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SETTINGS FOR IMPROVED BETATRON COLLIMATION IN THE FIRST RUN OF THE HIGH LUMINOSITY LHC*

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Abstract

The current betatron collimation system in the LHC is not optimized to absorb off-momentum particles scattered out from the primary collimators. The highest losses are concentrated in the downstream dispersion suppressor (DS). Given the increased beam intensity in the High Luminosity LHC (HL-LHC), there is concern that these losses could risk quenching the superconducting DS magnets. Consequently, a dedicated upgrade of the DS has been studied. However, at this stage, the deployment for the startup of the HL-LHC is uncertain due to delays in the availability of high-field magnets needed to integrate new collimators into the DS. In this paper, we describe the expected collimation setup for the first run of the HL-LHC and explore various techniques to improve the collimation cleaning. These include exploiting the asymmetric response of the two jaws of each primary collimator and adjusting the locally generated dispersion in the collimation insertion.

INTRODUCTION

An efficient control of beam losses is essential in the Large Hadron Collider (LHC) to ensure efficient operation and avoid quenches of the superconducting magnets [1, 2]. For this purpose, two dedicated cleaning insertion regions (IRs) exist in the LHC lattice, the momentum cleaning in IR3 and the betatron cleaning in IR7. In these insertions, a well-defined transverse hierarchy of collimators is deployed to diffuse and absorb the energy carried by the beam halo, before they impact on the superconducting magnets [3–5]. Nevertheless, there is inevitably some leakage of particles from the collimators. The fraction of particles lost in the aperture defines the cleaning efficiency. The majority of leaked particles have large momentum offsets and are immediately lost in the dispersion suppressor (DS), where the first dispersion peaks occur downstream of the IR.

The High Luminosity LHC (HL-LHC) project [6] aims to increase the bunch population from the LHC nominal value of 1.15×10^{11} to 2.3×10^{11} protons. The expected increase of losses in the IR7 DS might induce quenches in the superconducting dipole magnets located there [2]. Thus, it was foreseen to replace one of the main dipole magnets (8.33 T, 14.3 m) by two 11 T dipoles of 5.5 m each, opening up space for a new collimator, TCLD [7]. Their deployment, foreseen for Run 3 (2022-2025) [8], is postponed due to delays in the 11 T dipole production. Their availability for Run 4 (2029-2032) [9], the first run of HL-LHC, is under evaluation. In Run 3, proton intensities reach a maximum of 80 % of the HL-LHC target [10]. For ion beams, the absence of the TCLDs is mitigated by crystal collimators [11–13].

This paper introduces the Run 4 proton baseline scenario. Due to the uncertainty of the TCLD installation, as well as other changes to the operational scenario [14], alternative improvements to the cleaning performance must be explored [15]. In view of this, the effect of increased single pass dispersion and asymmetric collimator jaws is analyzed.

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BASELINE SCENARIO

The Run 4 optics and collimation settings are detailed in [14,15]. A normalized emittance of 2.5 μm rad and a beam energy of 7 TeV are assumed. Due to impedance concerns with the larger bunch population, it was decided to retract the IR7 primary collimators (TCP) by 1.8 σ (σ is the RMS beam size), together with a 1σ retraction of the IR6/7 secondary collimators (TCS), IR7 absorbers (TCLA) and IR1/5 tertiary collimators (TCT) compared to the nominal settings for 15 cm β^* [2]. The design report settings are referred to as "tight settings", while the new proposal is called "relaxed settings". A summary of key settings can be found in Table 1, where the number in the collimator name refers to the IR in which they are located. Note that the TCL/TCT settings in units of σ depend on the β^*.

Table 1: Comparison of some optics parameters and collimator settings between Run 4 [15] (relaxed) and the nominal HL-LHC design [6].

