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COLLIMATION SYSTEM UPGRADES FOR THE HIGH LUMINOSITY LARGE HADRON COLLIDER AND EXPECTED CLEANING PERFORMANCE IN RUN 3*

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Abstract

In the framework of the High-Luminosity Large Hadron Collider project (HL-LHC), the LHC collimation system needs important upgrades to cope with the foreseen brighter beams. New collimation hardware will be installed in two phases, the first one during the LHC second Long Shutdown (LS2), in 2019-20, followed by a second phase starting in 2024 (LS3). This paper reviews the collimation upgrade plans for LS2, focused on a first impedance reduction of the system, through the installation of collimators based on new materials, and the improvement of collimation cleaning, achieved by adding new collimators in the cold dispersion suppressor regions. The performance of the new system in terms of cleaning inefficiency for proton and lead ion beams is presented.

INTRODUCTION

The Large Hadron Collider (LHC) [1] at CERN is equipped with a sophisticated collimation system [2]. One of its main goals is to protect superconducting (SC) magnets against quench. Even if the system performance in Run 1 (2010-2013) [3] and in Run 2 (2015-2018) [4] was very satisfactory, with no collimation-induced quenches, relevant upgrades are necessary to cope with the beams foreseen by the High Luminosity LHC (HL-LHC) [5,6] project, which aims at increasing the integrated luminosity collected by the high-luminosity LHC experiments until 2024 by a factor 10 over a dozen years starting from 2026. To do so, a challenging upgrade will take place during the Long Shutdown 3 (LS3), 2024-2026, to equip the LHC ring with suitable hardware. Similarly, the LHC injectors [7] will be upgraded already in LS2, to be able to produce the necessary beams. The proton beams will be a factor 4 brighter in HL-LHC than the nominal LHC, thanks to the higher bunch population at injection, i.e. 2.3 10^{11} protons per bunch (ppb) instead of 1.15 10^{11} ppb, and the smaller normalised emittance, i.e. 1.7 μm instead of 3.5 μm.

In this paper, the current baseline upgrade of the collimation system is reviewed. Differently from the rest of the machine, collimation upgrades will take place already in LS2. The collimation system for Run 3 (2021-2023) is presented and its performance targets are assessed in simulation. Finally, some conclusions are drawn.

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THE PRESENT COLLIMATION SYSTEM AND ITS UPGRADE

The present collimation system features momentum cleaning, located in the insertion region 3 (IR3), and betatron cleaning, located in IR7 with the last stages in the experimental IRs for local protection.

Collimators are organised in families [1, 2]. Primary (TCP) collimators define the collimation cut; secondary (TCSG) collimators intercept beam particles out-scattered by TCPs, and shower absorbers (TCLAs) intercept the most forward secondary particles from TCPs and TCSGs. Tertiary collimators (TCT) offer local protection to the inner triplets (ITs) in IR1, IR2, IR5 and IR8, and reduce the background to the experimental detectors.

Collimators are made of two movable jaws, centred around the circulating beam [1,2]. TCPs and TCSGs are presently made of carbon-fiber-composite (CFC), a material that enhances robustness, as convenient for the stages closest to the beam. TCTs and TCLAs are made of Inermet 180, a heavy tungsten alloy, which maximises particle absorption at the expenses of robustness, as convenient for the last stages immediately upstream of sensitive equipment.

The planned upgrade will address the challenges set by the HL-LHC project, intervening on several aspects of the LHC collimation system [8].

Dispersion Suppressor (DS) collimation One DS collimator (TCLD) will be installed in cell 9 on each side of IR7 for cleaning the outgoing proton and heavy ion beams (see Fig. 1, left plots). To make space, a standard 8.33 T main dipole (MB) will be replaced by two shorter 11 T dipoles with the TCLD in between. One TCLD collimator will also be installed on each side of IR2 in cell 11, at the location of the connection cryostat, without 11 T dipoles, for Pb ion operation only (see Fig. 1, right plots). Losses in the DSs of IR1 and IR5 during Pb ion operation are mitigated by local bumps in the DS region that move losses at the location of the connection cryostat, with no need for dedicated collimators [9]. The complete DS collimation upgrade takes place in LS2.

