OPERATION OF THE LHC WITH PROTONS AT HIGH LUMINOSITY AND HIGH ENERGY

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Abstract

In 2015 the Large Hadron Collider (LHC) entered the first year in its second long Run, after a 2-year shutdown that prepared it for high energy. The first two months of beam operation were dedicated to setting up the nominal cycle for proton-proton operation at 6.5 TeV/beam, and culminated with the first physics with 3 nominal bunches/ring at 13 TeV CoM on 3 June. The year continued with a stepwise intensity ramp up that allowed reaching 2244 bunches/ring for a peak luminosity of $\approx 5 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and a total of just above 4 fb^{-1} delivered to the high luminosity experiments. Beam operation was shaped by the high intensity effects, e.g. electron cloud and macroparticle-induced fast losses (UFOs), which on a few occasions caused the first beam induced quenches at high energy. This paper describes the operational experience with high intensity and high energy at the LHC, together with the issues that had to be tackled along the way.

INTRODUCTION

The Large Hadron Collider at CERN, Geneva, is a 27 km long circular accelerator [1]. It is based on a superconducting two-in-one magnet design, with a design energy of 7 TeV/beam. It features 8 straight sections: 4 Interaction Regions (IRs) are reserved for accelerator equipment and 4 house particle physics experiments. IR3 and 7 are dedicated to the collimation system, IR4 houses the RF system and most of the beam instrumentation, IR6 is reserved to the beam dump system. IR1 and 5 contain the high luminosity experiments ATLAS and CMS, while IR2 and 8 accommodate the ALICE and LHCb experiments and beam injection.

The LHC was first started up with beam for short periods in 2008 and 2009. In 2010, a first experience with the machine was gained with moderate energy (3.5 TeV/beam), and moderate beam intensity (up to $\approx$200 bunches of 1.1×10^{11} p per bunch, or ppb). In 2011 the beam intensity was pushed to $\approx$1400 bunches of 1.4×10^{11} ppb. 2012 was fully dedicated to luminosity production, with even higher bunch intensities (1.6×10^{11} ppb) and energy (4 TeV/beam). In early 2013 beam operation was stopped for a first, 2-year long Long Shutdown (LS1) targeted to consolidation and maintenance, that allowed increasing the beam energy further.

After LS1, 2015 was the first year of beam operation close to design energy. The choice to operate at 6.5 TeV/beam was confirmed after the first results of the dipole training campaign that took place at the end of LS1. The LHC experiments expressed a strong preference for the use of 25 ns spaced beams, as opposed to the 50 ns spaced beams used in 2011-2012, which would result in a too-high number of inelastic collisions per crossing (pile-up). On the machine side though, 25 ns beams pose additional challenges, e.g. the formation of electron clouds (e-clouds) in the beam pipe and a higher number of fast loss events, named Unidentified Falling Objects (UFOs). Due to the many unknowns, 2015 was considered a year of commissioning, dedicated to preparing the machine for full luminosity production as of 2016 and until the end of Run 2.

This paper reviews the 2015 timeline and the reasons why it was shaped such, the luminosity figures that were achieved, including the main beam parameters that enabled them, and the main challenges that had to be faced (e-cloud, UFOs, circuit performance at high energy) and lessons learnt from them. Finally some other achievements and improvements are quickly recalled.

2015 TIMELINE

In 2015, operation with beam started relatively late in the year as the first three months were still devoted to hardware commissioning. Some details on the dipole training campaign to 6.5 TeV are given in a later section. The machine checkout interwove with the end of the hardware commissioning, and finally the first probe beams were circulated on Easter Day (5 April).

Beam commissioning, including also recommissioning of all machine protection systems, lasted 8 weeks and culminated with the first physics on 3 June. During this period, and despite the low intensity beams, issues were found at a precise location: fast loss events and an aperture restriction, now dubbed the ULO (Unidentified Lying Object, [2]).

The summer was devoted to a step-wise e-cloud scrubbing run and intensity ramp-up, first with 50 ns and then with 25 ns beams. In September and October, the intensity ramp-up with 25 ns continued, mostly limited by the e-cloud-induced heat load on the cryogenic system. Note that the month of August was particularly difficult as the machine availability was impaired by Single Event Effects on the Quench Protection Systems and by high UFO rates, so much that most of the luminosity production for the year happened in the months of September and October only.

