BEAM LOSSES, LIFETIME AND COLLIMATOR HIERARCHY

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Abstract

The aim of the LHC collimation system is to ensure a safe machine operation; it provides the LHC with passive protection and minimises the risk of magnet quenches induced by beam losses. In 2017, the LHC collimation system confirmed its excellent performance, with no magnet quenches due to losses from circulating beams while accommodating changes in machine configurations. The system availability in 2017 was also very good. The present work reviews key elements of the 2017 operation, from initial commissioning with beam to beam losses, lifetime and collimator hierarchy.

INTRODUCTION

The Large Hadron Collider (LHC) is equipped with a sophisticated collimation system [1], aimed at minimising losses around the ring, and in particular in superconducting (SC) magnets. The collimation system is an essential component of the LHC machine protection system; in case of drops of beam lifetime, the collimation system intercepts beam particles that otherwise would be lost in the machine, potentially inducing a quench[1], and hence machine downtime; moreover, it provides the machine with passive protection, in particular of the inner triplets and the detectors.

The LHC collimators are organised in families, with defined roles. Families are characterised by specific operational settings, jaw material and technical solutions adopted in their design. Moreover, families are arranged in well–defined transverse position hierarchy, such that each family absorbs the leakage from the upstream ones. Respecting the correct hierarchy between families is necessary to assure the desired cleaning performance.

Due to the finite absorbance of collimators, some unavoidable cleaning leakage reaches the machine cold aperture. The local cleaning inefficiency $\eta(s)$ maps the leakage around the machine; it is defined as the probability that a proton interacting with the collimation system is lost at a given position s along the ring. The highest values of local cleaning inefficiency in cold magnets are found in the Dispersion Suppressor (DS) immediately downstream of the betatron cleaning system, located in the Insertion Region 7 (IR7), even though this location is not the global aperture bottleneck. Hence, the quench limit of the magnets installed there sets the maximum loss rate that can be tolerated, determining for a given drop in beam lifetime the maximum intensity that can circulate in the machine. At the same time, the collimation system must be robust enough to withstand the thermo–mechanical load when the maximum tolerated loss rate is reached.

Many challenges lie beneath a smooth operation of the LHC collimation system. The collimator settings deployed during regular physics fills, updated according to the operational goals set every year, are a compromise between conflicting requirements. Smaller values of β^* at the high luminosity Interaction Points (IPs) imply a reduction of the available aperture; therefore, in order not to cut the beam core, the aperture budget taken by the collimation system must be reduced accordingly, with sufficient margins to the protected aperture, resulting in a reduction of the operational margins between collimators. Moreover, the last collimator family in the hierarchy should protect the aperture bottleneck with sufficient margin while minimising the background induced in the experimental detectors. As already mentioned, the primary cut should be loose enough to avoid cutting the beam core while effectively cleaning tails. Finally, collimator settings cannot be too tight otherwise the impact on impedance will be too high, and beams cannot be stabilised.

The present contribution reviews key elements of operation in 2017. Emphasis is given to coping with the available aperture, accommodating the pushed machine operational conditions while squeezing the aperture budget taken by the collimation system. An overview of the beam losses recorded during the year is also given. Finally, the work reviews the 2017 performance, which confirmed the excellent trend already achieved in the first two years of Run II. The most relevant hardware changes and software updates carried out during the 2016 Extended Year End Technical Stop (EYETS2016) are reported as well, together with highlights from the initial commissioning with beam.

APERTURE, HIERARCHY AND LUMINOSITY

Collimator Settings Hierarchy

Figure 1 shows the evolution of the settings of the betatron collimator families during Run II. The evolution is

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[1] A quench is the sudden transition of a magnet from its superconducting state to the normal conducting one. Such an event would prevent the beam to be regularly steered, focused or corrected, making operation impossible. Moreover, to recover from the superconducting state is a lengthy process, causing considerable machine downtime.

Table 1: 2017 collimator normalised settings in σ. Values at "End of Squeeze", "Collisions" and "XRPs IN" are given for β^*=30 cm; when different, values at β^*=40 cm are given in parenthesis.

