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DEVELOPMENT OF COLLIMATION SIMULATIONS FOR THE FCC-ee*

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Abstract

A collimation system is under study for the FCC-ee to protect the machine from the multi-MJ electron and positron beams and limit the backgrounds to the detectors. One of the key aspects of the collimation system design is the setup of simulation studies combining particle tracking and scattering in the collimators. The tracking must include effects important for electron beam single-particle dynamics in the FCC-ee, such as synchrotron radiation. For collimation, an aperture model and particle-matter interactions for electrons are required. There are currently no established simulation frameworks that include all the required features. The latest developments of an integrated framework for multi-turn collimation studies in the FCC-ee are presented. The framework is based on an interface between tracking codes, pyAT and Xtrack, and a particle-matter interaction code, BDSIM, based on Geant4. Promising alternative simulation codes and frameworks are also discussed. The challenges are outlined, and the first results are presented, including preliminary loss maps for the FCC-ee.

INTRODUCTION

The lepton Future Circular Collider (FCC-ee) is a design study for a future 97.5 km-long electron-positron collider with 4 operating modes at beam energies in the range 45.6–182.5 GeV, which would be part of the CERN accelerator complex [1]. In order to maximise the discovery potential and the luminosity, parameters such as the centre-of-mass energy for collisions, the stored beam energy, and the total synchrotron radiation power will be pushed beyond past and present lepton colliders. The stored beam energy reaches up to 20.7 MJ for the 45.6 GeV operation mode, which is comparable with the stored beam energy during Large Hadron Collider (LHC) operation with heavy-ion beams [2]. This is a new regime for lepton machines, in which beam losses could risk to damage equipment or quench any of the superconducting elements. A collimation system is therefore being designed for the FCC-ee [3, 4], not only to control detector backgrounds from synchrotron radiation (SR), but also to protect the collider from beam losses during both normal operation and failure scenarios.

Simulations are important tools for the collimation system design. Collimation tracking studies are the first step in determining the performance, where a distribution of particles corresponding to a selected beam loss scenario is tracked in a machine model with the collimators and the mechanical apertures included. For machines where beam losses can exceed the limits for safe operations, like the LHC, FCC-hh, and FCC-ee, it is important to track the particles out-scattered from the collimators. The requirements for collimation simulations are hence accurate and efficient tracking in the magnetic lattice, modelling of the scattering in the collimators, and accurate aperture loss recording. For lepton beams, synchrotron radiation (SR) must be supported in the particle tracking. In addition, due to the significant SR energy loss, the magnet strengths in the FCC-ee are adjusted to follow the beam energy around the ring (called optics tapering). This is essential for maintaining a centered closed orbit and must be included in the simulations. The goal of this study is to develop and benchmark a simulation framework that fits all the requirements for collimation simulations in the FCC-ee. The FCC-ee is a novel study in many aspects, also for optics design, model preparation, and particle tracking [5]. In the early design stages, it is necessary to consider and explore different software tools and pick the most appropriate ones for the studies. Tests and benchmarks are essential to ensure reliable and reproducible results, so the aim is to achieve adequate agreement between at least two software frameworks for each aspect of the studies.

SOFTWARE TOOLS

Different software tools were considered for FCC-ee collimation, including MAD-X [6], Merlin++ [7], pyAT [8], SixTrack [9], and Xtrack [10]. For the LHC, the most common software for collimation simulations is SixTrack in combination with a scattering routine for collimator interactions [11, 12], which can be built-in [13] or a coupling to FLUKA [14, 15]. In the SixTrack-FLUKA coupling framework [16–18], SixTrack performs tracking in the magnetic lattice and FLUKA simulates the physics interactions in 3D 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. In the current work it is used for benchmarks in an artificial configuration without radiation and tapering. Following evaluation and initial testing, a coupling between a particle tracking code and a Monte Carlo physical interaction code was selected also for FCC-ee. For the tracking, pyAT and Xtrack were chosen for further testing and develop-

