LHC Beam Operations: Past, Present and Future

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Abstract

A brief overview of LHC operations over the last 3 years is provided. Luminosity performance has been satisfactory and the factors that have been exploited are outlined. Availability and operational efficiency are discussed. Finally a brief overview of the planned long shutdown is given and estimates of the potential post shutdown performance are briefly enumerated.

1 Introduction

The LHC re-started initial commissioning with beam at the end of 2009. Since then the LHC has had three years of operations as summarized in Table 1. Essentially, 2010 was devoted to commissioning and establishing confidence in the critical machine protection system. 2011 saw the start of exploitation and the exploration of performance limits. Pushing these limits, outlined below, allowed the instantaneous luminosity performance to be increased throughout 2011. 2012 was a production year at an increased center of mass (COM) energy of 8 TeV. Again limits were pushed revealing some challenging issues at high bunch and total beam intensity.

The integrated luminosity performance over the 3 years can be regarded as good, with the LHC delivering enough integrated luminosity to enable ATLAS and CMS to announce the discovery of a Higgs-like boson on July 4th 2012.

Table 1: LHC operations 2010 - 2012

Year	Overview	COM energy	ATLAS/CMS integrated luminosity [fb^{-1}]
2010	Commissioning	7 TeV	0.04
2011	Exploring limits	7 TeV	6.1
2012	Production	8 TeV	23.1

One of the main features of operations in 2011 and 2012 was the use of high bunch intensity with 50 ns bunch spacing. As discussed below, this gave good instantaneous luminosity performance but at the cost of high pile-up to the high luminosity experiments. In 2011 the mean number of collision per crossing (mu) was around 12 with Poisson tails up to approximately 20. In 2012 mu had increased to around 30 collisions/crossing at the beginning of a fill with tails up to approximately 40.

Besides the delivery of high instantaneous and integrated luminosity to ATLAS and CMS, the LHC team was also able to deliver physics to a number of other users.

- 2010 and 2011 saw lead-lead ion runs which delivered 9.7 and 166 μb^{-1} respectively at an energy of 3.5Z TeV. Here the clients were ALICE, ATLAS and CMS.

- Luminosity levelling at around 4×10^{32} cm^{-2}s^{-1} via transverse separation, with a tilted crossing angle, enabled LHCb to collect 1.2 and 2.2 fb^{-1} in 2011 and 2012 respectively.
- ALICE enjoyed some sustained proton-proton running in 2012 at around 5×10^{30} cm^{-2}s^{-1} with collisions between enhanced satellite bunches and the main bunches.
- There was a successful $\beta^* = 1$ km run for TOTEM and ALFA. With t_{min} of approximately 0.0004 GeV^2 this was the first LHC measurement in Coulomb-Nuclear Interference region.
- The three years operational period culminated in successful proton-lead run at the start of 2013. Here the clients were ALICE, ATLAS, CMS and LHCb.

2 Performance

Basic variations on the equation for the luminosity of a collider are shown in Eq. 1, assuming round beams and equal values of the beta function for both beams in both planes in the latter equation.

$$\mathcal{L} = \frac{N^2 k_b f}{4\pi\sigma_x^*\sigma_y^*}F = \frac{N^2 k_b f \gamma}{4\pi\epsilon_n\beta^*}F \tag{1}$$

Here N is the number of particles per bunch, k_b is the number of bunches, f is the revolution frequency, γ is the usual relativistic factor, σ_x^* and σ_y^* are the horizontal and vertical beam sizes at the interaction point, ϵ_n is the normalized transverse emittance, β^* is the value of the beta function at the interaction point and F is the geometrical reduction factor arising from the crossing angle.

The corresponding values for these parameters at the peak performance of the LHC (so far) are shown in Table 2. The design report values are displayed for comparison. Remembering that the beam size is naturally larger at lower energy, it can be seen that the LHC has achieved 77% of design luminosity at 4 sevenths of the design energy with a β^* of 0.6 m (cf. design value of 0.55 m) with half nominal number of bunches.

