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BEAM BACKGROUND MEASUREMENT AT SuperKEKB/Belle II IN 2020

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Abstract

The SuperKEKB electron-positron collider began collision operation in 2018 and achieved the world-record luminosity of 2.4×10^{34} $cm^{-2}s^{-1}$ in June 2020. We pursue higher luminosity by squeezing beam sizes and increasing beam currents. Beam backgrounds induced by stray particles will also increase and might cause severe radiation damage to Belle II detector components and worsen the quality of collected physics data. To mitigate these backgrounds, we have carefully designed our interaction region and installed movable collimators in the machine. We present recent measurements of beam background at SuperKEKB. We have performed dedicated machine studies to measure each background component separately and found that beam-gas scattering and Touschek scattering in the positron ring are the dominant sources of background rates in Belle II. We also present the latest observations of injection background, which determines the timing of a required Belle II data acquisition trigger veto and therefore affects the integrated luminosity. We show the beam background extrapolation toward the expected higher-luminosity operation and our plans for further background mitigation.

BEAM BACKGROUND AT SuperKEKB

Particles in a beam bunch may deviate from the nominal beam orbit due to various reasons. If their deviation is large enough, they may hit machine components and generate secondary showers. Such an effect, called "beam-induced background (beam BG)," can be dangerous for detectors since it determines the survival time of sensor components and may lead to severe instantaneous damage. It can also increase sensor occupancy and irreducible analysis background.

The SuperKEKB accelerator aims for unprecedented luminosity with larger beam currents and smaller beam size than the KEKB accelerator, and the Belle II detector should survive under higher beam BG environments than the Belle experiment. The major beam BG sources at SuperKEKB are categorized into two groups, "single-beam BG" and "luminosity BG" [1]. Single beam BG sources are, a) Touschek BG, caused by stray particles due to scattering between beam particles in the same bunch, b) beam-gas BG, caused by stray particles due to scattering between beam particles and residual gas molecule, c) synchrotron radiation which hits interaction region beam pipes and may reach inner sub-detectors and d) injection BG, caused by unstable beam after each top-up injections. Luminosity BG source are, e) radiative Bhabha process ($e^+e^- \rightarrow e^+e^-\gamma$) and f) two-photon process ($e^+e^- \rightarrow e^+e^- e^+e^-$). As of 2020, beam-gas BG and Touschek BG from LER are the dominant BG sources, and luminosity BG is less than them. However, if SuperKEKB reaches higher luminosity by accumulating more beam currents, luminosity BG will dominate.

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COUNTERMEASURES

To cope with beam-gas BG and Touschek BG, movable collimators [2] installed in the main rings can cut off beam tails due to scattered particles before reaching the Belle II detector at the interaction region. Even though some scattered particles may escape the collimators, thick layers of tungsten shields installed around the final focusing magnets, where particles are lost, can protect Belle II sensor components from secondary showers generated by the beam loss. As of 2021, 31 movable collimators have been installed to the SuperKEKB main rings, as shown in Fig. 1. Seven horizontal collimators and four vertical collimators are installed for LER, and eleven horizontal collimators and nine vertical collimators for HER. Some of HER collimators are KEKB type with a one-side jaw, while others are SuperKEKB type with jaws on both sides. Horizontal collimators mainly stop stray particles due to Touschek scattering, while vertical ones mainly stop stray particles due to beam-gas Coulomb scattering.

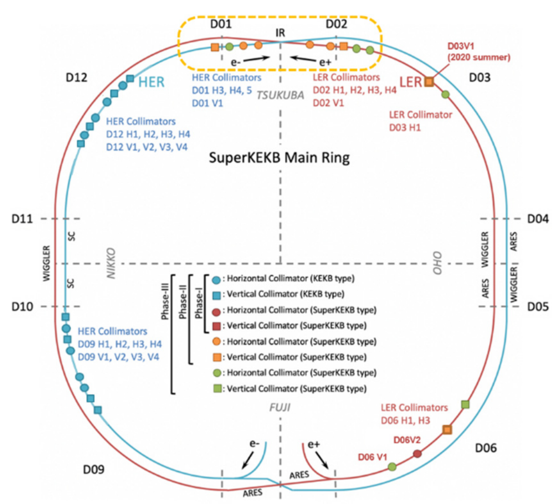

Figure 1: Location of SuperKEKB collimators.

Vertical collimators at SuperKEKB are extraordinarily challenging because they should be used at very narrow

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widths. The required distance of vertical collimator jaws from the beam orbit is only 2 mm or even narrower because the final focusing magnets of the nano-beam scheme have large vertical beta functions, and collimators to avoid beam loss inside the final focusing magnets should be closed accordingly. Since the loss rate in the Belle II detector strongly depends on vertical collimator widths, the moving mechanism of vertical collimator jaws should have a precision of ~50 µm.

