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STUDIES OF LAYOUT AND CLEANING PERFORMANCE FOR THE FCC–ee COLLIMATION SYSTEM

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Abstract

The collimation system of the electron-positron Future Circular Collider (FCC-ee) will have two main tasks: protect equipment from the multi-MJ beams and mitigate detector backgrounds. An integrated collimation system layout is presented, including beam halo collimation system in one insertion and synchrotron radiation collimation around the experimental interaction points. The Z-production operating mode is considered, which has a beam energy of 45.6 GeV and a stored beam energy of 17.8 MJ, making it the most critical one for machine protection. The collimation insertion optics, aperture model, and collimation configuration for this mode are presented. The beam loss cleaning performance of the collimation system is studied for selected beam loss scenarios using a set of novel tools that enable multi-turn tracking simulations.

INTRODUCTION

The lepton Future Circular Collider (FCC-ee) [1] is a design study for an electron-positron collider with a circumference of approximately 90 km. It features four operational modes at different beam energies: 45.6 GeV (Z-production), 90 GeV (W-production), 120 GeV (Higgs-production), and 182.5 GeV ($t\bar{t}$-production). The current parameter set has a target stored beam energy of up to 17.8 MJ for the most critical Z mode, and 0.3 MJ for the $t\bar{t}$ mode [2], leading to a risk of superconducting magnet quenches, equipment damage, radiation damage, and material activation, as a result of unavoidable beam losses. A robust collimation system is required to ensure safe operation of the collider under such conditions. The collimation system has the goals of protecting the machine from beam losses, and controlling the backgrounds to the physics experiments. The beam halo collimation must be designed to protect the aperture bottlenecks from regular and anomalous beam losses, and safely dissipate the loss power away from the physics detectors and other sensitive equipment. In addition to the beam losses, the collimation system must handle the photon losses due to synchrotron radiation (SR) emission in the vicinity of the interaction points (IPs), while also preserving the integrity of the collimators. While the FCC-ee interaction region (IR) geometry is optimised to reduce the SR losses in the detector [3], dedicated collimators are also needed in the IRs to intercept photons [4, 5]. To avoid excessive beam losses on the less robust SR collimators, and the associated detector backgrounds, the beam halo collimation system must protect the SR collimators. An integrated collimation system design for the Z operation mode is presented in this paper, for the latest FCC-ee layout and optics baseline and building on previous studies [6]. The new design includes a beam halo collimation system in a dedicated insertion, and SR collimators around all IPs. Simulation studies are presented as a first step towards assessing the performance of the collimation configuration presented.

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COLLIMATION CONFIGURATION

The collider tunnel layout used for the studies features a circumference of 91.2 km and 8 surface access points labelled A–L [7]. There are 4 IPs in the straight section insertions PA, PD, PG, PJ, and 4 technical insertions in PB, PF, PH, PL. Version 22 of the ring optics [8] is used, with $\beta^* = 10$ cm at the IPs and a single RF insertion in PH. The aperture model includes a 35 mm radius circular aperture in the arcs, and a 10 mm radius circular aperture at the IPs, with staggered transitions in between. Two-stage betatron and off-momentum collimation systems with specialised optics are installed in PF [9]. The betatron collimation system is located upstream of the auxiliary (non-collision) beam crossing in the middle of PF and consists of 1 primary collimator (TCP) and 2 secondary collimators (TCS) in each of the transverse planes, while the off-momentum collimation system is located downstream of the crossing and consists of 1 TCP and 2 TCSs in the horizontal plane. The settings for the betatron TCPs are selected to protect the aperture bottlenecks in the final focus doublets, estimated at 15.5 σ [10] (σ is the RMS beam size), with sufficient margin for alignment and beam tolerances [11]. The minimum gap of the TCP is constrained by requirements of the top-up injection scheme [12], requiring a 10.8 σ clearance, as well as by impedance and beam lifetime considerations. Therefore, the horizontal betatron TCP cut was chosen as 11 σ. The vertical betatron TCP is set at 65 σ to ensure a half-gap of at least 2 mm for impedance and mechanical stability reasons. The physical opening is only challenging for the vertical TCP due to the optics and the flat beams (the nominal geometric emittances are $\epsilon_x = 0.71$ nm, $\epsilon_y = 1.42$ pm), with the horizontal TCP having an opening of 5.5 mm. The off-momentum TCP is set to a momentum cut δ_c=1.6%, at the edge of the RF bucket acceptance, relative to a momentum cut in the arcs, δ_a=5.5%. The betatron and off-momentum secondary collimators are set to provide a minimum retraction of 2 σ or 0.1 mm from the corresponding TCP setting, as preliminary values, to ensure the collimation hierarchy is

