

OPERATIONAL CHALLENGES AND PERFORMANCE OF THE LHC DURING RUN II

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Abstract

The CERN Large Hadron Collider Run II saw an important increase in beam performance through both, improvements in the LHC and an increased beam brightness from the injectors, leading to a peak luminosity that exceeds the LHC design luminosity by more than a factor two. This contribution will give an overview of run 2, the main challenges encountered and it will address the measures applied to deal with and make use of the increased beam brightness. Finally potential areas where further performance improvement can be realized will be identified.

INTRODUCTION

Following the first Long Shutdown (LS1) in 2013 and 2014 during which the CERN Large Hadron Collider (LHC) and in particular the superconducting magnet interconnections were consolidated, the machine was re-commissioned at an energy of 6.5 TeV per beam in 2015, signalling the start of LHC Run II, covering the years from 2015 until the second Long Shut down (LS2) that will start in December 2018.

MULTI-ANNUAL OVERVIEW OF LHC RUNNING AND PERFORMANCE

Year 2015

The year 2015 was dedicated to establishing operation at 6.5 TeV per beam and with standard 25 ns bunch spacing [1], in order to prepare for substantial luminosity production during the years running up to LS2. The first three months were dedicated to magnet powering tests and the magnet training campaign to establish a reliable and reproducible magnet performance at magnetic fields equivalent to 6.5 TeV beam energy.

The beam commissioning was accomplished, using the 50 ns bunch spacing, considering that much experience was gained during Run I, but also to avoid electron cloud effects during this period. By mid-July, following a scrubbing run, the standard 25ns bunch spacing was used, initially with a reduced number of bunches to limit the total intensity and stored energy. Consequently, the beam intensity was ramped up until the end of the year by increasing step-wise the number of bunches injected to 2244 bunches per beam. Despite the prolonged periods of e-cloud scrubbing, the intensity ramp up was mostly limited by the heat load induced on the cryogenic system [2].

Year 2016

The year 2016 required only 4 weeks for the beam commissioning and was directly followed by an intensity ramp up and luminosity production, using the standard 25 ns bunch spacing. From Fig. 1, one can perceive that this was

also the first year with substantial luminosity production. On 26 June, after careful optimisation of the machine settings and beam brightness in the injectors, the LHC attained its design luminosity of $1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. In parallel, the injector chain prepared a high brightness 25 ns beam, based on a Batch Compression Merging and Splitting (BCMS) scheme [3]. The LHC took this beam successfully for the first time for physics on 19 July, resulting in a transverse emittance at the start of stable beams of $\sim 2 \text{ mm mrad}$. This, in combination with a reduction of the half crossing angle from $185 \mu\text{rad}$ to $140 \mu\text{rad}$ on 23 September, gave rise to a further gradual increase of the peak luminosity, as can be observed in Fig. 2, with a record peak luminosity of $1.4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

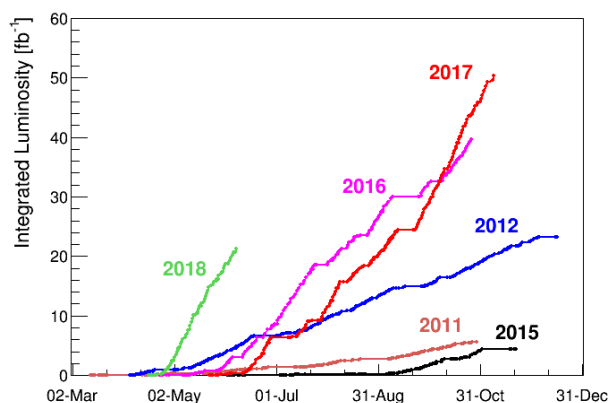


Figure 1: Multi-annual overview of the yearly integrated luminosity.

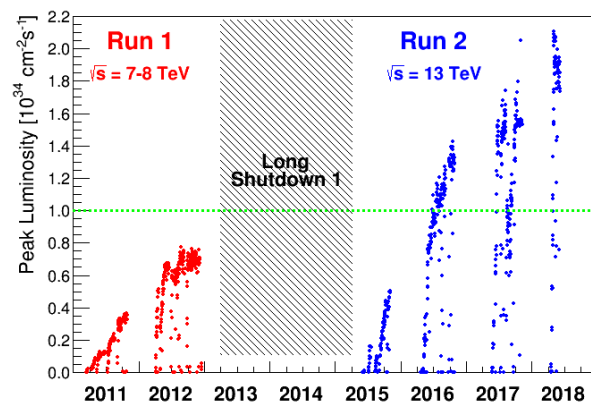


Figure 2: Multi-annual overview of the peak luminosity.

