# APPROACHING NOMINAL PERFORMANCE AT LHC

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*Abstract*

In 2015 the Large Hadron Collider (LHC) restarted for Run 2 after a two year long shutdown to consolidate the machine for operation at nominal beam energy. Following a few months of recommissioning and magnet training, the LHC operated for the first time at an energy of 6.5 TeV. The aim of this first year was to master operation at the higher energy and with beams of 25 ns spacing. In 2016 the performance could be pushed based on the experience of 2015, culminating with a luminosity 40% above the design value of $10^{34}$ cm$^{-2}$s$^{-1}$. With an availability for luminosity production of 50% integrated luminosities of 40 fb$^{-1}$ were delivered to each of the two large experiments. The status of the machine operation, performance and prospects for the rest of Run 2 and Run 3 will be discussed.

## INTRODUCTION

The Large Hadron Collider at CERN, Geneva, is a 26.7 km long circular accelerator [1]. It is based on a superconducting two-in-one magnet design with a target beam energy of 7 TeV. It features 8 straight sections: 4 Interaction Regions (IRs) are reserved for accelerator equipment and 4 house particle physics experiments: the two high luminosity experiments ATLAS and CMS, the medium luminosity experiment LHCb and the low luminosity experiment ALICE.

The LHC was first operated with beam for short periods in 2008 and 2009. In 2010 a first experience with the machine was gained at a beam energy of 3.5 TeV, and moderate beam intensity (up to ≈200 bunches of $1.1 \times 10^{11}$ p per bunch, or ppb). In 2011 the beam intensity was pushed to ≈1400 bunches of $1.4 \times 10^{11}$ ppb while 2012 was dedicated to luminosity production with higher bunch intensities ($1.6 \times 10^{11}$ ppb) and a beam energy of 4 TeV. In early 2013 beam operation was stopped for a 2-year long shutdown (LS1) to consolidate the magnet interconnection in view of reaching the design beam energy.

Beam operation resumed in 2015 at 6.5 TeV following a dipole training campaign that took place at the end of LS1 [2]. The LHC experiments expressed a strong preference for beams with 25 ns bunch spacing, as opposed to the 50 ns spacing used in 2011-2012, as this would result in a too high number of inelastic collisions per crossing (pile-up). On the machine side 25 ns beams pose additional challenges, e.g. the formation of electron clouds (e-clouds) in the vacuum chamber and a higher number of fast loss events, named Unidentified Falling Objects (UFOs) [3]. Given the number of new territories had to be explored, 2015 was considered a re-commissioning and a learning year, dedicated to preparing the machine for full luminosity production in 2016, with the aim of collecting over 100 fb$^{-1}$ until the end of 2018.

This paper presents the highlights of the 2016 LHC run, the luminosity figures that were achieved and the main challenges that had to be faced. Future improvements and energy increases will also be discussed.

## LUMINOSITY AND LHC PARAMETERS

The event rate $dN/dt$ of a physical process with a cross-section $\sigma_p$ is proportional to the collider luminosity $\mathcal{L}$

$$\frac{dN}{dt} = \mathcal{L}\sigma_p \tag{1}$$

that can be expressed in terms of machine and beam parameters as [4]

$$\mathcal{L} = \frac{kN^2 f}{4\pi\sigma_x^*\sigma_y^*}F = \frac{kN^2 f\gamma}{4\pi\beta^*\varepsilon}F \tag{2}$$

Here $k$ is the number of colliding bunch pairs, $N$ the particle population of each bunch, $f = 11.25$ kHz is the LHC revolution frequency. For round beams at the interaction point (IP) the beam sizes in the horizontal and vertical plane $\sigma_x^*$ and $\sigma_y^*$ are identical, and $\sigma_x^*\sigma_y^* = \beta^*\varepsilon/\gamma$ where $\beta^*$ is the betatron function at the interaction point (IP), $\varepsilon$ is the normalized emittance (independent of energy) and $\gamma$ is the usual relativistic factor. $F$ ($\leq 1$) is a reduction factor to account for geometric luminosity reductions due to the presence of crossing angles at the IP

The proton beam parameters are defined by the LHC injector chain. The minimum bunch spacing of 25 ns defines the maximum value $k = 2808$ . The bunch intensity is limited to $\approx 2 - 3 \times 10^{11}$ ppb for isolated single bunches and to $\approx 1.3 \times 10^{11}$ ppb for 25 ns bunch spacing, while the beam emittances range between 1 $\mu$m and 3.5 $\mu$m.

