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Beam background evaluation at SuperKEKB and Belle II

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Abstract: The SuperKEKB asymmetric electron-positron collider is the upgrade of the KEKB machine and it is expected to achieve the instantaneous luminosity of 8×10^{35} cm^{-2}s^{-1}, 40 times higher than the record of KEKB. With the increased luminosity, the beam background is expected to grow significantly with respect to KEKB, leading, among other effects, to possible radiation damage of detector components and to performance deterioration of the Belle II detector. SuperKEKB started operating in 2018, with a stepwise reduction of the beam size at the interaction point that has been done in the last two years, studying the evolution of background conditions. We present the studies performed in 2019 to evaluate the contributions of single beam and luminosity background sources, the conditions in which the Belle II detector has been operated so far and the prospects for future operation.

Keywords: Instrumentation for particle accelerators and storage rings - high energy (linear accelerators, synchrotrons)
Large detector systems for particle and astroparticle physics

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1 Introduction

The SuperKEKB [1] asymmetric e^+e^- collider is an upgrade of the KEKB machine that aims to provide the Belle II experiment [2] an unprecedented instantaneous luminosity of 8×10^{35} cm^{-2}s^{-1}, with an expected integrated luminosity of about 50 ab^{-1} in ten years of operation. The upgrade is based on the so called "nano-beam scheme", proposed for the first time by P. Raimondi for the SuperB project [3]. The main idea is of minimizing the vertical beta function of the beams at the interaction point (IP), maximizing the luminosity, which assuming flat beams and equal horizontal and vertical beam sizes for the two beams is given by:

$$L = \frac{\gamma_\pm}{2er_e}\frac{I_\pm \xi_{y\pm}}{\beta^*_{y\pm}}\frac{R_L}{R_{\xi_y}} \tag{1.1}$$

where γ is the Lorentz factor, e the elementary electric charge, r_e the electron classical radius, $I_\pm$ the beam current, $\xi_{y\pm}$ the beam-beam parameter, $\beta^*_{y\pm}$ the vertical beta function at the IP, R_L the luminosity reduction factor, R_{ξ_y} the beam-beam reduction factor. The + and - indices refer to the positron and electron beams respectively. A gain by a factor 40 in the instantaneous luminosity with respect to KEKB can be achieved by squeezing the beta-function by a factor 20 and doubling the beam currents. SuperKEKB basic design parameters are summarized in Table 1, together with parameters achieved by KEKB. The Belle II detector, an upgraded version of the Belle detector, surrounds the IP. Its vertex reconstruction performance was improved thanks to the new VerteX Detector (VXD), whose readout electronics can tolerate the 20 Mrad dose expected for the whole period of operation.

Table 1. Basic machine parameters achieved by KEKB, achieved in 2019 by SuperKEKB and SuperKEKB design values. The first number refers to the Low Energy Ring (LER), the second to the High Energy Ring (HER). (*) Luminosity achieved with Belle II detector ON. The machine reached a luminosity of 1.88×10^{34} with Belle II OFF.

	KEKB	**SuperKEKB**	
		2019	Design
Energy [GeV]	3.5/8.0	4.0/7.007	4.0/7.007
Beam current [A]	1.64/1.19	0.88/0.70	3.6/2.6
Number of bunches	1584	1576	2500
ε_x [nm]	18/24	2.0/4.6	3.2/4.6
$\xi_{y\pm}$	0.129/0.090	0.028/0.019	0.088/0.081
$\sigma^*_{y\pm}$ [nm]	940/940	140/180	48/62
$\beta^*_{y\pm}$ [mm]	5.9 /5.9	1.0/1.0	0.27/0.30
$\beta^*_{x\pm}$ [mm]	1200/1200	80/60	32/25
Luminosity [cm^{-2}s^{-1}]	1.71×10^{34}	$1.14 \times 10^{34*}$	8×10^{35}

2 Summary of operations in 2019

After the commissioning phase in 2018, Belle II started collecting physics data with the full detector in 2019. SuperKEKB restarted operations in 2019 with a vertical betatron function $\beta^*_y = 3$ mm for both beams, gradually squeezing it down to 1 mm at the end of 2019, while the horizontal beta function was reduced from 200 mm to 80 mm for LER and from 100 mm to 60 mm for HER. Machine parameters achieved by SuperKEKB at the end of 2019 are summarized in Table 1. A summary of HER and LER currents, and delivered luminosity, for the whole 2019 is shown in Figure 1. One of the limiting factors for beam currents was the background level, that caused high PMTs hit rate in the TOP (Time Of Propagation) sub-detector and a large leakage current in the Central Drift Chamber (CDC).

