LHC RUN 2: RESULTS AND CHALLENGES

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Abstract

The first proton run of the LHC was very successful and resulted in important physics discoveries. It was followed by a two-year shutdown where a large number of improvements were carried out. In 2015, the LHC was restarted and this second run aims at further exploring the physics of the standard model and beyond at an increased beam energy. This article gives a review of the performance achieved so far and the limitations encountered, as well as the future challenges for the CERN accelerators to maximize the data delivered to the LHC experiments in Run 2. Furthermore, the status of the 2016 LHC run and commissioning is discussed.

INTRODUCTION

The CERN Large Hadron Collider (LHC) [1, 2] is built to collide 7 TeV protons or heavy ions of equivalent rigidity. Following the downtime after an incident in one of the main dipole circuits during the first commissioning in 2008 [3], the operation restarted at lower beam energy to minimize the risk. Therefore, the first proton run (2010-2013) [4–6] was carried out at 3.5 TeV–4 TeV. Furthermore, a bunch spacing of 50 ns was used instead of the nominal 25 ns. This implied fewer bunches with larger intensity and hence a high peak luminosity but larger than nominal pileup. Run 1 resulted in about 30 fb^{-1} of proton data and important physics results, most notably the discovery of the Higgs boson [7, 8].

Run 1 was followed by a long shutdown (LS1, 2013–2014) with a large number of consolidation and upgrade activities [9]. The bus-bar splices between the superconducting magnets were improved, in order to make sure that the LHC could operate at higher energy without risk of repeating the 2008 incident. Run 2 started in 2015 and is planned to continue until the end of 2018. The main accelerator goals of Run 2 are to produce more than 100 fb^{-1} of data at a higher energy and using the nominal 25 ns bunch spacing, but with lower bunch charge for lower pileup.

The parameters achieved so far in Run 1 and Run 2, together with the design values, are shown in Table 1. At the time of writing in end of June 2016, the LHC has entered its production phase with a luminosity that has just reached nominal, a stored beam energy of around 250 MJ, and a good machine availability after a few initial technical issues. This article gives a review of the achievements so far, as well as the issues encountered and the challenges ahead for reaching the goals of the LHC.

BEAM FROM THE INJECTORS

The success of the LHC is highly dependent on the availability and the beam quality of the injector complex. Protons are injected at 450 GeV into the LHC, after passing through a chain of 4 accelerators: LINAC 2, PSB, PS, and SPS [10]. The present limitations on bunch intensity N_B and normalized emittance ϵ_n in the injector chain are summarized in Fig. 1 for the standard 25 ns LHC beam [11]. The brightness is limited by space charge effects in the PSB and the PS and the fact that, in the PSB, several injections are performed from LINAC 2 per PSB bunch. This means that in order to increase the intensity, more injections are needed, which occupy different phase-space areas and hence cause larger ϵ_n. In the SPS, longitudinal instabilities occur if $N_B \gtrsim 1.3{\times}10^{11}$ protons per bunch. The green dots in Fig. 1 show the actual achieved beams in 2015.

Figure 1 refers to the standard 25 ns LHC beams, which have been used so far in 2015–2016. Several different schemes exist [12], where the most interesting for LHC physics is the so-called BCMS beam (Batch compression, merging and splitting) [13, 14]. It has almost a factor 2 smaller ϵ_n, since lower-intensity bunches with smaller ϵ_n are taken from the PSB and merged in the PS to achieve about the same N_B as for the standard beam. However, fewer bunches per train can be achieved and hence a slightly smaller number of total bunches in the LHC.

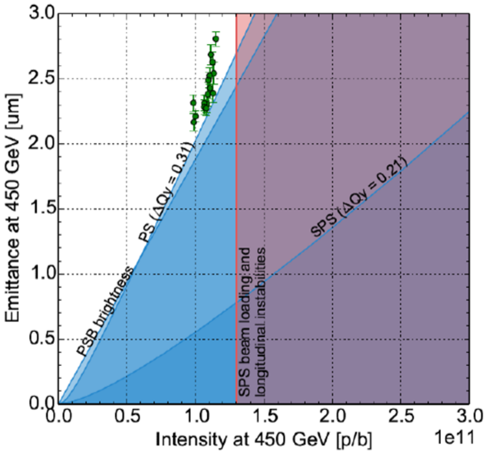

Figure 1: Limitations on the beam intensity and normalized emittance in the injector chain. The white area to the left represents the possible configuration space for the LHC beams and the green dots the beams used in 2015.

