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Challenges of present and future e^+e^- circular colliders

Collimation simulations for the FCC-ee

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Abstract: The collimation system of the Future Circular Collider, operating with leptons (FCC-ee), must protect not only the experiments against backgrounds, but also the machine itself from beam losses. With a 17.8 MJ stored energy of the electron and positron beams, they are highly destructive, and beam losses risk to cause damage or a quench of superconducting elements. Accurate collimation simulation tools and models are needed to design the collimation system and optimize the collimation performance, including magnetic tracking, synchrotron radiation and optics tapering, as well as particle-matter interactions. As no existing code was found that incorporated all these features, a new simulation software tool has been developed. The tool is based on an interface between a particle tracking engine, pyAT or Xtrack, and a Monte-Carlo particle-matter interaction engine for collimator scattering, BDSIM, which is based on Geant4. Results from a simulation of edge scattering from a beam halo collimator in the FCC-ee are presented to demonstrate the capabilities of the tool.

Keywords: Accelerator modelling and simulations (multi-particle dynamics, single-particle dynamics); Simulation methods and programs

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2024 JINST 19 T02004

Contents

1 Collimation at the FCC-ee

The lepton Future Circular Collider (FCC-ee) [1] is a design study for an electron-positron collider with a circumference of around 90 km and 4 operating modes with different beam energies aimed at studying different particles — 45.6 GeV (Z), 90 GeV (W), 120 GeV (H), and 182.5 GeV ($t\bar{t}$). With the current parameter set [2], the stored beam energy reaches 17.8 MJ for the Z operating mode. Such beams can be highly destructive and introduce a risk of superconducting magnet quenches, material damage, as well as radiation damage and activation of equipment close to the beam line. A robust collimation system is necessary to ensure the safe operation of the collider under these conditions.

Typically, the goal of a collimation system for a lepton collider is the control of backgrounds to the experiments from collision processes and single-beam processes. Collision backgrounds originate at the interaction points (IPs) due to processes such as radiative Bhabha scattering, while single-beam backgrounds arise from processes like synchrotron radiation, Touschek scattering, beam-gas interactions, and local beam losses. Previous lepton colliders such as the Large Electron Positron collider (LEP) [3] and PEP-II [4] had collimation systems designed with the main goal of controlling detector backgrounds. The modern SuperKEKB facility [5] is designed to reach a luminosity of $8 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, with the beam current reaching 3.6 A for the 4 GeV positron low-energy ring (LER), and 2.6 A for the 7 GeV electron high-energy ring (HER). In the SuperKEKB HER ring, the design stored beam energy reaches 0.18 MJ, and controlling beam losses becomes important also for protecting equipment. There are reports of higher than expected detector backgrounds, as well as damage to collimators and quenching of superconducting magnets as a result of sudden, unexpected beam losses [6]. The SuperKEKB collimation system is undergoing continuous optimization to improve the control of the backgrounds and the protection of equipment from beam losses. This experience highlights the importance of lepton collider collimation system design ahead of deployment, and the inherent damage potential of high-intensity beams. The FCC-ee Z mode will have around 2 orders of magnitude higher stored beam energy than the SuperKEKB

2024 JINST 19 T02004

HER, and a factor 6.5 higher energy, further exacerbating the challenges. In the domain of hadron colliders, The Large Hadron Collider (LHC) has a design stored proton beam energy of 362 MJ, which has already been exceeded in 2022 operation, and uses an advanced multi-stage collimation system to protect the superconducting magnets from beam losses [7–9]. While the FCC-ee stored beam energy is significantly lower than the nominal LHC proton beam stored energy, it is comparable to LHC heavy-ion stored beam energy of 20.5 MJ [10]. The LHC could not operate with ion beams without a sophisticated collimation system. Given the unprecedented stored beam energy, it is hence necessary to design the collimation system of the FCC-ee, drawing on the experience from both lepton colliders and hadron colliders.

In addition to the high stored beam energy, the FCC-ee is subject to significant constraints when it comes to the collimation system design. The aperture bottlenecks for most operating modes are found in the final focus quadrupole doublet [11]. These are superconducting and will be installed partially inside the physics experiment detectors, as part of the Machine-Detector Interface (MDI). This is one of the most sensitive areas in the collider and beam losses there can lead to a risk of superconducting magnet quenches, excess heat loads, and detector backgrounds.

A betatron collimation system must be set to protect the aperture bottlenecks with sufficient margin to allow for beam size beating, orbit fluctuations, and other effects. At the same time, the minimum aperture of the collimators is constrained by several requirements. The first constraint is selecting collimation system settings that do not cut into the stable beam core, to avoid unnecessary losses and limit the impact on the beam lifetime and luminosity. Another limitation is the beam impedance. The primary collimators are the closest devices to the beam and have a large contribution to the impedance. The top-up injection scheme [12] is also a constraint. To maintain a constant current, a top-up injection scheme, using a full energy Booster, is foreseen for the FCC-ee, with several top-up injection schemes considered [13]. In order to allow for the injection, the injected bunch must have enough clearance from the aperture-limiting collimators, even in the presence of injection oscillation, and dynamic orbit and beta beating effects.

Balancing these requirements to manage both the Synchrotron Radiation (SR) photon and beam losses in the FCC-ee requires detailed simulation studies. It is essential that the simulation studies can accurately represent the beam dynamics and the key operational aspects, as well as the relevant sources of beam losses and perturbations. This paper outlines the challenges for beam collimation simulations for future high-energy lepton colliders and the software developments intended to address them.

