ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-TUZAT0103

BEAM-INDUCED BACKGROUND SIMULATION AND MEASUREMENTS IN Belle II AT SuperKEKB*

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Abstract

Seeking New Physics beyond the Standard Model, the Belle II experiment at the SuperKEKB electron-positron collider has already reached a peak luminosity of about 4.7×10^{34} cm^{-2} s^{-1}. Its unprecedented target luminosity of 6.3×10^{35} cm^{-2} s^{-1} requires stable machine operation and proper control of beam-induced backgrounds for safe detector operation at high beam currents. The leading background components originating from stored and colliding beams can now be predicted with reasonable accuracy. Dedicated simulations based on the particle tracking software Strategic Accelerator Design (SAD) and Geant4 are used to predict beam-induced backgrounds. These simulations are important for studying realistic collimation scenarios, estimating associated background levels at future machine optics, and making informed choices between possible machine and detector protection upgrades.

This paper reports on the Belle II beam-induced background status in 2021–2022. It overviews background simulation and measurement methodology, and discusses the expected background evolution and mitigation strategies at higher luminosity.

INTRODUCTION

The Belle II/SuperKEKB [1–3] experiment is an upgrade of Belle/KEKB [4, 5] ran between 1999 and 2010. These two projects share same goals of i) studying CP-symmetry violation in a B-meson system, and ii) searching for New Physics beyond the Standard Model. This implies a certain set of requirements for the experiments such as: i) high collision luminosity to produce a large number of $B\bar{B}$-pairs; ii) asymmetric-energy colliding beams of particles to facilitate B-meson decay time difference measurements; and iii) a high quality general-purpose spectrometer (detector) around the interaction point (IP) of two beams for precise measurements of the $B\bar{B}$-mixing rate.

Inspired by Belle/KEKB achievements, which along with BaBar/PEP-II observed large time-dependent CP-asymmetries and contributed to the 2008 Physics Nobel Prize [6], Belle II/SuperKEKB aims to collect 50 times larger data set by the 2030s. To reach this goal, an extremely high collision luminosity above 1×10^{35} cm^{-2} s^{-1} is required. Therefore, the experiment upgraded almost all detector and collider sub-systems, and implemented so-called *nano-beam* and *crab waist* collision schemes to squeeze beam sizes at the IP and improve luminosity performance [7].

Since 2019, when the detector was rolled in for comprehensive data taking, SuperKEKB has reached the world highest peak luminosity of about 4.7×10^{34} cm^{-2} s^{-1} in June 2022, while Belle II has successfully accumulated more than 0.4 ab^{-1} of data, which is about as large as BaBar's data set collected in almost nine years of PEP-II operation [8].

The SuperKEKB is a 3 km-long circular collider of 4 GeV positrons and 7 GeV electrons accumulated in low-energy ring (LER) and high-energy ring (HER), respectively. Its design has 40 times higher collision luminosity ($\mathcal{L} \sim I_{\pm}/\beta_{\mathrm{y}}^{*}$) than KEKB with two times higher beam currents ($I_{\pm}$) and 20 times smaller vertical beta functions at the IP (β_{y}^{*}). This causes higher beam-induced backgrounds in the Belle II detector and leads to i) a high rate of particles leaving the beam, requiring a more frequent top-up beam injection, ii) damage of sensitive detector and collider components, reducing their longevity, and iii) a high rate of beam losses in the interaction region (IR), where the Belle II locates, increasing detector hit occupancy and physics analysis noise. To reach the target luminosity of 6.3×10^{35} cm^{-2} s^{-1}, a comprehensive understanding of beam-induced backgrounds and their countermeasures is essential.

In this paper, we describe main beam loss sources and their countermeasures, report on dedicated background measurements and simulation software, and discuss background estimation towards higher luminosity with a brief overview of our plans in order to facilitate stable and safe detector and machine operation.

BEAM-INDUCED BACKGROUND SOURCES

At SuperKEKB, stray particles which do not follow the nominal trajectory and hit the inner walls of the beam pipe or any other machine element are defined as lost. These particles interact with machine and detector materials producing electromagnetic (EM) showers and neutrons which may hit the detector. These losses we call a beam-induced background (BG).