Low-impedance upgrade Nine secondary collimators per beam with a new, low-impedance design (TCSPMs) will be installed in IR7. The TCSPM features Mo-coated, MoGr jaws. Four [10] TCSPMs per beam will be added in LS2, with three installed immediately downstream of present TCSGs, and one replacing the present TCSG.D4 collimator

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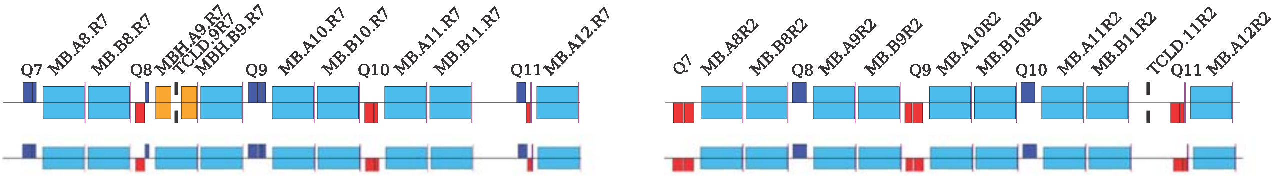

Figure 1: Run 3 (top) and Run 2 (bottom) layouts of the IR7 DS (left) and IR2 DS (right) of B1, with the new TCLD collimators, with and without 11 T dipoles. B2 layouts are symmetric. The beam goes from left to right.

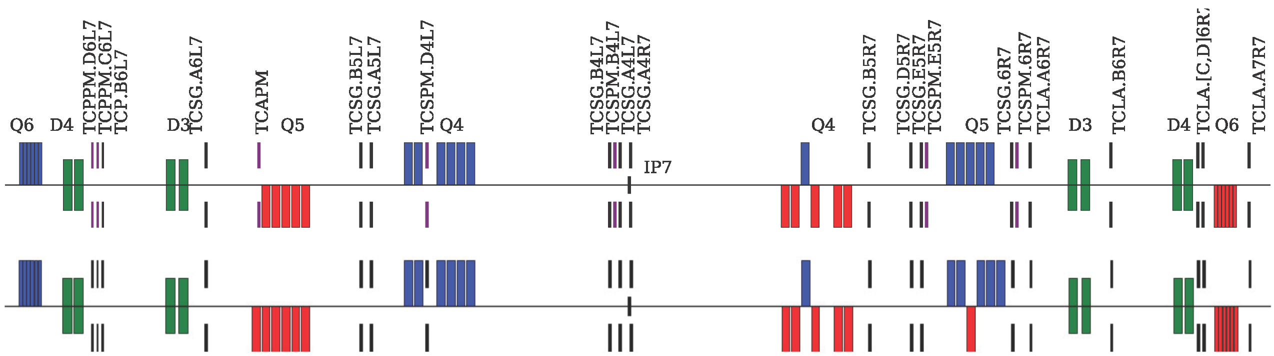

Figure 2: Run 3 (top) and Run 2 (bottom) layouts of the IR7 long straight section (LSS) of B1. New hardware is marked in purple. B2 layouts are symmetric. The beam goes from left to right.

on each beam (see Fig. 2). The remaining five TCSPMs per beam will be installed in LS3.

Experimental IR Upgrade Each high-luminosity IR will be equipped with four TCTs per incoming beam, to protect the IT and the matching section (MS), and three physics absorbers (TCLs) with three fixed masks per outgoing beam, to protect MS and DS from collision debris.

Consolidation It is also planned to consolidate the existing collimators that will remain operational during HL-LHC. This program starts in LS2 (see Fig. 2) with the renewal of two IR7 TCPs per beam and the addition of one passive absorber (TCAPM) per beam at the place of the first quadrupole module in cell 5 (Q5) in IR7, to increase the lifetime of warm quadrupoles [11]. The Q5 modules have to be re-wired and the IR7 optics was re-matched accordingly [12].

