Input from Evian 2011

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Abstract

The LHC Beam Operation workshop 2011 took place from 12th to 14th December. The principle aims of the workshop were to review 2011 LHC beam commissioning and beam operations experience, and to look forward to the operation of the LHC in 2012. Issues covered include: availability; injection; operational performance; beam loss and machine protection; system performance; limitations; and the outlook for 2012.

A concise summary of the workshop is presented and potential performance issues for 2012 are highlighted. Where material is covered in more depth at this workshop appropriate reference will be made.

INTRODUCTION

The 2011 LHC beam operation workshop took place in Evian from the 12th to 14th December. The principle aims of the workshop were to review 2011 LHC beam commissioning and beam operations experience with a eye to performance in 2012. The operations plans for 2012 were presented and discussions addressed the strategies for luminosity delivery and machine development priorities. The conclusions are summarized below. A provisional parameter list for 2012 was discussed and was used as input to the numbers presented at this workshop [1].

2011 - A BRIEF RECAP

The baseline operational scenario for 2011 unfolded as more-or-less as planned. Re-commissioning with beam after the Christmas technical stop took around 3 weeks. The exit condition from this phase was stable beams with low number of bunches. There was a ramp-up to around 200 bunches (75 ns) taking about 2 weeks. Multi-bunch injection commissioning also took place during this phase. A 5 day intermediate energy run (beam energy 1.38 TeV) took place towards the end of March. (Here the proton-proton collision energy is equivalent the nucleon-nucleon collision energy in the 3.5 Z TeV lead ion run.)

There was then a scrubbing run of 10 days which included 50 ns injection commissioning After an encouraging performance the decision was taken to go with 50 ns bunch spacing. A staged ramp-up in the number of bunches then took place with 50 ns bunch spacing up to a maximum of 1380 bunches. Luminosity levelling in LHCb via transverse displacement of the beams at the IP8 collision point was operational.

Having raised the number of bunches to 1380, performance was further increased by reducing the emittances of the beams delivered by the injectors and by gently increasing the bunch intensity. The result was a peak luminosity of 2.4×10^{33} $\mathrm{cm^{-2}s^{-1}}$ and some healthy delivery rates which topped 90 $\mathrm{pb^{-1}}$ in 24 hours.

The next major step up in peak luminosity followed a reduction in β^* in points 1 and 5 to a value of 1 m. This was made possible by careful measurements of the available aperture in the interaction regions concerned [2]. These measurements revealed excellent aperture consistent with a very good alignment and close to design mechanical tolerances. The reduction in β^* and further gentle increases in bunch intensity produced a peak luminosity of 3.8×10^{33} $\mathrm{cm^{-2}s^{-1}}$, well beyond expectations at the start of the year.

In conclusion, the LHC has reaped the benefits of exploiting: total beam intensity via bunch spacing and bunch intensity; reduced beam size by injecting smaller emittance beams; and by reducing β^*.

OPERATIONAL EFFICIENCY

It should not be imagined that the year's operation was easy. In general it was a continual battle as the LHC teams wrestled with the effects of high beam intensity and machine availability. Issues included: single event effects (SEEs); UFOs; vacuum instabilities and beam induced heating. These issues were directly addressed in this workshop.

In general the overall efficiency was pretty good considering that this is the LHC in the first full year of operation. The overall time in Stable Beams was 34% of the scheduled time for proton physics. However, the issues cited above caused a large number of premature dumps that meant that 50% of all Stable Beam fills lasted less than 3 hours. Concerted efforts to address the causes were made in the Christmas technical stop that followed the Evian workshop.

Turnaround

Turnaround is largely dominated by machine availability. When there are no faults, the injection phase is the dominating factor. In the injection phase time is lost to: beam preparation in injectors; transfer line stability; and beam loss during the injection process. Potential improvements at injection and in the ramp, squeeze, and pre-cycle for 2012 were enumerated [3].

Operational robustness

Following an intense effort in 2010, the nominal operational cycle (pre-cycle, injection, 450 GeV, ramp, squeeze, collisions, stable beams) proved to be robust. Improvements in automation and sequencing have lead to a largely rock solid process of driving the beam through the nominal sequence, which is now safer with much less scope for human error. There were some issues but in general the following may be noted.