Apart from a fire accident near the linac facility that forced a stop of the accelerator in April, SuperKEKB operations were smooth through the year, alternating physics runs with machine studies necessary for parameters optimization. At the end of the Spring and Fall runs, high current studies were performed with the Belle II detector off. During 2019, as done already during the commissioning runs in 2016 [4] and 2018, some time was devoted to background studies, to understand machine induced background components that affect the Belle II detector. In the next sections, a description of the main relevant background sources at SuperKEKB, and a summary of results of the corresponding background studies, are given.

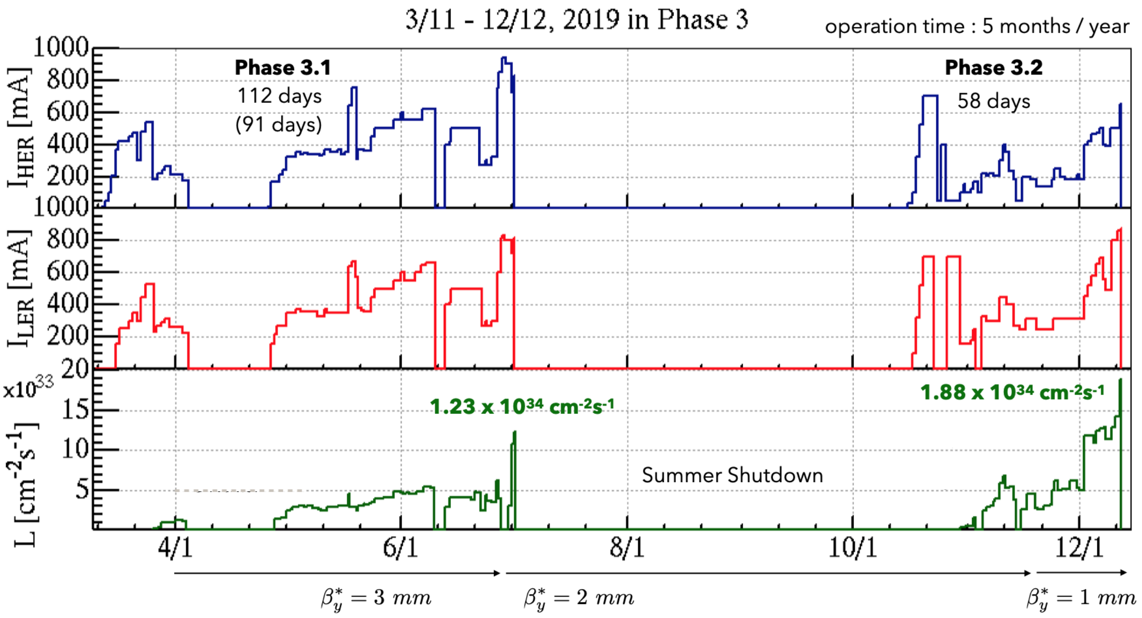

Figure 1. Summary of 2019 SuperKEKB operations: in blue and red, beam currents for HER and LER respectively are shown; in green, the delivered luminosity is shown.

3 Background sources in SuperKEKB

Among all possible background sources at an accelerator, some of them are particularly relevant at SuperKEKB:

- **Touschek effect**: is a single Coulomb scattering event where a small transverse momentum exchanged by two particles of the same bunch is transformed into a large longitudinal momentum, causing the loss of both particles. Lost particles eventually hit the inner surface of the beam pipe generating a shower that, if the hit position is close to the interaction region, can propagate to the detector. The loss rate is proportional to the square of the beam current and inversely proportional to the beam size, the number of bunches and the third power of the beam energy.

