

# THE FIRST YEARS OF LHC OPERATION FOR LUMINOSITY PRODUCTION

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## Abstract

A summary of the first 3 years of LHC operation is presented with a discussion on the performance ramp-up, operation efficiencies and system reliability. The main contributory factors to peak and integrated luminosity performance are outlined.

## INTRODUCTION

The LHC has four main experiments: ATLAS, CMS, ALICE and LHCb. Of these, ATLAS and CMS are general purpose detectors (GPD) designed for high luminosity and searches in a wide variety of channels. In the following the focus is on the delivery of instantaneous and integrated luminosity to the GPDs. ALICE and LHCb have also operated very successfully at lower luminosities and are briefly referenced.

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.

Table 1: LHC operations 2010 to 2012

Year	Overview	Energy [TeV]	Integrated luminosity [fb <sup>-1</sup> ]
2010	Commissioning	3.5	0.04
2011	Exploring limits	3.5	6.1
2012	Production	4.0	23.1

The integrated luminosity performance over the 3 years can be regarded as satisfactory, with the LHC delivering enough integrated luminosity to enable ATLAS and CMS to announce the discovery of a Higgs boson on July 4<sup>th</sup> 2012. The total integrated proton-proton luminosity delivered to ATLAS at 3.5 and 4 TeV by the end of 2012 can be seen in table 1.

## OVERVIEW OF THE FIRST THREE YEARS OF LUMINOSITY PRODUCTION

### 2010

Essentially, 2010 was devoted to commissioning and establishing confidence in operational procedures and the machine protection system. At this stage the basics were sorted out well, laying the foundation for what followed.

Ramp commissioning to 3.5 TeV was smooth and led to first collisions at 3.5 TeV unsqueezed on the 30<sup>th</sup> March 2010. Squeeze commissioning successfully reduced the  $\beta^*$  to 2.0 m in all four experiments. After the squeeze was

commissioned there was a period of stable beams punctuated with continued system commissioning.

In June the decision was taken to go for bunches with nominal intensity. This involved another extended commissioning period which included the need to stabilize single beam instabilities using octupoles, and the suppression of coherent beam-beam modes in colliding beams, initially using a tune split and then transverse feedback. There was a halting push through nominal intensity commissioning to a total stored beam energy of around 1 to 3 MJ. The LHC was held at or around this range for around 3 weeks. This period of steady running was used to fully verify machine protection and operational procedures.

To increase the number of bunches the move to 150 ns bunch trains was made and the crossing angles in the experimental IRs brought on. This necessitated a re-set up of the tertiary collimators and another full set of loss maps. A number of ramps and squeezes were necessary and the exercise was used as an opportunity to fully bed in the operational sequence.

A phased increase in total intensity was then performed. Before each step-up in number of bunches, an operational and machine protection validation was performed. Each step-up was followed by a few day running period to check system performance. The proton run finished with beams of 368 bunches of around  $1.2 \times 10^{11}$  protons per bunch, and a peak luminosity of  $2.1 \times 10^{32}$  cm<sup>-2</sup>s<sup>-1</sup>. The operational year ended with a 4 week lead-lead ion run.

### 2011

The beam energy remained at 3.5 TeV in 2011 and the year saw combined exploitation and the exploration of performance limits. Re-commissioning with beam after the Christmas technical stop took around 3 weeks. 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.

There was then a scrubbing run of 10 days which included 50 ns injection commissioning [1]. 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.

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  $2.4 \times 10^{33}$  cm<sup>-2</sup>s<sup>-1</sup> and some healthy delivery rates which topped 90 pb<sup>-1</sup> in 24 hours.

The next step up in peak luminosity followed a reduction

in  $\beta^*$  in ATLAS and CMS from 1.5 m to 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  $\beta^*$  and further gentle increases in bunch intensity produced a peak luminosity of  $3.8 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ , well beyond expectations at the start of the year.

### 2012/2013

2012 was a production year at an increased beam energy of 4 TeV. The choice was made to continue to exploit 50 ns and run with a total number of bunches of around 1380. Based on the experience of 2011, the decision was taken to operate with tight collimator settings. The tighter collimator hierarchy shadows the inner triplet magnets more effectively allowing a more aggressive squeeze to a  $\beta^*$  of 0.6 m. The price to pay was increased sensitivity to orbit movements, particularly in the squeeze, and increased impedance. The latter having a clear effect on beam stability as expected. Peak luminosity got up close to its peak pretty quickly. This was followed by a determined and long running attempts to improve peak performance. This was successful to a certain extent, revealed some interesting issues at high bunch and total beam intensity, but had little effect on integrated rates. Instabilities, discussed below, although never debilitating, were a reoccurring problem and there were phases when they cut into operational efficiency.

