

OVERVIEW OF PROTON-PROTON PHYSICS DURING RUN II

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Abstract

An overview of the main LHC proton-proton program at 6.5 TeV beam energy during Run II is presented. The paper summarizes the highlights and the limitations during each year from 2015 to 2018. It presents the strategy followed to achieve the initial luminosity goals while incorporating some of the features expected for High Luminosity LHC scenarios such as luminosity levelling, combined ramp and squeeze, Achromatic Telescopic Squeeze (ATS) optics, high-brightness and low e-cloud beams. The global performance of the machine in terms of beam losses, orbit stability and beam lifetime is also discussed.

INTRODUCTION

In Run II, from 2015 to 2018, the LHC has been accelerating for the first time proton beams at the unprecedented beam energy of 6.5 TeV [1–4]. Figure 1 shows the evolution of the delivered integrated luminosity to the ATLAS and CMS experiments. Each year the LHC was able to deliver more integrated luminosity per year, from the initial 4.3 fb^{-1} during 2015 to the 65 fb^{-1} during 2018. The total luminosity delivered to ATLAS and CMS during the full Run II was about 160 fb^{-1} .

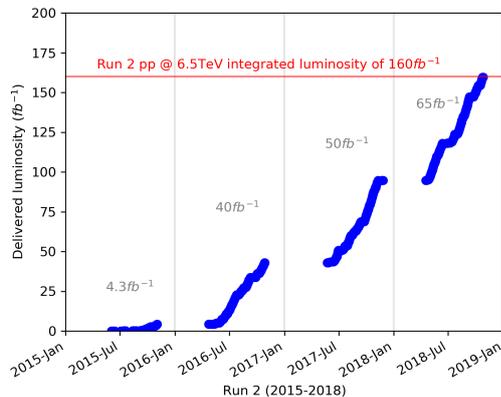


Figure 1: LHC delivered luminosity for the high luminosity experiments ATLAS and CMS with proton beams at 6.5 TeV.

HIGHLIGHTS OF THE RUN II

Run 2015

The first goal for 2015 was to operate the LHC with beams accelerated to 6.5 TeV. This was only possible after a long campaign of consolidations of superconducting magnets

and circuits that took place during the Long Shutdown 1 (LS1) [5, 6]. Three months were allocated for LHC hardware commissioning, conducting more than 10 000 magnet powering tests and an intensive dipole training campaign. Figure 2 shows the maximum dipole current achieved as a function of the number of training quenches. For sector 45, almost 80 quenches were necessary before reaching 11 500 A.

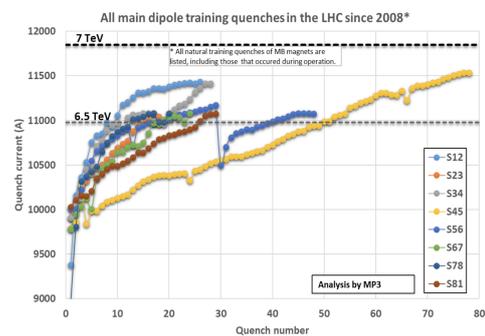


Figure 2: Maximum achieved current during the main dipole training campaign in the LHC since 2008, courtesy of M. Pojer.

The second goal of the year was to operate with 25 ns bunch spacing, meaning to overcome the e-cloud challenge. The strategy proposed was to mitigate the e-cloud by scrubbing, initially done, with 50 ns bunch spacing beams. Looking for beams with strong heat-load contribution, the doublet beam was also considered. Two bunches separated by 5 ns followed by other two after 20 ns. Due to several complications it was decided to drop this option and continue with scrubbing at top energy with both 50 ns and 25 ns beams [7, 8]. Therefore, an initial intensity ramp up was planned at 50 ns to continue scrubbing at top energy, but also to obtain experience with the new beam energy while benchmarking the new configuration with similar conditions as in Run I.

Very early in the run, fast losses in cell 15R8 for Beam 2 were observed and in some cases resulting in beam dumps and magnet quenches [9]. The solution was to insert an orbit bump (vertical 1 mm and horizontal -3 mm) after a warm up cycle of the beam-screen from 1.9 K to 80 K to 1.9 K. This mitigated the losses, but the so-called ULO (Unidentified Lying Object) in cell 15R8 and the orbit bump remained with us for the full Run II.

In August 2015, the second intensity ramp up at 25 ns started, with a consistent increase of peak luminosity. The optics were setup to squeeze the beams down to 80 cm in ATLAS and CMS. However, thanks to the K-modulation measurements it was found that the effective beta-star (β^*) was rather 86 cm due to a shift of the waist. K-modulation

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measurements proved to be very useful for the fine tuning of the machine and are now systematically performed.