2 Challenges for collimation simulations

One of the main types of studies performed for the collimation system include tracking an ensemble of macro-particles around the accelerator, simulating their interactions with the collimators and recording the loss positions. Such studies are performed routinely for the LHC [7], however, there are several factors that make such studies very challenging for the FCC-ee.

2.1 Particle tracking in the accelerator lattice

The large ring size places stringent requirements on the accuracy and efficiency of the particle tracking algorithms used. Collimation tracking studies typically involve a large number of primary particles tracked over hundreds to thousands of turns. In a 90 km ring, containing many thousands

2024 JINST 19 T02004

of magnetic elements, the tracking speed can become a bottleneck for the studies. Furthermore, to ensure accuracy, electron beam dynamics aspects, most notably SR, must be included in the model. This has additional implications for the FCC-ee, as the orbit offset accumulated due to SR emission must be compensated. In the case of the $t\bar{t}$ mode, this effect is so significant that no stable closed orbit exists if the SR orbit offset is not compensated. The compensation is achieved by scaling the magnetic strength of elements along the ring with the local momentum offset δ [1]. This is referred to as optics tapering, and is another required feature of particle tracking tools used for the FCC-ee. Furthermore, to optimize the luminosity, the FCC-ee is implementing the virtual crab-waist collision scheme using pairs of crab sextupoles around the interaction points [14]. The crab sextupoles and chromaticity correction sextupoles introduce strong non-linearities, which can have a significant impact on the beam. In particular, for particles at large amplitudes in the 6D phase space, such as the beam halo, the effect of the non-linearities can severely impact the available dynamic aperture. It is hence important to model the particle tracking with an element-by-element lattice, including non-linear elements. The effect of magnetic and alignment errors can further affect the beam distribution and reduce the dynamic aperture even further. These requirements have been previously identified for dynamic aperture studies [14, 15]. For collimation tracking studies, where the loss location of the tracked particles must be accurately determined, an accurate aperture model is also required. Definitions of all aperture profiles around the ring must be provided, including mechanical and beam tolerances affecting the available aperture. The beam dynamics at the FCC-ee will also be uniquely impacted by collision effects. For example, Beamstrahlung, the emission of synchrotron radiation in the magnetic field of the other beam during bunch crossings, is one of the effects limiting the luminosity and beam lifetime at the FCC-ee [16]. The effect of Beamstrahlung on the collimation studies should be studied in detail, together with other effects such as SR damping, and imposed as a requirement for tracking studies if a significant impact is observed.

2.2 Particle-matter interaction in the collimators

When electrons and positrons from the beam are intercepted by the collimators, they interact with the material [17, 18]. The main processes of interest for collimation are energy loss via radiative and ionization processes and angular deflection through multiple Coulomb scattering. The interaction cross-sections σ depend on the energy of the beam particle and the properties of the material, $\sigma = \sigma(E, A, Z)$, where E is the energy of the incoming particle, and Z, A are the atomic and mass numbers of the target material. For high-energy electrons and positrons, the energy loss is dominated by Bremsstrahlung, the emission of photons in the field of the material ions. These effects can be treated using statistical or approximate methods, but for the effect on individual particles, Monte Carlo particle-matter interaction packages offer the most accurate treatment [19]. Incorporating a microscopic scattering routine for interactions with the collimators, or a connection with a Monte Carlo physics engine, is hence a requirement for collimation tracking studies.

Another important effect is the dependence of the path length inside the collimator on the incidence parameters of the particle. The distance traversed in the collimator is determined by the collimator geometry and the coordinates of the incident particle. The impact parameter b is defined as the depth of the impact from the longitudinal edge of the collimator. The distance traversed in the collimator is determined by the impact parameter, the optical functions at the collimator location, and the collimator geometry. Shallow impact parameters or large angles of incidence can result in

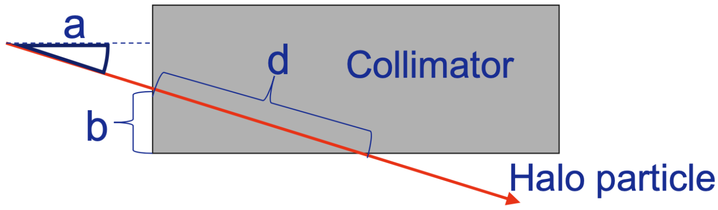

Figure 1. A simplified schematic of a particle impacting a collimator, showing the impact parameter b, the incidence angle a, and the distance traversed in the collimator d.

the particle escaping the collimator before interacting with the full length of absorptive material. The escaping particle can be within the mechanical and momentum aperture of the accelerator, leading to collimator leakage and causing de-localised losses. This effect is referred to as the transparent edge effect in LEP literature [20]. Recent reports from SuperKEKB [21] indicate that this effect is responsible for detector backgrounds, which were not captured by initial simulations.