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Table 1: Summary Table of Collimator Parameters and Settings for the FCC-ee Z Operation Mode

Type	Plane	Material	Length [m]	Gap [σ]
β prim.	H	MoGr	0.4	11.0
β sec.	H	Mo	0.3	13.0
β prim.	V	MoGr	0.4	65.0
β sec.	V	Mo	0.3	75.5
δ prim.	H	MoGr	0.4	29.0
δ sec.	H	Mo	0.3	32.0
SR BWL	H	W	0.1	18.6
SR QC3	H	W	0.1	16.7
SR QT1	H	W	0.1	14.6
SR QT1	V	W	0.1	196.4
SR QC2	H	W	0.1	14.2
SR QC2	V	W	0.1	154.2

maintained even in the case of β-beating or other dynamic effects [13, 14].

The beam halo collimators must be able to handle the loss of a significant fraction of the beam energy, and must therefore be robust. The collimator design parameters are taken from the first dedicated study on the topic [6, 15], and are based on materials used in the Large Hadron Collider (LHC) [16] and the High-Luminosity LHC (HL-LHC) [17]. The TCPs have 0.4 m long molybdenum graphite (MoGr) jaws, while the TCSs have 0.3 m long molybdenum (Mo) jaws. The TCSs are shorter than the TCPs because the less demanding robustness requirements allow a shorter collimator of a more absorptive material. The latest results suggest an updated TCP length of 0.33 m [6], which will be added in the baseline and studied in the future. There are also ongoing studies on the collimator materials [18], which will also be taken into account for future iterations, should better options than the materials chosen for HL-LHC become available. The assumption on the mechanical design is that halo collimators have two movable jaws. The SR collimators are installed upstream of each IP, with 4 movable two-jaw collimators in the horizontal plane and 2 in the vertical plane, for a total of 24 movable SR collimators in the ring. There are also 2 fixed SR masks per IP. The SR collimators must be able to absorb the energy of incoming photons, and feature 0.1 m long tungsten (W) jaws. The fixed SR masks are 2 cm long and also made of tungsten. The SR collimator settings are driven by the geometry and magnetic field configuration of the IR, and have been selected based on a dedicated study of SR propagation in the Machine-Detector Interface (MDI) of the FCC-ee [4]. The collimator parameters and settings are summarised in Table 1.The SR collimators are named based on the closest beam line element.

SIMULATION SETUP

The collimation configuration is studied using the new Xtrack-BDSIM coupling simulation framework [19, 20], which combines particle tracking in the magnetic lattice and particle-matter interactions in the collimators. The clockwise beam 1 with 45.6 GeV positrons is simulated. The cases studied are horizontal (B1H) and vertical (B1V) betatron losses, and off-momentum losses (B1-dp). The scenario considered is that of generic beam halo losses during a beam lifetime drop to 5 min in normal operation, where the beam distribution is sampled directly at the impacted collimator, such that all particles interact with the collimator on the first pass. The impact parameter is 1 μm, which was selected to model the effect of collimator edge scattering and provide a pessimistic estimate of the collimation performance. For the off-momentum loss scenario, the beam is sampled on one of the collimator jaws, corresponding to particles with negative momentum offset and no betatron amplitude. The off-momentum TCP is aligned with the divergence of the dispersive particle trajectory, $x' = \delta_c D'$, by applying a tilt of 123 μrad to the collimator jaws. This tilt was necessary, because otherwise the large angle of incidence would reduce the distance traversed in the collimator and would increase the collimator leakage [6]. In each case, 5×10^6 primary particles are tracked for 700 turns with SR enabled and with the magnetic strengths of the beam line elements adjusted to compensate the orbit shift due to SR energy loss (optics tapering). Particles that have lost more than 85% of the nominal energy are not tracked. All movable collimators are modelled in BDSIM, while the fixed SR masks are modelled as aperture restrictions in Xtrack. The distribution of losses along s is binned in 10 cm intervals and used to compute loss maps in terms of the local cleaning inefficiency $\eta = E_{\text{loss},\Delta s}/(E_{\text{loss, total}}\Delta s)$, where $E_{\text{loss},\Delta s}$ the integrated energy of particles lost in the region $[s, s+\Delta s]$ and $E_{\text{loss, total}}$ is the integrated loss energy over the whole ring.

