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COMPARISON OF Xsuite SIMULATIONS WITH MEASURED BACKGROUNDS AT SuperKEKB

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Abstract

Xsuite is a collection of Python packages developed to simulate beam dynamics in particle accelerators. It includes different modules that can be seamlessly integrated together and with both accelerator-specific and general-purpose Python tools, enabling the study of complex simulation scenarios. The Xcoll module, developed for collimation studies, allows the integration of beam–matter interaction simulations into tracking through various available scattering models, including those from the BDSIM/Geant4 toolkit. Originally developed for the Future Circular e^+e^- Collider (FCC-ee) collimation studies, the Xsuite–BDSIM interface is now in full production use for FCC-ee. Given the novelty of this simulation framework, a key challenge is its validation against experimental measurements. This paper presents the first comparison of Xsuite–BDSIM collimation simulations with experimental data from an e^+e^- collider, SuperKEKB.

INTRODUCTION

SuperKEKB [1, 2] is a 3016 m circumference e^+e^- B-factory located at KEK in Tsukuba, Japan. It consists of two storage rings: the 7 GeV e^- High Energy Ring (HER) and the 4 GeV e^+ Low Energy Ring (LER), delivering high-luminosity collisions to the Belle II [3] experiment, which performs precision measurements in the flavour sector and searches for physics beyond the Standard Model.

Beam losses are a major challenge for the Belle II detector, as they can cause backgrounds that degrade detector performance or even damage sensitive components. To mitigate them, SuperKEKB employs movable collimators that intercept halo particles before they reach the interaction region (IR). Radiation levels are monitored by dedicated detectors integrated into Belle II. These measurements provide continuous diagnostics and enable correlation studies between background levels and machine conditions.

Simulations are essential to predict backgrounds and ensure safe operation as the collider approaches its luminosity goal. At SuperKEKB, beam background simulations are typically performed using the SAD [4] tracking code with Geant4-parametrized collimator interactions. This approach has shown excellent agreement with experimental data from dedicated background studies [5, 6].

In this work, we benchmark the Xsuite–BDSIM simulation framework against one of these studies, performed in June 2020 [5]. Specifically, we compare simulated and measured dose rates at an IR diamond radiation monitor during a vertical collimator scan in the LER. This constitutes the first validation of Xsuite–BDSIM for collimation and background studies at a lepton collider.

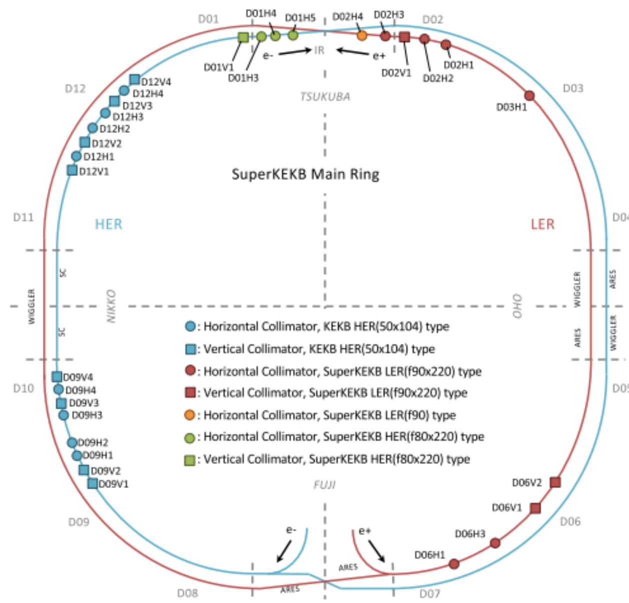

Figure 1: SuperKEKB collimator layout as of June 2020 [5].

BEAM-INDUCED BACKGROUNDS

The main single-beam background sources relevant to this study are Touschek and beam–gas scattering [5, 6]. These processes produce beam halo particles that can deviate from the nominal orbit and strike collimators or other components, generating secondary particles that may contribute to detector backgrounds.

Touschek scattering [7] results from large-angle intra-bunch Coulomb scattering, where transverse momentum is transferred into longitudinal momentum. The resulting off-momentum particles can exceed the local momentum acceptance and be lost downstream. This effect is especially relevant in low-emittance, high-current rings like SuperKEKB. Beam–gas interactions arise from scattering with residual gas molecules and include both elastic (Coulomb) and inelastic (Bremsstrahlung) processes. These interactions generate particles with large transverse amplitudes or momentum deviations, contributing to beam halo formation.

