ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA129

BEAM DYNAMICS STUDIES FOR THE FCC-ee COLLIMATION SYSTEM DESIGN

G. Broggi[1,2*], A. Abramov, R. Bruce, CERN, Meyrin, Switzerland
[1]also at Sapienza University of Rome, Rome, Italy [2]also at INFN-LNF, Frascati, Italy

Abstract

The electron-positron Future Circular Collider (FCC-ee) is being designed for stored beam energies up to 20.7 MJ, a value almost two orders of magnitude higher than any previous lepton collider. Considering the risk of any beam losses causing experimental backgrounds, magnet quenches, or even damage, a halo collimation system is under study to protect the most sensitive equipment from unavoidable losses. Beam dynamics and tracking studies are key aspects to evaluate the cleaning performance of the collimation system, and are essential in an iterative process to converge on an optimum performance. The first results of such studies, exploring various configurations of materials and collimator lengths, are presented, including also estimated beam loss distributions around the ring. In addition, an impact parameter scan on the primary collimators is performed to identify the most critical case for the protection of sensitive equipment.

INTRODUCTION

The Future Circular Collider [1] is a design study for a staged circular collider with a circumference of about 90 km, consisting of a luminosity-frontier, highest-energy electron-positron collider (FCC-ee) [2] followed by an energy-frontier hadron collider (FCC-hh) [3]. The FCC-ee layout considered in the following is the one from the 2019 Conceptual Design Report (CDR) [2], see Fig. 1, which foresees two interaction points (IPs) and four operation modes, with multi-MJ lepton beams of energy ranging from 45.6 GeV (Z-operation) to 182.5 GeV ($t\bar{t}$-operation). It is noted that an alternative layout with a slightly reduced circumference and four IPs has been recently proposed [4]. The FCC-ee beams have an inherent destructive capacity; therefore, a collimation system is indispensable, not only to reduce experimental backgrounds, as in present and past lepton colliders, but also to protect sensitive machine components from inevitable beam losses. This work presents the first beam dynamics and tracking studies to evaluate and optimize the cleaning performance of a preliminary FCC-ee collimation system design. This forms a basis that later collimation studies build upon, as the ones presented in Ref. [5]. Two collimator design configurations are considered: one taken over directly from the Large Hadron Collider (LHC) [6] and an updated design based on preliminary considerations on material robustness, thermal stability, and impedance [7]. In addition to the different materials and lengths in the two configurations, we investigate also possible improvements to the cleaning through a tilting of the primary collimator jaws. For the updated configuration, the results of an impact parameter scan on the primary collimators, performed to identify the worst, or critical, impact parameter and provide conservative estimates for the beam loss distribution along the accelerator, are also presented.

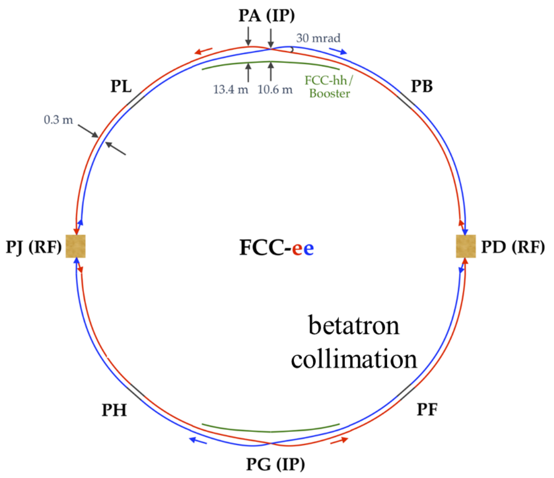

Figure 1: FCC-ee 2IP CDR layout, adapted from [2].

COLLIMATOR DESIGN

The FCC-ee collimation layout considered includes a betatron collimation insertion in the straight section PF, see Fig. 1. The two-stage betatron collimation system [8] includes two primary (TCP) and four secondary (TCS) collimators. Off-momentum and synchrotron radiation (SR) collimators are yet to be included. The LHC collimator geometry has been used as the first starting assumption on the collimator design [9], with 60 cm TCP and 100 cm TCS of Carbon-Fiber reinforced-Carbon composite (CFC) [10]. Possible improvements to this configuration have been studied in Ref. [7], where, from the LHC experience, a first palette of candidate collimator materials consisting of CFC, Molybdenum carbide-Graphite (MoGr) [11], Copper-diamond (CuCD) [12], Glidcop Al-15 (Glidcop) [13], Molybdenum (Mo) [14] and Inermet IT180 (Inermet) [15], has been comparatively assessed. Clearly, additional and more optimized material choices can be considered over the timeline of FCC-ee. An updated configuration consisting of two 33 cm MoGr TCP and four 30 cm Mo TCS has been proposed. This proposal is based on the three figures of merit reported in Ref. [14], namely, the Thermomechanical Robustness Index (TRI, to assess the material robustness against particle beam impacts), the Thermal Stability Index (TSI, to assess the ability of a material to keep geometrical stability under steady-state particle losses) and the Radio Frequency impedance Index (RFI, to assess the contribution of a mate-

