

# STUDY OF THE TOUSCHEK EFFECT IN THE FCC-ee

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## Abstract

The Future Circular electron-positron Collider (FCC-ee) is a design study for a 90.7 km circumference high-luminosity and high-energy  $e^+e^-$  collider. In electron and positron machines, the Touschek effect can cause large transverse-to-longitudinal momentum exchange, leading to particle losses that can limit the beam lifetime and produce distinct beam loss patterns. A quantitative assessment of this mechanism is therefore essential to identify regions potentially exposed to Touschek-induced losses and to determine its impact on the beam lifetime relative to other lifetime-limiting processes. This paper presents a study of the Touschek effect in the FCC-ee, performed using a Monte Carlo Touschek-scattering simulation routine newly implemented in the Xsuite framework. The results include Touschek-lifetime estimates for the FCC-ee and an evaluation of the arising beam loss patterns. The performance of the FCC-ee beam collimation system to safely dispose of Touschek losses is also assessed.

## INTRODUCTION

The FCC-ee [1,2] is a proposed 90.7 km circular  $e^+e^-$  collider designed for precision electroweak and Higgs physics. It will operate in four modes, with beam energies ranging from 45.6 GeV at the Z pole up to 182.5 GeV at the  $t\bar{t}$  threshold. In electron and positron storage rings, the Touschek effect [3] arises from single Coulomb scattering events between two relativistic particles within the same bunch, which can convert transverse momentum into longitudinal momentum. If the resulting momentum deviation exceeds the momentum acceptance of the machine, or if the resulting closed-orbit or betatron oscillations exceed the physical or dynamic aperture, particles are lost from the beam. The Touschek effect is typically the primary beam lifetime limiting effect in low-emittance electron and positron storage rings. The Touschek scattering rate is strongly suppressed with increasing beam energy, so its impact is expected to be less severe in high-energy machines such as the FCC-ee. Nevertheless, a quantitative assessment of the Touschek effect remains important to verify this expectation, assess how the FCC-ee collimation system handles these losses, and evaluate the resulting beam loss patterns and their effect on the machine.

This paper introduces the Touschek scattering simulation routine recently implemented in the Xsuite framework (full details can be found in Ref. [4]), and presents the results of its application to the FCC-ee Z operation mode. This represents the most critical case for the Touschek effect, as

it corresponds to the lowest beam energy and highest beam intensity among all FCC-ee operation modes.

## SIMULATION METHODOLOGY

A Touschek scattering routine has been recently implemented in the Xsuite [5] framework, following the approach by Xiao and Borland [6], originally developed for ELE-GANT [7]. This method uses a Monte Carlo sampling scheme combined with the Piwinski formalism [8] to evaluate the Touschek scattering rate and generate the kinematic parameters of the scattered particles. The Touschek scattering rate for particles with momentum deviation  $|\delta| > \delta_m$  is evaluated via Monte Carlo integration as [6]:

$$R_{MC} = \frac{V}{N} \sum_{i=1}^M \left[ \frac{v^*}{\gamma^2} \frac{d\sigma^*}{d\Omega^*} \sin \Theta^* \rho(\vec{x}_1) \rho(\vec{x}_2) \right]_i = \sum_{i=1}^M r_i, \quad (1)$$

where  $V$  is the sampled phase-space volume,  $N$  the total number of simulated scattering events, and  $M$  the number of scattered particles with  $|\delta| > \delta_m$ . Quantities with asterisks refer to the center-of-mass frame:  $v^*$  is the particle velocity,  $\Theta^*$  the scattering angle, and  $d\sigma^*/d\Omega^*$  the Møller differential cross-section [6].  $\gamma$  is the Lorentz factor,  $\rho(\vec{x}_1)$  and  $\rho(\vec{x}_2)$  the Gaussian phase-space densities of the two interacting particles, and  $r_i$  the rate contribution from the  $i$ -th scattered particle. Setting  $\delta_m = \delta_a$  (the local momentum acceptance) gives the Touschek beam loss rate.

For each Monte Carlo event, the coordinates of the two scattering particles are sampled from a six-dimensional Gaussian phase-space distribution at the given lattice location, using the local optical functions. The polar and azimuthal scattering angles  $\Theta^*$  and  $\Psi^*$  in the center-of-mass frame are also sampled, and the post-scattering momenta are obtained via a relativistic Lorentz boost.