The performance of the machine was also limited due to the quench protection system (QPS) triggering beam dumps with a resulting recovery time of about 3 hours. The issue was quickly understood. During LS1, 1 248 modified QPS boards were installed to be used for special tests (CSCM) to verify the splice quality after consolidations. These cards were a factor of 4 more sensitive to radiation. During the second technical stops (2015 TS2) these cards were exchanged and the availability of the system increased significantly.

The increase of luminosity was achieved by the increase of total intensity, injecting more bunches. The LHC was limited to a maximum of 2 244 bunches due to a concern on the material of the TDI that was limiting train injections to 144 bunches. The TDI was replaced during YETS15-16 to overcome this issue.

Run 2016

2016 was the first out of the 3 production years of Run II. The commissioning and intensity ramp up were relatively fast. Before the first technical stop the machine was filled with close to the maximum number of bunches.

It was decided to commission the combined ramp and squeeze. The beta-star in ATLAS and CMS was squeezed during the energy ramp up, down to 3 m and in LHCb down to 6 m. The change of optics during the ramp was possible thanks to an excellent control of the orbit, tunes and coupling through feed forward corrections and good machine reproducibility followed by fine corrections with active feed-backs. The cycle was configured with an additional squeeze segment, reducing even further the beta-star in ATLAS and CMS down to 40 cm, well below the design beta-star values.

The increase of peak luminosity was achieved by four pillars:

- Beta-star of 40 cm beyond nominal values.
- High-brightness beams, thanks to smaller emittances (BCMS beams).
- Optimization of the abort gap keeper, allowing to optimize the injection scheme.
- Half-crossing angle reduction, from 185 μrad down to 140 μrad (23rd Sep).

From July 2016, the LHC was colliding beams with peak luminosity above the design value of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

The crossing angle reduction had an impact on the beam lifetime and the correction of tune and coupling in collisions started to become more important [10], as shown in Figure 3 where the Beam 1 lifetime improves significantly after fill after applying tune trims. The lifetime of Beam 2 is already very high and did not seem to be affected by the tune trims.

Despite the good performance of the LHC during 2016 there were also several limitations:

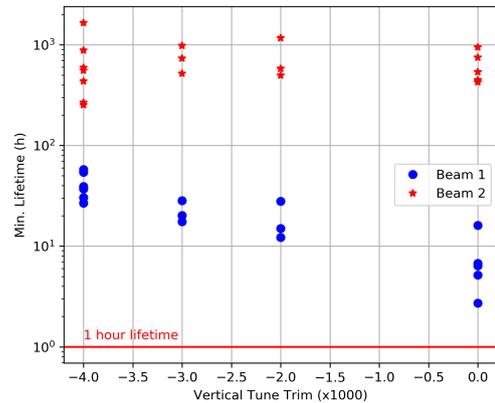


Figure 3: Minimum beam lifetime during crossing angle change as a function of the applied vertical tune trim in 2016.

- Short circuit with storage capacitors on the Proton Synchrotron (PS) main power supply (POPS). The re-start happened at the end of May with degraded POPS.
- Vacuum leak on the TIDVG core of the SPS dump limited the maximum number of bunches per train to 96 bunches, this implied a limit on the maximum number of bunches in the LHC of 2 220 bunches.
- LHC injection kicker out-gassing from ceramic connection (MKID Q5.R8 of Beam 2). This limited the maximum bunch intensity to 1.1×10^{11} p/b.
- Short circuit caused by a weasel on a 66 kV transformer in Point 8.
- Intermittent inter-turn short dipole circuit in sector 12 (31L2). Operations could continue with certain mitigation measures in order to reduce the probability to quench at high current.

Run 2017

The second production year started after a longer EYETS16-17 due to the replacement of the magnet in sector 12 (cell 31L2). During 2017, some of the High Luminosity LHC (HL-LHC) baselines were implemented operationally. The ramp and squeeze was more aggressive, beta-star in ATLAS and CMS was squeezed to 1 m and in LHCb to 3 m during the energy ramp up. An additional squeeze segment was implemented to squeeze further to 40 cm, this time using the HL-LHC baseline Achromatic Telescopic Squeeze (ATS) [4, 11, 12]. After a good performance of this optics it was decided to squeeze even further to 30 cm after the technical stop 2. The RF power was also reduced with the second HL-LHC baseline, the full RF detuning, allowing beam currents beyond nominal values.

Different levelling strategies were explored:

- Crossing angle anti-levelling in steps [13]. Starting with the half-crossing angle of 150 μrad and move to 120 μrad in steps of 10 μrad .

- Levelling in ATLAS and CMS by separation.