On 10 August an intermittent inter-turn short circuit was observed in one of the dipole magnets in half cell 31 left of IP2 (31L2) that is part of Sector 1-2, one of the eight sectors that constitute the LHC. Despite this, luminosity production continued with extra protection measures in place, but the decision was taken to replace the magnet during the

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upcoming Extended Year End Technical Stop (EYETS) of 2016-2017, which required a prolongation of the EYETS by one additional month.

The proton physics run ended on a very positive note with 40 fb⁻¹ integrated. The LHC continued running successfully for another 4 weeks with proton lead collisions.

Year 2017

Following the magnet replacement in Sector 1-2, requiring warming up and cooling down the 3 km-long sector, the hardware re-commissioning of the nearly 1600 circuits included a long list of additional tests to be performed on the sector that underwent the thermal cycle.

The first beam was injected on 29 April and first stable beams, with only a few bunches, was established on 23 May. Subsequently a period with interleaved commissioning and intensity ramp up followed. Before reaching 2556 bunches in stable beams on 19 July a one-week scrubbing run was performed to reduce the secondary electron emission yield of the beam screen, hence the production of electron clouds.

Earlier, already during the commissioning with beam, abnormal background radiation and sudden beam losses, some leading to beam dumps, were observed in the beam vacuum for both beams at the level of a magnet interconnect of half-cell 16 left of IP2 (16L2). These losses were induced by an accidental inlet of air into the beam vacuum with the beam screen at 20 K, following the magnet replacement [4, 5]. On 10 August a beam screen flushing was attempted where the beam screen is warmed up from its usual 20 K to 80 K with the aim to evaporate frozen gas and condensate it on the surrounding cold bore, out of the sight of the beam. Unfortunately, this flushing even degraded the situation.

Since the loss mechanism was suspected to be influenced by electron cloud, the injector chain produced the 25ns 8b4e beam that was used in the LHC as of 4 September. The 8b4e beam structure consists of eight bunches spaced by 25 ns followed by four empty buckets. This interleaved with SPS and LHC injection kicker gaps is then repeated around the circumference of the LHC, resulting in 1916 bunches per beam, and suppressing the electron cloud production drastically. Once proven successful in mitigating the 16L2 issue, this scheme was further enhanced in the injectors and a high brightness version, based on Batch Compression and Splitting was developed (8b4e-BCS). The main beam parameters for these beams that allowed efficient luminosity production, despite the 16L2 issue, are given in Table 2.

Following further measurements and studies on the available aperture it was decided to reduce the β -function at IP1 and IP5 from 40 cm to 30 cm. This together with the 8b4e-BCS beam resulted on 2 November in a new record of $2.06 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ for the peak luminosity as can be seen in Fig. 2. and Table 2. The number of inelastic collisions per bunch crossing (pile-up) in the experiments ATLAS and CMS was beyond the acceptable, consequently the instantaneous luminosity was levelled to $1.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, using levelling by beam separation.

The 2017 proton physics run that was hampered by the 16L2 issue nevertheless ended with a record integrated luminosity of 50 fb⁻¹.

Year 2018 (Current Year)

Although successful, but after running for a large part of 2017 with the 8b4e-BCS beam, all four experiments requested to revert from the 1868 bunches per beam for the 8b4e-BCS to the 2556 bunches of the BCMS beam. However, this could not be achieved without resolving the 16L2 issue. Therefore, Sector 1-2 was warmed up to 90 K during the YETS of 2017-2018, allowing the evacuation of about 7 litres evaporated gasses like oxygen and nitrogen, but not the water vapour, which was estimated to be 0.1 gram per beam vacuum [6].

The first beam was injected on 30 April and first stable beams, with only a few bunches, was established on 23 April. Subsequently, a period with interleaved commissioning and intensity ramp up followed. Before reaching 2556 bunches in stable beams on 5 May, which was thirteen days ahead of schedule.

During the intensity ramp-up, beam losses induced by 16L2, although much lower than in 2017, were present and closely monitored. These beam losses, see Fig. 3, are of two types: firstly, a steady-state or constant beam loss that depends on the total number of particles per beam. This beam loss is substantially lower than the threshold that could provoke a beam dump, thanks in particular to a special solenoid that was installed during the second half of 2017 [7]. Secondly, erratic beam loss spikes that add to the steady-state losses, potentially surpassing the dump threshold. The steady-state beam losses increase when the number of bunches increases, but the frequency of the beam loss spikes decreased the longer the beam circulates in the machine. These spikes were “conditioned away”, allowing running with the 2556-bunch BCMS beam in 2108.