Other background sources, such as injection-related losses, may contribute during top-up cycles but are not significant under the conditions considered and are therefore not included in this study. Radiative Bhabha scattering, while

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an important background source during collisions, is a two-beam process and thus irrelevant in single-beam operation. Accordingly, it is not addressed in this work.

Therefore, in this paper, Touschek and beam–gas scattering are the only single-beam background sources considered.

SuperKEKB COLLIMATION AND BACKGROUND STUDY

This section describes the SuperKEKB collimation system as of June 2020 and the background study analyzed in this paper. A detailed and up-to-date description of the SuperKEKB collimation system, including later upgrades, can be found in Refs. [8, 9].

The SuperKEKB collimation system [10] is designed to intercept off-orbit particles before they reach the IR, thereby reducing beam-induced backgrounds and protecting sensitive components. Each ring is divided into twelve sections (D01–D12), and hosts a set of movable collimators installed at high-beta locations. The HER and LER are equipped with 20 and 10 collimators, respectively, as shown in Fig. 1. Most collimators consist of two copper jaws with high-Z material tips made of W or Ta; the LER vertical collimator D06V1—central to this study—features a 5 mm long Ta tip.

On June 27, 2020, a dedicated single-beam background study was conducted on the SuperKEKB LER [5]. The D06V1 aperture was varied in steps, and radiation dose rates were recorded at the Belle II radiation monitors. In this work we focus on the QCS-FW diamond detector, located at +56.8 cm from the interaction point (IP) along the positron beam direction. The evolution of the D06V1 aperture and corresponding QCS-FW dose rate is shown in Fig. 2.

SIMULATION FRAMEWORK

In this study, we use Xsuite–BDSIM [11–13] to simulate beam losses at SuperKEKB/Belle II. These losses are then used as inputs to estimate the resulting background dose rates in the interaction region. Xsuite–BDSIM combines particle tracking in the accelerator lattice, handled by Xsuite [14], with detailed Monte Carlo simulations of particle–matter interactions in the collimators using BDSIM [15, 16], a Geant4 [17–19]-based toolkit.

To simulate the relevant background sources, we use dedicated routines for Touschek and beam–gas scattering, currently interfaced as stand-alone modules but developed with the goal of eventual integration into Xsuite. The beam–gas module models both Bremsstrahlung and Coulomb scattering during tracking, using arbitrary pressure profiles as input [20]. The Touschek routine combines a Monte Carlo method and Piwinski formula [21], following the approach presented in Ref. [22] and implemented in ELEGANT [23].

These simulations produce distributions of particles lost on the beam pipe aperture. To evaluate the resulting radiation dose rates in the Belle II diamond detectors, we use the Belle II Analysis Software Framework (basf2) [24, 25], whose background module estimates the dose rate in the IR monitors based on the spatial and kinematic distribution of particle losses on the inner beam pipe.

SIMULATION SETUP

To reproduce the June 2020 background study in simulation, the first step involved converting the lattice description from SAD (native to SuperKEKB) to Xsuite. This required a careful optics rematching strategy to account for the native differences between the two frameworks. Details on this conversion procedure and on achieving consistent lattice representation across optics codes can be found in Refs. [26, 27].

Accurate modeling of the SuperKEKB-type collimators was also essential for reproducing the experimental results. A new collimator model ("jcoltip") was implemented in BDSIM to reproduce the two-material structure of these devices, consisting of a copper body and a high-Z tip. The Xsuite–BDSIM interface via Xcoll was extended accordingly to support this new geometry.

Simulations were then performed with different D06V1 collimator apertures for each single-beam background source: Coulomb scattering, Bremsstrahlung, and Touschek.