The maximum beam current injected in the machine was limited by high losses in sector 12, cell 16L2. After a beam screen warm up in August, following a similar strategy as in 2015, the losses in 16L2 became more important and highly depending on the bunch beam intensity, limiting the total intensity per bunch. The problem in 16L2 is today understood as a vacuum leak following the exchange of the magnet, and the subsequent cool-down, in 2017, see [9]. However, 16L2 limited the bunch intensity during 2 years (2017 and 2018) to approximate 1.2×10^{11} p/b.

The increase of luminosity was then achieved by the use of beams inducing low heat-load, the so-called 8b4e (8 bunches 4 empty) with very small emittance. Peak luminosity went beyond $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, and levelling in ATLAS and CMS became necessary in order to keep the number of pile-up interactions within acceptable limits.

During YET17-18 the sector 12 was warmed to 80 K and several litres of gas were evacuated, however 0.1 g of water still remained in the machine.

Run 2018

The machine was setup with the same injection and combined ramp and squeeze as in 2017. Attempts to use a shorter energy ramp (PPLP) [14] were unsuccessful. The squeeze segment was setup again with ATS optics arriving directly to 30 cm in ATLAS and CMS [15].

Soon after the intensity ramp up the losses in 16L2 came back limiting the maximum bunch intensity to approximate 1.2×10^{11} p/b. The machine was pushed to the limit of intensity and number of bunches with the same type of beams (8b4e) and when the losses of 16L2 dumped, an empirical recovery procedure (having a short fill of 900 bunches) was regularly done which seemed to quickly condition the machine.

Despite the limitation from 16L2, the peak luminosity was systematically close to the $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ but more integrated luminosity was possible thanks to a well prepared levelling strategy:

- Continuous crossing angle anti-levelling, from initial $160 \mu\text{rad}$ smoothly in stable beams to $130 \mu\text{rad}$ as function of the beam current with steps of $1 \mu\text{rad}$.
- Beta-star levelling [16]. For the first time the LHC was changing dynamically optics in stable beams. The beta-star in ATLAS and CMS was reduced from 30 cm to 27 cm to 25 cm while colliding in stable beams.

MACHINE PARAMETERS

An overview of the main beam parameters during Run II is shown in Figure 4. In the figure, each point represents the data of one LHC fill. The description is, from top to bottom:

1. Number of bunches injected in the LHC.
2. Averaged bunch intensity injected in the LHC.

3. Total stored intensity in the LHC.

4. Peak luminosity in ATLAS and CMS when beams arrive to collisions (not necessary in stable beams).

The maximum number of bunches during Run II was 2556. The LHC could not be filled with 2808 bunches due to the usage of the low heat-load beam 8b4e. Bunch intensities were kept around 1.2×10^{11} p/b. Attempts to increase it were done until reaching the limit coming from the losses in 16L2. The overview of e-cloud and heat loads can be found at [17].

Overall, the stored intensity was kept around the 3×10^{14} p, just at the limit of 300 MJ, during most of Run II, going above these values shortly after 2017 and in 2018 during the intensity ramp-up. Despite these limitations, the peak luminosity was constantly increasing by pushing other beam and optics parameters, reaching the values of $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ towards the end of 2017 and maintaining it for the rest of the run. Table 1 shows the main beam parameters and settings for Run II compared with the design LHC values.

LEVELLING AND ANTI-LEVELLING

One of the last features tested and implemented in the LHC was a more complex and dynamic luminosity levelling. In this scenario, several processes need to be synchronized: collimator movements, orbit references and power converters. A luminosity server was setup [18] in order to implement the so-called orchestration of settings, together with a graphical user interface that combines luminosity optimization, emittance scans and the levelling options (among other things). This allowed to safely make changes to the configuration of the machine during stable beams with the added challenge of having a validated machine configuration (asynchronous beam dump test and loss maps) and the correct stability of orbit and beam lifetime needed during stable beams.

ORBIT STABILITY

Several of the developments during Run II were possible thanks to the excellent machine reproducibility and excellent orbit stability [19]. Figure 5 shows the root mean square (rms) of the LHC beam orbit with respect to the initial orbit in 2018. The figure shows that the orbit is drifting very smoothly during the year. There is an initial jump of about $20 \mu\text{m}$ with respect to the reference taken and an additional drift of a maximum of $40 \mu\text{m}$ for the rest of the year.

BEAM LOSSES

Beam losses need to be minimized in order to improve the performance of the machine. Their contribution can be studied by analyzing the amount of beam that is lost in each of the LHC cycle phases. The most critical phases are:

- **Ramp:** beam energy ramp from injection energy of 450 GeV to 6.5 TeV. Since 2016, the energy ramp contains also a partial beta-star squeeze.