IR	Family	Injection	Flat Top	End of Squeeze	Collisions	XRPs IN
IR7	TCP / TCSG / TCLA	5.7 / 6.7 / 10	5 / 6.5 / 10			
IR3	TCP / TCSG / TCLA	8 / 9.3 / 12	15 / 18 / 20			
IR6	TCDQ / TCSP	8 / 7.5	7.4 / 7.4			
IR2/IR8	TCT	13 / 13	37 / 15			
IR1/5	TCT	13	15	8.5 (9)		
IR1/5	TCL.4 / TCL.5 / TCL.6	out / out / out			15 / 15 / out	15 / 35 / 20

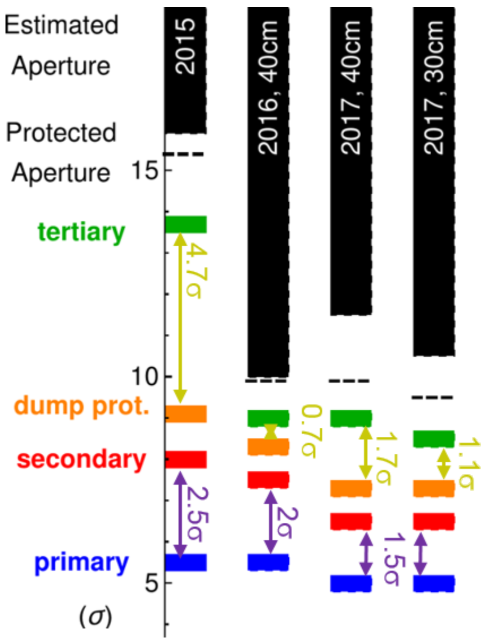

Figure 1: Evolution of the betatron collimator settings over past years during Run II.

towards an always smaller protected machine aperture, accommodating the quest for smaller β^* at the high luminosity IPs. This was possible thanks to a series of optimisations implemented over past years on different fronts.

For the start up in 2015, a prudent approach was taken, granting a protected machine aperture of 15.7 σ[2]; with the primary cut at 5.5 σ, this implies an aperture budget for the collimation system of 10.2 σ. In 2017, for the operational deployment of β^*=30 cm, the protected machine aperture was 9.5 σ; with the primary cut at 5 σ, the aperture budget of the collimation system amounted to 4.5 σ.

The gained margin between the measured aperture and the last collimator family (i.e. the tertiary collimators, named TCTs) seen in 2017 with respect to the previous year for the same value of β^* is due to the choice of a positive crossing angle in IP1 [2], and a value of crossing angle in IP1 and IP5 smaller than that of 2016 [3]; the latter was possible since a smaller beam–beam separation was allowed; both resulted in machine aperture larger than that of 2016. The reduced margin between TCTs and dump protection devices (TCDQ and TCSP) deployed starting from 2016 was possible thanks to a more favourable betatron phase advance between extraction kickers and horizontal TCTs in IR1 and IR5, drastically reducing the number of protons hitting the jaws of these collimators in case of an asynchronous beam dump (ABD) [3]. Finally, the stability and reproducibility of the optics and closed orbit of the LHC allowed to safely reduce the retraction between primary (TCP) and secondary (TCSG) collimators [4, 5, 6].

Table 1 summarises the collimator settings deployed throughout 2017, including also those at β^*=30 cm. The settings in IR6/7 were chosen to allow β^*=30 cm from the beginning of the year; in this way, minimal changes were required for pushing β^* from 40 cm (value at the start of 2017) to 30 cm.

Aperture

A comprehensive knowledge of the machine aperture is an essential ingredient for pushing the collimator settings while adequately protecting the machine. Hence, the aperture was carefully probed during the initial commissioning with beam for LHC operation at β^*=40 cm; most of the measurements were taken at the end of the squeeze beam process, when aperture is at minimum. It was possible to verify that the inversion of sign of crossing angle in the most constraining area (IP1) resulted in an aperture larger than that of 2016 by 1.5 σ. Moreover, dedicated scans, performed shifting the collision point in IP5 downwards, showed that the aperture in IR5 is not sensitive to the IP shift in the explored range.

