COLLIMATOR LAYOUTS FOR HL-LHC IN THE EXPERIMENTAL INSERTIONS*

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Abstract

This paper presents the layout of collimators for HL-LHC in the experimental insertions. On the incoming beam, we propose to install additional tertiary collimators to protect potential new aperture bottlenecks in cells 4 and 5, which in addition reduce the experimental background. For the outgoing beam, the layout of the present LHC with three physics debris absorbers gives sufficient protection for high-luminosity proton operation. However, collisional processes for heavy ions cause localized beam losses with the potential to quench magnets. To alleviate these losses, an installation of dispersion suppressor collimators is proposed.

INTRODUCTION

It is planned to upgrade the CERN Large Hadron Collider (LHC) [1] to the High-Luminosity LHC (HL-LHC) [2, 3] after about 10 years of operation. The main goal of the upgrade is to achieve an integrated proton luminosity of about 3000 fb^{-1} over a decade at each of the high-luminosity experiments ATLAS and CMS. For this goal, it is needed to operate with a yearly luminosity production that is more than an order of magnitude higher than in the first LHC run [4]. This can be made possible by using beams with higher intensity and lower emittance, as well as smaller β-functions (15 cm, to be compared with the nominal 55 cm) at the interaction points (IPs).

In its nominal proton configuration, the LHC operates with beams at an unprecedented energy of 7 TeV with a total stored beam energy of about 362 MJ per beam. The two beams are guided by superconducting magnets, which risk to quench if just a tiny fraction of the full beam is lost locally. In order to protect the cold magnets, a multi-stage collimation system has been installed [1, 5, 6]. The collimators are mainly installed in the insertion regions (IRs) called IR3 (momentum cleaning) and IR7 (betatron cleaning). However, there are also collimators installed around the IPs: Tertiary collimators (TCTs) provide local protection on the incoming beam, and physics debris absorbers (TCLs) are installed on the outgoing beam to intercept collision products.

The HL-LHC poses new challenges for the collimation system. The total stored energy will increase to about 700 MJ per beam (2.2×10^{11} protons per bunch), and the higher luminosity causes a higher rate of collision debris. Furthermore, major upgrades and layout changes are foreseen in the experimental IRs. As an example, the layout around ATLAS, in IR1, is shown in Fig. 1 for both the first LHC run in 2010–2013 (Run 1) and for HL-LHC. Most notably, in order to allow a very small $\beta^* = 15$ cm, new large-aperture inner triplet quadrupoles will be installed, and the novel ATS optics scheme [7] will be deployed. The layout at CMS, in IR5, is identical.

Apart from protons, the LHC operates also a shorter period every year with heavy ions (mainly Pb^{82+}). Physical processes in the collisions, specific to heavy ions, create secondary beams with altered magnetic rigidity that are lost in very localized spots, where they risk to quench magnets [8,9]. This could become critical in HL-LHC with an upgraded heavy-ion luminosity.

It is crucial to ensure that the HL-LHC is well protected by its collimation system during both proton and heavy-ion operation. This article investigates the local protection around the experiments and the need for upgrades. The global performance of the IR3 and IR7 beam cleaning system is discussed elsewhere [10, 11].

INCOMING BEAM

In the present LHC, a pair of TCTs (called TCT4), consisting of one horizontal and one vertical collimator, is installed in cell 4 on the incoming beam in front of each experiment. They should protect the local aperture bottlenecks that arise in the triplets in cells 1–3, when β^* is squeezed to small values, from both unavoidable losses during regular operation and accidental losses during beam failures, in particular asynchronous beam dumps. They should also decrease the experimental background [12]. All these aspects have to be verified for HL-LHC.

In HL-LHC, with $\beta^* = 15$ cm using ATS optics [7, 13], the critical aperture bottlenecks to be protected are no longer necessarily only in the triplet [14], which will be replaced to have a significantly larger aperture. The β-functions upstream of the TCT4 will also be significantly larger than in the nominal configuration, which could potentially introduce new bottlenecks, in particular in cells 4–5. If significant losses would be expected there, additional protection should be considered. This can be achieved by the installation of an additional pair of TCTs in cell 5, called TCT5, which should protect cells 4–5.