To avoid encounters in the roughly 100 m long vacuum chamber that is shared by both beams around each experiments, a crossing angle is introduced at the collision point. Depending on bunch intensity, bunch spacing and energy, the full crossing angle varies between 200 to 400 $\mu$rad for the two high luminosity experiments. The minimum separation between the beams should correspond to around 10 beam sizes to avoid issues with the long range beam-beam interactions [5]. A consequence of the crossing angle is a reduction of the luminosity due to the geometric overlap of the beams, $F \sim 0.65$ in 2016.

The minimum value of $\beta^*$ is defined by the mechanical aperture of the quadrupoles around the IPs, the crossing angle and the required margin between the beam halo and the aperture. $\beta^*$ could be lowered progressively over the years as the understanding of the LHC machine improved.

## TIME LINE OF THE 2016 LHC RUN

The first beams circulated during the 2016 Easter weekend, beam commissioning lasted four weeks and ended with the first physics fill on 23 April. Unfortunately the SPS beam




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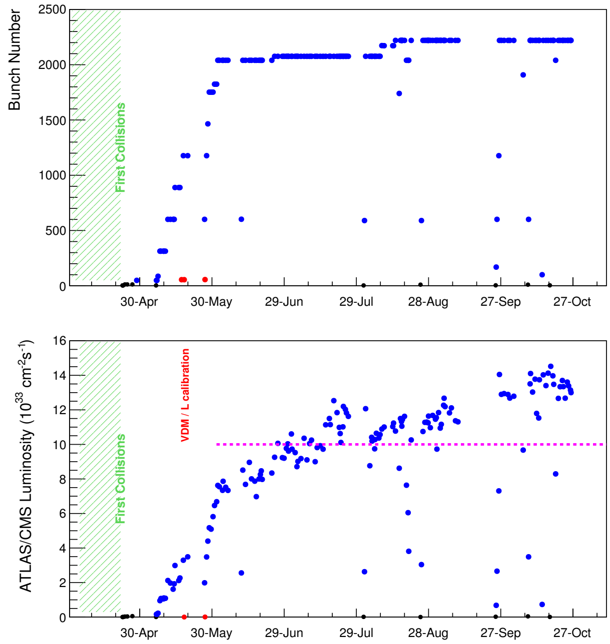


Figure 1: Number of bunches per fill (top) and peak luminosity per fill (bottom) during the 2016 run.

dump developed a vacuum leak early May, to avoid loosing too much time to exchange and condition a new dump, operation continued with a degraded SPS dump vacuum. As a consequence the maximum number of bunches that could be delivered to LHC by the SPS had to be limited to 144 instead of 288, limiting the maximum number of bunches to 2220 in 2016.

The summer was devoted to an intensity ramp-up with 25 ns beams, e-cloud scrubbing proceeded parasitically to physics operation as exercised in 2015. The evolution of the number of bunches and of the peak luminosity in ATLAS and CMS is presented in Fig. 1. The standard LHC beam with an emittance of $\sim 3\ \mu$m was used until mid July, when operation switched to a low emittance version of the beam with an injected emittance of $\sim 1.5\ \mu$m that resulted in a luminosity gain of 20%. In September the full crossing angle was reduced from 370 $\mu$rad to 280 $\mu$rad, boosting the luminosity by around 25%.

The proton-proton operation was interrupted throughout the year to accommodate special physics runs: very low and very high pile-up runs, luminosity calibrations and a 2.5 km $\beta^*$ run for forward physics. The last month of the run was dedicated to physics with proton and lead ion beams [6].

## LUMINOSITY PERFORMANCE

By the end of the 2016 proton physics running period the peak instantaneous luminosity reached $1.4 \times 10^{34}$ cm$^{-2}$s$^{-1}$ with 2220 bunches per beam (see Fig. 1). The main beam and machine parameters that allowed reaching such luminosities are presented in Table 1. Figure 2 presents the peak luminosity evolution between 2011 and 2016.