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ment. PyAT is a Python interface to the Accelerator Toolbox (AT) [19] library, which is actively used for beam dynamics studies in light sources, for example at ESRF [20, 21]. It supports lattice manipulation and tracking, including optics, tapering, damping time computation, matching and tuning, 6D tracking with SR, and aperture loss recording. Xtrack is a new general-purpose particle tracking code, part of the XSuite collection of packages. It supports 6D tracking of electron and positron beams with SR, including secondary particles produced in collimator interactions, optical function calculations, and aperture loss recording. For the physical interactions inside collimators, a coupling to BDSIM is developed for both pyAT and Xtrack. BDSIM [22–24] is a software package for simulation of radiation transport and charged particle backgrounds in accelerator beamlines, based on the Geant4 toolkit [25–27]. A dedicated interface to BDSIM was developed recently for coupling to tracking codes for collimation applications [28, 29]. The interface enables the automatic preparation of collimator models and sets up the Geant4 3D geometry, the materials, the physics lists and the interaction cuts. Particles are transferred to and from the tracking code at runtime, similar to the SixTrack-FLUKA coupling mechanism. As future development, a coupling to FLUKA is also envisaged.

SIMULATION SETUP

The newly developed frameworks are used to simulate losses on collimators for an FCC-ee reference scenario, selected to be betatron collimation for the 182.5 GeV mode. While not having the highest stored energy, this scenario is chosen because the effects of SR on the beam dynamics are the strongest and the beam energy is the highest. The optics is for the 2-interaction point (IP) Conceptual Design Report (CDR) layout and only a two-stage betatron collimation system is included, without off-momentum or SR collimators [4, 30]. Starting from a MAD-X lattice specification, the pyAT model is prepared from the thick-lens lattice model by the Xsequence package [31]. A thin-lens lattice model is exported to both SixTrack and Xtrack (using cpymad [32] for Xtrack).

The mechanical aperture model is derived from the first aperture studies in the full FCC-ee ring [33]. It uses a simplified main dipole aperture definition, a 35 mm-radius circle, for all dipoles and quadrupoles, with additional aperture transitions in the Machine Detector Interface (MDI) region, where the beam pipe has a radius of 15 mm. The accuracy and the longitudinal resolution of the aperture losses are refined in each simulation. SixTrack and pyAT use interpolated aperture markers during tracking, while Xtrack performs a post-processing back-tracking of losses. The losses are binned in 10 cm intervals for the loss maps. The collimator design parameters are tentatively taken from the LHC, with 60 cm primary and 1 m secondary collimators, made of carbon-fibre-composite (CFC). Studies of optmised collimator design are ongoing. A beam distribution is generated to impinge the horizontal primary collimator with an

