COLLIMATION SYSTEM FOR THE UPDATED FCC-hh DESIGN BASELINE

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Abstract

For the Future Circular Collider (FCC) Conceptual Design Report (CDR), the FCC-hh collimation system was studied and optimized for proton and heavy-ion operation with up to 8.3 GJ stored beam energy. There are currently studies ongoing for an updated design baseline, including a new ring layout, compatible with the FCC-ee, and optics, where the collimation insertions have undergone major changes. A first iteration on the adapted collimation system layout and settings for the new baseline is presented. The beam loss cleaning performance for proton beams is studied in multi-turn tracking simulations.

INTRODUCTION

The hadron Future Circular Collider (FCC-hh) [1] is a design study for a 90–100 km circumference energy frontier collider, providing 100 TeV centre of mass proton-proton collisions by utilising 16 T superconducting magnet technology. One of the challenges for the collider is the 8.3 GJ stored beam energy, which is a factor 23 higher than the design stored beam energy in the Large Hadron Collider (LHC) [2, 3], and a factor 12 higher than in the High-Luminosity LHC (HL-LHC) [4]. A robust collimation system is required, which, in extreme scenarios, can tolerate up 11.6 MW of beam loss power without damage or induced magnet quenches. The FCC-hh collimation concept was extensively studied for the Conceptual Design Report (CDR), and a good collimation performance was demonstrated in simulations, with no show-stoppers identified for proton [5–7] or heavy ion [8] beam operation. The main goal of the FCC-hh studies after the CDR has been to adapt the layout and optics to the new tunnel baseline and to ensure compatibility with the first stage electron-positron collider, FCC-ee. The collimation insertions are one of the areas where significant changes were necessary, relative to the CDR [9]. There is an ongoing study to adapt the FCC-hh collimation system design to the new baseline, which is the focus of this paper. The collimation system design changes and results from first loss map studies with the new configuration are presented.

COLLIMATION SYSTEM

There are several changes of the new baseline layout and optics design relative to the CDR [9], which are relevant for collimation. The new tunnel layout has a circumference of 91.72 km and a 4-fold symmetry, relative to the 97.75 km circumference and 2-fold symmetry in the CDR design. This has led to a reduction of the betatron collimation insertion length from 2800 to 2160 m, and an increase of the off-momentum collimation insertion length from 1400 m to 2160 m. Furthermore, the separation between primary and secondary physics experiments in the CDR has been lifted, with all 4 interaction points (IPs) now located in insertions with equivalent optics. Finally, the injection, extraction, and RF systems have been re-designed. These changes are extensive and require an adaptation of the collimation system, and an assessment of the resulting performance. There are two collimation insertions, PF for betatron cleaning and PH for off-momentum cleaning. The changes to the collimation insertion optics are detailed in [9]. In the new betatron collimation insertion, there is a reduction in the β-functions in the straight section and an increase of the dispersion function in the dispersion suppressor (DS), which has an effect on the collimation performance. The collimation system design has been adapted from the CDR. As for LHC collimation [2, 10–12], there is a multi-stage collimation system installed in each cleaning insertion, with primary collimators (TCP) closest to the beam, secondary collimators (TCSG) to intercept particles out-scattered by the TCPs, and active absorbers (TCLA) to stop low-energy particles from escaping the insertion. There are also tertiary collimators (TCT) upstream of the IPs to protect the aperture bottlenecks in the final focus superconducting quadrupole triplets. There are also the DS collimators (TCLD), like in the HL-LHC design [4, 13]. The TCLD collimators have a crucial role, as they intercept off-momentum particles with small transverse amplitudes, which cannot be stopped by the betatron collimators. There are TCLDs in each collimation insertion, and also downstream of the other experimental and technical insertions. There is also an asynchronous dump protection collimator (TCDQ) in the combined injection and extraction insertion PB, together with a TCLA and a TCLD to absorb particles out-scattered by the TCDQ. The collision debris absorbers downstream of the IPs, and the injection protection collimators are not yet included in the updated collimation baseline.

