ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-TUC4C2

MITIGATING COLLIMATION IMPEDANCE AND IMPROVING HALO CLEANING WITH NEW OPTICS AND SETTINGS STRATEGY OF THE HL-LHC BETATRON COLLIMATION SYSTEM*

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Abstract

With High Luminosity Large Hadron Collider (HL-LHC) beam intensities, there are concerns that the beam losses in the dispersion suppressors around the betatron cleaning insertion might exceed the quench limits. Furthermore, to maximize the beam lifetime it is important to reduce the impedance as much as possible. The collimators constitute one of the main sources of impedance in HL-LHC, given the need to operate with small collimator gaps. To improve this, a new optics was developed which increases the beta function in the collimation area, as well as the single pass dispersion from the primary collimators to the downstream shower absorbers. Other possible improvements from orbit bumps, to further enhance the locally generated dispersion, and from asymmetric collimator settings were also studied. The new solutions were partially tested with 6.8 TeV beams at the LHC in a dedicated machine experiment in 2022. In this paper, the new performance is reviewed and prospects for future operational deployment are discussed.

INTRODUCTION

Efficient management of beam losses is crucial for the effective functioning of the Large Hadron Collider (LHC) and to prevent the superconducting magnets from quenching [1, 2]. In order to achieve this, the LHC lattice includes two specialized cleaning insertion regions (IRs), namely the momentum cleaning in IR3 and the betatron cleaning in IR7. The deployment of a well-defined multi-stage transverse hierarchy of collimators in these IRs is intended to disperse and absorb the energy carried by the beam halo, thus avoiding any impact on the superconducting magnets [3–5]. However, there is inevitably some leakage of particles from the collimators. Of concern are leaked particles with large momentum offsets since they are lost in the dispersion suppressor (DS) downstream of the IR, where the first dispersion peaks occur.

The primary objective of the High Luminosity LHC (HL-LHC) project [6] is to double the bunch population from 1.15×10^{11} to 2.3×10^{11} protons. For the same loss assumptions, this will produce higher DS losses that may trigger quenches in the superconducting dipole magnets situated in that region [2]. To address this issue, the collimation upgrade baseline planned to substitute one of the main dipole magnets with two shorter 11T dipoles to create space in the DS for the installation of a new collimator, TCLD [7]. The implementation of these changes has been descoped due to delays in the production of the 11 T dipoles [8].

The latest beam-based assessment of collimation performance and quench limit of the most exposed DS magnets indicate that the present performance is compatible with the HL-LHC proton beam parameters [9]. Nevertheless, to minimize any uncertainty, alternative strategies to mitigate the losses in the IR7 DS are studied. New optics were developed for this purpose similar to those proposed in Ref. [10]. These optics increase the beta function at the primary collimators, as well as the single-pass dispersion from the primary to the secondary collimators and absorbers. Both of these changes reduce the fraction of particles leaking into the DS. Other mitigation methods using orbit bumps and special collimator setups were explored in Ref. [11].

Another concern for the HL-LHC is that the increased bunch brightness might trigger beam instabilities [12], in particular given recent results on the crab cavity impedance [13]. To maximize beam lifetime it is important to reduce the impedance as much as possible, and one of the main sources of impedance is the collimators [14]. With the increased beta functions of the new optics, the physical gaps of the collimators are increased. This reduces their impedance contribution, while ensuring the same collimation hierarchy.

A dedicated beam experiment in the LHC in 2022 aimed to test the new optics and the alternative mitigation methods. The initial results are summarized in this paper, and the prospects for future operational deployment are discussed.

OPTICS DESIGN AND COLLIMATION SETUP

The IR7 optics were rematched such that the beta functions in the primary and secondary collimators were maximized and the single pass dispersion from the primary collimators to the absorbers was increased. Matching of $(\beta_x, \beta_y, \alpha_x, \alpha_y, \mu_x, \mu_y, D_x, D_{px})$ at the start and end of IR7 was done to ensure that the optics change only had a local effect. The resulting optics are shown in Fig. 1.