- The injection process was sometimes challenging but once the beam was injected, baring any hardware problems, it made its way through the ramp and squeeze and into collisions without problems.
- A strict pre-cycling policy ensured excellent reproducibility and stability.
- There is very good transmission through the cycle, and beam lifetimes remain good throughout. Well over nominal bunch intensity with smaller that nominal emittances are taken through the cycle without problems. Beam parameter control (tune, orbit, chromaticity and coupling) is well mastered either with feed-back systems or feed-forward.

As always none of this comes for free and is the result of loving care and attention.

Machine protection

The year's operation was unpinned by superb performance of machine protection and associated systems. Indeed this had to be taken as given to even before starting the intensity ramp-up. The machine protection team has ensure rigorous machine protection follow-up, qualification and monitoring (Post Mortem analysis, MPP, rMPP). The beam dump, injection and collimation teams have pursued well-organized programs of set-up and validation tests which have permitted routine collimation of 110 MJ beams without a single quench from stored beams.

System performance

The LHC has enjoyed a excellent and mature system performance across the board. Systems include: Power converters; RF; Transverse feedback; Beam Instrumentation and feedbacks; LHC beam dump system (LDBS); Injection systems; Collimators; Vacuum; Magnets, magnet protection and associated systems; Cryogenics; and Technical infrastructure.

The performance is marked by: attention to detail, painstaking measurements, set-up, continued system development, improvements, optimization, and refinements.

Also of note is the maturity of tools, procedures and software.

- Software (LSA, Sequencer, Software Interlock System, etc) has been key in the effective exploitation of the LHC.
- Controls has seen limited problems and high availability of a very extended set of systems. Even the ergonomics in the CCC are getting better.
- A special mention should be made of the LHC databases which underpin operations and post-run analysis. Of particular note are the on-line LSA database and the miracle of the measurement and logging databases and Timber - their very widely used interface.

These tools, and others, couple with vigorous machine development to allow an impressive level of understanding of beam dynamics, the interplay between beam and beam related systems and of the various limitations briefly outlined above. They also bring, importantly, confidence in the operational process.

- **Transverse feedback** has successfully taken care of: Injection oscillations; Injection gap cleaning; Abort gap cleaning; Emittance preservation; Coherent instabilities. The systems is clearly implicated in all phases of operations.
- **Collimation** has seen the proton cleaning efficiency of 99.97% for 2010 maintained in 2011. Semi-automatic tool has improved collimator operation during alignment (reduced set-up time and eliminated beam dumps during set-up). The aim is for tight collimator settings in 2012 which should improve efficiency by factor 8, but reduce the TCP-TCSG margin by factor 1.5 at 4 TeV. Qualifications should be performed every 3 months, complemented by on-line monitoring.
- **Orbit and tune feedbacks** are clearly essential to operations. Most of the dumps ($\sim$33) we had in 2011 related to these systems should be avoided in 2012 thanks to: change of QPS thresholds to avoid RQTs trips; and hardware modifications to avoid BBQ saturation. Proposals to improve tune measurement should be tested at the beginning of the run. These include ADT gating in combination with BBQ gating.
- **Beam instrumentation** has had a great performance overall and allowed a profound understanding of the machine and paved the way for the impressive performance increase. By pushing performance we are the pushing demands on the systems. Of note is the emittance growth of 20% from SPS extraction to LHC collisions, understanding of which demands accurate, bunch by bunch measurement of beam size through the cycle with cross-calibration between the different measurements [4]. The are tight constraints on orbit stability and thus BPM stability and accuracy. LSS BPMs should be more reliable and improvements for 2012 are in the pipeline [5].

Beam from the injectors

The bunch spacings on offer from the injectors are shown in table 1. 50 ns proved a good choice in 2011 opening the way to an increased number of bunches and the excellent performance in terms of emittance and bunch intensity. The best that was taken into collisions in 2011 was around 1.45 $\times 10^{11}$ protons per bunch with less than 2 μm at extraction from SPS with around 2.3 μm going into collision. Both intensity and emittance clearly folded directly into luminosity.

Table 1: 2011 beam parameters for various bunch spacings at exit of SPS.

Bunch spacing [ns]	From booster	Protons per bunch	emittance [μm]
150	Single batch	1.1×10^{11}	1.6
75	Single batch	1.2×10^{11}	2.0
50	Single batch	1.45×10^{11}	3.5
50	Double batch	1.6×10^{11}	2.0
25	Double batch	1.2×10^{11}	2.7

Optics and aperture

LHC optics and aperture are in good shape and this represents a major achievement for the teams involved. The LHC has reached performance beyond expectations and beyond design with the successful squeeze commissioning and operation in 2011. There were many improvements from 2010 allowing a shorter squeeze with more robust operation.

