta_{x,y}^*$=30, and β_x^*=30 cm & β_y^*=7.5 cm (flat collision), respectively. The $\beta_{x,y}^*$ values considered in Tables 4 and 6 have been proposed and can be realized with the ATS scheme [11-13,25]. The $\beta_{x,y}^*$ values of Table 5 correspond to the minimum possible beta* available for the former SLHC Phase-I IR upgrade [45].

For each choice of IP beta functions, we consider alternative scenarios with crab cavities, higher-harmonic RF system (plus long-range beam-beam compensation), and 50-ns spacing (plus long-range beam-beam compensation) and, for each scenario, determine the bunch charge and total intensity required for delivering 300 fb^{-1} per year.

For the flat-beam cases the crossing angle has been taken to be 12.4σ^{*}', with σ^{*}' denoting the rms beam divergence at the IP in the plane of crossing. This crossing angle should be sufficient to confine the total tune footprint to a square with dimension 0.01x0.01 in tune units, e.g. see [10], possibly after adding a moderate long-range compensation. For the round-beam collision cases the crossing angle has been set to 8.5$\sigma_{x,y}^{*}$', requiring the presence of long-range beam-beam compensators.

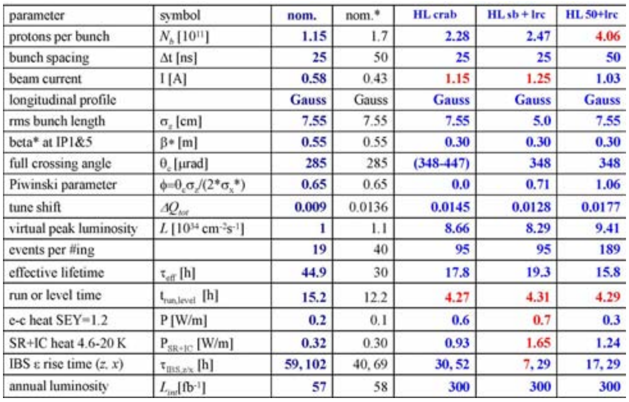
The intrabeam scattering growth rates quoted in Tables 4-6 were obtained by scaling the IBS rates computed for the nominal LHC collision optics with bunch intensity. For the ATS optics the IBS growth rates would be further modified by the beta wave in the arcs, leading to a welcome increase in the longitudinal IBS rise time [11].

Table 4: Example HL-LHC parameters sets with $\beta_{x,y}^*$=15 cm and nominal emittance.



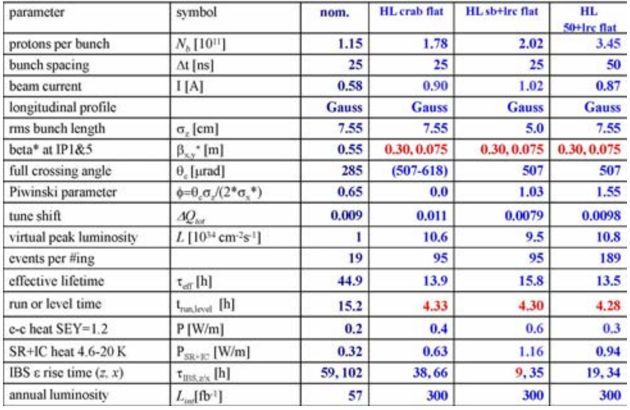
parameter	symbol	nom.	nom.*	HL crab	HL sb + lrc	HL 50+lrc
protons per bunch	N_b [10^{11}]	1.15	1.7	1.78	2.16	3.77
bunch spacing	Δt [ns]	25	50	25	25	50
beam current	I [A]	0.58	0.43	0.90	1.09	0.95
longitudinal profile		Gauss	Gauss	Gauss	Gauss	Gauss
rms bunch length	σ_z [cm]	7.55	7.55	7.55	5.0	7.55
beta* at IP1&5	$\beta*$ [m]	0.55	0.55	0.15	0.15	0.15
full crossing angle	θ_c [μrad]	285	285	(492-599)	492	492
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0.65	0.65	0.0	1.42	2.13
tune shift	ΔQ_{tot}	0.009	0.0136	0.011	0.008	0.010
virtual peak luminosity	L [10^{34} cm^{-2}s^{-1}]	1	1.1	10.6	9.0	10.1
events per #ing		19	40	95	95	189
effective lifetime	τ_{eff} [h]	44.9	30	13.9	16.8	14.7
run or level time	$t_{run,level}$ [h]	15.2	12.2	4.33	4.26	4.35
e-c heat SEY=1.2	P [W/m]	0.2	0.1	0.4	0.6	0.3
SR+IC heat 4.6-20 K	P_{SR+IC} [W/m]	0.32	0.30	0.63	1.30	1.09
IBS ε rise time (z, x)	$\tau_{IBS,z/x}$ [h]	59, 102	40, 69	38, 66	8, 33	18, 31
annual luminosity	L_{int}[fb^{-1}]	57	58	300	300	300

Table 5: Example HL-LHC parameters sets with $\beta_{x,y}^*$=30 cm and nominal emittance.



parameter	symbol	nom.	nom.*	HL crab	HL sb + lrc	HL 50+lrc
protons per bunch	N_b [10^{11}]	1.15	1.7	2.28	2.47	4.06
bunch spacing	Δt [ns]	25	50	25	25	50
beam current	I [A]	0.58	0.43	1.15	1.25	1.03
longitudinal profile		Gauss	Gauss	Gauss	Gauss	Gauss
rms bunch length	σ_z [cm]	7.55	7.55	7.55	5.0	7.55
beta* at IP1&5	$\beta*$ [m]	0.55	0.55	0.30	0.30	0.30
full crossing angle	θ_c [μrad]	285	285	(348-447)	348	348
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0.65	0.65	0.0	0.71	1.06
tune shift	ΔQ_{tot}	0.009	0.0136	0.0145	0.0128	0.0177
virtual peak luminosity	L [10^{34} cm^{-2}s^{-1}]	1	1.1	8.66	8.29	9.41
events per #ing		19	40	95	95	189
effective lifetime	τ_{eff} [h]	44.9	30	17.8	19.3	15.8
run or level time	$t_{run,level}$ [h]	15.2	12.2	4.27	4.31	4.29
e-c heat SEY=1.2	P [W/m]	0.2	0.1	0.6	0.7	0.3
SR+IC heat 4.6-20 K	P_{SR+IC} [W/m]	0.32	0.30	0.93	1.65	1.24
IBS ε rise time (z, x)	$\tau_{IBS,z/x}$ [h]	59, 102	40, 69	30, 52	7, 29	17, 29
annual luminosity	L_{int}[fb^{-1}]	57	58	300	300	300

Table 6: Example HL-LHC parameters sets for flat beams with $\beta_{x,}^*$=30 cm, $\beta_{,y}^*$=7.5 cm, and nominal emittance.



parameter	symbol	nom.	HL crab flat	HL sb+lrc flat	HL 50+lrc flat
protons per bunch	N_b [10^{11}]	1.15	1.78	2.02	3.45
bunch spacing	Δt [ns]	25	25	25	50
beam current	I [A]	0.58	0.90	1.02	0.87
longitudinal profile		Gauss	Gauss	Gauss	Gauss
rms bunch length	σ_z [cm]	7.55	7.55	5.0	7.55
beta* at IP1&5	$\beta_{x,y}^*$ [m]	0.55	0.30, 0.075	0.30, 0.075	0.30, 0.075
full crossing angle	θ_c [μrad]	285	(507-618)	507	507
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0.65	0.0	1.03	1.55
tune shift	ΔQ_{tot}	0.009	0.011	0.0079	0.0098
virtual peak luminosity	L [10^{34} cm^{-2}s^{-1}]	1	10.6	9.5	10.8
events per #ing		19	95	95	189
effective lifetime	τ_{eff} [h]	44.9	13.9	15.8	13.5
run or level time	$t_{run,level}$ [h]	15.2	4.33	4.30	4.28
e-c heat SEY=1.2	P [W/m]	0.2	0.4	0.6	0.3
SR+IC heat 4.6-20 K	P_{SR+IC} [W/m]	0.32	0.63	1.16	0.94
IBS ε rise time (z, x)	$\tau_{IBS,z/x}$ [h]	59, 102	38, 66	9, 35	19, 34
annual luminosity	L_{int}[fb^{-1}]	57	300	300	300

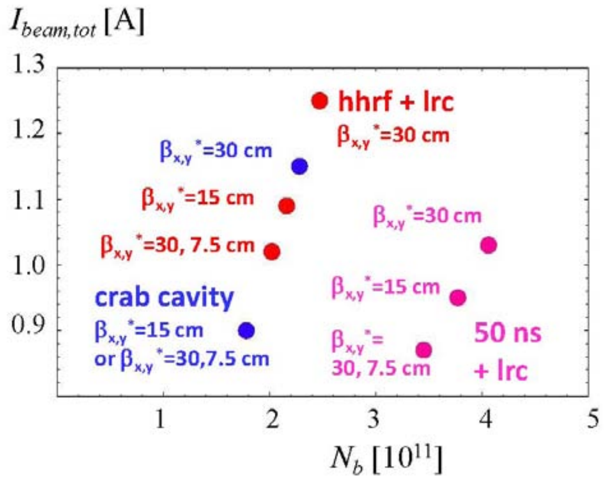


Figure 33: Total beam current and proton bunch intensity required for the different upgrade scenarios of Tables 4-6. “hhrf” refers to the higher harmonic RF system, “lrc” to long-range compensation.

Figure 33 graphically presents the results in the total-intensity/bunch-intensity plane. It is evident that 50-ns scenarios allow for larger IP beta functions and/or reduced total beam current at the same integrated luminosity, and that a flat beam-optics may be preferred compared with round beams. For 25-ns bunch spacing, the crab-cavity upgrade scenario is most appealing.

The luminosity time evolution is almost the same for all scenarios. Figure 34 displays a typical HL-LHC luminosity evolution over 24 h.

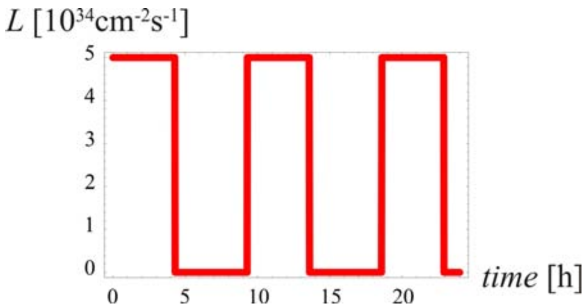


Figure 34: Luminosity evolution during a “typical day” at the HL-LHC. It is similar for all scenarios considered.

PRELIMINARY CONCLUSIONS

The HL-LHC parameter space is well defined. In order to achieve 300 fb^{-1} per year the following ingredients are required:

- about 1 A beam current (+/- 10%);
- potential peak luminosity 10^{35} cm^{-2}s^{-1};
- run time of 4.3 h, assuming 5-h turnaround time;
- β^* between 7.5 and about 30 cm, possibly flat.

A high(er) beam intensity helps in every regard. Both 50-ns and 25-ns scenarios are possible, with a preference for the former. Aiming at 200 fb^{-1} per year only would relax the intensity demand. The beam-beam limit (at a value of 0.02 or above) is no longer a serious constraint.

Several alternative scenarios for 300 fb^{-1} / year have been constructed using

- crab cavities;
- higher harmonic RF (shorter bunches) and long-range beam-beam compensation;
- 50-ns bunch spacing, large Piwinski angle, and long-range beam-beam compensation;

for each case considering the impact of different round or flat IP beta functions. Decreasing β^* from 30 to 15 cm is equivalent to 10-30% beam current increase (scenario-dependent).

Scenarios with 50-ns spacing are attractive, as are 25-ns scenarios with crab cavities.

PROPOSED ROADMAP & BRANCHING POINTS

Starting in 2011, LHC MDs for HL-LHC should address the following points

- ATS optics ingredients (beta wave, phase changes);
- long-range beam-beam limits;
- effect of crossing angle on the head-on beam-beam limit;
- limits related to electron cloud;
- “flat beam” optics, e.g. β_x^*/β_y^*~2, with an effective gain in aperture of Δn_1~1σ [8]; and
- effect of the crossing planes (H-V, V-V, H-H).

It is suggested to install prototype long-range beam-beam compensators in the LHC during the first long shutdown (2013), to develop & prototype compact crab cavity (2011-16) for beam test in (SPS+) LHC (2017), and to develop & install an LHC 800-MHz RF system (2016?).

In the coming years, LHC operational experience with electron-cloud and long-range beam-beam effects at 25-ns and 50-ns bunch spacing, results of ATS optics machine studies, and progress on crab-cavity development & crab-cavity beam testing will together determine the HL-LHC upgrade path to be taken.

ACKNOWLEDGEMENTS

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APPENDIX: LUMINOSITY DECAY AND LIFETIME

For the upgraded LHC a fast decay of beam intensity and luminosity is expected (with a typical time scale of a few hours), which is dominated by proton burn off in proton-proton collision. Contributions from intrabeam scattering and from gas scattering can be considered negligible in comparison. Under these conditions, the luminosity decay will not be exponential, but purely algebraic, and of the form [31]

$$L(t) = \frac{\hat{L}}{\left(1 + t/\tau_{eff}\right)^2} \qquad (4)$$

where τ_{eff} denotes the effective initial beam lifetime

$$\tau_{eff} = \frac{N_b n_b}{n_{IP} \hat{L} \sigma_{tot}} \qquad (5)$$

and we recognize the number of protons per bunch N_b, the number of bunches per beam n_b, the number of IPs, the initial peak luminosity $\hat{L}$ and the total interaction cross section σ_{tot}.

The beam and luminosity lifetimes are proportional to the total beam intensity and inversely proportional to the luminosity. An LHC luminosity upgrade implies shorter luminosity lifetimes unless the beam intensity is increased simultaneously. Or, in other words, for a given luminosity, the luminosity lifetime depends only on the total beam current.

Table 7 compiles helpful expressions describing the time evolution of luminosity and beam current, the optimum run time, and time-averaged luminosity without and with luminosity levelling, and for levelling of the beam-beam tune shift.

Table 7: Analytical expressions for the time evolution of luminosity and beam current, for the optimum run time, and for the average luminosity, with and without levelling, and considering two different levelling schemes. "T_{ta}" denotes the average "turnaround time", that is the time from the end of a "physics" fill to the start of the next "physics" period.

	w/o leveling	L=const	ΔQ_{bb}=const
luminosity evolution	$L(t) = \frac{\hat{L}}{\left(1+t/\tau_{eff}\right)^2}$	$L = L_0 \approx const$	$L(t) = \hat{L}\exp\left(-t/\tau_{eff}\right)$
beam current evolution	$N(t) = \frac{N_0}{\left(1+t/\tau_{eff}\right)}$	$N = N_0 - \frac{N_0}{\tau_{eff}} t$	$N(t) =$ $N(0)\exp\left(-t/\tau_{eff}\right)$
optimum run time	$T_{run} = \sqrt{\tau_{eff} T_{ta}}$	$T_{run} = \frac{\Delta N_{max} \tau_{eff}}{N_0}$	$T_{run} = \tau_{eff}$ $\min\left[\ln\left(\sqrt{1+\phi_{pw}(0)^2}\right),\right.$ $\left.\ln\left(\left(T_{ta}+T_{run}+\tau_{eff}\right)/\tau_{eff}\right)\right]$
average luminosity	$L_{ave} = \hat{L}\frac{\tau_{eff}}{\left(\tau_{eff}^{1/2}+T_{ta}^{1/2}\right)^2}$	$L_{ave} = \frac{L_0}{1+\frac{L_0 \sigma_{tot} n_{IP}}{\Delta N_{max} n_b} T_{ta}}$	$L_{ave} = \frac{\tau_{eff}}{T_{ta}+T_{run}}\left(1-e^{-T_{run}/\tau_{eff}}\right)$

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PERFORMANCE EVOLUTION AND EXPECTATIONS MANAGEMENT: LESSONS FROM TEVATRON AND OTHER MACHINES

V. Shiltsev (Fermilab)

Abstract

Below we review the LHC luminosity progress in 2010, discuss the luminosity evolution of the Tevatron collider at different stages of the Collider Runs, emphasize general dynamics of the process, compare with the performance of the other colliders analyze planned and delivered luminosity integrals, and discuss the expectation management lessons.

INTRODUCTION

In the past 9 months, we witnessed great progress in the LHC commissioning. Luminosity of the 7,000 GeV center of mass energy proton-proton collisions reached 205×10^{30} cm^{-2} s^{-1} , or 2% of the design value in less than 6 months – see Fig.1. That level of performance exceeds previous records of the luminosity at CERN set up for 90 GeV electron-positron collisions in LEP at 102×10^{30} cm^{-2} s^{-1} (1998) and for 31 GeV proton-antiproton collisions in ISR at 140×10^{30} cm^{-2} s^{-1} (1982). It is about half of the current Tevatron Run II luminosity record of 402×10^{30} cm^{-2} s^{-1}. On average, the LHC luminosity doubled every two weeks, and looking at the plot one could get an impression that if the LHC would not stop proton-proton operation in early November and continue to run and progress "as is", then it could overtake the Tevatron luminosity by mid-November, and will reach its design luminosity sometime mid-2011. So, why nobody believes that could happen?

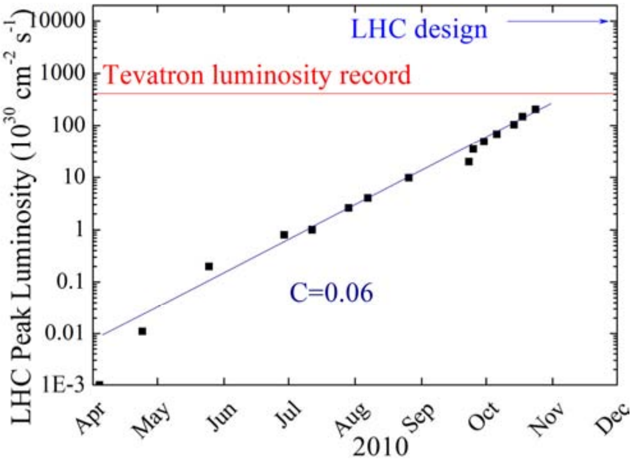


Figure 1: LHC peak luminosity progress in 2010.

The answer is that anyone familiar with performance of other colliders knows that such a fast performance progress is not something unique and unthinkable of at the early stages of the accelerator commissioning. For example, the Tevatron collider had seen luminosity improved by a factor of 12,000 in just three months early in 1987 (that is equivalent doubling the luminosity approximately every week!) and exceeded 1% of then design luminosity of 1.0×10^{30} cm^{-2} s^{-1} [1]. Progress beyond initial stage is determined by careful step-by-step uncovering, analysis and resolution of numerous problems. It was true for all past and present colliders colliders, despite their specific features (species, energies, intensities, etc) and we believe that LHC is not going to be totally unique in that regard – e.g., Table I demonstrates comparable sets of factors of importance for the performance for the Tevatron and LHC.

Table I: Comparison of major factors that play role in the performance progress speed for the Tevatron and LHC.

	TEV p-pbar	**LHC p-p**
State-of-the-art SC magnets	yes ~800	yes ~1800
(Old) Sophisticated injector chain	yes 6	yes 4
Antiproton production/storage/cooling	yes	no
Beam-beam effects limiting performance	yes	not yet?
Critical importance of collimation	~no	yes
Electron-cloud effects matter	no	yes
Space-Charge effects at low energies	yes	yes

Therefore, it seems reasonable to explore objective laws of the performance evolution of the colliders. In doing that, we will follow the logic of and some data from Reference [2].

THE TEVATRON PROGRESS AND “CPT THEOREM”

Analysis of the evolution and prediction of high energy colliders’ luminosity progress is of great importance for many: it tells machine physicists whether their scientific and technical decisions taken years ago were correct; for the experimental high energy physicists, it is the basis for their schedules and upgrade plans; for the management and funding agencies, it is an important input on the future facilities and projects. The Tevatron luminosity history – see Fig.2 - gives several important lessons in that regard. The luminosity increases occurred after numerous improvements, some of which were implemented during operation, and others introduced during regular shutdown periods.

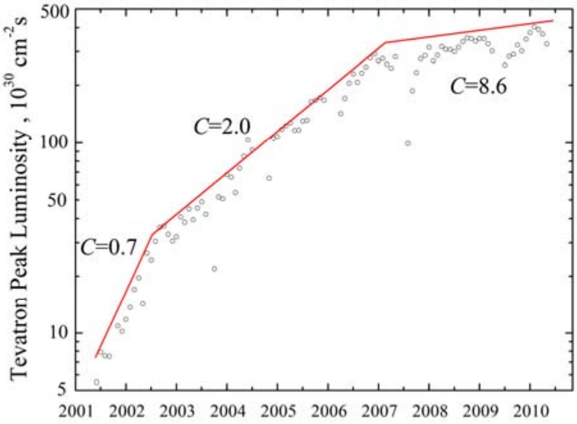


Fig.2: Tevatron peak luminosity progress during Run II (2001-2011).

A large number of improvements (see most of them listed in the Table I in Ref.[2]), took place in all the accelerators of the Collider complex, they were addressing all the parameters affecting the luminosity – proton and antiproton intensities, emittances, optics functions, bunch length, losses, reliability and availability, etc. – and led to fractional increase varying from few % to some 40% with respect to previously achieved level. As the result of some 30 improvements in 2001-2010, the peak luminosity has grown by a factor of about 50 from $L_i \approx 8\times10^{30}$ cm^{-2}s^{-1} to $L_f \approx 400\times10^{30}$ cm^{-2}s^{-1}, or about 14% per step on average. In principle, such complex percentages - "N% gain per step, step after step, with regular periodicity" - should result in the *exponential* growth of the luminosity $L(t+T)/L(t)=exp(T/C)$. Nevertheless, the pace of the luminosity progress was not always constant. As one can see from Fig.2, the Collider Run II luminosity progress was quite fast with $C\approx0.7$ year in the period from 2001 to mid-2002 when previous Run I luminosity level was (re)achieved; stayed on a steady exponential increase path with $C\approx2.0$ yr from 2002 till 2007, and significantly slowed down afterward, $C\approx8.6$. A plausible hypothesis - so called "CPT theorem for accelerators" - was proposed in Ref.[2], that over extended periods of operation, the performance of colliding facilities evolves in accordance with an approximate formulae:

$$C \cdot P = T \qquad (1)$$

where the factor $P=ln($luminosity$)$ is the "performance" gain over time interval T, and C is a machine dependent coefficient equal to average time needed to increase the luminosity by $e=2.71\ldots$ times, or boost the "performance" P by 1 unit. Both, T and C have dimension of time, and the coefficient C was called "complexity" of the machine, as it directly indicates how hard or how easy was/is it to push the performance of individual machine.

In general, the complexity should be dependent on how well understood are physics and technology of the machine.

EXAMPLES

Let us consider several more illustration of the "CPT theorem for accelerators" – see Figs. 3-10.

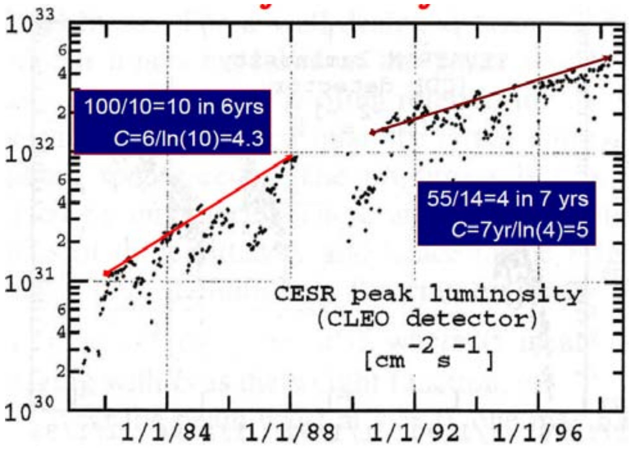


Figure 3: Luminosity history of e+e- collider CESR.

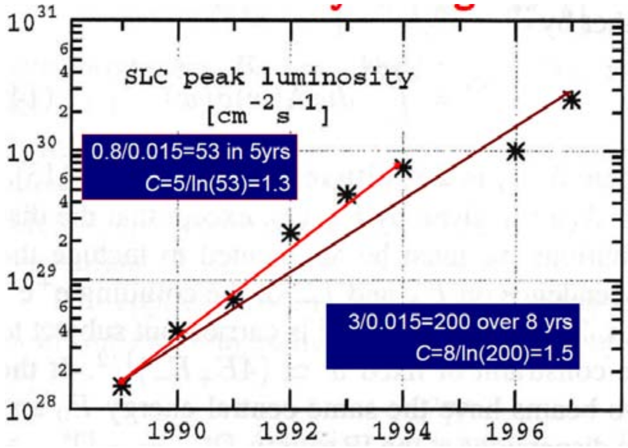


Figure 4: Luminosity history of e+e- linear collider SLC at SLAC.

