LHC OPERATION AT 6.5 TeV: STATUS AND BEAM PHYSICS ISSUES

G. Papotti, M. Albert, R. Alemany, E. Bravin, G. Crockford, K. Fuchsberger,
R. Giachino, M. Giovannozzi, G. Hemelsoet, W. Hofle, G. Iadarola, D. Jacquet,
M. Lamont, D. Nisbet, L. Normann, T. Persson, M. Pojer, L. Ponce, S. Redaelli,
B. Salvachua, M. Solfaroli, R. Suykerbuyk, J. Wenninger
CERN, Geneva, Switzerland

Abstract

LHC operation restarted in 2015 after the first Long Shutdown, planning for a 4-year long run until the end of 2018 (called Run 2). The beam energy was fixed at 6.5 TeV. The year 2015 was dedicated to establishing operation at the high energy and with 25 ns beams, in order to prepare production for the following three years. The year 2016 was the first one dedicated to production, and it turned out to be a record-breaking year, in which the goals in both peak and integrated luminosities with proton-proton beams were achieved and surpassed.

This paper revisits 2015 and 2016, shortly highlighting the main facts in the timelines, recalling the parameters that characterized luminosity production, and sketching the main limitations and the main highlights of results for selected topics, including a particular focus on the beam physics issues.

INTRODUCTION

The year 2015 marked the restart of LHC [1] operation with beam after its first Long Shutdown (LS1) [2]. The first three months were devoted to hardware commissioning, which included the dipole training campaign to 6.5 TeV. The machine checkout interwove with the end of the hardware commissioning, and finally the first probe beams were circulated on Easter Day (5 April). Eight weeks of beam commissioning followed, which included recommissioning of all systems, including machine protection systems. The summer was devoted to a step-wise scrubbing run and intensity ramp-up: first with 50 ns, then with 25 ns beams. A total of ~ 3 weeks were dedicated to electron-cloud scrubbing at 450 GeV [3]. In September and October the intensity ramp-up with 25 ns continued, mostly limited by the heat load induced on the cryogenic system [4]. The month of August was particularly difficult as the machine availability was impaired by Single Event Effects on the Quench Protection Systems [5] and by high UFO rates (Unidentified Falling Objects, [6]), so much that most of the luminosity production happened mostly in the months of September and October.

The year 2016 required only 4 weeks of recommissioning with beam, followed directly by operation with 25 ns beams. The 2015 performance with respect to electron-cloud could be recovered with only ~ 12 hours dedicated to scrubbing at injection energy [7]. Until mid-July, operation concentrated on proton-proton physics production, in order to accumulate as much data as possible for the summer physics conferences. The Machine Development (MD) program was then condensed in the second part of the year. The year was characterized by a much improved machine availability [8] that allowed integrating more than the yearly target despite a few limitations on the number of bunches and intensity.

This paper first reviews the luminosity performance achieved in 2015 and 2016, and then draws attention to the main limitations encountered, and some highlights of results for selected topics. This paper does not cover the lead ion runs (Pb-Pb in 2015 [9], and p-Pb and Pb-p in 2016), nor the special physics runs (e.g. van der Meer, high-beta, i.e. 90 m in 2015 and 2.5 km in 2016).

LUMINOSITY PERFORMANCE

The year 2015 was devoted to establishing proton-proton operation with 25 ns beams at 6.5 TeV, in order to establish a solid base for production in the rest of Run 2. The choice of β^* in ATLAS and CMS was 80 cm, which was cautious to allow some extra margins for machine protection purposes. At the end of the proton physics running period, the peak instantaneous luminosity reached $\sim 0.5\times10^{34}$ cm^{-2}s^{-1}, achieved when the number of bunches per ring was maximum for the year (i.e. 2244, see Fig. 1). The main beam and machine parameters that allowed reaching such luminosity are shown in Table 1, where also the Design Report and 2016 values are shown.