THE 2015 PROTON RUN

Because of the large number of changes applied in LS1, a significant recommissioning period was needed. Therefore 2015 was considered to be a commissioning year, with the main goal to reestablish high-intensity operation with the new running parameters. A beam energy of 6.5 TeV was

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Table 1: Typical proton running conditions in the LHC during operation so far in Run 1 (2010–2012) and Run 2 (2015–2016), shown together with the design parameters. The values of luminosity, crossing angle, beam-beam separation, geometric reduction factor, and number of colliding bunches, refer to the high-luminosity experiments in IR1 and IR5 only.

	Design	2010	2011	2012	2015	June 2016
Beam energy (TeV)	7.0	3.5	3.5	4.0	6.5	6.5
Protons/bunch (average at start of collisions)(10^{11} p)	1.15	1.0	1.3	1.5	1.1	1.1
Maximum number of bunches	2808	368	1380	1380	2244	2076
Maximum stored energy per beam (MJ)	362	23	112	143	277	266
Bunch spacing (ns)	25	150	50	50	25	25
Transverse normalized emittance ϵ_n, typical value in collision (μm)	3.75	2.6	2.4	2.4	3.5	3.4
half crossing angle (μrad)	143	100	120	146	145	185
Primary collimator cut (σ)	6.0	5.7	5.7	4.3	5.5	5.5
Secondary collimator cut (σ)	7.0	8.5	8.5	6.3	8.0	7.5
Tertiary collimator cut (σ)	8.3	15.0	11.8	9.0	13.7	9.0
Smallest allowed magnet aperture (σ)	8.4	17.5	14.1	10.5	15.5	9.9
β^* (m)	0.55	2.0–3.5	1.0–1.5	0.6	0.8	0.4
Maximum peak luminosity (10^{34} cm^{-2}s^{-1})	1.0	0.021	0.35	0.77	0.51	1.01
Total integrated luminosity (fb^{-1})		0.048	5.5	22.8	4.2	8.1

chosen as a compromise between energy reach and the time needed in terms of training quenches of the main dipole circuits to reach the nominal 7 TeV [15].

As shown in Table 1, a relaxed set of machine parameters were chosen for the 2015 operation, in order to ease the commissioning [16, 17]. The optical β-function at the collision point, β^*, was 80 cm, which is larger than the β^* =60 cm used in 2012, in spite of the higher energy and thus smaller beam size. This allowed a beam-beam separation of 11 σ, which gave room for a larger dynamic aperture than in 2012 [18]. Furthermore, the collimator settings used in 2015 were the 2012 settings kept in mm [17], in spite of the higher energy, which relaxed the impedance constraints compared to the alternative scenario of keeping the settings in σ. Furthermore, an additional 2 σ margin was introduced for machine protection. By relaxing these parameters, the risk that the operation would be perturbed by beam instabilities and sudden lifetime drops was kept small.

The hardware commissioning started in early 2015 and the first beams were circulating in April. The first operation took place with a small intensity, which was gradually ramped up, in order to give the opportunity to spot any machine protection issue early on. An initial physics run with 50 ns was performed, before the LHC moved to 25 ns operation in August and heavy ions in November. This was aimed at re-establishing operation at high stored energies before addressing limitations from electron cloud expected with the shorter bunch spacing.

The operation in 2015 was perturbed by several hardware issues. It was found that some electronic components of the quench protection system were not radiation hard, which caused single event upsets and spurious beam dumps [19]. This was fixed during a technical stop by replacing affected components.

The material of the movable absorbers for injection protection (TDI) showed non-conformities [20]. In order not to risk that the TDI would be damaged by miskicked beam, the maximum number of bunches per injection was limited to 144 as opposed to the nominal 288. High vacuum spikes were also observed during injection close to one of the two TDIs, and the level of the vacuum interlock had to be increased to avoid spurious beam dumps. It was later found that the TDI coating was damaged, and a possible link to the vacuum issues is studied. Both TDIs have been exchanged for the 2016 run with a new and improved design [20].