A lumped-element approach is used to model scattering around the ring during tracking. TouschekScattering elements are placed at discrete longitudinal positions, with spacing chosen to resolve the local variation of the optical functions. Scattered particles emerging from these elements with  $|\delta| > \delta_m$  are retained for tracking and assigned a weight [6]

$$R_i = \frac{r_i}{\sum r_i} \cdot \int R_P ds, \quad (2)$$

where  $R_P$  is the Piwinski scattering rate integrated between the current and the preceding TouschekScattering element. The Touschek lifetime is then

$$\tau_T = \frac{N_b}{\sum_{\text{lost}} R_i}, \quad (3)$$

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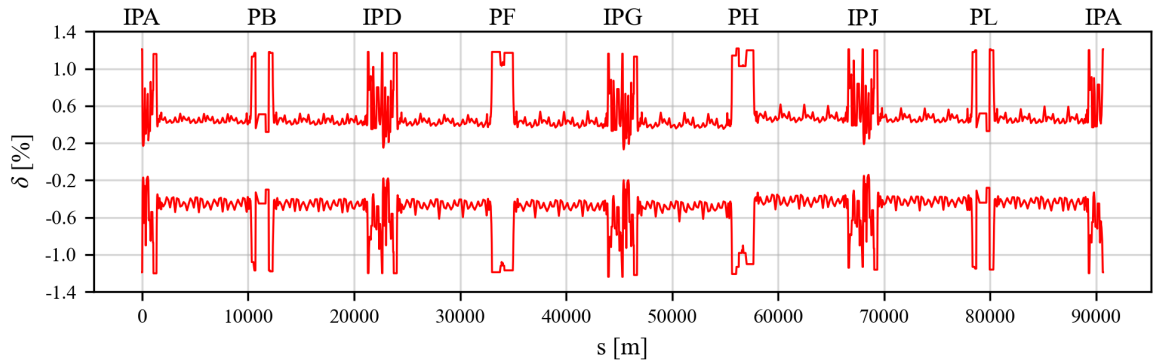


Figure 1: Local momentum acceptance profile for the FCC-ee (LCC V106.2) Z operation mode.

where  $N_b$  is the bunch population and the sum runs over all lost macroparticles. A speed-up strategy is applied by retaining only the highest-weight particles that account for a fixed fraction (e.g., 99%) of the total simulated rate as in Ref. [6].

The routine can be seamlessly used within Xsuite tracking simulations that include online Monte Carlo modeling of beam–collimator interactions via BDSIM/Geant4 [9–13] or FLUKA [14, 15], through the interface provided by the Xcoll package [16, 17], enabling studies of Touschek losses and their collimation at an unprecedented level of complexity. This capability has been successfully applied to the SuperKEKB collider [18] in the context of a validation effort of Xsuite-based collimation and background simulations against experimental data, yielding very good agreement [4, 19].

### Local Momentum Acceptance

A prerequisite for the Touschek simulation is an accurate profile of the local momentum acceptance (LMA)  $\delta_a(s)$  along the ring. This is obtained by tracking on-closed-orbit test particles with varying momentum deviations  $\delta$  for a given number of turns. The largest long-term-stable  $\delta$  at each longitudinal position  $s$  defines  $\delta_a(s)$ . The threshold  $\delta_m$  is then set as a fraction  $a_0 \approx 0.8$ – $0.9$  of the local  $\delta_a(s)$  to account for particles with nonzero betatron amplitudes that may be lost at smaller momentum deviations than the acceptance at zero betatron amplitude. The LMA profile for the FCC-ee Z lattice considered in this work, obtained through Xsuite tracking, is shown in Fig. 1.

## SIMULATION SETUP

The Touschek effect has been simulated for the FCC-ee positron beam (Beam 1) at a beam energy of 45.6 GeV, corresponding to the Z operation mode with the Local Chromatic Correction (LCC) optics V106.2 [20], using the nominal colliding-beam parameters in Table 1.

A total of 1214 Touschek scattering centers were placed non-uniformly along the 90.7 km ring, with denser sampling in regions where the optics vary more rapidly (e.g., the interaction regions) and coarser sampling where the optics is more regular (e.g., the arcs). A total of  $2 \times 10^7$  Touschek-scattered macroparticles were tracked over 1000 turns in

Table 1: FCC-ee beam parameters for the Z operation mode assumed in this study.

