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COLLIMATION PERFORMANCE OF THE 400MJ LHC BEAM AT 6.8 TEV

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Abstract

During the third operational run of the Large Hadron Collider at CERN, starting in 2022, the beam energy was increased to 6.8 TeV and the bunch population is planned to be pushed to unprecedented levels. Already in the first year of operation, stored beam energies up to 400 MJ were achieved. An improvement in cleaning performance of the LHC collimation system is hence required. In this paper we review the collimation system performance during 2022, and compare it to previous years. Particular attention is given to the performance during β^*-levelling, which is part of the nominal cycle in Run 3. The performance of the automatic alignment tools is also discussed. Finally, we review the stability of the collimation system, which was monitored regularly during the run for all machine configurations to ensure the continued adequate functionality of the system.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN [1] is the world's largest and most powerful particle collider. With the start of Run 3 in 2022 [2], the stored beam energy in the LHC has reached a new milestone of 400 MJ at a record energy of 6.8 TeV, representing a significant increase in luminosity that can be delivered to the experiments as compared to previous runs [3]. This is shown in Fig. 1, which shows the maximum energy of the beam for each physics fill in 2022. However, with higher stored beam energy, the risk of magnet quenches or damage to the accelerator components due to beam losses increases. A good performance of the collimation system is therefore crucial in controlling these losses and ensuring the safe and stable operation of the LHC.

In 2022, a levelling scheme [4] was implemented as part of the nominal cycle, where the high-luminosity experiments are operated at a constant luminosity of $\sim 2 \cdot 10^{34}$ cm^{-2}s^{-1} at the beginning of the fill. This limit is defined by the cryogenic cooling capacity available to cope with the heat load on the final focus quadrupoles due to collision debris and by the number of collisions per bunch crossing (pile-up) that can be managed by the detectors [5]. The levelling is implemented by changing the β function at the collision point, β^*, as had been successfully tested and applied in 2018 [6–8] but now with a larger range and much finer granularity. This is an important milestone for the upcoming high-luminosity upgrade for the LHC [9, 10], for which β^*-levelling is an essential ingredient.

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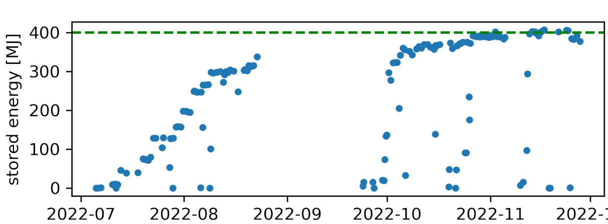

Figure 1: Stored beam energy per beam of each fill in 2022.

During LS2, 14 new collimators with low-impedance material and built-in beam position monitors (BPMs) were installed, as well as two new crystal collimators in the vertical plane. These are detailed in Table 1. Dedicated time was foreseen at the start of commissioning after LS2 to setup and test these new collimators. Overall, the 2022 commissioning of the collimator system was very successful, although longer than usual due to the new hardware and the increased complexity of the cycle. In operation, the collimation system safely and effectively managed the increasing stored energy, protecting the machine at all stages and during levelling, with no quenches resulting from circulating beam losses. The system's alignment was precisely and stably maintained during the rest of the year and no re-alignments were necessary.

Table 1: New Collimators Installed in LS2

	total	length [m]	material	region
TCP	4	0.600	MoGr	IR7
TCSPM	8	1.000	MoGr	IR7
TCLD	2	0.600	Inermet	IR2
TCPC	2	0.004	Si crystal	IR7

COLLIMATOR SETTINGS

The collimation system follows a strict hierarchy, as illustrated in Fig. 2. In two dedicated insertion regions (IR7 for betatron cleaning and IR3 for momentum cleaning), primary collimators (TCPs) intercept the primary halo of the beam. These are made of low-Z material, to avoid being damaged by the high intensity of the beam halo. As a consequence, a fraction of the halo scatters, and showers downstream of the TCPs are generated, creating a secondary beam halo. The latter is intercepted by secondary collimators (TCSs), still made of low-Z material, at a larger jaw opening. These are then followed by absorbers (TCLAs) downstream, at an even larger jaw opening and made from high-Z material to efficiently absorb showers that are generated by the TCSs. To protect the superconducting triplet magnets around the experimental insertions, the LHC collimation system also includes tertiary collimators (TCTs) upstream of the inter-

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Table 2: Collimator Settings in 2022, Expressed in Terms of the RMS Beam Size (σ) at 3.5 μm Emittance.