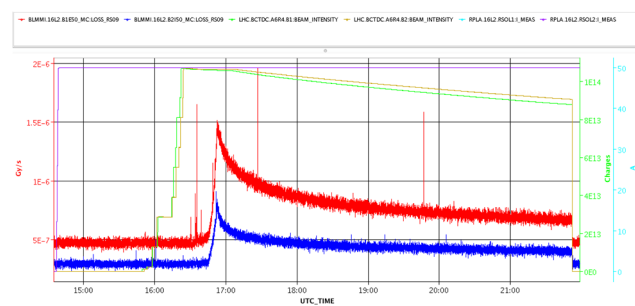


Figure 3: Beam loss monitors measurements in 16L2. The steady-state beam losses with superposed beam loss spikes for beam 1 (red) and beam 2 (blue).

The target for the 2018 proton physics run that ends on 27 October is to accumulate 60 fb⁻¹ of integrated luminosity. The year will end with a 24-day lead-lead ion run before going into a 1-week magnet training test to estimate the time required to increase the collision energy up to 7 TeV after LS2. A detailed breakdown of the days spend in each operational phase is given in Table 1.

Table 1: Time Allocation to the Different Operational Phases in 2018

| Phase | Days | Ratio [%] |
|---------------------------|------------|------------|
| Comm. & Intensity ramp up | 33 | 13.4 |
| Scrubbing (e-cloud) | 1 | 0.4 |
| 25 ns proton physics | 131 | 53.3 |
| Special physics runs | 17 | 6.9 |
| Setting up Pb-Pb ion run | 4 | 1.6 |
| Pb-Pb ion physics run | 24 | 9.8 |
| Machine Development | 20 | 8.1 |
| Technical Stops (3x) | 12 | 4.9 |
| Technical recovery | 4 | 1.6 |
| Total | 246 | 100 |

Performance Summary

The LHC machine and beam parameters for the years 2015 to 2018 are summarised in Table 2. The LHC machine availability and Stable Beam time for Run II are given in Fig. 4. Figure 2 shows the increase of the peak luminosity over the years, but also the slope with which this peak luminosity is reached is every year steeper, indicating an efficient re-commissioning of the machine and a fast intensity ramp up. The design luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ is indicated by the green line and was passed for the first time in 2016 and on 2 November 2017 the peak luminosity reached, was more than twice the design peak luminosity. The yearly integrated luminosity plot for the years 2011 until 2018 is given in Fig. 1. From this one can clearly distinguish the commissioning years 2011 (Run I) and 2015 (Run II) from the production years 2012, 2016, 2017 and 2018. The total integrated luminosity for each run is given in Fig 5. The target for the total integrated luminosity until end of Run II is 150 fb^{-1} , which is well in reach for 2018, the last year before LS2.

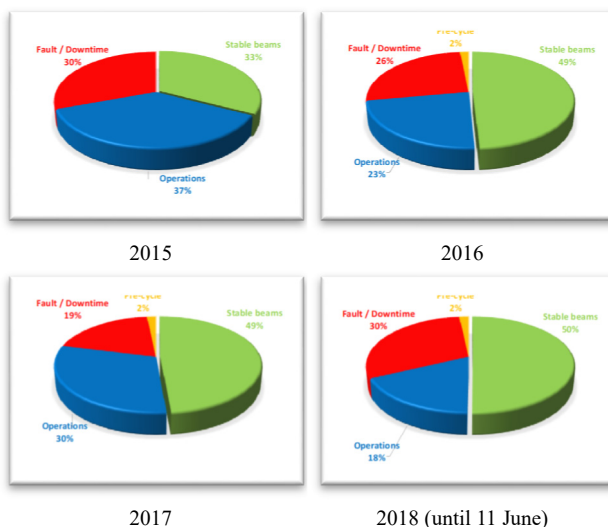


Figure 4: LHC availability for the years of Run II.

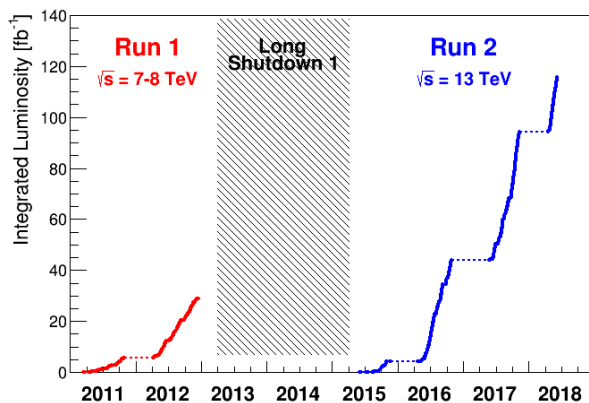


Figure 5: Multi-annual overview of the total integrated luminosity for Run I and Run II.

