CLEANING PERFORMANCE OF THE COLLIMATION SYSTEM OF THE HIGH LUMINOSITY LARGE HADRON COLLIDER*

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Abstract

Different upgrades of the LHC will be carried out in the framework of the High Luminosity project (HL-LHC), where the total stored energy in the machine will increase up to about 700 MJ. This unprecedented stored energy poses serious challenges for the collimation system, which was designed to handle safely up to about 360 MJ. In this paper the baseline collimation layout for HL-LHC is described, with main focus on upgrades related to the cleaning of halo and physics debris, and its expected performance is discussed. The main upgrade items include the presence of new collimators in the dispersion suppressor of the betatron cleaning insertion installed between two 11 T dipoles, and two additional collimators for an improved local protection of triplet magnets. Thus, optimized settings for the entire and upgraded collimation chain were conceived and are shown here together with the resulting cleaning performance. Moreover, the cleaning performance taking into account crab cavities it is also discussed.

INTRODUCTION

The increased total stored energy in the HL-LHC [1] of about a factor two with respect to the LHC design, calls for an improved cleaning performance of its collimation system [2]. The main limitations of the present system in view of the HL-LHC operations are [3]: (1) losses due to off-momentum or off-rigidity particles emerging from the betatron cleaning insertion, in the case of protons and ions, respectively; (2) losses due to heavy ion collision products around ALICE; (3) local protection of triplets and other insertion magnets around ATLAS and CMS; (4) impedance and robustness of materials of the collimator jaws.

For each of the items above, a dedicated solution has been conceived. Beam losses due to off-momentum particles scattering out of the primary collimators and due to heavy ions collision products can be cured by additional collimators in the dispersion suppressor of the two insertions. Local protection of the matching section of the high-luminosity points is provided by the addition of two collimators, compared to the present layout where only the triplet magnets are protected by tertiary collimators. Driving considerations for the final material choice are both an increased jaw robustness, and a reduced resistive-wall impedance with respect to the present materials used, which is the subject of a companion paper [4]. The final HL-LHC collimation layout based on the present baseline is described in detail in the next section.

Table 1: List of Movable LHC Collimators for the Run II and HL-LHC, per Beam

		Material		Number	
Name	**IR**	**Run II**	**HL-LHC**	**Run II**	**HL-LHC**
TCP	7	CFC	CFC	3	3
TCSG	7	CFC	-	11	-
TCSPM	7	-	Mo-Gr	-	11
TCLA	7	IT180	IT180	5	5
TCLD	7	-	IT180	-	2
TCP	3	CFC	CFC	1	1
TCSG	3	CFC	CFC	4	4
TCLA	3	IT180	IT180	4	4
TCTP	1/5	IT180	-	4	-
TCTPM	1/5	-	Cu-CD	-	8
TCL	1/5	Cu/W	Cu/W	6	4
TCLX	1/5	-	W	-	2
TCTP	2/8	IT180	IT180	4	4
TCLD	2	-	IT180	-	1
TCSP	6	CFC	CFC	1	1
TCDQ	6	C	C	1	1

BASELINE LAYOUT

As in the present LHC [2] two dedicated insertions are devoted to the beam collimation, IR3 and IR7, where momentum and betatron cleaning are performed, respectively. The limiting location of the entire ring in terms of collimation losses is represented by the dispersion suppressor (DS) of IR7 [5,6]. The main source of losses with proton beams is single diffractive events experienced by protons intercepted by the primary (TCP) and secondary (TCSG). Such protons are able to emerge from collimators, but are lost at the first peak of dispersion (i.e. in the IR7-DS) due to the large offset in momentum acquired. Dedicated collimators (TCLD) are to be placed in the IR7-DS cells 8 and 10 to mitigate these losses. The space for installing new collimators in the cold DS will be made available by replacing two present dipoles with shorter 11 T dipoles [7,8], and TCLDs are to be installed between them (cryostat unit). The same solution is adopted for the Beam 2. Similar limitations occur in IR7 for ion beams [10], which are cured by the same implementation. Collisions of heavy ions lead to a analogous limitation in the DS around the ALICE experiment (IR2), where secondary beams due to collision products [11, 12] are lost in the IR2-DS and can induce a magnet quench [13]. Thanks to special bumps, TCLDs in the IR2-DS can be installed in a connection cryostat in cell 10 without need for