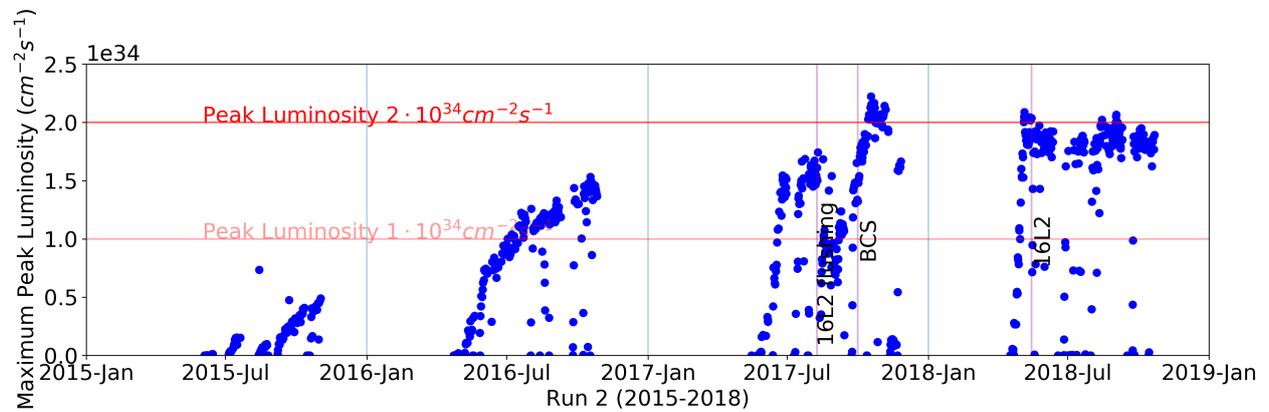
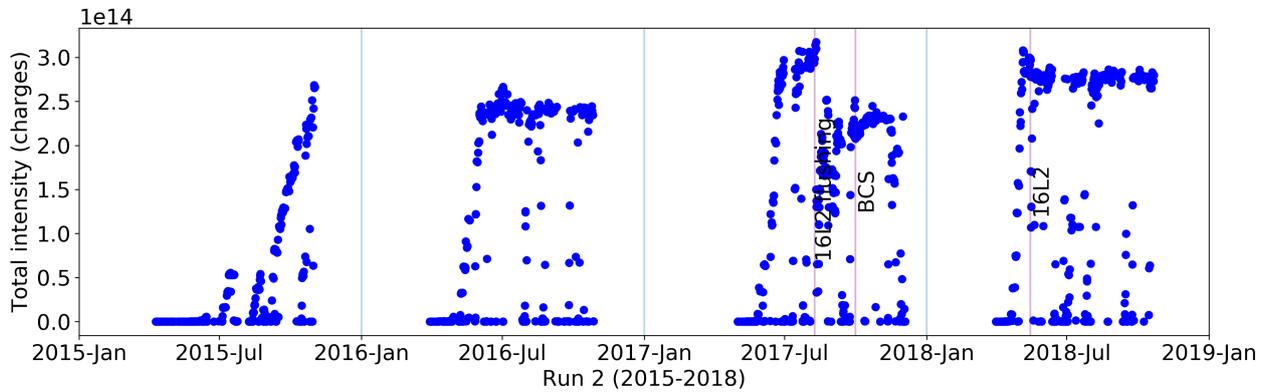
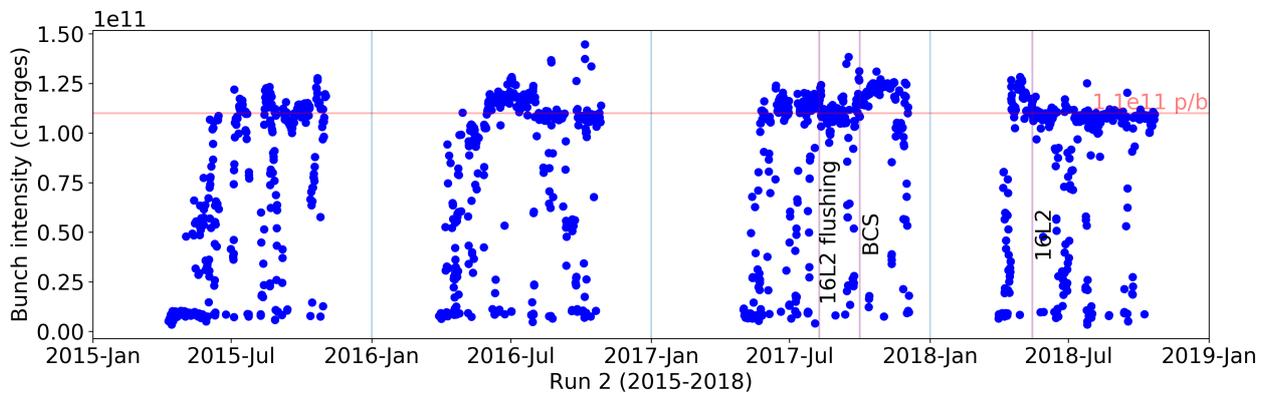
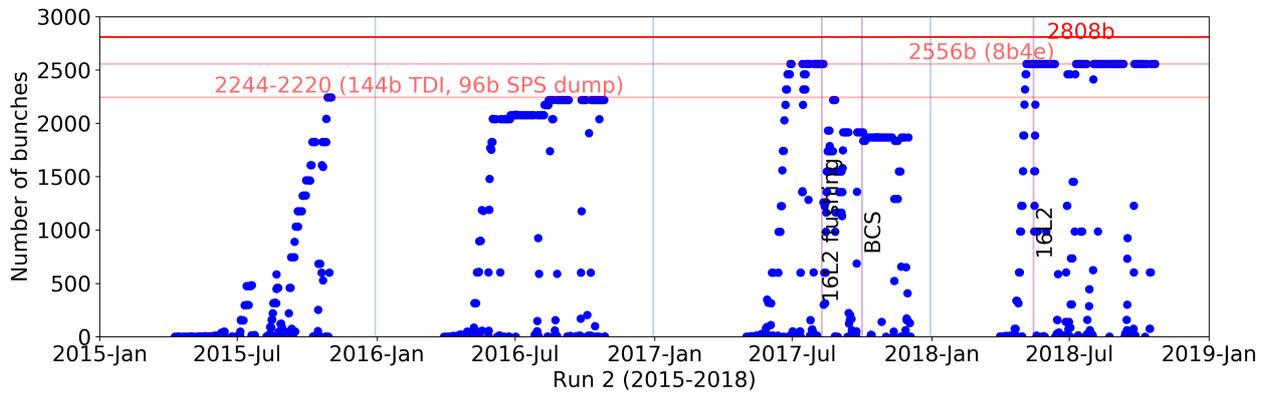