The locations of the collimators, planned for the final layout, are based on scaling from the CDR layout. The collimator openings are also adapted from the CDR and set in units of RMS beam size σ for the nominal normalised emittance $\epsilon_N = 2.2$ µm. There are several notable changes relative to the CDR configuration. The TCLDs in the betatron collimation insertion have been relocated upstream, due to the increased dispersion in the new layout. To reduce the losses in the PF DS, the TCSG have been closed by 0.2 σ and an additional TCLD collimator has been added, for a total of 4 TCLDs. The optics and the collimator layout in

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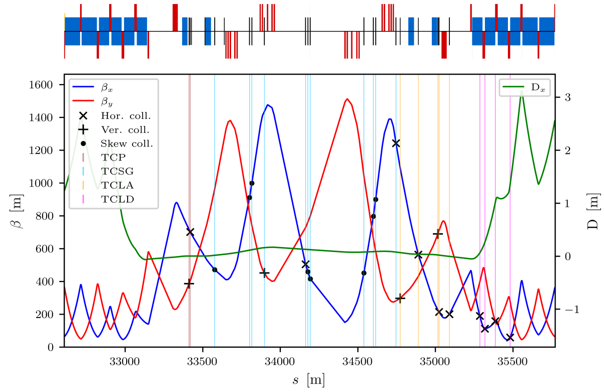

Figure 1: Optics and collimator layout in the betatron collimation insertion PF, showing the new configuration with 4 TCLDs. The magnetic element layout is shown on top.

Table 1: Summary Table of Collimator Parameters and Settings for the FCC-hh at Top Energy

Type	Material	Length [m]	Gap [σ]
TCP PF	CFC	0.3	7.6
TCSG PF	MoGr, CFC	1.0	8.6
TCLA PF	Inermet180	1.0	12.0
TCLD PF	Inermet180	1.0	35.1
TCP PH	CFC	0.3	18.1
TCSG PH	MoGr	1.0	21.7
TCLA PH	Inermet180	1.0	24.1
TCLD PH	Inermet180	1.0	35.1
TCT PA,D,G,J	Inermet180	1.0	12.1
TCLD PA,D,G,J	Inermet180	1.0	35.1
TCDQ PB	CFC	10.0	9.8
TCLD PB, PL	Inermet180	1.0	35.1

PF can be seen in Fig. 1. The reduced β-functions in PF, tighter TCSG settings, and the addition of another TCLD negatively impact the impedance, which should be evaluated. The first set of TCTs upstream of each IP has been shifted 160 m downstream, to 430 m from the corresponding IP, to ensure a sufficient opening for mechanical stability, with the minimum TCT half-gap for the new placement being 6.5 mm. The TCT collimators have also been retracted by 1.6 σ, to reduce the loss power on those collimators, the leakage into the superconducting inner quadrupole triplet, and the potential detector backgrounds. The configuration studied does not include the crossing angle, and there is sufficient aperture margin for relaxing the TCT settings [9], but the collision configuration with the crossing angle included should be verified in the future. The first iteration of the settings for the updated collimation system baseline can be found in Table 1. The materials are carbon fibre composite (CFC), molybdenum graphite (MoGr), and tungsten heavy alloy (Inermet180). It should be noted that the collimator placement and settings are preliminary, and a comprehensive study of the lattice integration of the TCLDs and TCTs is yet to be carried out.