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Table 2: HL-LHC Collimation Baseline Settings

Coll. Family	IR	Settings [σ]
TCP/TCS/TCLA/TCLD	7	5.7 / 7.7 / 10 / 12
TCP/TCS/TCLA	3	15 / 18 / 20
TCLD (ions only)	2	15
TCTP	1 / 2 / 5 / 8	10.5 / 30 / 10.5 / 30
TCL	1 / 5	12
TCSP/TCDQ	6	8.5 / 9

11 T dipoles. Orbit bumps are used to alleviate these losses around ATLAS (IR1) and CMS (IR5), without the need to install a cryostat unit [14].

Another significant change is the replacement of all IR7-TCSGs with new collimators called TCSPMs, made of Molybdenum-Graphite (Mo-Gr). This material can ensure robustness comparable to that of the present CFC [4], but a reduced resistivity. A jaw coating will be required, however, to ensure the stability of the HL beams. The present baseline assumes a pure Mo coating. Since operational efficiency is of paramount importance at HL-LHC [1], all new collimators will adopt Beam Position Monitor (BPM) buttons embedded in each corner of the two jaws [18]. This solution has been adopted for selected collimators (such as TCTPs) from the beginning of Run II [5, 6], proving that are reliable and fully operational [19]. The main gain given by these BPM buttons is a significantly improved performance in terms of operational flexibility and β^* reach [20].

Major upgrades of the high lumi points in IR1 and IR5, demand a good complete redesign of the collimation in these insertions to ensure adequate protection against incoming beam losses and cleaning of collision products. In order to achieve the design β^* of 15 cm, the new Achromatic Telescopic Squeeze (ATS) optics [15] require even larger betas at the triplet, so it remains a bottleneck as for the LHC even if it will be built with a larger aperture [1]. New critical aperture restrictions occur upstream of the triplet [16], which can be cured efficiently by an additional pair of tertiary collimators (TCTPs) in cell 5. This new layout of TCTPs (called TCTPMs) moves beam loss further away from the experiments, which could be beneficial for background. The composite material Copper-Diamond (Cu-CD) is considered for the TCTPM to improve robustness [4], which replace the present tungsten alloy (IT180). Collimation of physics debris is conceptually the same as in the present system, with three collimators (TCL) per beam per side of the interaction points IP1 and IP5, in cells 4, 5 and 6 [1]. For HL-LHC, two fixed masks will be required in addition on the IP-side of matching section magnets (Q5 and Q6). It is presently assumed that new collimators will have to be built for HL-LHC, adding BPM functionality, as it will not be optimum to work on the present highly radioactive TCLs. A new collimator design, referred to TCLX [21], is required in the recombination region upstream of the D2 separation dipole.

A summary of all the changes to the present LHC collimation layout that are in the HL-LHC baseline is given in Table 1. Changing of jaw material for TCPs and TCLDs is still under discussion, together with the option of a pure metallic