Figure 4: Beam parameters such as number of bunches, averaged bunch intensity, total stored intensity and peak luminosity at the LHC.

Table 1: Summary of beam and machine parameters during Run II compared to the LHC design values.

Parameter	Design	2018	2017	2016	2015
Energy (TeV)	7.0	6.5	6.5	6.5	6.5
Number of bunches	2808	2556	2556 - 1868	2220	2244
Number of bunches per train	288	144	144 - 128	96	144
Max. stored energy (MJ)	362	312	315	280	280
β^* (cm)	55	30 \rightarrow 27 \rightarrow 25	40 \rightarrow 30	40	80
Bunch population, N_b (10^{11} p)	1.15	1.1	1.25	1.25	1.2
Normalized Emittance Stable Beams (μm)	3.75	1.8 - 2.2	1.8-2.2	1.8-2	2.6-3.5
Peak Luminosity (10^{34} $\text{cm}^{-2}\text{s}^{-1}$)	1.0	2.1	2.0	1.5	< 0.6
Half Crossing Angle (μrad)	142.5	160 \rightarrow 130	150 \rightarrow 120	185 \rightarrow 140	185

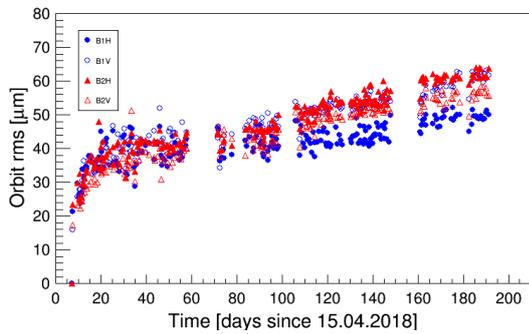


Figure 5: Root mean square (rms) of the LHC beam orbit with respect to initial orbit as function of time for 2018, courtesy of J. Wenninger.

- **Squeeze:** beams are squeezed in the main colliding IRs: ATLAS, CMS and LHCb. ALICE stays with the same beta-star from injection to collision ($\beta^* = 10$ m).
- **Collisions or Adjust:** after the beams are squeezed, the separation in the colliding IRs is collapsed and the beams start to collide, this is also called adjust.