Table 1: Beam and Machine Parameters from [1], and Achieved in 2015 and 2016

Parameter	**Design**	**2015**	**2016**
energy [TeV]	7	6.5	6.5
bunch spacing [ns]	25	25	25
β^* [m]	0.55	0.80	0.40
half crossing angle [µrad]	142.5	185	140
N_b [10^{11} ppb]	1.15	1.15	1.1
transverse emittance [µm]	3.75	3.5	2
number of bunches/ring	2808	2240	2220
L [10^{34} cm^{-2}s^{-1}] (peak)	1	0.5	1.4
pile-up μ (peak)	20	18	41
stored beam energy [MJ]	360	270	260

After the experience gained in 2015, in 2016 β^* was pushed to 40 cm. Additionally, the beam production scheme was changed from the standard one [1] to “Batch Compression, Merging and Splitting” [10], which creates brighter bunches (in particular, ~2 µm emittances reach collisions, to

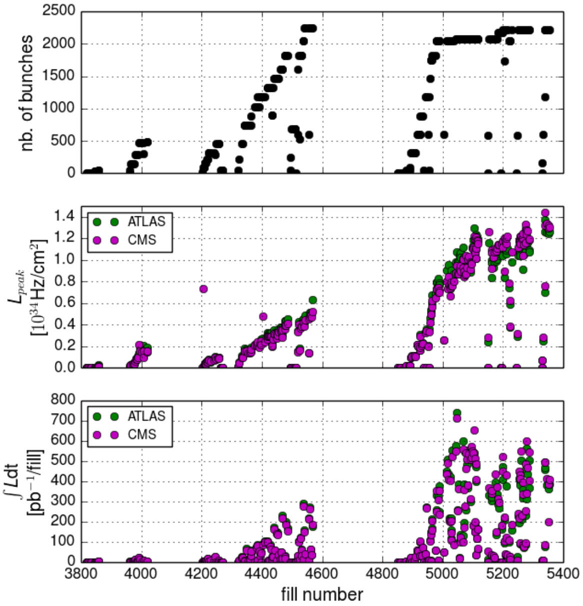

Figure 1: Performance plots for 2015 (fills 3800 to 4600) and 2016 (fills 4800 to 5400). Shown from the top: number of bunches per fill, peak luminosity per fill, and integrated luminosity per fill. Note that the quoted luminosity values do not take the latest calibrations from the experiments into account.

be compared to ~3.5 µm of the standard scheme). The smaller emittance, together with a reduction of the margins allocated for long-range beam-beam effects (from 10.5 beam σ to 9 beam σ), allowed a reduction of the crossing angle from 370 µrad to 280 µrad in the second part of the year. At the time of writing, the peak instantaneous luminosity reached $\sim 1.4 \times 10^{34}$ cm^{-2}s^{-1} (see also Fig. 1).

The luminosity integrated by ATLAS and CMS over the course of the 2015 proton physics run was just above 4 fb^{-1}, while LHCb and ALICE integrated 360 pb^{-1} and 9 pb^{-1}, respectively. While the integrated luminosity ran short of the initial projection, the production rates in the end of the run reached 200-250 pb^{-1} per day and ~ 1 fb^{-1} per week, which make good foundations for the next years.

In 2016, the integrated luminosity target, set to 25 fb^{-1} was exceeded, and at the time of writing, ~ 33 fb^{-1} have been accumulated at ATLAS and CMS. LHCb and ALICE integrated 1.5 fb^{-1} and 12 pb^{-1}, respectively. Up to 3.3 fb^{-1} were integrated at ATLAS and CMS in a single week.

While the statistics for the full year are not available yet, the ones for the summer period are quoted hereafter [8]:

- the statistics are calculated over a period of 79 days allocated to physics production, in between the first and second technical stops of the year; commissioning and machine development periods are not included.

- the machine time was divided in: 20% downtime, 1% precycles, 58% physics production, and 21% preparation for physics (and no faults). This can be compared to ~ 33 – 35% in physics in the previous years.

- 96 fills were brought into physics, 46 of which were dumped by operations, 47 aborted by faults, and 7 are suspected to be radiation induced aborts.

A number of improvements were put in place in order to improve the operational efficiency, e.g.: the inclusion of part of the betatron squeeze into the acceleration ramp (reduction of β^* from 11 m to 3 m, since 2015), and the use of a shortened precycle (to 3.5 TeV, in 2016). The minimum turn around time (time from the end of a physics fill to the start of the next one) is below 3 hours in both 2015 and 2016.

