OPERATION OF THE LHC AT HIGH LUMINOSITY AND HIGH STORED ENERGY

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Abstract

In 2011 the operation of the Large Hadron Collider LHC entered its first year of high luminosity production at a beam energy of 3.5 TeV. In the first months of 2011 the number of bunches was progressively increased to 1380, followed by a reduction of the transverse emittance, an increase of the bunch population and a reduction of the betatron function at the collision points. The performance improvements steps that were accumulated in 2011 eventually brought the peak luminosity to $3.6 \times 10^{33} \mathrm{cm}^{-2} s^{-1}$. The integrated luminosity delivered to each of the high luminosity experiments amounted to 5.6 fb^{-1}, a factor of 5 above the initial target defined in 2010. The operational experience with high intensity and luminosity at the LHC will be presented, together with the issues that had to be tackled on the road to high intensity and luminosity.

INTRODUCTION

The Large Hadron Collider (LHC) [1] saw in 2011 the first full year of high luminosity production at 3.5 TeV per beam. The goal of the two-year long running period 2011-2012 is to maximize the LHC physics outcome by either discovering or ruling out the existence of the Higgs boson. After operating at 3.5 TeV in 2010 and 2011, the energy of the beams was increased to 4 TeV in 2012 following the LHC Performance Workshop held in January 2012 [2].

A schematic view of the 26.7 km-long LHC ring which is composed of 8 arcs and 8 long straight sections (LSSs) is given in Fig. 1. Thanks to a two-in-one magnet design, the counter-rotating proton beams circulate in separated vacuum chambers and cross each other only in the experimental interaction regions (IRs): IR1 (that houses the ATLAS experiment), IR2 (ALICE), IR5 (CMS and TOTEM) and IR8 (LHCb). The other straight sections are dedicated to the radio-frequency system (IR4), the beam dumping system (IR6) and the momentum (IR3) and betatron (IR7) collimation systems. The injections of the clockwise beam 1 and anti-clockwise beam 2 take place in IR2 and IR8.

OPERATION OVERVIEW

Re-commissioning of the LHC in 2011 after the winter stop was carried out in a record time: 6000 powering tests were completed within 3 weeks and the machine check-out was performed in the shadow. Commissioning of the LHC with low intensity beam to first stable collision was achieved in 22 days. During this period the machine cycle was setup to 3.5 TeV, including the betatron squeeze to β^* of 1.5 m. The beta-beating was corrected to below 10% for

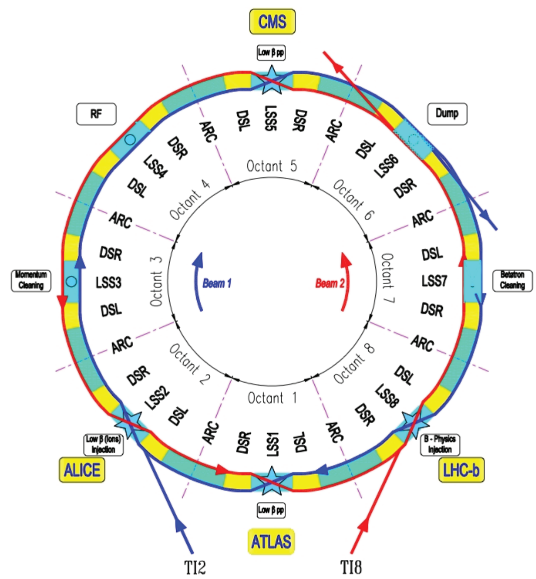

Figure 1: Illustrative layout of the 26.7 km-long LHC rings, featuring 8 arcs and 8 long straight sections (LSSs). Each LSS is surrounded by 2 dispersion suppressors (DSs) [1].

colliding beam conditions. The collimators were aligned to the beam at injection and at 3.5 TeV, and the settings were validated with controlled beam losses. The machine protection systems were re-commissioned and tested.

Following this initial period, the number of bunches was increased progressively. Each intensity step was analyzed in the light of machine protection before green light was given for the next intensity step [4]. The ramp up of the beam intensity to the maximum of 1380 bunches spaced by 50 ns was performed between April and end of July 2011. After an initial fast ramp up to 768 bunches (early May), the progress was slowed down by intensity related effects for the steps to 912, 1092, 1236 and 1380 bunches. Figure 2 illustrates the luminosity progression in 2011. On April 21^{st} 2011 the LHC luminosity exceeded for the first time the TEVATRON luminosity record.