In beam–gas simulations, 1500 scattering centers were uniformly distributed along the LER. To improve computational efficiency, cross sections were biased during the first turn to increase the scattering probability; scattered particles were then tracked for 999 subsequent turns without further beam–gas interactions to model the propagation of beam-gas-scattered particles through the ring [20]. A realistic pressure profile corresponding to a beam current of 200 mA

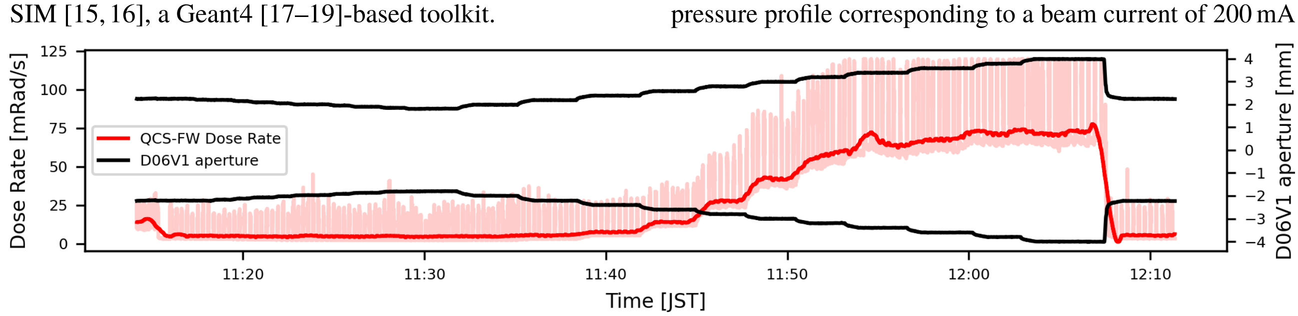

Figure 2: Measured dose rate at the QCS-FW diamond detector during the June 27, 2020 SuperKEKB LER background study, shown as a function of time and overlaid with the D06V1 collimator aperture. The raw dose rate (light red) is displayed alongside a smoothed trend (solid red). The study was performed at a beam current of 200 mA, using 978 bunches with horizontal/vertical emittances of 3.3 nm and 22 pm, respectively, and a bunch length of 5 mm [5].

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was used. Based on SuperKEKB experience, a single atomic gas species with atomic number $Z = 7$ was assumed for the entire ring.

Touschek simulations employed 1000 uniformly spaced scattering centers around the ring. Scattered particles were generated at each center and tracked for 1000 turns.

Approximately 10^7 primary particles were simulated for each beam–gas simulation, and between 2×10^7 and 3×10^7 for each Touschek simulation.

All simulations included the full nonlinear lattice, detailed beam pipe aperture, and realistic collimator geometry implemented in BDSIM/Geant4. Synchrotron radiation and machine errors were not included. The omission of synchrotron radiation is justified by the limited simulation time (1000 turns), which corresponds to about one-quarter of the damping time in the LER. At this level, synchrotron radiation is not expected to significantly alter the results.

For each case, particles lost within ±4 m of the IP (Belle II region) were recorded and used as input to basf2 to compute the dose rate at the QCS-FW diamond detector. The contributions from all background sources were then combined to estimate the total dose rate.

Following Ref. [5], a 150 µm vertical offset was applied to D06V1 to better match the observed dose response.

RESULTS

The simulation results were compared with experimental data collected during the D06V1 vertical collimator scan on June 27, 2020, presented in [5]. Figure 3 shows the relative dose rate measured by the QCS-FW diamond detector as a function of the D06V1 aperture, expressed in units of the vertical beam size ($\sigma_{\beta V}$). Xsuite–BDSIM predictions are overlaid on the experimental measurements.

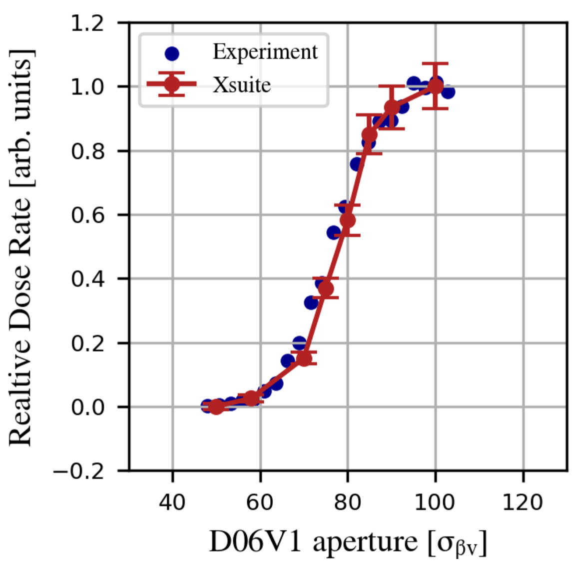

Figure 3: Comparison of simulated and measured relative dose rates in the QCS-FW diamond detector as a function of D06V1 collimator aperture, expressed in units of vertical beam size $\sigma_{\beta V}$. Simulated values were obtained with Xsuite–BDSIM, including beam–gas and Touschek sources.