The last month of beam operation was dedicated to physics with lead ion beams [3]. It is also worth recalling that proton-proton physics (PPP) operation was interrupted throughout

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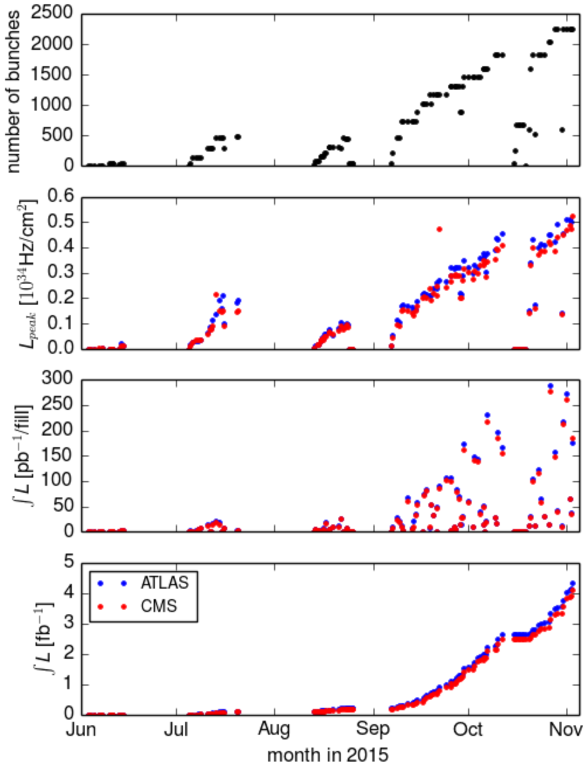

Figure 1: Performance plots for 2015: number of bunches per fill, peak luminosity per fill, integrated luminosity per fill, and luminosity integrated since the start of the year.

the year to accommodate special physics runs (e.g. a very low pile-up run, the 90 m run for forward physics, the proton-proton reference run at 2.51 TeV/beam), 3 scheduled stops for hardware maintenance (Technical Stops, TS), and three 5-day long Machine Developments sessions (MDs).

LUMINOSITY PERFORMANCE

By the end of the proton physics running period, the instantaneous luminosity reached $\sim 0.5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, with 2244 bunches/ring (see Fig. 1). The main beam and machine parameters that allowed reaching such luminosity are shown in Table 1, together with a comparison with the parameters in 2012 and the nominal ones [1]. In particular, the beam energy and number of bunches were higher in 2015, but the beams were brighter in 2012.

The luminosity integrated by ATLAS and CMS over the course of the 2015 proton physics run is just above 4 fb^{-1}, while LHCb and ALICE integrated 360 pb^{-1} and 9 pb^{-1}, respectively. The integrated luminosity ran short of the initial projection due to the delayed start (~1 month) and the difficulties encountered in August. The production rates in the end of the run though reached 200-250 pb^{-1}/day and ~1 fb^{-1}/week, which make good foundations for physics production in 2016 (see Fig. 1).

The luminosity lifetime was notably healthy, ~ 30 – 60 h. A LHC luminosity model is being developed [4], and indicates that IntraBeam Scattering (IBS), synchrotron radiation, and luminosity burn-off in IP1 and IP5 are the main phenomena to be taken into account. The losses from the start of acceleration to physics totalled on average to ~2% of the total intensity.

Table 1: Beam and Machine Parameters in 2012 and 2015 (Best Achieved), and from [1].

Parameter	Design	2012	2015
energy [TeV]	7	4	6.5
bunch spacing [ns]	25	50	25
β^* [m]	0.55	0.60	0.80
half crossing angle [μrad]	142.5	145	145
N_b [10^{11} ppb]	1.15	1.65	1.15
transverse emittance [μm]	3.75	2.5	3.5
colliding pairs in IP1 and 5	2808	1368	2232
number of bunches/ring	2808	1374	2244
L [$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	1	0.75	0.55
pile-up μ	~ 20	~ 35	~ 15
stored energy [MJ]	360	145	270

From studies with Wire Scanners (WS) on low intensity fills, IBS is the main source for horizontal emittance growth. In the vertical plane, a typical growth of ~5% in 10 minutes was measured at injection, indicating an additional source of emittance growth, which is not yet known but seemingly independent of beam brightness, chromaticity, octupole strength, transverse damper settings. The comparison between the WS measurements at injection on the first train and the emittance at the start of collisions derived from the ATLAS luminosity indicated an average growth of ~0.5 μm (25%) over the course of the cycle, resulting in ~3 μm emittances at the start of fill.

The emittance evolution in physics from luminosity scans [5] shows an average horizontal growth of ~0.03 μm/h and a vertical shrinkage of ~0.02 μm/h, so that the convoluted emittance is constant within the measurement error. Longitudinal shrinkage is also observed, and it is consistent with the expectation from synchrotron radiation damping [6]. The bunches are ~1.3 ns long after the controlled longitudinal blow-up applied during the ramp, and over the course of a long fill they decrease to below 0.8–0.9 ns. The shortening can trigger a loss of stability, and mostly dipolar oscillations were observed so far. A technique for bunch flattening with the purpose of restoring Landau damping was developed and tested as a mitigation measure [7].

