SIMULATIONS AND MEASUREMENTS OF INJECTION BACKGROUNDS AT SuperKEKB*

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Abstract

SuperKEKB is an electron-positron collider, where the beams collide inside the Belle II detector. The design luminosity has not yet been achieved, partly due to limited injection efficiency in both rings, which limits the achievable beam current. The injection process also generates significant background in the Belle II detector, requiring vetoes during data taking that reduce the detector efficiency. To improve the understanding of these issues, the injection process at SuperKEKB has been simulated using the Xsuite simulation framework, including detailed multi-turn tracking and particle-matter interactions in the collimators. The results of these simulations have been used as input for a Belle II detector simulation to estimate the resulting background levels. This paper presents the simulation methodology and the comparison between simulation results and experimental data, collected during the 2025 run, as a prerequisite for future applications of the simulation framework including further optimization of the background at SuperKEKB as well as similar studies for future lepton colliders.

INTRODUCTION

The SuperKEKB collider, shown in Fig. 1, is an asymmetric electron–positron collider operating with a 4 GeV positron Low Energy Ring (LER) and a 7 GeV electron High Energy Ring (HER) [1–3]. It delivers high-luminosity collisions to the Belle II experiment for precision studies of B-meson decays and searches for physics beyond the standard model [4]. The accelerator complex also includes an injector linac and a positron damping ring. Due to beam lifetimes well below 30 minutes in collision, the machine operates in top-up injection mode to maintain stable luminosity. Although a record luminosity of $5.1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ has been achieved, this remains well below the design value of $8 \times 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ [5]. Several factors limit machine performance, such as injection inefficiency, generating beam losses and detector background at each injection [6, 7]. In 2024, achieved injection efficiencies were 80% in the LER and 60% in the HER. As injection losses and background increases with beam intensity, understanding and mitigating these losses is essential for future luminosity improvements.

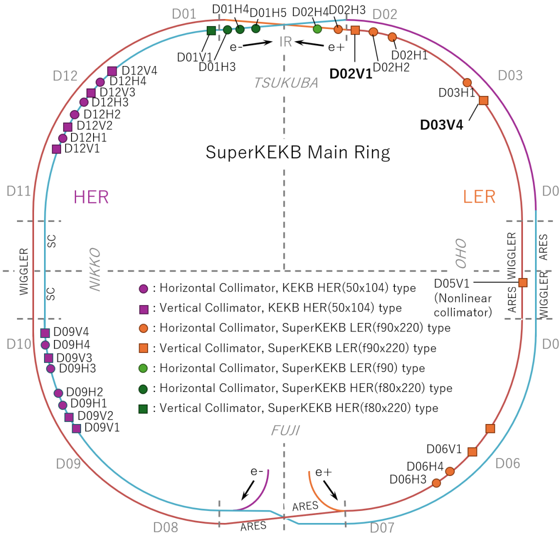

Figure 1: SuperKEKB collider layout with collimator location as of 2025. Courtesy of T. Ishibashi and S. Terui.

This paper presents a detailed simulation of LER injection losses and the resulting detector backgrounds, compared to measurements collected during the 2025 run.

SIMULATION SETUP

While Strategic Accelerator Design (SAD) [8] is commonly used for SuperKEKB studies, this work was performed using the Xsuite framework [9]. Xsuite, developed at CERN, combines accelerator-specific and Python-based tools for modeling complex effects such as collimation and beam-beam interactions. Collimation studies were carried out using the Xcoll module [10], including detailed aperture models and loss localization identification. Beam–matter interactions within the collimators were simulated through the Xsuite-BDSIM coupling [11, 12]. This work provides an important benchmark of the new tools. The full SuperKEKB lattice 2025c was converted from SAD to Xsuite using the SAD2XS converter [13], previously benchmarked [14], including a detailed interaction region (IR) aperture model and realistic collimator geometry. The distribution of the injected bunch is generated based on simulations of the beam transport between the injector and the main ring [15]. The distribution is rescaled to the measured emittances at the end of the transfer line ($\epsilon_y^n = 60\,\mathrm{mrad}$ $\epsilon_x^n = 170\,\mathrm{mrad}$) and

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tracked over multiple turns. The outputs are spatial and temporal loss distributions along the ring and at the collimators. Particles lost within ±4 m of the interaction point were then used as input to the Belle II detector simulation framework, namely basf2 [16], a Geant4-based environment with detailed IR and detector geometry.