To enable a meaningful comparison, both datasets were processed following the normalization procedure described in Ref. [5]. The baseline dose rate, corresponding to apertures smaller than 52 $\sigma_{\beta V}$, was subtracted from all points. The resulting values were then normalized to the average dose rate observed at large apertures (above 92 $\sigma_{\beta V}$), where the background level reaches a plateau.

As seen in Fig. 3, the Xsuite-based simulation accurately reproduces the overall shape of the dose rate curve. In particular, it captures the steep increase in dose rate around 60–80 $\sigma_{\beta V}$, followed by saturation at larger apertures.

Figure 3 corresponds to Fig. 16(a) in Ref. [5], which compares the same normalized experimental dataset with normalized dose rates predicted by SAD–Geant4 simulations. Our results demonstrate that Xsuite–BDSIM achieves a comparable level of agreement, validating its use for background modeling and collimation studies in e^+e^- machines.

This level of agreement confirms the robustness of the Xsuite–BDSIM simulation chain, including the lattice conversion, the new collimator model, and the dedicated background source routines. It supports the applicability of the framework to operational background predictions and further studies at SuperKEKB and future lepton colliders.

CONCLUSIONS AND OUTLOOK

We have presented the first benchmark of the Xsuite–BDSIM simulation framework against measured beam-induced background data at SuperKEKB. The study focused on a dedicated vertical collimator scan performed in the LER on June 27, 2020. Using realistic lattice optics, collimator geometry, and dedicated scattering models for beam–gas and Touschek processes, we simulated the expected dose rates at the QCS-FW diamond detectors and compared them to experimental measurements.

The simulations reproduce the measured relative trend with high accuracy. This result validates the Xsuite–BDSIM framework as a reliable tool for collimation studies in e^+e^- storage rings and demonstrates its ability to reproduce complex beam loss scenarios observed in operation.

The developments presented in this work — including the lattice conversion from SAD, the new two-material collimator model in BDSIM, and the integration of dedicated background source routines — provide a solid foundation for applying Xsuite-based simulations to SuperKEKB and other lepton colliders.

As a natural extension, future studies could explore additional collimator configurations and other background sources, such as injection-related or luminosity-induced backgrounds. Further improvements to simulation realism, including the inclusion of synchrotron radiation and machine imperfections, are also foreseen. These developments can support ongoing studies at SuperKEKB and contribute to the broader validation and deployment of Xsuite for future machines such as the FCC-ee [28, 29].

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REFERENCES

[1] K. Akai, K. Furukawa, and H. Koiso, "SuperKEKB collider," *Nucl. Instrum. Methods. Phys. Res., Sect. A*, vol. 907, pp. 188–199, 2018. doi:10.1016/j.nima.2018.08.017

[2] Y. Ohnishi *et al.*, "Accelerator design at SuperKEKB," *Prog. Theor. Exp. Phys.*, vol. 2013, no. 3, p. 03A011, 2013. doi:10.1093/ptep/pts083

[3] T. Abe *et al.*, "Belle II Technical Design Report," *arXiv*, 2010. doi:/10.48550/arXiv.1011.0352

[4] SAD Home Page, "Strategic Accelerator Design," 2025. http://acc-physics.kek.jp/SAD/

[5] A. Natochii *et al.*, "Improved simulation of beam backgrounds and collimation at SuperKEKB," *Phys. Rev. Accel. Beams*, vol. 24, p. 081001, 2021. doi:10.1103/PhysRevAccelBeams.24.081001

[6] A. Natochii *et al.*, "Measured and projected beam backgrounds in the Belle II experiment at the SuperKEKB collider," *Nucl. Instrum. Methods. Phys. Res., Sect. A*, vol. 1055, p. 168550, 2023. doi:10.1016/j.nima.2023.168550