Table 2: Performance related parameter overview

Parameter	Value in 2012	Design value
Beam energy [TeV]	4	7
β^* in IP 1,2,5,8 [m]	0.6,3.0,0.6,3.0	0.55
Bunch spacing [ns]	50	25
Number of bunches	1374	2808
Average bunch intensity [protons per bunch]	1.6 - 1.7×10^{11}	1.15×10^{11}
Normalized emittance at start of collision [μm]	2.5	3.75
Peak luminosity [cm^{-2}s^{-1}]	7.7×10^{33}	1×10^{34}
Max. mean number of collisions per bunch crossing	≈40	19
Stored beam energy [MJ]	≈140	362

One of the main reasons for the impressive luminosity has been the excellent beam quality delivered by the injectors. As shown in Table 3 the injector complex has succeeded in delivering beam with significantly more protons per bunch (ppb) than nominal with lower emittances than nominal. This is particularly significant for the 50 ns beam.

The LHC has proven capable of absorbing these brighter beams, notably from a beam-beam perspective. The clear cost has been increased pile-up for the high luminosity experiments which they have successfully learnt to deal with.

In brief the LHC has achieved good luminosity performance via the following.

- Exploiting the important advantage that high bunch intensities bring (with luminosity proportional to N_b^2). Here the bunch intensity has been up to 150% of nominal with the 50 ns bunch spacing.

Table 3: 2012 values of beam parameters at exit of SPS

Bunch spacing [ns]	Bunch intensity [ppb]	Emittance [μm]
50	1.7×10^{11}	1.8
25	1.2×10^{11}	2.7

- The normalized emittance going into collisions has been around 2.5 μm, thanks to very good injector performance and ability to conserve the emittance through the Booster, PS, and SPS. Some systematic blow-up at injection and in the ramp is seen in the LHC.
- It has proved possible to squeeze to a β^* of 60 cm thanks to measurement of a very good aperture in the interaction regions (credit to alignment, respect of mechanical tolerances, optics measurement and correction, and orbit correction).
- The total intensity has reached 2.2×10^{14} i.e. 70% of nominal. Here a fully trustworthy machine protection has been instrumental in providing the confidence to routinely deal with 140 MJ beams.

3 Overview of Machine Characteristics

The performance described above is on the back of some excellent system performance and some fundamental characteristics of the LHC [1].

- There is excellent single beam lifetime and on the whole the LHC enjoys excellent vacuum conditions.
- There is excellent field quality, coupled with good correction of non-linearities.
- Head-on beam-beam is not a limitation although long range has to be taken reasonably seriously with enough separation at the long range encounters guaranteed by sufficiently large crossing angles.
- Collective effects have been seen with the high bunch intensities. Single and coupled bunch instabilities have been surpressed using a range of tools (high chromaticity, Landau damping octupoles and transverse feedback).

Very good understanding of the beam physics and a good level of operational control has been established.

- There is better than expected aperture due excellent alignment and respect of mechanical tolerances.
- The β^* reach has been established and exploited. Reduction has been pursued aggressively, exploiting: the better than specified available aperture; tight collimator settings; and very good stability and reproducibility.

The complex operational cycle is now well established and is robust.

- The pre-cycle, injection process, 450 GeV machine, ramp, squeeze, collide are largely sequencer driven. There is generally good beam lifetime throughout the whole process.
- A strict pre-cycling regime means the magnetic machine is remarkably reproducible. This is reflected in the optics, orbit, collimator set-up, tune and chromaticity.
- Operations is unpinned by superb performance of machine protection and associated systems (beam interlock system, beam dump system, beam loss monitors, and collimation system). There is rigorous machine protection follow-up, qualification, and monitoring; all nonconformities are examined rigorously. The importance of this to the success of the LHC so far cannot be over stressed - there has been a move from commissioning to real confidence in less than two years.

Availability has, in general, been very good considering the size, complexity and operating principles of the LHC. An outline of 2012's availability is shown in Table 4. The percent of scheduled physics time spent in "Stable beams" in 2012 was around 36% of a total scheduled time for proton-proton physics of around 200 days. This is encouraging for a machine only 3 years into its operational lifetime. The machine is performing well and a huge amount of experience and understanding has been gained. There is good system performance, excellent tools, and reasonable availability following targeted consolidation. This is the legacy for post long shutdown 1 operation.