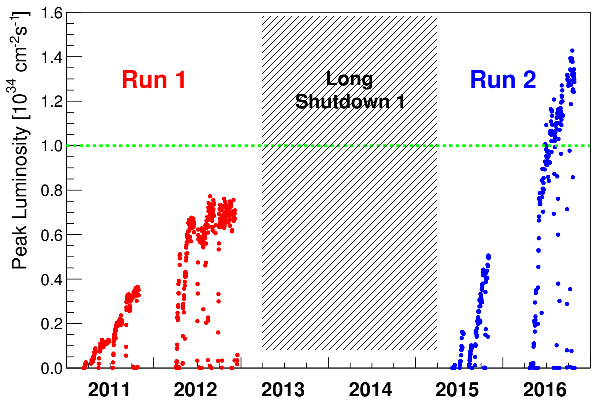


Figure 2: Evolution of the LHC peak luminosity between 2011 and 2016. The green horizontal line represents the design luminosity.

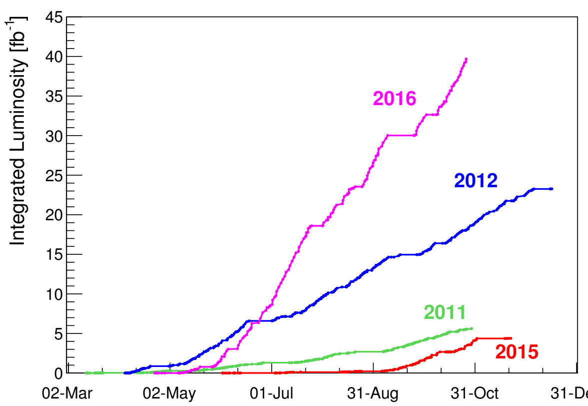


Figure 3: Integrated luminosity along the year between 2011 and 2016.

The luminosity integrated by ATLAS and CMS during the 2016 proton physics run reached 40 fb$^{-1}$ as shown in Fig. 3, while the LHCb and ALICE experiments integrated 1.9 fb$^{-1}$ and 13 pb$^{-1}$, respectively. The integrated luminosity exceeded the target of 25 fb$^{-1}$ in the high luminosity experiments thanks to a higher peak luminosity and to a much improved availability of 48% as compared to around 33% in the earlier LHC runs. The cryogenic system of the LHC achieved a system availability above 98% [7]. The full integrated luminosities for Run 1 and Run 2 are presented in Fig. 4.

## LHC OPERATION

The average turnaround time of the LHC (physics to physics) could be further reduced to 5.2 hours in 2016 for minimum turn around time of 2.5 hours. This corresponds to an improvement of one hour with respect to 2015. Injection remains the part of the cycle where most of the time is lost [8]. The remainder of the cycle with a combined ramp and partial squeeze to $\beta^*$ of 3 m, squeeze to $\beta^*$ of 40 cm and

Table 1: Beam and Machine Parameters for Collisions in 2012, 2016 and 2017 (projected) Compared to the Design

| Parameter | Design | 2012 | 2016 | 2017 |
|---|---|---|---|---|
| beam energy [TeV] | 7 | 4 | 6.5 | 6.5 |
| bunch spacing [ns] | 25 | 50 | 25 | 25 |
| $\beta^*$ CMS/ATLAS [cm] | 55 | 60 | 40 | 40 (33) |
| crossing angle [$\mu$rad] | 285 | 290 | 370 / 280 | 300 |
| bunch population $N$ [$10^{11}$ ppb] | 1.15 | 1.65 | 1.1 | 1.2 |
| normalized emittance $\varepsilon$ [$\mu$m] | 3.75 | 2.5 | 2.2 | 2.2 |
| number of bunches per ring $k$ | 2808 | 1374 | 2220 | 2556 |
| peak luminosity L [$10^{34}$ cm$^{-2}$s$^{-1}$] | 1 | 0.75 | 1.4 | 1.7 |
| peak average event pile-up $\mu$ | ~ 20 | ~ 35 | ~ 50 | ~ 55 |
| peak stored energy [MJ] | 360 | 145 | 270 | 320 |

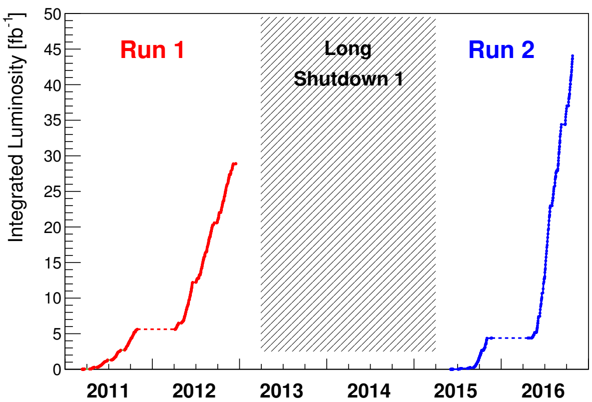


Figure 4: Evolution of the integrated luminosity for Run 1 and Run 2.

finally collisions is very reproducible thanks to a high level of automation.