LIMITATIONS

Electron Cloud

The 2015 experience [3] has shown that scrubbing at 450 GeV allows achieving sufficient mitigation for e-cloud instabilities and beam degradation occurring at low energy with 25 ns bunch spacing. In order to preserve good beam quality, the machine settings had to be optimized (e.g. chromaticity, Landau octupoles and transverse feedback, including a change of the working point). Nevertheless, e-cloud was still present in the machine, as witnessed by the heat load in the arcs, and operation was carried out at the limit of the heat load that the cryogenics system could handle (this included the continuous optimization of the filling schemes). Additionally though, a significant electron dose was accumulated during the physics fills: this resulted in a reduction of the e-cloud induced heat load in the arc dipoles by roughly a factor of two in two months of operation. The analysis also revealed the very large doses needed to observe an evolution of the heat loads at this stage, which are practically incompatible with a dedicated scrubbing run.

Thus, the baseline for 2016 became to spend only a short amount of time for dedicated scrubbing runs, as much as needed to recover a good beam quality for the 25 ns beams, and then continue scrubbing parasitically during the physics runs. In fact, partly due to hardware issues, only 12 hours were dedicated in 2016 to scrubbing at 450 GeV. The year 2016 was still characterized by a significant heat-load [7], which though was within the cryogenic limits, also as the total beam intensity was limited by other factors. An improved handling of the beam-induced dynamic heat-load and a thorough release of the cryogenics interlock levels resulted in cryogenics having no impact of beam operation.

Unidentified Falling Objects

Experience with UFOs in 2015 [6] has shown that, for operation at 6.5 TeV, UFOs have the potential to cause beam-induced quenches and disrupt operation. In 2015 (respectively 2016), 3 (resp. 3) quenches were induced and 17 (resp. 13) fills prematurely terminated. UFO events were as frequent as 40 events per hour in the initial phases of 2015, but luckily then the rates conditioned and stabilized at a plateau of 10 events per hour at the end of 2015 and 2 events per hour in 2016 (see Fig. 2).

The strategy with respect to quenches was revised in 2015 taking into account operational experience, and the Beam Loss Monitor (BLM) thresholds in the UFO time scales were raised to allow few UFO-induced quenches and avoid unnecessary dumps, in order to favour the overall machine availability. Thanks to these measures and the conditioning effect, UFOs were less of a worry than initially feared.

Radiation to Electronics

The failure rates of electronic equipment exposed to radiation is proportional to the radiation levels. At the Interaction Points (IPs) the radiation level is dominated by the integrated luminosity, while for the arcs the radiation levels are due mostly to beam-gas interactions, thus the circulating beam intensity.

In 2015, 14 beam aborts were due to radiation effects [11]. In 2016, only 3 beam dumps were radiation-related during the first 20 fb^{-1}, while the expectation was $\sim$ 1 dump per fb^{-1} [12]. While this is very good news as it goes in the direction of improving machine availability, the analysis is still ongoing. What can be concluded so far is that the arc radiation levels per unit luminosity are lower than in 2015, which in turn can be due to the lower vacuum pressure in the arc, or to the higher luminosity per proton achieved thanks to the smaller β^*. In any case, the LHC in 2016 is run as a very clean machine, the luminosity losses are burn-off dominated, and e-cloud was not at its limit.

Others

In 2015, the main limitation to the total number of bunches per ring was the heat load generated on the cryogenic system by e-cloud. In 2016, the intensity per bunch was limited to 1.1e11 ppb for a total of 2220 bunches because of outgassing taking place at a ceramic connection in one LHC injection kicker. Additionally, in the early 2016 a vacuum leak developed on the SPS internal beam dump [13], limiting the number of bunches to 96 in the SPS, thus also limiting the efficiency of the SPS-LHC transfer as the train length is limited. During the upcoming winter stop, the SPS beam dump will be replaced and additional pumping will be added at the sensitive location in the injection kicker. Note that the injection protection elements (TDIs and TCDIs) limits the transfer from the SPS to the LHC to 144 bunches at a time in case of BCMS beams.

