OPERATIONAL CHALLENGES (FEED FORWARD FROM EVIAN LHC OPERATION WORKSHOP)

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

• 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).

• 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 x 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.

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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".

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