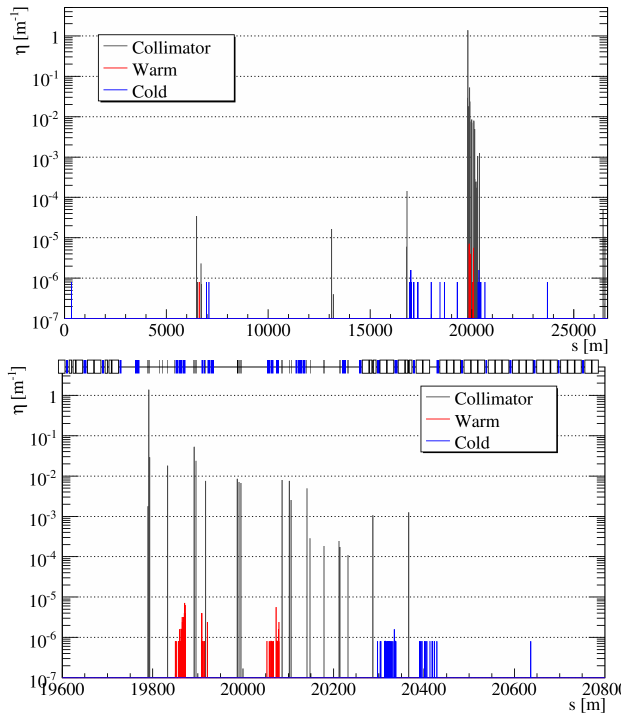

Figure 1: Expected beam loss pattern along the entire ring (top) and in IR7 (bottom) for an horizontal loss map. Blue: losses on cold magnets; Red: losses on warm magnets; Black: losses on collimators.

coating to further decrease the resistive-wall impedance [4]. The collimators that are not required to be changed as a part of the HL-LHC upgrade (i.e. TCLA, TCTP in IR2/8, TCSG in IR3 and dump protection collimators TCSP) are part of a collimation consolidation program to ensure an efficient operation of HL-LHC. For example, it is planned to replace all TCP by adding the BPM functionality.

BASELINE SETTINGS

The complex collimation system of HL-LHC is composed of 51 movable collimators for each beam. All these collimators are placed in a precise hierarchy that must be kept at any time. A possible breakage of such hierarchy can have serious consequences for the machine. An extended treatment of how these settings are defined, and the margins taken into account, is reported in [22]. The operational experience acquired during the LHC Run I and beginning of Run II gave useful inputs in this choice [23–25]. For example, we assume for HL-LHC a TCP/TCS retraction of 2 σ instead of 1 σ as in the LHC design report as a solid choice deployed in 2016. This could be reduced further, thanks to the lower impedance of the TCSPM and to the new BPM functionality. Taking into account all these considerations, the design collimator settings for HL-LHC operation in physics are reported in Table 2.

CLEANING PERFORMANCE

An extensive cleaning simulation campaign was carried out to evaluate the expected performance of the baseline

ISBN 978-3-95450-147-2

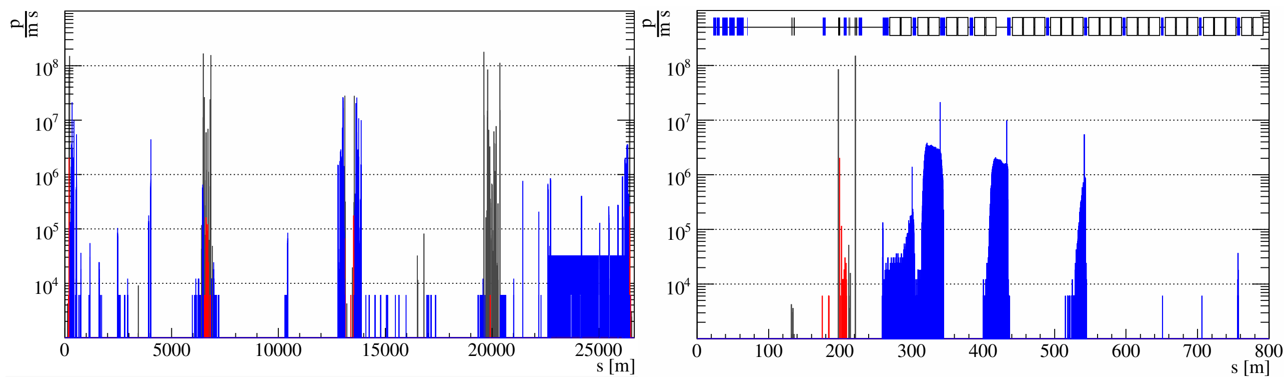

Figure 2: Expected beam loss pattern along the entire ring (left) and on the left side on IP1 (right) due to physics debris coming from IP1 and IP5, for $\mathcal{L} = 7.5 \times 10^{34}$ cm^{-2}s^{-1} and $\sigma_{\text{inel}} = 81.2$ mb at 7 TeV.