An aperture restriction, the so-called Unidentified Lying Object (or ULO, [14]), is present in the LHC since 2015. The orbit is steered away from the object with local orbit bumps of amplitude 3 mm in the horizontal plane and 1 mm in the vertical plane. The ULO has not disturbed operations since 2015.

A potential inter-turn short in sector 12 was discovered in August 2016 [15]. Additional monitoring instrumentation has been added, the BLM thresholds were lowered by a factor 3 to avoid UFO-induced quenches, and the Quench Protection System was locally modified to minimize the possibility of spurious triggers. The suspicious magnet will be replaced during the upcoming winter stop.

SELECTED HIGHLIGHTS OF RESULTS

Laslett Q Shift Automated Correction

An intensity-dependent tune shift was observed in 2015 [16]. The scaling with intensity followed the so-called Laslett tune shift, which arises from image currents on the beam screen induced by the beam itself. The scaling was measured for many fills at injection, and empirical parameters were derived. In 2016 an application that corrects this intensity-dependent tune shift was put into operation, and is since used regularly during injection to maintain the tunes under control, and avoid drifts that, combined with too high coupling, can cause beam instabilities and emittance blow up.

Optics Corrections

In 2016 the β^* was squeezed to 40 cm which is below the design β^* of 55 cm. The measurement of the uncorrected machine revealed a β-beating over 100%. After the correction procedure a rms β-beating below 1% at the two main experiments and an overall β-beating below 2% was measured [17]. This was achieved thanks to improvements in the excitation length with the AC-dipole, the incorporation of the results from K-modulation in the corrections and the use of weights for the different parameters. This is the lowest β-beating ever achieved for an optics in the LHC. The measured β^* is shown in Table 2. A good optics correction is crucial for safe operation as well as for providing equal amount of luminosity for the two main experiments.

Table 2: The Measured β^* after the Final Corrections for 2016

IP	**Beam**	β_x^* **[cm]**	β_y^* **[cm]**
1	1	39.8 ± 0.5	40.1 ± 0.1
1	2	39.8 ± 0.1	40.1 ± 0.1
5	1	39.9 ± 0.2	40.1 ± 0.1
5	2	39.5 ± 0.1	39.6 ± 0.2

Luminosity Levelling Techniques

The control of the pile-up, i.e. the number of inelastic collisions per crossing, has been a crucial subject since early LHC operation. Luminosity levelling by transverse separation has been operational since Run 1 at the low luminosity experiments LHCb and ALICE.

In two physics fills in 2016, simultaneous levelling at all 4 main experiments was also tried. While ALICE and LHCb were levelled to the standard values, the beams were separated also at ATLAS and CMS to reduce the luminosity by 20% with respect to the peak at the start of the fill. During the fill, the beams were manually steered in small steps to guarantee that the luminosity remained inside a ±2.5% band.