Below, we define the main types of beam-induced backgrounds which contribute the most to the machine and detector performance degradation and longevity.

Touschek BG is due to a single Coulomb scattering of two particles in the same beam bunch leading to their energy change. It is one of the major backgrounds in Belle II, mainly from the LER.

Beam-gas BG is caused by Bremsstrahlung and Coulomb scatterings of a beam particle by beam pipe residual gas

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[*] Work supported by the U.S. Department of Energy (DOE) via Award Number DE-SC0007852 and via U.S. Belle II Operations administered by Brookhaven National Laboratory (DE-SC0012704).

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ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-TUZAT0103

atoms changing their energy and trajectory, respectively. Since SuperKEKB reuses the HER beam pipe from the KEKB era and the LER beam pipe is newly constructed, the LER beam-gas losses contribute the most to Belle II backgrounds due to higher vacuum pressure.

Synchrotron radiation (SR) is generated by beam particles moving through a strong magnetic field of dipole magnets and final focusing superconducting quadrupole magnets (QCS) near the IP used for beam size squeezing. The current level of the SR is of no concern in terms of occupancy for the innermost layers of the vertex detector.

Injection BG is caused by the injected beam of particles into the main ring (MR). Due to a short beam lifetime ($<$ 1 hour), the machine operates in a so-called *top-up injection regime*. The perturbed by machine imperfections injected beam oscillates around the stored beam causing particle losses for a few milliseconds after injection. Low injection efficiency causes high injection beam losses around the MR, enlarging the DAQ dead time of the detector.

Luminosity BG is due to colliding beams at the IP. This type of backgrounds is induced by low energetic electron-positron pairs and gammas produced in two-photon and radiative Bhabha processes, respectively. At the current commissioning stage, the luminosity BG does not exceed the single-beam BG level. However, further luminosity increase will enhance this background making it dominant compared to other beam losses.

Sudden beam losses (SBLs) may occasionally occur in the LER or HER during stable machine operation at a specific location around the ring. Unfortunately, we still do not have a comprehensive explanation of such events. The potential candidates of the unexpected beam instabilities could be machine element failure, beam-dust interaction or vacuum element defects. It is a big problem for a safe and stable machine operation limiting bunch current increase above $\sim 0.7\,\mathrm{mA/bunch}$, while the target bunch current is about $\sim 1.4\,\mathrm{mA/bunch}$. Usually, only a few SBL events happen in a year. However, in 2022, we had more than 50 of them, which caused several QCS quenches and collimator damages. Figure 1 illustrates an example of the damaged collimator due to SBLs in 2021. Also, a local vacuum burst is detected in such events. Moreover, the damaged part of the collimator does not effectively collimate the beam, causing a background increase due to particle scattering off of the head protrusions. Therefore, the collimator aperture should be enlarged with further replacement of the entire jaw, leading to an extended period (weeks–months) of no beam due to radiation cooling down and replacement works.

BACKGROUND COUNTERMEASURES

To stop stray particles, a set of 11 and 20 movable masks (collimators) around LER and HER are installed [10–12]. By absorbing or strongly deviating off-trajectory particles, the collimators localize beam losses far from the IR, which significantly reduces detector backgrounds and helps to avoid QCS quenches. To minimise residual gas pressure in the beam pipe, we continuously perform vacuum scrubbing and installed heavy-metal shielding around the IR beam pipe to protect the detector against EM showers. Furthermore, the IP beryllium beam pipe is coated with a gold layer to suppress the SR. To avoid direct SR hits at the detector, the internal walls of the IR beam pipe have a ridged surface, while the incoming beam pipe has varying diameters collimating most of the SR photos. Since the injection BG could be even higher than other BGs, the Belle II DAQ utilizes an injection trigger veto to not trigger on high beam losses during $\sim 10\,\mathrm{msec}$ after each injection. This solution prevents us from taking noisy data. In addition, we continuously tune the injection chain to improve injection performances keeping the highest possible injection efficiency at the acceptable injection BG.