---

[*] giacomo.broggi@cern.ch

Table 1: Materials and lengths of the two collimator design configurations considered in this work

	TCP mat.	L_{TCP} [cm]	TCS mat.	L_{TCS} [cm]
CFC-CFC	CFC	60	CFC	100
MoGr-Mo	MoGr	33	Mo	30

rial to the RF impedance). Furthermore, the proposal draws on the experience developed for the Large Electron-Positron collider (LEP) collimation [16,17] and on approximated analytical considerations. More details can be found in Ref. [7]. The main parameters of the CFC-based initial design assumption and of the updated MoGr-Mo-based design are reported in Table 1. In the following sections, the cleaning performance of these two configurations are evaluated and compared through simulations.

SIMULATION SETUP

The Xtrack-BDSIM simulation tool [18–24] is used to simulate losses on collimators for an FCC-ee reference scenario, selected to be horizontal betatron collimation for the highest beam energy operation mode ($t\bar{t}$). Despite not having the highest stored beam energy, in such a scenario the beam experiences the strongest effects of SR on its dynamics. During a run, Xtrack performs magnetic tracking in the accelerator, while BDSIM performs full Monte Carlo particle-matter interaction simulations. The principle resembles the one of the Sixtrack-FLUKA coupling [25–30], used in the context of LHC collimation studies. The optics is the one for the 2IP CDR layout and the mechanical aperture model comes from the first aperture studies for the FCC-ee [31]. A pencil beam distribution, where all the beam particles have identical initial conditions, is generated to impinge the horizontal primary collimator TCP.A.B1 with an impact parameter of 1 μm (this approach is known as *direct halo* [32]). Five million primary positrons are tracked for 700 turns through an ideal machine without imperfections, but included the effects of SR and lattice tapering. The lattice tapering foresees to scale the strengths of all magnets according to the local beam energy taking into account the energy loss due to SR. The g4FTFP_BERT Geant4 physics list [33] is employed to simulate the physics processes and the losses on the aperture are binned in 10 cm intervals to get loss maps showing the loss distribution along the ring.

