FIRST DESIGN OF A PROTON COLLIMATION SYSTEM FOR 50 TEV FCC-HH

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Abstract

We present studies aimed at defining a first conceptual solution for a collimation system for the hadron-hadron option for the Future Circular Collider (FCC-hh). The baseline collimation layout is based on the scaling of the present LHC collimation system to the FCC-hh energy. It currently includes a dedicated betatron cleaning insertion as well as collimators in the experimental insertions to protect the inner triplets. An aperture model for the FCC-hh is defined and the geometrical acceptance is calculated at top energy taking into account mechanical and optics imperfections. Based on these studies the collimator settings needed to protect the machine are defined. The performance of the collimation system is then assessed with particle tracking simulation tools assuming a perfect machine.

INTRODUCTION

In the context of the Future Circular Collider study, the FCC-hh [1] is a proposed new hadron collider designed to provide *pp* collisions at a centre of mass energy of 100 TeV. For a nominal beam intensity of 10×10^{14} protons, the total stored energy per beam will be about 8500 MJ, a factor of 20 above the LHC. With such large stored energies, the FCC-hh beams will be highly destructive. Uncontrolled losses on the machine aperture can cause quenches of the superconducting magnets, or in the worst case material damage. This poses stringent requirements on the control of beam losses.

The main purpose of the collimation system is to provide efficient cleaning of the beam halo ensuring an operation safely below quench limits at injection and top energy. At the LHC this is achieved through a multi-stage cleaning [2] with two separate insertions for betatron and momentum collimation. Given the excellent performance of the LHC collimation system, validated up to energies of 6.5 TeV, the first conceptual solution for the FCC-hh collimation is a scaled-up system derived from the present LHC. This conservative, but solid approach allow us to evaluate the performance that we can achieve with the current state-of-the-art. Further improvements and technological developments will be considered at a later stage.

In this paper, we present a first baseline for a collimation system for the FCC-hh that includes betatron cleaning and tertiary collimators for protection of the inner triplets around the experiments. Momentum cleaning, not addressed here, is foreseen to be implement in the future in a dedicated insertion. After a description of the system's layout and optics, the aperture of the FCC-hh is reviewed. A detailed knowledge of the aperture margins in the machine is in fact necessary to ensure that every element, in particular cold ones, is protected by the collimation system. Based on the aperture studies, baseline collimator settings are proposed. The results of detailed particle tracking simulations are then presented and the performance of the system is assessed through the analysis of proton loss maps.

BASELINE FOR THE FCC-HH COLLIMATION SYSTEM

The baseline FCC-hh layout, described in [3], includes a dedicated betatron cleaning insertion with optics scaled from the LHC by a factor of 5. The scaling factor was chosen to achieve collimator gaps that are similar to the LHC ones, in order to avoid excessive impedance and to guarantee mechanical stability. The resulting optics functions are shown in Fig. 1 [3]. The number of collimators and their phase advances are the same as in the LHC and were optimised for three-stage cleaning [4]. Primary collimators (TCP), closest to the beam, intercept primary proton losses and give rise to a secondary halo that is intercepted by secondary collimators (TCS). Active absorbers (TCLA), placed outside TCS, catch showers from upstream collimators. In addition, tertiary collimators (TCT) are installed in the low-beta insertions, about 220 m upstream the interaction point, to provide local protection of the inner triplets. The same collimator material used at the LHC are assumed: carbon fibre composite for TCPs and TCSs, tungsten alloy for TCLAs and TCTs. It is planned to modify the collimator materials in the future, based on the outcome of new material studies that are ongoing in the context of the HL-LHC upgrade [5]. Further improvements of the system, such as addition of more collimators and optimisation of phase advances are also foreseen.

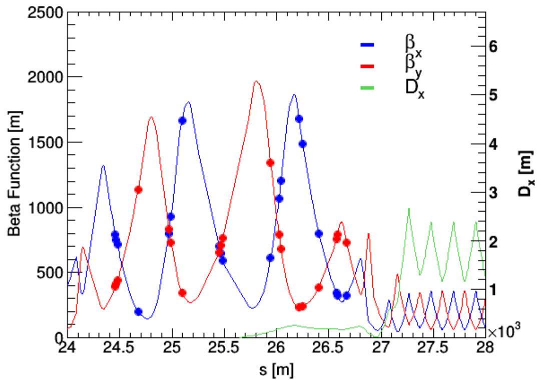

Figure 1: Optical functions for the betatron cleaning insertion. The markers show the location of collimators.