Parameter	Value
Beam energy [GeV]	45.6
Bunch population $N_b$ [ $10^{11}$ ]	2.02
Horizontal emittance $\varepsilon_x$ [nm]	0.72
Vertical emittance $\varepsilon_y$ [pm]	1.43
Bunch length $\sigma_z$ [mm]	16.7
Energy spread $\sigma_\delta$ [%]	0.134

the full nonlinear FCC-ee lattice, including the crab-waist collision scheme, a detailed aperture model, and the full collimation system. Beam–collimator interactions were modeled using BDSIM/Geant4 via the Xsuite–BDSIM coupling [17, 21] provided within Xcoll. Synchrotron radiation effects—including damping, energy recovery in the RF cavities, and magnetic lattice tapering—were included, while quantum excitation was excluded to avoid biasing the Touschek loss estimates with SR-driven losses.

Beam loss locations, together with the Touschek rate contribution of each macroparticle, were recorded and binned longitudinally in 10 cm intervals to generate the loss map presented in the following section.

## RESULTS

The simulation yields a Touschek lifetime of about 17 hours for the FCC-ee Z operation mode under nominal colliding-beam conditions. This value is well in the shadow of other beam loss mechanisms, in particular radiative Bhabha scattering (RBS) at the interaction points, which dominates the beam lifetime with  $\tau_{\text{RBS}} \approx 20$  minutes [22]. This confirms that Touschek scattering does not pose a limitation on the beam lifetime in the FCC-ee. Given that the Touschek loss rate is suppressed with increasing beam energy and further reduced at lower beam intensities, this conclusion holds for all other FCC-ee operation modes.

The spatial distribution of Touschek-induced losses along the FCC-ee ring is shown in Fig. 2, expressed as power loads per unit length and assuming the full stored beam energy of 17.8 MJ at the Z operation mode. Touschek losses are distributed across the full ring, reflecting the continuous

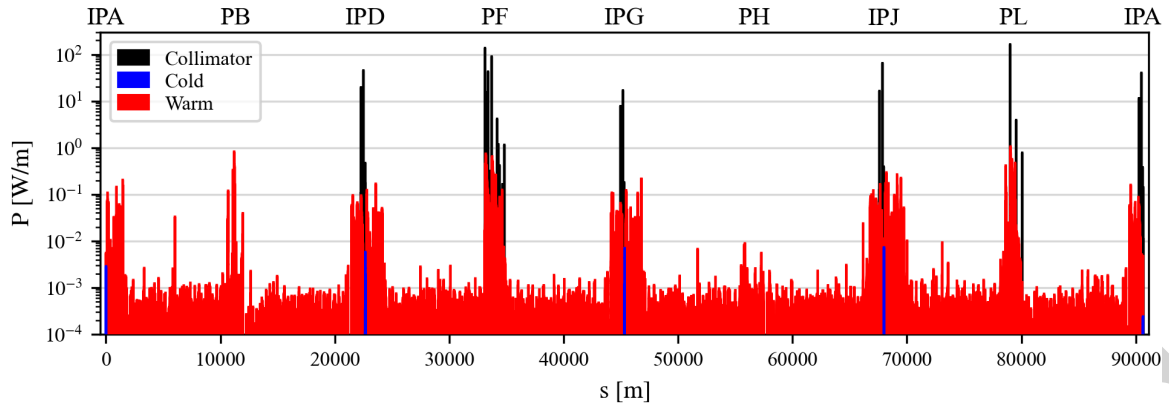


Figure 2: Touschek scattering loss map for the FCC-ee Z operation mode (LCC V106.2 optics). Losses are expressed as power load per unit length, binned in 10 cm intervals, except for collimators where the bin equals the collimator length.

intra-bunch nature of the scattering mechanism, but with a non-uniform pattern.

The highest losses are found in the PL long straight section, which hosts the FCC-ee off-momentum collimation system. The peak power load is observed on the primary off-momentum collimator, reaching about 200 W/m, corresponding to approximately 50 W on this 0.25 m-long collimator. It is worth noting that the PL section also hosts the RF system of the FCC-ee booster ring. At the time of writing, it has not yet been established whether the off-momentum collimation system can coexist with the booster RF system; studies are ongoing to assess whether radiation fields generated by off-momentum beam losses in this collimation region could adversely affect the booster RF system. Comparable losses of the order of 100 W/m are observed on the primary horizontal betatron collimators, located in the PF long straight section, which hosts the FCC-ee betatron collimation system.