collimation system for HL-LHC. Simulations are performed with `SixTrack` [26–28], for both beams and both planes, using the optics version 1.2. The initial distribution used is a pencil beam starting from the front face of the selected IR7-TCP with RMS impact parameter of few μm, and a statistics of about 12M protons tracked. Present collimator materials are used. However, no significant impact on cleaning is expected when using the new materials [17]. An example of expected beam loss pattern regarding the case of Beam 1 for a horizontal loss map is shown in Fig. 1. An excellent performance is expected with the presence of TCLDs, and clusters of losses usually present in the IR7-DS are almost completely cured. An improvement in cleaning of about a factor 10 with respect to the present system is predicted [30, 31]. Moreover, the TCLDs are very efficient also in intercepting off-momentum particles that would be otherwise lost in other arcs due to specific features of the ATS optics [30].

Cleaning with Crab Cavities

Cleaning simulations were also performed taking into account the presence of Crab Cavities (CC) in the lattice. The expected beam loss pattern along the entire ring is very similar to what obtained without CC (Fig. 1). Thus, it is not expected that the CCs have a significant impact on the cleaning performance of the system. These simulations were performed for the horizontal and vertical case of Beam 1, with nominal beam parameters. Similar results are expected for Beam 2. Failure scenarios of CC can be found in [32].

Physics Debris Absorption

Simulations were carried out also to evaluate the multi-turn cleaning of collision products. The inelastic products of 10M collisions generated with `FLUKA` were taken into account [33]. These products are used as initial distribution and the tracking is performed starting from IP1 and IP5 for both beams. Thus, the resulting beam loss pattern are normalized with respect to the expected inelastic cross-section at 7 TeV of about 81.2 mb [34, 35], and a peak instantaneous luminosity of 7.5×10^{34} cm^{-2}s^{-1}. The resulting beam loss pattern is shown in Fig. 2 (left). As can be seen from the plot in Fig. 2 (right) a rate below 2×10^{7} p cm^{-2}s^{-1} is expected around both IPs, thanks to the TCLs. Simulations were carried out also for debris due to elastic interactions, and its contribution to losses around the ring is found to be negligible. Only a very small fraction of the initial distribution (about 10^{-3}) impacts on IR7-TCPs, after thousands of simulated turns. This makes us confident that the proposed layout without DS collimation around IR1/5 is adequate for high-intensity proton operation with the new HL-LHC optics.

Ions Cleaning

Different loss mechanism with respect to the case of proton cleaning lead to a worsening of about a factor 100 in cleaning than with protons for the present system in the LHC [6]. The main source of losses in the IR7-DS is represented by the leakage of ions undergoing fragmentation due to nuclear interactions or electromagnetic dissociation in the IR7-TCPs and IR7-TCSGs [36]. Collimation quench tests performed in 2015 [37] show that important limitations in the achievable circulating intensity are expected also for Run III of the LHC. Recent simulations development allowed to have an evaluation of the expected beam loss pattern also in the case of ions collimation, as described in [36]. As shown in [38], a significant improvement of the cleaning performance also with heavy ions beams is expected thanks to the presence of the TCLDs. A refined evaluation of the gain factor is underway using improved simulation tools [39].

CONCLUSION

The baseline collimation layout for the high luminosity upgrade of the LHC was presented. The proposed solutions address satisfactorily the limitations that the present system would impose to the operation at higher stored energy and peak luminosity. While some details of the various upgrades remain to be finalized (coating solutions for IR7 collimators, design of some collimators in the IRs, final material choices), we are confident that the proposed upgrade can be deployed for a successful implementation of HL-LHC.

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ISBN 978-3-95450-147-2