It was very long operational year and included the extension of the proton-proton run until December resulting in the shift of a four week proton-lead run to 2013. Integrated rates were healthy at around the  $1 \text{ fb}^{-1}$  per week level and this allowed a total for the year of about  $23 \text{ fb}^{-1}$  to be delivered to both ATLAS and CMS.

### Other users

Besides the delivery of high instantaneous and integrated proton-proton luminosity to ATLAS and CMS, the LHC team was also able to fulfil a number of other physics programs.

- 2010 and 2011 saw lead-lead ion runs which delivered 9.7 and  $166 \mu\text{b}^{-1}$  respectively at an energy of 3.5Z TeV [3]. Here the clients were ALICE, ATLAS and CMS.
- Luminosity levelling at around  $4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$  via transverse separation, with a tilted crossing angle to make life difficult, enabled LHCb to collect 1.2 and  $2.2 \text{ fb}^{-1}$  in 2011 and 2012 respectively.
- ALICE enjoyed some sustained proton-proton running in 2012 at around  $5 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$  with collisions between enhanced satellite bunches and the main bunches.
- There was a successful  $\beta^* = 1 \text{ km}$  run for TOTEM and ALFA [4]. With  $t_{\min}$  of approximately  $0.0004 \text{ GeV}^2$

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 [5]. Here the clients were ALICE, ATLAS, CMS and LHCb.

## PERFORMANCE

One of the main features of operations in 2011 and 2012 was the use of the high bunch intensity with 50 ns bunch spacing offered by the injectors. As shown in table 2 the injector complex has succeeded in delivering beam with significantly higher bunch intensities with lower emittances than nominal. This is particularly significant for the 50 ns beam. Happily the LHC has proven capable of absorbing these brighter beams, notably from a beam-beam perspective. This fact has lead to the LHC choosing to operate with 50 ns in both 2011 to 2012 and pushing hard at this bunch spacing. The clear cost has been increased pile-up for the high luminosity experiments which they have successfully learnt to deal with.

Table 2: 2012 values of beam parameters at exit of SPS

Bunch spacing [ns]	Protons per bunch	Emittance [mm.mrad]
50	$1.7 \times 10^{11}$	1.8
25	$1.2 \times 10^{11}$	2.7
25 design	$1.15 \times 10^{11}$	3.75

In short the LHC has achieved good luminosity performance between 2010 and 2012 via the following.

- Exploiting the important advantage that high bunch intensities bring (luminosity proportional to  $N_b^2$ ). Here the bunch intensity has been up to 150% of nominal with the 50 ns bunch spacing.
- The normalized emittance going into collisions has been around 2.5 mm.mrad i.e. 67% of nominal. Again this is 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 [6]
- It has proved possible to squeeze to a  $\beta^*$  of 60 cm thanks to the measurement of good aperture in the interaction regions (credit to alignment, respect of mechanical tolerances, optics measurement and correction, and orbit correction and stability).

The corresponding values for the main luminosity related parameters at the peak performance of the LHC through the years are shown in table 3. The design report values are shown 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

Table 3: Performance related parameter overview

Parameter	2010	2011	2012	Design value
Beam energy [TeV]	3.5	3.5	4	7
$\beta^*$ in IP 1 and 5 [m]	3.5	1.0	0.6	0.55
Bunch spacing [ns]	150	75/50	50	25
Number of bunches	368	1380	1380	2808
Max. bunch intensity [protons per bunch]	$1.2 \times 10^{11}$	$1.45 \times 10^{11}$	$1.7 \times 10^{11}$	$1.15 \times 10^{11}$
Normalized emittance at start of fill [mm.mrad]	$\approx 2.0$	$\approx 2.4$	$\approx 2.5$	3.75
Peak luminosity [ $\text{cm}^{-2}\text{s}^{-1}$ ]	$2.1 \times 10^{32}$	$3.7 \times 10^{33}$	$7.7 \times 10^{33}$	$1 \times 10^{34}$
Max. mean number of events per bunch crossing	4	17	37	19
Stored beam energy [MJ]	$\approx 28$	$\approx 110$	$\approx 140$	362

sevenths of the design energy with a  $\beta^*$  of 0.6 m (cf. design value of 0.55 m) with half nominal number of bunches.