In order to operate the LHC at β^*=30 cm, a dedicated machine development (MD) activity (MD2180) [7] was carried out. The aperture was found smaller than the one at β^*=40 cm by 2 σ, in agreement with expectations. Only the horizontal aperture of B2 did not match expectations, showing to be larger, and hence not problematic.

Hierarchy Breakage

Lower values of β^* at the high luminosity IPs imply a decrease of the machine cold aperture; if the primary col-

[2] In the contribution, a normalised emittance of 3.5 μm is considered.

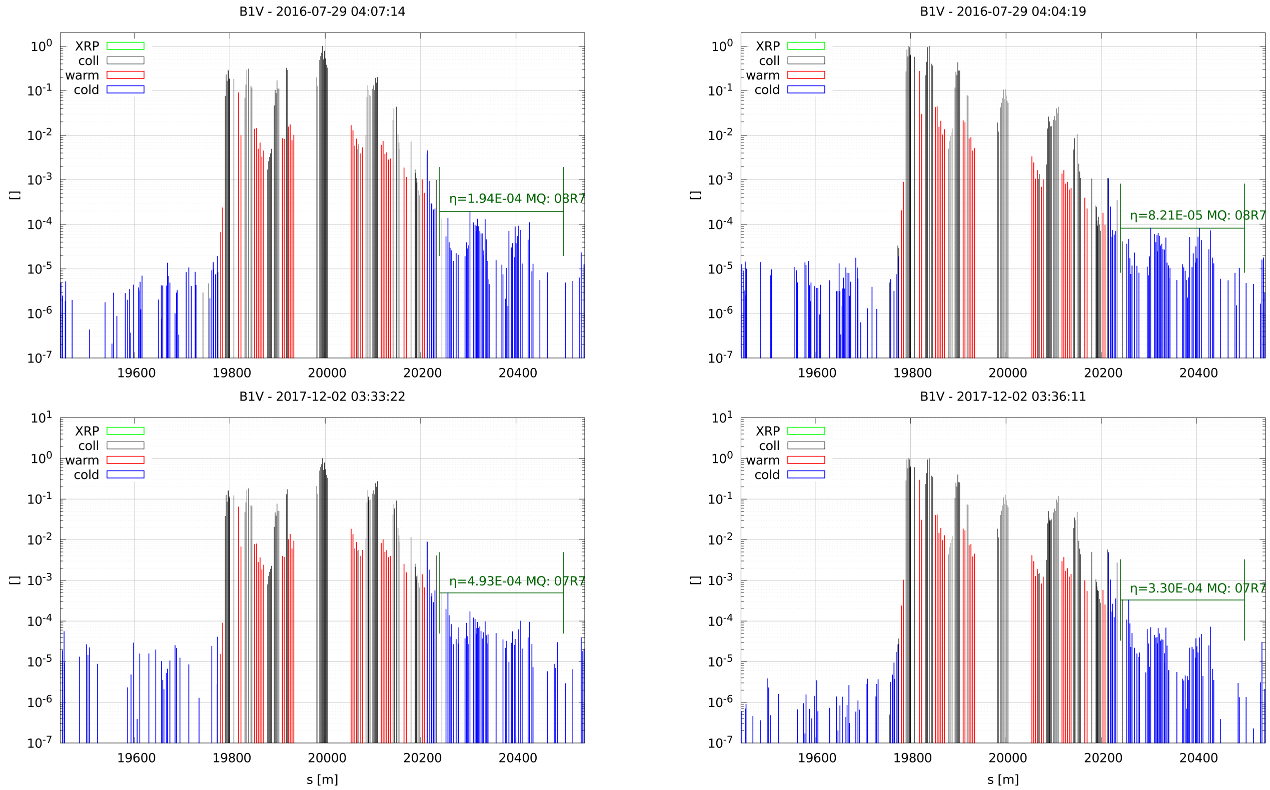

Figure 2: Loss pattern in IR7 with 1 σ TCP–TCSG retractions with the broken (left frames) and restored (right frames) hierarchy. The upper frames show measurements taken in July 2016 (MD1447); the lower frames show measurements taken in December 2017. In both years, the correct hierarchy is restored applying the same tilt angle of 350 μrad to the jaws of the TCSG.D4L7.B1.

limator cut is kept the same, the aperture budget allocated for collimators should be squeezed, reducing operational margins between families.