EXPECTED PERFORMANCE IN RUN 3

The Run 3 performance of IR7 collimation was evaluated in terms of cleaning inefficiency, i.e. the probability of a beam particle being lost at a given location [1,2]. The present system without TCLDs was limited by three loss clusters in the DS cells 9, 11 and 13 [13] (see Fig. 1) called DS1, DS2 and DS3, with the DS3 being relevant only for ions. The averaged losses over the exposed magnets in these locations, and in another one found in the DS of IR8 (IR8_DS) are used for the performance assessment. Simulations were run using the coupling [14] between Fluka [15, 16] and SixTrack [17, 18], with a statistics of ~10^6 beam particles per case.

Proton Beams

Details of the Run 3 optics are still under discussion. Since no significant local differences are expected in the IR7 optics, simulations were run with the HL-LHC collision optics V1.3 [5]. Standard HL-LHC collimation settings [5] and the LS2 upgrades were considered, except the IR7 Q5 module removal, which is not expected to significantly impact the IR7 cleaning [12]. Only B1 results are discussed.

As an example, Fig. 3 shows the cleaning inefficiency all around the ring in case of horizontal losses in B1 (B1H). Cold losses are very low and at the limit of the statistical significance (one simulated proton corresponds to a 10^{-6} inefficiency). The only exception is the cluster upstream of the IR7 TCLD, at the first 11 T dipole (see bottom plot in Fig. 3). Energy deposition calculations [19] showed that the peak power deposition in the SC coils of this magnet amounts to ~50 mW cm^{-3} with TCP jaws in CFC, while the estimated quench limit is ~70 mW cm^{-3} [20]. This estimate is based on a worst-case beam lifetime (BLT) drop to 12 min for up to 10 s with the full HL-LHC beams of 680 MJ, which is not expected to be available in Run 3 [21]. It should be noted that the quench limit of a nominal MB is about a factor 2–3 [19, 20] lower than that of the 11 T dipole.

Figure 4 shows the average B1H cleaning inefficiencies for the three locations that are most loaded with losses without TCLDs, i.e. the DS clusters immediately downstream of IR7 and in IR8. Different TCLD installation locations are considered: no installation, installation in cell 8 (previous baseline [5]), and installation in cell 9 (current baseline [8]). A TCLD in cell 8 improves the cleaning inefficiency with respect to the case of no TCLD, with remaining losses lo-

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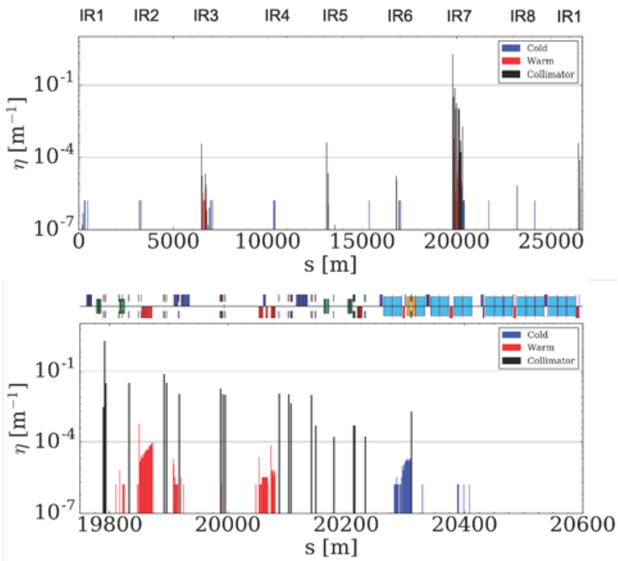

Figure 3: B1H proton loss map for Run 3: overview along the LHC (top) and zoom in IR7 (bottom). A single proton loss in the arc corresponds to η=1.6 10^{-6}. The zoom reports the average cleaning inefficiency upstream of the TCLD.