Operational efficiency has also been good and occasionally excellent as illustrated in table 4.

Table 4: Performance highlights

Max. luminosity delivered in one fill	237 $\text{pb}^{-1}$
Max. luminosity delivered in 7 days	1.35 $\text{fb}^{-1}$
Longest time in stable beams (2012)	22.8 hours
Longest time in stable beams over 7 days	91.8 hours

## OVERVIEW OF MACHINE CHARACTERISTICS

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

- The LHC has excellent single beam lifetime at 4 TeV before collisions of over 300 hours and on the whole the LHC enjoys excellent vacuum conditions in both warm and cold regions.
- With a peak luminosity of around  $7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ , the start of a fill the luminosity lifetime is initially in the range 8 to 10 hours increasing as the fill develops. There is minimal drifts in beam overlap during physics and the beams are generally very stable.
- There is excellent field quality, coupled with good correction of non-linearities. Certainly dynamic aperture appears not to be an issue.
- There is low tune modulation, low power converter ripple, and low RF noise.
- Head-on beam-beam is not a limitation although long range has to taken reasonably seriously with enough separation at the long range encounters guaranteed by sufficiently large crossing angles. The linear beam-beam parameter achieved in operations is around 0.02.

- Collective effects have been seen with the high bunch intensities. Single and coupled bunch instabilities have been suppressed 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.

- The linear optics is well measured and remarkably close to the machine model. The bare  $\beta$  beating is acceptable and has been corrected to excellent [7]. The availability of measurement and impressive analysis tools should be noted.
- The magnetic machine is well understood. The modelling of all magnet types by the FIDEL team has delivered an excellent field description at all energies [8]. This model includes persistent current effects which have been fully corrected throughout the cycle. A long and thorough magnet measurement and analysis campaign meant that the deployed settings produced a machine remarkable close to the untrimmed model.
- There is better than expected aperture due excellent alignment and respect of mechanical tolerances.
- The  $\beta^*$  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, and collide are largely sequencer driven. The sequence is generally reliable and good beam lifetime is maintained throughout the whole process.

- A strict pre-cycling regime means that the magnetic machine is remarkably reproducible. This is reflected in the optics, orbit, collimator set-up, tune and chromaticity. Importantly orbit stability (or the ability to consistently correct back to a reference) means that collimator set-up remains good for a year's run [9].
- The total intensity has reached  $2.2 \times 10^{14}$  i.e. 70% of nominal. Here a fully trustworthy machine protection system (detailed below) has been instrumental in providing the confidence to routinely deal with 140 MJ beams.

## AVAILABILITY AND ISSUES

Availability has, in general, been pretty good considering the size, complexity and operating principles of the LHC. Of note is the good availability of the critical LHC cryogenics system. Issues, outlined below, have seen vigorous follow-up and consolidation has been performed. An outline of 2012's availability is shown in table 5. A 257 day run included around 200 days dedicated to proton-proton physics. 36.5% of the time was spent in Stable Beams with an overall Hübner factor of around 0.18. This is encouraging for a machine only 3 years into its operational lifetime.

Table 5: LHC availability 2012

Mode	% of scheduled time
Access	14%
Setup	28%
Beam in	15%
Ramp and squeeze	8%
Stable beams	36%

There have inevitably been a number of issues arising during the exploitation of the LHC. A brief outline is provided below.

Initially single event effects (SEEs) caused by beam induced radiation to tunnel electronics was a serious cause of inefficiency. However this problem had been foreseen and its impact was considerably reduced following a sustained program of mitigation measures coordinated by the R2E (Radiation to Electronics) team [10]. There were several shielding campaigns prior to the 2011 run including relocations “on the fly” and equipment upgrades. The 2011/12 Christmas stop saw some “early” relocation and additional shielding and further equipment upgrades. This has resulted in the reduction of premature dumps from  $\approx 12$  per  $\text{fb}^{-1}$  to  $\approx 3$  per  $\text{fb}^{-1}$  in 2012, going a long way to helping the efficiency of integrated luminosity delivery.

UFOs (Unidentified Falling Objects) have now been well studied and simulated [11]. 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  $200 \mu\text{s}$ ). With the increase in energy to 6.5 TeV and the proposed move to 25 ns there is poten-

tially 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.