Table 4: LHC availability 2012

Mode	% of scheduled time
Access	13.8%
Setup	27.6%
Beam in	15.0%
Ramp and squeeze	7.1%
Stable beams	36.5%

4 Long Shutdown 1 (LS1)

The primary aim of LS1 is the consolidation of the superconducting splices in the magnet interconnects following the incident of 2008. This will allow the current in the main dipole and quadrupole circuits to be increased to the 6.5 and then 7 TeV level. Besides this a huge amount of maintenance and other consolidation work is to be performed. Some key LS1 work packages are outlined below [1].

- Measure all splices and repair the defective ones. Repeat for the 6 splices per interconnect (2 splices for the main dipoles and 4 for the 2 main quadrupole circuits). There are approximately 1700 interconnects in the machine.
- Consolidate interconnects with a new design (clamp, shunt)
- Finish installation of pressure release mechanisms on cryostats not yet so equipped
- Magnet consolidation: the exchange of weak cryo-magnets
- Consolidation of the current lead feed-boxes (DFBAs)
- Install collimators with integrated button BPMs (tertiary collimators and a few secondary collimators)
- Extensive experiments consolidation and upgrades
- Plus a lot of other maintenance work covering cryogenics, quench protection, electrical infrastructure, cooling and ventilation, Radio Frequency, beam dump absorber and magnet, change of dump switches (radiation), electron cloud mitigations

5 Possible Limitations for Post LS1

The most important issue to be discussed here is that of electron cloud. Although this has not been a serious issue with the 50 ns beam, there are potential problems with the 25 ns foreseen for post LS1 operation.

There were 3.5 days of scrubbing with 25 ns beams at 450 GeV between 6 and 9 December 2012. The tests saw regular filling of the ring with up to 2748 bunches with a total intensity per beam of up to 2.7×10^{14}. Scrubbing effects in the arcs saw quite rapid conditioning observed in the first stages. The secondary electron yield (SEY) evolution significantly slows down during the last scrubbing fills (more than expected by estimates from laboratory measurements and simulations) and preliminary conclusions [4] are that an electron cloud free environment with 25 ns beam after scrubbing at 450 GeV seem not be reachable in acceptable time. Operation with high heat load and electron cloud density (with blow-up) seems to be unavoidable with a corresponding slow intensity ramp-up. (In 2015 following the warm-up and opening of the entire ring to atmosphere, the SEY and vacuum conditions will be reset and initial re-conditioning will be required.)

UFOs (Unidentified Falling Objects) have now been exquisitely well studied and simulated [3]. There were occasional dumps in 2012 following adjustment of BLM thresholds at the appropriate time-scales (the beam loss spike caused by a UFO is typically of order 1 ms). With the increase in energy to 6.5 TeV and the proposed move to 25 ns there is potentially serious problem with the UFOs become harder (energy) and potentially more frequent (25 ns). Investigations have continued and potentially encouraging results from the 2013 quench test program are noted [3].

6 Post LS1 Operational Scenarios

6.1 Beam from the Injectors LS1 to LS2

The bunch spacings and associated performance on offer from the injectors post LS1 are shown in Table 5. 50 ns proved a good choice in 2011 and 2012 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 2012 was around 1.7 $\times 10^{11}$ ppb with an emittance of around 2.5 μm going into collision. Further imaginative developments on the PS side have led to the creation of the so-called BCMS (Batch Compression and (bunch) Merging and (bunch) Splittings) scheme [5] which offer remarkably low emittance coupled with healthy bunch intensity as shown in Table 5.

Table 5: Post LS1 beam parameters at the exit of SPS

Scheme	Bunch intensity [10^{11} ppb]	Emittance exit SPS [μm]	Emittance into collisions [μm]
25 ns	1.15	2.8	3.75
25 ns BCMS	1.15	1.4	1.9
50 ns	1.65	1.7	2.3
50 ns BCMS	1.6	1.2	1.6

6.2 50 versus 25 ns

50 ns offers:
- lower total beam current;
- higher bunch intensity (at the cost of having to wrestle with beam instabilities);
- lower emittance.