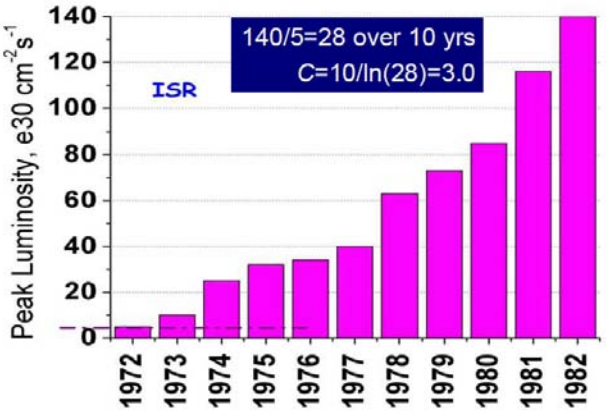


Figure 5: Luminosity history of p-p collider ISR at CERN.

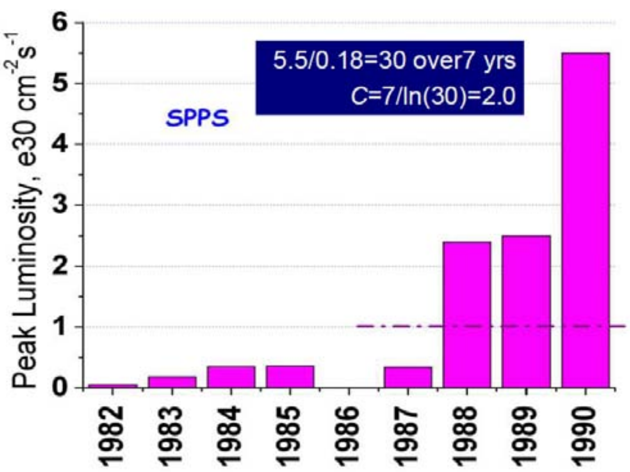


Figure 6: Luminosity history of p-p collider SppS at CERN.

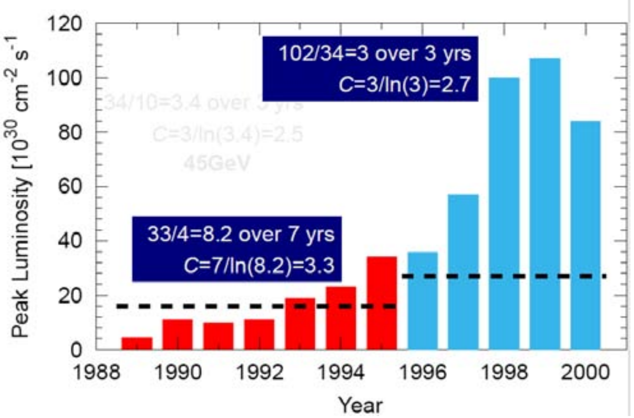


Figure 7: Luminosity history of e+e- collider LEP at CERN.

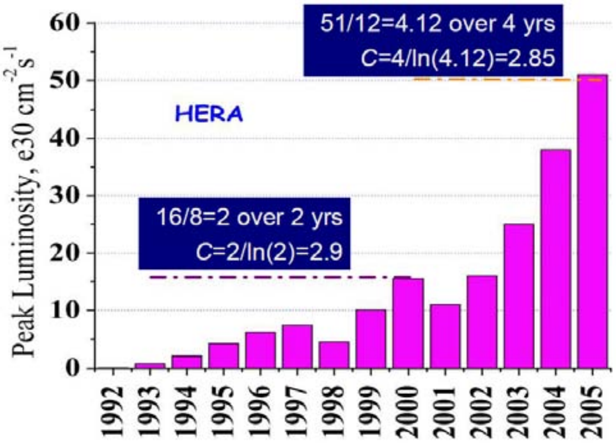


Figure 8: Luminosity history of e-p collider HERA at DESY.

In each figure we indicate – either by straight line or/and by a text box the increase of the record luminosity over certain period of time, and calculate corresponding complexity factors. Table II lists all of them for side by side comparison. One can see that in general, the hadron machines Tevatron, SppS, ISR, HERA and RHIC have average complexity of about *<C>=2.4* . Effective complexities in the very early periods of operation are very small *C=0.03-0.06* (Tevatron and LHC).

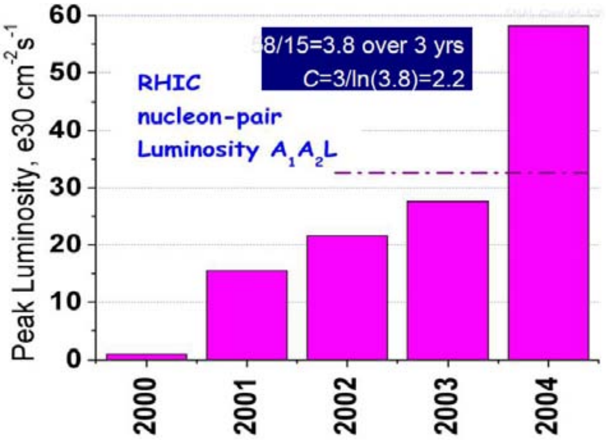


Figure 9: Luminosity history of p-p collider RHIC at BNL.

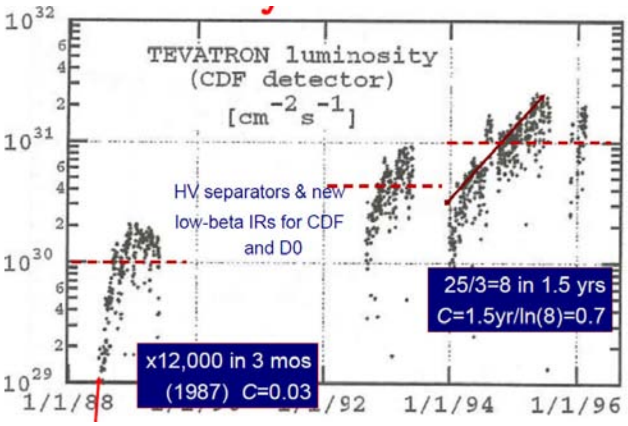


Figure 10: Luminosity history of the Tevatron proton antiproton collider at Fermilab in 1987-1996.

Table II: "Complexities" of colliding beam facilities.

	C	***years***
CESR *e+e-*	***4.3***	1883-1988
LEP I *e+e-*	***3.3***	1989-1995
SLC *e+e-*	***1.5***	1989-1997
HERA I, II *p-e*	***2.9***	1992-00-2005
ISR *p-p*	***3.0***	1972-1982
SppS *p-pbar*	***2.0***	1982-1990
Tevatron Run II *p-pbar*	***2.0***	2002-2007
RHIC *p-p*	***2.2***	2000-2004
Tevatron startup	***0.03***	1987
LHC startup	***0.06***	2010

Differences in machine complexity factors *C* may be due to various reasons: a) first of all, beam physics issues are quite different not only between classes of machines (hadrons vs e+e-) but often between colliders from the same class – all that affects how fast and what kind of improvements can be implemented; b) accelerator reliability may affect the luminosity progress, especially for larger machines with greater number of potentially not-reliable elements; c) another factor is capability of the team running the machine to cope with challenges, generate ideas for improvements and implement them; d) and, of course, the latter depends on resources available for each team.

Note, that the exponential growth is characteristic to advances in other areas of science and technology. E.g., the maximum energy achieved in particle accelerators grew by factor of 10 every 6 years over many decades [3]. It is often presented in semi-log "Livingston plot" and corresponds to C=2.6. Another example is the "Moore's Law" [4] of exponential growth of modern microprocessor speed that doubles every 20 months, yielding C=2.4.

PERFORMANCE EXPECTATION MANAGEMENT

It is well known that the expectations are the only measure of one's success, and that in the case when delivered value is (even slightly) less than expected value – see Fig.11 – then perceived value is much less then delivered one.

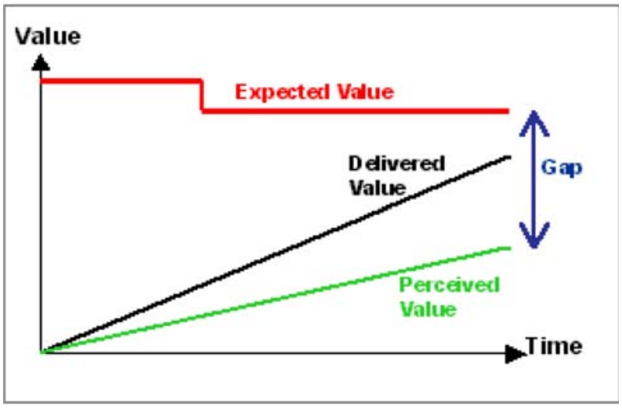
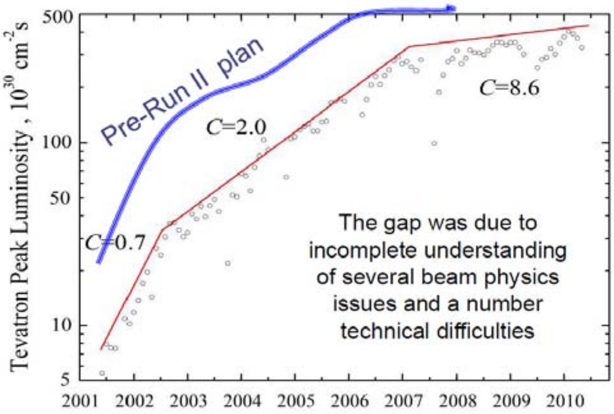


Figure 11: Perceived value of performance.



The gap was due to incomplete understanding of several beam physics issues and a number technical difficulties

Figure 12: The Tevatron luminosity performance and pre-Run II plan [5].

The Tevatron Run II was a victim of such physiological effect when it was realized that its performance in 2001-2003 was significantly below expectations – see Fig.12. The Run II start-up difficulties were objective (new machine – Main Injector was introduced in operation, Accumulator was greatly upgraded and not optimized, 36 bunches operation was totally new, etc) and a lot of studies were needed to understand and correct them, but, still, as the result the progress seemed unacceptably slow. Only the 2003 DOE review of the Tevatron operation revealed the technical roots of the situation and new approach was embraced: since then, the luminosity goals were expressed in terms of "base" goals that we believe have high degree of certainty of being achieved and "stretched" goals that represent our "best estimate" of the limit of performance to which the facility can be pushed (with the most likely outcome somewhere in between). It is of notion, that careful analysis of the issues and potential progress allowed properly set annual goals, and the Tevatron never missed them since 2003. That had greatly improved predictability of the machine performance and morale of the operating team.

CONCLUSIONS, RECOMMENDATIONS

One should not expect that the period of incredibly fast growth of the LHC luminosity - as in 2010- will last long. At some point the progress will most probably turn to the rate corresponding to complexity of C~2. Such a period of exploration and fight for ultimate performance with $C\approx2$ might take as short as 3-4 years and as long as 6-10 years It will be followed by relative stabilization of performance (either running out of ideas or preparing for a major upgrade). *A numerical example*: progress from $L=3\times10^{33}$ cm^{-2}s^{-1} to $L=5\times10^{34}$ cm^{-2}s^{-1} might take 6-9 years if C=2-3.

Expectations management is crucial. As in the case of the Tevatron, the LHC goals may need to be expressed in terms of two goals: "base" goal – that is believed has very high degree of certainty of being achieved and the "design" or "stretched" goal that represents your "best estimate" of the limit of performance to which the facility can be pushed. The goals and the ratio of "base" to "design" goals will depend on the level of understanding of the machine, e.g. the ratio might change from larger to smaller to reflect lower level of uncertainty in later years.

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ALICE AND LHCB IN THE HL-LHC ERA.

S. Bertolucci

Abstract

So far all the upgrade schemes have been studied assuming only two general purpose detectors, ATLAS and CMS, operating. Will Alice and LHCb run in HL-LHC time? When and what process to decide it? What are the beam parameters they want to exploit and the hardware changes they need in case of an upgrade?

PERFORMANCE REACH OF THE INJECTORS IN 2011

R. Steerenberg, T. Bohl, K. Cornelis, H. Damerau, A. Findlay, R. Garoby, S. Gilardoni, S. Hancock, K. Hanke, E. Métral, G. Métral, B. Mikulec, G. Rumolo, E. Shaposhnikova

CERN, Geneva, Switzerland

Abstract

The characteristics of the various LHC beams have been defined long before the LHC became operational. After a year of successful LHC running with the different types of LHC beams much experience has been gained in the LHC, but also in the injectors. This paper will summarise the defined and presently obtained beam characteristics of the LHC beams in the injector chain together with a brief overview of their production schemes and difficulties. Finally an outlook for 2011 will be presented, indicating the possible characteristics for the different LHC beams in the injector chain.

DOCUMENTED BEAM CHARACTERISTICS

The LHC beam characteristics for the 25 ns bunch spacing were defined at the beginning of this century. Once the 25 ns bunch spacing beam was available and tested in the different LHC injectors it became clear that beams with other bunch spacings, 50 ns and 75 ns, would be required. In 2004 the operational beam characteristics of all the LHC beam flavours were defined and summarized [1]. Table 1 gives an overview of these characteristics per accelerator in the LHC injector chain.

Although the 150 ns bunch spacing, indicated in italic at the bottom of table 1, was not yet specified in 2004, it has been added for completeness. The development of this additional flavour was requested late spring 2010 for use by the LHC in September 2010. The main parameters, besides the bunch spacing, that are important for the LHC, are the bunch intensity and transverse emittance at extraction of the SPS, which are identical for all multi-bunch beams. It should also be noted that the defined intensities for each machine do not take into account any beam losses in the injector chain. Therefore the upstream injector will have to provide slightly higher intensities making up for the losses. The PS typically delivers 1.3×10^{11} p/b for 1.15×10^{11} p/b extracted from the SPS. Another important observation is that the multi-bunch beams are all produced using double batch injection from the PS Booster into the PS; 4 bunches from the PS Booster during the 1st batch and 2 bunches during the 2nd batch, giving in total 6 bunches from the PSB that are then longitudinally split in the PS to the required number of bunches to be extracted towards the SPS.

MULTI-BUNCH BEAM PRODUCTION SCHEMES

The protons coming from LINAC2 are injected into the PS Booster using a classic multi-turn injection scheme. This means that the consecutive injected turns are accumulated in the horizontal phase space, resulting, in combination with coupling in the transverse plane, in approximately equal transverse emittances for both planes that increase proportionally with the number of turns and thus number of protons injected. This dependence is clearly visible from the measurements given in Fig. 1.

The total number of protons, required from the PS Booster to produce the different flavours of the multi-bunch LHC beams in the PS and SPS, varies proportionally with the number of bunches required at PS extraction.

Table 1: Documented LHC beam characteristics for the injectors [1]

	PSB extraction				**PS extraction**			**SPS extraction**			
Beam	**Ip/ring [x10^{11}]**	**$\varepsilon_{h/v}$ [μm] 1σ norm.**	**nb batch**	**nb bunch**	**Ip/bunch [x10^{11}]**	**$\varepsilon_{h/v}$ [μm] 1σ norm.**	**nb bunch**	**Ip/bunch [x10^{11}]**	**$\varepsilon_{h/v}$ [μm] 1σ norm.**	**$\varepsilon_{long.}$ bunch [eVs]**	**nb bunch**
PROBE	0.05 – 0.2	≤ 1	1	1	0.05 – 0.2	≤ 1	1	0.05 – 0.2	≤ 1	≤ 0.3	1
PILOT	0.05	≤ 2.5	1	1	0.05	≤ 3	1	0.05	≤ 3.5	≤ 0.8	1
INDIV	0.2 – 1.15	≤ 2.5	1	1 to 4	0.2 – 1.15	≤ 3	1 to 4	0.2 – 1.15	≤ 3.5	≤ 0.8	1,4 or 16
25 ns	2.4 – 13.8	≤ 2.5	2	4 + 2	0.2 – 1.15	≤ 3	72	0.2 – 1.15	≤ 3.5	≤ 0.8	1 - 4 x 72
50 ns	1.2 – 6.9	≤ 2.5	2	4 + 2	0.2 – 1.15	≤ 3	36	0.2 – 1.15	≤ 3.5	≤ 0.8	1 – 4 x 36
75 ns	0.8 – 4.6	≤ 2.5	2	4 + 2	0.2 – 1.15	≤ 3	24	0.2 – 1.15	≤ 3.5	≤ 0.8	1 – 4 x 24
150 ns	*0.8 – 4.6*	*≤ 2.5*	*1*	*3 x 2*	*0.2 – 1.15*	*≤ 3*	*12*	*0.2 – 1.15*	*≤ 3.5*	*≤ 0.8*	*1 – 4 x 12*

Therefore the transverse emittance of the different multi-bunch beams with different bunch spacing will decrease as the bunch spacing at the PS extraction increases.

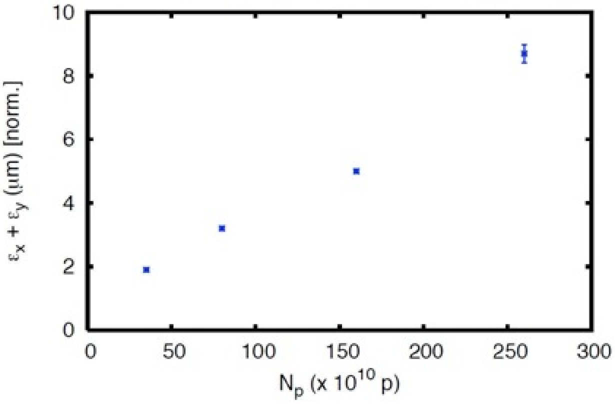


Figure 1: The sum of transverse horizontal and vertical emittance versus accelerated intensity in the PS Booster.

25 ns beam

The LHC multi-bunch beam with a bunch spacing of 25 ns is produced in the PS [2][3], using a double batch injection from the PS Booster, with 4 bunches injected during the first injection and 2 bunches 1.2 seconds later during the second injection. This gives a total of 6 bunches in the PS with an RF harmonic of h=7, leaving 1 bucket empty. Figure 2 illustrates the PS cycle with the long flat bottom, clearly indicating the two batches injected form the PS Booster.

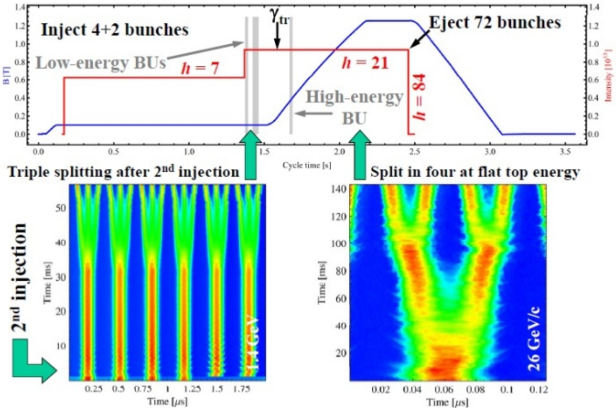


Figure 2: LHC 25 ns beam PS production scheme.

Once all 6 bunches are in the PS each bunch is split in 3 by changing the RF harmonic from h=7 through h=14 to H21, giving 18 bunches and leaving 3 buckets empty as is shown in the water fall plot in the left hand bottom of Fig. 2. Before and after this splitting process a controlled longitudinal blow-up is applied to obtain the desired longitudinal emittance before accelerating the beam through transition, indicated in Fig. 2 by the vertical gray bars. After acceleration to 26 GeV/c the beam is twice split in 2, increasing the number of bunches from 18 to 72, leaving 12 buckets empty to accommodate the rising edge of the extraction kicker. Just before extraction the bunches are rotated in longitudinal phase space using a non-adiabatic bunch rotation scheme for which the voltage of the 40 MHz and 80 MHz cavities is increased rapidly.

The initial longitudinal emittance received from the PS Booster is divided by a factor 12 as a result of the multiple longitudinal splittings. The controlled and uncontrolled longitudinal blow up along the PS cycle amounts to a factor of 3.23. Therefore the final longitudinal emittance can be calculated using Eq. 1.

$$\varepsilon_{long\ final} = \varepsilon_{long\ initial} \times \frac{3.23}{12} \tag{1}$$

The final longitudinal characteristics taking into account the high energy blow up after transition crossing are a bunch length < 4 ns and a longitudinal emittance of 0.35 eVs. The transverse emittance provided by the PS Booster is well preserved during acceleration and results in a round beam at PS extraction with transverse normalised emittances in both planes of 2.5 µm at 1σ and a bunch intensity of 1.3x10^{11} p/b.

During acceleration in the PS a dipolar longitudinal coupled bunch instability is damped using a feedback on 2 of the 10 MHz cavities as longitudinal kickers.

In 2001, e^--cloud like instabilities have been observed at high energy in the PS. In order to avoid these instabilities the processes of adiabatic bunch shortening and bunch rotation have been optimised to keep short bunches as little time as possible at 40 MHz.

The SPS suffers from, e^--cloud instabilities and therefore requires scrubbing in order to decrease the secondary electron emission yield of the vacuum chamber. When this scrubbing has been done the beam at extraction in the SPS has the characteristics as given in Table 1.

This beam also suffers from longitudinal coupled-bunch instabilities in the SPS, which are cured by using a 4th harmonic RF system and controlled longitudinal emittance blow-up [5].

50 ns beam

Initially the LHC multi-bunch beam with 50 ns bunch spacing was foreseen to be produced using double batch injection in the PS [2][3]. At extraction of the PS this beam provides 36 bunches spaced by 50 ns. The intensity per bunch remains the same as for the 25 ns beam. Therefore the PS Booster injects fewer protons per ring, resulting in much smaller transverse emittances than specified in Table 1. In 2009 it was decided to produce this beam using a single batch injection, reducing the time the beam has to wait on the PS flat bottom for the second batch injection, while remaining within the specified beam characteristics of Table 1.

Presently the 50 ns beam in the PS Booster is produced with 2 bunches from 3 PS Booster rings, requiring longitudinal bunch splitting and bunch phasing in order to be compatible with the PS injection at RF harmonic *h*=7. Figure 3 shows a tomogram of the two bunches beam at extraction of the PS Booster, clearly illustrating the *h*=1 and *h*=2 buckets, required for the correct phasing of the bunches.

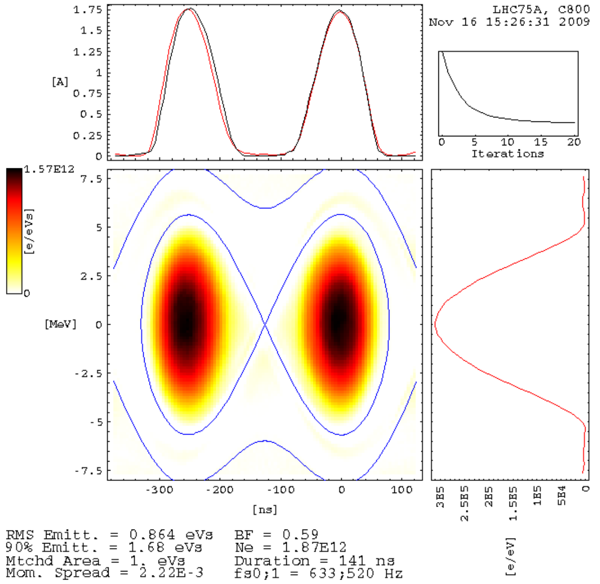


Figure 3: The longitudinal tomogram of the 2 bunches per ring at extraction in the PS Booster.

Figure 4 illustrates the PS cycle for the production of the 50 ns beam, clearly indicating the single batch injection from the PS Booster.

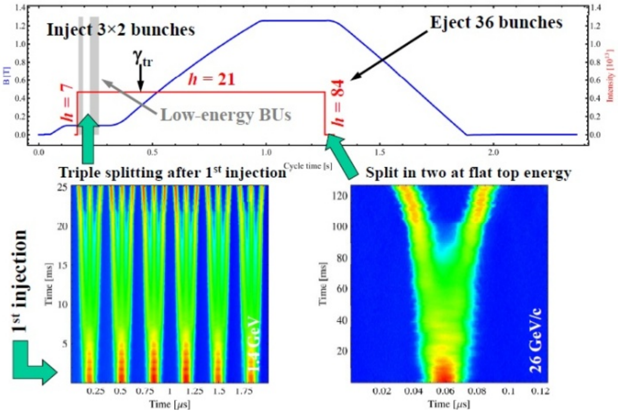


Figure 4: LHC 50 ns beam PS production scheme.

Once the 6 bunches are in the PS each bunch is split in 3 in exactly the same way as is done for the 25 ns beam. The difference with respect to the 25 ns beam lies mainly in the longitudinal bunch splitting at 26 GeV/c.