Commissioning of new optics has become routine and the optics behaves well and beta beating is correctable to within approximately 10% of design. The LHC aperture is good. The aperture at 450 GeV is greater that 12σ indicating nominal aperture is achieved (with margins). In 2011 first gentle interaction region aperture measurement at 3.5 TeV allowed a 50% step in peak luminosity via a squeeze to β^* of 1 m in points 1 and 5. In 2012 the orbit stability in the squeeze must be improved to allow operational use of tight collimator settings and the aperture must be re-measured at injection and at top energy. Given this a squeeze to β^* of 0.6 m in points 1 and 5 is possible [6].

LIMITATIONS

The high beam and bunch intensities achieved in 2011 revealed a number of issues.

- **Impedance effects on beam stability** Head-tail (single bunch & coupled bunch) instabilities and coupled bunch coherent modes have been combated with Landau damping octupoles and the transverse damper. Experience with tight collimator settings with high bunch intensity have led anticipation of needing octupoles to a high current (∼550 A) and stricter chromaticity control in 2012.

- **Beam induced heating** There have been numerous incidents of beam induced heating [7]:
  - injection kickers (with the potential to delay injection while they cool);
  - the double bellow module VMTSA (broken spring, dangling fingers);
  - the primary collimator in IR7 (1 dump, interlock increased);
  - TCTVB collimator in IR 2 & 8;
  - TDI collimators;
  - beam screens (all, longer bunch length and scrubbing eased operation);
  - Q6R5 which has limited cooling margin.

  Mitigation measures were taken, where possible, in the Christmas technical stop.

- **e-cloud and vacuum instabilities** The scrubbing campaign was clearly effective globally, however vacuum instabilities dogged operations throughout 2011. Some locations were found to be faulty interconnects where bad design or poor installation had led to problems (e.g. points 2 & 8, CMS, TDI). [8]

- Radiation to electronics (R2E) [9] and UFOs [10] are covered elsewhere in these proceedings.

AVAILABILITY AND OTHER ISSUES

Despite the inherent complexity of the LHC, availability remains acceptable. However, machine availability is dictated by the exposure to the intersecting failure space of a number of complex systems with huge number of components. Some very extensive equipment systems performed above expectations (considering mean time between failures etc.), but the failure space has been clearly inflated by high intensity effects.

Running with higher total beam intensity has provoked a number of issues including: UFOs; the effects of radiation to electronics in the tunnel; and increased vacuum activity possibly related to residual electron cloud. The RF team has had to carefully monitor the effects of higher beam intensity and adapt its interlock policy accordingly. Beam induced heating of injection kickers, beam screens, and collimators has been observed with a clear dependence on total intensity and bunch length.

One key factor in 2011 was the cost of premature dumps. These dragged the mean length of fill down considerable and had an important impact on the year's performance.

QPS

The QPS has demonstrated its reliability and capability to ensure the integrity of the protected superconducting elements. While most of the radiation induced faults are transparent to LHC operation, the number of beam dumps caused by spurious triggers is close to the maximum admissible limit [11]. None of the observed faults caused a total loss of magnet and/or circuit protection. Consolidation measures over the Christmas technical stop will not lead to zero radiation induced trips, but limit the number of faults despite increased luminosity. A comprehensive program of mitigation and consolidation was executed (DAQ, nQPS splice protection, IPQ/IPD/IT, 600 A).

Cryogenics

The major issues of 2010 (Cold Compressors - sub atmospheric filters - instrumentation) have been corrected and the cryogenics team have done their best to provide a correct availability in 2011 despite serious issues (degraded QRL45 or bearings/compressors). For beams, cryogenics availability for 2011 (89.7%) has reduced by mostly: various types of SEU, treatment to be completed; and cryogenics equipment (Compressors and diagnostics). Bad luck has resulted in the concentration of problems at P8 with the longest recovery. Both of these issues will be addressed in the Christmas technical stop. The electrical network (external and internal) have seen increased failures in 2011.

With beams, interesting tuning for beam induced effects and interactions with beam vacuum (beam screen cooling loops) has been performed, to be continued with increased luminosity. Very positive signs of good cryogenics performance observed on the majority of the sectors, allowing to consider 95% global availability reachable (Energy $\leq$ 5 TeV). At the time of the workshop the cryogenics team was looking forward to this intense and interesting Christmas break for consolidations and training, in order to be ready for the best integrated luminosity in 2012 [12].