Sizeable losses of up to tens of W/m are also observed on the IR local protection collimators, located approximately 400 m upstream of each interaction point, and on the first horizontal synchrotron radiation collimator. These efficiently intercept Touschek-scattered particles that might otherwise be lost further downstream and potentially contribute to detector backgrounds.

In the rest of the ring, losses on the mechanical aperture are of the order of 1 mW/m in the arcs, with peaks in the range 100 mW/m–1 W/m in high-dispersion regions, which correspond to local minima of the LMA (see Fig. 1). These regions are the PB straight section, where large dispersion is intentionally introduced to allow on-axis, off-energy top-up injection from the booster ring, and the vicinity of the interaction points (IPA, IPD, IPG, IPJ), where high dispersion peaks are intentionally introduced for local chromatic correction. Losses on the superconducting final-focus quadrupoles are of the order of a few mW/m, which is fully acceptable and well below the W/m levels that these elements receive from RBS losses.

Altogether, these results confirm that the Touschek effect is not a performance-limiting effect in the FCC-ee. The collimation system efficiently intercepts Touschek-induced

losses, helping to suppress power loads on the mechanical aperture and to mitigate potential concerns about detector backgrounds from Touschek losses in the interaction regions. Power loads on sensitive machine components such as superconducting magnets remain well within tolerable limits.

## CONCLUSIONS

A Touschek scattering routine has been implemented in the Xsuite framework and applied to the FCC-ee Z operation mode, which represents the most critical case for the Touschek effect among all FCC-ee operation modes. Simulations were performed under nominal colliding-beam conditions using the LCC V106.2 lattice.

The simulated Touschek lifetime of about 17 hours is well in the shadow of other beam loss mechanisms such as radiative Bhabha scattering, with  $\tau_{\text{RBS}} \approx 20$  minutes [22]. Given that the Touschek loss rate is strongly suppressed at higher beam energies and lower beam intensities, Touschek scattering is confirmed not to be a performance-limiting effect in any FCC-ee operation mode.

The beam loss patterns arising from Touschek scattering have been characterized in detail. The highest power loads are absorbed by the primary collimators in the off-momentum (PL) and betatron (PF) collimation insertions, at the level of 200 W/m and 100 W/m respectively, while IR local protection collimators and synchrotron radiation collimators efficiently intercept Touschek losses upstream of the interaction points. Losses on the mechanical aperture elsewhere in the ring are low, and power loads on the superconducting final-focus quadrupoles, at the level of a few mW/m, are well within tolerable limits.

These results also demonstrate that the FCC-ee collimation system is well suited to handle Touschek-induced beam losses.

## REFERENCES

- [1] M. Benedikt *et al.*, “Future Circular Collider Feasibility Study Report – Volume 1 Physics, Experiments, Detectors,” *Eur. Phys. J. C*, vol. 85, no. 12, p. 1468, 2025.  
[doi:10.1140/epjc/s10052-025-15077-x](https://doi.org/10.1140/epjc/s10052-025-15077-x)