MEASUREMENT METHODOLOGY

The data used in this study were collected during the collimator alignment campaign performed in November 2025. The goal of the alignment was to evaluate the offset between the collimator position and the beam orbit. The alignment is applicable only to SuperKEKB-type collimators [17], which feature two independently movable jaws. During the procedure, the collimator gap was kept constant while the collimator blocks were moved vertically in discrete steps, first upward to scan the bottom jaw and then downward to scan the top jaw. The alignment was performed on two LER vertical collimators, D02V1 and D03V4 (see Fig. 1), using a detuned optics configuration with $\beta_y^* = 8$ mm. To enhance the lifetime variation, an orbit bump was applied at the collimator location. The beam current was maintained at 35 mA with 393 bunches, through continuous top-up injection at 1 Hz. The injected beam charge was kept below 0.7 nC per shot using the so-called “daiginjo” beam configuration, obtained by closing a collimator upstream of the damping ring to reduce the injected charge without modifying the phase-space distribution.

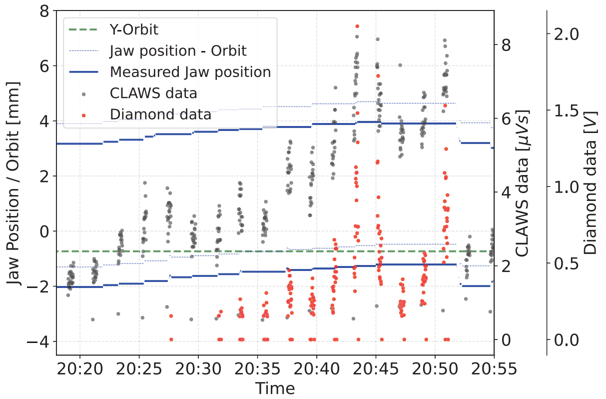

Figure 2: Snapshot of the collimator alignment measurements.

Each collimator position was held until the current decreased by 3%. At each step, 20 injections at 1 Hz were performed, resulting in a systematic scan of injection backgrounds, as shown in Fig. 2. Injection background was monitored using the Belle II diamond detector system [18], consisting of 28 detectors installed around the beam pipe in the IR to measure radiation dose rates. A subset of these detectors was instrumented with an oscilloscope, enabling injection-dedicated studies through triggers synchronized with each injection. The diamond detector QCS-FW-225 was selected for this analysis due to its sensitivity to LER losses. In addition, beam loss monitors (sCintillation Light And Waveform Sensors, CLAWS detectors [19]) installed at the collimators D02V1, D03V4 and D05V1 were used to measure local beam losses. Beam losses are quantified as the accumulated signal over a 2.18 ms window after each injection.

These two independent observables provide complementary information and are used for quantitative comparison with simulations.

ANALYSIS

The analysis was performed using only the D02V1 alignment scan data, as the CLAWS detectors were not operating reliably during the D03V4 alignment. Only the bottom-jaw scan was considered for this study. Measurement points for which both diamond and CLAWS data were available were retained, corresponding to periods with the orbit bump enabled. One additional point was discarded due to an incorrect collimator gap; the remaining dataset corresponds to a fixed gap of 5.2 mm. In total, six scan points were selected for comparison. The corresponding machine conditions were reproduced in simulation, and the injected beam was tracked for 500 turns, as no further losses were observed afterwards. The resulting particle losses along the ring were used to construct observables comparable to the measurements. For both measured observables, an uncertainty of $\pm 8\ \mu m$ on the jaw position was considered, originating from the jaw offset estimated during the alignment procedure.

CLAWS Data

For comparison with the CLAWS detectors, simulated losses within the D02V1 jaw were integrated over the full tracking duration. Statistical uncertainties were assigned assuming Poisson statistics on the loss counts. The CLAWS signals were corrected by subtracting the pedestal, defined as the average of measurements below 1.5 Vs. This threshold was chosen because, within the time window of interest, the signal remains well above this value, as shown in Fig. 2. Signals below the noise threshold were discarded. Measurements corresponding to identical collimator offsets were averaged, and uncertainties were taken as the standard deviation of the mean. Since no calibration factor is available to correlate the CLAWS signal into lost positrons on the collimator, simulated and measured datasets were compared after normalization to their respective maxima.

Diamond Data

The simulation provides dose rates (mRad/s) at the diamond detectors, in particular QCS-FW-225, for each configuration. Simulations with different random seeds were averaged, and the statistical uncertainty on the mean was estimated as $\sigma = \mathrm{std}(R_i)/\sqrt{N}$, where N is the number of seeds. Measured voltages were converted into dose-rate values using a previously determined calibration factor. The detector noise level, evaluated prior to the alignment, was found to be 2.75×10^4 mRad/s and signals below the threshold were discarded. Measurements at identical offsets were averaged