Since our vertical collimators have very narrow widths, Transverse-Mode Coupling Instability (TMCI) becomes significant. The shape of jaws should be carefully designed to achieve low impedance and mitigate TMCI. We usually use collimators at the location with large beta functions to separate the beam core and tail. However, TMCI constraints force us to install vertical collimators where vertical beta function (β_y) is relatively small [3]: TMCI depends on kick factor multiplied by β_y, and the kick factor at the required width is proportional to $\beta_y^{-3/4}$; therefore, TMCI is proportional to $\beta_y^{1/4}$.

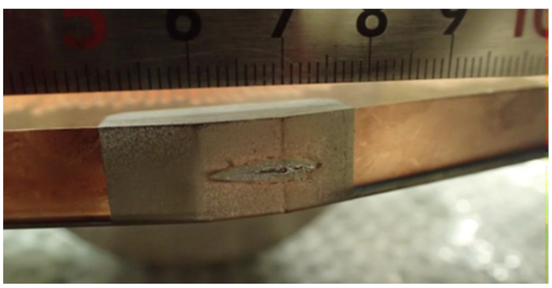

Figure 2: Photo of the collimator jaw severely damaged by the beam entering from the left and exiting to the right.

Since the jaws of vertical collimators are very narrow, an unstable beam could directly hit the jaws and severely damage them. Such accidents happened several times in 2020 [4], as shown in Fig. 2. We had to stop beam operation for several days per accident to replace damaged collimator jaws. A new vertical collimator with carbon jaws (instead of tungsten or tantalum) was developed [5] and installed to LER for 2020 autumn runs to avoid beam time loss due to collimator damage. Since the radiation length of carbon is longer than heavier materials, the longitudinal length of the jaw should be longer to stop beam particles, which makes its impedance larger. During machine operation, we found the impedance was even more significant than expected due to the non-resistive surface effect. The beam size blowup and the tune shift due to TMCI limited the bunch current for the beam operation. Therefore, we decided to remove the carbon-jaw vertical collimators from the ring before 2021 runs.

BEAM BACKGROUND MEASUREMENTS AND COMPARISON WITH SIMULATION

In 2020, we carried out dedicated machine studies to measure BG sources separately. When running with a single beam without collisions, the measured BG can be assumed to be mainly from Touschek BG and beam-gas BG. Touschek BG is proportional to beam current squared divided by bunch volume (mostly determined by vertical beam size) and the number of bunches, while beam-gas BG is proportional to beam current and vacuum pressure. If the number of bunches is varied while the beam current is unchanged, only Touschek BG changes and beam-gas BG stays constant. This allows us to measure Touschek and beam-gas components separately by applying linear fit to the measured BG against the inverse number of bunches. More details of the analysis framework are reported in [6].

Machine studies in 2020 show that the Time-Of-Propagation counter (TOP) is most vulnerable to beam BG among seven Belle II sub-detectors. The TOP PMTs have a finite lifetime and they should survive until the replacement work in 2022 summer. As shown in Fig. 3, LER beam-gas BG is still the largest component in TOP BG, although it has decreased from 2019 thanks to vacuum baking progress and tighter collimator settings. Other BG components, such as LER Touschek BG and luminosity BG, are smaller but not negligible.

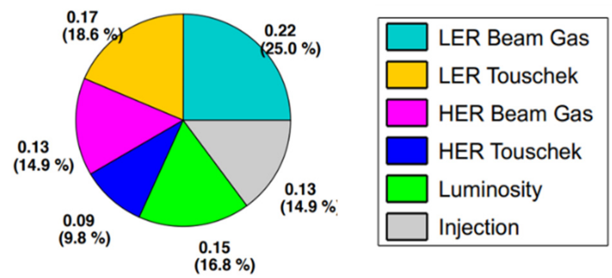

Figure 3: TOP background rates (and fractions) measured by machine studies in 2020 June, with beam currents of ~500 mA, 978 bunches, and $\beta^*_y = 0.8$ mm.

The measured BG rates should be compared with simulated BG rates so that the obtained fraction of data between MC can be used for correcting simulated BG rates at the future optics. We use SAD for multi-turn tracking of Touschek scattered particles and Beam-gas scattered particles. We recently implemented precise handling of scattering on collimator in multi-turn simulation [7], which improved HER simulation significantly. Luminosity BG and synchrotron radiation are handled within Geant4 geometry around the Belle II detector since they do not require multi-turn tracking.

Figure 4 (quoted from [8]) shows the preliminary results of the data/MC ratio from the 2020 machine studies for Belle II sensors. For most of Touschek and Beam-gas BG, the data/MC ratio is away from unity by a factor of 3-5, which is much smaller than in previous results where the discrepancy was by a factor of several hundreds or thousands. This improvement is achieved by the recent updates on the simulation side, which can now handle collimator scattering properly. For the luminosity BG, the data/MC ratio is almost one, which suggests that our simulation for luminosity BG is reasonably good and our estimation of BG rate at the design luminosity, which is dominated by luminosity BG, is reliable.