To assess the need of local protection in the experimental IRs in case of asynchronous beam dumps, we use SixTrack [15, 16] to simulate the losses around the LHC with the same method as in Refs. [17, 18]. We use the HL-LHC lattice version 1.0 [19] with baseline collimator settings [20]. Initial studies without any TCTs in the experimental IRs

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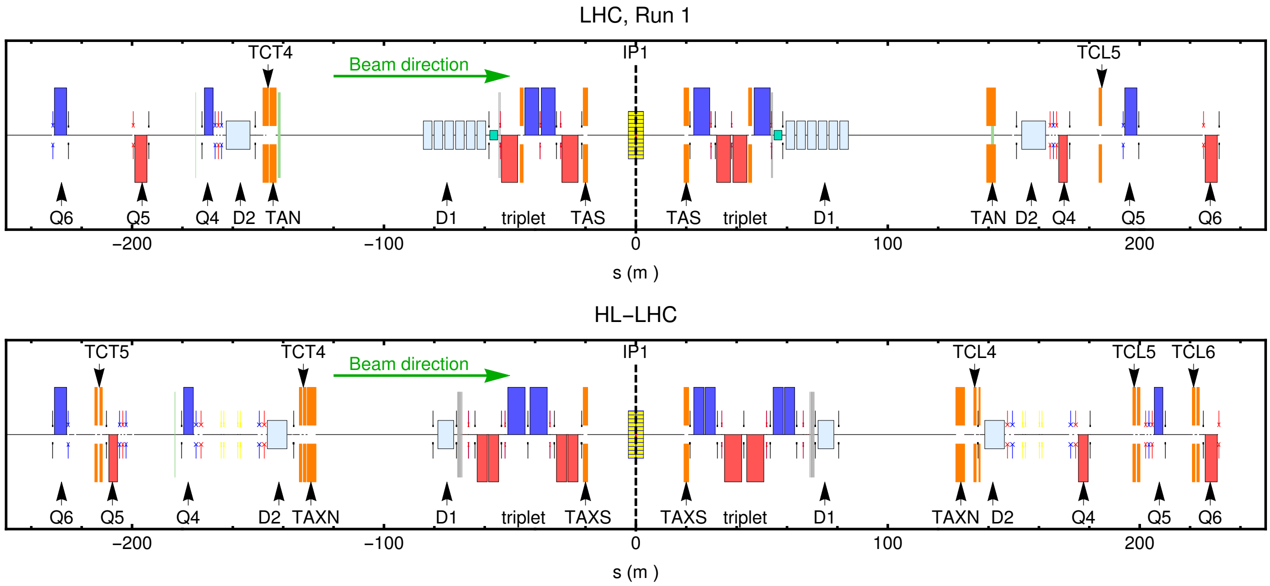

Figure 1: Layout of IR1, around the ATLAS experiment at $s = 0$, in the LHC during its first run 2010–2013 (top) and in HL-LHC (bottom) for B1, going from left to right. Collimators and fixed absorbers are indicated by orange color.

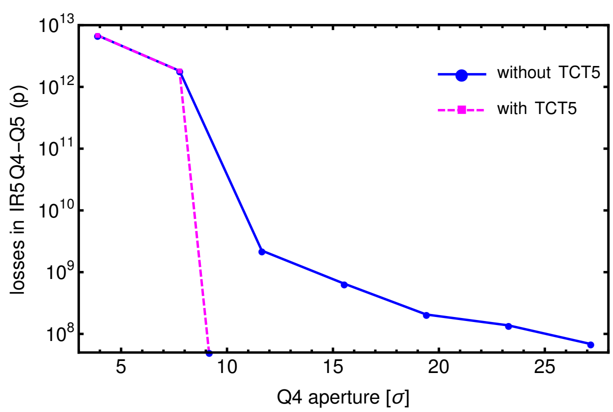

Figure 2: Integrated beam losses in the Q4 and Q5 magnets in IR5, beam 2, during asynchronous beam dumps, as a function of their normalized aperture. Results are shown with and without the TCT5, which was positioned at 10.5 σ.