3 Software development

Developing and maintaining software for FCC-ee studies is crucial at the early design stages, but there are numerous challenges involved [22]. For collimation simulations for the FCC-ee, the goal was to develop and benchmark a stable and scalable software platform, based as much as possible on existing and proved tools. The general methodology for collimation simulations was inspired from the LHC collimation studies. For the LHC, the most common software for collimation simulations is SixTrack [23, 24] in combination with a scattering routine for collimator interactions [7, 25]. The scattering routine can be a built-in one such as K2 [26] and Merlin [27], or a coupling to a Monte Carlo particle-matter interaction package such as FLUKA [28, 29] and Geant4 [30–32]. In the SixTrack-FLUKA coupling framework [33–35], SixTrack performs tracking in the magnetic lattice and FLUKA simulates the physics interactions in detailed geometry models of collimators. While lepton beams can be defined and tracked in the SixTrack-FLUKA coupling, SR is not supported, which makes this framework less suitable for FCC-ee studies. For the FCC-ee it was decided to implement a coupling between a particle tracking engine for magnetic lattice tracking, which includes additional effects such as SR and tapering, potentially including new implementations, with a particle-matter interaction engine for collimator scattering.

To select a particle tracking engine, a review of existing software packages was carried out, in view of the challenges previously discussed. The tracking engines considered included MAD-X [36], Merlin++[27, 37], pyAT [38], SixTrack, and Xtrack [39]. Software considered, but not tested included SAD, BMAD, and ELEGANT. The tools shortlisted for further development were pyAT and Xtrack, because of their performance and the ease of integration with an external collimator scattering routine. pyAT is the Python interface to the Accelerator Toolbox [40] tracking library. It is extensively used in light sources, and supports optics matching, 6D tracking with SR, and aperture loss recording for electron and positron beams. Xtrack is part of the new Xsuite collection of Python packages, and also supports the features outlined in section 2.

For the collimator scattering routine, Geant4 was selected as a starting point. It is planned to also use other scattering routines, such as FLUKA, in the future. Geant4 is a C++ package for the simulation of particle passage through matter, which includes a comprehensive selection of interaction processes for electron and positron beams, 3D geometry modelling tools, and support for arbitrary material definitions. Geant4 is a library and a specific implementation is required to use it. Rather than developing a custom code base for FCC-ee collimation using Geant4, the BDSIM [41] software was used, building upon an existing interface between SixTrack and BDSIM, previously developed for LHC collimation studies. BDSIM is a C++ package for simulating energy deposition and charged particle backgrounds in accelerator beam lines. It handles the preparation of Geant4 models, including geometry, materials, physics lists setup, as well as input and output. BDSIM has previously been used for studies of proton and heavy-ion collimation in the LHC, on its own, or coupled with SixTrack [42, 43]. The BDSIM interface to SixTrack was adapted for use with Xtrack and pyAT via a dedicated C++ to Python interface, called collimasim [44]. The advantage of this approach, depicted in figure 2, is that the data exchange between the tracking and the collimator scattering routines is performed dynamically at run time in a single computational process, rather than via output files in a multi-stage workflow or network ports.

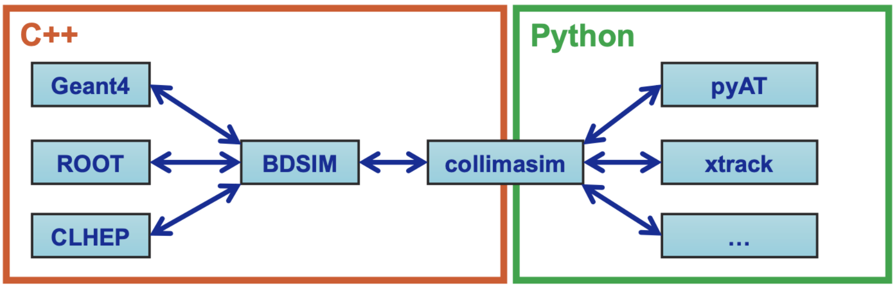

Figure 2. Schematic of the coupling between a tracking engine and a particle-matter interacting engine for collimator scattering. ROOT and CLHEP are C++ packages used by BDSIM, in addition to Geant4.

The initial distribution of particles is tracked in the tracking engine until a collimator is reached. Then the particles are transported to the Geant4 model, where the scattering is simulated, and eligible surviving particles are returned for further tracking. The Monte Carlo model is made up of individual collimator 3D geometry models, isolated in boxes of infinite absorber to eliminate cross-talk, as shown in figure 3, in a fashion similar to the SixTrack-FLUKA coupling, generated at run-time based on the collimator orientation and opening given in the inputs. The transforms from the tracking code to the correct collimator model are handled automatically. Currently, only block-jaw collimators are supported, but in the future arbitrary collimator geometries can be defined, using Geant4's GDML geometry description format.

When developing novel simulation tools, benchmarking must be performed to ensure the accuracy. The new software tools have been benchmarked for the FCC-ee against the SixTrack-FLUKA coupling for a fictitious case without SR and optics tapering, while pyAT-BDSIM and Xtrack-BDSIM were benchmarked against each other with SR and tapering. Results from the benchmarks between Xtrack-BDSIM and pyAT-BDSIM for the FCC-ee are discussed in section 4, with additional details reported in [45].

