THE FIRST YEARS OF LHC OPERATION

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(On behalf of the LHC team and international collaborators)

Abstract

The operational performance of the LHC machine both for proton and lead ion operation are reviewed for the period 2010 up to the present. The beam parameter path allowing the very high rate of collider performance is presented and discussed. The accelerator issues encountered and those somewhat surprisingly not encountered are also discussed. The short and longer term plans for the LHC are also briefly presented.

INTRODUCTION

The design of the LHC [1] involved many technical challenges and innovations. Table 1 gives a short list of some of the most notable challenges.

The magnetic system produces the highest superconducting field ever used (8.4 Tesla) for an accelerator and in addition employs "double-barrel" magnets where the apertures of both beams are within the same cold mass. The cryogenic system is the largest ever built and operates at 1.9K, and the power converters have a resolution of around 1ppm, and use a powering circuit for each octant of the machine.

Of constant major concern is the stored energy in the magnets and in the beam. For this reason the protection systems, including the collimation system, are crucial in the operation of the collider.

Table 1: Table of Technical Challenges of LHC

Circumference (km)	26.7	100-150m underground
Number of superconducting Dipoles	1232	Cable Nb-Ti, cold mass 37million kg
Length of Dipole (m)	14.3	
Dipole Field Strength (Tesla)	8.4	Results from the high beam energy needed
Operating Temperature (K) (cryogenics system)	1.9	Superconducting magnets needed for the high magnetic field
		Super-fluid helium
Current in dipole sc coils (A)	13000	Results from the high magnetic field
		1ppm resolution
Beam Intensity (A)	0.5	$2.2.10^{-6}$ loss causes quench
Beam Stored Energy (MJoules)	362	Results from high beam energy and high beam current
		1MJ melts 1.5kg Cu
Magnet Stored Energy (MJoules)/octant	1100	Results from the high magnetic field
Sector Powering Circuit	8	1612 different electrical circuits

FIRST 7TEV COLLISIONS

First collisions at 7TeV centre of mass energy were planned for March 30, 2010. The first two attempts at collisions resulted in beam losses for minor technical reasons. On the third attempt, the beams were successfully brought into collision.

The very first events with collisions at 7TeV are shown for the four detectors in Figure 1.

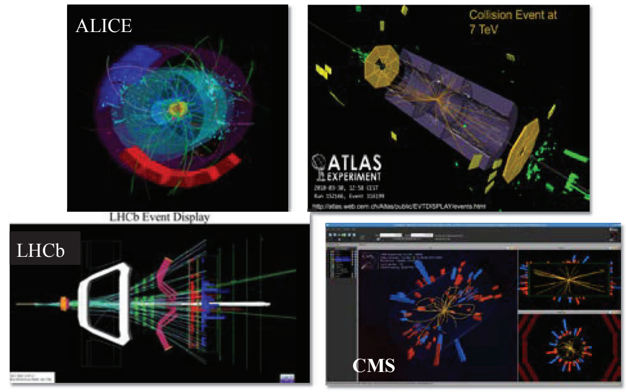

Figure 1: First events at 7TeV in the four LHC detectors.

LHC PERFORMANCE IN 2010/2011

Protons in 2010

Following the first collisions, the goal was to quickly increase the luminosity delivered to the experiments.
The equation for the luminosity is given below:

$$L = \frac{n_b \cdot N_{bunch,1} \cdot N_{bunch,2} \cdot f_{rev}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot R(\phi, \beta^*, \varepsilon_n, \sigma_s)$$

where:

- n_b is the number of bunches per beam;
- N represents the number of protons in a single bunch;
- β^* is the insertion region focusing parameter;
- ε_n is the normalised emittance (related to the cross-section dimension of the beam);
- and R is the interaction region geometric factor.