### *Machine Reproducibility*

The reproducibility of the LHC over a run is excellent thanks to orbit and tune feedbacks as well as feed-forward correction of persistent current decay (b2 and b3) at injection [9]. At 6.5 TeV the reproducibility of the key parameters is [10]: $\pm 0.002$ for the tunes, $< \pm 2$ for the chromaticity, $< \pm 0.002$ for coupling (C-) and $< 50$ $\mu$m for the r.m.s. orbit (Fig. 5). The reproducibility of the beams in collisions corresponds to $\pm 0.5\sigma^*$ at the high luminosity experiments where the IP beam size $\sigma^*$ is 11 $\mu$m.

### *Beam Transmission and Lifetimes*

Beam loss rates throughout the LHC cycles are very low, with typical intensity transmissions of 99.8% through the betatron squeeze and of 99.5% in the phase when beams are brought into collisions [11]. The highest power loss of beam to the collimation system reached around 10-50 kW, with isolated peaks around 100 kW, a fifth of the design value. Thanks to a very low and very stable collimation inefficiency of $1 - 3 \times 10^{-4}$ no beam induced quench was ever observed

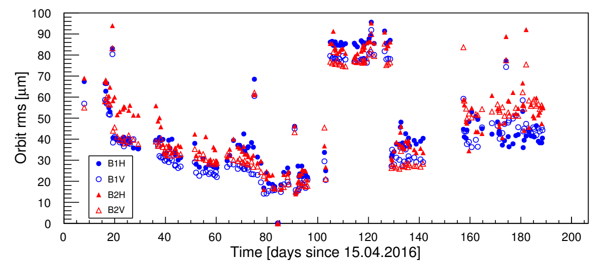


Figure 5: Evolution of the r.m.s. orbit change for collisions at 6.5 TeV in 2016. Each point represents one LHC fill and the reference corresponds to mid-July. The outliers are due to BPM calibration issues.

at the LHC, with the exception of UFO losses (see below) that cannot be intercepted by the collimation system. [12].

Initial beam lifetimes when beams are brought into collision can drop to a few hours, recovering after around two hours to reach a loss rate that is essentially compatible with the beam burn off rate in the four experiments.

### *Emittance Preservation*

Operation in 2016 started with standard LHC beams with a typical transverse emittance of ~ 3 $\mu$m. Middle of July operation switched to a low emittance beam variant produced using a longitudinal batch compression merging and splitting scheme (BCMS [13]) which increases the luminosity by around 20% as seen in Fig. 1. BCMS beams feature an emittance at injection into LHC of ~ 1.5 $\mu$m, i.e. a factor almost two better than the standard beams. The higher brightness comes however with a reduced train length at extraction from the PS of 48 bunches instead of 72 bunches. This reduces the total number of LHC bunches $k$ to around 2200 to 2550 as compared to 2780 for standard beams. The luminosity gain due to the increased brightness outweighes however the loss in number of bunches. Because of its much higher brightness the BCMS beam is more sensitive to emittance blowup due to IBS (mainly at injection) and to external noise. Between injection and collisions the emittance has increased typically from ~ 1.5 $\mu$m to ~ 2.2 $\mu$m, where most of the blow-up seems to appear during the ramp. The reason for the


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blow-up has not been uncovered, and extensive comparisons among the various devices providing emittance measurements were launched in 2016 to improve the understanding of the emittance evolution [14].

During the collisions at 6.5 TeV emittance blow-up due to IBS and noise is partly counter-balanced by synchrotron radiation damping. In the vertical plane (no IBS) emittances larger than $\sim$ 2.3 $\mu$m shrink, while smaller emittances grow. The un-modelled emittance growth is around 0.05 $\mu$m/hour [15].

### *Luminosity Imbalances*

Due to the impact of IBS on the horizontal plane, the horizontal emittances are generally larger than the vertical emittances, and the differences tend to increase with time. The crossing angle planes are different between the ATLAS (vertical) and CMS (horizontal) experiments to profit from passive compensation of long-range beam-beam effects. The differences between horizontal and vertical emittances lead to an expected difference in luminosity between the two experiments of up to $\sim$ 10% [16, 17]. Such an asymmetry was observed, but the differences did not agree with the model in certain phases. While part of the luminosity imbalance can be attributed to the crossing angles and the emittance asymmetries, another component seems to be due to measurement uncertainties of the LHC experiments.