2024 JINST 19 T02004

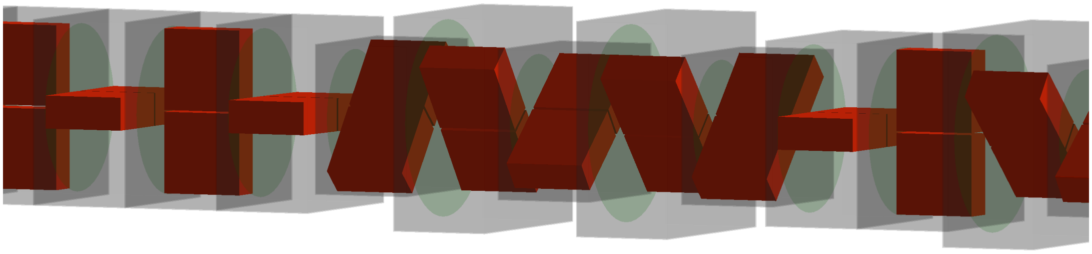

Figure 3. A visualization of an example BDSIM model used for collimator interactions, showing the collimator models (red) and the isolated cells (grey).

In addition to this, it should be noted that both Xtrack and BDSIM support hadrons as a primary particle type. Therefore, the newly developed tool can, in addition to the lepton studies, be used to study the collimation performance in, e.g., proton machines such as the LHC. This provides a big advantage and increased flexibility, since the same tool can be used to study collimation in a wide range of machines without the user needing to re-learn dedicated tools, and benchmarks can be performed against data from existing hadrons machines, such as the LHC. Therefore, Xtrack-BDSIM has been successfully benchmarked against SixTrack and the SixTrack-FLUKA coupling for LHC proton collimation, as well as compared to LHC proton measurements [46]. It is foreseen in the future to benchmark the new code with data from a lepton machine as well.

Planned future development of the collimation tools includes a coupling to FLUKA for collimator scattering, which will enable additional studies and benchmarks. In addition to this, as part of an FCC software framework development project funded by CHART [47], investigation is ongoing about the integration of interactions at the collision points to the simulations, including weak-strong beam-beam interaction, Beamstrahlung, and Bhabha scattering. There are ongoing developments of the Xsuite libraries that have focused on adding support for these features [48].

4 Collimation simulation benchmarking for the FCC-ee

In this section, an example of a complete collimation tracking study using the new pyAT-BDSIM and Xtrack-BDSIM frameworks for the FCC-ee is presented. The study presented is based on first assumptions about the collimation system, and it is primarily focused on the software tools. Details on the latest design of the FCC-ee collimation system are presented in other works [49], and are planned to be included in a dedicated future publication. The study is focussed on beam halo collimation for the FCC-ee 2 IP CDR layout [1] and the optics version 18.1 [50]. The model has 2 IPs located in the straight sections PA and PG, RF systems located in PJ and PD, and technical insertions located in PB, PF, PH, and PL. The lattice includes sextupoles, but does not include beam-beam interactions nor alignment and magnetic errors. A two-stage betatron collimation system is installed in the straight section PF [51], with the collimation stages placed at the optimal phase advance in each transverse plane following the method in [52]. Off-momentum collimation is not considered, but will be included in future studies. The collimator geometries used for the first tests are based on LHC collimators, with 0.6 m Carbon Fibre Composite (CFC) primary collimators, and 1 m CFC secondary collimators. This starting point is chosen over designs with more absorbing,

2024 JINST 19 T02004

high-Z materials due to robustness considerations in view of the multi-MJ stored beam energy. Optimisation of the collimator design parameters for loss cleaning, robustness, and impedance, is ongoing. There is one primary and two secondary collimators per transverse plane. The $t\bar{t}$ beam mode is considered, and the clockwise beam 1 is simulated (positrons, 182.5 GeV). This operating mode is not the most critical for collimation, with 0.28 MJ stored beam energy, but it has the highest beam energy and therefore the strongest effect of the SR on the beam dynamics. The collimation settings are preliminary and selected to protect the aperture bottleneck, which is around 15σ for the $t\bar{t}$ mode [11], where σ is the RMS beam size. The collimator settings are summarized in table 1.

Table 1. Collimator settings for the $t\bar{t}$ operation mode. The openings are shown in units of beam size (σ).

Collimator	Type	Plane	S position [m]	Opening [σ]
TCP.A.B1	Primary	H	42541.7	10
TCP.B.B1	Primary	V	42546.7	80
TCS.B1.B1	Secondary	V	42589.7	89.5
TCS.A1.B1	Secondary	H	42642.5	11.5
TCS.A2.B1	Secondary	H	42982.3	11.5
TCS.B2.B1	Secondary	V	43288.2	89.5

The aperture model features a 35 mm radius circular beam pipe in the arcs and a 15 mm radius inner beam pipe around the IPs, including the aperture transitions. Fixed masks and collimators in the MDI, optimized for absorbing SR photons, are foreseen for the FCC-ee, but are not included in the simulation model presented. It should be noted that optimizing the beam loss and SR backgrounds performance are separate, but closely connected studies, and future work will focus on delivering an integrated design. The SR collimation studies for the 2 IP lattice model suggest SR collimator settings around 15 σ_x [53], which is comparable to the aperture bottlenecks found and means that the SR collimators will have to be treated as part of the beam collimation hierarchy. The aperture is defined for each magnetic element and interpolated to 10 cm intervals during the simulation run for improved loss location resolution in both simulation tools. The aperture interpolation used is linear in Xtrack and nearest neighbour in pyAT. The lattice definition is exported from MAD-X to pyAT and Xtrack. It should be noted that pyAT uses a thick-lens lattice description, while Xtrack uses a thin-lens one.

