ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB006

OPTICS CONFIGURATIONS FOR IMPROVED MACHINE IMPEDANCE AND CLEANING PERFORMANCE OF A MULTI-STAGE COLLIMATION INSERTION

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Abstract

For a two-stage collimation system, the betatron phase advance between the primary and secondary stages is usually set to maximise the absorption of secondary particles outscattered from the primary. Another constraint is the contribution to the ring impedance of the collimation system, which can be decreased through an optimized insertion optics, featuring large values of the beta functions. In this article we report on first studies of such an optics for the CERN Large Hadron Collider (LHC). In addition to a gain in impedance, we show that the cleaning efficiency can be improved thanks to the large beta functions, even though the phase advance is not set at the theoretical optimum.

INTRODUCTION

An efficient beam-cleaning system is needed in any high-energy and high-intensity superconducting circular hadron collider in order to protect the machine from harmful beam losses, which can cause quenches of superconducting magnets or even material damage. Typically, a multi-stage collimation system is needed, as is the case at the CERN LHC [1], where a total of about 100 collimators are installed around the ring [2–6]. In order to ensure a good robustness to beam impacts, primary (TCP) and secondary (TCS) collimators are typically made of carbon-based materials, which do not have a good electric conductivity. Therefore, the impedance of the collimation system can become a serious limitation for beam stability and hence for the performance reach [7].

The collimator impedance in the transverse planes (x, y) scales with the coefficients

$$k_x = L\frac{\beta_x\left(\cos^2\psi + \frac{\sin^2\psi}{2}\right)}{n^3\sigma^3}, \qquad k_y = L\frac{\beta_y\left(\sin^2\psi + \frac{\cos^2\psi}{2}\right)}{n^3\sigma^3}. \tag{1}$$

Here L is the length of the collimator, β_u the optical function in plane u, and ψ is the angle of the collimator in the $x-y$–plane (defined such that a horizontal collimator has $\psi = 0$ and a vertical one has $\psi = \pi/2$). Furthermore, n is the half opening in units of the local RMS beam size $\sigma = \sqrt{\varepsilon\left(\beta_x\cos^2\psi + \beta_y\sin^2\psi\right)}$ in the collimation plane, and ε the geometric emittance. The impedance is minimized if the β-function in the collimation plane is maximized while β in the orthogonal one is minimized, although the latter dependence is weaker. It is thus clear that the optics can strongly influence the collimator impedance, and that a cleverly-designed optics might be used to decreased it.

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OPTICS INFLUENCE ON BEAM CLEANING

The optics of the cleaning insertion can also strongly influence the cleaning performance. When matching an optics for a two-stage cleaning system, the phase advances $\Delta\theta$ between primary and secondary collimators are typically selected as close as possible to a theoretical optimum θ_{opt}, derived for example in [8]:

$$\Delta\theta_{\text{opt}} = \arctan\frac{\sqrt{n_2^2 - n_1^2}}{n_1}, \tag{2}$$

where n_1 and n_2 are the normalized openings of the TCP and TCS, respectively. At this optimum phase, the cut of the TCSs on the scattering angle experienced by a particle in the TCP is minimized in *normalized* coordinates. Since the cut can never go down to zero, there will always be a certain amount of particles with smaller scattering angles that can still pass the TCS.

It should be noted that Eq. (2) optimizes the cut on the *normalized* scattering angle ΔP, given by

$$\Delta P = \Delta\phi\sqrt{\beta_{\text{TCP}}/\epsilon}, \tag{3}$$

with $\Delta\phi$ being the physical angular kick, and β_{TCP} the β function at the primary collimator. Equation (3) shows that for a given $\Delta\phi$, which is determined by the physical interaction in the material and hence cannot be changed, ΔP can be altered by changing β_{TCP}. If β_{TCP} is increased, a larger ΔP is obtained, thus increasing the normalized amplitude at the TCS. The optics can thus influence the cut on the *physical* scattering angles not only through $\Delta\theta$ but also through β_{TCP}.