Figure 6 shows the percentage of beam lost during the three phases mentioned above. As shown in the figure, the losses through the cycle are relatively small. In 2015 the average transmission from injection to collisions for Beam 1 was of 97.9 % and this corresponds to the worse period of the Run II. Table 2 shows the beam transmission for 2015 and for the full Run II, defined from injection to the end of the ramp, end of squeeze and when collisions start. The data contains only the LHC fills that arrived to collisions in stable beams conditions with more than 10^{12} p of stored intensity. This selection was done in order to remove the fills that were used for machine protection validation tests or machine setup. Less than 2% of the beam was lost during the cycle during Run II for Beam 1. For Beam 2, only 1.1% was lost on average.

BEAM LIFETIME

Continuous losses during the cycle reduce the beam intensity available for luminosity production. Fast losses and

Table 2: Beam transmission for all fills arriving to collisions with stored intensity above 10^{12} p.

	Phase	Beam 1	Beam 2
2015	Injection to Ramp	98.9 %	99.2 %
	Injection to Squeezed	98.8 %	99.0 %
	Injection to Collisions	97.9 %	98.2 %
Run 2	Injection to Ramp	99.4 %	99.6 %
	Injection to Squeeze	99.1 %	99.4 %
	Injection to Collisions	98.4 %	98.9 %

beam lifetime drops could quench the LHC magnets or increase the number of beam dumps due to losses.

The beam lifetime is defined as the decay time of the beam. It quantifies how fast or slow the beam is lost. It is a key parameter that sets a limit on the maximum stored beam current. Eq. 1 shows the definition of the beam lifetime τ , where I is the stored current and t is time.

$$I = I_0 \exp \frac{-t}{\tau} \quad (1)$$

The collimation system was designed to handle a maximum beam load of 500 kW during 10 s. With stored energies of 350 MJ; this sets a minimum allowed beam lifetime of 0.2 h. However, if the machine runs regularly with less losses (meaning beam lifetimes higher than 0.2 h) there could be more margin to increase the beam intensity.

Assuming that primary losses occur at the collimators, which is the case for most beam loss scenarios, the signal from the Beam Loss Monitors (BLM) downstream each collimator provides a precise measurement of the beam losses with a wide range of integration times. The BLM running sum of 1.3 s is used in the following analysis.

The most critical phases to monitor are the squeeze beam mode and the adjust (when collisions start). In Run II, beam lifetimes are high compared to the ones measured in Run I [20]. During the squeeze, the average beam lifetime of Beam 1 is around 200 h and of Beam 2 around 600 h. In adjust, it is well above 60 h.

However, inside those phases, sudden lifetime drops can occur. The minimum lifetime drop in squeeze and adjust during the full Run 2 is shown in Figure 7. In a very few