The 18 bunches are each split in 2, resulting in 36 bunches on RF harmonic *h*=84 with 1 out of 2 buckets filled and 12+1 buckets empty to accommodate the extraction kicker rising edge. The final non-adiabatic bunch rotation results in the same longitudinal bunch characteristics as for the 25 ns beam.

The initial longitudinal emittance received from the PS Booster is divided by a factor 6 as a result of the multiple longitudinal splitting. The controlled and uncontrolled longitudinal blow up along the PS cycle amounts to a factor of 2.33. Therefore the final longitudinal emittance can be calculated using Eq. 2.

$$\varepsilon_{long\ final} = \varepsilon_{long\ initial} \times \frac{2.33}{6} \qquad (2)$$

The final longitudinal characteristics are a bunch length < 4 ns and a longitudinal emittance of 0.35 eVs. The transverse emittance provided by the PS Booster is well preserved during acceleration and results in a round beam at PS extraction with transverse normalised emittances in both planes < 2.5 μm at 1σ and a bunch intensity of 1.3×10^{11} p/b.

During acceleration in the PS a dipolar longitudinal coupled bunch instability is damped using a feedback on 2 of the 10 MHz cavities.

No e^--cloud like instabilities have been observed neither in the PS nor in the SPS and the beam at the exit of the SPS is well within the characteristics given in Table 1. In case the longitudinal emittance from the PS is smaller than 0.35 eVs a controlled longitudinal blow up is applied in the SPS [5].

75 ns beam

Initially the LHC multi-bunch beam with 75 ns bunch spacing was also foreseen to be produced using double batch injection in the PS [2][3]. At extraction of the PS this beam provides 24 bunches spaced by 75 ns. However, the intensity per bunch remains the same as for the 25 ns and 50 ns beams. Therefore the PS Booster will inject fewer protons per ring, resulting in much smaller transverse emittances than specified in Table 1. In 2009 it was decided to produce this beam using single batch injection while remaining within the specified beam characteristics of Table 1.

Presently the 75 ns beam in the PS Booster is produced in the same way as for the 50 ns single batch injection beam with two bunches from three PS Booster rings.

Figure 5 illustrates the PS cycle for the production of the 75 ns beam, which is magnetically identical to the 50 ns single batch cycle.

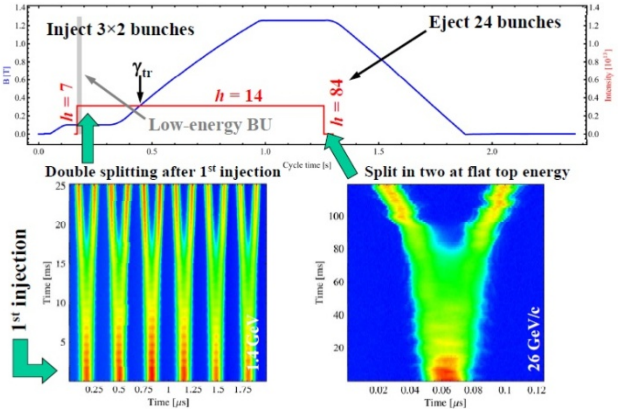


Figure 5: LHC 75 ns beam PS production scheme.

. Once the 6 bunches are in the PS each bunch is split in 2 and not in 3 as is done for the 25 ns and 50 ns beams. The 12 bunches are then accelerated using RF harmonic h=14 up to 26 GeV/c. On the flat top the beam is longitudinally split in 2, again followed by a non-adiabatic bunch rotation prior to extraction

The initial longitudinal emittance received from the PS Booster is divided by a factor 4 as a result of the multiple longitudinal splitting. The controlled and uncontrolled longitudinal blow up along the PS cycle amounts to a factor of 1.56. Therefore the final longitudinal emittance can be calculated using Eq. 3.

$$\varepsilon_{long\ final} = \varepsilon_{long\ initial} \times \frac{1.56}{4} \tag{3}$$

The final longitudinal characteristics are a bunch length < 4 ns and a longitudinal emittance of 0.35 eVs. The transverse emittance provided by the PS Booster is well preserved during acceleration and results in a round beam at PS extraction with transverse normalised emittances in both planes of < 2.5 μm at 1σ and a bunch intensity of 1.3x10^{11} p/b.

The longitudinal coupled bunch instability in the PS that is observed on the 25 ns and 50 ns beams during the ramp after transition crossing does not develop on the 75 ns beam. However, there is a longitudinal coupled bunch instability on the 26 GeV/c flat top that is a potential source of longitudinal emittance blow up and can therefore produce satellite bunches in the SPS. The longitudinal feedback based on 2 of the 10 MHz cavities cannot damp this instability as it requires frequencies that are beyond the bandwidth of the cavities. Means to reduce the longitudinal impedance sources for this instability, like adding more gap relays and putting the inactive cavities on a parking frequency, are being explored. The effectiveness of these measures will be evaluated during the 2011 run.

The SPS has no e^--could issues with this beam and at extraction from the SPS the beam is within the required characteristics as given in Table 1.

150 ns beam

The 150 ns beam is the youngest among the multi-bunch beams for the LHC. The request for this beam came late spring 2010 for use by the LHC in September, leaving a very short period for setting up such a beam and optimizing it for nominal performance, as specified in Table 1. At the extraction of the PS this beam provides 12 bunches at nominal intensity spaced by 150 ns. Therefore the PS Booster will inject even fewer protons per ring than for example with the 75 ns beam, resulting in much smaller transverse emittances than specified in Table 1.

The beam production in the PS Booster is based on the 75 ns beam, which normally provides a longitudinal emittance of 0.9 eVs at extraction, but which was brought down to 0.5 eVs. The 2 bunches produced in each of the 3 rings used are injected in the PS at RF harmonic h=7.

Figure 5 illustrates the PS cycle for the production of the 150 ns beam, clearly indicating the single batch injection from the PS Booster.

After injection the only controlled longitudinal blow up in the cycle is applied to increase the incoming bunches from 0.5 eVs to 0.6 eVs in order to achieve a good symmetric splitting in 2 of each bunch, resulting already at this stage in the 12 bunches on RF harmonic h=14 with a longitudinal emittance close to 0.35 eVs, as required at extraction, leaving very little margin for any non-controlled longitudinal blow up. After acceleration, but just before extraction the bunches are rotated non-adiabatically using the 40 and 80 MHz cavities in order to obtain the required longitudinal characteristics; bunch length < 4 ns and a longitudinal emittance of 0.35 eVs.

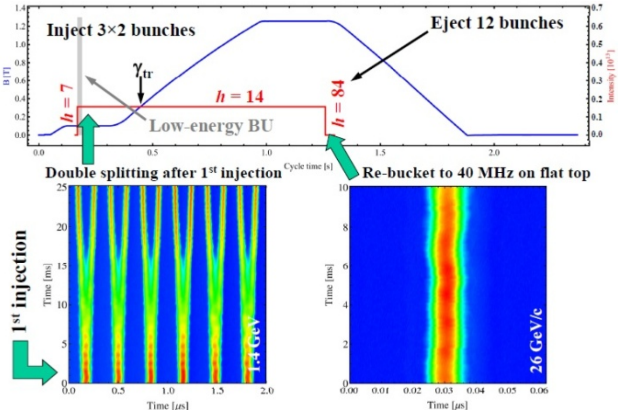


Figure 5: LHC 150 ns beam PS production scheme.

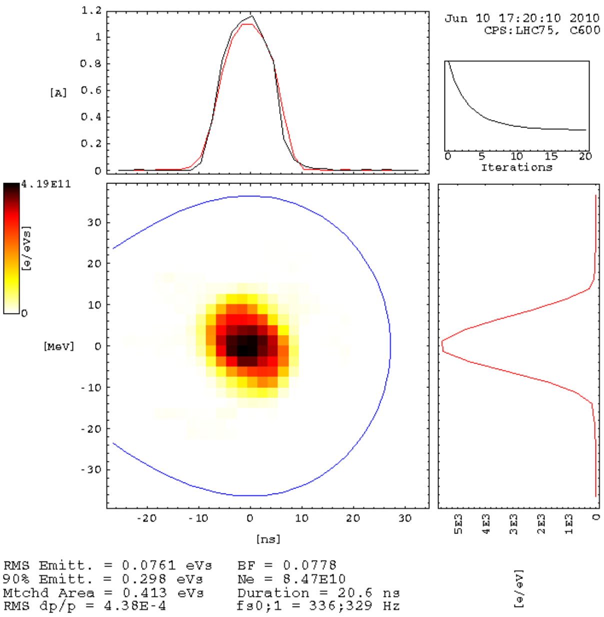
The initial longitudinal emittance received from the PS Booster is divided by a factor 2 as a result of the double splitting. The controlled and uncontrolled longitudinal blow up along the PS cycle amounts to a factor of 1.17. Therefore the final longitudinal emittance can be calculated using Eq. 4.

$$\varepsilon_{long\ final} = \varepsilon_{long\ initial} \times \frac{1.17}{2} \tag{4}$$

During acceleration, after transition crossing, the beam with an intensity of > 0.8x10^{11} p/b develops a quadrupolar coupled bunch instability, driven by the 40 and 80 MHz cavities and compromising the already very tight longitudinal emittance budget in the PS. A measurement of the quadrupolar bunch shape during the instability is given in Figure 6.

The beam with nominal intensity per bunch was nevertheless taken by the SPS and LHC up to a maximum of 8 instead of 12 bunches per PS extraction. The consequences of the quadrupolar longitudinal coupled bunch instability, satellite bunches due to too large longitudinal emittance, will most probably be more important for 12 bunches than observed when only 8 bunches were taken.

The transverse emittance provided by the PS Booster are well preserved during acceleration and result in a round beam at PS extraction with transverse normalised emittances in both planes < 2.5 μm at 1σ and a bunch intensity of 1.3x10^{11} p/b.



```
RMS Emitt. = 0.0761 eVs   BF = 0.0778
90% Emitt. = 0.298 eVs    Ne = 8.47E10
Mtchd Area = 0.413 eVs    Duration = 20.6 ns
RMS dp/p = 4.38E-4        fs0;1 = 336;329 Hz
```

Figure 6: Tomogram of a LHC 150 ns bunch in the PS during the quadrupolar coupled bunch instability. The bunch is not matched, but slightly stretched.

2010 OBTAINED BEAM CHARACTERISTICS

The multi-bunch beams as described in the previous section have been used in the LHC injector chain, mainly for machine development purposes. Some of the beams were pushed to higher intensities with the aim to explore limitations in the different injectors.

Table 2 gives an overview of the peak performances for the different LHC multi-bunch beams, achieved in 2010. These peak performances can by no means be considered as stable operational performances for the near future.

More details on the machine development studies that led to these performances can be found in [5].

The 25 ns beam as indicated in the first row of Table 2 has been produced close to, but within the specifications as given in Table 1. The transverse emittance at extraction of the SPS can perhaps be slightly reduced as will be proposed in the next section

In May and June 2010 the 25 ns beam intensity was pushed well beyond nominal, indicated in Table 2 as “25 ns HI”. A respectable 1.5x10^{11} p/b was produced at high energy in the SPS, but the transverse emittances were nearly a factor 3 higher than nominal. In addition the longitudinal beam quality was compromised due to transient beam loading in the PS cavities that caused degradation in the bunch-to-bunch reproducibility. The beam was also unstable in the SPS.

The 50 ns single batch beam with nominal intensity per bunch was produced and resulted in transverse emittances at high energy in the SPS that are much smaller, 2.5 μm, than nominal, 3.5 μm, showing excellent transverse emittance preservation from the PS Booster until the SPS extraction. During a machine development session the intensity on this beam was increased for which the beam characteristics are given in Table 2 in the row indicated by “50 ns SB HI” The maximum intensity obtained was 1.52x10^{11} ppb. The transverse emittance of 3.5 μm was measured at low energy in the SPS and is thus no guarantee for transverse emittances at extraction, which will have to be measured. In addition the bunch-to-bunch reproducibility, mainly in terms of bunch intensity along the batch, was compromised. Nevertheless this beam provides a large prospective for the LHC in terms of luminosity and deserves therefore further consideration.

The 75 ns beam was produced with nominal bunch intensity with much smaller transverse emittances, 2 μm, at extraction than specified in Table 1. However, presently the intensity is limited by the longitudinal coupled bunch instabilities observed on the 26 GeV/c flat top in the PS for which no longitudinal feedback is available.

Table 2: Obtained LHC beam characteristics for the injectors in 2010 (peak performances)

	PSB extraction				**PS extraction**			**SPS extraction**			
Beam	**Ip/ring [x10^{11}]**	**$\varepsilon_{h/v}$ [μm] 1σ norm.**	**nb batch**	**nb bunch**	**Ip/bunch [x10^{11}]**	**$\varepsilon_{h/v}$ [μm] 1σ norm.**	**nb bunch**	**Ip/bunch [x10^{11}]**	**$\varepsilon_{h/v}$ [μm] 1σ norm.**	**$\varepsilon_{long.}$ bunch [eVs]**	**nb bunch**
25 ns	16	2.5	2	4 + 2	1.3	2.5	72	1.15	3.6	≤ 0.8	1 - 4x 72
25 ns HI	25	3.6/4.6	2	4 + 2	1.7 (1.9)	5	72	1.5	~ 10	≤ 0.8	1 - 3 x 72
50 ns SB	16	2.5	1	3 x 2	1.3	2.5	36	1.15	2.5	≤ 0.8	1 - 4 x 36
50 ns SB HI	24	3.5	1	3 x 2	1.8	3.5	36	1.5	(3.5)	≤ 0.8	1 - 4 x 36
75 ns SB	11	1.5	1	3 x 2	1.3	1.8	24	1.2	2	≤ 0.8	1 – 4 x 24
150 ns SB	5	< 1.5	1	3 x 2	1.3	< 2	12	1.2	≤ 2.5 (1.6)	≤ 0.8	1 – 4 x 12

Further studies in 2011 will have to confirm if the proposed measures, like extra gap relays for the 10 MHz cavities and putting the inactive high frequency cavities on a parking frequency, will cure or at least reduce the instability, allowing for a potential increase of intensity.

Finally the 150 ns beam was used extensively and successfully by the LHC during the last period of the proton run. The transverse emittance was blown up in a controlled way in the PS to meet the requirements of the LHC, which was ~2.5 μm. The beam, without controlled transverse blow up, has a transverse emittance of ~ 1.6 μm at extraction of the SPS, which was taken once by the LHC for a test. In case this beam will be required for a longer period of time by the LHC its performance, especially in terms of longitudinal stability for intensities beyond 0.8×10^{11}, needs to be improved, requiring studies, machine developments and possibly hardware modifications on the RF equipments.

POSSIBILITIES AND ISSUES FOR 2011

Possible improvements

Two improvements that potentially can be implemented in a short period of time and that will be of benefit for the brightness of the multi-bunch LHC beams out of the injectors are:

- The increase of the beam current at the exit of LINAC2 from presently ~ 160 mA to 180 mA as specified in [4]. The main advantage is an intensity increase at injection in the PS Booster for constant transverse emittance.
- Returning to double batch injections for the 50 ns and 75 ns variants of the multi-bunch beams. The main advantage will be the reduced transverse emittance of the beams coming from the PS Booster because fewer turns have to be accumulated in the horizontal phase space for the production of a single bunch per ring.

Issues

The increase of the LINAC2 current from the presently 160 mA to 180 mA, as specified [4], requires, in addition to a very good conditioned source, an increase of the amplifier tubes' anode voltage, a parameter that will then be applied for all LINAC pulses and not just the ones producing the high brightness LHC beams. This increase of anode voltage reduces significantly the life time of these tubes.

Last year the RFQ started sparking after increasing the intensity, in particular when many high intensity beams like ISOLDE and CNGS were present in the PS Booster super cycle. Therefore the increase will have to be tested thoroughly and should be justified.

Returning to double batch injections for the PS will surely result in smaller transverse emittances and provide potential to increase the intensity per bunch. However, it is presently not clear how large this potential is. This will have to be explored during machine development sessions in 2011.

It will also require more beams to be setup, in particular in the PS Booster as each "user" in the PS will require 2 "users" in the PS Booster. The maximum number of "users" available is limited to 24 and cannot be extended due to hardware limitations in the control system. Presently all 24 "users" in the PS Booster are assigned to different beams, required for LHC, non-LHC physics and machine developments. Therefore it will require a new way of working with the available number of "users", relying heavily on a 100% unfailing archiving system to restore archived settings in the machine hardware, depending on the needs of the LHC. As a consequence the switching times between the different multi-bunch beams might be longer and some limitations on machine developments may arise. This way of working will therefore impose careful planning of the required beams in order to leave time for validation after restoring an archive.

Double batch injection in the PS also requires very good magnetic field stability, with identical conditions for both injections, 1.2 seconds apart. Presently the PS suffers from fluctuations of ~ 0.5% on the magnetic field at injection, but this goes unnoticed for the single batch injected beams. The consequences, in terms of transverse emittance growth, will have to be evaluated during setting up or machine development sessions in 2011 and all efforts will have to be applied to reduce the injection field fluctuations.

Another consequence of double batch injection is the lengthening of the PS cycles from 2.4 seconds to 3.6 seconds, resulting in a longer flat bottom in the SPS and this a longer filling time for the LHC.

An advantage of returning to double batch injection is the increased resolution of the number of bunches that can be selected by switching on or off PS Booster rings. For the 75 ns beam this will go from 8 bunches per PS Booster ring for single batch injection to 4 bunches per PSB ring for double batch injection. For the 50 ns beam this will go from 12 to 6 bunches per PSB ring. This increased resolution might be useful for the injection scheme as used in the LHC, where after the injection of the Probe beam the first multi-bunch injection will take place with a reduced number of bunches with respect to the remainder of the filling with bunch trains. However, the switch of the number of bunches between the first and second injection of the multi-bunch beam in the LHC has also consequences in the PS. In order to keep the bunch splitting symmetric a few cavity phase related parameters in the PS need to be adjusted manually. Approaches to making these changes more automatic and less prone to human error are being explored.

Other issues not necessarily related to returning to double batch injection are:

- Controlled transverse blow up; following the small transverse emittances of the LHC beams, but in particular for the 150 ns beam, the LHC required a controlled transverse emittance blow up. A few years ago a strategy, to preserve the transverse emittances as long as possible in the injector chain, was decided and it was defined that the controlled blow up to tailor the final required transverse emittance would be done in the SPS. Due to limitations on the SPS transverse damper settings, for the different multi-bunch beams, this blow up is presently done ad-hoc in either the PS Booster or the PS, with the risk of losing track of where different blow ups are performed. It is therefore requested that the settings of the SPS transverse damper can be different for the different users (ppm-mode)

- Controlled longitudinal blow up; the same request as for the controlled transverse blow up was made for the controlled longitudinal blow up in the SPS, which was implemented during the 2010 – 2011 technical stop and will be operational for the 2011 run.
- When ions are produced in parallel in the PS, 2 of the 80 MHz cavities are tuned for protons and 1 for ions, leaving no hot spare in case one of the cavities breaks and a manual intervention will have to take place in order to retune a cavity excluding the nominal production of either ions or protons.
- Satellite bunches can be a result of too long bunches or too large longitudinal emittances extracted from the PS and injected in the SPS. Using a 3rd 80 MHz cavity at extraction in the PS can result in shorter bunches for larger longitudinal emittances. The effectiveness of this will have to be confirmed during machine development sessions in 2011. This proposal is not compatible with ion operation in the PS, unless an additional cavity or pulse-to-pulse tuning can be installed.
- The injectors will require more logging in order to make post mortem analysis on issues that happen during the filling of the LHC possible. As an example it would be very useful to have the wall current monitor signals in the injectors digitised and logged during the last turn of each cycle going to the LHC. These extensions to the logging capabilities in the injectors will require investments in terms of money and support from the equipment groups.

Possible 2011 beam characteristics

For the single bunch beams no changes are foreseen as there is little or nothing to gain. However, the emphasis should be on the 50 ns and 75 ns beams, with the 150 ns as fall back solution. Returning to the double batch injection for the 50 ns and 75 ns beams together with further development of these beams could not alone lead to smaller emittances, but also to higher than nominal bunch intensities.

However kicker out gassing and e-cloud issues in the SPS will have to be evaluated and dealt with for the enhanced performance of the different beams.

Table 3 provides a list of realistic beam characteristics that can be obtained in 2011 for operational use to fill the LHC.

The 25 ns beam with double batch injection is produced within the nominal characteristics and leaves little margin for improvement. The only possibility to enhance the performance of this beam within the present production scheme can be obtained by increasing the LINAC2 source current to 180 mA, which will lead to smaller emittances and potentially allows for injecting more protons and return to the nominal emittances.

The performance of the 50 ns and 75 ns single batch injection beams is known from last years' experience. Nevertheless they were produced during machine development sessions and some time will be needed to make them operationally available in a stable way.

The 50 ns and 75 ns double batch beams were not used since a long time. Therefore the 50 ns beam characteristics given in Table 3 remain to be confirmed and can perhaps be enhanced further during machine development sessions.

Table 3: Possible 2011 LHC multi-bunch beam characteristics for the injectors

	PSB extraction				**PS extraction**			**SPS extraction**			
Beam	**Ip/ring [x10^{11}]**	**$\varepsilon_{h/v}$ [μm] 1σ norm.**	**nb batch**	**nb bunch**	**Ip/bunch [x10^{11}]**	**$\varepsilon_{h/v}$ [μm] 1σ norm.**	**nb bunch**	**Ip/bunch [x10^{11}]**	**$\varepsilon_{h/v}$ [μm] 1σ norm.**	**$\varepsilon_{long.}$ bunch [eVs]**	**nb bunch**
25 ns DB	16	2.5	2	4 + 2	1.3	2.5	72	1.15	3.6	0.7	1 - 4 x 72
50 ns SB	24	3.5	1	3 x 2	1.75	3.5	36	1.45	~ 3.5	≤ 0.8	1 - 4 x 36
50 ns DB	8	1.2	2	4 + 2	1.3	1.3	36	1.15 (?)	1.5 (?)	≤ 0.8	1 - 4 x 36
75 ns SB	11	1.5	1	3 x 2	1.3	1.8	24	1.2	2	≤ 0.8	1 - 4 x 24
75 ns DB	5.5	0.9	2	4 + 2	1.3	0.9	24	1.2 (?)	1 (?)	≤ 0.8	1 – 4 x 24
150 ns SB	5	< 1.5	1	3 x 2	1.2	< 2	12	1.1	≤ 2.5 (1.6)	≤ 0.8	1 – 4 x 12

The characteristics for the 75 ns double batch beams are a ‘tentative guess” and were never obtained. This beam will therefore require still some time to be set up correctly before confirming, let alone enhancing its performance.

The 150 ns beam seems to be usable by the LHC with 8 out of 12 bunches at nominal intensity, but substantial work is needed to stabilise this beam. However, is the 150 ns beam still required and if so, how much work and financial resources for equipment modifications should be devoted to its optimisation?

CONCLUDING REMARKS

The experience gained in 2010, mainly during machine development sessions, on the different multi-bunch beams in combination with the better knowledge of the LHC machine capabilities have led to a realistic set of enhanced beam characteristics for the multi-bunch LHC beams. The explanation of the production schemes of each of the multi bunch beams also outlined the major difficulties and limitations for each of these beams.

A substantial amount of machine development time, in addition to the time needed for the LIU activities, is required to obtain enhanced performance on these beams and to make them operationally available.

In order to be able to prepare and provide good quality beams from the injectors, clear requirements sufficiently ahead of time need to be established and communicated. It is also important to provide understanding of the beam parameters that are critical for the LHC, but also those that are less critical.

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POSSIBILITY OF A HIGHER PSB TO PS TRANSFER ENERGY

O. Aberle, A. Blas, J. Borburgh, D. Bozzini, M. Buzio, O. Capatina, C. Carli, T. Dobers, L. Fernandez, A. Findlay, R. Folch, S. Gilardoni, N. Gilbert, K. Hanke, T. Hermanns, E. Mahner, B. Mikulec, A. Newborough, M. Nonis, S. Olek, M. Paoluzzi, S. Pittet, I. Ruehl, G. Rumolo, R. Steerenberg, J. Tan, D. Tommasini, W. Weterings, M. Widorski, CERN, Geneva, Switzerland

Abstract

Following the Chamonix 2010 workshop a task force has been set up to study the feasibility and the impact of an energy upgrade of the PS Booster from the present 1.4 GeV to about 2 GeV. The working group has confirmed the feasibility of such an upgrade, and analysed in detail the impact on the accelerator hardware along with a cost estimate and a tentative planning. The outcome of the task force will be summarized, with particular emphasis on the remaining limitations, risks and uncertainties.