Parameter	Run 4	Design
β^*_{min} [cm]	20	15
bunch population [10^{11} p^+]	2.3	2.3
TCP7 [σ]	8.5	6.7
TCS7 [σ]	10.1	9.1
TCLA7 [σ]	13.7	12.7
TCDQ6 [σ]	11.1	10.1
TCS6 [σ]	11.1	10.1
TCT1/5 [σ] (for β^*_{min})	13.2	10.4
TCL1/5 [σ] (for β^*_{min})	16.4	14.2

Particle losses are simulated in SixTrack [16, 17] coupled to FLUKA [18–21], using optics version HLLHCV1.5 [22]. Losses on the accelerator aperture are binned over the length of the accelerator, in 10 cm long bins. The energy lost into the aperture is normalized to the total energy lost in the collimators, as well as the bin length. Losses are referred to as horizontal or vertical depending on whether their primary impacts are on the horizontal or vertical primary collimators.

A set of simulated loss maps, zoomed into the IR7 region, is shown in Fig. 1, for the β^*=20 cm settings in Table 1: (a)

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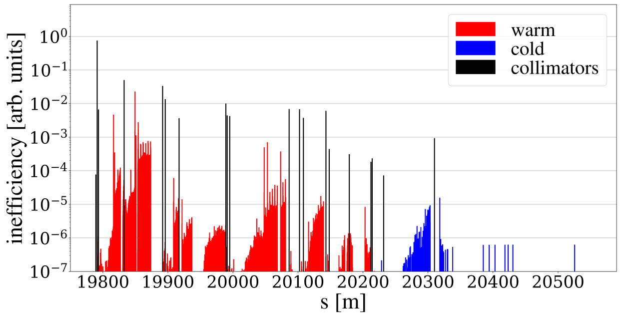
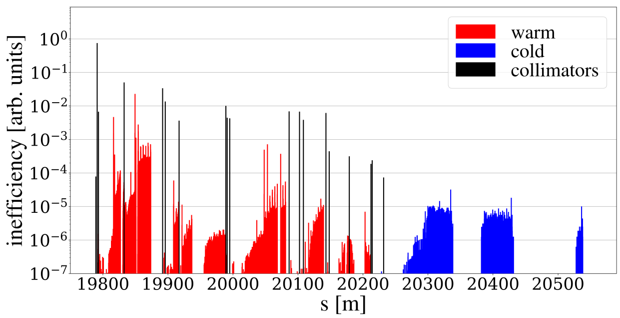
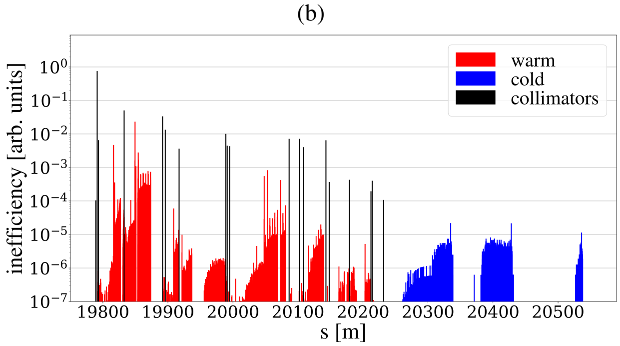


(a)



(b)



(c)

Figure 1: Example loss maps zoomed into IR7 for a few cases. (a) is for relaxed settings including the TCLD at β^*=20 cm, (b) excludes the TCLD and (c) has a dispersive orbit bump and TCLAs offset by 3 σ.

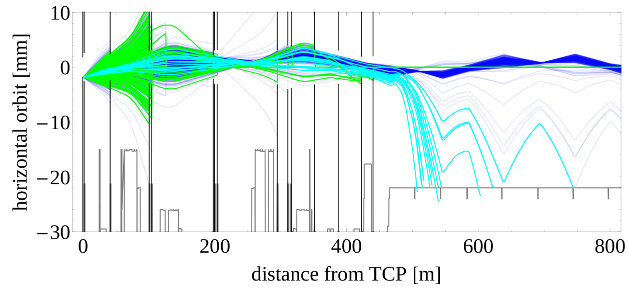
includes the TCLD (nominal, upgraded layouts), while in (b) and (c), the layout without the TCLD is assumed. There are three main loss clusters in the DS (blue). The TCLD cuts the latter two almost completely, while the losses in the first cluster are cut by up to 83 %. The relaxed collimator settings increase the DS losses by 5 %. The goal is to mitigate the worsening as much as possible, for a possible scenario without the TCLD. There is no significant difference for different β^* configurations since the IR7 optics remain unchanged.