Other limits came from so-called UFOs (unidentified falling objects), which are believed to be dust particles falling into the beam [21–25]. The interactions of the the beam with UFOs induce particle showers on nearby elements, which caused 18 beam dumps and 3 quenches in 2015. Some conditioning of UFOs with time has been observed, and efforts have been done to optimize the beam loss monitor thresholds to minimize the downtime from dumps and quenches.

Furthermore, several beam dumps and quenches at the beginning of the 2015 run, always triggered by beam losses in the same dipole, were attributed to an unidentified lying object (ULO) [26]. Dedicated tests, where the beam was moved in steps around the aperture in this magnet, allowed to map out the shape of an aperture restriction, possibly a lying object, at the bottom of the vacuum chamber. The situation was solved by introducing an orbit bump to steer the beam with sufficient clearance past the ULO.

The main beam-physics related constraint that the LHC faced in 2015 was related to electron cloud (EC), which was since long foreseen to be a major performance limitation [27–29]. Free electrons may be accelerated by the beam towards the vacuum pipe. On impact, secondary electrons are produced, which in turn are accelerated and cause an avalanche effect. The consequences are an increased heat load on the beam screens, increased vacuum pressure, and single or multi-bunch instabilities.

For the LHC, the main issue has been that the heat load to the cryogenic system limits the number of bunches that can be injected (2244 at the end of 2015) [30, 31]. The heat load was found to differ between machine sectors, which is not well understood. Because of a conditioning effect, special scrubbing runs were carried out, to condition the EC to a level where the beam quality is acceptable. Further conditioning was observed over the 2015 physics run. It should be noted, however, that due to the TDI limitation, longer trains of 288 bunches could not be injected, and hence the scrubbing was less efficient. Further limitations due to vacuum degradation at the injection kickers have also been encountered.

Some beam instabilities were encountered, driven mainly by EC, impedance, and an interplay between the two. The beams could, however, be stabilized through a high chromaticity, high octupole current and high damper gain [31,32], although the resulting increased tune spread, in combination with the tune spread from EC, made the tune footprint at 450 GeV reach the third order resonance. This was mitigated by a slight change in vertical tune. Efforts are also ongoing to improve the diagnostics and measurements of instability-related data [33].

Performance limitations due to beam-induced heating of various components, which were frequently encountered in Run 1, have been mitigated by a large effort to minimize the impedance and fix equipment non-conformities during LS1 [34, 35].

In spite of these issues, the LHC was in 2015 successfully commissioned at 6.5 TeV and 25 ns bunch spacing, and a total of 4.2 fb^{-1} of proton data was collected by the experiments.

THE 2015 HEAVY-ION RUN

The 2015 heavy-ion run with Pb-Pb collisions started in mid-November and lasted for about a month [36]. A commissioning period was followed by a reference proton run at the equivalent nucleon center-of-mass energy and the Pb-Pb run. The Pb beam energy was 6.37Z TeV, (Z is the nuclear charge), which provided a center-of-mass energy of over 1 PeV. This is a record for heavy-ion colliders.

A limitation to the achievable luminosity for heavy ions is bound-free pair production (BFPP), in which a colliding Pb ion captures an electron at the collision point and is subsequently lost locally in the dispersion suppressor, due to the change in charge [37]. These losses have been predicted to possibly induce quenches [38], which was shown also experimentally in 2015 [39, 40]. This effect was alleviated in 2015 by orbit bumps that moved the losses longitudinally to a harmless location in IR1 and IR5 [41].

The Pb run profited from an very good machine availability (around 80%), which was better than in the proton run, and about 40% of the time was spent in physics [42]. Because of excellent injector performance, an average of 1.6×10^8 ions per bunch was achieved at the start of collisions [36]. This largely surpassed the design value of 7×10^7 ions per bunch and was a key to achieving a peak luminosity of 3×10^{27} cm^{-2}s^{-1}, exceeding the peak design luminosity by a factor 3, as shown in Fig. 2.

At the end of 2016, there will be a p-Pb run, partly at the same energy as in 2013 [43, 44], but mainly at the maximum available beam energy of 6.5 Z TeV. Another Pb-Pb run is scheduled in 2018.