INTRODUCTION

One of the outcomes of the 2010 Chamonix workshop [1] was that an increase of beam energy from 1.4 GeV to about 2.0 GeV would ease injection of high intensity and high brilliance beams into the PS [2], and thus help removing bottlenecks in the injector chain. Given that consolidation of the ageing machine would be required anyway to allow for reliable operation throughout the lifetime of the LHC, the question was raised whether such an energy upgrade could be done, and what resources would be needed in addition to the consolidation program. The task force set up immediately after the workshop has tried to cover the complete accelerator hardware and all aspects of operation, in order to obtain an as complete picture as possible of the technical modifications that would be needed and the impact in terms of resources. The task force was also mandated to evaluate the time lines of such a potential upgrade, taking into account that work in the injectors would be constrained by the long LHC shutdowns.

The following items have been addressed by the working group, composed of representatives of the various groups involved[*]:

- beam dynamics
- magnets and magnetic measurements
- RF system
- beam intercepting devices
- power converters
- vacuum system
- instrumentation
- commissioning and operation
- extraction and transfer
- controls
- electrical systems
- cooling and ventilation
- radiological protection
- transport and handling
- survey

Further working group members were representatives of the consolidation program, the design office, the US-LARP collaboration, experts of the PS machine and other specialists as needed.

The findings of the working group have been published in [3]. In the following sections the areas with significant impact will be addressed in detail.

GENERAL CONSIDERATIONS

The mandate of the study group was to consider 2 GeV energy for LHC type beams in the PSB only. However, at a very early stage of the investigations it became clear that the cost drivers would not change when extending the energy upgrade to all beams. The baseline scenario is therefore to enable the machine to execute every cycle at 2 GeV. At the same time, it is suggested to upgrade the Booster to PS transfer line (BTP) for ppm (pulse-to-pulse modulation) operation. The Booster itself and the injection into the PS are already fully ppm. This means that the complete Booster including the transfer line and PS injection would be able to alternate between 1.4 GeV and 2 GeV cycles from cycle to cycle if needed. This scenario gives the maximum operational flexibility. Modification of the transfer line to ISOLDE (BTY) was not considered within the frame of this study. It is therefore assumed that ISOLDE beams remain at the present energy of 1.0/1.4 GeV. In case ISOLDE would like to take advantage of 2 GeV beams, this would require a separate project with its own budget.

For completeness we have studied a scenario where we would not do the ppm upgrade of the BTP line (which would mean moderate cost savings) and execute only LHC type beams at 2 GeV. In that case one would need to suppress 1.4 GeV fixed-target physics cycles whenever LHC type beams are present in the injectors (i.e. during LHC filling but also during setting up). We found that such a scenario would yield some moderate cost savings, while the loss of non-LHC physics would be unacceptable [4].

With regard to the time frame of the upgrade, we were asked to aim at rapid implementation, even before Linac4 comes on-line. After some initial considerations this turned out to be technically challenging (acceleration from 50 MeV Linac2 energy to 2.0 GeV) and schedule

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[*] With the implementation of the LHC injector upgrade project, the modifications for injection of the H^- beam from Linac4 have recently been added as an additional item.

wise unrealistic (long lead time for equipment design and procurement). Therefore, it is assumed that the 2 GeV upgrade is put in place with Linac4, and that we have to base all our considerations on Linac4 beam parameters.

We have considered intermediate beam energies between 1.4 GeV and 2.0 GeV. If we would have found that slightly lower beam energy than 2.0 GeV would have resulted in significant cost savings, and would have in particular avoided changing the Main Power Supply (MPS), such a scenario could have been considered a viable option. However, we found that the present MPS cannot run at any higher energy than 1.4 GeV and needs therefore to be replaced in any possible scenario.

EXPECTED PERFORMANCE GAIN WITH 2 GEV

There is a general consensus that increasing the beam energy will facilitate injection of high intensity beams into the PS. The gain can be quantified by looking at the formulas for the space-charge induced tune spread [5]

$$\Delta \mathrm{Q_x} = \frac{R_p N_b}{2\pi^{3/2}\gamma^3\beta^2\sigma_z}\oint\frac{\beta_x(s)ds}{\sigma_x(s)[\sigma_x(s)+\sigma_y(s)]} \quad (1)$$

and

$$\Delta \mathrm{Q_y} = \frac{R_p N_b}{2\pi^{3/2}\gamma^3\beta^2\sigma_z\sqrt{\varepsilon_y}}\oint\frac{\beta_y(s)ds}{\sigma_x(s)+\sigma_y(s)} \quad (2)$$

Injection at 2 GeV lowers the space charge effect by a factor $(\beta\gamma^2)_{2GeV}/(\beta\gamma^2)_{1.4GeV} = 1.63$. That is, keeping the same space charge tune spread as present, about 65% more intensity could be injected. Equations (1) and (2) contain also terms $1/\sigma_z$, which means that keeping the longitudinal emittance at the present values the bunch length would decrease which would limit the above quoted gain to about 40%. However, as the PS bucket size will increase at 2 GeV, it is believed that one can allow for larger longitudinal emittance and thus compensate for this effect. Another knob to further increase the injected intensity would be to accept a larger transverse emittance, but recent requests from the LHC for low-emittance beams led us to discarding this option.

In summary, from theoretical arguments the gain in injected intensity is expected to be at least 65%.

IMPACT OF ENERGY INCREASE ON BOOSTER EQUIPMENT AND SYSTEMS

Magnets

The natural first question to be asked is if the Booster main magnets can achieve the field levels required for operation at 2 GeV. However, the magnets have been sufficiently over designed such that this is not an issue. A concern was however whether mechanical stress would become an issue when pulsing the magnets permanently with 2 GeV cycles. In order to address this issue, a stress test has been performed where a spare magnet has undergone 5000 cycles at a field level corresponding to twice the one at 1.4 GeV. No degradation of the magnet was found [6]. However, some minor mechanical modifications needed to be implemented before going to high field levels.

Another issue was that the saturation of the outer rings increases even more than it is already the case at 1.4 GeV. This issue could be satisfactorily solved by changing the present solid retaining plates by laminated ones.

Furthermore, the present water cooling system is insufficient. The requirements on the magnet cooling depend essentially on the magnetic cycle. It was managed to design a 2 GeV cycle where the r.m.s. current remains within 10% of the present one [7]. By staying within this limit it turns out that only minor modifications to the cooling circuits will be required which can be carried out in situ. A higher r.m.s. current would have necessitated a more severe revision of the magnet cooling, which would have probably required removal of the main magnets from the tunnel.

Apart from the main magnets there are a number of auxiliary magnets to be considered. They are mainly used at injection energy and not considered to be an issue. However the study is to be completed. As for the transfer line to the PS, about 15 to 18 out of the 59 magnets will need to be changed. Before this figure can be confirmed, the optics study of the transfer line needs to be completed, which in turn depends on the re-design of the PS injection region (see below). Furthermore the PS injection bumpers and a number of low-energy correctors and quadrupoles need to be checked.

RF System

The complete renovation of the Booster high level and low level RF is planned in the frame of the consolidation program. On the low-level side this consolidation will include the transverse damper and the RF cables. The main part of the RF consolidation will concern the high-level C02, C04 and C16 systems. Notably the consolidation of the C04 system is mandatory to achieve 2 GeV, while consolidation of the C02 and C16 is not mandatory for the energy increase but required to ensure reliable operation over the next 25 years. It is important to notice that it is a necessary condition for the 2 GeV upgrade that the mandatory items of the RF consolidation program are completed within the time frame of the upgrade project.

Beam Intercepting Devices

The Booster dump has been subject to investigations since the question came up whether it would support beam intensities expected with Linac4. The option to dump these beam intensities at an energy of 2 GeV came then as an additional constraint. It became clear that the present Booster dump needs to be replaced by one adapted to the expected beam parameters, and that a spare dump is needed. This activity is covered by the consolidation project and is well under way. Removal of the existing dump is being planned with participation of RP.

A second intercepting device which potentially needs replacement is the beam stopper BT.STP10. It remains to be confirmed whether it can operate at 2 GeV beam energy. If this is not the case, a new design and production of two units will be required. This has tentatively been allocated in the consolidation program.

Power Converters

The biggest impact of a 2 GeV upgrade would be for the power converters, notably the Booster Main Power Supply. The present Booster MPS can neither deliver the r.m.s. nor the peak current required for 2 GeV operation. The present 1.4 GeV is a hard limit, and the present MPS cannot pulse at any higher value than that.

Increasing the peak power using traditional thyristor technology would have an unacceptable effect on the whole Meyrin network. Therefore, it is proposed to replace the MPS by a POPS-type [8] power supply using a capacitor bank (Figure 1). The available voltage increases and would allow for faster ramping, thus reducing the r.m.s. current. The capacitor bank totally absorbs the peak power. This would at the same time allow dividing the machine into two circuits (inner and outer rings) thus making the trim power supplies used for rings 1 and 4 obsolete. The new main power supply would require a new building for which a location has already been identified. Apart from the MPS a number of smaller power supplies cannot operate at 2 GeV and need to be replaced.

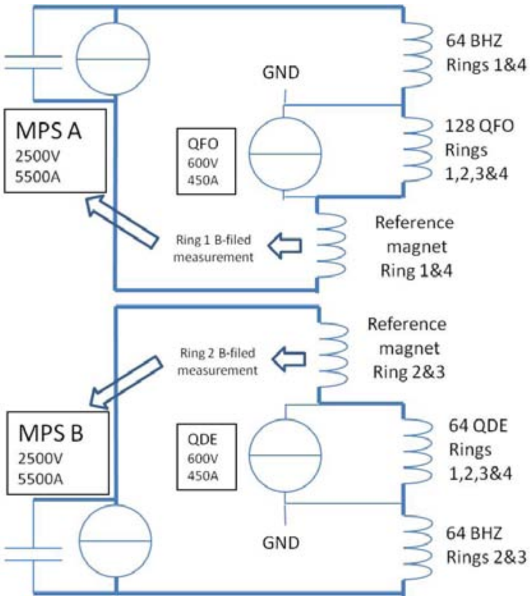

Figure 1: Lay-out of new POPS-type main power supply.

Extraction, Transfer and PS Injection

A number of extraction elements can operate at 2 GeV without modifications. However, notably the extraction kickers (BE.KFA) and recombination septa (BT.SMV) need to be re-designed and re-built. Some other elements, like the extraction septum BE.SMH, would require modification (re-inforcement of the cooling).

A critical issue is the PS injection septum. The septum would need to be replaced by a longer one for 2 GeV injection, which in turn requires the whole PS injection region to be re-designed. This work is presently in progress. It is hoped that a solution can be found where the injection point remains in PS straight section 42 (SS42) as presently the case. Otherwise it could be moved to SS41, but at the expense of re-designing the BTP line. At the moment work is in progress and a conclusion is expected for early 2011. The PS injection kickers have been confirmed to work at 2 GeV if operated in short-circuit mode. This will result in a small, but acceptable emittance growth.

Electrical Systems

The present power consumption of the Booster is around 10 MVA. The main consumers of electrical power are the power converters and the cooling and ventilation systems. As for the power converters, an increased request of about 100% is expected for the transfer line power supplies, which will be compensated by a 25% decrease estimated for the new MPS. For the cooling and ventilation systems, the required electrical power will be 15-20% above the present one. There is no more power available from the transformers for general services, and the 18 kV “cubicles” cannot be extended. Furthermore the whole electrical system on the Meyrin site needs consolidation. A re-design has started, which includes the increased power needs of a 2 GeV Booster in the frame of a global re-design of the electrical network on the Meyrin site.

Cooling and Ventilation

As for the electrical network, the future design of the cooling system will depend on the needs, mainly the ones of magnets, power converters and RF. A survey of the different work packages has so far not revealed any increase in cooling needs. Therefore, a refurbishment of the cooling station and some distribution piping is considered sufficient.

As for ventilation, no specific needs have been identified. Therefore a complete refurbishment of the existing plant, while keeping the same functionalities, is planned. However, new buildings (e.g. the one for the new MPS) need to be included. Furthermore RP aspects need to be considered when the ventilation system is refurbished.

Other Work Packages

We have investigated the impact on other, smaller work packages with the same care as for the high-impact ones described in more detail above. We have not found any unmanageable items, but derived a number of actions and cost items which went into our general budget and time estimate.

The work package “Booster Injection” will be transferred from the Lianc4 project to the Booster upgrade project including the associated budget.

RESOURCES AND TIME LINES

The resources in terms of budget and manpower have been detailed and published in [3]. We have disentangled the cost of consolidation, i.e. of keeping the Booster operational for the next 25 years but without energy upgrade, and the additional cost of upgrading the machine for 2 GeV operation.

The time lines of the upgrade project are constrained by the long LHC shutdowns. When drafting our planning we have assumed long LHC stops in 2012 and 2016, and come up with a planning that aims at commissioning of the 2 GeV Booster and the Linac4 injection simultaneously in 2016 (Figure 2). Recent discussions have suggested to install and commission the H^- injection first, and commission the 2 GeV upgrade during the following long LHC shutdown. Such a planning can also be envisaged and would have the advantage to spread out the workload rather than concentrating all activities in one shutdown.

It is a common comment with regard to all possible installation and commissioning schedules that the timelines can only be respected if the resources laid out in [3] are made available entirely and at the time when they are needed.

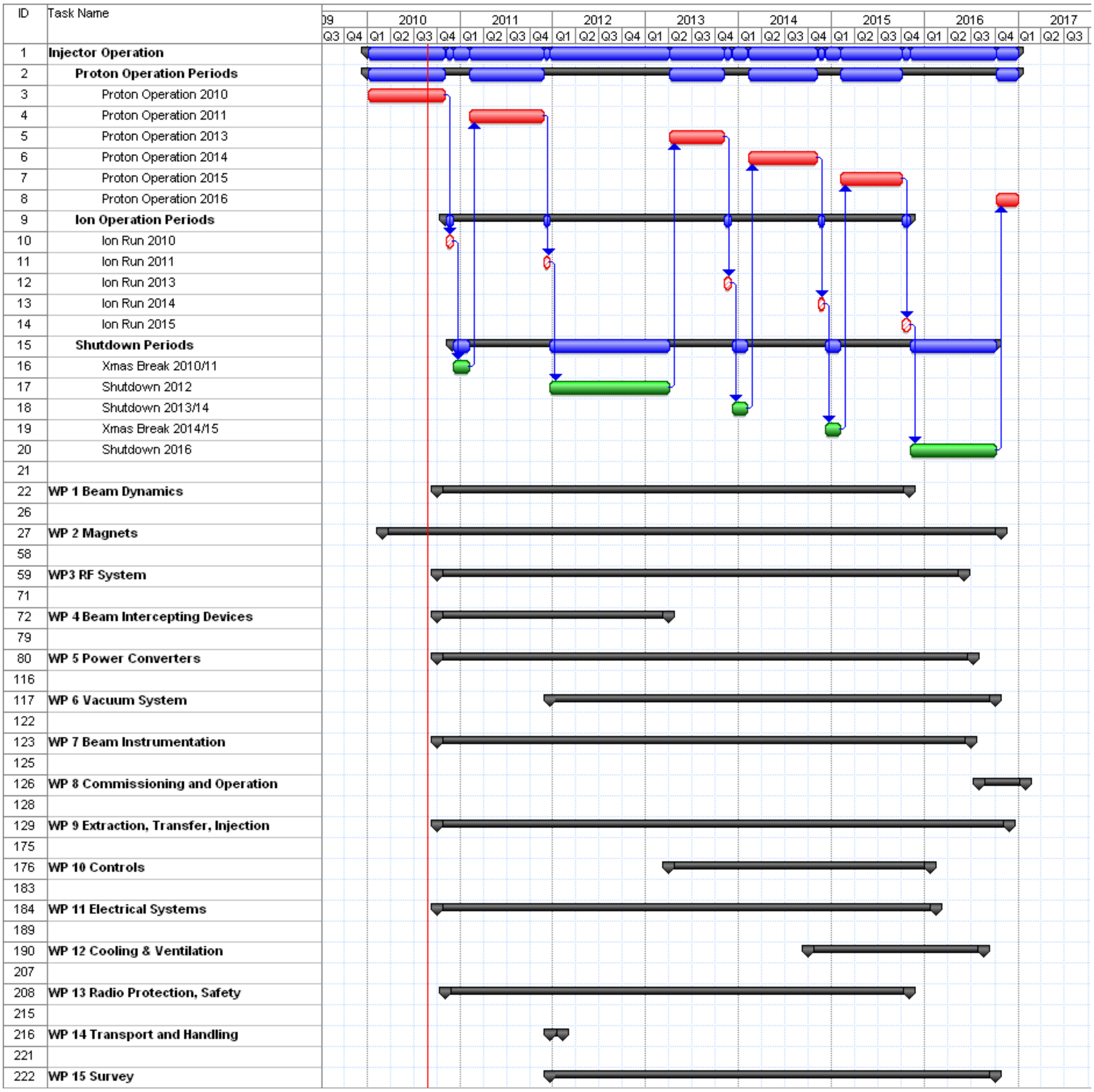

Figure 2: Tentative project planning based on long LHC shutdowns in 2012 and 2016.

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PS POTENTIAL PERFORMANCE WITH A HIGHER INJECTION ENERGY

S. Gilardoni, S. Bart Pedersen, J. Borburgh, D. Bodart, P. Chiggiato, H. Damerau,
S. Hancock, G. Metral, S. Pittet, C. Rossi, G. Rumolo, R. Steerenberg, M. Widorski
CERN, Geneva, Switzerland

Abstract

In the context of the LHC Injectors upgrade project, the PS has to be brought up to – and to operate reliably at – the level of performance required by the HL-LHC until the end of the LHC lifetime. The study has started on the potential benefits of increasing the injection energy. An overview of the impact of this upgrade will be presented, with a preliminary estimate of the beam characteristics at the SPS entrance and the remaining performance limitations. The necessary hardware modifications will be described, highlighting the critical systems and the risks. The program for the 2011 machine studies and hardware interventions for refining these plans will be presented.

INTRODUCTION

As explained in [1], the role of the PS in the production of the LHC-type beams is to conserve the transverse emittances produced in the PSB and to produce the final longitudinal bunch spacings. Different causes of transverse emittance blow-up were already studied in the past, with the first and the most critical one indentified as the large Laslett tune shift from space charge. This blow-up affects particularly the first batch of the double-batch beams, while the beam is waiting for the second injection after 1.2 s. During this period, the first batch might experience an emittance blow-up if the tune shift is larger than -0.3. As proposed in [2], this effect can be reduced by increasing the injection energy in the PS by a suitable amount, as already done in the past when the PSB extraction energy was pushed from 1 GeV to 1.4 GeV, and at the same time it allows injecting higher beam intensities without a relevant blow-up. Other effects can also contribute to the final transverse emittance like head-tail instability at injection energy, TMCI at transition crossing, electron cloud at extraction, as discussed in the following sections.

The second and more fundamental role of the PS is to define the final longitudinal structure of the beam, in terms of bunch spacing, via a series of RF gymnastics. Again, many factors can contribute to spoil the longitudinal beam quality like coupled bunch instabilities or transient beam loading.

All these effects have to be considered and analyzed to finally determine the future possible performances of the PS as HL-LHC injector with an upgraded injection energy.

DRAFT FUTURE PERFORMANCES

As mentioned, the transverse emittance delivered by the PSB has to be conserved by the PS as much as possible. Thanks to a series of MDs in the 2010 run and thanks to the PS operation as LHC injector, the following conclusions could be drawn:

- For a Laslett tune shift smaller than -0.3, no significant transverse emittance blow-up is observed.
- For large Laslett tune shift, tests were done with a maximum $\Delta Q_x \approx -0.34$ and $\Delta Q_y \approx -0.56$, the emittance increases were lower than the ones measured in past studies. This does not authorize to draw any conclusion yet, like accepting by default very large tune shifts, but it indicates the necessity to repeat the studies with a very systematic measurement campaign.
- Tests with ultimate-like beams showed that more than 1.7 10^{11} ppb peak performance is achievable with 25 ns and 50 ns bunch spacing, but today only with reduced beam quality and operationally not maintainable.

According to the mentioned points, a very first and educated estimate of the future beam performances could be summarized as in Table 1, under the following hypothesis:

- Linac4 will be fully operational with nominal performances.
- The PSB transverse emittances will be uncorrelated from the beam intensities.
- The injection energy of the PS will be upgraded to 2 GeV.
- The beams will be produced in double batch.
- No transverse emittance blow-up is assumed between injection and extraction.
- The entire program proposed for the PS upgrade will be realized.

The future performances were determined, for the first block of Table 1, by a) assuming the best transverse emittance delivered today to the SPS for the LHC beams, i.e., 2.5 μm rad delivered already at PS injection and extracted without any blow-up; b) fixing the longitudinal emittance within the increased acceptance of the PS at 2 GeV and rescaling from the current performances; c) computing the

Table 1: Draft of LHC beam parameters after the PS upgrade

Intensity PS extract. (ppb)	**Bunch spacing** per ring	$\epsilon_{(x,y)}$ **PS extract. (1 σ norm)**	**Laslett** $\Delta Q_{x/y}$	$\epsilon_{longit.}$ **@ PSB**	**PSB int.**	**Comment**
3.0 10^{11}	25 ns	2.5 μm rad	-0.24 **-0.37**	$\leq$ 2 eVs (160 ns)	$\approx$400 10^{10}	*Streched goal*
1.9 10^{11}	25 ns	2.5 μm rad	-0.14 -0.22	$\leq$ 2 eVs (160 ns)	$\approx$240 10^{10}	**Baseline**
3.0 10^{11}	50 ns	2.5 μm rad	-0.11 -0.17	$\leq$ 2 eVs (160 ns)	$\approx$190 10^{10}	*Streched goal*
1.9 10^{11}	50 ns	2.5 μm rad	-0.07 -0.11	$\leq$ 2 eVs (160 ns)	$\approx$125 10^{10}	**Baseline**
1.7 10^{11}	25 ns	1.5 μm rad	-0.30 -0.30	$\leq$ 2 eVs (160 ns)	$\approx$220 10^{10}	Minimum $\epsilon_{(x,y)}$
2.0 10^{11}	25 ns	1.8 μm rad	-0.30 -0.30	$\leq$ 2 eVs (160 ns)	$\approx$250 10^{10}	Minimum $\epsilon_{(x,y)}$
2.7 10^{11}	50 ns	1.1 μm rad	-0.30 -0.30	$\leq$ 2 eVs (160 ns)	$\approx$170 10^{10}	Minimum $\epsilon_{(x,y)}$

intensity the PSB would have to deliver to reach a given intensity at extraction and adding 5-10% margin for losses.

In doing this, it became clear that going beyond the 1.9 - 2.0 10^{11} ppb would be difficult both on the transverse and on the longitudinal side. Whereas 2.0 10^{11} ppb seems to be feasible, going up to 3.0 10^{11} seems to be quite difficult, due to the large Laslett tune shift at injection and due to the large intensity per bunch that the RF would have to manipulate during the different bunch splittings.

The second part of Table 1 presents the performances considering the minimum transverse emittance reachable for a given intensity and a maximum Laslett tune shift of -0.3. In this case, no eventual transverse emittance blow-up was included, even if some would probably occur for such small emittances but it cannot be easily quantified yet.

The final intensity per bunch is expected to be within the longitudinal bunch length required by the SPS, i.e., 4 ns for a total emittance of 0.35 eVs.

INJECTION AT 2 GEV

The existing injection from the PSB is realized by a septum in straight section (SS) 42 which bends the beam on a slow bump formed by four independent bumpers. Finally the beam is deviated on the closed orbit by a full turn kicker (KFA45). The slow bump, with the amplitude shown in Fig. 1, last for about 0.8 ms (half sinus). A first analysis of the injection element operation at 2 GeV lead to the following conclusions. The existing septum cannot be upgraded for the 2 GeV operation: a new one that occupies the entire straight section was designed, with one of the injection bumpers installed in the primary vacuum vessel to make use of the maximum space available (see Fig. 2). The remaining three other bumpers might operate at 2 GeV, but they were designed with a captive vacuum chamber: in case of a magnet failure, an entire straight section have to be removed causing also the venting of the septum requiring the bake-out of the latter to recover the operational vacuum. A study has been launched to design new half-magnets.

The power converters of the magnets and the septum will be studied during 2011.