	IR7 [σ]			IR3 [σ]			Dump [σ]		TCT [σ]				TCL [σ]		
	n_{TCP}	n_{TCS}	n_{TCLA}	n_{TCP}	n_{TCS}	n_{TCLA}	n_{TCDQ}	n_{TCSP}	IP1	IP2	IP5	IP8	4	5	6
injection	5.7	6.7	10	8	9.3	12	8	7.5	13	13	13	13	-	-	-
flat top	5	6.5	10	15	18	20	7.3	7.3	18	37	18	18	-	-	-
$\beta^* = 60$cm	5	6.5	10	15	18	20	7.3	7.3	12	37	12	18	24	58.3	14-16
$\beta^* = 30$cm	5	6.5	10	15	18	20	7.3	7.3	8.5	37	8.5	18	17	42	20
XRP OUT	5	6.5	10	15	18	20	7.3	7.3	8.5	37	8.5	18	17	17	20

action points (IPs), made of a high-Z tungsten alloy [1, 11]. Finally, there are dedicated collimators downstream of the IPs to intercept physics debris (TCLs).

As the value of the optical β-function at the triplet magnets scales inversely to β^*, the aperture at the triplet is tightest at the the smallest β^* value. The settings of the collimation system and its hierarchy are hence defined at the smallest $\beta^* = 30$ cm, and the settings during the other steps in the cycle are inferred from here. During β^*-levelling, the TCT and TCL jaw openings were kept constant in mm at all β^*, going from 12σ at $\beta^* = 60$ cm to 8.5σ at $\beta^* = 30$ cm[12]. The rest of the collimation system is not affected by these local changes and the same settings as in 2018 were applied [13]. The full system settings are reported in Table 2; note that during collisions one has two configurations, with the Roman pots (XRP) in or out. The only collimator that is affected by this change is the TCL5, which is then opened.

ALIGNMENT

Significant improvements were achieved in the time spent aligning the collimator system. The Fully-Automatic Beam-Based Alignment (BBA) was performed for the first time in parallel during operation. The general experience was very smooth and the alignment could be carried out in short times, as it took only 1h25m to align the full system for one point in the cycle. This time is an upper limit, as it is limited by the amount of cross-talk between the different beams; see [14–23] for a detailed discussion on this topic.

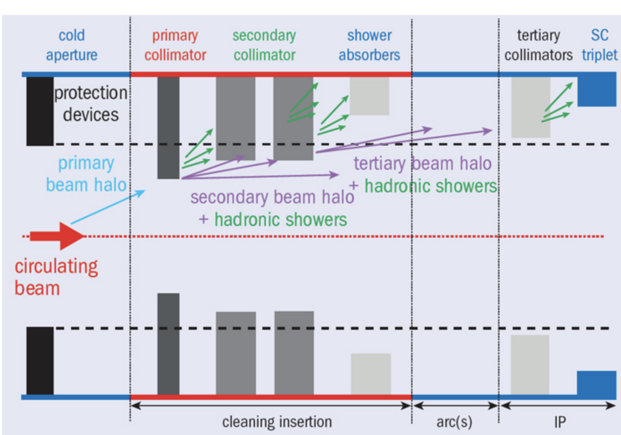

Figure 2: Hierarchy of the LHC collimation system.

One peculiarity was the beam-based alignment of the TCL6, as with the new optics developed for Run 3 the beam size is extremely small at this location ($\sigma \sim 70\mu m$). This implies that small steps of the collimator jaw movement can quickly create high losses. This was dealt with particular care, and no spurious dumps during the alignment were triggered.

The installation of the new collimators has the additional advantage that those can be aligned with BPMs. Contrary to the case with BBA, where the collimator needs to touch the beam to be able to derive the position of the beam, the alignment with BPMs can be done while the jaws remain far open as the beam position will be read out by the BPMs directly [16]. Not only is this more precise, it is also a much faster approach as all collimators can be aligned in parallel without the issue of cross-talk. It took less than 8 minutes to align all 16 collimators with BPMs. Furthermore, this procedure allows an angular alignment to be performed within a few seconds, as there are BPMs in all jaw corners, both upstream and downstream [21]. This allowed us to identify collimators with large tilts, and pass our findings to the survey team who consecutively accessed the machine to realign the tanks containing the collimators. Three collimators were adjusted in this way: TCP.C6L7.B1 (a tilt of 240 μrad before the intervention, and 100 μrad afterwards), TCSPM.B4L7.B1 (-410 μrad before vs. -200 μrad after), and TCP.C6R7.B2 (-890 μrad before vs. -280 μrad after) [24].

After the beam centres were found by the alignments at each static point in the cycle, dedicated functions have been generated semi-automatically to connect the different settings over the full cycle [25].

APERTURE MEASUREMENTS

Measuring the aperture at injection is an essential step in commissioning the collimation system, as it defines the clearance for circulating beams at high intensity [26]. Furthermore, it is necessary to verify that the aperture at the tightest β^* is in line with what is expected from simulations, validating the settings of the TCTs (and, by extension, of the full hierarchy). Both measurements have meticulously been performed and the system validated during early commissioning in spring 2022 [27]. The results are reported in Table 3, and confirm that the aperture remains in the shadow of the collimation system at all times. The results from the collimator scan (CS) are confirmed by a beam-based alignment (BBA) afterwards. For both planes and beams,

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the bottleneck was found in the inner triplet around the IP. These results are perfectly in line with what was measured in 2018 [26].