2016 PROTON PARAMETERS

To explore further the LHC physics potential, a significantly higher integrated luminosity is needed than in 2015. The goal is to surpass 100 fb^{-1} in the whole Run 2 and 25 fb^{-1} in 2016, which is considered as a production year. Therefore, the parameters of the LHC have to be pushed to increase the peak luminosity, while at the same time the machine availability and the time spent in physics should be maximized. The parameters for 2016 are shown in Table 1 and we outline here how they were chosen.

The luminosity $\mathcal{L}$ for round beams and optics can be written as

$$\mathcal{L} = \frac{N_B^2 f_{\mathrm{rev}} k_B}{4\pi \beta^* \epsilon_{xy}} \times F, \tag{1}$$

where f_{rev} is the revolution frequency, k_B the number of bunches per beam, $\epsilon_{xy} = \epsilon_n/(\gamma_{\mathrm{rel}}\beta_{\mathrm{rel}})$ is the geometric emittance and F a geometric reduction factor. It can never be larger than 1 and is given by

$$F = \frac{1}{\sqrt{1 + \frac{(\sigma_s \tan\phi)^2}{\epsilon_{xy}\beta^*}}}. \tag{2}$$

Here σ_s is the bunch length and ϕ the half crossing angle.

As seen from Eq. (1), there are different ways to push the luminosity. Firstly, the intensity can be increased through k_B and N_B, where the latter gives a larger gain due to the square dependence in Eq. (1). There could be a possibility to push N_B towards the SPS limit of 1.3×10^{11} at the expense of slightly larger ϵ_n (see Fig. 1). This is more challenging for electron cloud and impedance effects. To stay within the stability boundaries, N_B can be increased incrementally to find the optimum. Similarly it is planned to gradually increase k_B while staying within the EC heat load limits, which was started already in 2015.

The transverse beam size can be decreased by acting on ϵ_n or β^*. The BCMS beams could be used to decrease ϵ_n, but it is desirable to finish all EC scrubbing studies with the standard beam before moving to BCMS, which risks also to be more prone to instabilities and worse lifetime due to the higher brightness [32, 35]. It is also still to be quantified how much ϵ_n of the brighter BCMS beam increases through the LHC cycle, before entering collisions.

Moreover, β^* can be decreased, independently of constraints on ϵ_n and intensity. In the LHC, β^* is limited mainly by the available aperture. When β^* is decreased, the β-function in the triplets of the final focusing system increases.

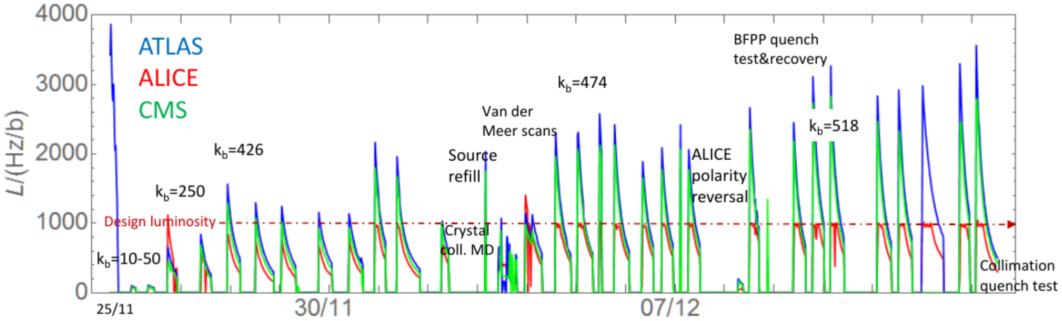

Figure 2: Luminosity for 3 of the 4 experiments, during the 2015 Pb-Pb run showing the progressive increase of number of bunches, k_b and the interruptions of regular data-taking. The dashed line shows the design luminosity [1]. The figure is taken from Ref. [36]. The ATLAS luminosity has recently been recalibrated and the peak corresponds to 3×10^{27} cm^{-2}s^{-1}.

The triplet aperture, normalized by the beam σ, therefore decreases, but it is only allowed to decrease so much that the collimation system still protects the aperture [45–47]. To reduce β^*, one can reduce ϕ in order to gain aperture margin or optimize the collimators to protect a smaller aperture.

