PROCEEDINGS OF SCIENCE

# LHC STATUS AND PLANS (INCLUDING UPGRADES)

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The results of the LHC during the last year of operation of Run I are shown (updated to the date of the conference). Particular attention is put on the limits of the machine, to the solutions to reduce their impact and the plan to fix them, together with a long planning for improvement of the performance.

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[1] Speaker

## 1. Introduction

The nominal LHC parameters [1], with a luminosity of $10^{34}$ $cm^{-2}s^{-1}$, imply a number of collisions per crossing between 30 and 50; the resulting $10^9$ collisions per second constitute a big challenge for the detectors and for the acquisition and analysis of data. The experiments have in fact to deal with very complicate collision patterns to analyse and about 15 millions gigabytes of data are produced per year, requiring for an incredible computational power.

In terms of challenges for the LHC, the machine is working at a factor 200 in stored beam energy (360 MJ) with respect to any other machine ever built. And this is possible thanks to, in particular, a complex collimation system and a reliable beam dumping system.

### 1.1 The collimation system

To operate at nominal performance the LHC requires a large and complex (multi-stage) collimation system. Differently from previous colliders, which used collimators mostly for experimental background conditions, the LHC can, in fact, only run with collimators, due to the very small quench limit (few $mJ/cm^3$) of its magnets. And the collimation hierarchy has to be respected at any stage of operation in order to achieve satisfactory protection and cleaning.

Lower $\beta^*$ implies tighter collimator settings as well as a careful alignment, together with beam sizes and orbit well within tolerance. In Table 1, the settings for all collimators are listed, as they were used during the three years of operation.

| **Year** | **2010** | **2011** | **2012** | **Nom.** |
|---|---|---|---|---|
| **E [TeV]** | 3.5 | 3.5 | 4 | 7 |
| **$\beta^*$[m]** | 3.5 | 1.0 | 0.6 | 0.55 |
| **TCP** | 5.7 | 5.7 | 4.3 | 6.0 |
| **TCS@7** | 8.5 | 8.5 | 6.3 | 7.0 |
| **TCLA@7** | 17.7 | 17.7 | 8.3 | 10.0 |
| **TCS@6** | 9.3 | 9.3 | 7.1 | 7.5 |
| **TCT** | 15.0 | 11.8 | 9.0 | 8.3 |
| **Aperture** | 17.5 | 14.1 | 10.5 | 8.4 |

**Table 1:** Summary of collimator settings (in normalized sigmas) used during the three years of operation.

### 1.2 Interaction region geometry

In the IRs, the beams are first combined into a single common vacuum chamber and then re-separated in the horizontal plane. Because of the tight bunch spacing and to prevent undesired parasitic collisions, in the region where the beams circulate in the common vacuum chamber, a parallel separation is applied in one plane (mostly effective at the IP), which is collapsed to 0 when the beams are colliding; a crossing angle is also used in the other plane.

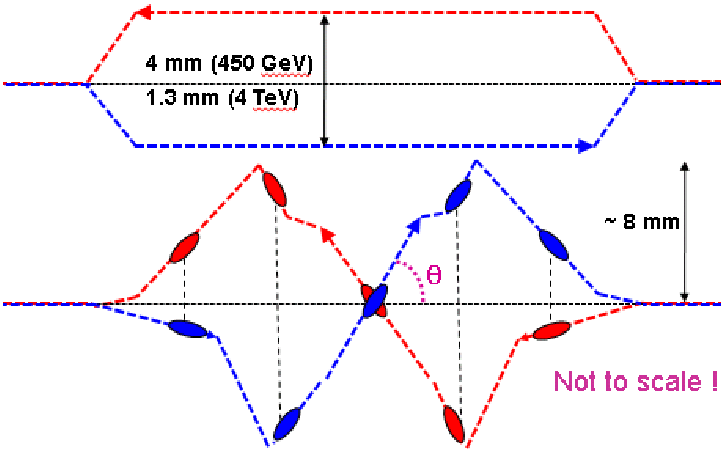

**Figure 1:** separation and crossing angles.

## 2. Motivation for an upgrade

Two are the main drivers for the upgrade of a machine: more energy and more luminosity. For the first case, it means increasing either the circumference (new machine) or the bending field, which demands for a new technology (which is the objective of the high energy LHC program).