## CHALLENGES AND LIMITATIONS

### *Intensity Limitations at Injection*

The bunch population and bunch intensities were limited at injection by the SPS beam dump vacuum leak (maximum of 144 bunches instead of 288) and by e-cloud induced vacuum pressure in the injection kicker ceramic vacuum chambers next to the Q5 quadrupole. Both limitations should be lifted for the 2017 with a new SPS beam dump and improved pumping speeds next to the injection kickers.

### *Electron-cloud and Scrubbing*

Electron clouds have been observed at the LHC since the start of beam operation with bunch trains (for 150, 75, 50 and 25 ns spacings [18]). Their signatures include vacuum pressure rise, increased heat load on the cryogenic system, beam size growth, single- and multi-bunch instabilities. *Scrubbing runs* at injection energy have been regularly incorporated in the annual schedule to lower the Secondary Emission Yield (SEY) of the vacuum chamber by exposure to electron cloud doses. Once the machine is ready to accept beams with hundreds of bunches the physics run may proceed, and beam scrubbing is performed parasitically during physics production.

The SEY was reset after LS1 as most of the machine was exposed to air. This imposed an extended period of scrubbing in preparation for 25 ns beams, which totalled to 3 weeks in 2015 [19]. Thanks to a sophisticated feed-forward system the cryogenic system is now able cope with very high heat load transients [20]. The LHC was then operated with

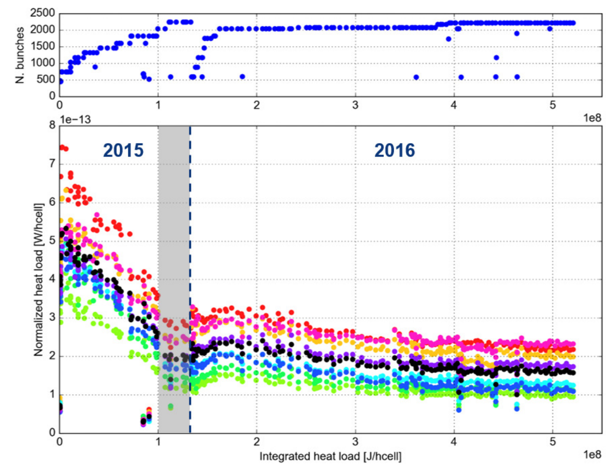


Figure 6: Evolution of the number of bunches per beam (top) and the heat-load per half cell ($\approx$ 50 m) normalized to the beam intensity in 2015 and 2016 [21].

25 ns beams until the end of the 2015 proton run, staying at the limit for the cryogenics heat-load, which defined the maximum number of bunches per ring as shown in Fig. 6. The good SEY conditions were preserved at the start of the 2016 run which could proceed with a minimal scrubbing run [21]. The heat-load from e-clouds continued to decrease gently along the 2016 run, saturating towards the end of the physics run. The difference in heat load by almost a factor two between difference LHC sectors, visible in Fig. 6, is not understood.

### *Fast Beam Loss Events*

Fast loss events, nicknamed Unidentified Falling Objects (UFOs), have been observed at the LHC since 2010 [3]. The loss duration is in the millisecond time range, and UFOs are believed to be due to dust particles falling in the beam pipe and interacting with the beam, creating particle showers that deposit energy in the magnets and that are then detected by the Beam Loss Monitors (BLM). UFOs caused $\approx$20 dumps per year during Run 1. They affect machine availability, as the most intense ones can trigger a beam dump by the BLM system, or initiate a magnet quench and the subsequent long time for cryogenics conditions recovery.

Following the long shutdown UFO rates in 2015 were as high as 30-40 events per hour, and decreased with beam time (*conditioning*) to $\approx$10 events per hour [22]. They caused 22 beam dumps including 3 beam-induced quenches in 2015. The initial strategy was to prevent if possible all UFO-induced magnet quenches [23], but it was realized in 2015 that most of the UFOs events leading to beam dumps would not have caused quenches. Thus the policy changed and the BLM thresholds were increased to allow a few UFO-induced quenches per a year. A further increase was put in place in 2016, while the UFO rates presented in Fig. 7 continued to come down to around 2 UFOs per hour [24].

The dump numbers were stable in 2016 at 21 beam dumps including 3 beam-induced quenches.