- **Beam-gas scattering**: occurs between beam particles and atoms of the residual gas in the beam pipe. Coulomb scattering changes the particle trajectory, while the particle energy can decrease by bremsstrahlung. The loss rate is proportional to the beam current and to the residual gas pressure. Before 2019 runs, additional vertical collimators were installed in the LER to improve the beam-gas background reduction.
- **Synchrotron radiation**: consists of photon emission from beam particles when subject to acceleration. Synchrotron radiation power is proportional to the beam current and to the fourth power of beam energy, and is inversely proportional to the square of the bending radius of dipole magnets. In the interaction region, the main contribution originates from superconductive quadrupoles. Photon energies range from a few keV to tens of keV.
- **Luminosity background**: is mainly due to Bhabha and two-photon processes. Electron and positron energies decrease after the Bhabha process, with particles being over-bent by the Final Focus magnets and lost, hitting the beam pipe and generating electromagnetic showers; in the radiative process, photons propagate along the beam axis and interact with the iron of magnets, producing neutrons via the photo-nuclear resonance mechanism. In the two-photon process, low momentum electron-positron pairs are produced and can hit the inner tracking detectors, affecting their tracking performance.
- **Injection background**: the injected beam performs betatron oscillations around the stored beam, until the perturbation is fully damped, which can take up to a few tens of milliseconds. When injected particles are passing through the interaction region, they are influenced by the strong fields of the final focus quadrupole magnets, therefore if they are on the edge of the transverse phase space, they can be lost inside the interaction region.

4 Background studies performed in 2019.

During 2019 runs, the SuperKEKB and Belle II groups dedicated some time for background studies, to evaluate background components due to the sources described in the previous section. In the following, some of the background studies performed in the Fall 2019 run are presented, with the latest results.

4.1 Single beam background studies

The first step to evaluate beam induced backgrounds was the estimation of single-beam background components (Touschek and beam-gas). In the model used to separate these two components, the observable of any sub-detector is composed by two terms, one proportional to Touschek scattering and the other proportional to beam-gas scattering, as shown in Equation 4.1. Re-normalizing properly the observable, data are distributed on a straight line, whose intercept with the y-axis represents the beam-gas component and whose slope represents the Touschek component, as shown in Figure 2.

$$Obs. = T \cdot \frac{I^2}{\sigma_y n_b} + B \cdot IPZ_{eff}^2 \qquad \longrightarrow \qquad \frac{Obs.}{IPZ_{eff}^2} = T \cdot \frac{I}{PZ_{eff}^2 \sigma_y n_b} + B \tag{4.1}$$

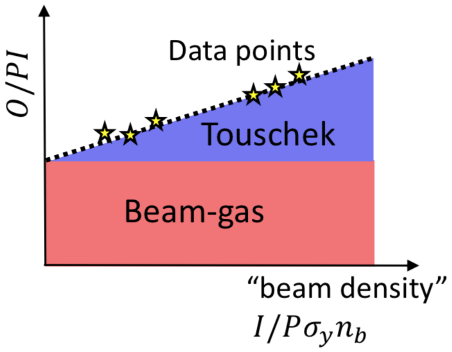

Figure 2. Model used for the single beam background study.

During single beam studies, data were taken with different number of bunches and beam sizes, in order to change only the Touschek component of beam backgrounds. All Belle II sub-detectors found the same result: LER background dominates, with beam-gas being the highest contribution. Results for the Silicon Vertex Detector (SVD), for which the observable is represented by the occupancy of silicon detectors, are shown on the left side of Figure 3. Results of single beam background components were compared to Monte Carlo (MC) simulations, to evaluate data/MC ratios that were used to extrapolate background levels to design machine parameters. Due to uncertainties in fitting the data and to possible inconsistencies in the simulation that are under study, the biggest discrepancies between data and MC were observed for HER Touschek component, for which data/MC ratios up to 1100 were evaluated. With such high data/MC ratios, the extrapolation to final machine parameters, shown on the right side of Figure 3 for the SVD, says that background levels will be too high, with HER Touschek being a major component, exceeding the 3% occupancy limit after which tracking performance of the vertex detector will deteriorate significantly. However, this scenario does not look realistic, since it is affected by high uncertainties. Moreover, a reduction of background level is expected due to machine optimization and new collimators to be installed in the future.