If margins are too tight, unavoidable misalignment or tilt errors may lead the TCSG jaws to stick further into the beam than the TCP ones, breaking the regular collimator hierarchy, with consequent loss of performance. The loss of performance in IR7 directly translates into larger losses in the downstream DS where the highest cleaning inefficiency is found and margins to quench are at minimum. Therefore, the re–alignment to the beam of the entire collimation system performed during the initial commissioning with beam is a key set up activity, necessary every year.

A series of MD activities were carried out in 2015 (MD314 [4]), 2016 (MD1447 [5]) and 2017 (MD2191 [8]), in order to assess the stability of the alignment, the limits in squeezing the operational margins and the consequent impact on impedance. These activities allowed to spot a hierarchy breakage on B1V when the TCP–TCSG retraction is decreased to 1 σ, which is the retraction foreseen by the nominal LHC [1]. It was also possible to see that compensating for the misalignment angle of the TCSG.D4L7.B1 allowed to restore the regular IR7 hierarchy. Figure 2 shows the loss pattern in IR7 with 1 σ TCP–TCSG retractions with the broken hierarchy (left frames) and with the restored one (right frames) when correcting for the aforementioned tilt angle. Measurements were performed by inducing controlled losses by means of white noise injected in the beam via the transverse damper (ADT). The upper frames show measurements taken in July 2016 (MD1447), whereas the lower frames show measurements taken in December 2017 [9], applying the same tilt angle of 350 μrad to the same TCSG.D4L7.B1.

Pushing Luminosity

In addition to carefully measure the machine cold aperture and make the best use of the operational margins between families, interlocks on the beam orbit at TCTs were a "conditio sine qua non" for pushing β^* down to 30 cm in operation. The interlocks were particularly relevant in IR1 and IR5, where the margins between TCTs and machine cold aperture are at minimum; there, the interlocks were set at 1 σ. The verification of the proper set up of the interlock was a joint effort involving several teams in different departments across the Accelerator and Technology Sector (ATS); its final validation [10] went through detailed checks with beam and monitoring the activity of the interlock during the whole period of data taking at β^*=40 cm. No dumps were observed in 2017 operation once the interlock was activated.

Crossing angle "anti–levelling" was first deployed in 2017 [11] to further optimise the instantaneous luminosity, and hence the integrated one. It consists of reducing the crossing angle in steps while keeping the beams in collisions; in this way, the loss of instantaneous luminosity due to proton burn–off in collisions can be partially compensated by pushing the geometrical factor towards one. Crossing angle anti–levelling was actually deployed in operation via a dedicated control interface [12], responsible not only to change the optical crossing angle knobs, but also to move the TCL.4 and TCT collimators in the concerned planes synchronously. The extreme conditions that the software could handle operationally had to be qualified with dedicated loss maps.

BEAM LIFETIME AND LOSSES

Loss spikes and drops of beam lifetime are a concern for the regular operation of the collimation system and, ultimately, of the LHC. In fact, when the beam lifetime is at minimum, beam loss rates are at maximum and the collimation system should limit losses in the machine cold aperture, preventing quenches; moreover, the highest tolerated beam loss rate determines the maximum beam intensity that can be circulated. To make sure that the maximum loss rate is not exceeded and to avoid premature beam dumps, the thresholds of the Beam Loss Monitors (BLMs) affected by collimation losses must be aligned to the readout expected at the maximum loss rate. In this way, costly machine down–time due to the lengthy recovery from a quench can be avoided.