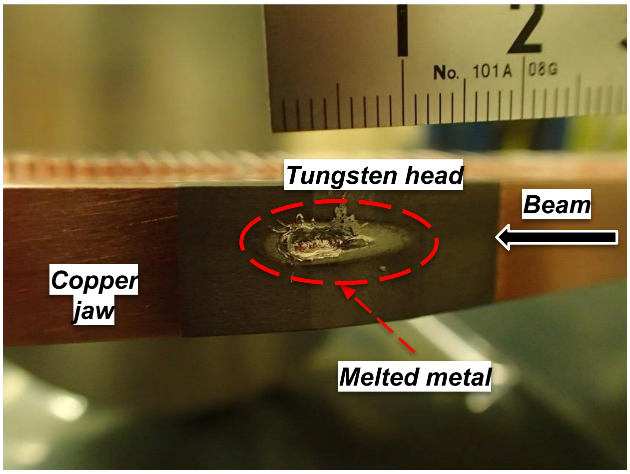

Figure 1: A severely damaged HER vertical collimator head due to sudden beam losses [9].

We use a set of diamond sensor-based detectors (Diamonds) to monitor the radiation dose rate around the IR beam pipe, see Figure 2. Four sensors highlighted in green are a part of the fast beam abort system [13]. In addition, the sCintillation Light And Waveform Sensors (CLAWS) detector system [14] monitors Belle II backgrounds in time with beam injection into the MR. Moreover, we have integrated CLAWS into the beam abort logic. The fast neutron flux in the accelerator tunnel is measured by compact Time Projection Chambers (TPCs) [15], while thermal neutron counting around Belle II is done by He^3 tubes [16].

Against SBLs, we plan i) to upgrade the abort system for fast abort signal triggering, ii) to use low-Z materials (e.g. graphite) for collimator heads, making them more robust [17], and iii) to perform vacuum system inspection, beam dynamics study and installation of additional beam loss monitors around the ring to understand the nature of SBLs better.

BACKGROUND MEASUREMENTS

When we change global machine optics settings (e.g. squeeze the beam at the IP) or install new equipment (e.g. collimators), we perform dedicated beam background mea-

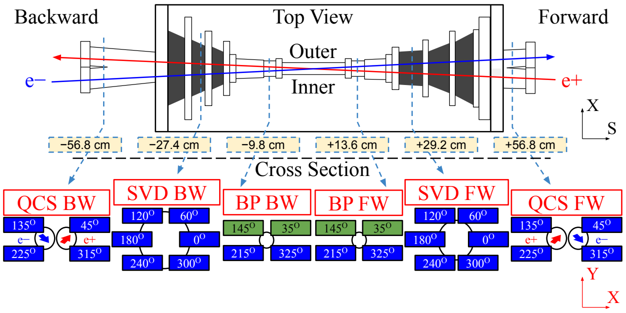

Figure 2: Diamond detector configuration in the IR. The detectors' azimuth angles are indicated in rectangles.

surements in Belle II at SuperKEKB, usually twice a year. To disentangle different background components, we run the machine in a single-beam mode, meaning that only one ring is filled with a beam at a time, and then fill both rings for luminosity background measurements. By changing the number of bunches circulating in each ring, we distinguish between Touschek and beam-gas backgrounds since the former is proportional to the beam current squared and inversely proportional to the number of bunches and bunch volume, while the latter is proportional to beam current and vacuum pressure. Since the power of the SR is proportional to the fourth power of the beam energy, we consider the SR background only for the HER beam in the Belle II pixel detector (PXD), which surrounds the IP beam pipe. At the collision operation, the single-beam fit results help estimate the contribution of the luminosity background, which is linearly proportional to the measured luminosity value.