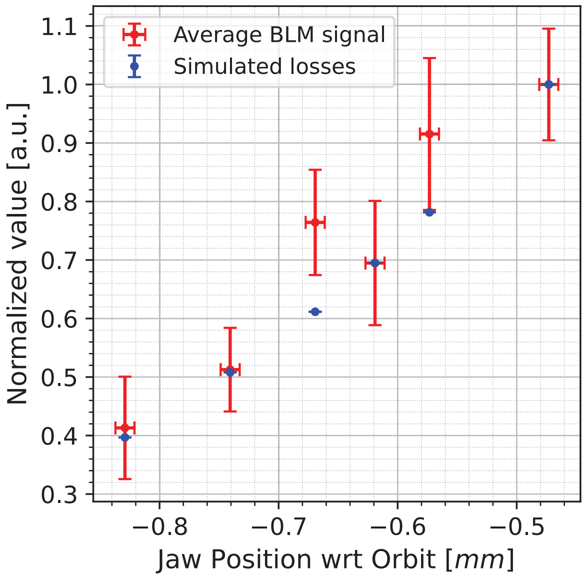

Figure 3: Comparison between normalized simulated losses at D02V1 and normalized CLAWS measurements as a function of the bottom jaw offset with respect to initial position.

and uncertainties assigned as the standard deviation of the mean. Although an absolute comparison is in principle possible, simulated dose rates are approximately one order of magnitude smaller than measurements, likely due to machine imperfections and injection errors not included in the model. Another contribution could arise from the injected beam distribution, which does not account for errors and higher-order effects in the transfer lines. Further differences may also come from the uncertainties on the measured conversion factor. Therefore, simulated and measured datasets were compared using normalized values.

RESULTS

Simulations and measurements are compared based on the normalized losses at the collimator and on detector backgrounds as a function of the collimator position. Figure 3 shows the comparison between the normalized simulated losses at D02V1 and the normalized CLAWS signal measured at the same location. The loss rate at D02V1 increases as the bottom jaw approaches the beam orbit. Simulation and measurements exhibit a monotonic behavior and the simulation framework reproduces the loss location and its dependence on the collimator position with good accuracy.

Figure 4 shows the comparison between the normalized simulated dose rates at the QCS-FW-225 diamond detector and the normalized diamond measurements. As observed for the CLAWS measurements, the trend is monotonic, however the experimental data exhibit larger uncertainties. These uncertainties are likely due to the low-intensity configuration used during the alignment, which results in a reduced injection background and consequently less clean measurements. Furthermore, even in simulation, only 1% of the particles lost in the IR produce a hit in the detector. Nevertheless,

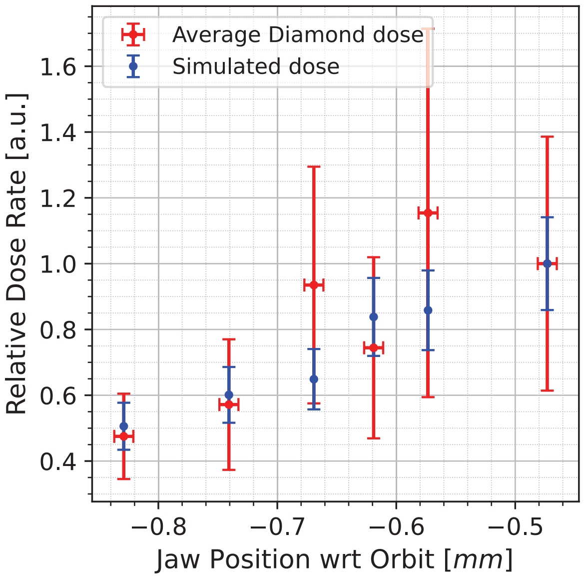

Figure 4: Comparison between normalized simulated dose rates at QCS-FW-225 and normalized diamond detector measurements as a function of the bottom jaw offset with respect to initial position.

the simulation reproduces the trend of the measured data within the estimated errors (at least a few thousand particles lost at the detector in each simulated run). The remaining differences can be attributed to effects not included in the tracking simulation model, such as machine imperfections, orbit fluctuations, and on a not fully accurate detector response simulation. The data indicate that D02V1 plays a dominant role in intercepting injection-induced background, in agreement with simulations.

CONCLUSION

Injection-induced backgrounds represent a significant limitation to achievable luminosity at SuperKEKB due to their impact on detector performance. In this work, a detailed simulation chain based on Xsuite was developed to model injection losses and injection-induced background at the Belle II detector. A comparison with measurements collected during the LER collimator alignment campaign shows good agreement between simulated and observed losses at the collimator, as well as between simulated and measured dose rates at the diamond detector at the Belle II experiment, as a function of collimator configuration. These results highlight the key role of D02V1 in mitigating IR injection losses. The consistent behavior observed in these two independent measures confirms the capability of the simulation chain to describe both local injection losses and injection background far from the beam loss source in the Belle II detector.

Future work will focus on improving the model and optimizing collimator settings to further reduce detector backgrounds during injection.

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