The collimation system has hardware constraints in terms of resistance to thermal stresses. In case of losses, BLM thresholds at collimators are essential not only to avoid quenches but also to maintain thermal stresses below the tolerated limits. In case of fast losses (e.g. single turn losses), for which the BLM system is of limited help due to the time required to trigger a dump (i.e. 3–4 turns), damage to the collimator hardware is prevented by means of a careful choice of jaw material of the collimators closest to the beam (which must maximise robustness), optimum collimator settings and optics phase advance to the least robust collimators (which maximise absorbance).

For the regular operation of the LHC, the beam lifetime is an indicator of machine performance, routinely used during knob corrections along the cycle, or during machine setting up or MD activities, since it promptly shows the response of the beam to specific trims. The beam lifetime is estimated from the instantaneous loss rate reconstructed from the BLM signals at specific locations in the collimation region and the BCT signal. Online monitoring is provided to the crew in the CERN Control Centre (CCC) by a graphical user interface (GUI); the GUI has undergone several upgrades in 2017, both in the software and in the underlying infrastructure, allowing for more on–line and post–mortem in–depth analyses.

The analysis of the beam lifetime over the entire operational year allows to assess the machine performance throughout the cycle. In the following, preliminary results of such an analysis are outlined for the past year.

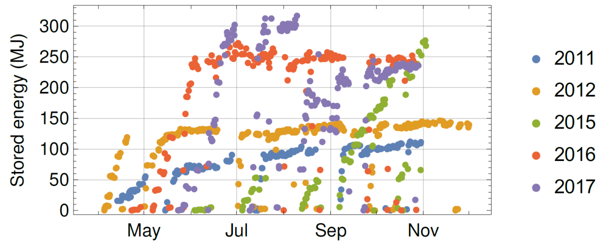

Figure 3: Evolution of the total energy stored in the LHC beams during last year and previous ones.

Total Stored Energy

Figure 3 shows the total energy stored in the LHC in 2017, compared to that of previous years. During the first half of 2017, it was possible to reach the unprecedented value of 300 MJ, limited shortly after because of 16L2 issues [13] to the same limit as the one of 2016 [14] (which was affected by the issues at the SPS dump and LHC injection kickers MKIs).

Transmission and Lifetime

The upper frame of Fig. 4 shows the evolution throughout 2017 of the beam transmission in “SQUEEZE” beam mode (operationally used to squeeze β^* from 1 m to 40 cm or 30 cm). No matter the configuration, B1 is more lossy than B2; the situation slightly improved once β^*=30 cm was made operational. During “ADJUST” (operationally deployed when beams are brought in collision) similar values are found, even though the period with the lower β^* worsened the picture. The overall transmission looks worse with respect to that of 2016 [14].

The lower frame of Fig. 4 shows the evolution throughout 2017 of the minimum beam lifetime in “SQUEEZE” beam mode. Consistently with the transmission plots shown in the upper frame, the higher losses seen on B1 are reflected in lower values of the minimum beam lifetime. In general, values are lower than those in 2016 [14].

Overall Losses

Presently, losses in IR7 are of no concern for LHC operation, even though the cumulative dose received by equipment installed in IR7 steadily increases. The yearly–integrated BLM signals [15], directly proportional to the yearly losses, show the asymmetry already noticed with the analysis of the beam transmission and lifetime, i.e. larger losses in IR7 are seen on B1. Possible concerns may arise in view of the High Luminosity LHC (HL–LHC) project [16], for which mitigation actions are already planned – e.g. the removal of the first module of the warm Q5 and the installation of a new passive absorber at its place, reducing the ageing of the overall magnet assembly.