Technical stops

A very nice analysis [13] concluded that there were no systematic source of trouble over the five technical stops in 2011. It seems clear that recovery from the technical stops is improving. The need to improve fault details recording was noted again.

2012

The 2012 schedule, as of February 2012, foresees:

- The end of powering tests around the 7th March.
- A few days of machine checkout without beam. Some delay at this stage is foreseen as CMS recover fully from the unplanned vacuum intervention that took place in January 2012. First beam is now planned for 14th March.
- 3 weeks re-commissioning with beam. The exit condition from this phase is “stable beams” with a low number of bunches.
- A 3 day scrubbing run with 25 ns beam. The timing of the scrubbing run is flexible and is contingent on good progress in the re-commissioning phase.
- Intensity ramp-up is planned to be reduced to 7 steps in 2012: 3 fills and 6 hours with 48b, 84b, 264b and 624b; 3 fills and 20 hours with 840b, 1092b, 1380b. 3 weeks for 1380b and peak performance are within reach.
- There will be four 5 day technical stops during the year. Each stop is followed by 2 days to re-establish peak performance.
- There are 22 days of machine development. The length of the first MD block has been reduced to 3 days.
- Atlas foresees ZDC installation (5 days minimum) during last technical stop which precedes the ion run. This removes the need to discuss whether or not the final technical stop should take place or not.
- A 4 day set-up period precedes the 4 week proton-ion run.

For the proton physics run the 36th International Conference on High Energy Physics (ICHEP2012) in Melbourne 4 - 11 April 2012 provides a virtual constraint. The experiments would like to maximize the integrated luminosity delivered before the middle of June to allow a healthy update of the results presented at the winter conferences. Realistically optimistic estimates are in the 3 to 4 fb^{-1} range to be delivered by the 17th June.

Table 2: Breakdown of LHC’s 2012 schedule.

Activity	Time assigned
Machine check-out	2
Commissioning with beam	21
Machine development	22
Technical stops	20
Scrubbing run	3
Technical stop recovery	6
Initial intensity ramp-up	21
Proton physics running	126
Special physics runs	8
Ion run setup	4
Ion physics run	24

In the estimates presented below, 150 days for proton physics are assumed including ramp and technical stop recovery time.

OPERATION IN 2012

Beam energy

At Chamonix 2011 there was lively debate regarding the decision to run at 4 TeV (with a 50 s main dipole energy extraction time constant). One of the main arguments against 4 TeV was the number of spurious quenches observed in 2010. In 2011 the number of spurious quenches was radically reduced. This was achieved mainly thanks to the improvements introduced to the quench protection system and the installation of snubber capacitors. There have been no beam induced quenches above 450 GeV. It can be noted that 2011 saw: better hardware commissioning procedures (no quenches during this phase); better operational procedures with beam; only 1 single magnet spurious quench with beam (firing of quench heater probably due to an SEU); better knowledge of the RRR (250±50) of the copper bus bars. Given this input, and a more detailed analysis elsewhere, there appears to be no reason to not operate at 4 TeV in 2012 [15]. The decision to operate at 4 TeV was confirmed at Chamonix 2012.

Bunch spacing

The bunch spacings on offer from the injectors are shown in table 1. Looking forward to 2012, 50 ns has proven performance in both the LHC and the injectors. In comparison with 25 ns there are less long range encounters, potentially allowing a lower β^*. There is some limited room for increasing bunch intensity (and perhaps reducing emittance blow-up), however the high luminosity per bunch does bring higher pile-up.

The 25 ns beam has lower bunch current and higher emittances from injectors and would require considerably more total current to match the equivalent 50 ns performance. The higher 25 ns beam current could potentially bring more problems (UFOs, SEEs, RF, vacuum instabilities). There are around twice the number of long range encounters and with larger emittances, there is reduced potential to squeeze. An extended scrubbing period would required to get 25 ns operational. On the positive side the pile-up would be significantly lower.

A comparison of the achievable performances is given below. However, the advantages of 50 ns for the 2012 run are clear.

Squeeze

The collimation group has proposed the use of tight collimator settings in 2012. By bringing the primary and secondaries in further, the system is able to protect a smaller aperture (expressed in beam sigma) in the experiments' interaction region thereby allowing the reduction of β^* well below the minimum of 1 m used in 2011.