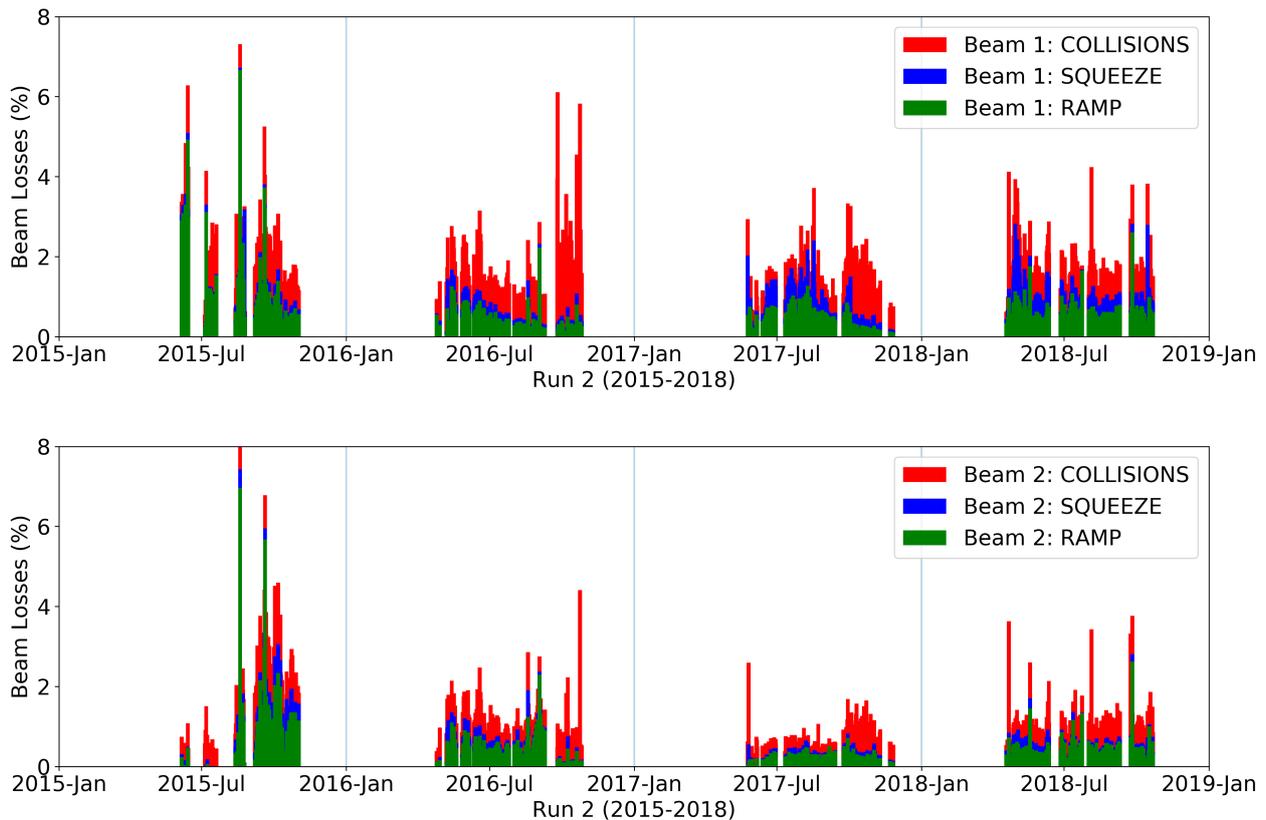


Figure 6: Percentage of beam lost during the LHC cycle for all fills arriving to collisions with stored intensity above 10^{12} p.

cases the beam lifetime was below 1 h as can be seen in Figure 7. On average, for all the fills in Run II, the minimum beam lifetimes during squeeze was above 30 h (although much higher for Beam 2, around 150 h). During adjust, the average minimum beam lifetimes are more similar for the two beams, 16 h for Beam 1 and 30 h for Beam 2. Differences between Beam 1 and Beam 2 are observed since 2016, when in general the beam lifetime of Beam 2 was better. This behaviour was maintained with larger and smaller differences during the rest of the run. It generally observed, during Run II, that beam instabilities were less critical than during Run I, see [21].

LHC SCHEDULE

The number of days dedicated to physics production, special runs and machine developments is discussed with the experiments on a yearly basis. Table 3 shows the number of days allocated for each phase during Run II, excluding the days during CERN Christmas holidays. Figure 8 shows those numbers in percentage for each year.

About 40% of the time was dedicated to proton-proton main physics productions with the exception of 2015 where more time was allocated for commissioning and only 25% to physics production. Every year between 5% to 7% of time was reserved for machine developments covered in [22] and between 5% to 13% for special physics programs [23]

which include: high beta at injection, ion run, Van der Meer physics, etc.

SUMMARY

Overall, Run II was an excellent period despite the different events encountered along the way. The initial goals for Run II were achieved, providing in total 160 fb^{-1} of integrated luminosity to ATLAS and CMS at 6.5 TeV beam energy with 25 ns bunch spaced beams, and an additional rich special physics program. During the run, some of the proposed baselines for High Luminosity LHC were also tested and in many cases became the operational scenario, as for the case of the ATS optics. This was thanks to the effort of all the involved teams which always found a way to push the LHC to new limits.