The beam loss scenario is generalized horizontal betatron losses, which means particles with a large transverse amplitude, intercepted by the horizontal primary collimator. This loss scenario is designed to cover slow beam diffusion processes, as a result of which particles from the beam core drift out to larger amplitudes, populating the beam halo and eventually being lost on the primary collimator. The actual process is not simulated, instead the initial distribution is sampled at the collimator, with an impact parameter of 1 µm. The impact parameter is selected from a previously-performed impact parameter scan, such that it gives the worst collimation performance. The worst impact parameter is used for all simulated particles in order to obtain a pessimistic performance estimate and to probe the beam loss distribution arising from the collimator leakage. 5×10^6 primary positrons are tracked for 200 turns with SR and optics tapering.

The particle losses are presented in figure 4 in terms of the local cleaning inefficiency η [54],

$$\eta\ [\mathrm{m}^{-1}] = \frac{E_{\mathrm{loss},\Delta\mathrm{s}}}{E_{\mathrm{loss,total}}\Delta s}, \tag{4.1}$$

where $E_{\mathrm{loss},\Delta\mathrm{s}}$ is the integrated energy-weighted particle loss count in a region $[s, s + \Delta s]$, and $E_{\mathrm{loss,total}}$ is the integrated energy-weighted particle loss count over the whole circumference. Losses on the aperture in the final superconducting quadrupole magnets in the region ±8 m from each IP are marked as 'cold', whereas losses on the aperture in normal conducting elements in the rest of the ring are marked as 'warm'. It should be pointed out that the beam screen is warm in the whole machine, including in the superconducting final focus quadrupoles.

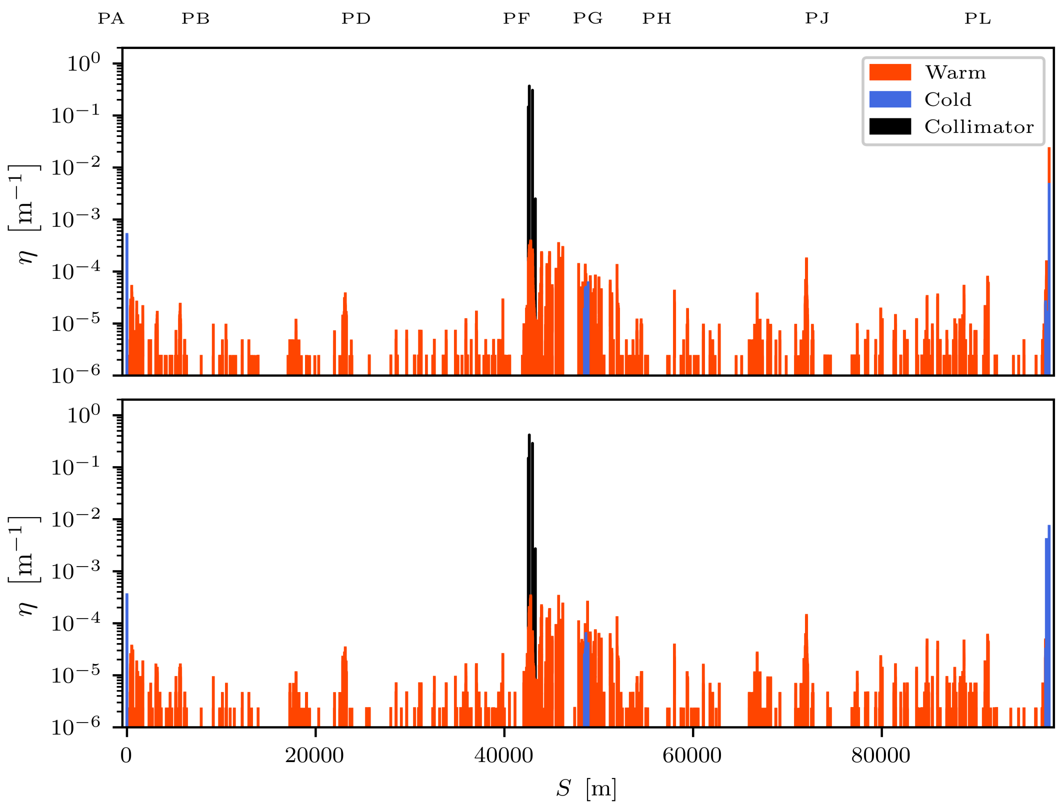

Figure 4. Horizontal betatron loss map for beam 1 in the FCC-ee $t\bar{t}$ mode, from Xtrack-BDSIM (top) and pyAT-BDSIM (bottom). Cold and warm losses refer to losses in superconducting and normal conducting elements respectively. The locations of the straight sections PA–PL are labelled on top. The beam moves from left to right.