Table 2: Overview of LHC Machine and Beam Parameters for Run II Compared to the Design Values

| Parameter | Design | 2015 | 2016 | 2017 | 2018 |
|--|----------------|-----------|--------------|-----------|---|
| | Beam type: Std | Std | Std/BCMS | BCMS | 8b4e 8b4e-BCS BCMS |
| Energy [TeV] | 7 | 6.5 | 6.5 | 6.5 | 6.5 |
| Number of bunches per ring | 2808 | 2244 | 2040/2076 | 2556 | 1916 1868 2556 |
| Bunch spacing [ns] | 25 | 25 | 25 | 25 | 25 25 25 |
| Bunch population N_b [10^{11} p/b] | 1.15 | 1.15 | 1.2 | 1.2 | 1.2 1.25 1.2 |
| Transv. norm. emittance SB ϵ_n [mm mrad] | 3.75 | 3.5 | 3.5/2.1 | 2.1 | 2.3 1.8 2 |
| Betatron function at IP1 and IP5 β^* [m] | 0.55 | 0.8 | 0.4 | 0.4 | 0.4/0.3 0.3 0.3/0.25 ⁽³⁾ |
| Half crossing angle [μrad] | 142.5 | 145 | 185 | 150 | 150 150/110 ⁽¹⁾ 160/130 ⁽¹⁾ |
| Peak luminosity [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$] | 1 | 0.55 | 0.83/1.4 | 1.74 | 1.9 2.06/1.5 ⁽²⁾ 2.1 |
| Maximum pile up μ (per bunch crossing) | ~ 20 | ~ 15 | $\sim 20/35$ | ~ 45 | 70/60 ⁽²⁾ 80/60 ⁽²⁾ 60 |
| Stored beam energy [MJ] | 360 | 270 | 345 | 320 | 240 245 320 |
| Integrated luminosity per year [fb^{-1}] | n.a. | 4.2 | 39.7 | 50.2 | n.a. |

⁽¹⁾ Minimum crossing angle during crossing angle anti-levelling

⁽²⁾ Value after luminosity-levelling by separation

⁽³⁾ Minimum betatron function during betatron anti-levelling

SOME BEAM PERFORMANCE CHALLENGES

Tune & Chromaticity Shifts

On a plateau, like for beam injection where the magnet current is stable, the magnetic field multipoles drift due to current redistribution in superconducting cables, leading to drifts in tune Q and chromaticity Q' [8, 9]. These drifts whose magnitudes depend on the magnet powering history, need to be compensated. For the LHC this is implemented in the form of a feedforward based on a field description model (FiDeL). This accurate feedforward maintains the tune Q and chromaticity Q' constant along the entire plateau, but does not take into account any tune changes induced by the beam itself during the injection process.

The beam injection process in the LHC consists of accumulating a large number of high brightness bunches that itself will provoke a tune shift. This instantaneous Lassel tune shift is corrected taking into account the beam intensity.

Both mechanisms have been tested and deployed and are successfully used in the day-to-day operation of the LHC.

Electron Cloud and Heat Load

Since the start of LHC operation with bunch trains e-cloud has been observed and represents one of the main performance limitations for the LHC. These e-clouds cause transverse emittance blow up and potentially can run the beam unstable, causing losses. In addition their production puts a large constraint on the cryogenic system as they form a major source of heat load on the beam screen. Continued studies have largely enhanced the understanding of the phenomena and have led to the development of very powerful measurement and simulation tools [10].

The production of e-cloud strongly depends on the secondary electron emission yield of the beam screen. Simulations and experience have shown that the surface of the beam screen can be conditioned by exposing the beam screen for prolonged period to high rates of e-cloud.

In practice, at the start of a yearly run and once the LHC is sufficiently commissioned to house a large number of bunches at low energy, a scrubbing run of which the length varies from one to about five days, depending on the work performed during the YETS (e.g. vacuum chamber opening) is scheduled to re-establish conditions that allow to accelerate safely a full machine to high energy for collisions. The running for physics will then further, although slightly, scrub the machine.

Transverse Emittance Growth

The transverse emittance is together with the beam intensity one of the main parameters for high luminosity production. It is therefore important to preserve the emittance as much as possible and to minimize blow up in any of the processes. Intense measurement campaigns and careful analysis have revealed that the transverse emittance blows up beyond expectations which are deduced from

simulations [11, 12], principally during the injection plateau and acceleration. IBS is the dominating factor for the emittance growth at low energy. However, the growth rate is larger than the IBS contribution and therefore requires further investigation and understanding.