CLEANING IMPROVEMENTS WITH EXISTING HARDWARE

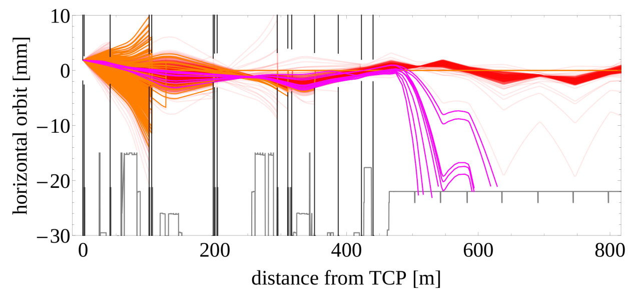
Comparing the cleaning efficiency of the two jaws of the horizontal TCP individually, the positive (left, as seen by the beam) jaw has about a factor of two better efficiency than the negative (right) jaw. This has been demonstrated in measurement using both ion beams [8], and protons [23]. In Fig. 2 the tracks of particles scattered out of the jaws are plotted. The same distribution, mirrored about the horizontal axis, is used in both cases. The tracks are not symmetric around the center and tend towards the negative in the first part. The particles lose energy during their interaction with the TCPs, and their tracks are offset by the single pass dispersion generated by a downstream dipole magnet. Depending on the phase of the betatronic motion, the actual collimator cut of the secondary collimators into the beam is deeper for the particles coming out of the positive jaw. Conversely, there are more particles from the negative jaw that manage to exit the collimation system without being intercepted. These particles have large momentum offsets (mean 6.75 TeV, sigma 0.18 TeV) and are consequently lost in the DS region where the dispersion function starts rising.

From this it is apparent that the cleaning efficiency could be improved by increasing the dispersion. Another possibility is to offset selected collimators. Both methods are explored below.

Dispersion is created by dipole magnets and displaces the trajectories of off-momentum particles. In IR7 there are four horizontal corrector magnets that can be used to create a closed orbit bump of 9.3 mm. The n1 aperture (see definition in [24]) calculation gives a smallest value of 18.9σ which is considered acceptable. The orbit is shown together with the nominal and new single pass dispersion in Fig 3. The maximum absolute single pass dispersion in the right



(a)



(b)

Figure 2: Tracks of particles scattered out of the horizontal primary collimator jaws, (a) for negative jaw and (b) for positive jaw. Blue/Red particles survive, Green/Orange particles would be lost in the DS if not for the secondary collimators, Cyan/Magenta particles leak out and are lost in the DS. Black lines are collimators and gray are the aperture.

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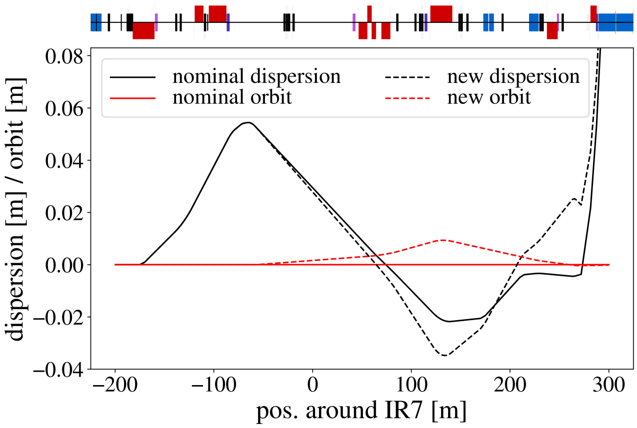

Figure 3: Comparison of the single pass dispersion starting at the primary collimators for the nominal case (solid lines) and the orbit bump (dashed lines).