In the resulting loss map in figure 4 it can be observed that the losses from particles escaping the primary collimator occur over the whole circumference of the accelerator. The agreement between pyAT-BDSIM and Xtrack-BDSIM with SR and optics tapering is good. Small differences can be observed, mainly around $s = 47$ km and $s = 97$ km, but this was found to be an effect of the different aperture interpolation methods. This is a valuable benchmark, because pyAT and Xtrack have entirely separate input preparation methods, optical function calculation routines, and

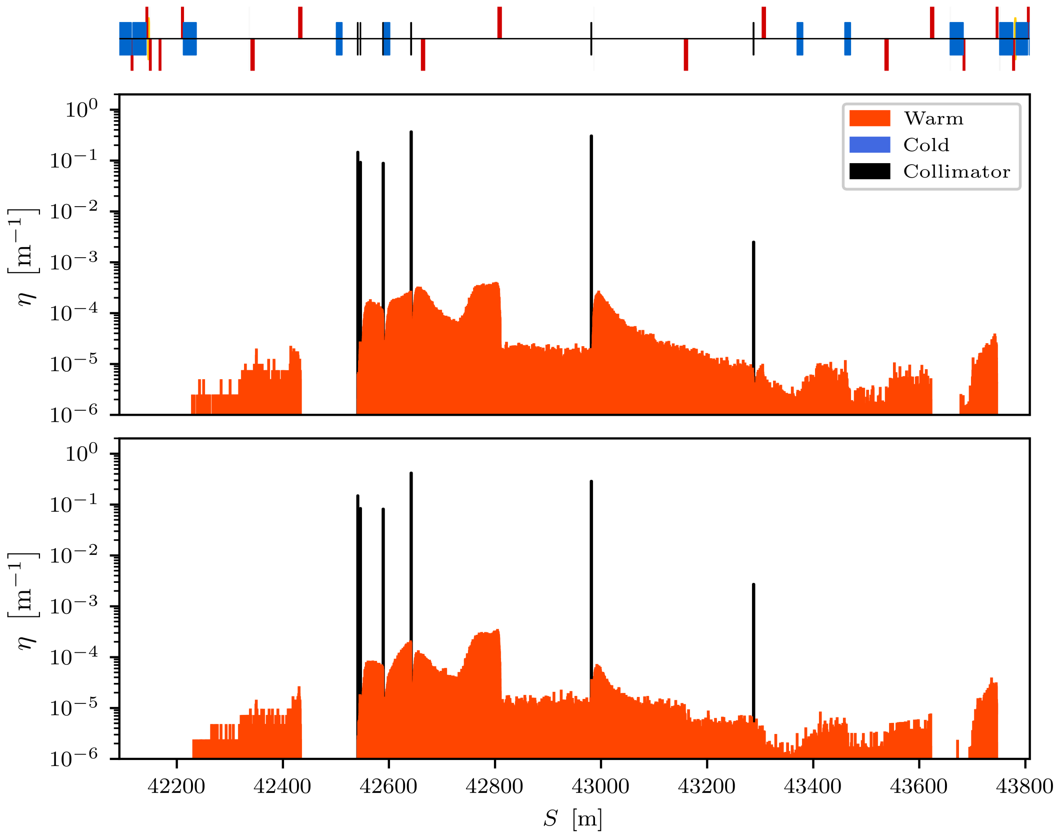

Figure 5. Horizontal betatron loss map for beam 1 in the FCC-ee $t\bar{t}$ mode, from Xtrack-BDSIM (top) and pyAT-BDSIM (bottom). Zoom view of the collimation insertion PF. The magnetic elements are depicted on top: dipole-blue, quadrupole-red, sextupole-yellow, collimator-black. The beam moves from left to right and the collimator loss bars depicted correspond to the collimators listed in 1.

tracking algorithms. The loss distribution on the collimators and the aperture in the collimation insertion, PF, is shown in figure 5. It can be observed that losses from particles out-scattered by the primary collimator occur over the whole length of the insertion, with more than 96% of all the losses in the simulation concentrated in this region, mostly on the collimators. The escaping particles have a broad distribution in the transverse coordinates and momentum, due to the scattering in the collimator, which introduces a mismatch to the lattice. They are also subject to effects like SR and sextupole kicks, meaning that the resulting loss distribution is influenced by both the phase advances from the collimators and the non-linear beam dynamics. Element-by-element tracking in the full magnetic lattice is hence important to capture all loss pattern features. The same loss pattern is reproduced in both pyAT-BDSIM and Xtrack-BDSIM, with only minor differences. For this loss scenario, the maximum losses are recorded on the first horizontal secondary collimator (TCS.A1.B1 from table 1), which is not directly impacted by primary beam particles. This highlights the need to perform dedicated energy deposition simulations in the future to characterise the impact of beam losses on all elements in the collimation insertion.

It can be seen in figure 4 that a small fraction of the losses reach the experimental insertions, PA and PG, and cause losses in the superconducting final focus quadrupoles. The losses in PG are significantly lower than the losses in PA, which is an effect of the scattered particle propagation through the lattice. The current value for the minimum beam lifetime, which must be tolerated in operation, is 5 minutes. Normalizing the loss distribution to this beam lifetime, the integrated loss power over a region ±100 m from the IPs reach up to 5.7 W. This loss scenario demonstrates that integrated particle tracking and collimator interaction simulations have the potential to identify losses, which could have otherwise been overlooked. The same simulation models can be applied to other beam loss scenarios by changing the input particle distribution and the power normalization, which can be used to guide collimation system design and help resolve performance bottlenecks.