Collision debris is also responsible for losses in the cold aperture of the machine, which scale directly with luminosity. For instance, collision debris is responsible for losses seen further downstream in the arcs surrounding the exper-

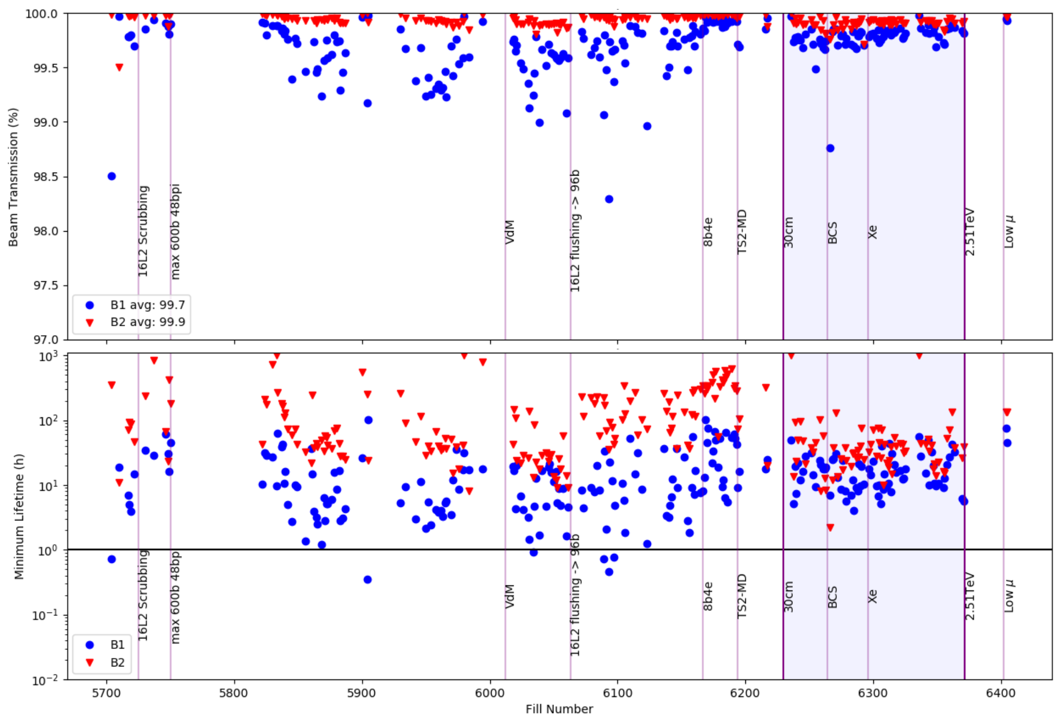

Figure 4: Evolution throughout 2017 of the beam transmission (upper frame) and of the minimum beam lifetime (lower frame) in "SQUEEZE" beam mode for different machine configurations. The period highlighted in magenta refer to the deployment of β^{*}=30 cm for regular operation.

imental insertions. The analysis is still on–going [15], and no firm conclusions can be drawn at the time of writing. Moreover, in 2017 there were 10–15 dumps in 50 fb^{-1} [15] due to effects of Radiation to Electronics (R2E) in the RR tunnels (still located in the Long Straight Sections, but very close to the arcs). These dumps constitute the largest fraction of the R2E dumps, and they occurred when roman pots (XRPs) and debris absorber collimators (TCLs) were closed to operational settings. Simulations [17] show that there is a strong contribution from TCLs, but also from XRPs. On a long term perspective, R2E failures in the RRs are expected to drop below 1 fault per system per HL–LHC year after the Long Shutdown 2 (LS2), thanks to the deployment of radiation–tolerant electronics [18].

HARDWARE CHANGES, COMMISSIONING AND PERFORMANCE

All the changes which took place during the 2016 Extended Year End Technical Stop (EYETS2016) were done mainly for tests with beam in view of the HL–LHC project [16]:

- a prototype of TCSPM was installed on Beam 2 in slot D4R7 [19]. The installation was important for validating the design of the new low–impedance IR7 secondary collimators, especially for choosing the material coating the jaws. In fact, the collimator is equipped with three stripes of material that can be exposed to the beam to perform impedance measurements;
- the TCTPH.4R5.B2 and TCL.4L5.B2 were replaced with tungsten collimators with in–jaw wires [20]. The changes were aimed at testing the compensation of long–range beam–beam effects in IR5 on Beam 2 via powering the wires;
- one crystal per plane was installed in IR7 on Beam 2 [21], to repeat on Beam 2 the tests of crystal collimation already performed on Beam 1;
- the horizontal primary collimator of Beam 1 in IR7 (i.e. the TCP.C6L7.B1) was equipped with Beam Position Monitors (BPMs) [22].