About an increase in the luminosity, if we look at the luminosity formula (1)

$$L = \frac{k N_b^{\,2} f}{4\pi\sigma_x^*\sigma_y^*} F = \frac{k N_b^{\,2} f \gamma}{4\pi\beta^*\varepsilon^*} F \qquad (1)$$

with $\sigma_x^*\sigma_y^* = \dfrac{\beta^*\varepsilon^*}{\gamma}$ for round beams,

γ = E/E0,

f is the revolution frequency (11.25 kHz),

k is the number of colliding bunch pairs,

$N_b$ is the bunch population,

σ is the beam size at IP,

ε* is the normalized emittance,

β* the betatron (envelope) function at the IP,

F is a reduction factor due to the crossing-angle,

we can recognize several ways for the maximization of the luminosity:

- increase the energy (we come back to the need of a new technology)
- increase the number of bunches or the protons per bunch (depending on the injector chain performance)
- reduce the beam size (injector performance)
- reduce β*

- reduce the emittance.

## 2.1 What limits the β*?

In the high luminosity IRs, the triplet quadrupoles define the machine aperture limit for squeezed beams; β* is constrained by the beam envelope, the margin between TCT and triplet and the crossing angle.

During 2011, the β* was reduced from 1.5 to 1 m; the first result resulted from the interpolation of the aperture measurements at 450 GeV, while for the second one, aperture measurements were done at 3.5 TeV. In 2012, the β* was further reduced, thanks to the increase in energy (smaller beams) and the use of tight collimator settings.

An additional reduction of the β* would demand for larger aperture triplets.

## 2.2 What limits the number and population of bunches?

High bunch population and tight bunch spacing make the beams prone to instabilities related to impedances, i.e. to self-generated fields (called wake field in time domain, beam-coupling impedance in frequency domain): two particles travelling in the same direction interact through the direct space charge effect and through the pipe wall (wall impedance).

In 2012 instabilities have become more critical due to higher bunch intensity and tighter collimators settings. The cures chosen are the use of transverse feedback (‘damper’ that measures the oscillations and sends corrective deflections) and of non-linear magnetic fields (sextupoles, octupoles, beam-beam) that produce a frequency spread among particles, which kills coherent motion.

Also, the number and population of bunches is limited by the electron cloud effect, that is the excitation of electrons from the pipe walls (often appearing as an avalanche) when intense, shortly spaced bunches are passing through the pipe. This was observed in the LHC as soon as the operation with trains started and became worst and worst moving down in bunch spacing from 150, 75, 50 to 25 ns. It is normally associated to vacuum pressure rise, single-bunch and multi-bunch instabilities (leading to incoherent beam size growth) and heat load on the cryogenics. The chosen remedy is the conditioning by beam-induced electron bombardment (“scrubbing”) leading to a progressive reduction of the threshold above which the avalanche occurs.

## 2.3 Heating damage

High intensity beams may deposit large amounts of power via the EM fields they generate; this might come from design, manufacturing or installation errors that may lead to damage of accelerator components. This was the case, in the LHC, for components like the mirror of the synchrotron light telescope, some RF fingers and the highly deformed beam screen in an injection protection device (Figure 2).

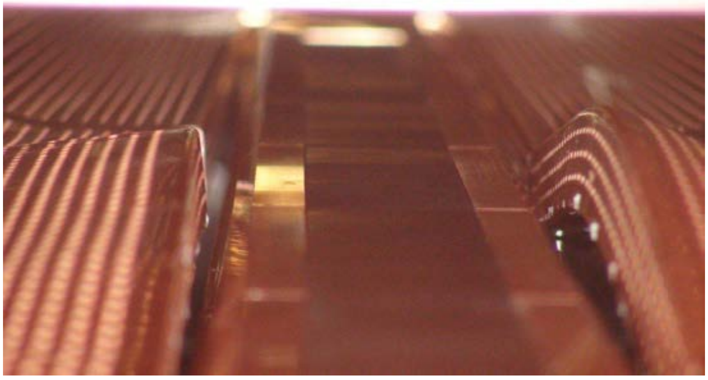

**Figure 2:** damaged beam screen in an injection protection device.

### 2.4 Unidentified Falling Objects

The UFOs are thought to be small (10’s of mm) dust particles falling into the beam, which generate very fast beam losses. If the losses are too high, the beams are dumped to avoid a magnet quench. The number of such events in the past years has been [2]:

18 beam dumps in 2010
17 beam dumps in 2011
15 beam dumps so far in 2012.

A progressive decrease of the UFO rate has been observed in the past, but they might become a serious issue for 7 TeV operation, since the losses induced in the magnets by the UFOs will increase by a factor 3 (density at shower max in the magnets) and the tolerable loss will go down by a factor 5 (higher B field): scaling the rate and amplitudes of 2012 one predicts at least one beam dump per day.