Collimator Cuts

When protons impact one of the primary collimators, a certain fraction of them scatter out. These protons generally receive transverse kicks, as well as a loss of momentum. Downstream secondary and absorber collimators are designed to dispose of the largest fraction of this halo in the multi-turn beam dynamics [15], such that most of their energy can be dispersed in the warm section of IR7. A

* Work supported by the High Luminosity LHC project

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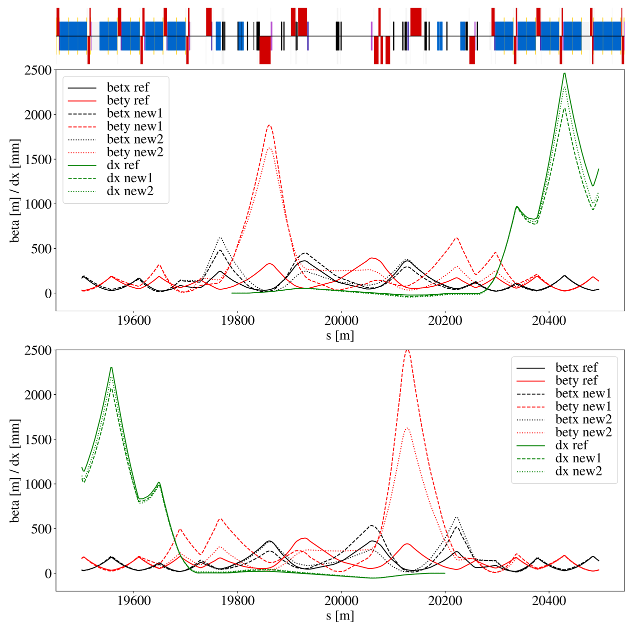

Figure 1: Comparison of new optics used in experiment (dashed lines), new optics proposed for HL-LHC (dotted lines) and nominal optics (solid lines) in IR7.

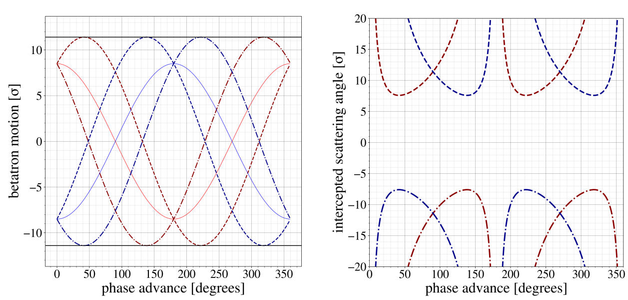

Figure 2: (left) betatron motion of particles scattered by the primary collimator jaws (right) minimum scattering angle required to be intercepted by secondary collimator depending on phase for the four cases shown in (left).

certain fraction of particles losing momentum due to single-diffractive scattering can by-pass the secondary collimators if they do not receive enough transverse kicks. These particles impact the superconducting magnets in the DS.

Figure 2 shows the normalized transverse amplitude as a function of the phase for particles scattered out of the jaws of one of the primary collimator. There are two jaws, and particles can be kicked positively or negatively, leading to four distinct cases (only looking at one dimension here). In the figure, the four particles are kicked with an amplitude such that they just reach the jaws of the secondary collimator (black lines) at the locations of optimum phase advance. The required minimum kick to reach the necessary amplitude can be calculated from [15]:

$$K_c = s_1 \frac{n_2}{sin(\mu)} - s_2 \frac{n_1}{tan(\mu)}$$

where n_1 and n_2 are the primary and secondary collimator settings in units of σ, μ the phase advance from the primary to the secondary collimator, s_1 the sign of the kick and s_2 the sign of the transverse position of the jaw. This minimum kick is shown in Fig. 2. By placing the collimators close to the optimal phase advances, the cuts can be minimized, which should limit the leakage. There are however a couple of complications, (i) the particles that leak to the DS have large δ (up to tens of ‰) (ii) the small dispersion introduced by the dogleg dipoles shifts the cut of horizontal and skew collimators such that one jaw effectively has a tighter setting, and vice versa.

The new optics minimizes the cuts of the secondary collimators in two ways; the beta function at the primary collimators is increased such that the normalized kicks on the out-scattered particles are increased. A larger fraction of particles are thus intercepted. Secondly, the single pass dispersion is increased. If the beta function squared increases less than the dispersion, the momentum cut is reduced and more particles are intercepted. Care has to be taken if, for example, the dispersion peak is around a phase of 180°, the two orbits on one side (negative or positive) are intercepted more deeply, decreasing the leakage. Conversely, the other two orbits see a shallower cut, increasing the leakage. If the dispersion is increased by too much, it can lead to an increased net leakage to the DS.