We use our analysis results to extrapolate the measured beam-induced background toward higher beam currents assuming fixed collimator settings. Figure 3 shows an example of beam background evolution for the Time of Propagation (TOP) particle ID system as the most vulnerable Belle II sub-detector. The results are based on December-20, 2021 measurements scaling to June 2022 beam parameters and collimator settings. Wider HER collimators in 2022 significantly increase the HER beam-gas background shown in Figure 3 compared to 2021 rates listed in Table 1.

Table 1: Measured background composition in the TOP detector in June 2021 at LER and HER beam currents of about 730 mA and 650 mA, respectively, 1174 bunches, and luminosity of $2.6{\times}10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$.

Background	**Rate, MHz/PMT**	
	LER	HER
Beam-gas	0.70	0.11
Touschek	0.44	0.11
Injection	0.11	0.03
Luminosity	0.45	

As demonstrated in Table 1 and Figure 3, in 2021 and 2022, Belle II did not limit beam currents since background rates were acceptable and below limits. However, it will limit SuperKEKB eventually, without further background mitigation. Therefore, to reach the target luminosity of $6.3{\times}10^{35}\,\mathrm{cm^{-2}\,s^{-1}}$, an upgrade of crucial detector components is foreseen. For instance, we plan to replace TOP short-lifetime conventional microchannel plate photomultiplier tubes (MCP-PMTs), which quantum efficiency strongly degrades with the background increase [19].

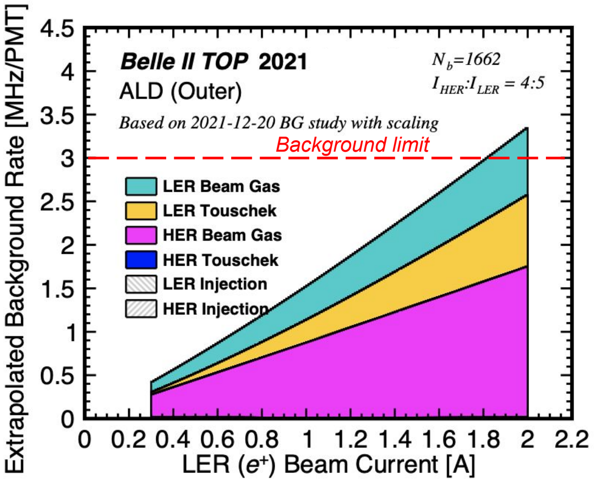

Figure 3: The extrapolated single-beam background in the TOP detector as a function of beam currents [18].

We will discuss in more detail the current Belle II background status in upcoming publications [20].

BACKGROUND SIMULATION

We developed a dedicated software for the Monte-Carlo beam-induced background simulation in Belle II. We use it for several reasons: i) to study the impact of beam optics parameters on Belle II backgrounds, ii) to develop new collimators in SuperKEKB, iii) to mitigate backgrounds better through the machine or detector adjustments and upgrades, and iv) it helps us predict background evolution at future machine settings.

We start with the multi-turn particle tracking in the machine using the Strategic Accelerator Design (SAD) software developed at KEK [21]. Beam-gas and Touschek scattered bunches of particles are tracked for 1000 machine turns, which corresponds to 10 ms of the real machine operation. The particles that reach the machine aperture (beam pipe or collimators) are defined as lost, and their coordinates are stored. Recently, we have improved the code by implementing a realist collimator profile and particle interaction with collimator materials, see Figure 4. Moreover, for the beam-gas background simulation, we use the measured vacuum pressure distribution, which is not uniformly flat around the ring. More details regarding the multi-turn particle tracking in SAD for SuperKEKB can be found in Reference [12].

Then, all lost particles within the IR, which hosts Belle II (±4 m from the IP), and accelerator tunnel (±30 m from the IP) we transfer from SAD to Geant4 [22–24] for detector