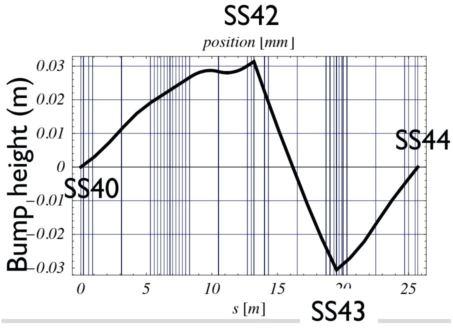

Figure 1: Beam trajectory at the maximum of the injection bump. The position of the bumpers are indicated by the numbering of the straight sections (SS) where they are installed

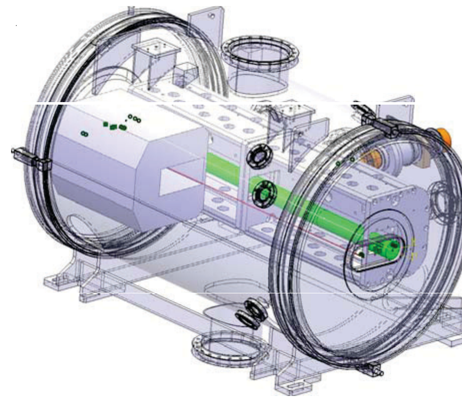

Figure 2: Desing of the new 2 GeV septum with the bumper embedded in the vacuum tank. The injected beam is represented by the green cylinder

Concerning the injection kicker, tests done in 2010 showed that the kicker could provide enough strength to inject 2 GeV LHC-type beams if operated in short-circuit. A predicted degradation of the kicker flat-top in this operation-mode caused an emittance blow-up of about 10% for the LHC beams: it is believed that this can be cured by the use of the transverse damper, not yet operational at the time of the tests. This kind of operation, however, will not allow the injection of the multi-bunch non-LHC type beams at 2 GeV: this issue is still under investigation. In particular, a new kicker installed in SS53 was proposed to compensated the missing strength of the KFA45 for this kind of beams.

A preliminary study was also done to determine the impact of losses at 2 GeV, in particular the eventual increase of the dose levels at the Route Goward [3]. Preliminary FLUKA simulations showed that the dose levels, for the same amount of losses present today at 1.4 GeV, would bring to a more than linear increase of the dose. It is important to notice that, if only the LHC-beams will be injected at 2 GeV, the dose increase would be probably negligible: this is because already the current losses of the non-LHC beams are causing large doses, requiring already today an increase of the shielding on top of the tunnel. Further studies will be carried out during 2011 to better evaluate the eventual losses at 2 GeV and the required increase of the shielding, considering the operation of all the beams at 2 GeV and with the present losses.

FLAT BOTTOM AT 2 GEV

As mentioned in the previous sections, the production of the LHC-beam for high-brillance is done by injecting two batches, separated by 1.2 s. During this period, the first batch can experience a transverse emittance blow-up due to the Laslett tune shift, but also losses due to the well-known head-tail instability. The first mechanism is going to be deeply studied in 2011-2012, since some of the 2010 experimental results of do not fully agree with earlier studies [4]: it is of vital importance to understand as much as possible the emittance increase mechanism. Concerning the head-tail instabilities, further studies, both theoretical and with MDs, will be done in the next years since the rise time of the instability will be 50% smaller at 2 GeV. Losses and/or emittance blow-up could be cured by different methods like: a) using octupoles, as done in the past. The hardware is still installed in the PS, plus some more octupoles installed for the MTE (Multi-Turn Extraction) extraction could be also used; b) introducing linear coupling as done today by skew quadrupoles. In this case, as described later, it is of primary importance to assess the performance of the magnets and power converters at 2 GeV; c) the working point adjustment that is not done today but the Pole-Face-Windings (PFW) could be used to control the chromaticity. The use of the slow-extraction and MTE sextupoles could be also envisaged; d) the transverse feedback which is available but not operational. Studies should be done for the latter to determine if the instability frequency is well within the band-width of the system.

The hardware, in terms of magnets and power converters, used at 2 GeV were also analyzed. The 50 horizontal and the 40 vertical correctors will be tested at 2 GeV during MDs in 2011, since it seems that they reserve some margin. On top of this the new orbit correction procedure, using YASP with SVD [5], indicates that a dispersed correction around the ring lead to a small current for each magnet, well below the maximum current of the equipments. More concerns are the lattice and the skew quadrupoles. The lattice quadrupoles are iron-less magnets, air cooled, inserted in the combined function main magnets. Those quadrupoles are used as trim to control the working point at low energy. The skew quadrupoles are of the same type, some of them with extra coils to act as vertical correctors. For those magnets, in particular the last ones, the large RMS current required on the 1.2 s long injection flat-bottom might constitute an issue, in particular due to the overheating of the coils. Some tests done in 2010 already showed the need of replacing the skew-combined function magnets, whereas further studies in 2011 will assess the limits of the other magnets. Some tests will be also done to control the working point with the PFW at injection, to in case reduce the load on the trim quadrupoles. Concerning the power converters of the different magnets, a consolidation program was already launched, and new specifications for 2 GeV operation will be taken into account.

TRANSITION CROSSING

Transition crossing is a delicate moment in the acceleration cycle due to the frozen longitudinal motion. The extrapolation to determine the stability of the upgraded LHC-beam was done by considering the current beam operation.

For the longitudinal plane, no limitations at transition crossing would be expected for beyond-ultimate LHC beams. Considering the peak current of the non-LHC beams, which only allows an estimation and not a direct scaling for future operation, no longitudinal instabilities are expected up to 2 10^{11} ppb (for the 25 ns beam and at PS extraction), according to observations during the ultimate LHC25 tests. The peak current of the different beams is presented in Table 2, together with the other non-LHC beams: clearly the AD and the TOF beams are more challenging in the current operation than the upgraded LHC beams.

Transverse instabilities were observed for the TOF-like beams in the past [6] in agreement with more recent studies [7]. The vertical TMCI (Transverse-mode coupling instability) can cause relevant beam losses or a significant transverse emittance blow-up: the threshold of this instability however is above the parameters of the future LHC-beams and should not constitute a problem. Further studies will be carried out in 2011-2012.

Table 2: Beam parameters at transition crossing

LHC spac. ns	**10^{11} ppb at eject.**	**Int. 10^{11} ppb**	**ϵ_l eVs**	**Pk. curr. at γ_{tr} A**
25 nom.	1.3	5.2	0.65	8.4
25 ult.	2.1	8.4	0.65	14
50 nom.	1.3	2.6	0.65	4.2
50 bey. ult.	3.0	6.0	0.65	9.7
CNGS		17	1.4	15
AD		40	2.3	23
TOF		89	2.6	40

RF RELATED ISSUES

The LHC-beam bunch spacings are produced in the PS by 2-3 bunch splittings produced by 4 different RF systems with different frequencies: 10, 20, 40 and 80 MHz cavities have to manipulate the beam during the PS cycle. The production of the LHC25 beam, as described in [1], is done thanks to a triple splitting at injection energy plus two consecutive bunch splittings at 26 GeV/c to produce the final 72 bunches. Finally, before extraction the beam is phase rotated in the longitudinal phase space, i.e., the bunch length and the energy spread are exchanged to shorten the bunches to 4 ns, fitting then in the 5 ns long buckets in the SPS. At every bunch splitting, and close to the ultimate intensity, the transient beam loading causes a relative intensity errors of up to 20% (± 10%) in bunch intensity: the final intensity per bunch over the 72 bunches before extraction typically features a modulation as presented in Fig. 3. This effect creates a bunch intensity modulation in the LHC, but also decrease the transfer efficiency in the SPS.

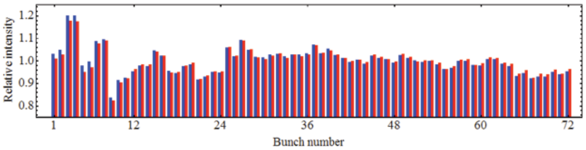

Figure 3: Bunch intensity along the batch for the 25 ns nominal LHC beam prior extractions averaged on ten cycles. The two colors indicate two different analysis techniques

A second deleterious effect is produced by a coupled-bunch instability observed during acceleration and flat top, which causes a degradation of the longitudinal emittance. It is important to notice that, as presented in [8], the SPS longitudinal acceptance sets very stringent limits around the nominal parameters, i.e., the bunches should not be longer than 4 ns and the emittance at 0.35 eVs, otherwise significant losses are observed in the SPS well beyond the few percents. To cure this kind of instabilities, new one-turn delay feed-backs will be studied and installed, not only for the 10 MHz RF cavities, but probably also for the 20 MHz, 40 MHz and 80 MHz cavities. Additionally, an improved coupled-bunch feedback with a dedicated kicker is going to be studied.

Table 3: Summary of RF-HW interventions for the different RF systems

Priority	**Item**	**When**
[1]	New coupled-bunch FB	2012
2	Dedicated kicker cavity	2015-20
10 MHz		
[1]	1-turn delay FB	2011
1	Renovate FB amplifiers	2011-15(?)
1	Slow ph. loops for each cavity	2013-14
2	New amplifier (1 tube/gap)	2014-18 (?)
20 MHz		
1	1-turn delay FB	2012
2	Slow ph. loops for each cavity	2012
40 MHz		
[1]	Automatic tuning system	2011
1	1-turn delay FB	2012
2	New FB amplifier in grooves	2014
2	Slow ph. loops for each cavity	2012
3	Study more voltage per cavity	2013
3	New power supplies	2014-(?)
80 MHz		
1	1-turn delay FB	2012
1	Automatic tuning system	2011-12
2	Slow ph. loops for each cavity	2012
2	New FB amplifier in grooves	2014
2	Fast ferrite tuner	2016
3	Study more voltage per cavity	2013
3	New power supplies	2014-(?)
3	Extra 80 MHz cavity	not scheduled

A preliminary list of interventions required to improve the current RF systems, considering or not the 2 GeV upgrade plus the interventions needed to increase the final intensity per bunch, can be found in Table 3, under the following assumptions: a) the years of completion are crudely estimated, some of the items may only be fully implemented beyond 2017; b) items with priorities in brackets indicate activities already ongoing before the upgrade studies started; c) the priorities may change according to the outcome of the studies proposed. A more complete and detailed review of the PS-upgrade related RF issues and possible cures can be found in [9].

ELECTRON CLOUD STUDIES

Electron cloud formation was observed in the past during transition crossing and during the bunch shortening and rotation on the 26 GeV/c flat top [10]: the current LHC beam production scheme with a fast phase rotation was decided to avoid transverse instability probably electron-cloud driven. In the most recent measurements, a net increase of the pressure was observed during the bunch shortening, with a clear correlation with the number of bunches present in the machine (see Fig. 4 [11]). Only on one occasion, in 2006, a beam instability was observed, spoiling the transverse emittance of the beam: this would happen if the bunch length of the 25 ns beam before the last phase rotation is shorter than 11-12 ns. Unfortunately it was not possible to prove that it was due to electron cloud. In 2011-2012, a new campaign of measurements and simulations will be done, since there is still no guarantee that electron cloud would not constitute an issue for the LHC-type beams for the upgrade.

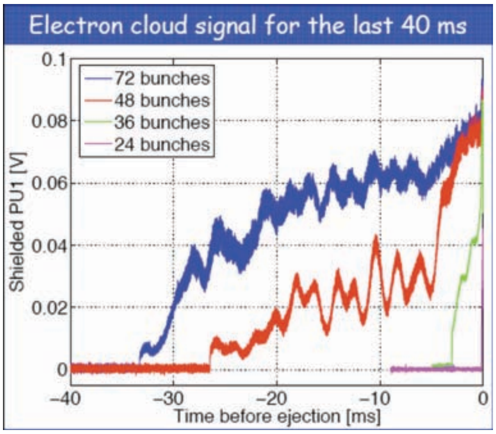

Figure 4: Electron-cloud signal measured by one of the detectors of the PS during the last 40 ms of an LHC cycle. Clearly, the signal increases with the number of bunches for a fixed 25 ns bunch spacing [11]

MDS FOR 2011

A first plan of MDs was elaborated to determine the machine limitations, both in terms of existing hardware and beam performances. A preliminary list is shown in Table 4:

The list of MDs appeared to be quite long, and most of the studies will start in 2011 and will continue in 2012, also to avoid interfering with the normal machine operation and the studies in the other injectors.

A list of priorities will be set up in the first part of the run, according also to a first revision of the beam dynamics studies that could constitute a limitation for the final performances, as presented in [12].

CONCLUSION

The injection energy increase to 2 GeV, together with the Linac4 injection in the PSB and a relevant upgrade of the PS RF systems, could lead to a maximum intensity delivered to the SPS up to 3.0 10^{11} ppb with an emittance of 2.5 μm rad (1 σ normalized) for the 25/50 ns (double batch, 72/36 bunches with 6 PSB rings) or smaller emittances could be produced at the price of the intensity per bunch for 25 ns bunch spacing. However, the intensity of 3.0 10^{11} ppb should be considered as the upper limit or the streched goal of the upgrade. A lower intensity of 2.0 10^{11} ppb will be considered as the baseline for the PS upgrade since the final machine performances, i.e., the maximum intensity per bunch will depend on how far the RF limitations could be finally pushed.

The 2 GeV injection will require a major upgrade of the injection elements, except probably the injection kicker if the non-LHC beam would operate at 1.4 GeV.

During the following years, a revision of the limit of the emittance blow-up due to the Laslett tune shift will be done to determine the maximum intensity at injection without causing a relevant transverse emittance increase.
A large number of studies is foreseen already for 2011, both as MDs as on the simulation side to better extrapolate the limits to the 2 GeV upgrade.

Non-LHC beam injection at 2 GeV was also analyzed, with some concerns about the eventual increase of the radiation levels in the ring.

Table 4: MDs proposed for 2011

Subject	**Goals**
Injection/matching studies	Improve inj. optics
Acceleration on h=7 at 2 GeV	Porch for longitudinal and transverse studies
HW limitations at 2 GeV	Orb. correctors trim quadrupoles
Working point using the PFW	Control chromaticity and WP at 2 GeV
RF manipulations at 2 GeV	Tests of first splitting
Emittance evolution on 2 GeV	Head-tail instability, Laslett tune shift
Shorter flat bottom	Double injection in less than 1.2 s
Transition crossing	TMCI related studies
e-cloud	Study electron cloud at 26 GeV/c
Longitudinal instability	Determine upgrade longit. beam quality
Optimum transfer to SPS	Study best longit. beam characteristics

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ELECTRON CLOUDS IN THE SPS: PROGRESS IN THE ANALYSIS OF CURES/MITIGATIONS MEASURES AND POTENTIAL SCHEDULE OF IMPLEMENTATION

J.M. Jimenez, CERN, Geneva, Switzerland

Abstract

After a brief review of the studies (simulations and measurements) made so far, a set of priorities for new studies will be presented and justified. These proposals will include all studies related to coating techniques, clearing electrodes, active feedbacks, together with their related instrumentation.

The feasibility, state-of-the-art, hard limits and open questions, required infrastructures, schedule implications, phasing feasibility of the proposed mitigation solutions will be considered in the framework of an upgrade of the SPS (i.e. without removing the beampipes from the magnets) and in the framework of combining the SPS upgrade with its required long-term consolidation (exchange of the magnet beampipes as an alternative). A tentative schedule of milestones in the decision making will be presented and discussed.

INTRODUCTION

Operating the SPS with high bunch intensity, up to 2.5×10^{11} p/bunch and small emittances (LHC requirements) at 25 ns bunch spacing cannot be guaranteed due to the following limitation of the electron cloud effect that have been identified: pressure rise (beam gas scattering, dose rates to tunnel and components) and beam instabilities (transverse emittance blow-up and single bunch vertical instability). This statement is confirmed by many studies and Machine Developments (MD) carried out in the framework of the SPS-U Study Group [1]. Indeed, these studies allow the identification and understanding of the potential limitations. Significant progresses have been made on the effects of beams and beam scrubbing and other mitigation solutions mainly amorphous carbon a-C studied in the SPS.

This talk is a summary of the views of the author and meant for a recommendation to the Project Leader. For detailed results and pictures, please refer to presentations given during the LIU Day [2].

REVIEW OF THE STUDIES MADE SO FAR

Beam Scrubbing

Beam scrubbing is successfully used since 1999 to reduce the electron cloud activity in the SPS but complete suppression was never achieved except in field free regions. Even after a dedicated week of beam scrubbing, residual electron cloud activity remains in the bending sections.

This result illustrates the fact that the beam scrubbing is a mitigation solution and not a suppressing method. Indeed, beam scrubbing has intrinsic limitations. Decreasing the secondary electron yield (SEY, δ) needs larger electron bombardment doses (log behaviour); the closer we operate to the threshold for a given bunch population the lower will be the electron bombardment thus the electron doserate.

Since the electron cloud is a threshold phenomenon with a build-up varying with the bunch train length, the use of higher bunch populations and smaller bunch spacing during the scrubbing runs is the optimum choice. The scrubbing will then allow running at lower bunch population and larger bunch spacing. Indeed, the scrubbing is most efficient when we operate subsequently with a lower bunch intensity taking profit from threshold effect, resulting in the avalanche no longer building up.

Coatings

The coating techniques i.e. diode and magnetron sputtering are mastered techniques at CERN. Amorphous carbon (a-C) (Fig.1) has been selected since it provides a low SEY (<1.1) (Fig.2) and is only slightly affected by venting to atmosphere. In addition, it does not require any activation (bake-out) to provide such a low SEY.

Right from the beginning, two options have been considered:

- Coating the beampipes in-situ, i.e. without removing the beampipes from the magnets. The use of the dipole field of the magnet itself to enhance the glow discharge used for the sputtering has been tested with limited success, the coating being inhomogeneous.
  Using an internal magnetron sputtering looks more promising since tested successfully in a 50 cm beampipe mock-up with identical shape. The tooling is being prepared to coat a 2 m dipole chamber by March’11.
- Coating the beampipe prior to their installation in the magnets. This option is the easiest and preferred solution from the coating point of view. Indeed, it will allow using the magnetron sputtering facilities developed and successfully used for the non-evaporable getter (NEG) coatings of the long straight sections of the LHC, where more than 1250 beampipes were coated.
  This option ensures the homogeneity (Fig.1) of the coating but implies to open the magnets to install the new coated beampipe.

The efficiency of the coatings and their behaviour in terms of deterioration of the SEY upon venting and long time aging in the machine need still more investigations for validation. The present results and limitations are the following:

- The ECM (e-cloud monitors) in the SPS show effective mitigation of the e-cloud even for coatings exposed to the machine operation during 2 years and vented for more than 2 months in between [2]. However, for the coatings in the main machine dipoles (4 prototypes) the diagnostics available in the SPS accelerator allow only indirect measurements through pressure readings. Some of the experiments carried out [2] were not always very conclusive, pointing out the risk of artifacts while using the existing pressure sensors as diagnostics.
- The static outgassing of the coating per surface area is larger than for stainless steel, but this disadvantage can be mitigated by coating only the portion of the pipe which is relevant for e-cloud.
- The quality and especially the adhesion of the coating is strongly dependant from the efficiency of the surface preparation (cleaning). Obviously, this is easier to solve with new beampipes. It becomes an issue if the beampipes have to be cleaned once installed in the magnets. The radiation issues, identified as a potential show stopper, have been studied and preliminary measurements are promising. After cleaning the beampipes of 15 magnets coming from the SPS tunnel, no activation of the liquids used for the cleaning and rinsing have been measured.
- The lower deposition rate imposed by the maximum temperature allowed in the magnet (insulation of the coils, 120°C) during the in-situ coating has to be taken into account but is not a major issue.
- The ageing and peel-off is of concern and has been studied with particle counter measurements and by visual inspection of the samples installed in the electron cloud monitors for 2 years in the SPS. No sign of peel off has been observed (Fig.3). No dust is coming out from the samples, even though exposed to electron bombardment and radiation doses.
- Simulations are needed to identify the maximum length acceptable without coating, as it will be very difficult to coat all exposed surfaces of the beampipes. The feasibility of the coating of the short straight sections is a concern and need to be studied. In addition, removing the quadrupoles from their place in the tunnel will lead to a new machine since these magnets will not come back to the same place. Another issue is the expected radiation dose to the personnel which can prevent the coatings from being acceptable.

The required infrastructures and tooling depend strongly on the option selected: coating of the existing beampipe in magnets or coating of new beampipes. On one hand, doing these operations at the surface in optimized infrastructures has many advantages. So far, no building has been identified and building a new one is not compatible in term of schedule and costs. On the other hand, this solution has the disadvantage of too many transports which will increase the duration of the activities. An alternative is to reuse the SPS ECX5 cavern, an option successfully used for the consolidation of the cooling circuits of the SPS magnets. The final choice will impact significantly the schedule. If the option of coating in-situ is retained, the transport of the magnets will dominate the schedule; the opening and closing of the magnets will dominate for the second option i.e. new beampipes. The second solution is also more difficult to do in the ECX5 cavern due to the limited space available. Both options can be considered in a staged approach, however, the use of the ECX5 cavern will imply the dismounting and re-commissioning of the tooling since the set-up cannot stay in the cavern during the operation with beams. This staged approach can only be considered if the shutdown durations are at least 4 months, and 3 shutdowns will be required to complete the work.

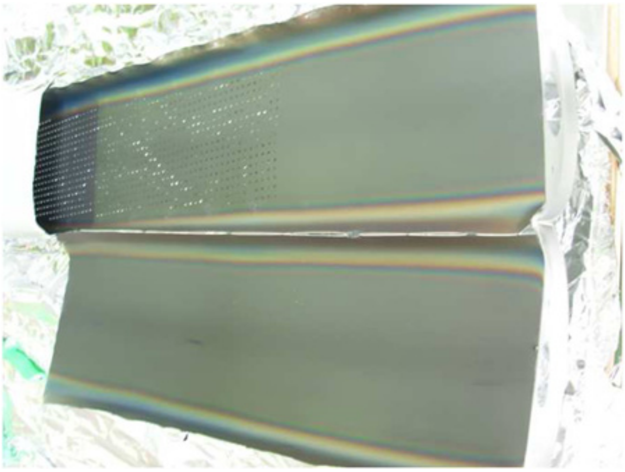

Fig.1: Picture of an SPS dipole chamber coated with amorphous carbon (a-C).

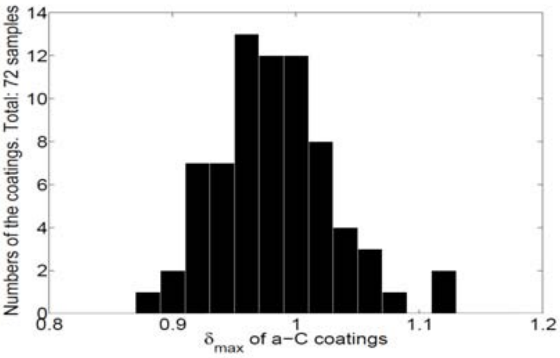

Fig.2: Distribution of SEY measured on various samples coated with amorphous carbon (a-C).

Fig.3:

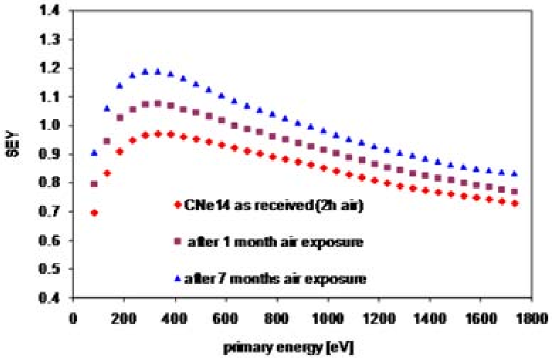

Fig.3: Measured SEY ageing of a stainless steel sample coated with amorphous carbon (a-C) installed in an electron cloud monitor.

Clearing electrodes

Clearing electrodes have been used successfully in the past in particle accelerators. In the SPS, the clearing electrodes shall be placed vertically to take into account the trapping of the electrons spiraling along the dipole field lines. The feasibility study has not been pushed forward since resulting in a aperture restriction (~1 mm in total) and due to impedance issues. The clearing electrodes have been validated at low magnetic field in the PS ring [3,4] but undoubtedly, the studies are much less advanced than with coatings. Some issues are still pending:

- Required clearing voltage which should be compatible with all energies and beam configurations.
- Cost and maintenance of the cabling and required power supplies and their long term reliability (active system with feedthroughs exposed to corrosion risks) still need to be evaluated.
- The difficulty to equip the quadrupoles and short straight sections could also be an issue since they represent about 15% of the total length of the ring.
- Engineering issues are more challenging compared to the coating. Indeed, equipping the new chambers will result in a significant increase in cost since mechanical tolerances for manufacturing (twist and straightness) shall be significantly decreased as compared to existing beampipes.

The infrastructures and tooling required are comparable in size and building surface with the one needed for the coating solution. This is not the case for the skills of the technicians doing the work: mechanics and welders for the clearing electrodes, plasma discharge experts for the coatings. Retrofitting the clearing electrodes in the existing dipole chambers will require development of complex tooling and a long development and optimization time, at least 2 years.

Feedback system

The feasibility study of a high bandwidth feedback system has been started in the framework of LARP. This system will require a new pick-up, a new kicker, high speed digitization and digital treatment as well as power amplifiers.

The new pick-up is a long strip lines pick-up, at least 1.5 m. The complex design resulting from the required accuracy and 50 Ohm impedance is technically challenging but feasible.

The new kicker has also a complex design but is technically feasible. The electromagnetic simulations could be delegated to L. Berkeley Laboratory in the framework of the LARP collaboration.

The high speed digitization and digital treatment required for the high bandwidth are a technical challenge. The prototype system being developed in the framework of LARP, will only be able to treat a small number of bunches.