[7] 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

[8] S. Terui *et al.*, ' 'Low-Z collimator for SuperKEKB," *Nucl. Instrum. Methods. Phys. Res., Sect. A*, vol. 1047, p. 167857, 2023. doi:10.1016/j.nima.2022.167857

[9] S. Terui *et al.*, "Collimator challenges at SuperKEKB and their countermeasures using nonlinear collimator," *Phys. Rev. Accel. Beams*, vol. 27, p. 081001, 2024. doi:10.1103/PhysRevAccelBeams.27.081001

[10] T. Ishibashi *et al.*, "Movable collimator system for SuperKEKB," *Phys. Rev. Accel. Beams*, vol. 23, p. 053501, 2020. doi:10.1103/PhysRevAccelBeams.23.053501

[11] 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

[12] A. Abramov *et al.*, "Development of collimation simulations for the FCC-ee," in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 1718–1721. doi:10.18429/JACoW-IPAC2022-WEPOST016

[13] 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, pp. 474–478. doi:10.18429/JACoW-HB2023-THBP13

[14] G. Iadarola *et al.*, "Xsuite: an integrated beam physics simulation framework," in *Proc. HB'23*, Geneva, Switzerland, Oct. 2023, pp. 73–80. doi:10.18429/JACoW-HB2023-TUA2I1

[15] L. 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

[16] L. Nevay *et al.*, "BDSIM: Automatic Geant4 Models of Accelerators," in *Proc. ICFA Mini-Workshop on Tracking for Collimation*, CERN, Geneva, Switzerland, p. 45, 2018. doi:10.23732/CYRCP-2018-002.45

[17] J. Allison *et al.*, "Recent developments in Geant4," *Nucl. Instrum. Methods. Phys. Res., Sect. B*, vol. 835, pp. 186–225, 2016. doi:10.1016/j.nima.2016.06.125

[18] S. Agostinelli *et al.*, "Geant4—a simulation toolkit," *Nucl. Instrum. Methods. Phys. Res., Sect. A*, vol. 506, pp. 250–303, 2003. doi:10.1016/S0168-9002(03)01368-8

[19] J. Allison *et al.*, "Geant4 developments and applications," *IEEE Trans. Nucl. Sci.*, vol. 53, pp. 270–278, 2006. doi:10.1109/TNS.2006.869826

[20] G. Broggi *et al.*, "Beam losses due to beam-residual gas interaction in the FCC-ee," presented at IPAC'25, Taipei, Taiwan, June 2025, paper MOPM036, this conference.

[21] A. Piwinski, "The Touschek Effect in Strong Focusing Storage Rings," *arXiv*, 1999. 100.48550/arXiv.physics/9903034

[22] 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

[23] M. Borland, "ELEGANT: A flexible SDDS-compliant code for accelerator simulation," Argonne National Lab., IL, USA, Tech. Rep., 2000. doi:10.2172/761286

[24] T. Kuhr *et al.*, "The Belle II Core Software: Belle II Framework Software Group," *Comput. Softw. Big Sci.*, vol. 3, no. 1, 2018. doi:10.1007/s41781-018-0017-9

[25] Belle II Collaboration, ' 'Belle II Analysis Software Framework (basf2)," doi:10.5281/zenodo.5574115

[26] J. Salvesen *et al.*, "Consistent representation of lattices between optics code for FCC-ee, SuperKEKB and more," presented at the 70th ICFA Adv. Beam Dyn. Workshop High Luminosity Circ. e^+e^- Colliders (eeFACT'25), Tsukuba International Congress Center (EPOCHAL), Tsukuba, Japan, March 3–7, 2025.

[27] J. Salvesen *et al.*, ' 'Modelling optics and beam-beam effects of SuperKEKB with Xsuite," presented at IPAC'25, Taipei, Taiwan, May 2025, paper MOPM034, this conference.

[28] A. Abada *et al.*, "FCC-ee: The Lepton Collider," *Eur. Phys. J. ST*, vol. 228, no. 2, 2019, pp. 261–623. doi:10.2172/1527435

[29] M. Benedikt *et al.*, "Future Circular Collider Feasibility Study Report Volume 2: Accelerators, technical infrastructure and safety," CERN, Geneva, CERN-FCC-ACC-2025-0004, 2025. doi:10.17181/CERN.EBAY.7W4X