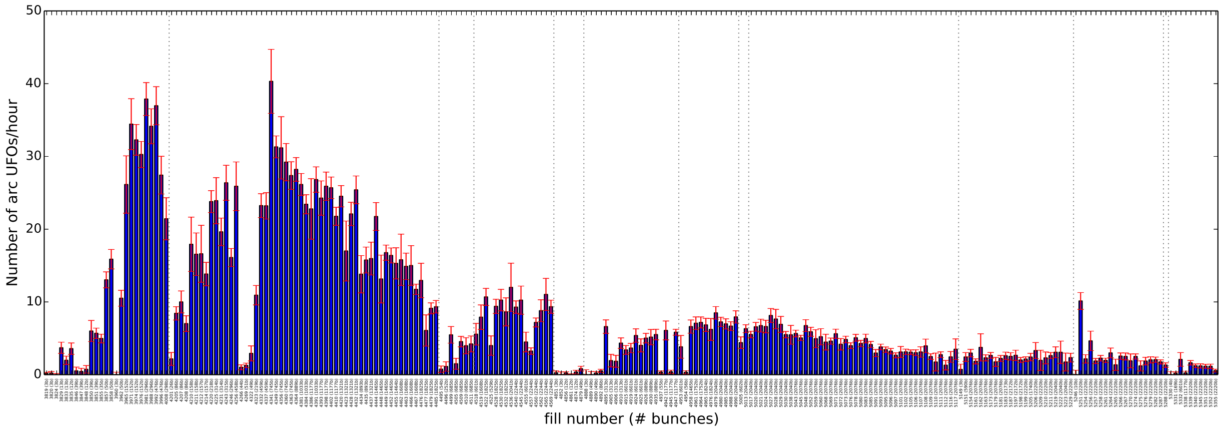

Figure 2: Rates of arc UFO events during physics production ("Stable beams") in 2015 and 2016. A "UFO" is an event that reaches at least 2×10^{-4} Gy/s in the 640 µs integration time of the BLM system, recorded by at least two nearby monitors (< 40 m apart) in cells ≥ 12. The horizontal axis indicates the fill number and the number of bunches circulating per ring. The vertical dotted lines separate different operational periods (e.g. different bunch spacing, technical stops, machine development periods, etc).

Orbit drifts of yet unknown cause resulted in luminosity excursions to the limits of the acceptance band. These orbit drifts are often present, but are more evident when the beams are slightly displaced instead of colliding fully head on.

Luminosity levelling by β^* was studied in Machine Development sessions in 2012 and 2015 [18]. In 2015, a continuous betatron squeeze was demonstrated during which the beams remained colliding to better than one beam sigma transverse separation. The long term stability and the orbit reproducibility were measured by repeating the study after a few months, and they were found to be in agreement with the predictions.

Luminosity levelling by crossing angle was studied in a Machine Development session in 2016 [19]. Also this technique worked smoothly, with beam losses and orbit drifts well under control. The study was so successful that the technique can be considered for operation already in 2017.

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 [20], RF systems and transverse dampers, including new simulation tools [21]; the improved handling of beam induced effects and transients in the cryogenic system [22]; to note only a few.

PROJECTIONS

The goal for the whole Run 2 in terms of integrated luminosity is set to 100 fb^{-1}. After the success in 2016, 2017 and 2018 will probably be expected to produce 40-45 fb^{-1} each. It is worth stressing that there is a limit on the maximum peak luminosity at $\sim 1.7 \times 10^{34}$ cm^{-2}s^{-1} set by the cryogenics cooling capabilities for the inner triplets at the high-luminosity experiments. Similar limits are also set in data taking at the experiments, mostly deriving from the maximum pile-up that can be handled per event. Given the limitations on the maximum peak luminosity, the achievement of the integrated luminosity target relies on a good machine availability, for which 2016 constitutes a very good omen.

One choice that will present itself again will be the one between standard and BCMS beams. BCMS beams offer the advantage of the lower emittance (and thus crossing angle), leading to a higher luminosity per bunch pair. Fewer bunches can be transferred at a time, resulting in less bunches per ring but less e-cloud. Standard beams allow an extra 30% of bunches per ring at the price of higher emittance and less luminosity per bunch pair, but with the advantage of a lower pile-up (and increased understanding of e-cloud in view of HL-LHC). This choice will require input from the experiments, and in case pile-up is an issue, the feasibility of luminosity levelling techniques was already proven.

CONCLUSIONS

The second Run of LHC operation will be half complete by the end of 2016. While 2015 was dedicated to establishing operation at 6.5 TeV with 25 ns beams and small β^*, 2016 was fully dedicated to physics production. The peak performance in 2016 exceeded the design values, reaching $\sim 1.4 \times 10^{34}$ cm^{-2}s^{-1}. This was possible by squeezing to 40 cm, and thanks to the brighter beams from injectors. A good delivery of integrated luminosity is also by now guaranteed, as more than 33 fb^{-1} were delivered in 2016. This was enabled by the improved machine availability. UFOs have conditioned down, and radiation to electronics effects are below expectations, but e-cloud is conditioning very slowly.

The LHC has moved from commissioning to exploitation, and enjoys the benefits of the decades-long international design, construction, and installation effort. A huge amount of experience and understanding has been gained and fed-forward into operation. The astounding results and progress represent a phenomenal ongoing effort by all the teams involved.

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