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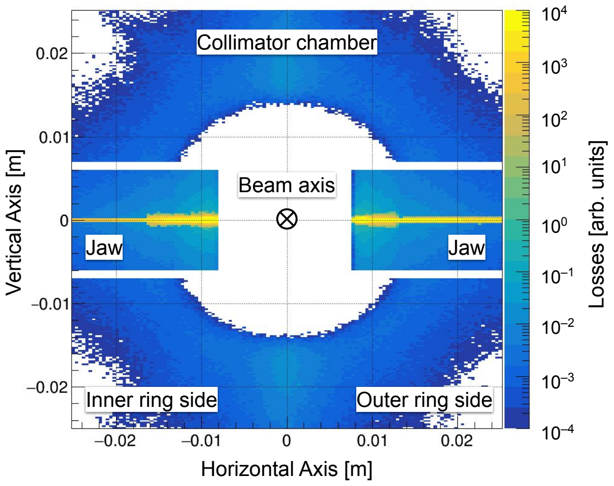

Figure 4: Simulated lost particles at the LER horizontal collimator.

response modelling. Also, we use the same Geant4 model for luminosity and SR background simulation.

In the past two years, we invested a lot of effort into improving our Geant4 model. As a result, the latest version realistically describes detector materials and accelerator tunnel, including the IP beam pipe, detector shielding, tunnel walls and machine equipment.

Validation

In 2021, we performed dedicated measurements at SuperKEKB to validate our simulation software [12]. Two collimator aperture scans were done in the LER, measuring radiation dose rates by Diamonds. First, we gradually closed the aperture of the narrowest vertical collimator, located ∼ 1 km upstream of the IP. As a result, we observed a significant reduction in the IR dose rate in a single-beam mode. Then, we moved back the vertical collimator to its initial aperture and gradually closed the horizontal collimator, located about 16 m upstream of the IP. The horizontal collimator scan showed a similar trend with a noticeable reduction of IR backgrounds until a certain aperture when the particles scattered off of the collimator head, so-called tip-scatterings, started to contribute to IR beam losses increasing backgrounds at a narrower aperture. Our simulation of the collimator aperture scans reproduces the measurements with a good agreement, validating the correct implementation of collimator profiles and tip-scattering models into the particle tracking code.

Accuracy

As an accuracy check, we calculate ratios of measured (data) to simulated (MC) backgrounds based on dedicated studies conducted in 2020–2021. Due to discussed simulation improvements and the accurate Geant4 model, our current data/MC ratios are within one order of magnitude from unity. Figure 5 shows data/MC ratios for the Belle II luminosity background, which is expected to be the dominant detector background beyond 1×10^{35} cm^{-2} s^{-1}. It is a substantial improvement compared to the past measurements in 2016 [25] and 2018 [26]. It also confirms our good understanding of the main beam loss processes in SuperKEKB. In addition, we use these ratios to estimate detector backgrounds at higher luminosities [27].

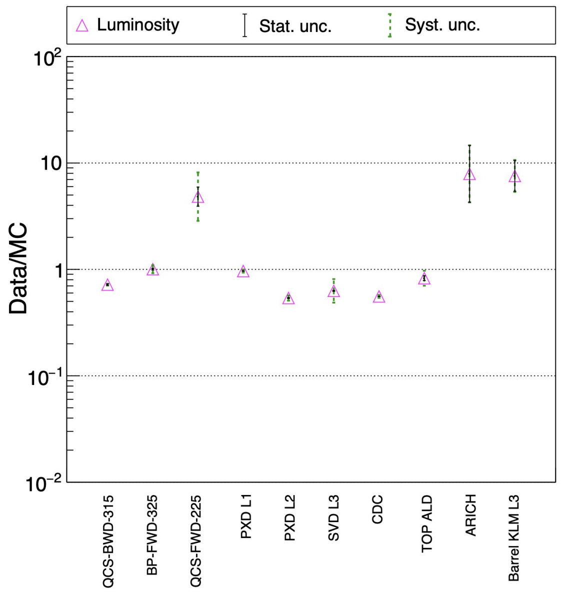

Figure 5: Calculated luminosity background data/MC ratios for Belle II sub-detectors based on dedicated background measurements at SuperKEKB in 2020–2021 [27].