The high bandwidth feedback system will be a useful diagnostic tool which would certainly help to cure electron cloud induced coherent effects. But, this system will not help when the emittance growth is dominated by incoherent effects which cannot be damped. A concern exists also on the potentially high power required to correct effects on all bunches due to the fast growth rates. At this stage of the studies, the following points are challenging but not thought to be “showstoppers”:

- Adjustment of the loop delay will be very delicate for the high frequency high bandwidth system (GHz)
- Mix-up with longitudinal motion is possible if bunches not are stable longitudinally
- Suppression of common mode signal crucial to avoid amplifier saturation and to allow good usage of the dynamic range available
- It could be required to split the system into several bands in order to be able to cover the entire frequency range

The new high bandwidth feedback system will require modifications of the layout, pulling of additional cables and local shielding against radiation in the tunnel to house electronics and amplifiers. The preferred location is in BA3 (dispersion suppressor) since it is close to the low level RF equipment, an advantage as the required RF signals for digitization and synchronization are readily available. Alternatively, BA5 can be used but will require pulling optical fiber cables for transmission of the RF (clock and synchronization) signals.

The proposed schedule foresees the modification of the layout and the installation of new cables during the 2011-12 winter technical stop for the demonstrator. Following its validation which is expected to be completed by end of 2013, the go-head for the final version could be given. Then, the new electronics will become available two years after the complete validation with the demonstrator (2014-15). The final system needs the installation of the new pick-up and a new kicker. These systems could also be ready by end 2013. The layout modification and cabling could be advanced to the winter technical stop in 2012.

PROPOSED MILESTONES

The schedule to be followed in order to be ready for the installation in 2016 is challenging.

By end of September 2011, the following milestones have to be fulfilled:

- Feasibility studies on clearing electrodes,
- Industrialisation of a-C coatings,
- Enhancement of electron cloud for scrubbing purposes,
- Development of additional electron cloud diagnostics,
- SPS MD measurements to validate efficiency of proposed solutions

Then, by end of December 2011, the preparation of a prototype section of 1 or 2 a-C coated half-cells has to be completed in order to allow the installation during the winter technical stop 2011-12. Special efforts shall be made to have all diagnostics available on due time.

By end of September 2012, it will be time to proceed to a complete evaluation. Waiting for Chamonix will not be an option since it would be too late for the preparation of the winter technical stop 2012-13. The aim is to install a pilot sector of about half an arc (~450 m).

The final decision shall be made end of 2016 for a complete implementation in the long shutdown of 2017-2018.

CLOSING REMARKS

Questions still to be answered

Despite the huge work carried out in the framework of the SPS-U Study Group, questions still need to be answered.

The clearing electrodes, an electron suppression method, cannot be pushed forward without looking into details of the impact on aperture, impedance and lifetime. The technical solution, full-scale feasibility, in particular for the quadrupoles and short straight sections, as well as the cabling and powering must be studied.

The coating with amorphous carbon (a-C), an electron mitigation solution, is much more advanced since it is at the industrialisation stage. Still, the lifetime, stability with venting, outgassing rates, in-situ coating and coating of the short straight sections, in particular of the quadrupoles, need to be validated.

The scrubbing run is also a mitigation solution but its efficiency for higher bunch populations i.e. more than 1.7×10^{11} protons per bunch still need to be validated. Machine development (MD) time are required for this validation.

The use of a bandwidth feedback system to cure the effects of the electron cloud on the beams is pending until positive results from the demonstrator with high speed digitization and digital treatment are available.

Finally, as stated earlier, simulations are needed to provide the electron cloud budget, the stability expected, the emittance growth, the impedance from electrodes and the effectiveness of a high bandwidth feedback.

Priorities versus Resources

At this stage of the project and considering the need to start validating the proposed solutions already during the next winter technical stop, the efforts devoted to the different proposed solutions will need to be reconsidered.

The status of the mitigation solutions (scrubbing and coatings) is satisfactory. The scrubbing run is scheduled and MDs have been requested. In addition, the LHC scrubbing run will also provide valuable information. The studies on coatings are progressing well; new approaches have been tested recently showing very promising results from the “industrialization” point of view. However, their validation with beams needs certainly strengthening of the efforts on diagnostics.

The feedback systems can be on track with reasonable efforts. Indeed, the collaborations in the framework of LARP will help for the electronics and simulations as the engineering and manufacturing can be internalized.

The situation of the clearing electrodes is more uncertain since running “out-of-phase” as compared to the other ongoing studies. The resources to be allocated to achieve a status which could allow a decision making are still reasonable in theory, but in practice, where to find them? Then, going for industrialization of the clearing electrodes is another challenge.

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LESSONS FROM SPS STUDIES IN 2010

E. Shaposhnikova, CERN, Geneva, Switzerland

Abstract

The experimental studies done in the SPS in 2010 were devoted both to a validation of some already proposed upgrades (as chamber coating) and to uncovering new limitations by pushing up injected bunch intensity. The first results obtained for ultimate (injected) LHC beam with 25 ns and 50 ns bunch spacing, each beam available only during one MD session in the SPS, will be presented together with results for a single high intensity bunch. The limitations envisaged during these MD studies will be discussed together with other SPS bottlenecks. Possible cures and mitigation will be revisited. An option for improvement of beam stability in the SPS, opened again by successful demonstration of reduction of the SPS transition energy, will also be discussed. The potential for delivering small transverse emittances now and after upgrades will be analysed. An attempt will be made at summarizing the accessible range of beam parameters (intensity per bunch as a function of distance between bunches and emittance).

REVIEW OF 2010 MD STUDIES

Since a few years the SPS is able to deliver at top energy up to four batches of LHC bunches spaced at 25 ns, 50 ns or 75 ns with bunch intensity of 1.2×10^{11} and nominal longitudinal (0.6 eVs) and transverse (3.5 μ m) emittances. These beams suffer from various limitations which, together with their cures, were studied by the SPSU Study Group [1] with a help of operation teams. Already at the end of 2010 the 50 ns and 75 ns spaced beams from MD-type became operational and were regularly taken by LHC. An overview of dedicated MD sessions available for studies with LHC-type beams is given in Table 1.

The main part of experimental studies in the SPS in 2010 was devoted to a validation of some already proposed SPS upgrades [2]. One of them is amorphous carbon (a-C) coating of the vacuum chamber [3] as a mitigation measure against e-cloud effect, the main limitation for a 25 ns spaced beam.

Another important studies were done with ultimate (1.8×10^{11}) bunch intensities, available for the first time this year from the SPS injectors [4] both in a single bunch and in bunch trains. Even twice higher than ultimate intensity was available for single bunches. All single bunch studies were performed during year using parallel MD cycles. The same is true for MD studies of a new optics with a low transition energy [5].

The most important results of these MD sessions are presented below with exception to those concerning e-cloud, which are reviewed in [6]. Due to different LHC upgrade scenarios based on smaller than nominal transverse emittances [7]-[9], special attention is paid to the transverse emittance measurements with purpose of estimating the potential for delivering small transverse emittances now and after upgrades.

W	date	bunch spac.	N_{max}^{inj}	comment
17	27-29.04	25 ns	nom.	“scrubbing” run ded. SC, low loss
22	02-03.06	25 ns	ult.	36 h, ded. SC
29	20-21.07	25 ns	nom.	almost lost
35	03-04.09	50 ns 25 ns	ult. nom.	8 h, 4 batches
42	19-20.10	25 ns 50 ns	nom. nom.	36-72 bunches ded. SC
45	09.11	50 ns	nom.	floating
46	17-18.11	75 ns	nom.	

Table 1: Overview of MD studies with LHC beams in the SPS in 2011, some of then done in dedicated supercycle (ded. SC).

SINGLE BUNCH

Main subjects of different MD sessions in the SPS in 2010 were related to known intensity and beam quality limitations. For a single bunch these limitations are from TMCI (Transverse Mode Coupling Instability), loss of Landau damping, space charge effect and longitudinal instability.

Studies of single high intensity bunches in the SPS were done using two different MD cycles - MD1 cycle with 4 s flat bottom, no acceleration and LHCFast cycle with short flat bottom (60 ms) and acceleration to 450 GeV/c.

TMCI has been observed in the SPS for proton bunches with small longitudinal emittances [10]. Last year the TMC instability threshold was measured [11] for a single bunch with longitudinal parameters close to those of the nominal LHC beam (emittance of 0.31 eVs and 4σ bunch length 3.6 ns). The threshold of 1.6×10^{11}, found for vertical chromaticity $\xi_v \sim 0$, is very close to the prediction obtained from simulations with the SPS impedance model [12]. Up to 6% particle losses were observed for injected intensities of 1.8×10^{11} and practically no loss for an intensity of 1.4×10^{11}.

For a matched voltage the threshold intensity scales as $N_{th} \propto |\eta|\varepsilon$, where $\eta = 1/\gamma^2 - 1/\gamma_t^2$ and therefore has its minimum at injection (above transition, $\gamma_t = 22.8$).

Possible measures to push this potential limitation up in intensity are: increased vertical chromaticity, capture voltage or longitudinal emittance, wide-band transverse feedback and of course impedance reduction (after identification). The first three options above could lead to continuous particle loss on the long flat bottom. A feasibility study of active damping of the single bunch vertical instability using a wide-band feedback system [13] is under way in collaboration with LARP [14].

The new possibility which was seriously studied at the end of the last year is an increase in $|\eta|$ by reduction of transition energy. Indeed at 26 GeV/c the TMCI threshold is higher for $\gamma_t = 18$ than for nominal $\gamma_t = 22.8$ by a factor 2.86. The preliminary results are presented below in the separate section.

For intensities up to 2×10^{11} the transverse settings in the SPS were optimised and single bunch with ultimate intensity was accelerated to 450 GeV/s with low loss and low chromaticity. Even much higher than ultimate bunch intensities, up to 3.5×10^{11}, were prepared in the PS complex and injected into the SPS. To reduce losses it was necessary to follow an increase in bunch intensity by an increase in the vertical chromaticity.

The effect of a high harmonic (800 MHz) RF system on the TMCI threshold has been also studied both in MDs and by simulations [11] but results are not yet conclusive.

More problems (losses) were observed with smaller injected emittances. It was necessary to blow-up, initially very small, injected transverse emittances in the PS (1.5 μm) in order to reduce their blow-up and particle losses in the SPS. Note that from theory and simulations a higher TMCI threshold is expected for smaller transverse emittances. Vertical and horizontal emittances measured at 26 GeV/s in the SPS during different MDs ([11], [15] and OP shifts) for various bunch intensities are plotted in Fig. 1. These measurements were performed with the 200 MHz RF voltage in the range (1.8-2.0) MV, $\xi_h = 0.25$ and ξ_v increasing with intensity from 0 to 0.3. The 800 MHz RF system was off.

Measurement point at the lowest intensity (corresponds to the 50 ns spaced LHC beam with a very small transverse emittance (produced with the double batch injection scheme in the PS in 2008) and nominal bunch intensities, shown on these plots for comparison with single bunch data.

A linear fit to the dependence of the vertical and horizontal emittances (data shown with red circles) on bunch intensity has correspondingly following form

$$\begin{aligned} \varepsilon_H &= -1.14 + 2.22N/10^{11}, \qquad (1) \\ \varepsilon_V &= -1.03 + 2.17N/10^{11} \qquad (2) \end{aligned}$$

As one can see, these fits (shown in Fig. 1 with a dashed line) don't go through the origin and therefore most probably describe emittance blow-up additional to the effect of space charge which in simplified case would be proportional to the brightness $N_b/\varepsilon_{H,V}$. More accurate measurements are planned in 2011.

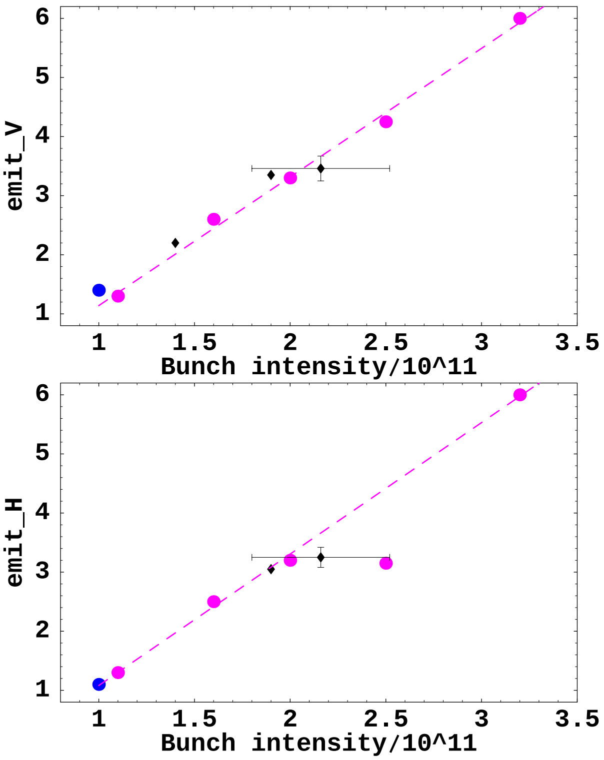

Figure 1: Vertical (top) and horizontal (bottom) normalised emittances measured at 26 GeV/s in the SPS for different bunch intensities together with linear fit (dashed line) to some data (big circles).

As for all other transverse emittance measurements presented below, these data were obtained from one wire scanner (WS) acquisition per cycle (due to a difference between ”in” and ”out” movement of the WS) with the first point (possible) at 10 ms after injection. In case of many bunches in the ring, average for all bunches is presented. Various improvements are foreseen by BE/BI Group for 2011 (e. g. the second, linear, WS with possibility to gate acquisition over 50-100 ns) [17]. Another problem with beam instrumentation for very high intensities (MOPOS) was solved towards the end of the 2010 run.

LHC BEAMS

Multi-bunch limitations

MD studies with nominal multi-bunch beams were also first of all connected with known intensity limitations. The e-cloud, generated by the presence of many bunches in the ring, is at the origin of the single bunch vertical instability and horizontal coupled-bunch instability (cured by existing transverse damper). Other multi-bunch limitations are beam losses, longitudinal coupled-bunch instabilities, beam loading in the 200 MHz and 800 MHz RF systems as well as heating of different machine elements (e.g. MKE and MKDV kickers) and vacuum issues (beam dump, MKDV and MKDH outgassing, ZS septum sparking).

Most of the MD time with nominal LHC beams in 2010 was devoted to e-cloud studies, the results are presented in [6]. A summary of MD sessions available in 2010 is given in Table 1.

After intensive studies during first MDs in 2010 the settings on ZS kickers have been changed and limitation due to its sparking and outgassing have been removed [18].

The longitudinal coupled-bunch instability of the LHC beam in the SPS is characterised by a very low intensity threshold. Indeed a single LHC batch with 2×10^{10} p/bunch becomes unstable during acceleration at ~ 250 GeV/c.

To stabilise the beam controlled emittance blow-up is performed twice during the cycle, in addition to the use of the 800 MHz RF system as a Landau cavity in bunch-shortening mode throughout the cycle. The 800 MHz voltage during the cycle usually follows the 200 MHz voltage program at 1/10 level. The first blow-up is with mismatched voltage at injection. During the second one, above 200 GeV/c, the emittance is increased to 0.6 eVs. The emittance blow-up in a double RF system has its own limitations due to the presence of beam loading [24].

Ultimate intensities

25 ns beam As one can see from Table 1, there were two MD sessions in 2011 with LHC type beams having ultimate injected bunch intensity, first with beam spaced at 25 ns and then later with a 50 ns beam.

During the first MD in week 22 maximum intensity injected into the SPS was 1.88×10^{11}/bunch, longitudinal emittance was 0.38-0.4 eVs and transverse emittance $\varepsilon_{H/V} = 4.5/5$ μm. Transverse emittance blow-up to $\sim 10\mu$m (larger in H-plane and for more batches in the ring) was measured at 450 GeV/c (with $\xi_{H/V} = 0.2/0.3$). A large variation in bunch length across the batch was observed both for the injected beam and on the flat top. Bunch length on the flat top was 1.6 ns (average over the batch) and 1.8 ns maximum. During this high intensity operations some issues with MOPOS and FBCT were seen. Maximum bunch intensity achieved at 450 GeV is 1.6×10^{11}/bunch for one batch in the ring. Increasing the number of batches led to a decrease in bunch intensity on the flat top with approximately 1.5×10^{11}/bunch for 3 batches in the ring, see Fig. 2 (top).

Already 12 bunches were unstable longitudinally on the flat bottom even with the 800 MHz on. During this MD particle loss (flat bottom plus capture) reduced from 30% at the beginning of the MD to 20% at the end, probably due to scrubbing of the ring by the e-cloud. However no direct e-cloud observations were possible due to absence of the reference StSt liner. Capture losses were reduced after modification of the 200 MHz RF voltage program (from a 0.65 eVs constant bucket area to a 0.75 eVs bucket) through the cycle.

During this MD the temperature and pressure increase in the many special magnets became critical [20] aggravated by the fact that SPS supercycle consisted only of the LHC cycle (no other users). It was necessary to reduce RF voltage on the flat top from 7.2 MV to 5.5 MV, limit maximum number of batches in the ring to 3 and to stop the beam 3 times to permit cool-down of the MKE4. The MKE6 magnet (with serigraphy) had very high outgassing (maximum pressure of 9×10^{-7}) but conditioning effect has been observed as well. The MKPs suffered from the outgassing in TIDVG (situated nearby) during beam dumps. It is planned to shorten the period of the installation of 5 serigraphed MKE4 magnets from 3 to 2 shutdowns [20]. The SEY of the silver paint and ferrite should be measured to study the reasons for outgassing of the MKE6. Transverse and longitudinal impedances of the MKP have been measured as well.

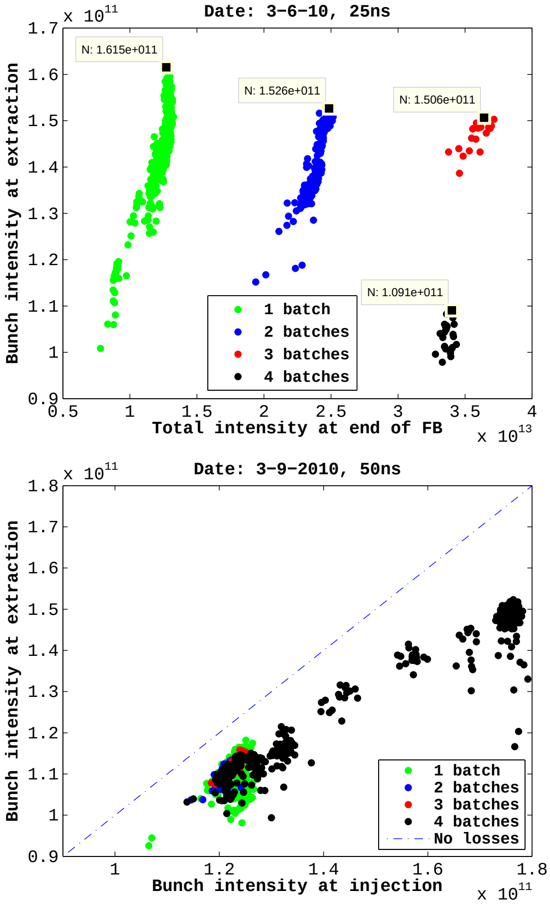

Figure 2: Bunch intensity at 450 GeV/c as a function of injected intensity for different number of batches in the ring during MD W22 with a 25 ns beam (top figure) and MD W35 with a 50 ns beam (bottom) [19].

50 ns beam Only 8 hours at the end of the MD block were available for this MD, performed also in parallel with LHC setting-up with another type of the beam (150 ns spaced) - the experience to be avoided in future MD planning [21].

Maximum intensity injected into the SPS was 1.8×10^{11}/bunch in 4 batches of 36 bunches. Maximum bunch intensity achieved on the flat top was 1.5×10^{11} with losses increasing with bunch intensity and reaching 15% for the injected ultimate intensity, see Fig. 2 (bottom). Measured in the SPS at 26 GeV/c transverse emittances were $\varepsilon_{H/V} = 3.2/3.9\ \mu$m. Nominal voltage program was used during this MD. Initially relatively small chromaticities were increased but this did not have any effect on losses. Obviously more time for optimisation needed in 2011.

The e-cloud signal for a 50 ns beam, being at least factor 10 smaller than for 25 ns spaced beam (for the same bunch intensity and twice smaller total), was nevertheless slightly growing with bunch intensity above nominal [22].

Nominal LHC beam

Already during the first MD in 2010 (scrubbing run) reduction of losses to 5% (from previous minimum value of 7%) was obtained for a 25 ns spaced beam with much smaller than in the past chromaticities [28]. One possible explanation is related to short shutdowns during last two years and as a result much smaller venting of the SPS vacuum chamber. Indeed, the effects caused by the presence of the electron cloud are considered at the moment to be the most important intensity limitations for this beam. They lead to transverse emittance blow-up and instabilities. They could also be at the origin of beam losses. Note that careful low-level RF setting-up was also absolutely essential.

On a few occasions, Table 1, nominal 50 ns and 25 ns beams were studied using the dedicated MD cycle in the SPS (as in week 42). After some time during this type of MD, even with a single batch with a 50 ns spacing, this led to a problem with the MKE magnets heating.

Summary of beam parameters achieved in the SPS in 2010 both for nominal and ultimate (injected) beams is presented in Table 2.

parameter		LHC nominal			LHC ultimate		
spac.	ns	25	50	75	25	50	ind.
N_b	10^{11}	1.2	1.2	1.2	1.5	1.5	3.2
n_b		288	144	96	216	144	1
N_{tot}	10^{13}	3.5	1.7	1.2	3.2	2.2	0.03
ε_L	eVs	0.7	0.5	0.5	0.8	0.6	0.4
$\varepsilon_{h/v}$	μm	3.6	2.0	2.0	10		6.0

Table 2: Beam parameters achieved at 450 GeV in 2010 for nominal and ultimate injected intensities.

Transverse emittances Majority of MD sessions in 2010, see Table 1, were devoted to studies with nominal LHC beams with different bunch spacings. The collection of transverse emittance measurements done during these MD sessions by different people ([15], operation team and others) is shown in Fig. 3.

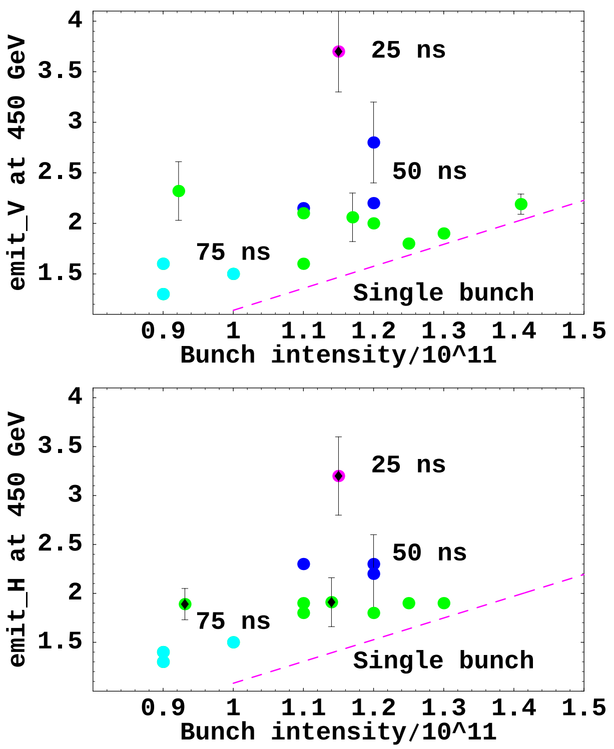

Figure 3: Vertical (top) and horizontal (bottom) normalised emittances measured at 26 GeV/s in the SPS for different bunch spacings and bunch intensities together with the fit (2) from single bunch data. The 200 MHz RF voltage was 2.0 MV, $\xi_h = 0.25$, $\xi_v = 0.3$. Low intensity points for a 75 ns beam were measured with 8 bunches per batch.

Transverse emittances of beams with 75, 50 and 25 ns bunch spacings measured in 2010 at various intensities are very different, with maximum emittances for a 25 ns beam and a 75 ns beam being close to the single bunch limit (2). These values are also often determined by injectors. Indeed injected emittances for 50 and 75 ns beams were higher than in the past (with double batch injection in the PS). No transverse emittance blow-up was observed at the end of the cycle for a 50 ns beam (2.5 μm at extraction) while for a 25 ns beam with the same number of bunches per batch (36) the measured vertical emittance grew with the number of batches reaching a value of 3.7±0.9 μm for 4 batches [15]. The blow-up of a 25 ns beam is most probably due to the e-cloud effect. The horizontal emittance was around 3.5 μm. Bunch-by-bunch emittance measurements with higher accuracy are required to investigate the origin of the observed emittance blow-up.