In 2010, the objective set for the integrated luminosity in 2011 was 1fb^{-1}. To achieve this integrated luminosity calculations had shown that a peak luminosity of $1x10^{32}$ cm^{-2}s^{-1} should be reached by the end of 2010. Figure 2 shows that the peak-luminosity objective was exceeded by more than a factor of 2. This result was obtained mainly by increasing the number of bunches and the current per bunch.

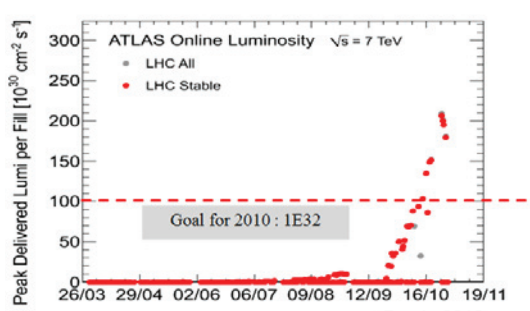

Figure 2: Peak luminosity during 2010 (goal and achieved).

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In 2010, the integrated luminosity delivered to each of the high luminosity detectors (ATLAS and CMS) was $45pb^{-1}$.

Lead Ions in 2010

The change-over from protons to lead ions went very quickly, taking only 4 days to produce colliding lead ions. Operation of the LHC with lead ions was performed for about 4 weeks and produced luminosities well above expectations.

Protons in 2011

The global strategy for operation in 2011 was firstly to re-establish the good performance of 2010 with up to several hundred bunches, followed by beam cleaning and then to increase the number of bunches towards 900 (maximum achievable with a bunch spacing of 75ns). To mitigate against vacuum runaway caused by electron cloud build-up, beam cleaning was done before the increase of the total intensity. Bunch spacing of 50ns was used so as to increase the effectiveness of the beam cleaning. Following the successful beam cleaning runs with 50ns spacing it was decided that physics operation could continue with 50ns thereby increasing the potential maximum number of bunches to close to 1400. In order to allow the accumulation of such large numbers of bunches the number of bunches in the bunch trains coming from the injectors had to be increased. In the first half of the year the trains of bunches were increased progressively from 12 to 144, each step carefully validated by the machine protection panel. Figure 3 show the evolution of the number of bunches, bunch spacing with the peak luminosity in the high luminosity detectors (Atlas shown) as well as the luminosity in the LHCb experiment. It can be seen from Figure 3 that following the change-over to 50ns bunch spacing, the maximum number of bunches (1380) was reached by the end of June. The second half of the year involved reduction of the transverse emittance with an increase in the single bunch intensity followed by a reduction in the β*.

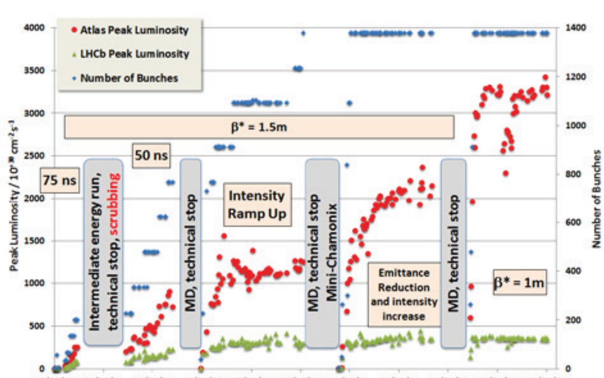

Figure 3: Evolution of operational performance in 2011.

The progress with the beam parameters (Figure 3) produced a peak luminosity in 2011 of $3.6x10^{33}$, significantly higher than that needed for the goal integrated luminosity of $1fb^{-1}$.

Figure 4 shows the evolution of the integrated luminosity during 2011 for Atlas, CMS, and LHCb. It can be seen that the 2011 goal of $1fb^{-1}$ was achieved very early in the year and a total of $6fb^{-1}$ was achieved before the year-end (note that the luminosity calibration was re-evaluated after the end of data taking).

