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REVISED COLLIMATION CONFIGURATION FOR THE UPDATED FCC-hh LAYOUT

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Abstract

The collimation system for the hadron Future Circular Collider (FCC-hh) must handle proton beams with an unprecedented nominal beam energy and stored beam energy in excess of 8 GJ, and protect the superconducting magnets and other sensitive equipment while ensuring a high operational efficiency. The recent development of the 16-dipole lattice baseline for the FCC-hh, and the associated layout changes, has necessitated an adaptation of the collimation system. A revised configuration of the collimation system is presented, considering novel high-beta optics in the betatron collimation insertion. Performance is evaluated through loss map studies, with a focus on losses in critical areas, including collimation insertions and experimental interaction regions.

INTRODUCTION

The hadron Future Circular Collider (FCC-hh) [1] is a design study for a 91 km circumference energy frontier hadron collider, providing 84 TeV to 120 TeV centre of mass proton-proton collisions by using advanced magnet technology. One of the challenges for the collider is the stored beam energy of up to 8.3 GJ for the Conceptual Design Report (CDR) [1] reference 50 TeV energy per beam, which is a factor 21 higher than the achieved stored beam energy in the CERN Large Hadron Collider (LHC) [2], and a factor 12 higher than in the High-Luminosity LHC (HL-LHC) design [3]. The stored beam energy could be even higher, 10 GJ, for the upper end 60 TeV per beam if the CDR beam intesnity is considered. A highly efficient collimation system is required to ensure safe operation of the collider and avoid the risk of superconducting magnet quenches during regular operation and accidental loss scenarios, while tolerating instantaneous loss power of up to 11.6 MW in design loss scenarios for the CDR beam energy, based on the LHC design loss scenarios. The first design of the FCC-hh collimation system, based on a scaled version of the system installed in the LHC, was developed for the CDR [1, 4], where a comprehensive study campaign found that the system was adequate for operation with nominal proton and heavy-ion beams [5, 6]. The current focus of FCC-hh studies is to align the ring layout and infrastructure to the first-stage lepton collider, FCC-ee, and to explore new design concepts. As a result of the post-CDR studies, there have been significant changes in the ring layout and optics, which affect the collimation performance and must be studied in detail. This paper provides an outline of the configuration of the latest FCC-hh baseline, the adaptations required for the collimation system, and preliminary results from collimation tracking studies.

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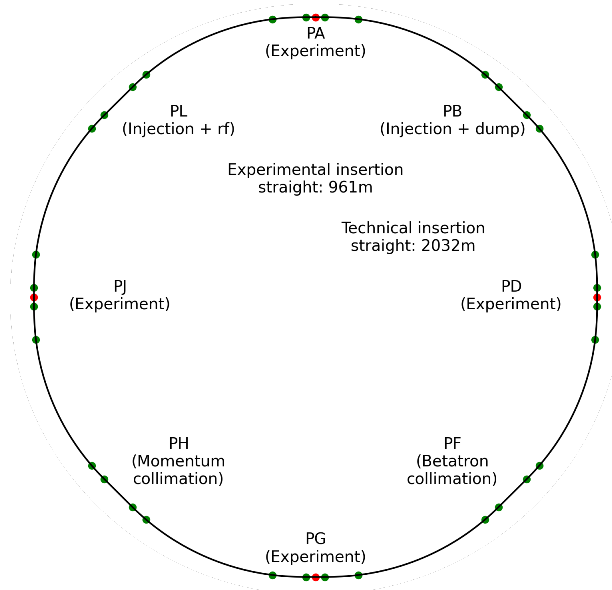

Figure 1: Layout of the FCC-hh, showing the experimental insertions PA, PD, PG, PJ, and the technical insertions PB, PF, PH, and PL. Interaction points are shown as red dots, and dispersion suppressor boundaries with green dots.