To find an optics that maximizes the TCS cut into the $\Delta\phi$ distribution, we can thus impose conditions also on β_{TCP}, in addition to the well-known method to match $\Delta\theta$ as close as possible to Eq. (2).

This is illustrated in Fig. 1, which shows an example of the cut on $\Delta\phi$ as a function of $\Delta\theta$, using typical numerical values from the LHC obtained by transforming the equations in [8]. As can be seen, increasing β_{TCP} can substantially reduce the cut on $\Delta\phi$, which is also rather flat around the optimum $\Delta\theta$, especially for the larger β_{TCP}-values. Often a smaller $\Delta\phi$-cut is achieved at a non-optimal $\Delta\theta$ and large β_{TCP} rather than at $\Delta\theta_{\text{opt}}$ and small β_{TCP}.

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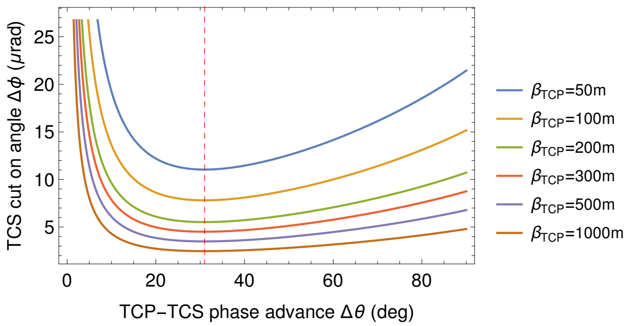

Figure 1: Example of cuts from the TCS on the scattering angle of particles exiting the TCP, as a function of the TCP-TCS phase advance $\Delta\theta$, for several different values of β_{TCP}. Typical numerical value for the LHC proton operation have been used: $n_1 = 6$, $n_2 = 7$, $\epsilon_n = 3.5\ \mu$m, $\gamma_{\mathrm{beam}} = 7461$. The dashed vertical line shows the optimum phase advance $\Delta\theta_{\mathrm{opt}}$ from Eq. (2).

In the LHC, the highest losses on cold magnets leaking out from the collimation system are typically observed in the dispersion suppressor (DS) downstream of the cleaning insertion IR7. They are caused by off-energy protons that have experienced single diffractive scattering in the TCP. Some of them have an insufficient angular kick to reach the TCSs in the straight section, but have a large enough energy offset to hit the aperture where the dispersion rises in the DS. Decreasing the TCS cut in angle could thus help intercepting these particles and improve the cleaning efficiency.

An additional argument for a large β_{TCP} is that a given normalized amplitude increase in units of σ of halo particles, typically caused by diffusion, translates into a larger physical amplitude at the TCP. This means that a particle with a given transverse diffusion speed typically hits deeper into the jaw with a larger physical impact parameter b. Therefore, it traverses a longer distance inside the material and has a larger probability of being stopped by a nuclear inelastic interaction directly in the TCP.

A NEW IR7 OPTICS FOR LHC

There are thus reasons from the point of view of beam cleaning to increase β_{TCP}, possibly even at the expense of moving away from the optimal phase advance to the secondary collimators. These requirements go in the same direction as the constraints from impedance in Eq. (1). Therefore, in the following we discuss an attempt to create a new optics for IR7 in the LHC, with the aim of improving both impedance and cleaning efficiency.

A matching was performed using the MAD-X program [9], where a macro was implemented to vary the quadrupole strengths in order to minimize (k_x, k_y) in Eq. (1). Further matching constraints include keeping the total phase advance of the insertion constant in both planes, and to match the periodic boundary conditions of the neighbouring arcs at the start and end of IR7. No constraint was imposed on any phase advance between collimators.