Once the maximum number of bunches was reached, the bunch intensity was increased slowly in July and August, while simultaneously reducing the beam emittance. Bunch intensity peaked at 1.35×10^{11} p with an average normalized emittance around 2.2 μm. At the end of August the peak luminosity reached $2.2 \times 10^{33} \mathrm{cm}^{-2} s^{-1}$. The high luminosity experiments had integrated close to 3 fb^{-1} of luminosity.

The last period of operation with protons in September and October was marked by a reduction of β^* from the

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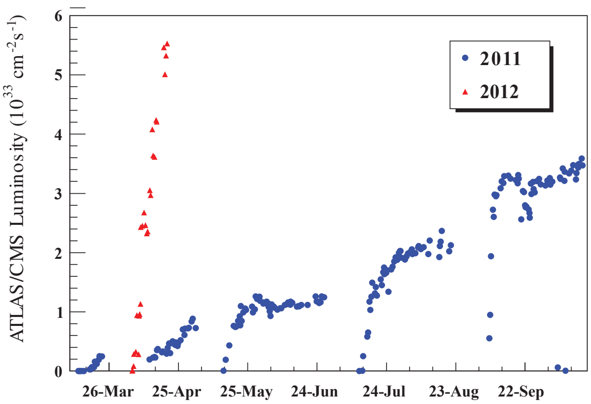

Figure 2: Peak luminosity evolution in 2011 and 2012.

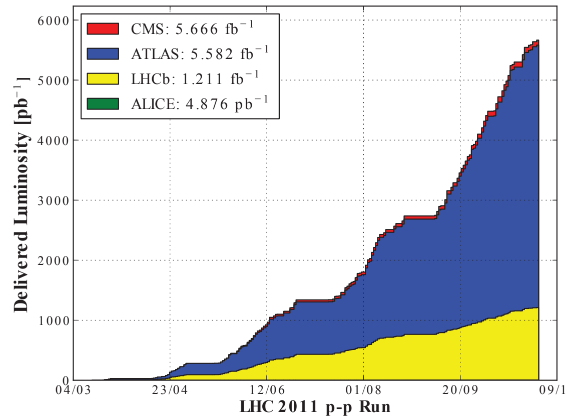

Figure 3: Evolution of the integrated luminosity delivered in 2011.

Table 1: LHC parameters for proton operation. The values for 2012 reflect the status in May 2012.

Parameter	Value		
	Design	2011	2012
Beam energy [TeV]	7.0	3.5	4.0
Peak luminosity [10^{33}cm^{-2}s^{-1}]	10	3.6	5.4
Stored energy [MJ]	362	112	115
Bunch intensity [10^{10}p]	11.5	14.5	13.5
Number of bunches	2808	1380	1380
Bunch spacing [ns]	25	50	50
Norm. transv. emittance [μm]	3.5	2.4	2.4
β^* in IR1/IR5 [m]	0.55	1.0	0.6

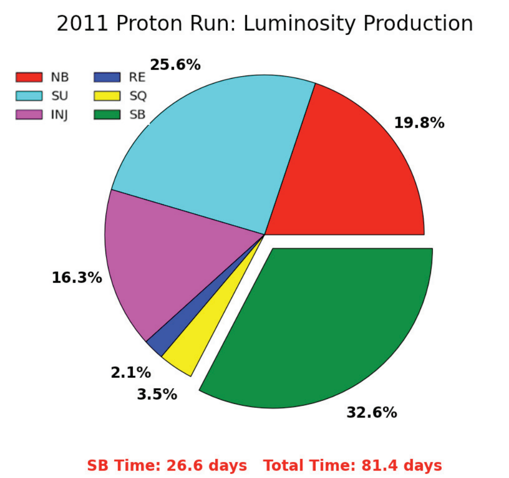

Figure 4: Distribution of the proton run in the different phases.

initial 1.5 m down to 1 m. This reduction became possible following measurements of the local aperture near the IRs at 3.5 TeV [5]. The measurements revealed that the assumptions for extrapolating aperture measurements performed at injection were too conservative, and that some margin for lowering β^* was available. Operation with β^* of 1 m became operational within a single week and the luminosity soon reached 3.6×10^{33}cm$^{-2}s^{-1}$ for a stored beam energy of 112 MJ. The conclusion of an incredible period of continuous performance increase brought as a final result a total integrated luminosity of 5.6 fb^{-1} for the high luminosity experiments, see Fig. 3. The peak machine parameters in 2011 are given in Table 1 together with design values.

Efficiency

In order to analyze the machine availability, the operational cycle is split into six phases as shown in Fig. 4. The phases are: 'NB' (no beam, access), 'SU' (beam setup), 'INJ' (injection phase), 'RE' (energy ramp), 'SQ' (squeeze and collision preparations) and finally 'SB' for stable collisions (experiments data-taking). The fraction of scheduled operation time spent colliding beams for the experiments amounts to 33%. The average length of the SB periods was 5.8 hours, the majority of the fills being dumped by interlocks. The average turn-around time was 6.5 hours. The cryogenics system dominated the downtime with a total of 21 days, followed by the SPS injector, electrical perturbations and the quench protection system [3].