LAYOUT AND OPTICS CHANGES

The first major redesign of the FCC-hh layout after the CDR was completed in 2023 [7] and featured a significant change of the ring geometry, to match the tunnel layout and the FCC-ee collider rings, as well as changers to the optics. The first collimation studies for the new FCC-hh configuration were carried out with an early iteration of the design [8], and showed that the changes impact the performance of the collimation system. The latest development of the FCC-hh layout and optics have resulted in a new stable baseline, which implements further design changes. The layout of the ring is shown in Fig. 1.

The main differences include a change in circumference to 90.66 km, down from 91.17 km in the previous iteration and 97.75 km in the CDR, shortening of the technical insertions from 2160 m to 2032 m, and changes to the geometry of the interaction region (IR) to displace the interaction points (IPs) radially outwards to match the FCC-ee IPs, leading to IR shortening from 1400 m to 936 m. The experimental IRs also feature new dogleg geometry, due to the use of superconducting separation and recombination dipoles, as well as a new dispersion suppressor (DS) geometry. There

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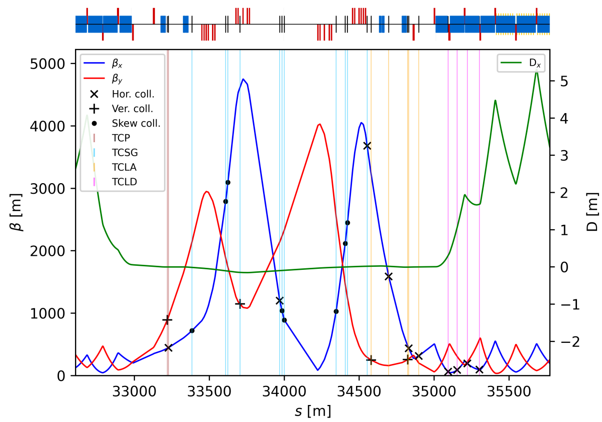

Figure 2: Optics and collimator layout in the betatron collimation insertion PF, showing the new configuration with 4 TCLDs. The magnetic element layout is shown on top.

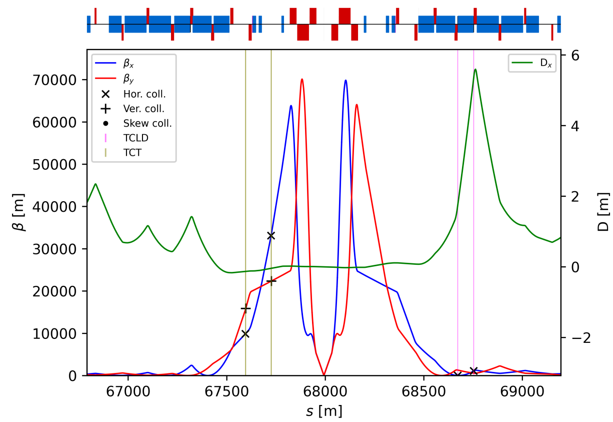

Figure 3: Optics and collimator layout in the experimental insertion PJ, showing the TCT and TCLD collimators.

is also a shift to a 16-dipole arc cell instead of a 12-dipole one and the associated changes in the dispersion suppressor geometry for the technical insertions. The increased beam size in the arc due to the 16-dipole cell configuration has necessitated a change in the beams screen profile, to preserve the required beam clearance. The optics and aperture models for all insertions have been integrated into the ring design.