4.2 Luminosity background

After evaluating single beam background components, it was possible to extract the luminosity background from collisions data, subtracting single beam backgrounds evaluated before. Data were recorded while varying the luminosity with three different techniques: changing the vertical offset between beams, changing the number of filled bunches, and letting beams decay. There was a clear observation of a luminosity background component, although it was different depending on the technique used to change luminosity, suggesting that there are other effects to be further studied in order to evaluate the pure luminosity background component. Overall, the luminosity background

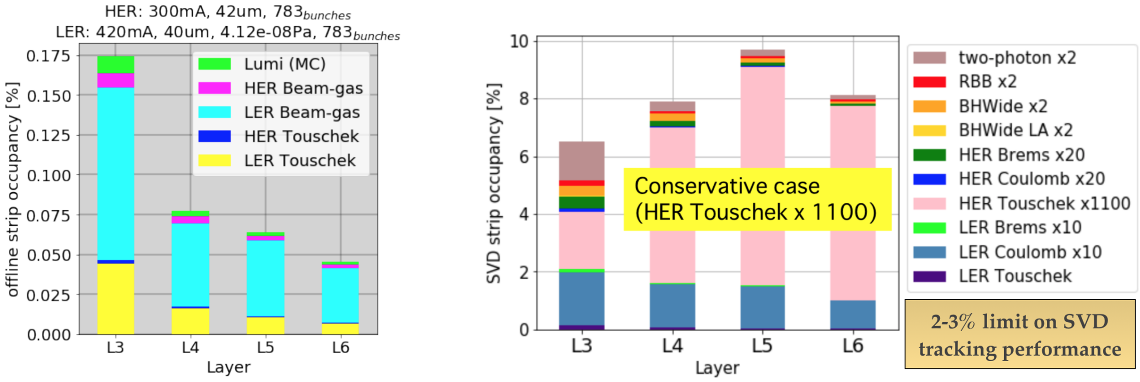

Figure 3. SVD occupancy - On the left, results of December 2019 background studies. On the right, extrapolation of background levels to nominal machine parameters.

component was not the dominant one in 2019, as expected since instantaneous luminosity is still a factor 40 less than the design one. Results for the TOP sub-detector of Belle II are shown in Figure 4, with the luminosity component added on top of the single beam components.

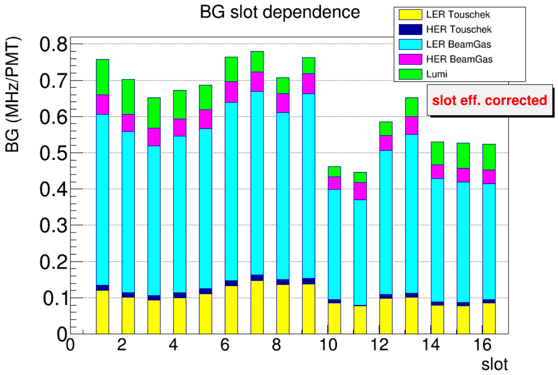

Figure 4. TOP PMT hit rate observed during December 2019 background studies, showing single beam and luminosity components.

4.3 Synchrotron radiation

Being proportional to the fourth power of the beam energy, synchrotron radiation was expected mainly from the HER. Despite the countermeasures taken against synchrotron radiation, it was observed by the PiXel Detector (PXD) in several runs during 2019. In particular, during Fall 2019 run, two different sources of synchrotron radiation were observed: one during injections, with photons emitted by injected bunches hitting the PXD after a backscattering on the edge of the Ti part of the beam pipe, as shown in Figure 5. This synchrotron radiation component was mitigated by slightly changing the beam orbit angle. A second component of synchrotron radiation was observed during beam storage, and was thought to be caused by the increased horizontal dispersion. This requires dedicated studies, that are planned for the 2020 run to further mitigate synchrotron radiation. An additional gold layer to be added on the outer surface of the beryllium beam pipe in the interaction region is also being considered.