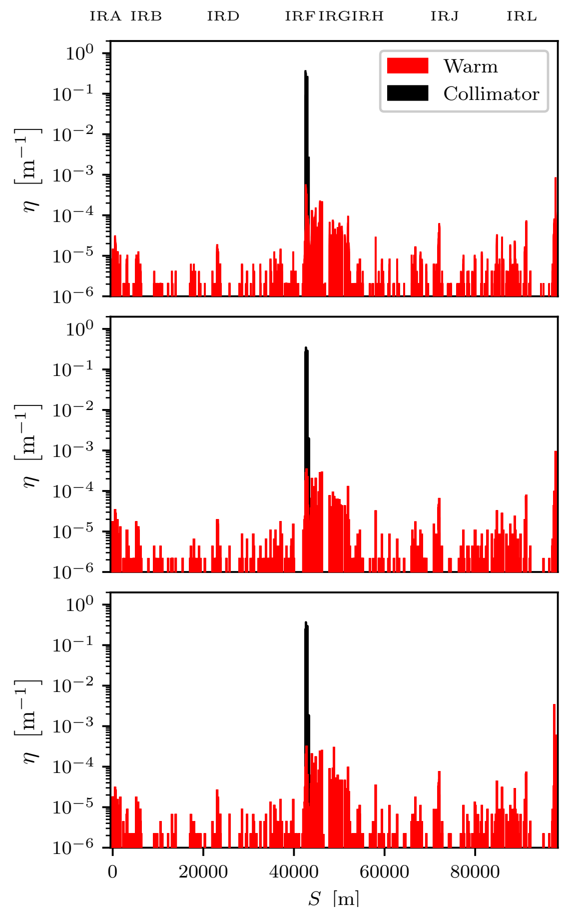

Figure 1: Loss map for collimation losses in the full FCC-ee ring, showing results from SixTrack-FLUKA (top), Xtrack-BDSIM (middle), and pyAT-BDSIM (bottom).

impact parameter of 1 m and 5×10^{6} positrons are tracked for 700 turns through an ideal machine without imperfections.

RESULTS

Loss map studies are performed for the three simulation frameworks: SixTrack-FLUKA, Xtrack-BDSIM, and pyAT-BDSIM. The loss maps show the cleaning inefficiency $\eta = E_{\mathrm{loss},\Delta s}/(E_{\mathrm{loss,\,total}}\Delta s)$, where E_{loss} is the integrated energy of the losses and Δs is a region of s. The results for the case without radiation and tapering can be seen in Fig. 1.

The aperture losses around the full ring from all three frameworks show good agreement, with integrated losses in the main loss clusters matching within 30%. SixTrack and Xtrack show a particularly good agreement for all loss clusters observed. In pyAT, an additional loss spike is observed at s = 48.8 km and the location of the large loss cluster at s = 97.5 km is shifted upstream, relative to the other simulations, due to small differences in the aperture model interpolation. It should also be noted that SixTrack and Xtrack use identical thin-lens lattice models and the same tracking algorithms, while pyAT slices the thick-lens lattice internally and uses different algorithms. Future benchmarks should consider the effects of the numbers of slices

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Table 1: Comparison of Collimator Cleaning Inefficiency η between SixTrack-FLUKA (ST), Xtrack-BDSIM (XT), and pyAT-BDSIM (PA) for the Loss Maps Without Radiation and Tapering

Collimator	η_{ST} m^{-1}	η_{XT} m^{-1}	η_{PA} m^{-1}	$\frac{\eta_{XT}}{\eta_{ST}}$ [ ]	$\frac{\eta_{PA}}{\eta_{ST}}$ [ ]
TCP.A.B1	0.363	0.272	0.249	0.75	0.69
TCP.B.B1	0.091	0.098	0.103	1.08	1.14
TCS.B1.B1	0.068	0.065	0.065	0.97	0.96
TCS.A1.B1	0.317	0.347	0.366	1.09	1.15
TCS.A2.B1	0.261	0.289	0.295	1.11	1.13
TCS.B2.B1	0.003	0.002	0.002	0.75	0.70

Table 2: Comparison of Primary Particle Losses for All Loss Map Cases Simulated in Xtrack-BDISM and pyAT-BDSIM, 5×10^6 Particles are Tracked for 700 Turns in All Cases

Scenario	Losses [%]	Last loss turn
Xtrack	99.72	700
pyAT	99.89	700
pyAT rad.	98.74	78
Xtrack rad.	93.20	81
Xtrack rad. (quant.)	96.08	700

and the effects of the dipole and quadrupole fringes. In the collimation insertion, a general agreement is also observed in the collimator and aperture losses. A comparison of the losses on collimators is listed in Table 1, showing agreement within 30 % for all cases. In this region, the agreement is better between Xtrack and pyAT, while SixTrack shows significantly lower aperture losses immediately downstream of the collimators. A possible source of the differences is the collimator geometry. FLUKA uses realistic LHC collimator models, with jaw tapering and a collimator tank [17], while BDSIM uses block jaws with the active length of the collimator. Additional benchmarks with identical geometry, and multi-turn loss analysis must be performed to fully understand the differences observed.