show significant losses on the triplets, and smaller losses on Q4 and Q5, even with the perfect machine aperture and the dump protection collimators at their perfect position. If the IR aperture is artificially reduced to mimic various imperfections, a corresponding increase in losses is observed. It should be noted that apertures down to 12 σ are allowed [20]. As an example, the integrated losses in the quadrupoles in cells 4–5, Q4 and Q5, are shown in Fig. 2. It can also be seen that the introduction of the TCT5 in the simulation, upstream of Q4-Q5, efficiently cures all losses there as long as the normalized TCT aperture is smaller than the apertures it should protect. The same holds for the triplet.

Furthermore, we study losses from collimation cleaning in the experimental IRs, also using SixTrack. The simulation method used is identical to the one described in Ref. [21] and the detailed results are discussed in Ref. [22]. Figure 3 shows as example the integrated losses in the triplets in IR1 and IR5 during a scan over a range of TCT settings (using both TCT4 and TCT5), and assuming initial horizontal beam losses on the primary collimators (TCP) in IR7. Nominal collimator settings are used. The apertures in the triplet, Q4, and Q5, were artificially reduced to 8.7 σ, in order to study a very pessimistic machine configuration with apertures close to the LHC design TCT setting at 8.3 σ. The simulations were normalized to a beam lifetime of 12 minutes, which is the minimum specified for the collimation system [1]. For HL-LHC, it corresponds to an instantaneous loss rate on the IR7 TCP of 8.6×10^{11} protons/s.

It can be seen that, for this worst-case scenario, the triplet receives significant losses as long as its aperture is smaller than the TCT opening—it should be noted that the 7 TeV quench limit assumed for the design of the LHC is about 5.4×10^{6} protons/s for local losses [23], although this is known today to be pessimistic. However, if the TCTs are more than about 0.5 σ closer to the beam than the triplet aperture, all losses are efficiently blocked. The same holds for the losses in Q4 and Q5. This retraction comes from the fact that each TCT collimates in a single plane, while the triplet losses are sometimes caused by particles having non-negligible offsets in both transverse planes. As the beam screen is octagonal, the combination of horizontal and vertical excursions can cause a particle to be lost at the triplet, even though the normalized aperture in the collimation plane is larger at the triplet than at the TCTs.

It should be noted that particles in SixTrack are only tracked until they undergo an inelastic interaction in a collimator. However, when halo protons hit the TCTs, nuclear and electromagnetic showers develop. Some secondary particles even reach the experimental detectors, where they

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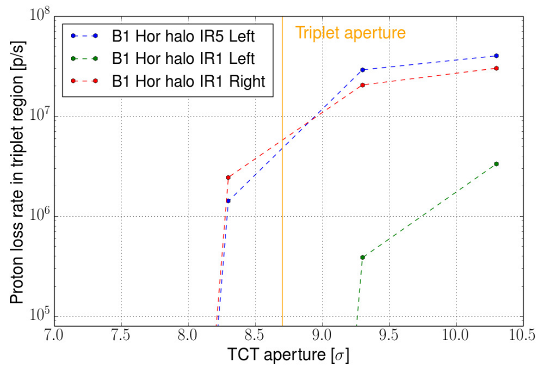

Figure 3: Integrated cleaning losses in the triplets, simulated with SixTrack, as a function of the TCT setting for HL-LHC with nominal collimator settings. The triplet apertures were simultaneously reduced to 8.7 σ and no losses were observed right of IR5. The LHC design quench limit, which now is known to be pessimistic, is at 5.4×10^6 p/s.

cause background [12]. The addition of the TCT5 could help in significantly reducing this background component. This is discussed in detail in Ref. [24].

The TCT5 is thus beneficial both for passive protection, cleaning, and background reduction, and it has now been added to the HL-LHC baseline. This can be seen in Fig. 1, where the TCT5 is found about 210 m upstream of the IP.