RESULTS

The loss maps for the full ring is shown in Fig. 1, and a zoom of the collimation insertion PF is shown in Fig 2.

From Fig. 1 it is clear that particles out-scattered by the TCPs are lost over the full circumference of the ring, and in particular near the aperture bottlenecks in the experimental IRs. The collimation system successfully absorbs most of the losses, with >99.96% of all losses concentrated in the collimation insertion PF for all cases simulated. Assessing the beam power loss at 5 min lifetime, only 1.7 W out of the total loss of 59.2 kW are found in the regions ±100 m from the IPs. From the distribution of the losses in PF, shown in Fig. 2, it can be observed that the TCSs absorb a significant fraction of the particles scattered out from the TCPs, with the first vertical TCS experiencing the highest losses for the B1V case. In the off-momentum case, the configuration with the TCP aligned to the beam envelope shows a good efficiency, with all particles stopped on the first turn, and no losses observed beyond PG. It should be noted that for the case of parallel jaws and the same impact parameter, the integrated losses in the downstream PG reach 1.3 kW. The collimator angular alignment has a dramatic effect in the off-momentum simulation scenario, so the sensitivity of losses on the collimator tilt [6], and the operational feasibil-

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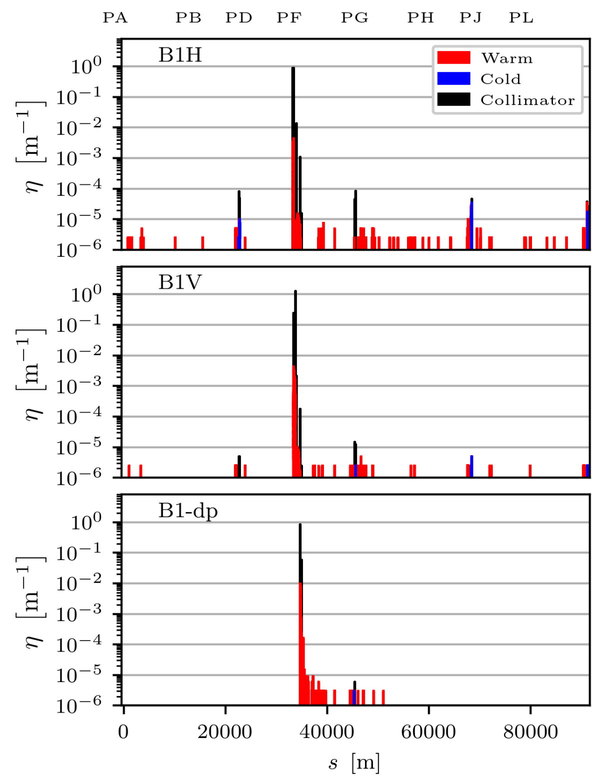

Figure 1: Loss map for collimation losses in the full FCC-ee ring for the Z-mode, showing the studied loss scenarios: betatron horizontal (top), betatron vertical (middle), and off-momentum with tilted primary collimator (bottom).

ity of tilted collimator jaws should be studied in detail. The collimation performance in the betatron loss scenarios is sufficiently good with un-tilted collimator jaws. The maximum recorded incident loss power on any SR collimator is 0.4 W, in PG, for the B1H case. The losses on SR collimators in PG are shown in Fig. 3. The energy deposition and induced backgrounds from beam losses on the SR collimators should be evaluated in future studies. Energy deposition studies are also essential for evaluating the impact of the beam losses on the beam line elements in PF and in the experimental IRs. As the scaling from aperture losses to energy deposition and the equipment loss tolerances are not well defined at this time, it is not possible to make a definitive statement on whether the collimation system performance fulfills the requirements.