EXPERIMENT

The experiment was split into two parts; one focused on setting up the new optics, and one dedicated to the measurement of the collimation cleaning performance and impedance. The measurements were planned to be done in a few different configurations, by combining the optics proposed in Ref. [10] and the methods proposed in Ref. [11]: (i) nominal optics and settings for reference (ii) new optics, nominal collimator settings (iii) new optics with orbit bump for increased dispersion, nominal collimator settings (iv) new optics with orbit bump and asymmetric TCLA settings (v) new optics with single-sided collimator jaws for reduced impedance.

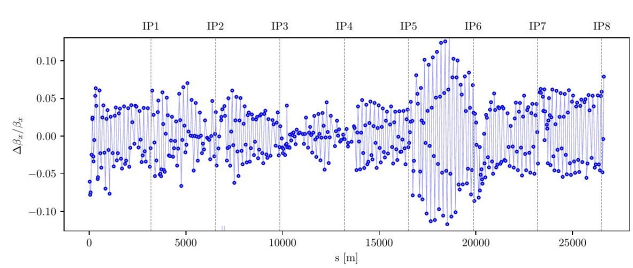

Figure 3: Optics measurement, Beam 1, worst plane.

Optics Setup

For the first part, three bunches of 1×10^{10} ppb were injected in each beam and accelerated to top energy (6.8 TeV). Next, the transition to the new optics was deployed. To en-

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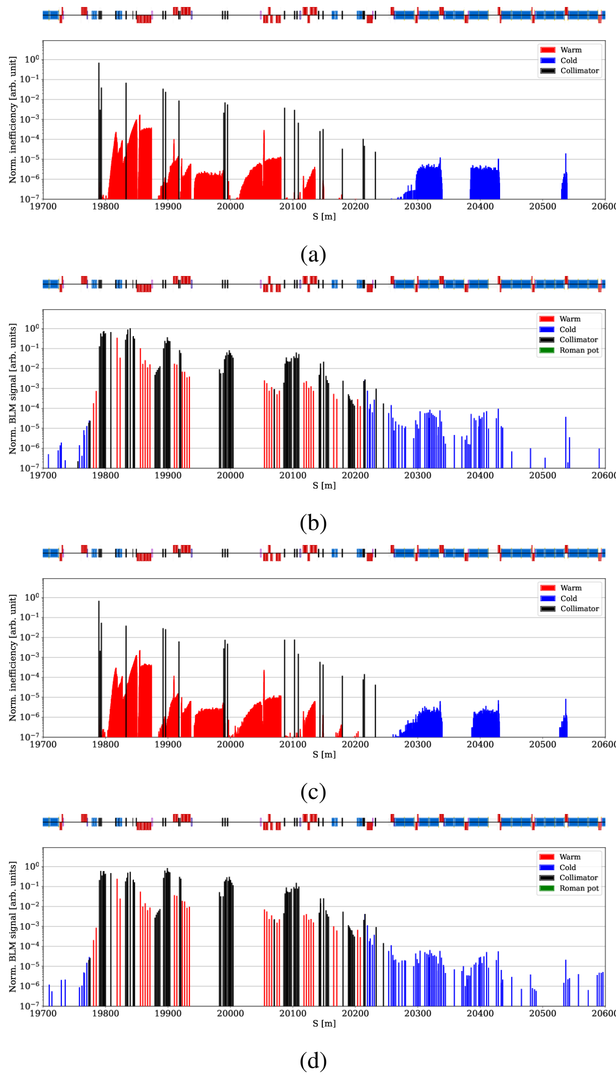

Figure 4: Beam 1 vertical loss maps comparing nominal optics (a)/(b) to new optics (c)/(d) for both simulations and measurements. The three critical cold DS clusters are easily seen in the simulated loss maps.

sure a good transition, ten matched intermediate steps were used, with an estimated maximum transient beta beating of 1%. Once the final step was reached, the new optics were measured using the AC dipole [16, 17], which provides coherent transverse kicks on the full beam. The maximum beta beating measured was 13%, whereas around IP7 it stayed below 7% (see Fig. 3). No optics corrections were deemed necessary in this condition. The collimators in IR7 were not realigned due to a lack of time, although no significant orbit deviations were observed on the collimator button BPMs.