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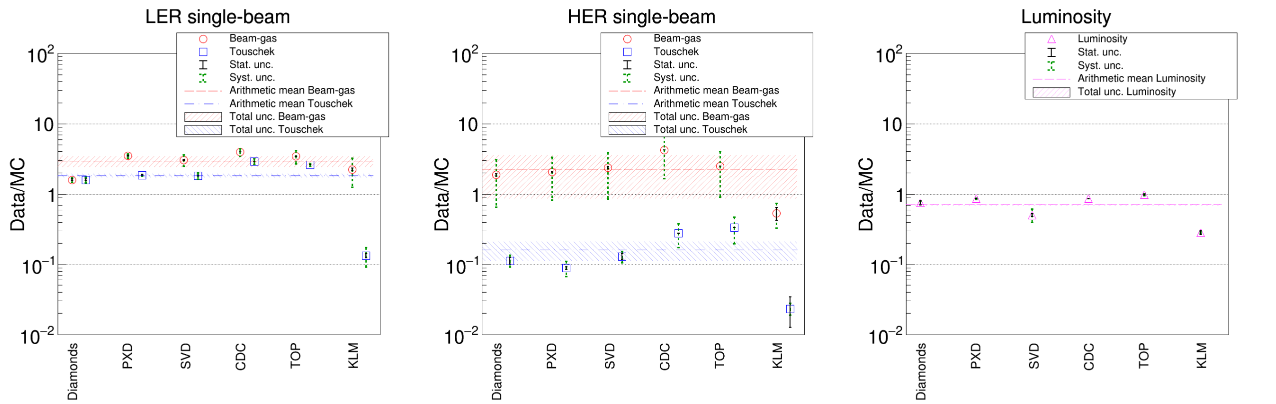

Figure 4: Data/MC ratio for each BG source on Belle II sensors, measured in 2020 machine studies [8].

INJECTION BACKGROUND

SuperKEKB requires top-up injection during physics runs since its beam lifetime is short. After each injection, Belle II DAQ applies trigger veto because the injected bunches become unstable for a while after injection and sensors show higher hit rates, which is called "injection BG". The typical duration of the injection veto window is ~10 milliseconds for LER and ~5 milliseconds for HER, which corresponds to 5-10 % of DAQ deadtime [9]. To accumulate more integrate luminosity, we need to shorten the duration of injection BG.

Dedicated machine studies are conducted in 2020 to understand the behavior of injection BG. The duration is found to be proportional to the bunch current with a single beam. It becomes much longer with collisions, which suggests that the beam-beam effect plays an important role. With a careful look into Belle II data during injections, it is found that not only the injected bunch but also the later bunches cause noisy hits on sensors. This implies that some coupling between the injected bunch and the later bunches exists, but its mechanism is not fully understood yet.

FUTURE EXTRAPOLATION AND FURTHER MITIGATION IDEAS

Beam BG will increase as we accumulate more beam currents to reach higher luminosity. Figure 5 shows the extrapolated TOP single-beam BG rates at higher beam currents. Note that this is a simplified extrapolation from 2020 results and does not include any BG mitigation in the future. The upper limit of TOP single-beam BG rate was 1.2 MHz in 2020 and has been relaxed to 3 MHz until the replacement work in 2022 summer. The limit might be further relaxed to 5 MHz if we replace them once again around 2026. However, even with the relaxed threshold, the acceptable current (~1.5 A) will be smaller than the design current (2.6 A), which means further beam BG mitigation is necessary.

There are several BG mitigation ideas currently being discussed. As the experiment will run longer, beam-gas BG will gradually get smaller as the vacuum pressure (especially in LER) improves thanks to the progress of vacuum baking. Using even narrower collimator settings or adding new collimators is expected to reduce single-beam BG

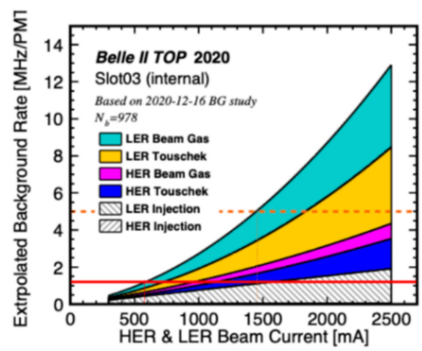

Figure 5: Expected TOP BG rate by simple extrapolation assuming NO mitigation in future [10].

components, but increased TMCI will limit bunch current for the beam operation and limit the maximum luminosity we can reach. During the long shutdown in 2022 summer, we plan to install additional heavy metal shields around the bellows pipes, which connect the final focusing magnet cryostat and the Belle II vertex detector volume. The area around the bellows pipes is currently not shielded well and secondary showers leaking out from her causes background hits on Belle II outer detectors. We have also started early discussion of major modifications on the final focusing magnet system. If the vertical aperture of beam pipe inside the final focusing magnet can be enlarged, vertical collimator width can also be enlarged accordingly and TMCI is expected to be mitigated.

SUMMARY

Beam background components at SuperKEKB are separately measured by machine studies in 2020. Our simulation reproduces the measured background rates with better precision than before, thanks to recent improvement in collimator scattering. The duration of injection background determines data taking deadtime and should be minimized. The beam background rate extrapolated to the design luminosity is not acceptable, and several mitigation ideas are being considered.

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