The new hardware had no impact on machine availability, and tests could be successfully performed.

During the initial commissioning with beam, in addition to the extensive hardware tests regularly performed for the machine start–up, the "5$^{\text{th}}$–axis functionality" was validated [23], fundamental for the tests with the TCSPM.D4R7.B2 (the low–impedance prototype collimator) and the two wire collimators. This functionality allows to displace the entire collimator tank (and hence the jaws) transversely along the non–cleaning plane, allowing to align the desired material stripe or the compensating wire to the beam. Software improvements were mainly related to the collimator GUI for alignment and the underlying

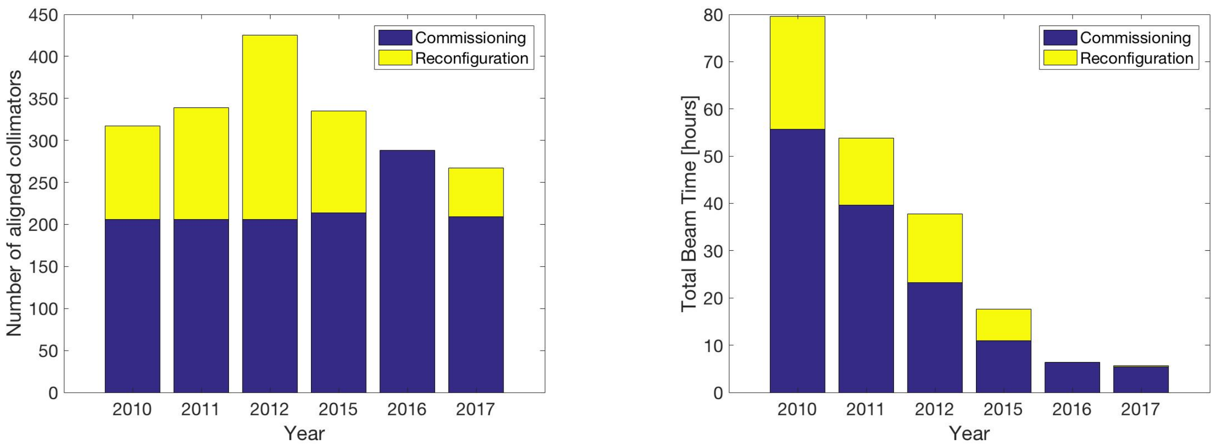

Figure 5: Evolution over years of the number of collimators re–aligned during commissioning and set–up activities, and time required to accomplish alignment.

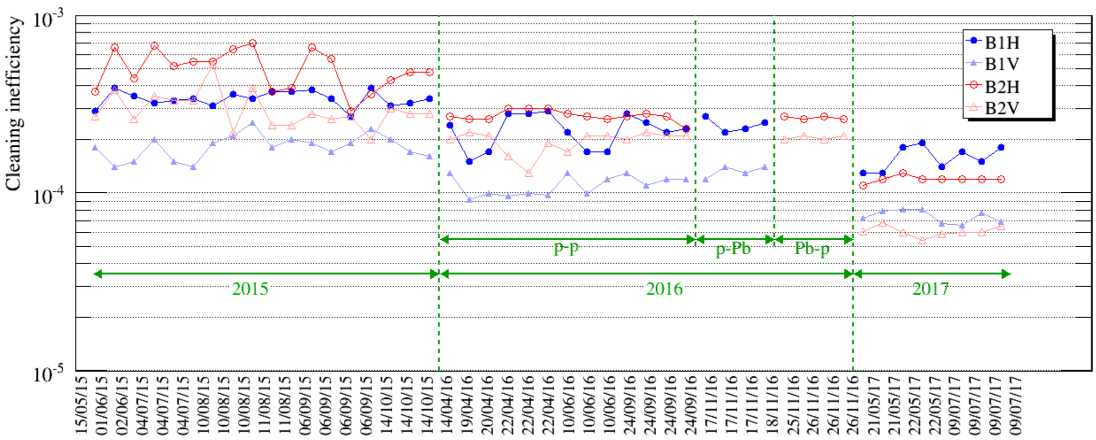

Figure 6: Evolution over years of the peak local cleaning inefficiency in the IR7 DS. The net improvement over the years was achieved thanks to tight