COLLIMATION SYSTEM

The betatron collimation is installed in PF and momentum collimation in PH. Each of the dedicated collimation insertions has a multi-stage collimation hierarchy with progressive cuts in transverse amplitude, including primary collimators (TCP) closest to the beam, secondary collimators (TCSG) to intercept particles out-scattered by the TCPs, and absorbers (TCLA) to stop lower-energy particles escaping the straight sections. The experimental IRs have tertiary collimators (TCT) to provide local protection to the aperture bottlenecks, and all insertions have dispersion suppressor collimators (TCLD) to intercept off-momentum particles. The experimental IRs have two TCLD collimators each, which have the primary goal of stopping collision debris. The injection/extraction and RF insertions also have 2 TCLDs each. In PF there are 4 TCLD collimators, and in PH there are 3, to intercept particles with low transverse amplitudes and large momentum offsets. Finally, there are a dump protection collimator (TCDQ) and a pair of associated TCLAs in PB. The collimation configuration is preliminary, and future iterations are expected in both the collimator layout and settings. In PF, new optics are used, based on the latest studies of high-beta collimation optics for betatron collimation in the LHC [9] and HL-LHC [10]. The expected benefits of this configuration are an improvement in the loss cleaning performance and a reduction in the collimator impedance. The optics and collimator layout for PF can be seen in Fig. 2. Previous studies have found that PF and PH TCLDs play a crucial role in controlling collimation losses throughout the ring [8]. They have been integrated into the new lattice at preliminary locations, designed to offer a staggered momentum cut and distribute the collimation losses over all collimators.

Another important open point is how to select the layout of the TCTs in the IRs. In the previous versions of the FCC-hh, as well as in the LHC and HL-LHC, the global aperture bottlenecks in the collision configuration are found in the inner quadrupole triplets, where the beams are squeezed for collision at the IPs. The TCTs have therefore been placed in the straight section to provide local protection for the triplets. In the current FCC-hh configuration, the aperture bottlenecks in collision configuration are located in the final cell of the DS upstream of the IP. This requires a change of the layout and the TCTs must be relocated further upstream to protect the bottlenecks, which is a major change that must be carefully assessed. In the model presented, the collimators are still in the straight section and are set to protect the triplet aperture, as shown in Fig. 3. Note that the crossing angle is not included in the model used for numerical simulations.

The collimator openings are set in units of the RMS beam size σ for the nominal normalised emittance $\epsilon_N = 2.2\,\mu$m. The settings of the collimators are listed in Table 1.

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	10.6
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	22.1
TCLD1 PA,D,G,J	Inermet180	1.0	125.4
TCLD2 PA,D,G,J	Inermet180	1.0	35.1
TCDQ PB	CFC	10.0	10.8
TCLA PB	Inermet180	1.0	14.8
TCLD PB, PL	Inermet180	1.0	35.1

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SIMULATION SETUP

In previous FCC-hh studies, the SixTrack-FLUKA coupling [11–15] has been used for collimation tracking studies. For the results presented here, the Xsuite-BDSIM coupling [16–18] has been used for the numerical simulations. This is done to benefit from advanced Xsuite features not available in SixTrack, including the definition and interpolation of arbitrary vertex-defined aperture profiles and synchrotron radiation for proton beams. The results have been benchmarked with SixTrack-FLUKA and an adequate agreement was found. Note that the coupling of Xsuite to FLUKA is in development, as part of the Xcoll package [19], and will also be used for simulations in the future.

The simulated loss scenario is horizontal betatron halo losses from a 12 min beam lifetime drop for the clockwise beam (Beam 1) at the top energy of 50 TeV. The initial particle distribution impacts the horizontal primary collimator on the first pass with an impact parameter of 1 μm, and 10^8 primary protons are tracked for 700 turns after interaction with the collimator. The tracking energy cut is set to 98% of the beam energy, much higher than the minimum arc energy cut of 0.32‰. A simplified octagon aperture model is used for ease of comparison with previous studies. The losses around the ring 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 $E_{\mathrm{loss},\Delta s}$ is the integrated energy of the particles lost in the region $[s, s+\Delta s]$, and $E_{\mathrm{loss,\,total}}$ is the integrated lost energy over the whole ring. A preliminary superconducting magnet quench limit is used to assess the performance of the collimation system, in terms of a critical local cleaning inefficiency $\eta_q = 3\times10^{-7}\ \mathrm{m}^{-1}$ for protons at 50 TeV [5].