However the perhaps crippling cost at 6.5 TeV is the very high pile-up which will certainly require levelling to be operationally useful. On the other hand 25 ns has a number of negative points which include:
- more long range collisions: requiring a larger crossing angle and thus higher β^*;
- higher emittance;
- seriously more electron cloud with the need for scrubbing;
- higher UFO rate;
- higher injected bunch train intensity;
- higher total beam current.

However, the push will be to go for 25 ns to avoid the inefficiencies and cost of high pile-up.

6.3 Potential Performance

The potential performance for four scenarios enumerated in Table 5 are shown in Table 6. The estimates assume:
- a beam energy of 6.5 TeV;
- a 1.1 ns bunch length (nominal);
- a scheduled 150 days of proton physics with a reasonable optimistic availability (Hübner factor ≈ 0.2);
- 85 mb visible cross-section.

It should be noted that the 50 ns options necessitates the use of a levelling scheme of some sort, as yet unproven operationally.

From Table 6 one notes the following.

Table 6: Post LS1 performance estimates - usual caveats apply

Scheme	Number of bunches	Bunch intensity [10^{11} ppb]	β_x^*[cm]/β_y^*[cm]/ half crossing angle [μrad]	Emittance [μm]	Peak luminosity	Pile-up	Int. lumi. fb^{-1}
25 ns	2760	1.15	55/43/189	3.75	9.3×10^{33}	25	24
25 ns BCMS	2520	1.15	45/43/149	1.9	1.7×10^{34}	52	45
50 ns	1380	1.6	42/43/136	2.3	1.6×10^{34} level to 0.8×10^{34}	87 level to 44	40
50 ns BCMS	1260	1.6	38/43/115	1.6	2.3×10^{34} level to 0.8×10^{34}	138 level to 44	40

- The nominal 25 ns parameters gives more-or-less nominal luminosity at 6.5 TeV as might be expected.
- The BCMS 25 ns scheme gives peak luminosities of 1.7×10^{34}cm^{-2}s^{-1} with peak <mu> of around 50 with 83% of the nominal intensity.
- The now operational 50 ns scheme gives a virtual luminosity of 1.6×10^{34} cm^{-2}s^{-1} but with a pile-up of over 70 making levelling mandatory.
- The BCMS 50 ns scheme gives a virtual luminosity of 2.3×10^{34} cm^{-2}s^{-1} with a pile-up of over 100 making levelling even more mandatory.

7 Conclusions

The LHC has shown the results of excellent design, construction, and installation. Operation is now well bedded in and both instantaneous and integrated luminosity performance is healthy. The injector complex has performed very well and delivered 50 ns beam with high bunch intensities and low emittance. Machine availability has been reasonable for a machine the size and complexity of the LHC.

The LHC carries forward a wealth of experience from operation at 3.5 and 4 TeV, and is anticipating operation at 6.5 TeV in 2015 following a two year shutdown. There are potential issues. Measures to address and mitigate these are under examination.

Acknowledgments

The success of the LHC represents a huge international effort at all phases: design, construction, installation, commissioning and operations.

References

1. M. Lamont, Status of the LHC, Proceedings of the International Workshop on Discovery Physics at the LHC - Kruger 2012.
2. R. Tomas Garcia, Optics and dynamic aperture at 4 and 6.5 TeV, Proceedings of the LHC Beam Operation workshop - Evian 2012 (to be published).
3. T. Baer, UFOs, Proceedings of the LHC Beam Operation workshop - Evian 2012 (to be published).
4. G. Iadarola, Electron Cloud and Scrubbing, Proceedings of the LHC Beam Operation workshop - Evian 2012 (to be published).
5. R. Steerenberg, Post LS1 25 ns and 50 ns options from the injectors, Proceedings of the LHC Beam Operation workshop - Evian 2012 (to be published).