HIGH INTENSITY ISSUES

Electron Cloud

Before starting operation with trains of bunches spaced by 50 ns, the surface of the vacuum chamber had to be conditioned during a week in April to reduce electron cloud effects and obtain acceptable vacuum conditions [6]. The strategy for this 'scrubbing run' that was performed at injection energy was the following: progressive increase in the number of injected bunches; injection up to the vacuum interlock thresholds; change of intensity and filling scheme to improve the scrubbing efficiency. Ensuring stability of the beams required large chromaticity and high transverse feedback gain. The beneficial effects of the beam scrubbing became soon apparent in terms of vacuum improvement and reduction of emittance blow-up.

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Heating

Along the run a number of issues associated to abnormal heating of components within the vacuum chamber, often coupled with vacuum activity, were observed and had to be solved. Heating affected RF fingers due to installation issues as well as protection device jaws. Problems were also encountered due to gas trapped on the cold magnet bores in some LSS that was released in the presence of high intensity beams. Regulation of the cooling of the beam screen protecting the magnet bore from the beam EM fields and synchrotron radiation proved delicate and required some time for optimization.

Radiation Effects

With the increase of luminosity the rate of radiation induced problems to tunnel electronics rose steadily, leading frequently to beam dumps from failing electronics [7]. Cumulative doses of few 10^6 high energy hadrons (>20 MeV) were recorded in certain critical locations. This led to the early planning of new shielding, relocation of electronics and to improvements of firmware to mitigate radiation effects on signal processing. The fast reaction allowed to mitigate the consequences for the 2011 run, preparation of additional measures for the winter stop 2011-2012 could be initiated at an early stage. With the mitigation in place, the rate of failures should not increase in 2012 despite higher peak luminosity.

Beam Loss

Despite the stored energy of over 100 MJ, no magnet quench was induced accidentally during 3.5 TeV operation. This is the result of the excellent performance of the collimator system in cleaning beam losses [2], and to an excellent and reliable machine protection system. The stability of the orbit and the reproducibility of the collimator positions was so good that no re-alignment of the collimators had to be done during the run.

Unexpected fast beam losses on the millisecond time scale were observed all along the ring circumference [8]. Those loss events, believed to be due to micron-sized dust particles and nicknamed "Unidentified Falling Objects" (UFOs), eventually led to beam dumps by the beam loss monitoring system. Fortunately the rate of those events decreased by a factor ≈ 5 during the 2011 run.

OPERATIONAL ASPECTS

LHC operation relies heavily on automatization and sequencing for high intensity operation. The LHC is driven through its cycle by a Sequencer that executes the vast majority of tasks. Sequencing reduces significantly the number of human errors and standardizes the cycle. Manual adjustments are normally limited to beam injection (tune, chromaticity measurement and correction), to luminosity optimization (beam separation scans) and to machine experiments and developments periods.

Field errors due to persistent currents from the superconducting magnets are controlled by automatic feedforward at injection [9]. The sextupolar component is particularly critical, and the chromaticity is typically stabilized to ± 1 unit at injection. To ensure stability of the beam, a fast transverse feedback system is active continuously for high intensity operation [2, 3]. Further stabilization is achieved with strong octupoles. During ramp and squeeze, tune and orbit are corrected back to their targets by feedbacks. Due to the tight tolerances on the orbit, operation of the LHC without orbit feedback is not possible. During collisions the orbit and tune feedbacks are switched off, as the machine is very stable at high energy.

CONCLUSION AND OUTLOOK 2012

The beam commissioning and first two years of LHC beam operation have been very successful, with a rapid increase of the luminosity and the stored energy of the beams, in particular in 2011 where the peak luminosity exceeded $10^{33}\text{cm}^{-2}s^{-1}$. For the startup of the LHC in 2012 the betatron squeeze was reduced further to β^* of 0.6 m, close to the nominal value at 7 TeV. Together with a planned increase of the bunch intensity to 1.6×10^{11} p, a peak luminosity above $6 \times 10^{33}\text{cm}^{-2}s^{-1}$ are expected. The overall target for 2012 is the delivery of another 15 fb^{-1} in order to confirm existence or exclude the Higgs boson. Scaled to 7 TeV the present peak luminosity would exceed $2 \times 10^{34}\text{cm}^{-2}s^{-1}$, twice the LHC design luminosity.

ACKNOWLEDGMENTS

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