CONCLUSION AND OUTLOOK

A collimation configuration for the 4 IP FCC-ee Z mode was developed, including a beam halo and SR collimation system. The configuration was studied in simulations for the loss scenario of beam lifetime drop to 5 min, corresponding to 59.2 kW of beam loss power. Horizontal and vertical betatron losses, as well as off-momentum losses were considered. The halo collimation system demonstrates good loss cleaning, with only up to 1.7 W reaching the IRs, and up to 0.4 W impacting any SR collimator. For the off-momentum losses,

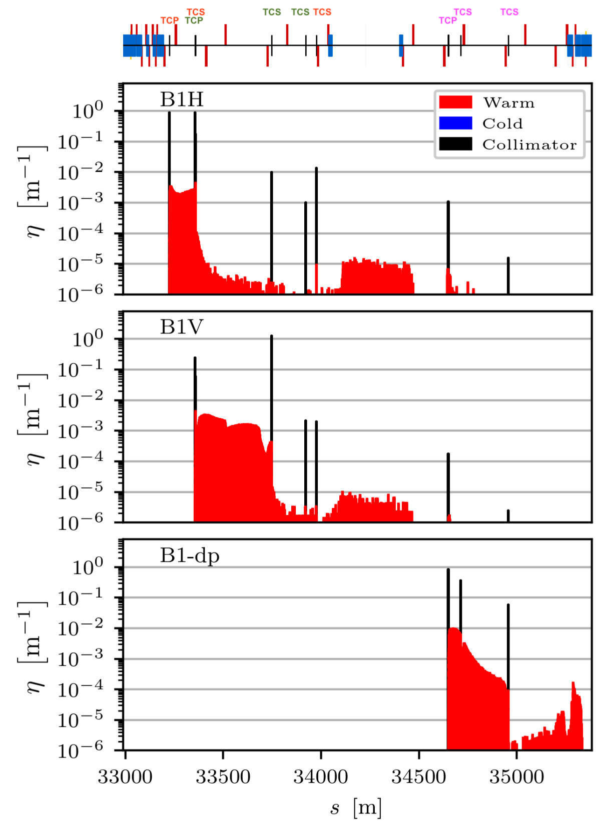

Figure 2: Loss map in the collimation insertion PF for the Z-mode, showing betatron horizontal (top), betatron vertical (middle), and off-momentum with aligned primary collimator (bottom). The beamline elements are shown above, with collimators labelled and coloured by function: hoizontal—orange, vertical—green, off-momentim—magenta.

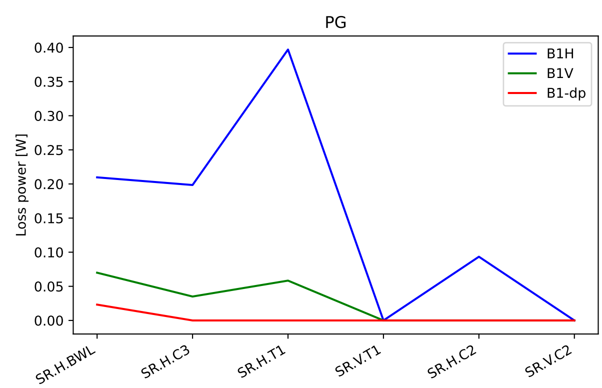

Figure 3: Distribution of the collimation losses on the synchrotron radiation collimators in PG. The beam moves from left to right an the IP is to the right.

the angular alignment of the collimator to the beam envelope was found to be crucial for the cleaning performance. The sensitivity of the losses to the collimator alignment should be studied in the future to validate this approach. Energy deposition studies, loss tolerance estimates for crucial equipment, and detector background studies are needed to fully assess the collimation system performance. The other FCC-ee operating modes and other beam loss scenarios, such as fast failure modes, will be studied in the future.

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