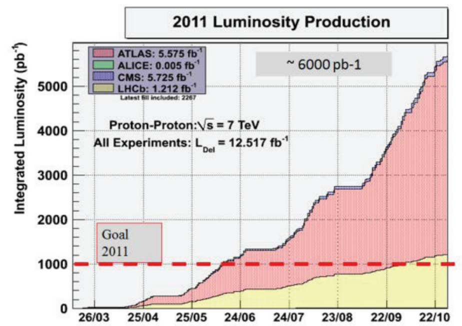

Figure 4: Integrated luminosity in 2011.

It should be noted that the LHCb peak luminosity is limited by the number of events per bunch crossing (event pile-up) and that their luminosity is maintained at the maximum acceptable level throughout the run (luminosity levelling). The technique used for levelling is continuous transverse steering of the "head-on" collisions. Surprisingly this technique does not produce any detrimental effects to the beam via the beam-beam effect. Figure 5 shows a typical luminosity run for LHCb.

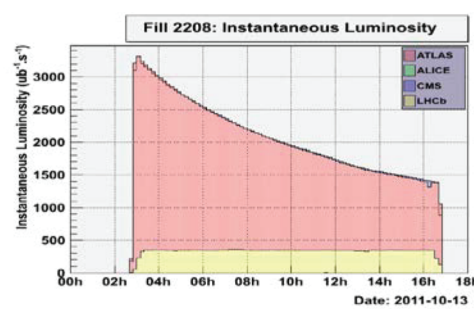

Figure 5: Luminosity levelling in LHCb by transverse steering.

ESTIMATES OF PERFORMANCE IN 2012

Priorities for 2012

Following the 2012 LHC performance workshop (Chamonix), the LHC priorities set by the CERN management were:

- The LHC machine must produce enough integrated luminosity to allow ATLAS and CMS to **independently** discover the Higgs before the start of Long Shutdown 1 (LS1) which starts at the end of 2012.
- The proton-lead ion run at the end of 2012 must be well prepared.

- The necessary machine experiments to allow high energy, useful high luminosity running after LS1 must be performed during 2012.

Table 2 gives the estimates of the integrated luminosity needed in order to achieve the top priority of discovery of the Higgs Boson.

Table 2: Estimates of Required Integrated Luminosity for Discovery of the Higgs Boson

Year	fb-1	signal (in σ)	Beam Energy	
2011	5	2.5	3.5	
2012	15	5	3.5	Needed
2012	11.5	5	4.0	Needed
2012	13.3	5	4.0	addditional 15% for pile up and margin

It is evident from Table 2 that a minimum integrated luminosity of 13.3 fb^{-1} (at 8TeV collision energy) is needed to produce a “5σ” discovery signal for the Higgs boson.

Based on the statistics of 2011 and the beam parameters foreseen in 2012, an estimate of the performance of LHC in 2012 was made towards the end of 2011. This is shown in Figure 6 where slightly more than 16fb^{-1} are predicted, exceeding the needs by a comfortable margin. Figure 6 also shows the actual intregrated luminosity delivered.

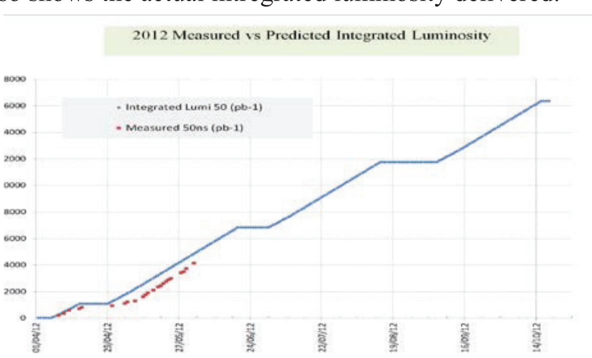

Figure 6: Estimated and actual integrated luminosity.