Cleaning Performance

For the second part of the experiment, the beams were dumped and new beams were injected. A total of 16 bunches with 1×10^{10} ppb, as well as one bunch with 1.5×10^{11} were injected into Beam 1. Due to an unrelated issue at injection, Beam 2 had to be cut out of the program. The configurations with orbit bump, asymmetric TCLA settings and single-sided collimator jaws also had to be left out due to severe time delays. In the end only the vertical plane of Beam 1 could be measured with the new optics. The cleaning performance was measured using a white-noise excitation of the transverse damper (ADT [18]) on a specific bunch. This increases the emittance such that particles are lost from the beam core and, by design, impact the primary collimators. The beam losses are then measured throughout the length of the ring by approximately 4000 ionization chamber beam loss monitors (ICBLMs) [19]. The individual BLM signals are then normalized by the total signal of the collimator BLMs.

The expected cleaning performance was simulated in SixTrack-FLUKA [20–25]. Figure 4 shows a comparison of the losses under normal conditions to the new optics, as measurements and simulations. The absolute loss levels differ between simulations and measurements, since the full particle showers are not simulated [26]. In the DS most of the lost energy comes from protons with a δ up to about 15%, which are tracked in the simulations. For absolute power deposition simulations, detailed FLUKA studies are necessary [27]. Empirically it has been shown [26] that comparing relative changes in DS losses between different configurations is quantitatively comparable to measurements.

From the simulations it is expected to see a reduction of the peak losses in the first, second and third clusters by a factor of 0.58, 0.62 and 0.35, respectively. In the measurements, the reduction factors were 0.64, 0.72 and 0.47.

To estimate the significance of the observed reduction, three repeated loss maps were done in a separate fill with 2023 flat top optics and collimator settings [28]. For each DS cluster, the mean of the peak losses over the three measurements was calculated. The measured ranges around these means were 0.99–1.02, 0.90–1.06 and 0.88–1.09, for clusters 1, 2 and 3 respectively. While a statistical analysis is not possible on the limited set of data, it seems likely that the measured reduction factors are due to the new optics. The agreement is better on the first cluster, which is also consistent with the fluctuations observed in the repeated loss maps. Furthermore, a set of ten loss maps were done at different stages of the cycle in 2023 at top energy, where the cleaning performance is expected to remain stable [29]. The standard deviation of the peak losses in those measurements was 5.2 %, hence the measured reduction factors are significant and compatible with the simulated values.

Impedance

Impedance is measured by applying small kicks with the ADT on two different bunches of different intensity. The relative tune shift between the two bunches can then be used to calculate the impedance [30]. The vertical impedance has the smallest reduction, by 10 % with the new optics. Also including the effect of the single-sided jaws, it decreases by 20 %. The expected horizontal tune shifts are 1.2×10^{-4} and 2.4×10^{-4} in the two different configurations, while the vertical tune shift is about a factor of two smaller. No measurements could be done due to the time constraints.

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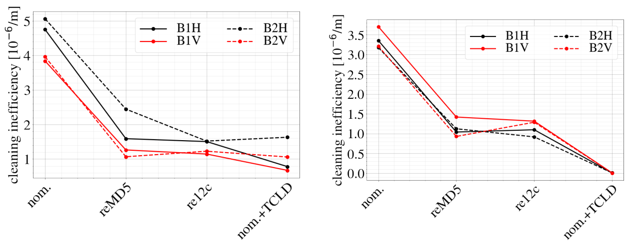

Figure 5: Average losses in the first (left) and second (right) DS clusters for horizontal (H) and vertical (V) loss maps, both beams. *reMD5* are the experiment optics, while *re12c* are the further improved optics for HL-LHC.

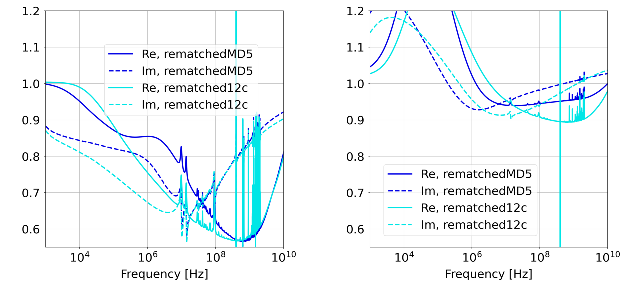

Figure 6: Comparison of the ratio of impedance in the new optics to the nominal optics, horizontal (left) and vertical (right). *reMD5* are the optics used in the experiment, while *re12c* are the further improved optics for HL-LHC.