5 Conclusion

The FCC-ee collimation system must be able to safely handle stored beam energy of up to 17.8 MJ while abiding by stringent constraints. Dedicated collimation simulation tools are required to design and optimize the system. Established accelerator physics simulation software tools do not cover all the requirements for collimation simulations in this machine. For the particle tracking aspect of the simulations, the required features include synchrotron radiation, optics tapering, aperture modelling, and beam-beam effects. In addition to the tracking through the lattice, scattering in the collimators must be included. For this aspect, accurate modelling of the collimator geometry, materials, and particle-matter interactions for electron and positron beams is required. An integrated framework for collimation simulations, based on a coupling between a particle Xtrack and BDSIM has been presented, which fulfils these requirements, hence making it possible to study and optimize in detail the collimation performance in future lepton colliders. In addition to the lepton capabilities, it supports also other particle types such as protons, meaning that the same tool can be seamlessly applied to model collimation in a wide range of accelerators.

As an example case study with the new code, a complete model of the 2 IP FCC-ee $t\bar{t}$ mode lattice has been used, including SR and optics tapering, a beam halo collimation system, and a detailed aperture model. The loss scenario simulated covers edge scattering from the horizontal halo collimator. The results show losses over the whole accelerator circumference due to particles out-scattered from the collimator. Ongoing studies are focussed on applying the simulation techniques presented to the design and optimization of the FCC-ee collimation system.

Acknowledgments

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References

[1] FCC collaboration, *FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2*, *Eur. Phys. J. ST* **228** (2019) 261.

[2] K. Oide, *Collider Optics*, talk given ath the *FCCIS 2022 Workshop*, CERN, Geneva, Switzerland, 5–9 December 2022.

[3] G. von Holtey et al., *Study of beam induced particle backgrounds at the LEP detectors*, *Nucl. Instrum. Meth. A* **403** (1998) 205.

[4] R.S. Matter, *PEP-II New High Power Low Impedance Movable Collimator*, SLAC-PUB-8630, SLAC, U.S.A. (2000) [DOI:10.2172/765016].

[5] SuperKEKB collaboration, *SuperKEKB Collider*, *Nucl. Instrum. Meth. A* **907** (2018) 188 [arXiv:1809.01958].

[6] T. Ishibashi et al., *Movable collimator system for SuperKEKB*, *Phys. Rev. Accel. Beams* **23** (2020) 053501.

[7] R. Bruce et al., *Simulations and measurements of beam loss patterns at the CERN Large Hadron Collider*, *Phys. Rev. ST Accel. Beams* **17** (2014) 081004 [arXiv:1409.3123].

[8] R. Bruce et al., *Reaching record-low β^* at the CERN Large Hadron Collider using a novel scheme of collimator settings and optics*, *Nucl. Instrum. Meth. A* **848** (2017) 19.

[9] S. Redaelli, *Beam Cleaning and Collimation Systems*, in the proceedings of the *2014 Joint International Accelerator School: Beam Loss and Accelerator Protection*, Newport Beach, U.S.A., 5–14 November 2014, p. 403–437 [DOI:10.5170/CERN-2016-002.403] [arXiv:1608.03159].

[10] R. Bruce et al., *Performance and luminosity models for heavy-ion operation at the CERN Large Hadron Collider*, *Eur. Phys. J. Plus* **136** (2021) 745 [arXiv:2107.09560].

[11] M. Moudgalya, *First Studies of the Halo Collimation Needs in the FCC-ee*, MSc. thesis, Department of Physics, Imperial College London (2021).

[12] M. Aiba et al., *Top-up injection schemes for future circular lepton collider*, *Nucl. Instrum. Meth. A* **880** (2018) 98.

[13] R. Ramjiawan et al., *Concepts and Considerations for FCC-ee Top-Up Injection Strategies*, *JACoW* **IPAC2022** (2022) 2106.

[14] K. Oide et al., *Design of beam optics for the Future Circular Collider e^+e^--collider rings*, *Phys. Rev. Accel. Beams* **19** (2016) 111005 [*Addendum ibid.* **20** (2017) 049901] [arXiv:1610.07170].

[15] A. Bogomyagkov, S. Sinyatkin, S. Glukhov and E. Levichev, *Dynamic aperture limitation in e^+e^- colliders due to synchrotron radiation in quadrupoles*, *Phys. Rev. Accel. Beams* **22** (2019) 021001 [arXiv:1811.04554].

[16] A. Bogomyagkov, E. Levichev and D. Shatilov, *Beam-beam effects investigation and parameters optimization for a circular e+e- collider TLEP to study the Higgs boson*, *Phys. Rev. ST Accel. Beams* **17** (2014) 041004 [arXiv:1311.1580].

[17] Particle Data Group collaboration, *Review of Particle Physics*, *Prog. Theor. Exp. Phys.* **2022** (2022) 083C01.

[18] A. Lechner, *Particle interactions with matter*, *CERN Yellow Rep. School Proc.* **5** (2018) 47.

[19] N. Mokhov, *Simulation of Particle-Material Interactions*, arXiv:2006.09866.

[20] G. Von Holtey, *Electron beam collimation at LEP energies*, CERN-LEP-BI-87-04 CERN, Switzerland (1987).

[21] A. Natochii et al., *Improved simulation of beam backgrounds and collimation at SuperKEKB*, *Phys. Rev. Accel. Beams* **24** (2021) 081001 [arXiv:2104.02645].

[22] D. Sagan et al., *Simulations of future particle accelerators: issues and mitigations*, 2021 *JINST* **16** T10002 [arXiv:2108.11027].

[23] R. De Maria, A. Mereghetti, J. Molson and K. Sjøbak, *SixTrack Status*, *CERN Yellow Rep. Conf. Proc.* **2** (2020) 11.