FUTURE

Table 3: CERN 10 Year Plan

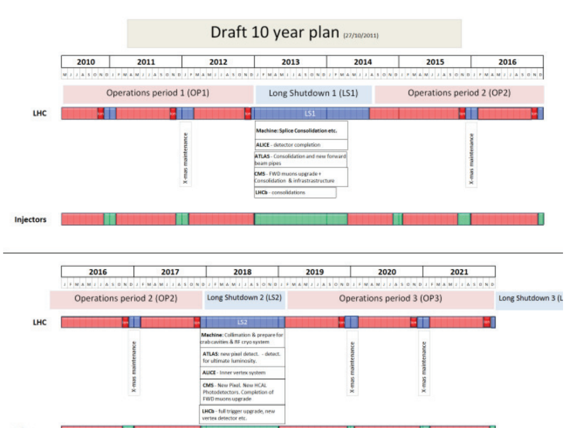

Table 3 shows the 10 year plan for the LHC and the CERN machines. During LS1 all necessary improvements needed for the LHC to reach design energy of 7TeV per beam will be carried out. A major part of this work is the repair and upgrade of the magnet interconnects which caused the incident in 2008.

Estimated Performance in 2015

Following LS1 there is foreseen 3 years of operation at maximum energy. The estimated performance in 2015 (at around 6.5TeV per beam) is given in Figures 9(a) and (b) with 50ns and 25 ns bunch spacing, respectively.

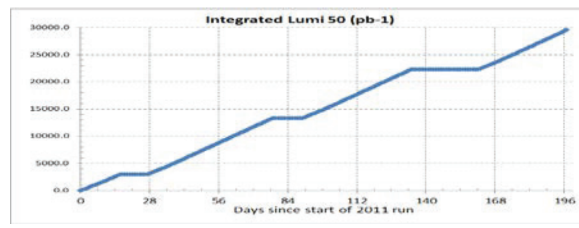

Figure 7(a): Integrated Luminosity Estimate for 2015 (50ns).

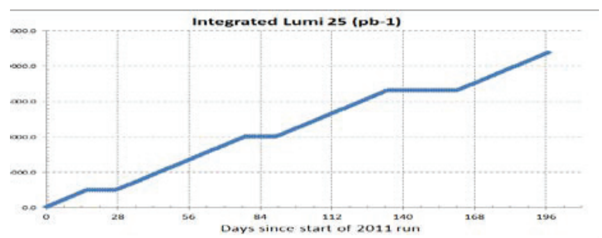

Figure 7(b): Integrated Luminosity Estimate for 2015 (25ns).

Operation at bunch spacings of 50 ns will be problematic for the detectors due to the large pile-up factor. In the particular case of Figure 7(a) the pile-up factor is around 50. Consequently operation with the conditions of Figure 7(b) is more likely with a lower integrated luminosity but a lower pile-up factor of around 17.

Upgrade of the LHC Injector Chain (LIU)

Operation at high energy will be followed by LS2 which is foreseen for the upgrade of the injectors (LHC Injectors Upgrade (LIU)). The injector upgrades are foreseen so as to deliver the beam parameters needed for the HL-LHC upgrade. This requires

1. Connection of the Linac4 to the PS Booster, (if not already achieved) which requires a new PS Booster injection channel
2. Upgrade PS Booster from 1.4 to 2.0 GeV requiring a new main power supply for the magnets, a new RF system etc. aswell as upgrades to the transfer lines, new instrumentation etc.
3. Upgrades to the PS: with a new injection region for 2.0 GeV, new/upgraded RF systems and upgrades to feedbacks systems and beam instrumentation etc.

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4. Upgrades to the SPS will require mitigation against electron cloud effects. This could require a new very high bandwidth feedback system and/or a new coating of the vacuum system. The SPS will also need reduction of the impedance, improved feedback systems and large-scale modification to the main RF system.

LS2 will be followed by 3 years of operation at maximum luminosity after the brightness improvements in the injector chain, The following shutdown (LS3) is a crucial shutdown and will comprise the work needed for the luminosity upgrade of HL-LHC.