RESULTS

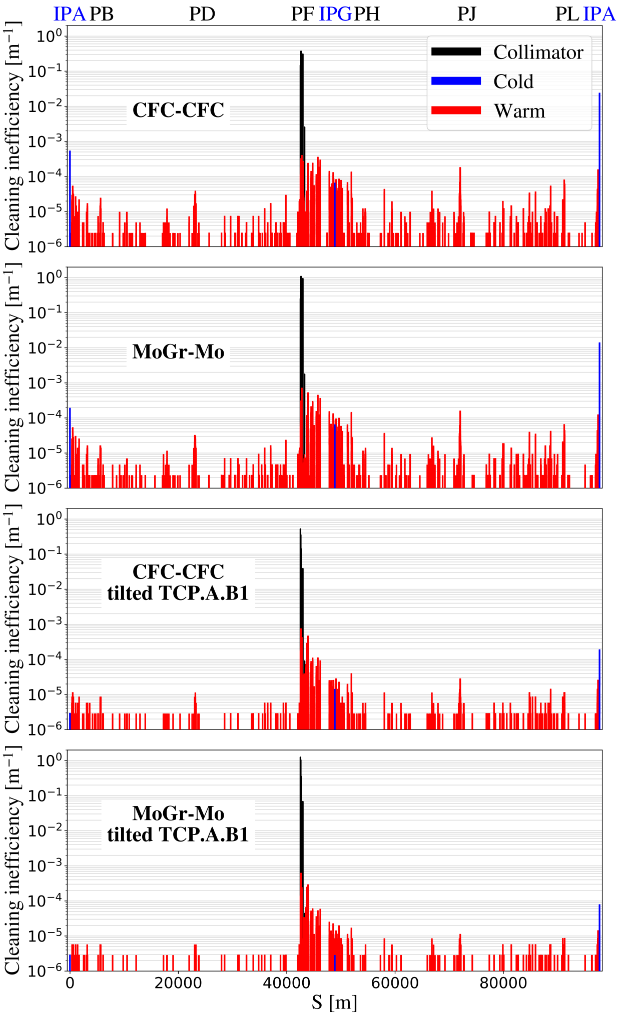

Figure 2: Loss maps showing the beam loss distribution along the FCC-ee ring ($t\bar{t}$-mode). From top to bottom: CFC-CFC design, MoGr-Mo design, CFC-CFC design with tilted TCP.A.B1 and MoGr-Mo design with tilted TCP.A.B1.

The simulation results are reported in Fig. 2 by means of loss maps. The cleaning performance of the configurations considered in the two top plots are similar. Significant losses are observed around the IPs in both cases, but with the MoGr-Mo configuration the peak and integrated cold losses around IPA are reduced of almost a factor of 2. This region is the most critical one, as high cold losses, i.e., losses on superconducting components, are observed. The superconducting components around IPA are the final focusing quadrupoles needed to provide optimized optics for colliding beams. Although not visible from these simulations, the MoGr-Mo choice has the important advantage of having a reduced impact on the global RF impedance, as in this configuration, the collimators are significantly shorter than the CFC-CFC design ones (see Table 1), and the RFI of the proposed materials is significantly better than the CFC one (see Table 2). The similarity in the performance of these two configurations is likely due to the fact that the effective collimator active length is shorter for particles impacting the collimator with large angles and small impact parameters. A possible mitigation strategy includes adjusting the collimator angle or the optics so that particles impacting the collimator will see a higher effective active length. Therefore, simulations in which the primary collimator TCP.A.B1 is tilted to match the beam divergence at the collimator (see Fig. 3), equal to 66.7 μrad, have also been performed.

Table 2: RFI values for the materials employed in the discussed designs. The higher the RFI, the lower the material contribution to the RF impedance. Values from Ref. [14]

	CFC	MoGr	Mo
RFI	0.38	1	4.4

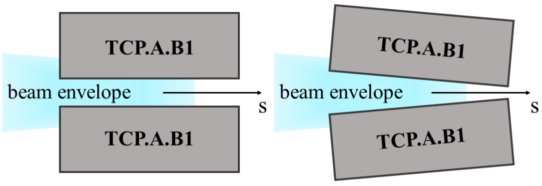

Figure 3: Parallel collimator jaws (left) and tilted collimator jaws aligned to the beam envelope (right).

The loss maps corresponding to this scenario are reported in the two bottom plots of Fig. 2 for both the considered designs. By tilting TCP.A.B1, losses decrease along the whole ring and the increase in the performance with the MoGr-Mo design becomes more evident. In particular, the peak and integrated cold losses around IPA and IPG are reduced by a factor of about 3 and 5 respectively compared to the CFC-based design. The losses that are still visible are likely due to particles escaping TCP.A.B1 before traversing its entire length and successively not intercepted by the TCS. This happens because electrons/positrons traversing matter do not follow a straight path as they are also subjected to angular scattering.

IMPACT PARAMETER SCAN

The impact parameter can be defined as the transverse depth into the collimator jaw at which a particle is intercepted at its first hit. For collimation simulation studies, beams with the worst impact parameter are typically simulated to provide a conservative estimate of the cleaning performance. This is particularly important since the actual impact parameters in the real machine are difficult to simulate and measure. This is due to the fact that the physical processes leading to beam losses, and hence the resulting impact parameter, are typically very sensitive to imperfections, non-linearities, corrections, etc., which are effectively impossible to know accurately for all the installed elements. The worst, or critical, impact parameter is the one that leads to the largest fraction of total losses reaching given critical regions of the machine. The dependence of this figure of merit on the impact parameter, and the critical impact parameter value, are determined in *impact parameter scans*. Considering the MoGr-Mo design, Xtrack-BDSIM simulations are performed to carry out this analysis. The scan is performed for the three scenarios reported in Table 3.