[24] Sixtrack, http://sixtrack.web.cern.ch/SixTrack/.

[25] R. Bruce et al., *Status of SixTrack with collimation*, *CERN Yellow Rep. Conf. Proc.* **2** (2018) 1.

[26] A. Mereghetti et al., *SixTrack for Cleaning Studies: 2017 Updates*, in the proceedings of the *8th International Particle Accelerator Conference*, Copenhagen, Denmark, 14–19 May 2017, pp. 3811–3814 [DOI:10.18429/JACoW-IPAC2017-THPAB046].

[27] H. Rafique et al., *Status of MERLIN*, *CERN Yellow Rep. Conf. Proc.* **2** (2020) 27.

[28] A. Ferrari, P.R. Sala, A. Fassò and J. Ranft, *FLUKA: A multi-particle transport code (program version 2005)*, CERN-2005-10, CERN, Geneva (2005) [DOI:10.5170/CERN-2005-010].

[29] T.T. Böhlen et al., *The FLUKA Code: Developments and Challenges for High Energy and Medical Applications*, *Nucl. Data Sheets* **120** (2014) 211.

[30] J. Allison et al., *Recent developments in Geant4*, *Nucl. Instrum. Meth. A* **835** (2016) 186.

[31] GEANT4 collaboration, *GEANT4–a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250.

[32] J. Allison et al., *Geant4 developments and applications*, *IEEE Trans. Nucl. Sci.* **53** (2006) 270.

[33] R.B. Appleby, F. Cerutti and A. Mereghetti, *FLUKA-SIXTRACK Coupling for the SPS Scrapers*, *CERN Yellow Rep. Conf. Proc.* **2** (2020) 205.

[34] E. Skordis et al., *FLUKA coupling to Sixtrack*, *CERN Yellow Rep. Conf. Proc.* **2** (2020) 17.

[35] A. Mereghetti et al., *SixTrack-Fluka Active Coupling for the Upgrade of the SPS Scrapers*, in the proceedings of the *4th International Particle Accelerator Conference*, Shanghai, China, 12–17 May 2013, pp. 2657–2659.

[36] MAD-X, http://cern.ch/mad/.

[37] R.B. Appleby et al., *Merlin++, a flexible and feature-rich accelerator physics and particle tracking library*, *Comput. Phys. Commun.* **271** (2022) 108204 [arXiv:2011.04335].

[38] W. Rogers, N. Carmignani, L. Farvacque and B. Nash, *pyAT: A Python Build of Accelerator Toolbox*, in the proceedings of the *8th International Particle Accelerator Conference*, Copenhagen, Denmark, 14–19 May 2017, pp. 3855–3857 [DOI:10.18429/JACoW-IPAC2017-THPAB060].

[39] Xsuite, https://xsuite.readthedocs.io/en/latest/.

[40] Accelerator Toolbox (AT), http://atcollab.sourceforge.net/.

[41] L.J. Nevay et al., *BDSIM: An accelerator tracking code with particle-matter interactions*, *Comput. Phys. Commun.* **252** (2020) 107200 [arXiv:1808.10745].

[42] L.J. Nevay et al., *BDSIM: Automatic Geant4 Models of Accelerators*, *CERN Yellow Rep. Conf. Proc.* **2** (2020) 45.

[43] A. Abramov, *Ion Beam Collimation for Future Hadron Colliders*, Ph.D. thesis, Royal Holloway University of London, Egham, U.K. (2020).

[44] collimasim, https://gitlab.cern.ch/anabramo/collimasim.

[45] A. Abramov et al., *Development of Collimation Simulations for the FCC-ee*, *JACoW* **IPAC2022** (2022) 1718.

[46] G. Broggi, *First study of collimator design for the FCC-ee*, MSc. thesis, Politecnico di Milano (2022).

2024 JINST 19 T02004

[47] CHART, https://chart.ch/.

[48] P. Kicsiny et al., *Towards Beam-Beam Simulations for FCC-ee*, *JACoW* **eeFACT2022** (2023) 165.

[49] A. Abramov et al., *Studies of layout and cleaning performance for the FCC-ee collimation system*, in the proceedings of the *14th International Particle Accelerator Conference*, Venezia, Italy, 7–12 May 2023, pp. 348–351 [DOI:10.18429/JACoW-IPAC2023-MOPA128].

[50] FCC collaboration, *FCC-ee lattice*, https://zenodo.org/record/6344457 [DOI:10.5281/ZENODO.6344457].

[51] A. Abramov, F.S. Carlier, J. Molson, M. Moudgalya, M. Hofer, R. Bruce et al., *FCC-ee Aperture and Collimation*, talk given at the *FCC week 2021*, CERN, Geneva, Switzerland, 28 June–2 July 2021.

[52] J.B. Jeanneret, *Optics of a Two-stage Collimation System*, *Phys. Rev. ST Accel. Beams* **1** (1998) 081001.

[53] M. Lückhof, *Background Processes Affecting the Machine-Detector Interface at FCC-ee With Focus on Synchrotron Radiation at 182.5 GeV Beam Energy*, Ph.D. thesis, Hamburg University, Hamburg, Germany (2020).

[54] C. Bracco, *Commissioning scenarios and tests for the LHC collimation system*, Ph.D. thesis, École Polytechnique, Lausanne, Switzerland (2009).

2024 JINST 19 T02004