ACKNOWLEDGEMENTS

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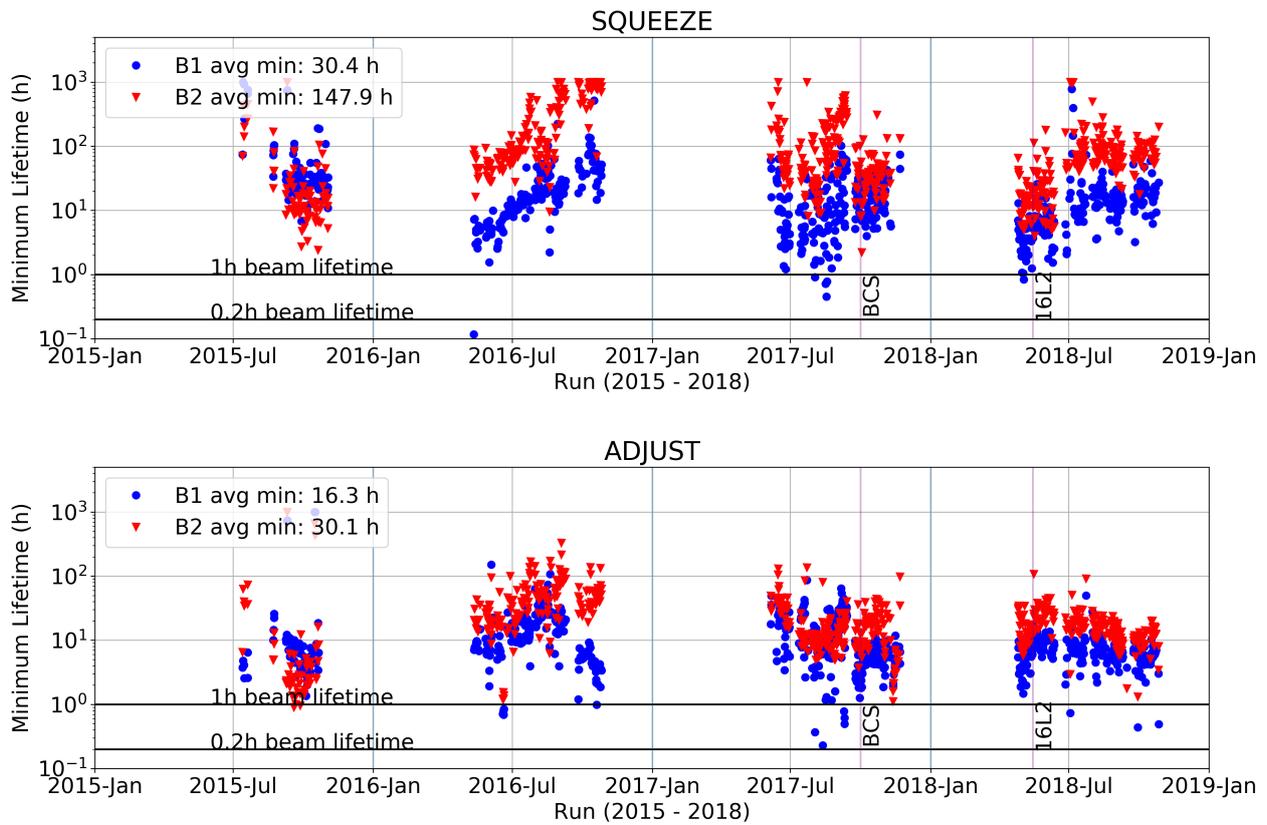


Figure 7: Minimum beam lifetimes during Squeeze and Adjust beam mode.

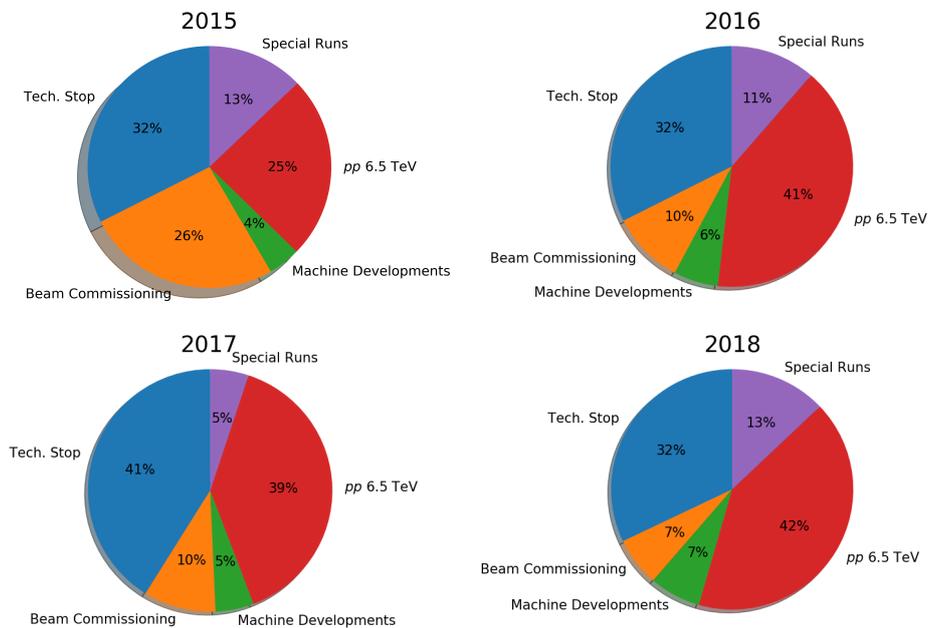


Figure 8: Distribution of time for the different activities in Run II.

shop. The LHC had a successful Run II thanks also to the good coordination by M. Lamont (deputy BE head) and P. Collier (BE head).

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Table 3: Number of days allocated for the LHC schedule in Run II.

Year	Total	Technical Stop	Beam Setup	Machine Developments	Special Physics	Standard Physics
2015	351	114	91	15	45	86
2016	353	114.5	34.5	21	40	143
2017	355	146	34	18	18	139
2018	349	112	23	24	45	145

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