Luminosity Upgrade (HL-LHC)

Operation with nominal LHC performance of a luminosity of $10^{34}cm^{-2}s^{-1}$ and 25 ns bunch spacing implies for the high luminosity experiments a mean pileup of approximately 20 events per bunch crossing. Following the upgrade of the detectors in LS3, it is possible that an event pileup of ~100-140 events per bunch crossing could be accepted. Higher pileup rates would require much more costly upgrades of the detectors, and for this reason the HL-LHC upgrade project aims at a peak operational luminosity of $5\text{-}7x10^{34}cm^{-2}s^{-1}$. In order to meet the HL-LHC goal of an integrated luminosity of 200 to $300fb^{-1}$ per year, the HL-LHC upgrade therefore needs luminosity levelling during the physics runs. This technique intentionally reduces the possible peak luminosity as a function of the beam intensity and aims to produce a constant luminosity level during a run. The machine parameters for the HL-LHC are therefore tailored for a peak "virtual" luminosity well above $5\text{-}7x10^{34}cm^{-2}s^{-1}$, but with a constant luminosity of $5\text{-}7x10^{34}cm^{-2}s^{-1}$ during the physics run by continuously adjusting the beam parameters. This procedure avoids event pileup rates which are unacceptably high in the detectors while maximizing the integrated luminosity over a fill.

A simplified plot of luminosity with levelling at $5x10^{34}$ $cm^{-2}s^{-1}$ is shown in Figure 8.

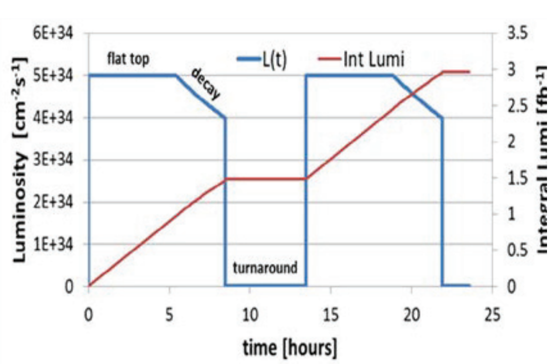

Figure 8: Levelling at $5x10^{34} cm^{-2} s^{-1}$.

The HL-LHC project requires increased bunch charge and low emittance from the injectors to be provided by the LIU project. In addition, very low β* (10-20 cm) are also required in Atlas and CMS requiring new insertions with high field quadrupoles. In addition crab-cavities are foreseen to increase the possible peak luminosity and allow luminosity levelling as well as a new enhanced collimation system. See Table 4 for a possible parameter set which would allow $250fb^{-1}$ per year with an average pile up rate of 140 during the luminosity levelled operation.

Table 4: Possible Parameters for HL-LHC with Pile up of 140

parameter	nominal	HL-LHC (25 ns)	HL-LHC (50 ns)
protons per bunch	1.15	**2.2**	**3.5**
rms bunch length [cm]	7.55	**7.55**	**7.55**
beta* at IP1&5 [m]	0.55	**0.15**	**0.15**
normalized emittance[μm]	3.75	**2.5**	**3.0**
maximum total b-b tune shift	0.011	**0.015**	**0.019**
potential peak luminosity	1	**24**	**25**
actual (levelled) peak luminosity	1	**7.4**	**3.8**
(pile up, average value)	19	**140**	**140**
needed availability	(50)	**45**	**72**
annual integrated luminosity	(37)	**250**	**250**

The project is presently in the R&D Phase with a major R&D effort for high-field magnets. Intense studies are also underway for the design of a crab cavity system. Due to the very high luminosity and the effect of radiation on the electronics (single event upsets), it is foreseen to move the most critical power converters to the surface thus requiring superconducting links to feed the power converters with the electrical current. It is also foreseen to improve the cryogenics system by sectorizing the main magnets, the RF system and the insertion quadrupoles.and the collimators.

Construction of technical equipment for HL-LHC will start around 2016-17 in preparation for installation during Long Shutdown 3 (2022).