Longitudinal emittance The necessity of the longitudinal emittance blow-up for a 50 ns spaced beam was analysed. Stability of a 50 ns beam with the 800 MHz RF on in bunch-shortening mode seems to strongly depend on injected bunch length (emittance), Fig. 4. For the nominal voltage program the beam was unstable on the flat top for an injected bunch length below 3.5 ns (probably also more unstable towards the batch tail). This effect could be observed even locally, when only a few bunches had a smaller bunch length (emittance) at injection. On the other hand transmission in the SPS decreases from 95 % to 88 % when the injected emittance is increased from 0.33 eVs to 0.5 eVs due to the corresponding increase in bunch length [25]. In this case controlled emittance blow-up during the ramp is required for stability on the flat top. These observations could be an indication of the loss of Landau damping due to the reactive impedance of the SPS [2].

Note that in 2008 for a 50 ns spaced beam the nominal bunch intensity (1.1×10^{11}) was achieved at 450 GeV/c with very small longitudinal (0.4 eVs) and transverse (1.2&1.5 μm) emittances [26]. This beam was stable on the SPS flat top without the controlled emittance blow-up required in 2010.

LOW TRANSITION ENERGY OPTICS

The decrease in transition gamma from 22.8 to 18 was proposed and achieved by lowering the present tunes (26.13 and 26.18) by 6 units [5]. Maximum dispersion is also increased from 4.8 m to 9 m. For a low transition energy the expected increase in TMC and longitudinal coupled bunch instability threshold is proportional to the factor η. However for the same longitudinal parameters the voltage also scales as η which could prove to be a limitation for fast cycles and beam transfer to LHC.

The new optics was confirmed during many MD sessions by measuring the optics functions and the synchrotron frequency from the quadrupole oscillations [27]. Chromaticity was also measured and calibrated. No signature of the TMCI was observed for injected single bunches with intensities in the range $(2.7 - 3.3) \times 10^{11}$. Initially the voltage on the flat bottom was too low (1.8 MV) and this led to continuous particle loss $\sim$ 10 %. No transverse emittance blow-up could be measured on the flat bottom for bunches with $\varepsilon_{\mathrm{H/V}} = 2.0/2.3$ μm at 2.6×10^{11} and $\varepsilon_{\mathrm{H/V}} = 2.5/2.7$ μm at 3.3×10^{11}. With limited time for optimisation, single bunch was accelerated to 450 GeV/s using the LHCfast3 cycle. For an intensity of 2.6×10^{11} on the flat top emittances were $\varepsilon_{\mathrm{H/V}} = 2.4/2.9$ μm. The next important step will be to inject bunch trains to study multi-bunch effects, in particular e-cloud effects and longitudinal coupled-bunch instability during the ramp.

For the same bunch intensity transverse emittances measured during MDs with low transition energy are significantly smaller than those with nominal optics, Fig. 5 (top).

This could be explained by the increase in beam stability and an absence of emittance blow-up related to the effect of transverse impedance below the TMCI threshold. However, in order to evaluate space-charge limit, the measured points should be scaled down in intensity due to 10% losses and also longer bunches at the too low voltage of 1.8 MV (the same as with nominal optics), Fig. 5 (bottom). After scaling by 30% down in intensity these emittances (together with low intensity point at nominal optics) have a linear fit $\varepsilon_V = 1.4(N/10^{11})$, which goes through the origin and corresponds to a space charge limit of 0.13. For the nominal LHC bunch at 26 GeV/c the space-charge tune spread ΔQ_{sc} is 0.05 [28]. The tolerable limit for the space-charge tune spread in the SPS from past experience (ppbar) was believed to be around 0.07, but much higher value has

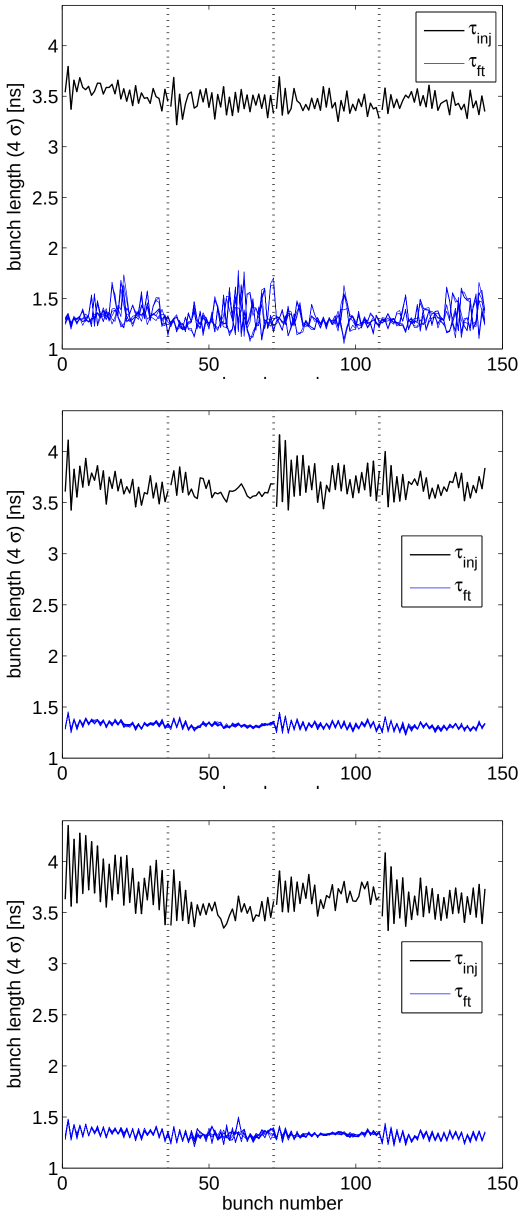

Figure 4: Bunch length at injection (upper trace) and on flat top (lower trace) for a 50 ns spaced beam with nominal bunch intensity and without controlled emittance blow-up [23]. The 800 MHz RF is on. Beam with small injected longitudinal emittance (top figure) is unstable on flat top and it is stable with larger emittances (middle). Bunches with small emittances can also become unstable locally (bottom).

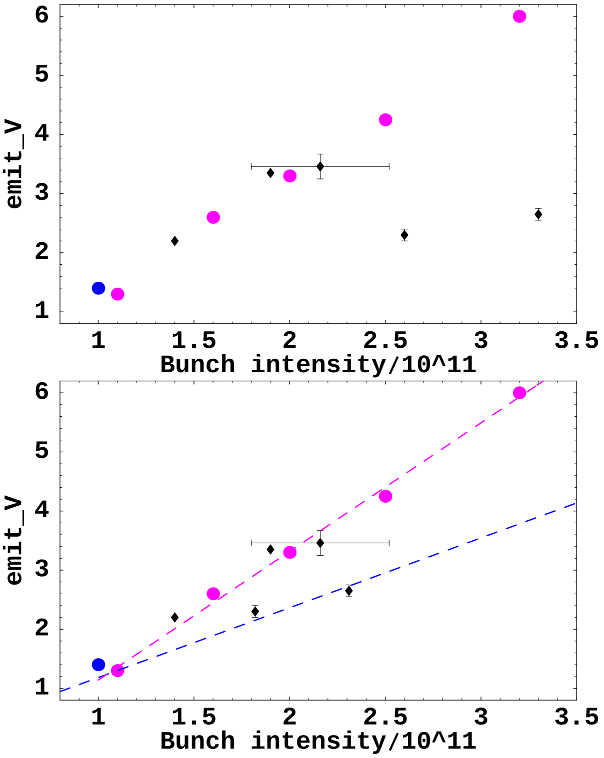

Figure 5: Top figure: vertical normalised emittances measured at 26 GeV/c in the SPS for nominal (as in Fig. 1) and low transition energy optics (two new points on the right). In bottom figure points for the low transition energy optics are scaled down in intensity and shown together with linear fits to both nominal and low γ_t data. The 200 MHz RF voltage was 2.0 MV, $\xi_h = 0.25$, $\xi_v = 0.3$.

been achieved for ions [29]. Accurate measurements with correct voltage and after working point optimisation will be done in 2011.

Note that in order to obtain the same longitudinal parameters the RF voltage during acceleration cycle should be increased $\propto \eta$, Fig. 6. Already maximum voltage (7.5 MV) is used now for extraction to LHC, but probably controlled emittance blow-up for the same intensity can also be reduced. Indeed the threshold for the loss of Landau damping $N_{th} \sim \varepsilon^2 \eta \tau$. Taking into account that bunch length scales as $\tau \sim (\varepsilon^2 \eta / V)^{1/4}$, with low γ_t optics one will need for stability smaller emittance $\varepsilon \sim \eta^{-1/2}$. Then this smaller emittance will give the same bunch length in the new optics as with the present optics.

For ultimate LHC intensities N_{ult} larger controlled emittance blow-up will be needed to stabilise the beam. To have the same bunch length at the larger emittance, which is $\propto \sqrt{N}$, one would need a voltage N_{ult}/N_{nom} times higher than the present 7.5 MV, which means 10.5 MV for the ultimate bunch intensity. It is also possible that for these high intensities larger longitudinal emittances are required at 450 GeV in LHC itself. Then beam transfer to the LHC 400 MHz RF system from the SPS 200 MHz RF system becomes critical.

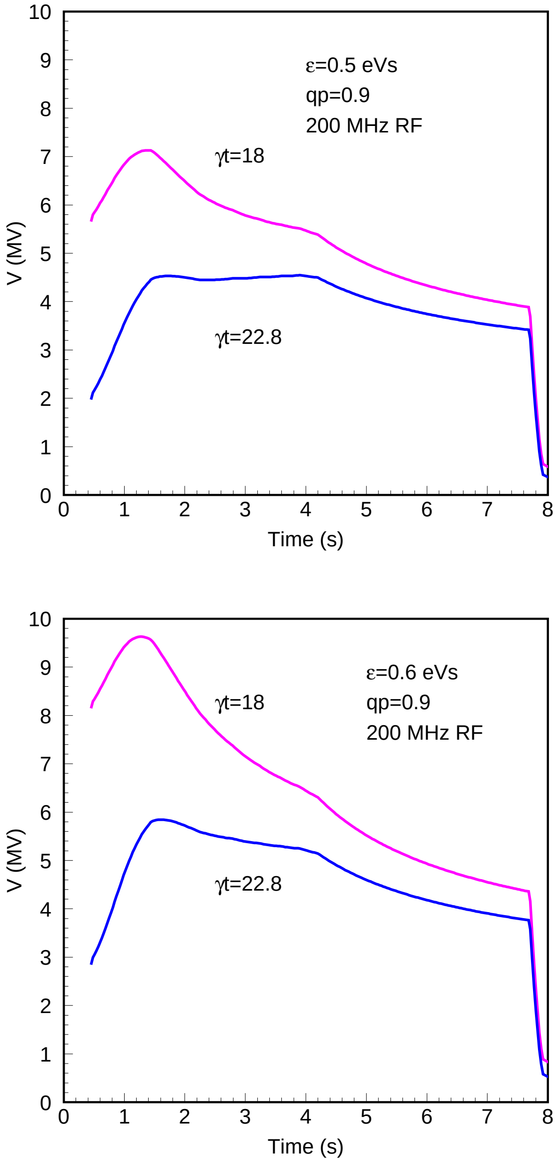

Figure 6: The 200 MHz RF voltage program required for a constant filling factor in momentum (0.9)i for two longitudinal emittance of 0.5 eVs (top) and 0.6 eVs (bottom) in nominal and low γ_t optics.

On the other hand, the existing two 5-section cavities can provide much less voltage at ultimate LHC current. A solution to this problem is to rearrange the existing 4 cavities (with 2 spare sections) into 6 cavities of shorter length with 2 extra power plants which allow simultaneously to reduce beam loading per cavity, increase available voltage and even reduce total beam coupling impedance, see [2] for more details.

The most critical question to answer in 2011 is what, smaller, emittance is required for longitudinal beam stability on the flat top in low γ_t optics.

SUMMARY

While the nominal 25 ns beam is in a good shape (low beam losses with low chromaticity), ultimate LHC beams need much more studies and optimisation. Due to large losses only a maximum bunch intensity of 1.5×10^{11} could be obtained on the flat top both for 50 ns and 25 ns spaced beams. A 25 ns beam also suffered from longitudinal instabilities on the flat bottom and large transverse emittance blow-up during the cycle.

The threshold of the TMCI was measured as a function of vertical chromaticity and was found to be at the ultimate intensity for zero chromaticity. More losses and blow-up were observed for small injected emittances.

Very promising results for beam stability and transverse emittance preservation were obtained with the low γ_t optics.

Analysis of available transverse emittance measurements done in 2010 allow to hope for a 3 μm emittance for the ultimate beam spaced at 50 and 75 ns already now, and with the 25 ns spacing after e-cloud mitigation. Even lower emittances, 2.5 μm, can probably be obtained now with the low γ_t optics for 50 and 75 ns ultimate beams if RF voltage (during the cycle and at transfer to LHC) turn out to not be a problem. After upgrades (e-cloud and impedance reduction) one can hope to be at the space charge limit (2.5 μm for ultimate intensity) for both 50 ns and 25 ns beams. These values are nevertheless very preliminary and should be carefully evaluated. For experimental studies one needs small PS beam and improved transverse emittance measurements in the SPS

The main SPS limitations for ultimate intensity have been identified. They are the e-cloud effect, beam loading in the 200 MHz RF system, transverse mode coupling (TMCI) and longitudinal coupled bunch instabilities. Hardware modifications needed for the SPS upgrade were summarised in [2] and reviewed by the SPSU Task Force (led by V. Mertens). Proposed measures to overcome the known limitations are now under study by the LIU-SPS in the frame of the LIU project [7]; they include e-cloud mitigation, impedance reduction and RF upgrade.

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ALTERNATIVE/COMPLEMENTARY POSSIBILITIES

C. Carli, M. Benedikt, H. Damerau, R. Garoby, B. Goddard, K. Hanke, S. Hancock, S. Gilardoni
CERN, Geneva, Switzerland

Abstract

Schemes aiming at increasing the brightness of LHC proton beams available from the PS complex by means alternative or complementary to the standard upgrade path defined after the 2010 Chamonix workshop, based on Linac4 and an upgrade of the PSB to PS transfer energy, are investigated. Compression of batches in the PS after acceleration to an appropriate intermediate energy allows increasing the beam brightness by reducing the length of the batch provided by the PS and thus distributing the available intensity to a smaller number of bunches. Furthermore a study of short Rapid Cycling Synchrotron (RCS) as new PS injector is proposed. The short circumference of one seventh of the PS is on the one hand suitable to reach high beam brightness required and for transfer to the PS. On the other hand the target kinetic energy of 2.0 GeV is a challenging goal.

INTRODUCTION

Present PS Scheme to generate LHC Bunch Trains

The procedure to generate LHC bunch trains in the PS, implemented about 10 years ago to avoid longitudinal microwave instabilities [1] during the initially envisaged debunching rebunching procedure at the flattop, is described in references [1,2,3].

Note that the only RF gymnastics applied are double and triple bunch splittings and transfers to higher harmonics RF systems (“rebucketing”) for bunch compression. No harmonic number changes modifying the bunch spacing (without splitting), i.e., batch compression or batch extension, are applied. Hence, the harmonic number of the PS must be a multiple of 7 already at injection.

Furthermore, this scheme does not make optimum use of the available four Booster rings: With single batch PSB to PS transfer, only three instead of the available four Booster rings provide each one two bunches. The situation is similar for double batch transfer where only six out of possible eight $h_{PSB} = 1$ bunches are used. An attempt to use all four Booster rings without batch compression (or extension) is described in [2] for operation with Linac4. The next possible harmonic number of the PS containing the factor 7 at injection is $h_{PS} = 14$*. Three bunches per PSB ring and usage of all four rings allows filling twelve out of 14 PS buckets with one transfer. However, a practical implementation is difficult since (i) the generation of three about equal bunches per Booster ring with an appropriate spacing requiring to superpose three RF harmonics and (ii) the required recombination kicker rise times are not compatible with the existing hardware. Operating the PS with even larger harmonic numbers at injection is ruled out due to PS Booster ejection and recombination kicker limitations. Thus, generation of LHC bunch trains without batch compression or extension and making optimum use of the available four Booster rings seems not feasible without expensive upgrades.

Scenarios presented

The scenarios presented are alternative or complementary to the standard LHC proton injector upgrade path defined as a result of the 2010 Chamonix workshop, comprising Linac4, an increase of the Booster to PS transfer energy and upgrades of PS and SPS. In particular, the following two schemes were studied:

- Batch compression in the PS after acceleration to an appropriate intermediate energy: the starting point for this proposal is the observation that a more efficient use of the four Booster rings is incompatible with RF gymnastics in the PS without batch compression (or extension). Introduction of further batch compression steps after acceleration to an intermediate energy allows further increasing beam brightness. Finally, the total intensity is distributed over a smaller number of bunches provided per PS cycle and thus the beam brightness, is increased.
- Study of a short Rapid Cycling Synchrotron (RCS) as new PS injector: An RCS with a circumference of one seventh of the PS is suitable to fill the PS for the generation of LHC bunch trains (without batch extension or extension). Critical aspects are whether such a machine can reach the target kinetic energy of 2.0 GeV, and provide the required brightness with the 160 MeV Linac4 as injector. Preliminary investigations on such an RCS are reported.

BATCH COMPRESSION IN THE PS

Motivation

Attempts to optimize the usage of the four available Booster rings without batch compression (or extension) did not result in an attractive scheme [2]. Thus, schemes with batch compression [4], i.e. RF gymnastics where the harmonic number in the PS is increased in small steps such that empty buckets are inserted and the spacing between bunches is reduced without splitting, are proposed. Additional batch compression steps further increase the beam brightness available from the PS:

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* Filling four out $h_{PS}=7$ PS buckets with one single transfer from the Booster, as proposed in another context [4], is ruled out here since the number of bunches is strongly reduced. Note that one of batch compression schemes described yields the same number of bunches per PS batch, but with significantly increased brightness.

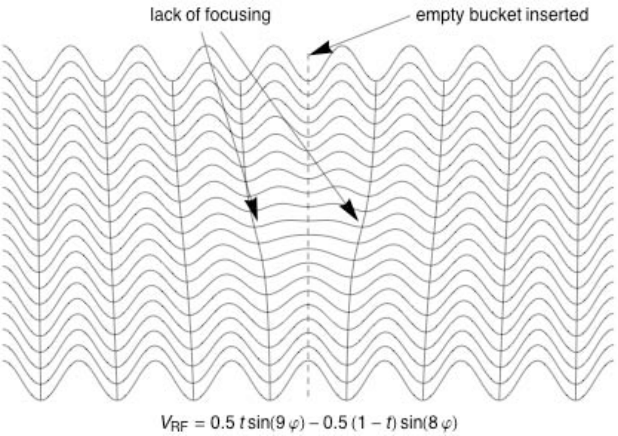
- At injection, as much of the PS circumference as possible is filled with beam to maximize the total intensity for given transverse emittances (most favourable bunching factor).
- After acceleration to an appropriate intermediate energy to reduce direct space charge effects, batch compression is applied to concentrate the available intensity in a fraction of the PS circumference. Hence, LHC bunch trains generated by the PS become shorter and the available intensity is distributed over a smaller number of bunches. The beam brightness is increased.

Even though batch compression schemes can be combined with a Booster energy upgrade, the working hypothesis underlying the schemes presented here is that the beam will be injected into the PS at 1.4 GeV. Eight bunches are injected into the PS to bring the machine close to the transverse direct space charge limit. For operation with Linac2, this is achieved by two PSB batches with one bunch generated per ring. With Linac4 one Booster to PS transfer with two bunches generated per ring will be sufficient[†].

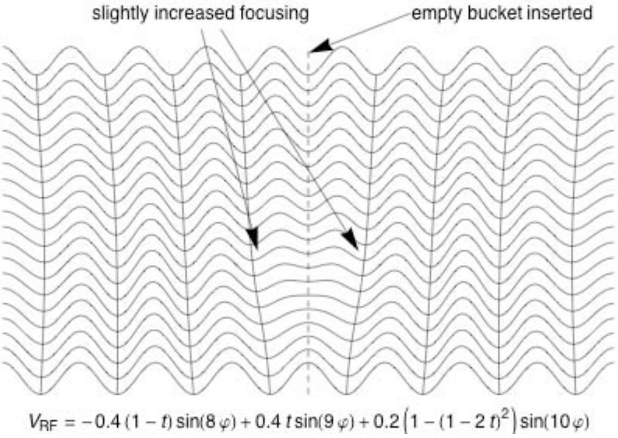
The batch compression schemes presented generate LHC bunch trains with 25 ns spacing. With 50 ns bunch spacings higher intensities (by a factor, which may be smaller than two) per bunch within the same transverse emittances are expected.

General Remarks on Batch Compression

The most favourable bunching factor is achieved by injecting the eight bunches into $h_{PS} = 8$ buckets. However, this is somewhat conflicting with the conditions for efficient batch compression working well with (i) a partially filled machine and (ii) for low harmonic numbers[‡]. The reason is visible in Fig. 1 showing the RF potential during the transition from a harmonic number 8 to 9 to insert an empty bucket at the center. A beating phenomenon is visible in the upper image of Fig. 1 showing the direct transition from $h_{PS} = 8$ (ramped down linearly) to $h_{PS} = 9$ (ramped up linearly) without additional RF components. Longitudinal focusing around stable phases close to location, where the additional empty bucket is inserted, and thus longitudinal acceptance is significantly reduced. The situation can be somewhat improved with the help of an additional RF component as shown in the lower image of Fig. 1 with an additional $h_{PS} = 10$ component. Even thought the batch compression step from $h_{PS} = 8$ to $h_{PS} = 9$ is part of the simulations presented below, feasibility still has to be proven experimantally. Note that the next batch compression step from $h_{PS} = 9$ to $h_{PS} = 10$ is an issue as well due to this beating phenomenon.



Without additional harmonics



With h_{PS}=10 component

Figure 1: Time evolution (mountain range) of the RF potential during batch compression from $h_{PS} = 8$ to $h_{PS} = 9$ with and without additional $h_{PS} = 10$ component.

A Batch Compression Scheme yielding 64 LHC Bunches spaced by 25 ns per PS Cycle

The low energy part of a batch compression scheme yielding 64 bunches spaced by 25 ns per PS cycle is sketched in Fig. 2. Eight bunches are injected into the PS. Injection and first acceleration takes place with harmonic $h_{PS} = 8$ if feasible or with $h_{PS} = 9$. After acceleration to an intermediate plateau, one or two batch compression steps yield eight bunches with $h_{PS} = 10$. Afterwards the bunches are split resulting in 16 bunches at $h_{PS} = 20$. After a final batch compression step the required harmonic number $h_{PS} = 21$ is reached and the beam is accelerated to the flattop. After two more double splitting steps, 64 bunches with 25 ns spacing are obtained (smaller longitudinal emittances and one double splitting step less would yield 32 bunches spaced by 50 ns). With this scheme, each bunch injected into the PS is split into eight bunches for LHC, whereas with the present production procedure each injected bunch is split into 12 bunches. Assuming that the intensity per injected bunch will be similar to present operation and possible limitations other than transverse

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[†] If the PS is operated with a harmonic number different from $h_{PS} = 8$, the spacing between the two bunches from one Booster ring are adjusted by an additional first harmonic RF component in the Booster.

[‡] From this point of view and for single batch PSB to PS transfer, (with Linac4) filling four $h_{PS} = 4$ buckets is attractive. This option has been ruled out since the RF frequencies required are not possible with the present PS RF system.

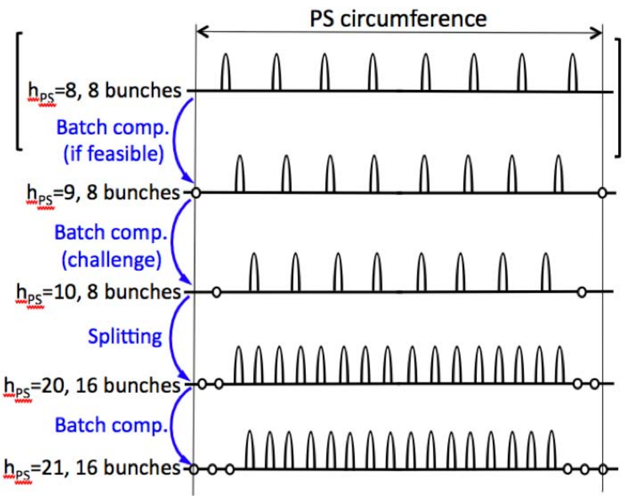

Figure 2: Low energy part of RF gymnastics for a batch compression scheme yielding 64 LHC bunches spaced by 25 ns per PS cycle.