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FCC-HH APERTURE

A first aperture model for the FCC-hh was defined. The geometrical aperture of the arc is given by the beam screen, assumed to be of rect-ellipse shape and dimensions 2 × 15 mm (width) and 2 × 13.2 mm (height). The mechanical aperture in the experimental insertion was designed as described in [6]. In the collimation insertion and matching sections, the same mechanical aperture as in the LHC was assumed. The effective aperture of the machine was then computed element by element using the MADX code [7,8], taking into account the optical tolerances listed in Table 1. This parameter set, proposed in [9] to calculate the HL-LHC aperture, was refined with respect to the LHC design parameters based on operational experience. In addition, the same mechanical and alignment tolerances used at the LHC design phase [10] were assumed. These vary for different magnet classes and are ≤ 2.5 mm (mechanical) and ≤ 1.6 mm (alignment).

Table 1: Optical Tolerances for Aperture Calculations (Collision Energy).

Parameter	Name	Value
Radial closed orbit excursion	CO^{peak}	2 mm
Beta-beating	$\Delta\beta/\beta$	21%
Momentum offset	δ_p	2×10^{-4}
Relative parasitic dispersion	k_D	0.10

The effective aperture was calculated for a beam energy of 50 TeV and optics for $\beta^\star = 0.3$ m and $L^\star = 36$ m. The aperture bottleneck of the ring was found at the superconducting triplet with a value of 16.2 σ, where σ is the local beam size computed using a normalised emittance of 2.2 μm. This is expected at collision energy, since at this location the available aperture is reduced by the large beta functions required to achieve small beam sizes at the interaction points and by the crossing and separation schemes. In the rest of the ring the available aperture was found to be above 30 σ.

BASELINE COLLIMATOR SETTINGS

Collimator settings have to be defined in a way that ensures protection of the minimum machine aperture with sufficient margin. Given that at top energy the aperture limitation lies in the inner triplet, this constrains the opening of the tertiary collimators (TCT). Furthermore, a strict hierarchy between collimator families must be respected for optimal cleaning performance and machine protection. In the present LHC system, TCTs are not robust and have to be placed outside protection devices, such dump protection collimators (TCDQ), which in turn should be at larger aperture than TCPs and TCSs. For FCC-hh, we define settings in a similar way to minimise the risk of major losses close to the experiments. In Table 2 we present the baseline collimator settings for the FCC-hh at top energy that provide a minimum protected aperture of 15.5 σ. These settings correspond to the HL-LHC baseline settings [9] scaled to the FCC-hh normalised emittance of 2.2 μm and result in collimator gaps (in mm) that are comparable to the LHC ones. Given the aperture calculations shown in the previous section, these settings would allow to reach $\beta^\star = 0.3$ m for an interaction region design with $L^\star = 36$ m.

Table 2: Baseline Collimator Settings at Top Energy, Expressed in Units of σ for a Normalised Emittance of 2.2 μm. Dump protection collimators (TCDQ) are shown for completeness although they are not yet implemented in the layout.

Description	Name	Settings [σ]
Primaries	TCP	7.2
Secondaries	TCS	9.7
Absorbers	TCLA	12.6
Dump	TCDQ	11.4
Tertiaries	TCT	13.7
Protected aperture		15.5

TRACKING SIMULATIONS

Tracking simulations were performed with SixTrack [11–15] to assess the cleaning performance. The initial particle distribution was an annular halo at 7.2 σ and a thickness $\delta\sigma = 0.0015$ in the horizontal plane, a normal distribution cut at 3 σ in the vertical plane and no energy errors. The average impact parameter on the TCP was about 4 μm. 6.4 million particles were tracked for 200 turns for the case of a perfect machine and using collimator settings from Table 2.

Cleaning Inefficiency

The performance of the collimation system is described by the cleaning inefficiency η_c, defined as the ratio of surviving protons above radial amplitude A_0 over the number of protons absorbed by the collimation system (N_{abs}):

$$\eta_c(A_0) = \frac{N_p(A > A_0)}{N_{\text{abs}}}. \qquad (1)$$

Similarly, to study the off-momentum population, we can define a cleaning inefficiency as a function of the relative momentum deviation $\delta p/p$, by substituting in the above equation the amplitude A with $\delta p/p$. The cleaning inefficiency of the system is shown in Figure 2. At an aperture of 16 σ, corresponding to the triplet aperture, the cleaning inefficiency is about 3×10^{-3}, while at $\delta p/p = 0.7\%$, corresponding to the momentum acceptance of the arc, the cleaning inefficiency is below 10^{-5}.