- [2] M. Benedikt, *et al.*, “Future Circular Collider Feasibility Study Report – Volume 2 Accelerators, technical infrastructure and safety,” *Eur. Phys. J. ST*, vol. 234, no. 19, pp. 5713–6197, 2025.  
doi:10.1140/epjs/s11734-025-01967-4
- [3] C. Bernardini, *et al.*, “Lifetime and beam size in a storage ring,” *Phys. Rev. Lett.*, vol. 10, pp. 407–409, 1963.  
doi:10.1103/PhysRevLett.10.407
- [4] G. Broggi, “FCC-ee collimation system design,” Ph.D. thesis, Sapienza Università di Roma, Rome, Italy, 2026.
- [5] G. Iadarola, *et al.*, “Xsuite: an integrated beam physics simulation framework,” in *Proc. HB'23*, Geneva, Switzerland, Oct. 2023, paper TUA2I1.  
doi:10.18429/JACoW-HB2023-TUA2I1
- [6] A. Xiao and M. Borland, “Monte Carlo simulation of Touschek effect,” *Phys. Rev. ST Accel. Beams*, vol. 13, p. 074201, 2010. doi:10.1103/PhysRevSTAB.13.074201
- [7] M. Borland, “elegant: a flexible SDDS-compliant code for accelerator simulation,” Argonne National Laboratory, Argonne, IL, USA, Tech. Rep. LS-287, 2000.  
doi:10.2172/761286
- [8] A. Piwinski, “The Touschek effect in strong focussing rings,” DESY, Hamburg, Germany, Tech. Rep. DESY 98-179, 1998.  
doi:10.48550/arXiv.physics/9903034
- [9] L. J. Nevay *et al.*, “BDSIM: an accelerator tracking code with particle–matter interactions,” *Comput. Phys. Commun.*, vol. 252, p. 107200, 2020.  
doi:10.1016/j.cpc.2020.107200
- [10] L. J. Nevay *et al.*, “BDSIM: automatic Geant4 models of accelerators,” in *Proc. ICFA Mini-Workshop on Tracking for Collimation*, CERN, Geneva, Switzerland, 2015.  
doi:10.23732/CYRCP-2018-002.45
- [11] J. Allison *et al.*, “Recent Developments in Geant4,” *Nucl. Instrum. Methods Phys. Res. A*, vol. 835, pp. 186–225, 2016.  
doi:10.1016/j.nima.2016.06.125
- [12] S. Agostinelli *et al.*, “Geant4 – a simulation toolkit,” *Nucl. Instrum. Methods Phys. Res. A*, vol. 506, no. 3, pp. 250–303, 2003. doi:10.1016/S0168-9002(03)01368-8
- [13] J. Allison *et al.*, “Geant4 developments and applications,” *IEEE Trans. Nucl. Sci.*, vol. 53, no. 1, pp. 270–278, 2006.  
doi:10.1109/TNS.2006.869826
- [14] C. Ahdida *et al.*, “New capabilities of the FLUKA multi-purpose code,” *Front. Phys.*, vol. 9, p. 788253, 2022.  
doi:10.3389/fphy.2021.788253
- [15] G. Battistoni *et al.*, “Overview of the FLUKA code,” *Ann. Nucl. Energy*, vol. 82, pp. 10–18, 2015.  
doi:10.1016/j.anucene.2014.11.007
- [16] F. Van der Veken, *et al.*, “Recent developments with the new tools for collimation simulations in Xsuite,” in *Proc. HB'23*, Geneva, Switzerland, Oct. 2023, paper THBP13, pp. 474–478.  
doi:10.18429/JACoW-HB2023-THBP13
- [17] B. Lindstrom *et al.*, “Xcoll–BDSIM coupling for beam collimation,” in *Proc. IPAC'25*, Taipei, Taiwan, June 2025, paper MOPSO30, pp. 653–656.  
doi:10.18429/JACoW-IPAC2025-MOPSO30
- [18] K. Akai, K. Furukawa, and H. Koiso, “SuperKEKB collider,” *Nucl. Instrum. Methods Phys. Res. A*, vol. 907, pp. 188–199, 2018. doi:10.1016/j.nima.2018.08.017
- [19] G. Broggi *et al.*, “Comparison of Xsuite Simulations with Measured Backgrounds at SuperKEKB,” in *Proc. IPAC'25*, Taipei, Taiwan, June 2025, paper MOPM035, pp. 379–382.  
doi:10.18429/JACoW-IPAC2025-MOPM035
- [20] P. Raimondi, S. M. Liuzzo, L. Farvacque, S. White, and M. Hofer, “Local chromatic correction optics for Future Circular Collider  $e^+e^-$ ,” *Phys. Rev. Accel. Beams*, vol. 28, no. 2, p. 021002, 2025.  
doi:10.1103/PhysRevAccelBeams.28.021002
- [21] A. Abramov, *et al.*, “Collimation simulations for the FCC-ee,” *J. Instrum.*, vol. 19, p. T02004, 2024.  
doi:10.1088/1748-0221/19/02/T02004
- [22] K. Oide, “Beam-beam lifetime with LCC lattice at Z & W,” presented at the 222nd FCC-ee Accelerator Design Meeting, CERN, Meyrin, Switzerland, Mar. 2026. <https://indico.cern.ch/event/1665511/contributions/7006071/>