Table 3: Scenarios simulated for the impact parameter scan

	SR	**tapering**	**TCP.A.B1 tilted**
NO R&T	✗	✗	✗
R&T	✓	✓	✗
R&T + tilt	✓	✓	✓

The case without radiation and tapering (NO R&T) is simulated to allow the study of a simplified scenario that is more comparable to the well-known LHC case. More details can be found in Ref. [7]. The integrated losses from 6 m upstream of IPA to 6 m downstream of IPA are chosen as representative quantities for the overall cleaning performance. The scan result is reported in Fig. 4, where an impact parameter of 1 μm gives the highest losses in the NO R&T case which goes down to 0.1 μm in the R&T case and further down to 0.05 μm in the R&T + tilt case. Higher losses are observed for the R&T case, but the addition of collimator tilt reduces the losses even beyond the NO R&T case.

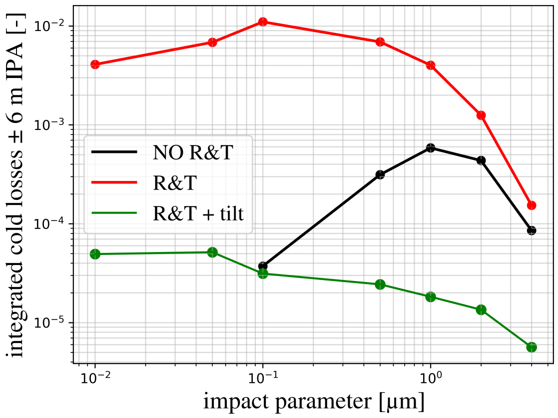

Figure 4: Impact parameter scan result without radiation and tapering (NO R&T), with radiation and tapering (R&T) and with radiation and tapering with TCP.A.B1 aligned to the beam divergence (R&T + tilt).

CONCLUSION AND OUTLOOK

First beam dynamics and tracking studies have been conducted to address the FCC-ee collimation design. The studies compared the cleaning performance of an updated MoGr-Mo-based collimation system design to the previous CFC-based design assumption. The MoGr-Mo design showed better cleaning performance, in particular when aligning the collimators to the beam divergence, which on its own is found to bring a large gain in performance. This is a promising result and an important input to future studies that the collimator jaws must be aligned to the beam envelope. The sensitivity to any small errors on the angular alignment must be carefully investigated, along with alternative mitigation strategies, such as optics adjustments. The outcome of these studies forms a first basis for further studies on beam losses, robustness and impedance, which are all key studies in the iterative process leading to a final collimation system design. The full engineering design of the FCC-ee collimation system is well beyond the scope of this study; therefore, alternative configurations will be studied in the future, also taking into account the ongoing research and development in the material field (see for instance Ref. [34]). An impact parameter scan identified critical impact parameters in different scenarios, which is an essential input for future simulation campaigns needed to quantify the performance of the collimation system in relation to beam loss tolerances. Future developments of this work include the repetition of these studies for the other FCC-ee operation modes, starting from the Z, the one with the highest stored beam energy. Additionally, these studies will be repeated for the alternative 4IP layout recently proposed.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA129

REFERENCES

[1] A. Abada *et al.*, “FCC Physics Opportunities,” *Eur. Phys. J. ST*, vol. 79, no. 6, 2019, p. 474.

[2] A. Abada *et al.*, “FCC-ee: The Lepton Collider,” *Eur. Phys. J. ST*, vol. 228, no. 2, 2019, pp. 261–623.

[3] A. Abada *et al.*, “FCC-hh: The Hadron Collider,” *Eur. Phys. J. ST*, vol. 228, no. 4, 2019, pp. 755–1107.

[4] J. Keintzel, A. Abramov, M. Benedikt, M. Hofer, P.J. Hunchak, K. Oide, *et al.*, “FCC-ee Lattice Design”, in *Proc. 65th ICFA Adv. Beam Dyn. Workshop High Luminosity Circular e+e- Colliders (eeFACT’22)*, Frascati, Italy, Sep. 2022, pp. 52–60. `doi:10.18429/JACoW-eeFACT2022-TUYAT0102`

[5] A. Abramov, *et al.*, “Studies of layout and cleaning performance for the FCC-ee collimation system.” presented at IPAC’23, Venice, Italy, May 2023, paper MOPA128, this conference.

[6] O. Brüning *et al.*, “LHC Design Report v.1 : the LHC Main Ring,” *CERN Report*, no. CERN-2004-003-V1, 2004.

[7] G. Broggi, “First Study of Collimator Design for the FCC-ee,” Master’s thesis, Politecnico di Milano, 2022.

[8] M. Hofer, *et al.*, “Layout and Optics for a Collimation Section in FCC-ee,” *FCC week 2021 (contributed talk)*, 2021.