### 2.5 Radiation to Electronics

Operation in these years has shown that the electronics in the tunnel suffers from beam loss induced single event errors (especially quench protection system electronics, power converter and cryogenics PLCs): 74 of these events were observed in 2011 and 140 in 2012 [3]. Despite the increased luminosity production and consequent increase in loss rate, the number of SEE in 2012 was kept low thanks to a series of mitigation actions: equipment relocation (sometimes to surface), additional shielding and more error robust firmware. 2011 Christmas mitigation actions served to reduce the SEUs by a factor 3. A massive campaign of relocation and shielding is also planned for LS1.

## 3. Machine performance

The performance of the LHC in its first three years (Table 2) have been really impressive, above all if compared with the nominal design parameters.

| Parameter | 2010 | 2011 | 2012 | Nom. |
|---|---|---|---|---|
| **E [TeV]** | 3.5 | 3.5 | 4.0 | 7.0 |
| **$N_b$ [$10^{11}$/b]** | 1.2 | 1.45 | 1.6 | 1.15 |
| **k** | 368 | 1380 | 1380 | 2808 |
| **Spacing [ns]** | 150 | 75/50 | 50 | 25 |
| **Stored E [MJ]** | 25 | 112 | 140 | 362 |
| **ε (μm rad)** | 2.4 | 2.4 | 2.5 | 3.75 |
| **β* [m]** | 3.5 | 1.5/1 | 0.6 | 0.55 |
| **L [$cm^{-2}s^{-1}$]** | $2x10^{32}$ | $3.5x10^{33}$ | $7.6x10^{33}$ | $10^{34}$ |
| **Beam-beam/IP** | -0.0054 | -0.0065 | -0.0069 | -0.0033 |
| **Pile-up@beg.fill** | 8 | 17 | 38 | 26 |

**Table 2:** Parameters and performance in 2010-12.

The strategy followed to reach this performance is shown in Figure 3, where the comparison of peak luminosities in 2011 and 2012 is given.

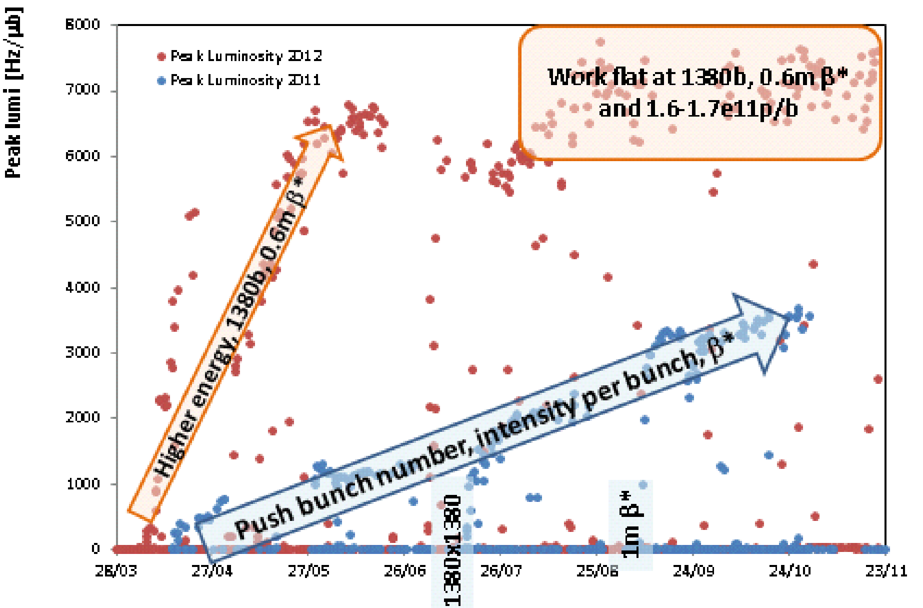

**Figure 3:** Peak luminosity in 2011 and 2012.

The results, in terms of integrated luminosity, obtained so-far by the LHC are shown in Figure 4: with a target of 15-20 $fb^{-1}$, the present result is about 22 $fb^{-1}$.