Three options have been proposed [6]:

- A β^* of 70 cm based on tight collimator settings and a linear combinations of margins based on last year's experience. (The margins are those related to beta beating, set-up, positioning and orbit movements.)
- A β^* of 60 cm based on tight collimator settings and adding the margins in quadrature.
- A back-up solution of 90 cm based on intermediate collimator settings similar to those used operationally in 2011. The settings represent a well-understood set-up with proven performance.

The tight settings are not yet proven having been tried a couple of times in 2011. An end-of-fill attempt passed off without problems, however instability problems were observed at the end of squeeze (with high intensity). Issues to be resolved include improved orbit control in ramp and squeeze in particular at matched points in the squeeze. Instability/impedance control is anticipated with high Landau damping octupoles settings and tighter chromaticity margins during routine operation.

Tight settings offer over 20% increase in performance but increased sensitivity to beam perturbations with a potential impact on efficiency. The effects of strong octupoles remain to be seen as does Operations' ability to control the chromaticity to the stated margins.

POTENTIAL PERFORMANCE

The potential performance for four scenarios are shown in table 3. For clarity 3.5 TeV figures are suppressed. The scenarios are:

1. 50 ns beam with β^* = 90 cm and intermediate collimator settings;
2. 50 ns beam with β^* = 70 cm and tight collimator settings, linear combination of margins;
3. 50 ns beam with β^* = 60 cm and tight collimator settings, margins combined in quadrature;
4. 25 ns beam with β^* = 80 cm and intermediate collimator settings.

Table 3: Potential performance in 2012. Collimators refers to the choice of intermediate or tight settings. Margins to the option of combining these linearly or in quadrature.

Option	1	2	3	4
Collimators Margins	int linear	tight linear	tight quad.	
ϵ_N [μm]	2.5	2.5	2.5	3.3
β_* [cm]	90	70	60	80
Crossing angle [μrad]	240	268	290	380
Reduction factor	0.9	0.86	0.83	0.75
Colliding pairs	1331	1331	1331	2700
Protons/bunch $\times 10^{11}$	1.55	1.55	1.55	1.15
Peak luminosity cm^{-2}s^{-1}	4.9	6.0	6.7	3.9
Pile-up	24	29	33	9
Days of physics	150	150	150	140
Int. luminosity	12.7	15.5	17.5	9.4

From the table 3, it is clear that tight settings and a squeeze to either 70 or 60 cm are of importance if the stated goals are to be met in good time in 2012. For this reason it is foreseen to start with tight settings and qualify them with reasonably high intensities bunches ($48\times1.4\times10^{11}$)

as soon as possible (with octupoles at an appropriate level). Squeeze settings to 0.6 m and 0.7 m should be prepared. Commissioning to 0.6 m initially should be performed with the usual measurement and correction of orbit, optics, chromaticity at 90, 70 and 60 cm.

Integrated Luminosity

Besides table 3, estimates for the potential integrated luminosity for 2012 have been presented elsewhere [17]. Assuming 4 TeV, a β^* of 70 cm and 148 days of physics, the estimates were: around 16 fb^{-1} for 50 ns; and 10 fb^{-1} for 25 ns. These agree with other recent estimates based on around 150 scheduled days for physics. (Note ramp-up time and recovery from technical stop is included in the quoted scheduled days.)

OTHER ISSUES

- The β^* in IR8 will remain at 3 m in 2012.
- An inclined crossing scheme in IR8 is proposed and under investigation. This will serve to reduced the net crossing angle in LHCb, which is particularly large for one polarity setting.
- The β^* in IR2 will be reduced to 3 m in 2012. Combined with satellite-main collisions, this should give Alice their desired luminosity. Plans for artificially induced ”enhanced” satellites are shelved.

CONCLUSIONS

Evian 2011 was a very productive workshop. It looked back at 2011 - a remarkable year which saw excellent performance and an awful lot of lessons learnt. It undoubtedly lays a good foundation for another challenging year in 2012. The principal goal is clearly the delivery of around 15 fb^{-1} to each of Atlas and CMS to allow the independent exclusion or discovery of the Higgs. This should be possible in 2012 given:

- an increase in energy to 4 TeV;
- injector performance equal or better than that of 2011 - the hope here is to push towards an offered maximum of around 1.6 $\times 10^{11}$ protons per bunch with the predicted increase in transverse emittance;
- the use of tight collimator settings allowing a reduction in β^* to 70 or 60 cm;
- continued LHC machine availability in the same order or better than that experienced in 20011 - the mitigation measures foreseen for key system will be critical in this regards.

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