SIMULATION SETUP

The collimation performance is studied in particle tracking simulations using the SixTrack-FLUKA coupling [14, 15]. In this framework, SixTrack [16, 17] is used to track particles in the magnetic lattice, while FLUKA [18, 19] is used to perform Monte Carlo simulations of particle-matter interactions in the collimators. The simulated loss scenario is horizontal betatron halo losses for Beam 1 at the top energy of 50 TeV. This scenario was identified as one of the most critical ones during the CDR studies. In the simulation, the initial particle distribution is set up to impact the horizontal primary collimator on the first pass with an impact parameter of 1 μm, and 10^8 primary protons were tracked for 700 turns after the original scattering. The resulting aperture losses are binned in 10 cm intervals and are presented as loss maps in terms of the local cleaning inefficiency $\eta = E_{\mathrm{loss},\Delta s}/(E_{\mathrm{loss,\,total}}\Delta s)$ [20], where $E_{\mathrm{loss},\Delta s}$ the integrated energy of particles lost in the region $[s, s{+}\Delta s]$ and $E_{\mathrm{loss,\,total}}$ is the integrated loss energy over the whole ring. The design specification for the collimation system from the CDR is a 12 min beam lifetime drop, sustained for 10 s without superconducting magnet quenches. To compare with this specification, the quench limit of the magnets is converted to a critical local cleaning inefficiency $\eta_q = 3 \times 10^{-7}$ m^{-1} for protons at 50 TeV [5], which should not be exceeded.

RESULTS

The loss map for the full ring is shown in Fig. 2, and a zoomed-in view of the collimation insertion PF is shown in Fig. 3. It can be observed that most losses are concentrated on collimators in the collimation insertions PF and PH. Losses are also observed on the TCTs and TCLDs in the experimental insertions, as well as in the technical insertions PB and PL. The collimation performance is generally good, but local losses following out-scattering from the collimators are a concern. Clusters of losses in superconducting elements that exceed the estimated quench limit can be observed in the DS of PF and PL. The highest loss cluster is in the DS of PF, downstream of the last TCLD, as seen in Fig. 3. Even with a 4th TCLD, the power load on those

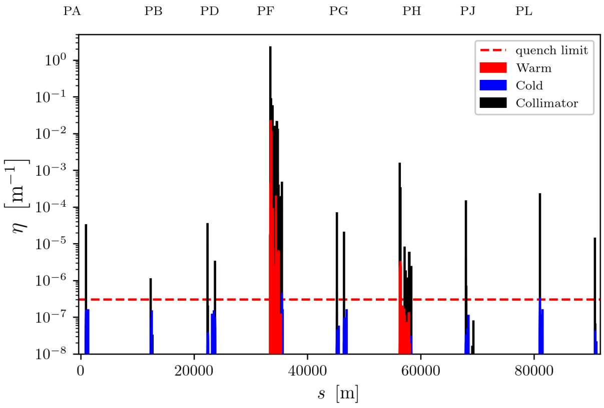

Figure 2: Loss map for collimation losses in the full FCC-hh ring for horizontal betatron losses at top energy.

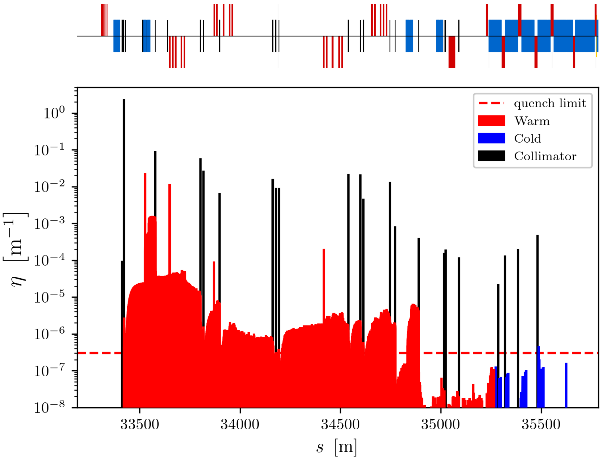

Figure 3: Loss map in the betatron collimation insertion PF for horizontal betatron losses at top energy. The layout of beam line elements is shown on top.