Beam induced heating has been an issue and essentially all cases have been local and in some way due to non-conformities either in design or installation. The guilty parties have been clearly enumerated [12]. Design problems have affected the injection protection devices (TDI) and the mirror assemblies of the synchrotron radiation telescopes. Installation problem have occurred in a low number of vacuum assemblies.

Beam instabilities are an interesting problem that dogged operations through 2012. Although never debilitating there were times when they cut into operational efficiency. It should be noted that these problems paralleled a gentle push in bunch intensity with the peak going into stable beams reaching around  $1.7 \times 10^{11}$  protons per bunch i.e. ultimate bunch intensity. Cofactors included increased impedance from tight collimator settings; smaller than nominal emittance; and operation with low chromaticity during the first half of the run [13].

The final 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. During the scrubbing run with 25 ns beams at 450 GeV between 6 and 9 December 2012, scrubbing effects in the arcs saw quite rapid initial conditioning. The secondary electron yield (SEY) evolution significantly slowed down during the last scrubbing fills and preliminary conclusions [14] are that an electron cloud free environment with 25 ns beam after scrubbing at 450 GeV seem not be reachable in a reasonable time. Operation with high heat load and electron cloud density (with blow-up) seems to be unavoidable with a corresponding slow intensity ramp-up.

## SYSTEM PERFORMANCE

The LHC has enjoyed an excellent and mature system performance across the board. This performance has come about by: attention to detail; painstaking measurements and set-up; continued system development and optimization. Space precludes a detailed performance breakdown; a few key points are given below.

The **injection** process is well mastered but there are a number of outstanding problems which have cut into availability [15]. The stability of transfer lines is not ideal and frequent steering can be necessary. This is principally linked to the stability of both the SPS orbit and the SPS extraction kickers. Several issues, mainly caused by beam induced heating and frequent cycling, were encountered at the injection protection devices (TDI) at both injection points. There have also been a number of failures of the injection kickers (MKI) which have also suffered from beam induced heating. Consolidation of both the MKIs and TDIs is foreseen for LS1.

In general the **LHC Beam Dump System (LBDS)** has worked impeccably as required. No major operational problems or long downtime were caused by the LBDS [15]. Beam based set-up and checks are performed at the start of the operational year. The downstream protection devices form part of the collimator hierarchy and their proper positioning is verified periodically. Full post-operational checks are performed (IPOC and XPOC) after each dump. Some weak points have been identified and the system will be upgraded and made safer for operation at 6.5 TeV.

**Collimation** has maintained an excellent proton cleaning efficiency [9]. Semi-automatic tools have improved collimator set-up times during alignment. The operational strategy in 2011-2012 saw only one full alignment in IR3/IR7. Cleaning efficiency and the hierarchy is checked by periodic loss maps. Alignment of the tertiary collimators is repeated for new physics configurations.

Operation was pinned by excellent performance of **Machine Protection System** and associated sub-systems [16]. The machine protection team has ensure rigorous machine protection follow-up, qualification and monitoring. The beam drives a subtle interplay of the LBDS, the collimation system and protection devices, which rely on a well-defined aperture, orbit and optics for guaranteed safe operation. The beam dump, injection and collimation teams have pursued well-organized programs of set-up and validation tests which have permitted routine collimation of 140 MJ beams without a single quench from stored beams.

**Transverse feedback** has successfully dealt with: injection oscillations; injection gap cleaning; abort gap cleaning; emittance preservation; and coherent instabilities. The system is implicated in all phases of operations. Novel applications have proved very useful in machine studies.

**Orbit and tune feedbacks** are essential to operations. Orbit feedback is obligatory in the ramp and squeeze, tune feedback in the ramp only.

**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.

Superb performance of the **power converters** is observed with excellent tracking between reference and measured and excellent tracking between the converters around the ring.

There was good performance from the key **RF** systems: power, beam control, low level and diagnostics [19].

**Software and controls** have benefited from a coherent approach and early deployment on the injectors and transfer lines and have facilitated rather than hampered commissioning. After the inevitable debugging, things have settled down and operations enjoys some excellent facilities and functionality.

## CONCLUSIONS

The LHC is performing well and a huge amount of experience and understanding has been gained over the last 3

years. There is good system performance, excellent tools, and reasonable availability following targeted consolidation. Good luminosity performance has been achieved by harnessing the excellent beam quality from injectors and fully exploiting the options in the LHC.

The overall performance is the result of a remarkable amount of effort on the part of all the teams involved.

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