Status of the LHC

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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 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. At this stage the basics were sorted out well, laying the foundation for what followed. 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 centre of mass (COM) energy of 8 TeV. Again limits were pushed revealing some interesting 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/the Higgs boson on July 4th 2012.

| Year | Overview         | COM energy | 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 (μ) was around 12 with Poisson tails up to approximately 20.
In 2012 mu had increased to around 30 events/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 deliver physics to a number of other users.

- 2010 and 2011 saw lead-lead ion runs which delivered 9.7 and 166 $\mu$b$^{-1}$ respectively at an energy of 3.5Z TeV. Here the clients were ALICE, ATLAS and CMS.
- Luminosity levelling at around $4\times10^{32}$ cm$^{-2}$s$^{-1}$ via transverse separation, with a tilted crossing angle to make life difficult, 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 $5\times10^{30}$ 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 $t_{\text{min}}$ 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 (1) and (2).

$$\mathcal{L} = \frac{N^2 k_b f}{4\pi \sigma_x^* \sigma_y^*} F$$  \hspace{1cm} (1)

Assuming round beams and equal values of the beta function for both beams in both planes, this may be expressed:

$$\mathcal{L} = \frac{N^2 k_b f \gamma}{4\pi \epsilon_n \beta^*} F$$  \hspace{1cm} (2)

Here:
- $N$ is the number of particles per bunch
- $k_b$ is the number of bunches
- $f$ is the revolution frequency
- $\gamma$ is the usual relativistic factor
- $\sigma_x^*$ and $\sigma_y^*$ are the horizontal and vertical beam sizes at the interaction point
- $\epsilon_n$ is the normalized emittance
- $\beta^*$ is the value of the beta function at the interaction point
- $F$ is the geometrical reduction factor arising from the crossing angle

The second variation (2) nicely illustrates the parameters that the LHC has exploited in the last 3 years in the search of instantaneous luminosity performance. 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 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 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.
Table 2. Performance related parameter overview

| Parameter                          | Value in 2012 | Design value |
|------------------------------------|---------------|--------------|
| Beam energy [TeV]                  | 4             | 7            |
| \(\beta^*\) 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 \(-1.7 \times 10^{11}\) | 1.15 \times 10^{11} |
| Normalized emittance at start of fill [mm.mrad] | 2.5 | 3.75 |
| Peak luminosity [cm\(^{-2}\)s\(^{-1}\)] | 7.7 \times 10^{33} | 1 \times 10^{34} |
| Max. mean number of events per bunch crossing | \(\approx 40\) | 19 |
| Stored beam energy [MJ]            | \(\approx 140\) | 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 succeed in delivering beam with significantly more protons per bunch than nominal 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 3. 2012 values of beam parameters at exit of SPS

| Bunch spacing [ns] | Protons per bunch | Emittance [\(\mu m\)] |
|--------------------|-------------------|------------------------|
| 50                 | \(1.7 \times 10^{11}\) | 1.8                    |
| 25                 | \(1.2 \times 10^{11}\) | 2.7                    |

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.
- 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.
- It has proved possible to squeeze to a \(\beta^*\) 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 \(2.2 \times 10^{14}\) 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.
Operational efficiency has also been good and occasionally excellent as illustrated in table 4.

| Table 4. Integrated performance highlights |
|------------------------------------------|
| Max. luminosity delivered in one fill     | 237 pb⁻¹ |
| Max. luminosity delivered in 7 days       | 1.35 fb⁻¹ |
| Longest time in stable beams (2012)       | 22.8 hours|
| Longest time in stable beams over 7 days  | 91.8 hours (55%) |

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.

- 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-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.
- Collective effects have been seen with the high bunch intensities. Single and coupled bunch instabilities have been supressed 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 [1].
- There is a very good magnetic model which includes dynamic effects. This a major contributory factor to excellent agreement with the optics model. It has also allowed the once feared persistent current decay and snapback to be tamed.
- 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, collide are largely sequencer driven. The devils is in the details but on the whole the process is well mastered. 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. 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 [2].
• Operations is unpinned by superb performance of machine protection and associated systems. This includes the beam interlock system, the beam dump system, the beam loss monitors, and the collimation system. There is rigorous machine protection follow-up, qualification, and monitoring; all non-conformities are examined rigorously. The importance of this to the success of the LHC so far can not be over stressed - there has been a move from commissioning to real confidence in under two years.

Availability has, in general, been pretty good considering the size, complexity and operating principles of the LHC. Issues, outlined below, have seen vigorous follow-up and consolidation has been performed. A outline of 2012’s availability is shown in table 5. 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 it’s 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.

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

4. Issues
There have inevitably been a number of challenges arising during the exploitation of the LHC. A brief outline is provided below together with potential mitigation measures.

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 sustained program of mitigation measures coordinated by the R2E (Radiation to Electronics) team. The success of their efforts are impressive. 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 fb\(^{-1}\) to \( \approx 3 \) per fb\(^{-1}\) in 2012, going a long way to helping the efficiency of integrated luminosity delivery.

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].