FESA classes [24]. The newly installed collimators were imported in the LSA database, fully commissioned and aligned. The full commissioning of BPMs at collimators was performed, including scans for non–linear coefficients, done in collaboration with BE–BI colleagues.

Collimator alignment was smooth, and despite the relative large amount of collimators that had to be re–configured to accommodate β^*=30 cm at the high luminosity IPs, the penalty in set–up time was negligible (see Fig. 5), thanks to the deployment of BPMs [25].

Figure 6 shows the evolution over years of the peak local cleaning inefficiency in the DS downstream of IR7. The net improvement visible over the years was made possible thanks to tightening the collimator settings and pushing the IR7 collimator hierarchy.

The collimation system registered a very low number of faults in 2017 [26]. According to the post–mortem data browser [27], the collimation system triggered only 8 dumps in the entire year: 7 were due to hardware faults (e.g. a faulty temperature sensor or jaws being stuck), and 1 due to a suspect Unidentified Falling Object (UFO). None of them was due a specific issue repeated over the year. No dump occurred during data taking, since 4 dumps took place at injection energy, 3 during the ramp, and only 1 at flat top energy, while going in collision.

CONCLUSIONS

The LHC collimation system is a key player in protecting the machine cold aperture against beam losses, for a high–efficiency operation with stored beam energies up to 300 MJ. Being a multi–stage cleaning system, ensuring the correct collimator hierarchy is essential to guarantee the required levels of protection. Hence, it is crucial to annually probe during commissioning and in MD blocks the available aperture and margins on the hierarchy, in order to push performance.

An important fraction of the aperture budget is taken by the collimation system. In 2017 and in past years, this fraction was decreased reducing gradually the operational margins between collimator families and against the machine aperture. In view of operation in 2018, relevant knobs to push performance are:

- reducing crossing angle and/or further squeezing β^* during physics, to partially compensate the loss of luminosity due to the reduction of beam intensity. This strategy is aimed at increasing the integrated luminosity per fill, profiting from the reduction with time of the impact of beam–beam effects on the beam dynamic aperture for the same crossing conditions;
- reducing the retraction between IR7 collimator families. Measurements carried out in 2017 and in past years showed that the retraction between TCP and TCSG collimators can be lowered to 1 σ; nevertheless, the deployment of these settings at start up is not advisable, especially because of the complexity of the required angular alignment;
- keeping a small retraction between TCT collimators and the TCDQ absorbers. This configuration, already deployed in operation in 2016, is applicable only if the phase advance between the MKD dump kickers and the TCT collimators is safely kept lower than 30°.

The beam lifetime in 2017 was worse than in the previous year, and the integrated losses in IR7 have consistently increased. Among the two beams, B1 saw the highest losses, in agreement with findings from past years. The registered levels of losses are not an issue for the present LHC operation in terms of dose to IR7 warm elements and equipment in the arcs, SEUs in the RR tunnels, etc... Nevertheless, relevant mitigation actions are taking place in LS2 in the context of the HL–LHC project.

As in previous years, the LHC collimation system had an excellent performance during 2017. The initial commissioning with beam was smooth. The local cleaning inefficiency, highest in the DS downstream of IR7, was improved compared to past years, thanks to tighter IR7 collimator settings. The LHC collimation system also proved its flexibility and tighter settings were deployed, accommodating new optics conditions at the IPs, allowing to reach a β^* of 30 cm in the high luminosity experiments after TS2, increasing the daily production of luminosity in 2017 [28].

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