Loss maps simulations were also performed with radiation and tapering in Xtrack-BDSIM and pyAT-BDSIM, with SR damping modelled as an average effect. In Xtrack, a loss map was also simulated with quantum fluctuations enabled. The quantum fluctuations in Xtrack are modelled via random photon emission, using the same formalism as in MAD-X. The resulting loss maps are shown in Fig. 2.

The loss pattern in the ring is similar to the case without radiation and tapering, which can be qualitatively explained by the fact that the largest losses occur during the first few turns. The main differences with the case without radiation and tapering are an altered collimator loss distribution and a significant increase in the losses around s = 97.5 km. For the scenario with only average SR damping modelled, particles circulating on a longer time frame are damped, and the losses have a cutoff around turn 80, as shown in Table 2.

When quantum fluctuations are enabled, the losses continue at a lower rate for all turns simulated. This leads to

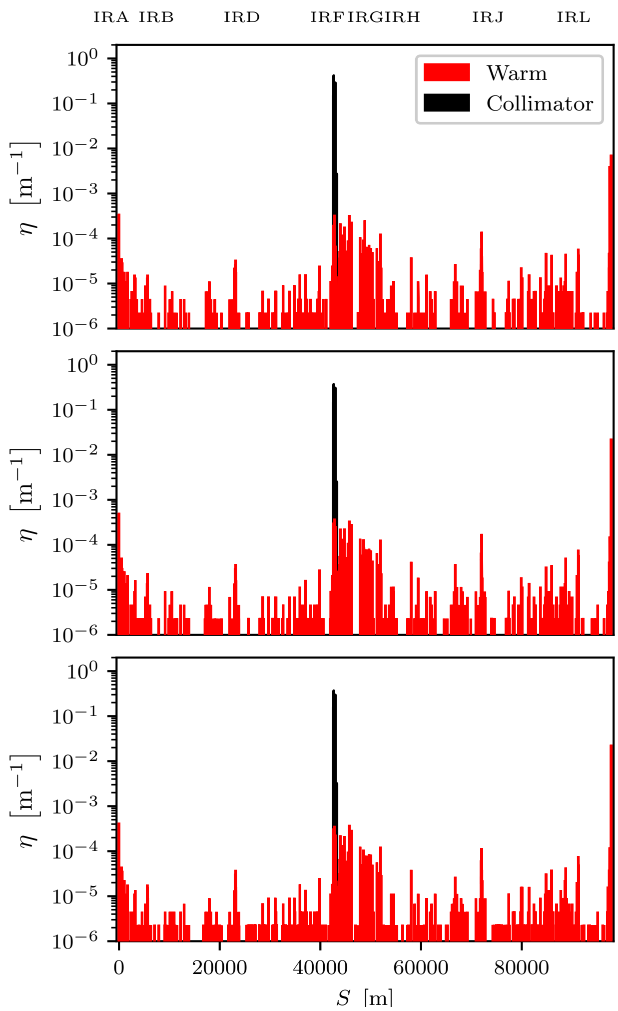

Figure 2: Loss map for collimation losses in the full FCC-ee ring, showing results from pyAT-BDSIM (top) and Xtrack-BDSIM (middle) with only radiation damping enabled, and Xtrack-BDSIM (bottom) with quantum fluctuations enabled.

diffusive losses seen in the majority of the ring. The results presented are preliminary, but they demonstrate how the SR can lead to potentially important changes in the loss distribution.

CONCLUSION AND OUTLOOK

The first software frameworks for collimation simulations in the FCC-ee, Xtrack-BDSIM and pyAT-BDSIM, have been developed and benchmarked against SixTrack-FLUKA without radiation and tapering, showing good agreement. Preliminary loss maps studies with radiation and tapering have been performed and good agreement is also observed for this case. Additional benchmarking of the particle tracking and collimation interactions is required in the future to fully validate the new tools. Planned future developments include implementing a coupling to FLUKA and introducing other dynamic effects, such as beam-beam interactions.

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