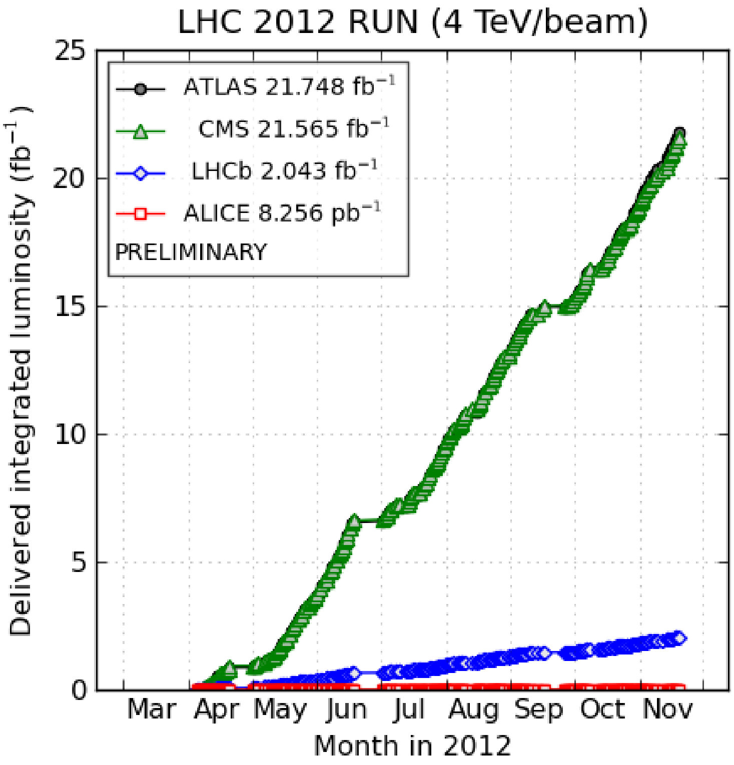

**Figure 4:** Integrated luminosity along the year 2012.

## 4. The upgrade program

The 10 years plan for the LHC foresees three long shut-down (LS) of the machine for major upgrades.

### 4.1 LS1

The objective of LS1 [4] is to prepare the machine for 6.5/7 TeV operation in 2015. The actual plan includes:

- The consolidation of the 13 kA splices with the approved design of shunt and insulation (open 1695 interconnections and redo ~1500 splices)
- The installation of the missing DN200 valves, as completion of the compensatory measures in case of major incident
- The replacement of 15 dipole and 4 quadrupole weak magnets (weak insulation, faulty quench heaters, wrong beam screen, missing correctors)
- The consolidation of faulty circuits
- The R2E mitigation actions, with relocation of electronics in 3 points
- The installation of collimators with integrated button BPMs (tertiary collimators and a few secondary collimators).

All these activities will be performed in about 20 months, after which the machine should be able to work at 7 TeV (most probably initially 6.5, to have a reduced number of training quenches).

### 4.2 LS2

The second long shut-down will be mainly devoted to a major upgrade of the injectors (LINAC4, 2GeV PS Booster, SPS coating). Nonetheless, many interventions will be performed on the LHC too:

- The dispersion suppressor cryo-collimators with 11 T in 1 IP, to avoid off-momentum protons on SC dipoles
- Vertical SC links in P1, P5 (IT and stand-alone)
- Cryogenics at point 4, with the separation between SC magnets and RF cavities cooling circuit
- Improved triplet cooling
- Some beam diagnostics
- Some collimators.

The declared objective is obtaining a luminosity of $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$.

### 4.3 LS3

1.2 km of the LHC tunnel will be modified during LS3, with new triplets and separation-recombination dipoles plus matching section quadrupoles, with new cryogenics and vertical links for all new elements. Also, the crab cavities should be installed, to cope with the problem of the crossing angle, and new instrumentation and collimators. The declared objective is to push the performance above the ultimate ($5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ or more) and an integrated luminosity of 3000 fb$^{-1}$ by 10-12 years.

## 5. Conclusions

The progress in the performance of the LHC has been so far breath-taking.

The LHC is performing incredibly well (even better than expected) an this is possible thanks to the quality of the design, construction and installation and to the thorough preparation in the injectors which are delivering beams well beyond nominal parameters.

A solid upgrade program is in a very mature state, even if the final parameters will depend on the capacity of the experiments to manage pile-up.

## 6. Acknowledgment

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## References

[1] O. Bruning et al., *LHC Design Report*, Geneva : CERN, 2004. - 548 p.

[2] T. Baer, *private communication*.

[3] LHC Post-mortem database, ihttp://lhc-postmortem.web.cern.ch/lhc-postmortem/

[4] F. Bordry et al., *The First Long Shutdown (LS1) of the LHC*, presented in IPAC 2013, Shanghai, June 2013.