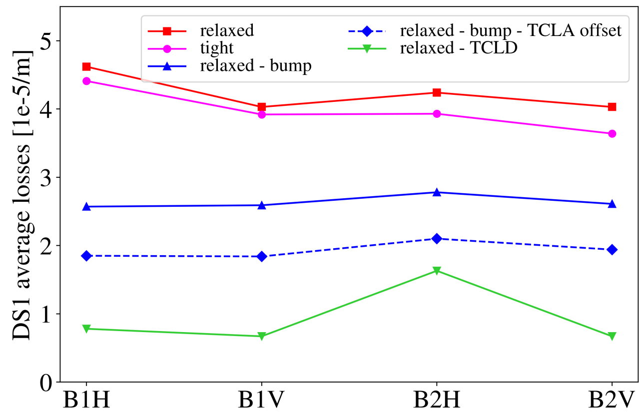

Figure 4: Comparison of the average losses in the first DS cluster for the different scenarios. B1(2) refers to beam 1(2), while H refers to horizontal and V to vertical loss maps.

part is increased from 22 mm to 35 mm at the first peak and from 3 mm to 25 mm at the second peak. This leads to a tightening of the momentum cut at the secondary collimators from approximately 10 % to 7 %. This cut mainly affects particles that would end up in the first loss cluster in the DS.

The TCLA settings can be changed to catch more of the particles that are otherwise lost in the DS. There are however several constraints that must be fulfilled: the collimator hierarchy (TCP-TCS-TCLA) must be respected with margins for optics imperfections [25], the gaps should not be reduced since this increases the impedance [26], and the TCLA must be in the shadow of the dump protection collimator (TCDQ) such that it does not see primary losses during asynchronous beam dumps [27]. For these studies, the TCLA gap was kept constant, while the center of the jaws was shifted horizontally by three sigmas, in the last two collimators. The phase advance from the extraction kicker magnets is such that the beam is displaced in the same direction as the TCLA offset.

A loss map for the case with a TCLA offset of 3 σ and the dispersive orbit bump is shown in Fig. 1c. There is a clear reduction in the first loss cluster, although the second and third clusters are not improved significantly.

DISCUSSION

A summary of the average loss levels in the first DS cluster for the different scenarios is shown in Fig. 4. The dispersive orbit bump can improve the total DS cleaning efficiency by up to 25%, mainly through a cut of losses in the first cluster. Adding an offset of 3 σ to the final horizontal TCLAs provides a further improvement, reaching a 35 % cut compared to the nominal relaxed settings. To catch the losses in the second and third clusters, where the momentum offset of the lost particles is smaller (average of 1.4 % instead of 5.1 %), one would need larger orbit bumps or collimator offsets than compatible with the aperture and collimation hierarchy.

The first DS cluster is under normal conditions the one with the largest losses, making it the most critical. The losses integrated over this cluster can be reduced to levels about a factor of two larger than would be achieved through the installation of the TCLD. However, the 11T dipoles are expected to have a larger quench limit than the standard dipoles [28]. Care has to be taken that the aperture is protected in presence of the orbit bump and that the TCDQ to TCLA hierarchy is not affected for asynchronous beam dumps. Otherwise these methods are achievable in operation without major impact and show potential for dealing with a possible lack of TCLDs in Run 4.

The collimator performance can still be optimized further by also increasing the beta functions at the TCPs, as studied in [29], which both increases the normalized kicks on the scattered particles, and the single pass dispersion in IR7.

CONCLUSIONS

The consequences on the collimation cleaning performance with proton beams due to the new baseline for HL-LHC Run 4 were presented. The required relaxed collimator settings lead to a worsening of the local cleaning efficiency by up to 8 %. It is uncertain whether or not the TCLD in IR7 can be installed due to the potential unavailability of 11T dipoles – if not, there is a further worsening by about a factor of ten. The betatron losses are mainly due to particles with large momentum offsets. Consequently, orbit bumps that increase the single pass dispersion at the collimators can partially mitigate this increase. Offsetting some of the collimators around the beam axis can help further. Combining the two techniques, an improvement by up to 35 % in the total DS losses was achieved in simulations.

Previous estimates [2] indicate that the dipoles in IR7 are close to the quench limit. With the 35 % reduction demonstrated in this paper, pending a final assessment through energy deposition simulations and measurements in the LHC, especially of the peak losses, there is good hope that there will be sufficient margin.

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