Energy Upgrade (HE-LHC)

A preliminary study has been started to investigate a possible energy upgrade of the LHC in the years following the high luminosity operation (after delivery of the $3000fb^{-1}$). This study has two main considerations

1. Study of maximum field dipole magnets using a combination of superconductors such as Nb^3Sn, Nb^3Al, and High Temperature Superconductors
2. Investigating the possibility of a larger tunnel of around 80km circumference in the CERN region.

Clearly a combination of these two options could be a possible route for a substantial increase in the energy of a HE-LHC.

The emphasis for the moment has been on the study of high field magnets and is being carried out in collaboration with our US colleagues through the LARP programme. Table 5 gives a very preliminary parameter list of a possible energy upgrade inside the existing LHC tunnel. Surprisingly the beam parameters are not too frightening (with the exception of the 20Tesla main magnets!) A very interesting parameter at these very high energies is the emittance damping time of around 1 hour possibly providing increasing luminosity as a function of time during physics data taking!

Table 5: Very Preliminary Parameters for a Possible Energy Upgrade of the LHC (HE-LHC)

	nominal LHC	HE-LHC
beam energy [TeV]	7	16.5
dipole field [T]	8.33	20
dipole coil aperture [mm]	56	40-45
#bunches / beam	2808	1404
bunch population [10^{11}]	1.15	1.29
initial transverse normalized emittance [μm]	3.75	3.75 (x), 1.84 (y)
number of IPs contributing to tune shift	3	2
maximum total beam-beam tune shift	0.01	0.01
IP beta function [m]	0.55	1.0 (x), 0.43 (y)
full crossing angle [μrad]	285 (9.5 $\sigma_{x,y}$)	175 (12 σ_{x0})
stored beam energy [MJ]	362	479
SR power per ring [kW]	3.6	62.3
longitudinal SR emittance damping time [h]	12.9	0.98
events per crossing	19	76
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	2.0
beam lifetime [h]	46	13
integrated luminosity over 10 h [fb^{-1}]	0.3	0.5

The energy upgrade of the LHC inside the existing tunnel would also require the following significant upgrades (see Figure 9 for the modifications to the CERN complex)

- High-gradient quadrupole magnets for arc and IR
- Fast cycling SC magnets for ~1.3TeV injector
- Cryogenic handling of SR heat load (first analysis; looks manageable)
- Dynamic vacuum stabilization in the presence of synchrotron radiation

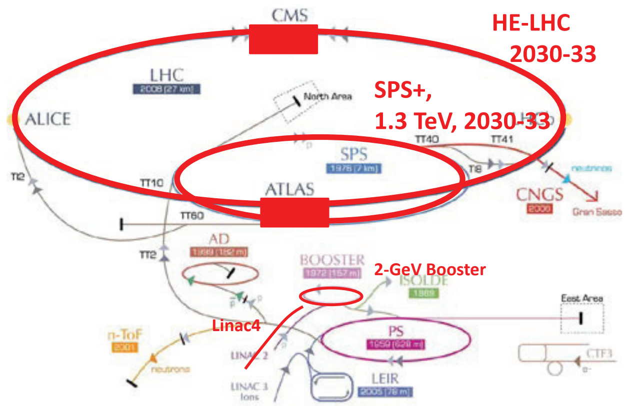

Figure 9: Possible layout of HE-LHC in the existing tunnel.

ACKNOWLEDGMENTS

This paper summarizes the work carried out by hundreds if not thousands of scientists, engineers and technicians both employed by CERN and very importantly by the many institutes that collaborate with CERN. It is a great personal pleasure to acknowledge the incredible contributions and dedication of such a wonderful team.

REFERENCES

[1] “LHC Design Report”, CERN-2004-003 (2004).

More than 100 papers on the operation of the LHC were presented to this IPAC12 conference. The proceedings will therefore be a rich source of reference for the LHC.

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