Table 3: Aperture measurements at $\beta^* = 30$cm

Plane	CS [σ]	BBA [σ]	Bottleneck
B1H	11.5 to 12.0	> 10.9	Q2L5
B2H	11.0 to 11.5	12.5 to 13.0	Q2R5
B1V	9.5 to 10.0	> 10.0	Q3L1
B2V	9.5 to 10.0	> 10.0	Q3R1

COLLIMATION PERFORMANCE

Once the aperture was verified, the settings of the full collimation system had to be validated with betatron, off-momentum, and asynchronous dump loss maps (LMs) before high-intensity beams were allowed. These LMs have to be performed at each static point in the cycle, and, with the addition of β^*-levelling to the nominal cycle, additional LMs had to be performed in steps of 5% β^*. In general, this validation needs to be repeated for each machine configuration where the optics and/or collimator settings are changed, after each technical stop, or every three months if the other two cases did not happen before. In 2022, a reduced number of loss maps were repeated after a technical stop in September. Moreover in June, betatron LMs were performed during the energy ramp in steps of 500 GeV. In total, 201 validation LMs have been performed in 2022, which were executed smoothly thanks to a new controls software tool developed in the beginning of the year.

An important metric deduced from the LMs is the local cleaning inefficiency in the dispersion regions of IR7 and IR3, which is represented by the peak loss in the cold aperture normalised to the losses on the TCPs. This is reported in Fig. 3 for the different steps in the cycle, for the initial validation during commissioning and for the revalidation after the technical stop. These values are completely in line with the performance in 2017 and 2018 when the same collimators in IR7 were used [28], with small but visible improvements in some LMs due to the new material in the IR7 TCPs. Also note that the cleaning inefficiency is remarkably stable along the cycle and over the year, even without realigning the system, attesting to an efficient and precise alignment procedure. Furthermore, the evolution of losses on the TCTs during β^*-levelling was investigated, and, as expected, losses scale exponentially w.r.t. β^* and reach values of 10^{-3} of those at the TCP. These are high but manageable values, and the background to the experiments remained under control at all times. This was an impressive result, given the achieved performance in terms of stored beam energy.

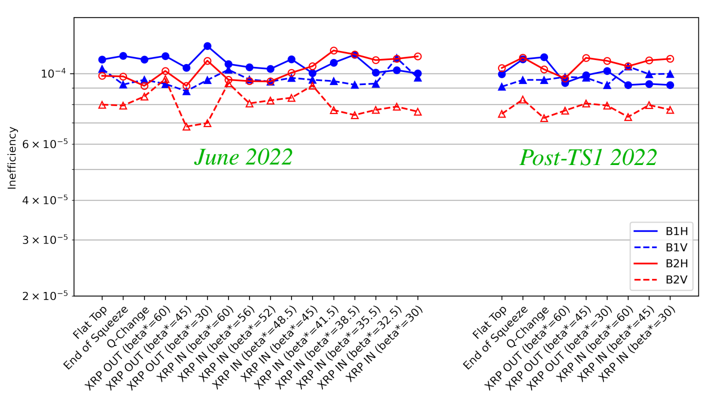

Figure 3: Cleaning inefficiency in the dispersion region over the year 2022.

Unfortunately, after the technical stop (Post-TS1), several LMs demonstrated a consistent increase of losses. The LMs at injection were of particular worry, as in some cases one of the injection protection collimators accumulated more losses than the TCPs, thus breaking the hierarchy. To investigate this, a whole set of additional loss maps were performed, scanning different operational parameters, and it was found that the effect was due to the Landau octupole settings in September compared to those June [29]. This mechanism is not yet fully understood, and further investigations are planned in early 2023.

After commissioning was completed, the LHC moved to producing physics fills. In the first two months, the number of bunches and/or bunch intensity was gradually increased towards the projected value for 2022; see Fig.1. At several stages in this intensity ramp-up, the performance of the collimation system was evaluated to validate the next intensity increase. The collimator positioning was extremely stable during the year, with no dumps due to uncontrolled collimator movements and only two dumps due to a drifting jaw position measurement. There were three more dumps due to an interlock glitch which was shown to be related to an overload of the controls hardware (solved by replacing the hardware), and four dumps due to collimator temperature interlocks (solved by increasing the interlock threshold).

CONCLUSION

Overall, the LHC collimation system has performed exceptionally well in 2022, managing a more complex cycle at higher beam momentum and higher total stored beam energy. The collimation system has also become more complex, with the deployment of several new collimators installed as part of the HL-LHC upgrade. Furthermore, the updated alignment and loss maps software tools have lead to a significant reduction in the required commissioning time and made the operation of the system less prone to in human error. The cleaning inefficiency is on par with previous results, even during a complex scheme such as the β^*-levelling. Finally, the stability and reproducibility of the collimation system was very good, and the operational downtime due to collimators were limited and well under control.

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