Acceptable values of ϕ are given by what normalized beam-beam separation can be tolerated without degrading the dynamic aperture so much that the lifetime suffers. In 2015, a normalized beam-beam separation of 11 σ was used but a reduction to 10 σ has been shown to be possible [18, 48, 49], which has been implemented for the 2016 run.

An extensive machine development (MD) program on collimator settings, carried out in 2015, showed that the secondary collimators in IR7 could be moved in by 0.5 σ without jeopardizing the long-term stability of the cleaning or increasing the impedance too much [35,50]. Furthermore, tertiary collimators (TCTs) were previously kept rather open to minimize the risk that they, or the triplets behind them, could be damaged during an asynchronous beam dump [47]. These settings could now be significantly reduced, using a new optics in which the fractional phase advances between the dump kicker, TCTs and triplets are close to 0° or 180°, so that they can never be hit by primary beam during such an accident. This has resulted in a very important gain in protected aperture [51–53].

With the tighter collimation hierarchy and the smaller beam-beam separation, β^* =40 cm is the 2016 baseline, which was studied in detailed MDs [54]. This is well below the nominal value β^* =55 cm, and it relies also on a very well aligned triplet aperture [51].

The geometric factor F in Eq. (1) can be increased by decreasing ϕ (discussed above) or σ_z, which is limited by EC effects [31] and longitudinal instabilities [55]. In 2015, an RMS bunch length $\sigma_z \approx$ 10 cm was deployed, which has been slightly decreased in steps in 2016, to approach the boundary of acceptable values. It should be noted that in the LHC, σ_z shrinks during the fills due to synchrotron radiation. Therefore, σ_z at the start of the fill should be large enough that no instabilities appear later in the fill. A longitudinal blowup during the fill is under study [55].

OPERATIONAL EXPERIENCE IN 2016

The recommissioning in 2016 with new parameters was smooth. The new β^* =40 cm optics could be corrected to a peak β-beat of less than 5% thanks to improved methods [56–58] and the absence of perturbing triplet movements as in 2015. The new collimator settings were successfully put into operation and showed excellent cleaning performance [59]. However, technical issues caused delays. About 6 days were lost due to interventions on the PS main power supply and its spare, and another 6 days due to a 66 kV transformer short circuit caused by an animal. Further delays were caused by water infiltration in IR3 that induced faults on contacts on collimator cables. This is summarized in Fig. 3, which shows the luminosity production since May 2016.

Another delay was caused by a vacuum leak the SPS beam dump, which still prevents trains longer than 96 bunches.Therefore, the plans of increasing k_B towards the maximum possible are, at the time of writing, put on hold due and k_B is temporarily limited to 2076 bunches, as seen in Table 1. With the shorter trains, the EC effects are less pronounced, and the intensity could quickly be ramped up to about 2000 bunches. The intensity rampup over time in 2016 is shown in the bottom plot of Fig. 4, where it can be compared to previous years of operation. It can be seen that the LHC now regularly stores about 250 MJ of energy per beam during the physics fills.

Apart from the mentioned faults, the recent availability has been excellent, as seen in Fig. 3, with systems such as cryogenics, power converters, RF, diagnostics and collimation working reliably. In one week, the LHC spent 75% of the time in physics. Many long fills of more than 20 h were possible, with a record of 0.74 fb^{-1} produced in one fill. After decreasing the bunch length in steps, the peak luminosity has now reached the nominal 10^{34} cm^{-2}s^{-1}. Compared to the nominal scenario, the bunch population in collision is about the same, but about 25% fewer bunches are used, and slightly larger beam-beam separation and bunch length. This is compensated by a 27% smaller β^* and slightly smaller emittance (see Eq. (1) and Table 1).