collimators is high, up to 5.4 kW for a 12 min beam lifetime. The highest collimation inefficiency in cryogenic elements reach $\eta = 4.6 \times 10^{-7}$ m^{-1}, 55% higher than the estimated quench limit. This is in contrast with the results from the CDR studies, where a sufficient loss suppression could be achieved with 3 TCLDs in the betatron collimation insertion, even in the presence of imperfections, which are not modelled in the studies presented. If no further improvements are made, the current collimation performance places a limit of 20 min on the minimum tolerable beam lifetime. This is an approximate value and energy deposition studies are needed to estimate the peak energy deposition in the superconducting magnets. The losses on the TCTs in the experimental insertions are shown in Fig. 4. It can be observed that the first set of TCTs (TCT-H/V-1) intercept significantly more losses than the second set (TCT-H/V-2), and that losses occur on both the horizontal and the vertical TCTs. The inner triplets are well-protected in this scenario, but the available margin to the aperture should be checked after the crossing angle is added to the optics model. The layout of the TCTs and TCLDs in the experimental insertions must be optimised, in particular in view of the changes foreseen for the interaction region geometry [9]. The backgrounds to the detectors from losses on the TCTs should also be evaluated.

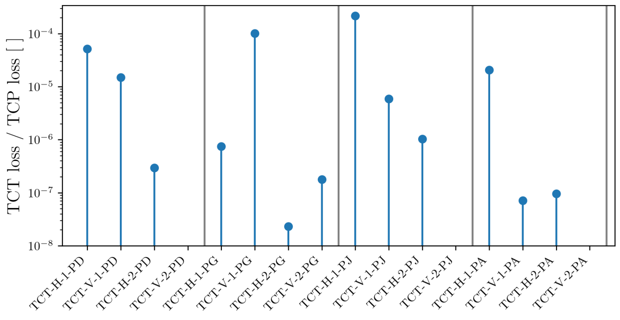

Figure 4: Losses on the tertiary collimators (TCT) in the experimental insertions, normalised to the loss on the horizontal primary collimator (TCP). The order is as seen by the beam moving from left to right, starting at the first IP, with the gray lines delimiting the experimental insertions.

FUTURE DEVELOPMENT

The new shortened betatron collimation insertion presents a challenge for the collimation system design. There were several iterations performed, and the parameter set presented is the latest one. It offers a factor of 20 improvement over the initial scaling of the CDR system to the new layout [21]. During the design iterations, it was found that for this loss scenario, the distribution of losses in the full ring has a strong dependence on the placement and settings of the PF TCLDs, and future studies should focus on their optimisation. Additional mitigation strategies considered, which are motivated by experience from the LHC, include optimising the insertion optics [22], and operating with asymmetric primary collimator settings [23]. Fixed masks for magnet protection are also an option [7]. It is important to perform impedance and energy deposition studies for the new configuration. The energy deposition studies are required to quantify the quench risk for the most exposed superconducting magnets, and the robustness of the collimators [5]. Given the changes to the off-momentum collimation insertion, the case of off-momentum losses at injection must be studied. The longer PH should offer increased flexibility to improve the off-momentum cleaning performance. Failure modes, such as asynchronous beam dump, should also be studied with the new injection and extraction system design.

CONCLUSIONS

The new FCC-hh design has introduced significant changes relative to the CDR one, including altered length and optics for the collimation insertions and the other technical insertions. The first iteration of an updated design for the FCC-hh collimation system for the new layout was studied. The betatron and off-momentum collimation systems were adapted from the CDR studies, with adjustments for the new layout, including the addition of an extra TCLD in PF, adjustment of the TCSG settings in PF, and altered TCT collimators placement and settings. The performance of the collimation system was studied in simulation for the case of horizontal betatron losses at top energy, which is one of the most demanding scenarios. While a good general collimation performance was shown, there were several loss clusters in the ring where the losses exceed the estimated, approximate quench limit by up to 55%, when the 12 min beam lifetime criterion is applied. It was found that the losses in the whole ring are sensitive to the placement and settings of the TCLD collimators in PF. Future design iterations should optimise the collimator placement and settings, or the beam optics, to bring all the losses in the ring below the quench limit. Impedance and energy deposition studies are also necessary to validate the new collimation baseline, as well as studies of off-momentum collimation performance, detector backgrounds, and failure scenarios.

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