OUTGOING BEAM

The collimators on the outgoing beams, downstream of the experiments, should intercept both scattered primary beam particles and secondary particles created by the collisions, in order to protect the magnets downstream. In Run 1, this was done by a single horizontal collimator in cell 5, called TCL5, in IR1 and IR5. No physics debris collimators were installed at the low-luminosity experiments in IR2 and IR8.

For Run 2, starting in 2015, the collimation system in IR1 and IR5 has been upgraded with additional TCLs in cells 4 and 6, in order to cope with the expected higher luminosities and requirements from forward-physics experiments. Energy deposition studies [25] have shown that the Run 2 layout with three TCLs should provide sufficient protection against luminosity debris also for proton operation in HL-LHC, provided the TCL4 is upgraded to have thicker jaws. This layout is shown in Fig. 1.

Collisional losses for heavy ions have to be treated separately, as different physical processes determine the dominant losses [8, 9]. Ultra-peripheral electromagnetic interactions, which change the magnetic rigidity of the incoming ions, take place when the impact parameter is larger than the nuclear diameter. The dominant process is bound-free pair production (BFPP), where an ion acquires one (BFPP1) or two (BFPP2) extra electron, thus changing its charge. A large variety of electromagnetic dissociation processes is also possible, where the most common ones are a loss of one (EMD1) or two (EMD2) neutrons. These secondary beams are shown in Fig. 4.

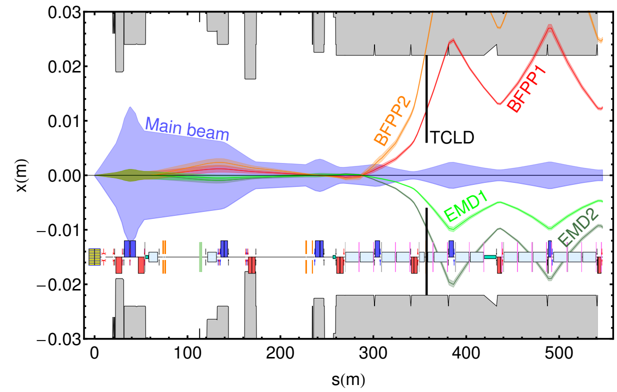

Figure 4: Secondary horizontal beam envelopes with changed magnetic rigidity emerging from IR2, shown together with the aperture and the main beam. The BFPP1 beam is the most intense, followed by EMD1 and EMD2. The BFPP2 beam is very weak and poses no danger of quenching magnets. A TCLD collimator installed in the position indicated by the black line around s = 360 m can intercept the most dangerous beams.

Because of their different charge, ions that have undergone BFPP or EMD can be lost on the aperture if the dispersion is large enough, potentially in a very localized spot. The induced heating risks to quench the impacted magnet—energy deposition studies [26] show that, if the ALICE luminosity is upgraded as foreseen by a factor 6 to 6×10^{27} cm^{-2}s^{-1}, the induced heat load could be a factor 2 above recent estimates of the quench limit [27].

It is therefore planned to reduce these losses with an additional horizontal collimator, called TCLD, in cell 10 in the dispersion suppressor on each side of IR2 [28], as shown in Fig. 4. This is similar to what is planned for IR7 [10, 11], where an existing main dipole is replaced by two shorter 11 T dipoles, which create space for a collimator. Alternative alleviation methods using orbit bumps are also under study [29].

Presently it is foreseen to install TCLDs only in IR2. They may also be needed in IR1 and IR5 where heavy-ion luminosities will be similar but the losses more manageable because of differences in the optics.

CONCLUSIONS

We have evaluated the expected regular and accidental beam losses in the experimental IRs for HL-LHC. Simulation studies have shown that it is very beneficial for the protection of the cold magnets to install an extra pair of TCTs in cell 5 on the incoming beams in IR1 and IR5. On the outgoing beam in IR1 and IR5, the HL-LHC keeps the Run 2 layout, including three TCLs. For heavy-ion operation, with an upgraded luminosity in IR2, a TCLD is needed to intercept secondary beams with changed magnetic rigidity.

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