The progress of the production of integrated luminosity is shown in the top plot of Fig. 4, together with the data

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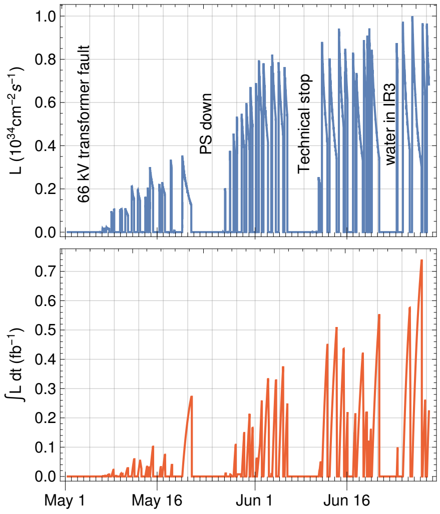

Figure 3: The instantaneous luminosity (top) and the integrated luminosity per fill (bottom) at the ATLAS experiment in May and June 2016.

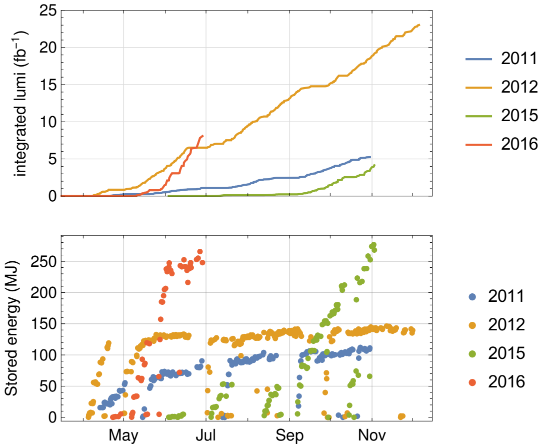

Figure 4: The accumulated luminosity at the ATLAS experiment (top) and the stored beam energy in each fill (bottom) over the years of LHC operation so far.

collection in previous years. The rate at which the LHC is gathering data is, since the end of May 2016, faster than any previous year, and more than 2 fb^{-1} per week could be produced. This is due to both the higher luminosity and the very good availability. So far, the LHC has on June 29 2016 collected 8.1 fb^{-1} for the high-luminosity experiments, which surpasses the 2015 run already by almost a factor 2.

CONCLUSION AND OUTLOOK

The LHC is presently (June 2016) on a good track of for reaching its 2016 goal of at least 25 fb^{-1}, thanks mainly to recent good availability, a very small β^*, and a good luminosity lifetime. The years 2017 and 2018 will also be focused on luminosity production, and it would be desirable to produce more than 40 fb^{-1} per year in order to exceed 100 fb^{-1} in Run 2. Therefore, further efforts to improve the performance are likely to be needed. It is also crucial for the success of the LHC that the recent good availability is maintained or even improved. Studies are performed to understand all causes of LHC downtime and how different faults depend on each other, so that efforts for improved reliability can be focused where they are needed the most [42]. In parallel, various means are studied in order to further increase the luminosity along the lines outlined above.

A main challenge for the LHC is to push the intensity limit from EC heat load. During the 2016 run, the conditioning effect has hardly been visible, however, only the shorter 72 and 96 bunch trains were used. To further understand and push the limits, tests should be done with longer trains of 288 bunches or the special doublet beam, which was developed for this purpose [60].

If the intensity cannot be further increased due to e.g. electron cloud, the high-brightness BCMS beams could be a good option. Moreover, further MD studies are planned to explore the long-range beam-beam effect and to find out whether the crossing angle can be further decreased without losing in luminosity lifetime. Preliminary studies have shown that a beam-beam separation even down to 8 σ could be feasible with BCMS beams [18]. The collimation hierarchy is also under study, where it might be possible to further reduce the openings. The limitations are given both by machine protection constraints, impedance, and stability of the cleaning hierarchy [47], in order to gain further in β^*. Combining these improvements, there is hope that the design luminosity could be exceeded by several tens of percent [61]. Further developments, such as flat optics, are also under study.

The LHC beam energy is presently 6.5 TeV, however, further tests could be envisaged to evaluate more precisely the number of additional training quenches that are required to reach 7 TeV, and thus how costly it is in terms of time [15].

Another long shutdown (LS2) is planned 2019–2020, in which major upgrades are foreseen in particular for the injector complex [62]. Tentatively, LS2 will be followed by Run 3 to 2023 and then LS3 (2024–2026), where major upgrades for high-luminosity LHC are to be installed [63]. With these improvements, the goal is to produce around 3000 fb^{-1} over the following 10 years.

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