Loss Maps for a Perfect Machine

The cleaning inefficiency defined in Eq. (1) has the advantage of being independent of the longitudinal coordinate s and can be studied without the need of an aperture model. However losses are typically distributed longitudinally. It is therefore useful to define a local cleaning inefficiency η_c

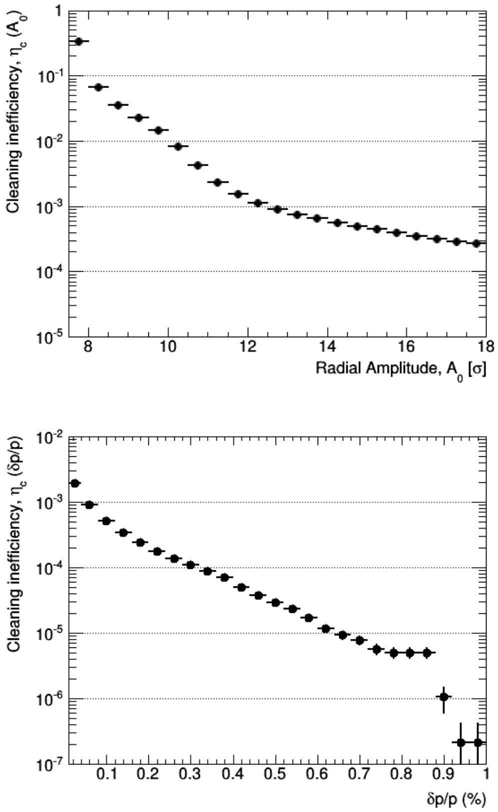

Figure 2: Cleaning inefficiency as a function of radial amplitude A_0 (top) and momentum off-set $\delta p/p$ (bottom).

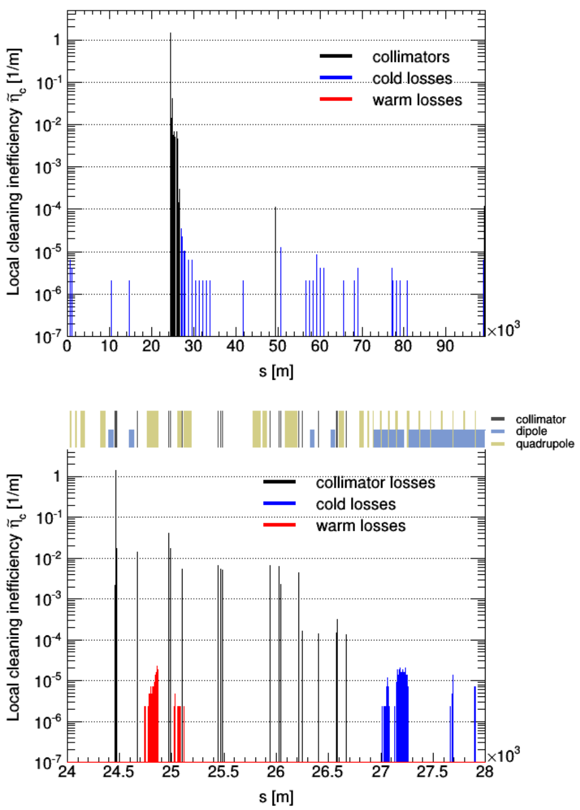

Figure 3: Horizontal loss map for the entire ring (top) and zoom in the betatron cleaning insertion (bottom). The interaction points are at $s = 0$ and 49660 m respectively.

which is a function of s and is calculated in loss maps as:

$$\tilde{\eta}_c(s) = \frac{1}{\Delta s} \cdot \frac{N_{\text{loss}}(s \rightarrow s + \Delta s)}{N_{\text{abs}}}, \tag{2}$$

where Δs is the bin size (here 10 cm) and $N_{\text{loss}}(s \rightarrow s + \Delta s)$ is the number of particles lost in the aperture between position s and $s + \Delta s$.

The horizontal loss map for the whole ring and a zoom in the betatron cleaning insertion are shown in Fig. 3. The largest cold losses occur in the dispersion suppressor (DS) downstream of the betatron cleaning insertion, where two clusters of losses are observed in correspondence to local peaks in the dispersion function. The peak cleaning inefficiency is 1.2×10^{-5} in the first cluster and 2.2×10^{-5} in the second cluster. These losses are due to particles from single diffractive interactions at the primary collimators. Similar performance limitations are observed at the LHC and have been extensively studied in the context of the HL-LHC upgrade [16]. The LHC solution consists in the installation of new collimators in the DS upstream of the critical locations. This solution intercepts locally beam halos with a significant off-momentum component and has also the advantage to reduce losses in other locations around the ring. At the FCC-hh an analogous solution can be applied and the design of the DS can be optimised to improve the performance of the system with additional local protection collimators. Details of such implementation are being studied for different FCC layout options.

CONCLUSIONS

A conceptual design for the FCC-hh betatron collimation system, scaled-up form the present LHC solution, was presented. Baseline collimator settings were proposed based on aperture calculations for the whole ring. The cleaning inefficiency of the system was investigated and loss maps were shown. Similarly to the LHC, the performance limitation was identified to be in the cold losses in the dispersion suppressor downstream of the betatron cleaning insertion. The addition of collimators in the dispersion suppressor and a layout optimisation will be investigated in the future and are expected to provide significant improvements. Detailed performance estimates can only be assessed once the quench limits of FCC-hh magnets will be known, but this first implementation of a multi-stage system already provides encouraging results. The results of these tracking simulations will provide a first set of input for the collimator hardware design, which should be compatible with the loss scenario of the FCC-hh.

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