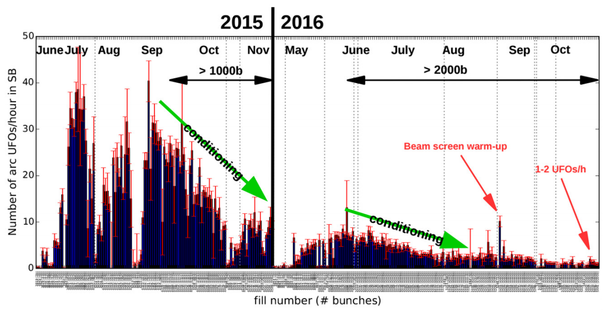


Figure 7: The evolution of the UFO rate (events per hour) in 2015 and 2016 with a clear conditioning during the runs. Each point correspond to one LHC fill.

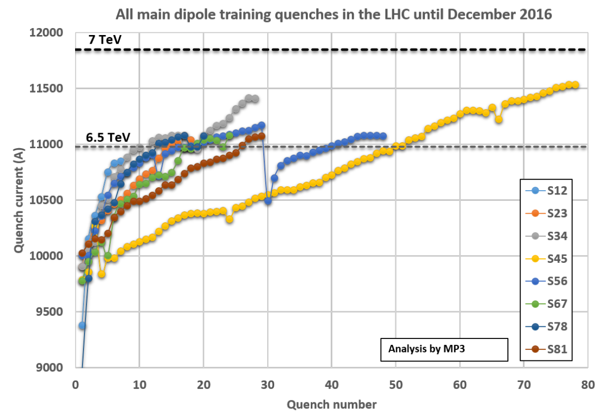


Figure 8: Number of dipole training quenches as a function of the field (expressed in circuit current). Two sectors (S34 and S45) were pushed to 6.75 TeV (11'500 A) in December 2016.

## LHC PERFORMANCE OUTLOOK

### *Luminosity Performance*

The projected beam and performance parameters for 2017 are presented in Table 1. During the shutdown a dipole magnet with a suspected intermittent short was exchanged. This operation required a complete warm up of one sector which is likely to reset the e-could conditioning. E-cloud scrubbing of that that sector will have to be performed in parallel to physics, which may slow down the intensity ramp up. With the intensity limitations lifted at injection, the intensity per bunch should approach $1.2 \times 10^{11}$ ppb in collision. Relying again on the BCMS beam the number of bunches will be increased to 2550. The machine will restart in 2017 with the same $\beta^*$ of 40 cm as in 2016 with the option to squeeze to 33 cm later in the year. The machine optics structure will be made compatible with the ATS scheme [25, 26] developed for the LHC luminosity upgrade. The peak luminosity is could reach $1.7 \times 10^{34}$ cm$^{-2}$s$^{-1}$ which corresponds to the cooling limit of the low-beta quadrupoles [27]. The target for the integrated luminosity is 45 fb$^{-1}$ which would double the total at 6.5 TeV (Fig. 4). The target of 100 fb$^{-1}$ is well within reach for LHC Run 2.

### *Beam Energy Reach*

Operating the superconducting magnet circuits close to the design energy meant that most systems were operated close to the design margins. For this second LHC run, it was decided to aim operating the main dipole magnet at 6.5 TeV. Training the dipole magnets to that energy level requited a total of 175 primary quenches for 1232 magnets, see Fig. 8. This is mostly traced back to the production batches, but details are still under study. Additionally, 5 training quenches were observed during beam operation in 2015. Following the training campaign a better understanding of the quench behaviour makes it possible to predict that 300 – 400 additional quenches are required to reach 7 TeV [2]. In December 2016 a campaign to bring two LHC sectors to the nominal 7 TeV field was interrupted at 6.75 TeV as a short circuit developed in a bypass diode due to metallic debris displaced by the helium waves [28]. The short could fortunately be burned away [29].

## CONCLUSIONS

In 2016 the LHC first reached and later exceeded its design luminosity by 40%. Beams with 25 ns bunch spacing became the standard for operation at 6.5 TeV, with up to 2220 bunches per ring, laying a stable foundation for the 2017 run. The time in collision for physics data taking reached almost 50% over the past year, boosting the integrated luminosity to an unexpected 40 fb$^{1}$. This performance was obtained despite intensity limitations at injection and the 2017 run is expected to break new records, including reaching the cryogenic cooling limit of the low-beta quadrupoles.

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