FUTURE PLANS AND PROSPECTS

We use the newly improved background simulation and dedicated measurements to predict background evolution at future machine settings. According to the results presented in Reference [27], Belle II backgrounds will remain high but acceptable until a luminosity of about 2.8×10^{35} cm^{-2} s^{-1} is reached. For the target luminosity of about 6.3×10^{35} cm^{-2} s^{-1}, machine condition is very uncertain to make an accurate background prediction.

To reach the goal collecting about 50 ab^{-1} of data by the 2030s, we plan several upgrades of the machine and detector [19, 27] during future two long shutdown (LS) periods: LS1 in June 2022 – October 2023, and LS2 starting in 2027. Figure 6 schematically shows the timeline of the peak and integrated luminosity projection toward future machine parameters.

Below, we list Belle II/SuperKEKB major upgrades planned for the next decade.

- Detector upgrades are planned for LS1 and include damage sensors replacement, fully assembled PXD with two layers, and replaced short-lifetime conventional MCP-PMTs in the TOP detector. More details in Reference [19].

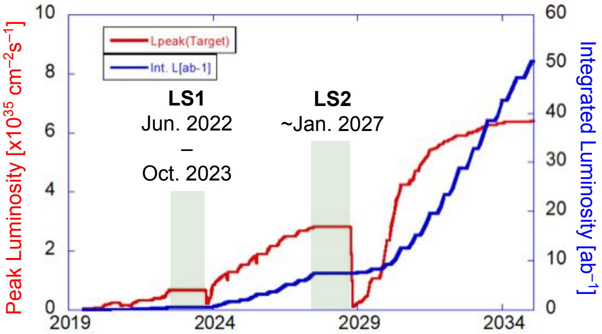

Figure 6: The Belle II/SuperKEKB luminosity projection based on the current machine achievements. Adopted from Reference [28].

- Install additional shielding during LS1 inside and outside Belle II against the SR, EM-showers and neutrons. We plan to add more polyethylene and concrete shielding on endcaps and around final focusing magnets.
- Consider a collimation system upgrade for LS1 and LS2, replacing damaged collimators with more robust collimator heads. Also, a so-called non-linear collimator (NLC) in the LER is foreseen for LS1 [27, 29, 30]. The NLC design, implementation and its impact on beam collimation will be accurately described by the Belle II/SuperKEKB team in future publications.
- To reach the target luminosity, the IR redesign during LS2 is under discussion.
- SuperKEKB beam dynamics stability, beam-beam interaction and injection performance require special attention since uncontrolled beam instabilities, beam size blow-up and high rate of injection beam losses cause machine and detector performance degradation, DAQ dead time duration increase, injection efficiency drop, and detrimental effects on the machine and detector component longevity. Therefore, the injection facility and machine feedback system upgrades, as well as accurate beam dynamics studies are under consideration.

SUMMARY

The Belle II/SuperKEKB experiment has successfully rolled in as a new generation *B*-factory searching for New Physics beyond the Standard Model. Its ultimate goal is to integrate a 50 times higher data set than its predecessor Belle/KEKB. The collider aims to reach an unprecedented luminosity of about $6.3{\times}10^{35}$ cm^{-2} s^{-1} by the 2030s. Such an extreme collision rate in the interaction region surrounded by Belle II induces high beam backgrounds in the detector. A dedicated set of countermeasures was implemented to protect sensitive detector and machine components. Furthermore, we plan to install additional detector shielding during two consecutive machine stops in the next decade to reinforce the detector protection against EM showers and neutrons.

In this paper, we revisited major beam loss mechanisms, leading to high beam backgrounds in the detector, and their countermeasures. Also, we reported on the current background status in Belle II and mentioned crucial stumbling blocks limiting further beam current increase, which should be mitigated by future machine upgrades. Finally, our improved background simulation agrees with measurements and helps us predict beam-induced background evolution at higher beam currents and luminosities. Although the final machine design for the post-LS2 period is unclear, the Belle II background is expected to be acceptable at least until the luminosity of about $2.8{\times}10^{35}$ cm^{-2} s^{-1}, if the assumed collimation settings are achieved.

ACKNOWLEDGMENTS

The authors are grateful to Belle II and SuperKEKB colleagues for their hard work and contribution.

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