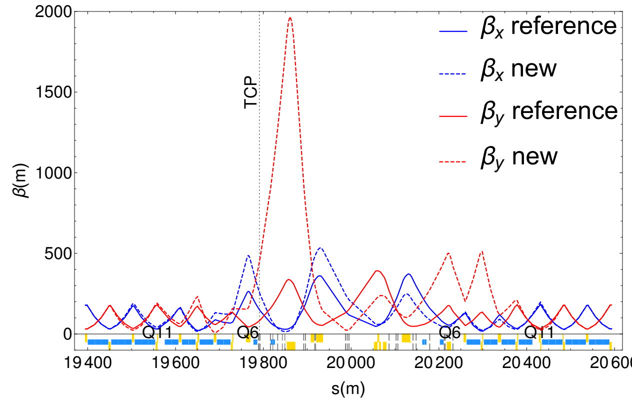

Figure 2: The obtained β-functions in the new optics for beam 1, compared to the reference case.

The starting point of the matching was the 2018 operational LHC optics, for which the IR7 optics is essentially identical to the LHC design optics [1]. We call this the *reference* optics in the following. For all cases we assumed the 2018 normalized collimator openings in units of beam σ [10].

Several matching strategies were tried, and the most successful one consisted of a two-step approach. In a first step, each of the two counter-rotating beams (B1 and B2) was matched separately by varying the strengths of the individually-powered quadrupoles (called Q6–Q13) within their allowed strength limits. In a second step, B1 and B2 were matched simultaneously, starting from the best solution found in the first step and using the quadrupoles Q4–Q5 in addition to Q6–Q13.

Several attempts were made, and the optical functions of the most promising solution are shown in Fig. 2. Only B1 is shown, but the result for B2 is rather similar. The obtained β_{TCP} goes up to $\beta_x = 260$ m and $\beta_y = 420$ m, which is significantly larger than $\beta_x = 150$ m and $\beta_y = 83$ m for the reference optics. The obtained gain in (k_x, k_y) relative to the reference optics is shown in Table 1. Two cases of collimator layouts are considered: the 2018 layout, where all installed collimators were made of CFC, and the future layout for Run 3 (starting 2022), where four TCS and two TCP collimators per beam have been replaced by new low-impedance units made of MoGr with a Mo coating on the TCSs [7, 11]. In the latter case, which is relevant for future operation with the new collimators, an approximate collimator impedance gain of 25%–26% is obtained with the new optics. Larger gains of 28%–40% are obtained for the old CFC layout. This is not so much short of the gain provided by the collimator upgrade (second row of Table 1).

It should be noted that Table 1 shows the gain from the collimator impedance alone, and that the relative gain in the real machine is smaller, especially for the case with low-impedance collimators, where the fraction of the total ring impedance originating from collimators is smaller.

The β-functions in the vertical plane exhibit very large peaks (see Fig. 2), which reduce the beam-stay-clear. Com-

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putations, using MAD-X and the beam tolerances defined for HL-LHC [12], show that the available normalized aperture in IR7 at top energy decreases from 48 σ to 24 σ, still staying within the specifications. However, the computed aperture at injection drops below 7 σ, which is not acceptable, although aperture measurements with beam should confirm the limits. On the other hand, the new optics is not needed at injection, where both the impedance and cleaning are less critical. Therefore, if such an optics would be used in LHC operation, it would have to be introduced in several steps during the energy ramp—this has to be further studied.

Table 1: Ratio in Impedance Coefficients (k_x, k_y) in Eq. (1), Summed Over all LHC Collimators for Various Combinations of Reference Optics (RO), New Optics (NO), CFC Collimators (CFC) and MoGr Collimators (MoGr)

	B1H	**B1V**	**B2H**	**B2V**
(NO, CFC)/(RO, CFC)	0.62	0.73	0.62	0.74
(RO, MoGr)/(RO, CFC)	0.52	0.71	0.53	0.71
(NO, MoGr)/(RO, CFC)	0.39	0.52	0.40	0.53
(NO, MoGr)/(RO, MoGr)	0.75	0.74	0.75	0.74

SIMULATED CLEANING PERFORMANCE

In order to compare the cleaning performance for the new optics with the reference case, simulations of the halo impacting on the collimators and the residual loss distribution were performed using SixTrack [4, 13–21], which has been successfully benchmarked against LHC beam loss measurements [4, 6, 22]. A simulation setup similar to [4] was used, with a direct halo impacting the TCPs with an average impact parameters $b = 0.01\ \sigma$ in all cases.