[9] A. Abramov, *et al.*, “FCC-ee Aperture and Collimation,” *FCC week 2021 (contributed talk)*, 2021.

[10] “CGT Carbon web site.” `https://cgt-carbon.com/carbon-fiber/cfc-material`.

[11] J. Guardia-Valenzuela *et al.*, “Development and properties of high thermal conductivity molybdenum carbide - graphite composites,” *Carbon*, vol. 135, 2018, pp. 72–84.

[12] M. Portelli *et al.*, “Thermomechanical Characterisation of Copper Diamond and Benchmarking with the MultiMat Experiment,” *Shock Vib.*, 2021, pp. 72–84.

[13] “Höganäs AB Glidcop AL-15 Data Sheet.” `https://www.hoganas.com/en/powder-technologies/products/glidcop/glidcop-al-15/`.

[14] A. Bertarelli, “Beam-Induced Damage Mechanisms and their Calculation,” *CERN Yellow Reports*, vol. 2, 2016, pp. 159–227.

[15] “Plansee web site: Tungsten-based composites.” `https://www.plansee.com/en/materials/w-mmc.html`.

[16] “LEP design report, v.2: The LEP main ring,” *CERN Report*, no. CERN-LEP-84-01, 1984.

[17] G. Von Holtey, “Electron beam collimation at LEP energies,” in *Proc. PAC ’87*, Washington D.C., March 1997, pp. 1252–1254.

[18] A. Abramov *et al.*, “Collimation simulations for the FCC-ee,” 2023, submitted to JINST.

[19] “Xsuite website.” `https://xsuite.readthedocs.io/en/latest/`.

[20] L. Nevay, *et al.*, “BDSIM: An accelerator tracking code with particle–matter interactions,” *Comput. Phys. Commun.*, vol. 252, 2020, p. 107200.

[21] L. Nevay, *et al.*, “BDSIM: Automatic Geant4 Models of Accelerators,” in *Proc. ICFA Mini-Workshop on Tracking for Collimation*, CERN, Geneva, Switzerland, 2018, p. 45.

[22] J. Allison, *et al.*, “Recent developments in Geant4,” *Nucl. Instrum. Methods. Phys. Res. B*, vol. 835, 2016, pp. 186–225.

[23] S. Agostinelli, *et al.*, “Geant4—a simulation toolkit,” *Nucl. Instrum. Methods. Phys. Res. A*, vol. 506, no. 3, 2003, pp. 250–303.

[24] J. Allison, *et al.*, “Geant4 developments and applications,” *IEEE Trans. Nucl. Sci.*, vol. 53, Feb 2006, pp. 270–278.

[25] R. De Maria *et al.*, “SixTrack Version 5: Status and New Developments”, in *Proc. IPAC’19*, Melbourne, Australia, May 2019, pp. 3200–3203. `doi:10.18429/JACoW-IPAC2019-WEPTS043`

[26] “Sixtrack web site.” `http://sixtrack.web.cern.ch/SixTrack/`.

[27] G. Battistoni, *et al.*, “Overview of the FLUKA code,” *Annals Nucl. Energy*, vol. 82, 2015, pp. 10–18.

[28] C. Ahdida, *et al.*, “New Capabilities of the FLUKA Multi-Purpose Code,” *Front. Phys.*, vol. 9, 2022, pp. 788253.

[29] “FLUKA web site.” `https://fluka.cern/`.

[30] E. Skordis, *et al.*, “FLUKA coupling to Sixtrack,” in *Proc. ICFA Mini-Workshop on Tracking for Collimation*, CERN, Geneva, Switzerland, 2018, p. 17.

[31] M. Moudgalya, “First studies of the halo collimation needs in the FCC-ee,” Master’s thesis, Department of Physics, Imperial College London, 2021.

[32] R. Bruce, *et al.*, “Simulations and measurements of beam loss patterns at the CERN Large Hadron Collider,” *Phys. Rev. ST Accel. Beams*, vol. 17, Aug 2014, p. 081004.

[33] M. Novak, “Physics list,” *First Geant4 Tutorial Workshop in Sao Paulo (contributed talk)*, Instituto de Física da Universidade de São Paulo, Feb 2019.

[34] A. Perillo-Marcone, *et al.*, “Beam absorbing material candidates for primary collimators for FCC-ee.” presented at IPAC’23, Venice, Italy, May 2023, paper MOPL060, this conference.