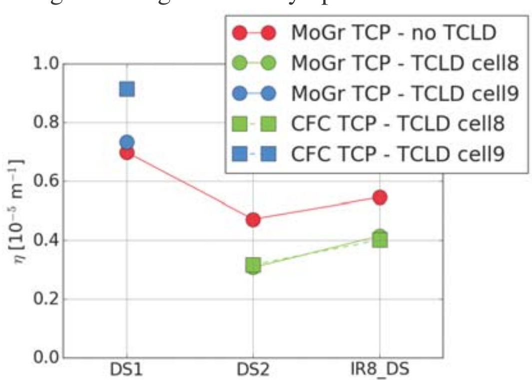

Figure 4: Average proton cleaning for different scenarios. Note that no losses are found in DS2 and IR8_DS with TCLD in cell 9 (blue points).

cated mainly at MBs. The TCLD installation in cell 9 cleans all but the first cluster, motivating the choice of the baseline change. It should be noted that losses are concentrated on the upstream 11 T dipole (Fig. 3, bottom graph at $s \approx 20.3$ km), which is expected to have a quench margin higher than that of a nominal MB [20]. The same figure shows also that the new TCP jaw material slightly improves the DS1 average cleaning inefficiency. Results for B1V are very similar.

Ion Beams

Figure 5 shows the B1H loss map for colliding beams with the Run 3 layout, normalized as in Ref. [22]. Similarly to the case of proton beams, almost all cold losses along the ring are cleaned by the TCLD installation in cell 9. Table 1 summarises the average cleaning inefficiencies. The TCLD in cell 8 improves the cleaning in DS1 but leaves DS2 and DS3 exposed. On the contrary, the TCLD in cell 9 improves the cleaning in all three clusters. No significant impact from the TCP jaw material is observed in the DS clusters

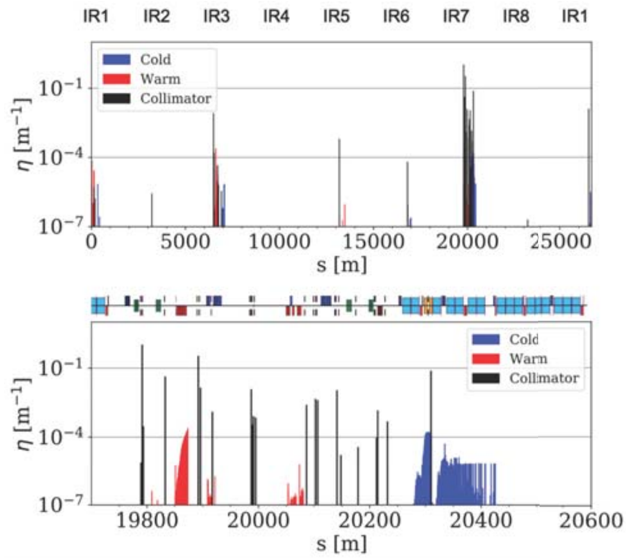

Figure 5: B1H Pb ion loss map all along the LHC ring (top) and zoom in IR7 (bottom) for colliding beams.

Table 1: Average Cleaning Inefficiency in the Three IR7 DS Clusters for Pb Ions

TCLD location	TCP material	DS1 [$\times 10^{-4}$]	DS2 [$\times 10^{-4}$]	DS3 [$\times 10^{-4}$]
-	CFC	3.721	6.011	3.897
cell8	MoGr	0.017	4.185	4.089
	CFC	0.021	3.747	4.514
cell9	MoGr	0.268	0.017	0.001
	CFC	0.249	0.011	0.028

downstream of the TCLD; a slight worsening is seen on the first cluster upstream of the TCLD.

In addition to cleaning studies, the IR2 TCLD installation was proven necessary through simulations of secondary ion beams from Pb-Pb collisions [19]. These TCLDs, mitigating losses in the IR2 DS due to the bound-free pair production process [23, 24], are needed to meet the HL-LHC Pb-Pb luminosity goals, which will be at reach already in Run 3 [25].

CONCLUSIONS

The LS2 will see the first installation of the upgraded collimation system for HL-LHC, with immediate benefit for the operation in Run 3. The installation will improve the betatron cleaning performance for proton and ion beams and reduce the impedance contribution to the machine budget; it will also improve the cleaning of secondary ion beams coming from ultra-peripheral interactions in IR2. In addition to these improvements, this upgrade will allow gaining operational experience with the new hardware ahead of the full implementation of HL-LHC planned in 2024-25. Measurements with beam will also give the opportunity to refine the design of the hardware to be installed in the future.

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