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 [4]. Design problems have effected the injection dumps (TDI) and the mirror assemblies of the synchrotron radiation telescopes. Installation problem have occurred in a low number of vacuum assemblies.

Instabilities were 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.

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.

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 $2.7 \times 10^{14}$. 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 [5] 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.)

5. 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. Key LS1 work packages are outlined below.

- 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)
- Measures to further reduce SEE (R2E) - the R2E project is aiming for 0.3 premature dumps per fb$^{-1}$ via a combination of: equipment relocations at 4 LHC points; additional shielding; and critical system upgrades (QPS, FGC)
- 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
6. Post LS1

6.1. Energy
The magnets coming from the damaged sector 34 do not show degradation of performance, and the best estimates to train the LHC (with large errors) are: 30 quenches to reach 6.25 TeV; and 100 quenches to reach 6.5 TeV [6]. With two quenches/day this would mean between 2 to 5 days of training per sector. The proposed plan is to try to reach 6.5 TeV in four sectors in mid 2014. Based on that experience, the decision can then be made to go at 6.5 TeV or step back to 6.25 TeV.

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 required 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 $\beta^*$;
- 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. Beam from the injectors LS1 to LS2
The bunch spacings and associated performance on offer from the injectors post LS1 are shown in table 6. 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 $1.7 \times 10^{11}$ protons per bunch with an emittance of around 2.5 $\mu$m going into collision. Further imaginative developments on the PS side have lead to the creation of the so-called BCMS (Batch Compression and (bunch) Merging and (bunch) Splittings) scheme [7] which offer remarkably low emittance coupled with healthy bunch intensity as shown in table 6.

This scheme should open the way to well above nominal performance in the post LS1 era. Major upgrades of the injectors, including the increase of the Booster to PS transfer energy, and the connection of LINAC4 to the Booster will only take place during LS2. These upgrades should open the way in their turn to ultimate LHC performance (i.e. peak luminosity of order $2.3 \times 10^{34}$ cm$^{-2}$ s$^{-1}$).

6.4. Potential performance
The potential performance for four scenarios enumerated in table 6 are shown in table 7. The estimates assume:
- a beam energy of 6.5 TeV;
- a 1.1 ns bunch length (nominal);
Table 6. Post LS1 beam parameters at the exit of SPS

| Scheme          | Protons per bunch $[10^{11}]$ | Emittance exit SPS $[\mu m]$ | Emittance into collisions $[\mu m]$ |
|-----------------|-------------------------------|------------------------------|-------------------------------------|
| 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                                 |

- a scheduled 150 days of proton physics with a reasonable optimistic availability (Hübner factor $\approx 0.2$);
- 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.

Table 7. Post LS1 performance estimates - usual caveats apply

| Scheme          | Number of bunches | Protons per bunch $[10^{11}]$ | $\beta_x^* [\text{cm}] / \beta_y^* [\text{cm}] / \text{half crossing angle [} \mu \text{rad]}$ | Emittance $[\mu m]$ | Peak luminosity $[10^{34} \text{cm}^{-2}\text{s}^{-1}]$ | File-up | Int. lumin $[\text{fb}^{-1}]$ |
|-----------------|-------------------|-------------------------------|-----------------------------------------------|---------------------|-------------------------------------------|---------|-----------------------------|
| 25 ns           | 2760              | 1.15                          | 55/43/189                                    | 3.75                | 9.3e33                                    | 25      | 24                          |
| 25 ns BCMS      | 2520              | 1.15                          | 45/43/149                                    | 1.9                 | 1.7e34                                    | 52      | 45                          |
| 50 ns           | 1380              | 1.6                           | 42/43/136                                    | 2.3                 | 1.6e34                                    | 87      | 40                          |
| 50 ns BCMS      | 1260              | 1.6                           | 38/43/115                                    | 1.6                 | 2.3e34                                    | 138     | 40                          |

From table 7 one notes the following.

- 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 a healthy $1.7 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ with peak $<\mu \text{n}u>$ of around 50 with 83% of the nominal intensity.
- The now operational 50 ns scheme gives a virtual luminosity of $1.6 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ but with a pile-up of over 70 making levelling mandatory.
- The BCMS 50 ns scheme gives a virtual luminosity of $2.3 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ with a pile-up of over 100 making levelling even more mandatory.

7. Long term plans

An outline of the tentative 10 year plan is presented below. Some adjustments will surely be made over the coming years. The results from operation at high energy will naturally be important and could well lead, to, say, a delay of LS2.
2015 - 2017 Physics operation, initially at 6.5 TeV. One might hope for a peak luminosity in the region of \(1.7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\). 2015 will be a re-commissioning year and likely to deliver less integrated luminosity than a nominal year at 6.5 TeV.

2018 Long shutdown 2 - here the main focus will the injector complex upgrade including connection of LINAC4 to the booster.

2019 - 2021 Given the increased performance of the injectors, it might possible to approach the ultimate performance of the LHC i.e. a luminosity of \(2.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\).

2022 Long shutdown 3: this is essentially for the HL-LHC upgrade which includes the installation of new inner triplet magnet assemblies.

8. Conclusions
The LHC has shown the results of excellent design, construction, and installation. Operations 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.

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