HLLHCV1.6 OPTICS

Given the promising results from the simulations, which are now supported to some extent by measurements, it is planned to deploy the optics in the HLLHCV1.6 baseline [31]. Using the Xsuite optimizer package [32], a few changes were implemented to improve upon the experiment optics: (i) the peak beta function was reduced to increase aperture margins and to limit the effect of field errors in the warm quadrupoles (ii) the TCP beta functions were increased further, up to about 368 m, to increase the normalized kicks (iii) the absolute dispersion at the second dispersion peak was increased from 3.6 cm to 4.5 cm to better absorb the off-momentum particles (iv) the phase advance constraint over the IR was removed to provide more freedom in the matching, it will be compensated elsewhere in the ring (v) the vertical beta function towards the end of the IR was reduced since it significantly increased the vertical impedance in the horizontal TCLAs. The optics are shown in Fig. 1.

Figure 5 shows a comparison of the average DS losses in the first two clusters for the optics used in the experiment, adjusted for HL-LHC (*reMD5*), and the new version (*re12c*). The nominal optics as well as nominal optics with the TCLD are also shown. The *re12c* optics have an improved performance, more consistent between the planes and the beams. The peak losses are also improved, down from 1.75×10^{-5} in *reMD5* optics to 1.1×10^{-5} in the new version. For the first DS cluster, this performance is as good as the nominal optics with TCLD, and the peak losses are up to 60 % lower.

Concerning the impedance, a comparison of the total impedance in the whole ring is shown for the different optics in Fig. 6. The horizontal impedance shows a significant improvement by almost a factor of two in the region of interest around 1 GHz. The vertical improvement is smaller, at about 10 %. The reason for this small improvement comes from a collimator in the momentum cleaning insertion that produces about as much vertical impedance as all collimators in IR7 combined. This collimator has a small horizontal beta function in order to keep a large normalized dispersion for the momentum cleaning. The vertical beta function is therefore large, at 395 m. An attempt to reduce this vertical beta function, without adversely affecting the IR3 optics as a whole, is ongoing. The octupole threshold has been calculated assuming bunch intensities of 2.3×10^{11} p^+ over a range of chromaticities from 0-20. The maximum H/V threshold in Beam 1 is 434/397 A, 343/392 A, 340/382 A for the nominal, *reMD5* and *re12c* optics, respectively. The values are similar for Beam 2. If the vertical beta function of the collimator in IR3 can be reduced, it is expected that the vertical octupole threshold could be reduced to similar values as the horizontal threshold.

CONCLUSIONS

The absence of TCLD collimators in HL-LHC, as well as concerns about the crab cavity and collimator impedance, motivated the study of an improved IR7 optics. The optics were redesigned, and the simulations show promise both in terms of cleaning performance and impedance. The improved cleaning performance is on a similar level to that of normal optics together with the TCLD, and should be confirmed with energy deposition studies in FLUKA. Furthermore, the impedance reduction decreases the octupole threshold by 100 A in the horizontal and 18 A in the vertical plane, increasing the beam lifetime. Further reductions of vertical impedance are being investigated.

A version of the optics was tested in a dedicated experiment in the LHC in 2022, although only the cleaning performance for one beam and one plane could be measured. The results are consistent with the simulations, providing strong confidence in the estimates for the optimized HL-LHC performance, and the optics is foreseen to be implemented into the HLLHCV1.6 baseline. Nevertheless, further measurements are planned to definitively confirm the benefits, before relying on this optics for HL-LHC. The alternative strategies that were originally planned for the experiment should also be investigated in future beam tests, to provide more room for mitigation in case of need.

ACKNOWLEDGMENTS

We would like to thank S. Fartoukh for very useful discussions on the optics design, M. Solfaroli for the implementation of the optics in the machine, the OMC team for the optics measurements and the MD coordinators for their strong support of the experiment.

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