RESULTS

The simulated loss map for the full ring is shown in Fig. 4. Overall, the collimation system provides a good loss suppression, with most of the losses concentrated in the collimation insertions PF and PH, but several isolated loss clusters approach or exceed the estimated quench limit. TCLA col-

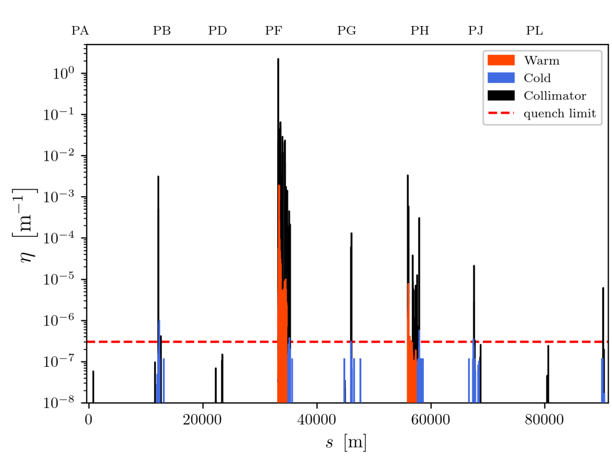

Figure 4: Loss map for collimation losses in the full FCC-hh ring for horizontal betatron losses at top energy.

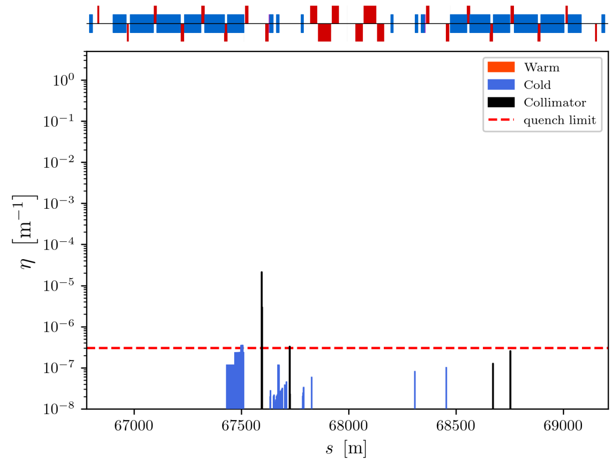

Figure 5: Loss map in the experimental insertion PJ for horizontal betatron losses at top energy. The layout of beam line elements is shown on top.

limators in PB are exposed to significant losses, leading to a cold loss cluster from collimator leakage that exceeds the quench limit by a factor of 3.3. Lower-magnitude cold loss clusters due to collimator leakage occur also downstream of the TCLDs in PF, PH. The final area of concern are the IRs in PG and PJ, where cold-loss clusters occur upstream of the TCT collimators, at the locations of the aperture bottlenecks, as seen in Fig. 5. In this preliminary configuration, the high-beta optics in PF do not offer improved loss cleaning, relative to the previous configuration studied [8], even with relaxed TCT and TCDQ settings. However, it should be noted that the collimation layout in PF and the rest of the ring has not yet been optimised, including the optics, phase advance, and settings of the collimators, which is the likely explanation for the observed performance.

SUMMARY AND FUTURE WORK

The latest FCC-hh layout and optics baseline have introduced significant changes with respect to the CDR design. Novel high-beta optics have been utilised for the betatron collimation insertion, and a new preliminary layout of TCT and TCLD collimators along the ring has been implemented. First collimation-tracking studies have been performed for the new configuration using the Xsuite-BDSIM coupling for the horizontal betatron halo loss scenario. Significant loss suppression is demonstrated, although loss clusters due to collimator leakage in PB, PF, and PH are found to exceed the estimated quench limit. Additional loss clusters are found upstream of the TCT collimators, where they cannot be directly mitigated with the current collimation layout. While the collimation performance is worse than previously observed and the reasons are not well understood, the new fixed baseline offers the opportunity to carry out detailed studies and optimisation. The next step is to review the collimator layout in PF and the IRs. The impedance, energy deposition, off-momentum collimation studies at injection and failure scenarios will be studied afterward.

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