We show in Fig. 3 the simulated cleaning inefficiency (defined in [4]) in IR7 for a vertical halo, with the highest losses on the TCPs to the left in the figures, and a small leakage reaching the cold magnets in the DS to the right. Two main loss clusters can be seen, which we call DS1 and DS2. The ratios of the integrated losses in these clusters between the new and reference optics are shown in Table 2. Overall, very encouraging cleaning improvements in the range of 38%–57% are observed with the new optics.

Table 2: Ratio of Cleaning Inefficiency in the DS1 and DS2 Clusters Between the New and Reference Optics

	DS1	**DS2**
B1H	0.62	0.42
B1V	0.43	0.49

CONCLUSIONS AND OUTLOOK

We have shown that larger β-functions at collimators in a multi-stage cleaning system can have a beneficial effect on both impedance and the cleaning performance. Since the collimators are typically placed at half-gaps given in units

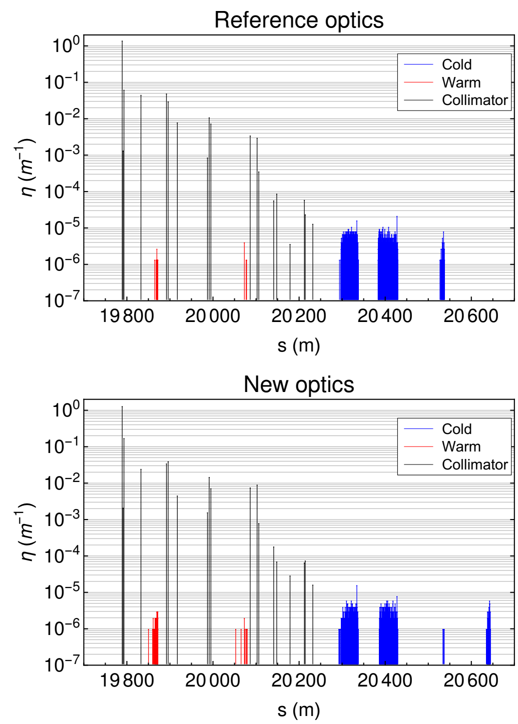

Figure 3: Simulated cleaning inefficiency from SixTrack for the reference and new optics for vertical losses in B1.

of the betatronic beam size σ, the larger β-function values imply larger physical gaps that decrease the impedance. Furthermore, the angular kick received in the scattering processes translates, at a larger β, into a larger normalized amplitude kick, thus decreasing the physical kick required to hit the secondary collimators. In addition, large β-functions lead also to a larger physical amplitude increase, causing a deeper impact on the primary collimator. Larger physical gaps have a positive impact also on operational aspects, such as precision of the gap in σ and tolerances on, e.g., orbit distortions.

Based on these considerations, we have matched a new optics for the LHC betatron cleaning insertion IR7, for which we calculate an approximate decrease of the collimator impedance by 25%–38%, and simultaneously a simulated improvement of the cleaning performance of 38%–57%, depending on the scenario. As future work, more detailed calculations of the impedance reduction should be done, including the full ring. The new optics could possibly be tested with beam in the LHC to study the improvements experimentally. It remains to be seen if the predicted gain factors are significant enough to stand well above the uncertainty of the beam measurements. The production of intermediate optics for a smooth transition from the nominal optics also still remains to be done.

ACKNOWLEDGEMENTS

We thank would like to thank S. Fartoukh, A. Mereghetti, and J. Molson for discussions and inputs.

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