Table 3: Emittance Growth per Process and Beam Type

| Process | BCMS | | 8b4e-BCS | |
|--------------|-------|-------|----------|-------|
| | H [%] | V [%] | H [%] | V [%] |
| Injection | 15 | 9 | 17 | 15 |
| Acceleration | 5 | 22 | 43 | 45 |

The main contribution to the transverse emittance blow up appears during acceleration and can amount to an emittance growth of up to ~ 45% in the vertical plane for the highest brightness beam (8b4e-BCS) and ~ 22% for the BCMS beam (Table 3). A reduction of this growth will directly translate in a higher peak luminosity, but the mechanism behind the blow up is not yet fully understood and a working group, combining all the observations and concentrating efforts to understand and possibly mitigate the issue has been established. Minimizing this emittance growth will be very important, as during Run III the beam brightness from the upgraded injectors will gradually increase.

Beam Life Time

Beam lifetime is normally dominated by luminosity burn-off, but beam loss through other mechanisms can contribute to the reduction of the beam life time. A big effort is made to build a solid luminosity model for the LHC [12], allowing comparison between the theory, the theoretical model and beam observations, hence providing understanding on the amount of non-luminosity burn-off losses.

This model has already identified currently unexplained losses at the start of collisions and shows that the lifetime of beam 2 during the remainder of the fill is not too far away from model-based lifetime. However, there is a significant difference in lifetime for beam 1, which is being studied, but remains not fully understood. The intensity pattern along the bunch trains during collisions hints e-cloud as a potential source, but this remains to be confirmed.

PREPARING THE FUTURE

In view of the HL-LHC operation, some methods and principles foreseen are already being implemented and tested on the LHC to validate them fully and to gain operational experience.

Levelling & Anti-Levelling

Luminosity levelling is generally applied to reduce the number of inelastic collisions per bunch crossing when the instantaneous luminosity, the collider can provide, too high is. This has been done routinely for the two low luminosity experiments (ALICE and LHCb) since the start of the LHC.

However, in 2017 the achieved peak luminosity also exceeded the pile-up limit of ATLAS and CMS, hence levelling by beam separation was applied.

As a result of luminosity burn-off during collisions the dynamic aperture increases, allowing for the reduction of crossing angles and β -functions and therefore increasing the instantaneous luminosity [13]. This anti-levelling scheme has been developed, tested and validated during dedicated machine development (MD) sessions and deployed in steps. In the second half of 2017 the anti-levelling by reducing the half crossing angle from 150 μ rad in three steps to 120 μ rad was deployed and used operationally. In 2018 the steps were removed and since then a more continuous crossing angle anti-levelling, based on the dynamic aperture evolution is used. Also the β^* anti-levelling was added to reduce the β^* from 30 cm to 25 cm in two steps [14].

Both anti-levelling schemes increase the luminosity production with a few percent, but the gain in operational experience is also very important for the HL-LHC era.

Achromatic Telescopic Squeeze Optics

The Achromatic Telescopic Squeeze (ATS) allows for very small β -functions in the IPs, while correcting the chromatic aberrations induced by the inner-triplets on either side of the experiments [15], required for the HL-LHC [16]. This scheme has been developed, tested and validated during dedicated machine development (MD) sessions and came to sufficient maturity in 2016 to be deployed operationally at the start of 2017.

In the year preceding the deployment and with the aim of optimising of the magnetic cycle, part of the squeeze was started during the ramp, using the process called Combined Ramp & Squeeze (CRS) [17]. This allows arriving at the 6.5 TeV flat top with a β^* of 1 m for the two high luminosity experiments (ATLAS and CMS). A further squeeze down to a β^* of 30 cm is applied on the flat top. The last part of this squeeze, from a β^* of 40 cm to 30 cm, is relying on the ATS. In 2018 two further squeeze steps down to 27.5 cm and 25 cm were added towards the end of the fill with the aim to optimise luminosity production after sufficient luminosity burn-off.

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CONCLUSION

LHC Run II is successfully underway to reach the goal of 150 fb⁻¹ set for Run I and Run II. The machine and beam performance are continuously improved through thorough understanding of the underlying systems and physics processes, but there are still challenges among which beam emittance growth and beam life time optimisation.

Run II saw also important steps towards HL-LHC operation. The ATS optics was successfully deployed and used,

although not yet to its full extend. Luminosity levelling and anti-levelling, based on beam separation, crossing angle and β^* are now used routinely and will be further develop.

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