MISCELLANEA

Electron-cloud and Scrubbing

E-clouds have been observed at the LHC since the start of beam operation with bunch trains (for 150, 75, 50 and 25 ns spacings [8]). Their signatures include vacuum pressure rise, increased heat load on the cryogenic systems, beam size growth, and single- and multi-bunch instabilities. “Scrubbing” runs at injection energy have been regularly incorporated in the annual schedule to allow the reduction of the Secondary Emission Yield (SEY) of the LHC beam screens by increasing the exposure to beam and thus the accumulated dose. This allows preparing the machine for physics running with improved beam parameters.

The SEY was reset after LS1 as most of the machine was exposed to air. This imposed the need for an extended period of scrubbing in preparation for 25 ns beams, which totalled to 3 weeks in 2015, split in two parts. First, 10 days with 50 ns beams aimed at preparing the machine for the 50 ns intensity ramp-up. Then 2 weeks of scrubbing with 25 ns beams aimed at enabling physics production with 25 ns beams. The LHC was then operated with 25 ns beams until the end of the PPP run, staying at the limit for the cryogenics heat-load, which defined the maximum number of bunches per ring.

In 2015 with 25 ns beams, 2 weeks of scrubbing allowed accumulating 6 mC/mm^2, to be compared to 94 mC/mm^2 in 2 months of physics [9]. In 2016 dedicated scrubbing is minimized, and scrubbing in parallel to physics will start as soon as possible.

UFOs

Fast loss events, nicknamed Unidentified Falling Objects, have been observed at the LHC since 2010 [10]. These losses are in the ms time range and they are most likely due to dust particles moving in the beam pipe and interacting with the beam, creating particle showers that are then detected by the Beam Loss Monitors. UFOs caused ≈20 dumps/year in Run 1 and were feared to be one of the main limitations to operation in Run 2, due to lower margins for losses in the superconducting magnets, and the higher losses created per event at higher energy. They affect machine availability, as the most intense ones can trigger a beam dump, or initiate a magnet quench and the subsequent long time for cryogenics conditions recovery.

UFO rates in 2015 were as high as 30-40 events per hour, and decreased with beam time ("conditioning"), to ≈10 events/hour [11]. They caused ≈20 beam dumps and 3 beam-induced quenches. The strategy for 2015 had initially been to prevent all UFO-induced magnet quenches [12]. It was realized over the course of the year, though, that most of the events that caused dumps would not have caused quenches. Thus the policy changed, and the BLM thresholds were increased to allow a few UFO-induced quenches in a year. A further increase is in place for 2016.

Circuit Performance at 6.5 TeV

Running the superconducting magnet circuits close to the design high energy meant that most systems were operated close to the design margins. For example, earth faults appeared in the main dipole circuits, both during hardware commissioning and beam operation. Some were intermittent, and a few have yet to be pinned down. One could be "blasted" away with a high voltage pulse as it was caused by a small piece of debris shorting the two plates of a diode.

For this second LHC run, it was chosen to bring the main dipoles to 6.5 TeV/beam. The quench training campaign took longer than expected: while about 100 quenches were expected across the 8 sectors, a total of 175 were needed. This is mostly traced back to the production batches, but details are still under study. Additionally, 5 training quenches were observed during beam operation. A possible test for bringing 2 sectors to the nominal 7 TeV/beam might be carried out before the next Long Shutdown.

The magnetic reproducibility of the LHC is one of its strengths, and allows an excellent control of beam parameters like tune and chromaticity [13, 14].

Machine Developments

Fifteen days were invested in MDs in 2015, organized and reviewed by the LHC Studies Working Group. Highlights of the results are: the preparation of $\beta^* = 40$ cm for operation in 2016, the commissioning of a combined ramp and squeeze [15], the demonstration of the feasibility of keeping the beams in collisions while squeezing [16].

Others

Many systems and subjects cannot be covered in this contribution due to space limitations. Some can nevertheless be quickly recalled and referred to: the excellent performance of the hardware systems, e.g. the collimation system and new methods to validate it [17], RF systems and transverse dampers, including new simulation tools [18]; the improved handling of beam induced effects and transients in the cryogenic system [19]; the very high accuracy of the optics corrections, including the measurement of the waist position at the IR and its correction implemented in 2016 [20, 21].

CONCLUSIONS

2015 was successful for LHC operation: 25 ns beams were collided routinely at 6.5 TeV, with up to 2244 bunches per ring, laying a stable foundation for the 2016 physics production. Despite the intensity ramp up not being fully finished, at the end of the year the production rates reached 200-250 pb^{-1}/day and 1 fb^{-1}/week. The good peak luminosities and the excellent luminosity lifetimes were enabled by an excellent transmission through the cycle, low, non-burn-off losses during physics, and acceptable rates for emittance growth. E-clouds and the consequent abundant heat-load for the cryogenic system remain a challenge for 2016. Additionally, during the year much improvement was gained in the understanding of the machine and how to operate it, both during regular operation, during scrubbing and during machine developments.

Yet and again, successful operation was made possible by an excellent system performance and experts' motivation.

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