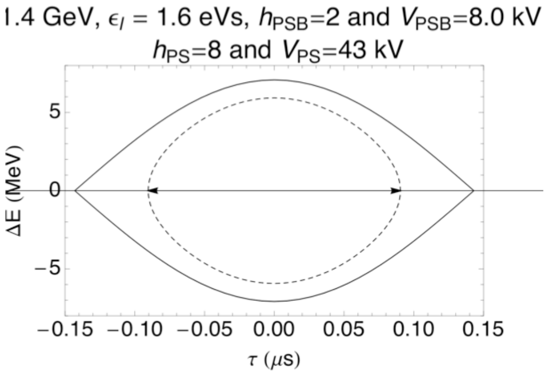

Figure 3: RF buckets occupied by a 1.6 eVs beam at PSB to PS transfer at 1.4 GeV.

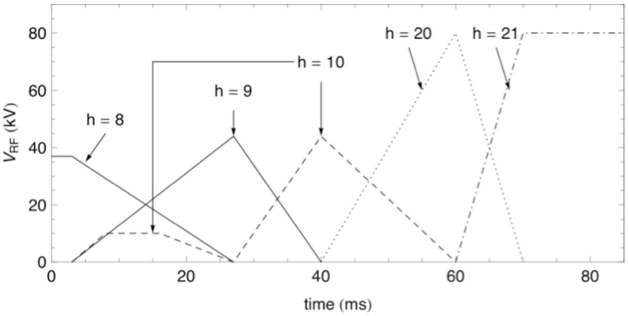

Figure 4: Time evolution of RF voltages for the simulation of the batch compression scheme yielding 64 LHC 25 ns bunches per PS cycle.

direct space charge effects can be solved, one expects a beam brightness increase by a factor 1.5 with respect to the present case An extrapolation from the initial PS design for LHC [6] with later adaptations [1], yields 2.23 10^{11} protons per LHC bunch within 2.5 μm emittances (rms, normalized) at PS injection (the brightness available for the LHC will be lower due to blow-up and losses along the chain)[§].

Assuming a longitudinal emittance of 0.35 eVs per LHC bunch at PS ejection and allowing for blow-up by a factor 1.75, the longitudinal emittance per injected bunch (corresponding to 8 LHC bunches) has to be 1.6 eVs (total). RF Buckets and areas occupied by a beam with 1.6 eVs at transfer shown in Fig. 3 require RF voltages, which appear reasonable in both machines. Acceleration of beams with low harmonic numbers and small longitudinal emittance may imply a temporary increase of the direct space charge tune shift caused by shorter bunches. With a slowed down acceleration to 2.5 GeV and RF voltages extrapolated from the present ones, small temporary increase of the direct space charge tune shift by about 10% has been obtained.

ESME [8] simulations of the gymnastics sketched in Fig. 2 at a 2.5 GeV intermediate plateau have been carried out with the evolution of RF voltages plotted in Fig. 4. Phase space plots for half of the PS circumference, with the center of the batch at the very right, obtained during the simulations are shown in Fig. 5. Even though the time evolutions assumed could be further optimized, the result looks promising with a few perturbations visible on the outer bunches due to non-adiabatic effects and possible temporary reduction of the bucket area.

LHC filling with PS batches containing 64 bunches with 25 ns spacing, instead of 72 with the present scheme, has been investigated. A scheme accumulating up four PS batches in the SPS allows injecting 2688 bunches with 25 ns spacing per LHC ring, i.e. about 4% less than with the present nominal filling scheme.

A Batch Compression Scheme yielding 48 LHC Bunches spaced by 25 ns per PS Cycle

The low energy part of a scheme with more compression steps to further increase the beam brightness and yielding 48 bunches spaced by 25 ns per PS cycle is sketched in Fig. 6. Again, eight bunches are injected into the PS. Injection and first acceleration takes place with harmonic $h_{PS} = 8$ if feasible, or with $h_{PS} = 9$. After acceleration to an intermediate plateau, five or six batch compression steps yield eight bunches at $h_{PS} = 14$. Afterwards a special RF gymnastics extrapolated from triple splitting [1] is applied to transform two bunches into three bunches. The procedure can be interpreted as a combination of an incomplete bunch recombination followed by triple splitting. However, both for triple splitting and this procedure transforming two bunches into three, at some moment (at time 90 ms in Fig. 8) the ratio between the three RF components (h_{PS} = 7, 14 and

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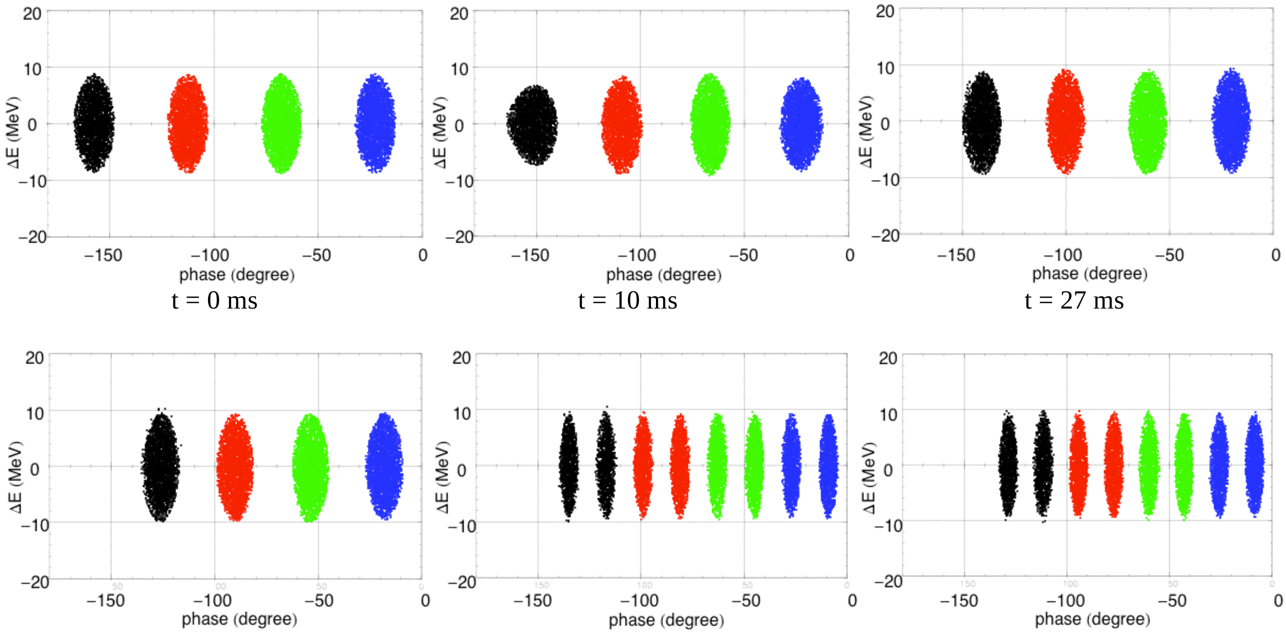
[§] This estimates looks somewhat optimistic given present operational experience from the 2010 run [3], but allows comparison with a similar scaling to estimate the intensity of 2.77 10^{11} protons per LHC bunch possible with a Booster energy upgrade to 2 GeV [7]. Note however that the scenario with batch compression does not require double batch PS filling and, thus, the beam stays only for a short duration at injection energy.



t = 0 ms t = 10 ms t = 27 ms

t = 40 ms t = 60 ms t = 70 ms

Figure 5: Longitudinal phase space plots obtained in ESME simulations during the batch compression process for the generation of 64 LHC 25 ns bunches per PS cycle.

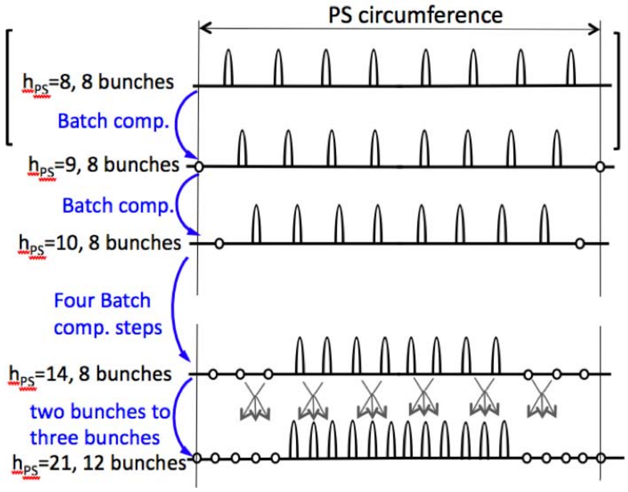


Figure 6: Low energy part of RF gymnastics for a batch compression scheme yielding 48 LHC bunches spaced by 25 ns per PS cycle.

21) involved has to take on values such that three small buckets form within the large bucket. The complexity of the process is not significantly larger than triple splitting, if the starting point is two bunches at $h_{PS} = 14$. Twelve bunches in $h_{PS} = 21$ buckets are accelerated to the flattop. After two more double splitting steps, 48 bunches with 25 ns spacing are obtained (smaller longitudinal emittances and one double splitting step would give 24 buches spaced by 50 ns).

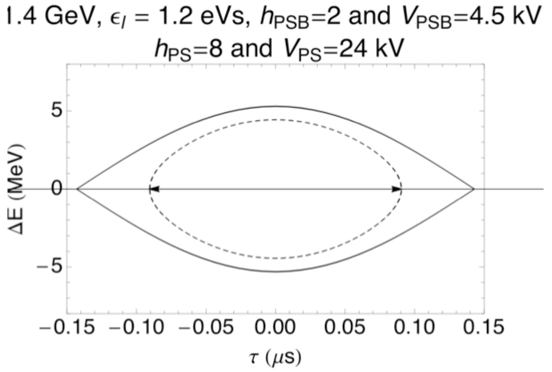


Figure 7: RF buckets and are occupied by a 1.2 eVs beam at PSB to PS transfer at 1.4 GeV.

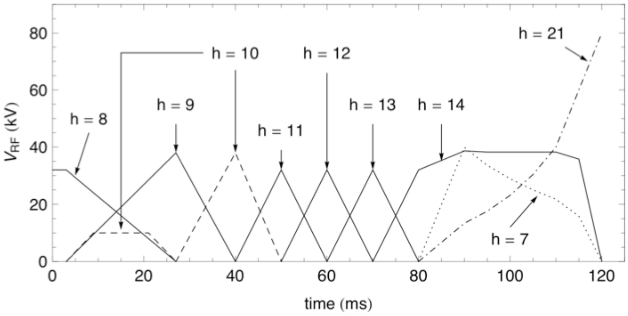


Figure 8: Time evolution of RF voltages for the simulation of the batch compression scheme yielding 48 LHC 25 ns bunches per PS cycle.

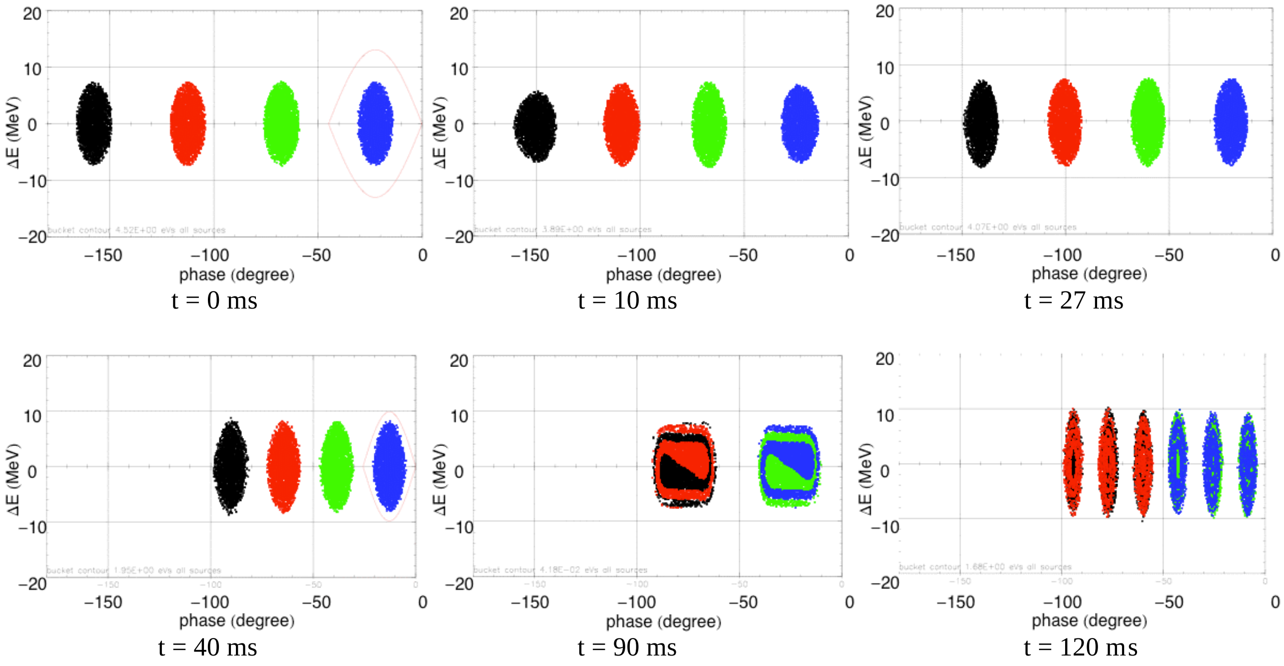


Figure 9: Longitudinal phase space plots obtained in ESME simulations during the batch compression process for the generation of 48 LHC 25 ns bunches per PS cycle.

With this scheme, each bunch injected into the PS is split into six bunches for LHC, whereas with the present production procedure each injected bunch yields 12 bunches. One may therefore expect a beam brightness increase by a factor 2.0 with respect to the present case and 3.0 10^{11} protons per LHC bunch within 2.5 μm emittances at PS injection (the brightness available for the LHC will be lower due to blow-up and losses along the chain).

Assuming a longitudinal emittance of 0.35 eVs per LHC bunch at ejection and allowing for blow-up by a factor 1.75, the longitudinal emittance per bunch at injection has to be 1.2 eVs. RF Buckets occupied by bunches with 1.2 eVs shown in Fig. 7 require RF voltages, which are somewhat lower in both machines than for other standard operations.

ESME [8] simulations of the gymnastics sketched in Fig. 6 at a 2.5 GeV intermediate plateau have been carried out with the evolution of RF voltages plotted in Fig. 8. Phase space plots obtained with these simulations are shown in Fig. 9. Even though the ESME simulation results of the procedure look very promising, setting up with beam might be tedious and delicate due to the complexity of the RF gymnastics required.

LHC filling with PS batches containing 48 bunches with 25 ns spacing has already been worked out in another context and documented in reference [5]. A scheme accumulating up five PS batches in the SPS allows injecting 2592 bunches with 25 ns spacing per LHC ring, i.e. about 8% less than with the present nominal filing scheme.

RAPID CYCLING SYNCHROTRON

A short Rapid Cycling Synchrotron proposed as new PS injector is sketched in Fig. 10 and main parameters are given Tab. 1. The motivations and implications of a circumference of only one seventh of the PS are :

- For the generation of LHC beams with 25 ns or 50 ns spacing, it is natural to generate the structure needed for acceleration without complex RF gymnastics by operating such an RCS with harmonic number $h_{RCS} = 3$ and to fill 18 out of $h_{PS} = 21$ buckets with six transfers (see sketch in Fig. 10). Fast RCS ejection and PS injection kickers are required on the other hand to allow this simplification of the RF gymnastics in the PS. The natural choice for the generation of LHC 75 ns beams is to operate the PS with $h_{PS} = 14$ and to fill 12 buckets with 6 transfers from the RCS running with $h_{RCS} = 2$.
- The short circumference is suitable to obtain high brightness beams with low injection energies. Still with the 160 MeV beam from Linac4, the target beam brilliance and the transfer schemes described above, the beam experiences direct space tune shifts larger than $\Delta Q = -0.5$ for a short duration.
- It may be a challenge to reach the target ejection energy $E_{kin} = 2.0$ GeV[**]. To this end, both the bending magnet filling factor and the maximum magnetic field need to be maximized.

[**] A study [9] presented at the 2010 Chamonix workshop ruled out such a short RCS since, at that time, the target transfer energy and beam brightness was even higher.

- An attractive location for the RCS, which requires only short transfer lines, is the inside of the PS ring as sketched in Fig. 1 (the location has to be refined taking PS infrastructure and transfer lines into account).

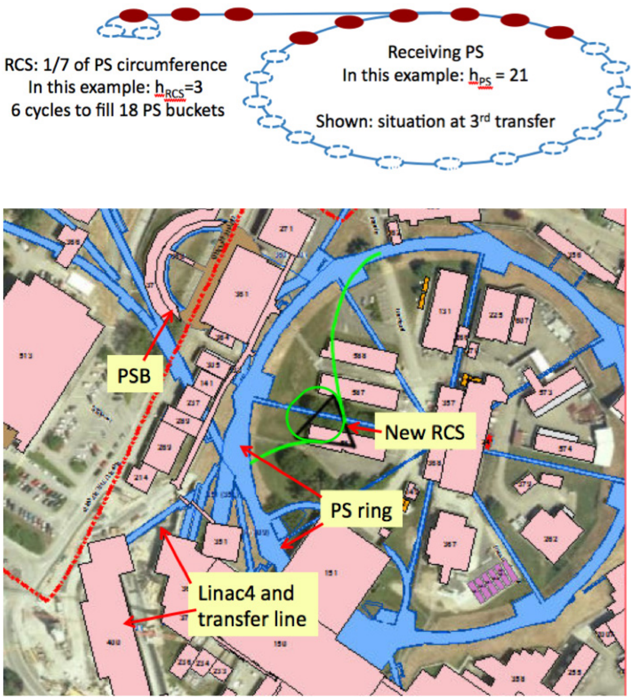


Figure 10: Short rapid cycling synchrotron

Table 1: Main parameter of an RCS

Energy range	160 MeV to 2 GeV
Circumference	(200/7) π m ≈ 89.76 m
Repetition rate	~10 Hz
RF voltage	60 kV
Harmonics	h = 2 or 3
Frequency range	3.48 MHz (h=2 at injection) to 9.5 MHz (h=3 at ejection)
Beam param's for LHC[††] (for lower emittances scale down intensity accordingly)	Intensity: ≤ 12×2.7 10^{11} p/cycle Transv. emittance: $\varepsilon^*_{rms} \approx 2.5$ µm Long. em.: $\varepsilon_l < 4\times0.27$ eVs/bunch for 25 ns beams (in practice determined by RCS acceptance)
Lattice	FODO with 15 cells and 3 periods, 4 cells in arc, straight with one cell
Tunes	$4 < Q_{H,V} < 5$
Rel. gamma at transition	~4
Bending magnet filling	56 % (probably optimistic)
Maximum magnetic field	1.16 T (likely to increase)

Magnetic Cycle and Direct Space Charge Tune Shift

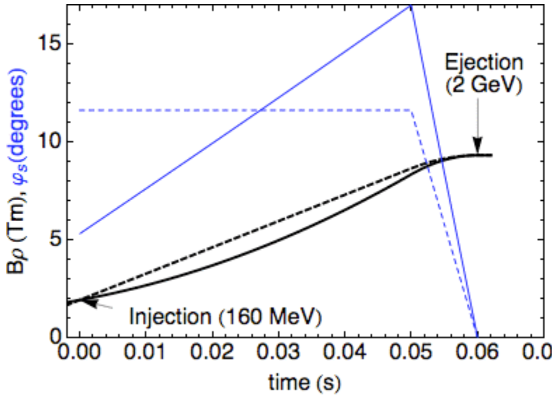


Figure 11: Magnetic cycles (thick curves) and synchronous phases (thin curves) for two ramps assumed for an RCS.

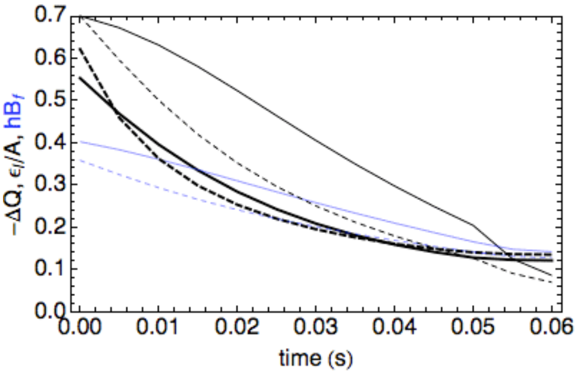


Figure 12: Direct space charge tune shift (thick black lines), ratio between longitudinal acceptance (thin black curves) and bunching factor (thin blue or grey curves) for the two cycles shown in Fig. 11.

For first rough investigations, two magnetic cycles for acceleration within 60 ms (educated guess for 10 Hz repetition rate) have been assumed and are plotted together with resulting synchronous phases in Fig 11: (i) a linear ramp with a 10 ms rounding before the arrival at the flat top (dashed curves) and (ii) a combination of two parabolic pieces to slow down the ramp at injection in order to improve the bunching factor at low energy and, in turn, the maximum direct space charge tune shift (solid curves)[‡‡]. Direct space tune shift have been estimated: (i) adjusting the longitudinal emittance to 70% of the acceptance[§§] at the beginning of the ramp, (ii) transverse emittance and intensity given in Tab. 1 and (iii) estimating the bunching factor from the height of the area occupied by the beam. Direct space charge tune shifts,

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[††] Parameters expected with Linac4 and a PSB 2 GeV upgrade scaling from the initial proposal from the beginning of the 1990ies to prepare the PS complex for LHC [5].

[‡‡] These magnetic cycles have been used to obtain first estimates. For a thorough study, possible waveforms must be adjusted to the technical limitations of power supplies (and possibly magnets).

[§§] For operation of the RCS with harmonic numbers h_{RCS} = 3 and the generation of 25 ns or 50 ns LHC trains, this procedure yields emittances smaller than the maximum in Tab. 1. For h_{RCS} = 2 and 75 ns trains, the longitudinal emittance obtained is slightly too large for the magnetic cycle with smaller ramp at the after injection.

bucket filling factors (ratio between the longitudinal emittance and acceptance) and bunching factors are shown in Fig. 12.

First Ideas on the Lattice

A large bending magnet filling factor is required to reach the target energy with the short fixed circumference of the RCS. Thus, a FODO lattice being an efficient focusing structure has been chosen. Low periodicity three with three arcs and three straight sections allows reducing the total length of the straight sections. Straight sections are dedicated to injection, ejection and RF systems. The relativistic gamma factor γ_{tr} at transition must be above the one at ejection $\gamma_{ej} = 3.13$ but on the other hand must not be too large to keep the total number of cells reasonable. This is obtained by choosing a horizontal tune Q_H between 4 and 5. The lattice proposed consists of a total of 15 FODO cells implying still a large phase advance per cell. Arcs have a length of 4 cells and straight sections one cell. Lattice functions are shown in Fig, 13.

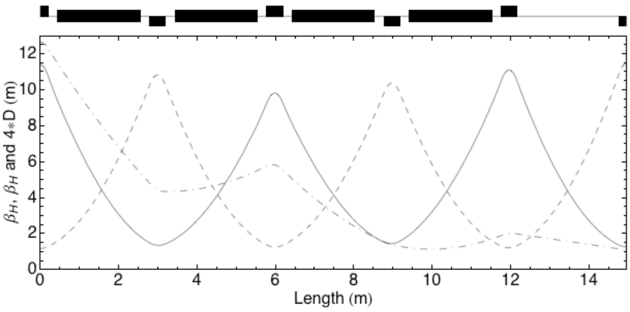

Fig 13: Lattice functions for one half cell extending from the center of the arc to the center of the straight section. Solid, dashed and dot-dashed lines denote the horizontal betatron function, the vertical betatron function and the dispersion.

Since in the arc space has to be made available for correction magnets, possibly instrumentation and other equipment, the bending magnet filling factor of 56% should be considered an optimistic upper limit of what can be achieved. Thus, the maximum bending field of 1.16 T is a lower limit for the one required to reach 2 GeV. A thorough design, allocating sufficient space for all equipments required, is needed for a more realistic estimate.

After a first preliminary study, injection and ejection look challenging, but feasible.

CONCLUSIONS

Batch compression schemes in the PS are a promising option to increase the brightness in the PS without expensive hardware modifications, but require significant manpower to set up the RF gymnastics and to upgrade the beam control system. In particular, the scheme yielding 64 bunches per PS cycle is based on RF gymnastics with a complexity comparable to the present scheme in the PS. Machine experiments are planned for the 2011 run.

First basic parameters of a short RCS to replace the PS Booster have been given. Such a machine looks challenging, but not impossible. A thorough study, comprising in particular investigations on all critical subsystems and on beam dynamics with direct space charge tune shifts exceeding -0.5, is required to clarify technical feasibility and whether an RCS is an attractive option competitive with a Booster 2 GeV upgrade in terms of cost. Advantages of this approach are that a new machine allows for a modern design, good reliability and construction and running-in in parallel with operation of the complex with the existing Booster.

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