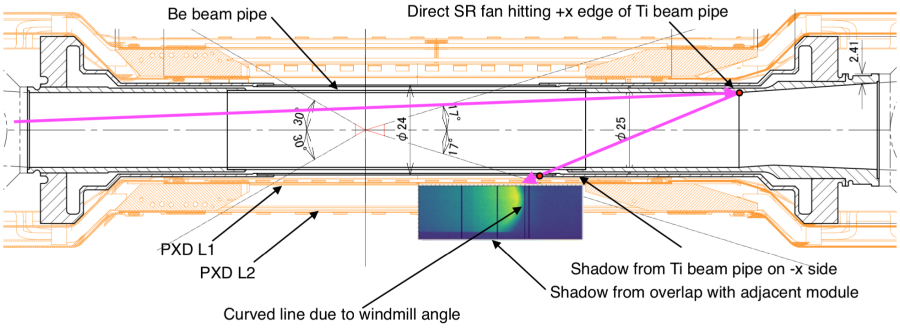

Figure 5. A scheme of a possible explanation of synchrotron radiation observed by PXD, with photons being back scattered towards the inner PXD sensors.

4.4 Injection background

In May 2019, SuperKEKB group successfully conducted an intensive campaign to improve injection efficiency and reduce injection background, in order to switch to continuous injection mode, which entails keeping the beam currents almost constant by performing top-up injections. To cope with the remaining injection background, the Belle II trigger system uses a full veto period after the injection combined with a gated period (3.6 μs veto window every 10 μs). The Electromagnetic Calorimeter (ECL) is used to evaluate the time window in which injection background is observed: for HER the time window is limited to a few milliseconds, while for LER it can be much longer, up to several tens of milliseconds, making the veto window wider. This means that, when injection in LER is performed, the DAQ dead time is up to 14%, while it should be kept below 5% to maximize data taking efficiency. Possible reasons for such a long injection background may be found in the injection kicker of the LER. Studies will be conducted during 2020 runs to better understand the cause of LER injection background and to mitigate it in order to reduce DAQ dead time during injections.

4.5 Vertex studies

The last study presented was conducted reconstructing the vertices of background events, without the constraint of the IP location. In this way it was possible to reconstruct the location of the interaction that produced the event in the detector. Results of this study are shown in Figure 6: the horizontal axis (z) is parallel to the beam direction, and z = 0 corresponds to the IP. Two hot spots in the forward region are clearly visible, at z = 0.6 m and z = 1.1 m. The location of these hot spots corresponds to the LER beam pipe. In particular at z = 1.1 m one of the final focus superconducting magnets is located and the beam pipe is very narrow, so background events were expected to be generated there. The location has been surrounded with tungsten shields to absorb secondary particles. Some of these secondary particles produced at z = 1.1 m are probably responsible for the hot spot at z = 0.6 m, where there are less tungsten shields, so the effect is more visible. To overcome the problem, a new bellows pipes design is under discussion, with additional shields that can absorb these secondary particles, reducing background levels in the detector.

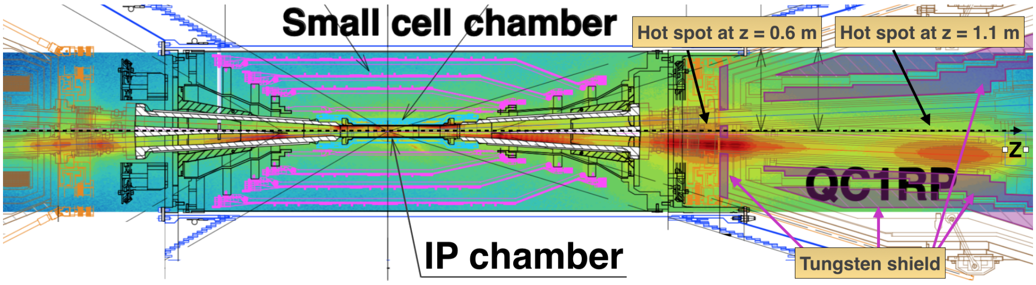

Figure 6. Top view of the vertices reconstruction studies with no constraints on the IP position, with part of the interaction region geometry superimposed. Hot spots in the forward region corresponds to locations where particles producing background are lost.

5 Conclusions and prospects towards 2020

During 2019, SuperKEKB and Belle II operated smoothly. Many systematic studies were performed to understand and reduce beam background components, which so far had an impact on some Belle II sub-detectors: the counting rate of photomultipliers used by TOP and CDC leakage current imposed a limitation on beam currents, while the observed synchrotron radiation can be dangerous for the PXD and must be limited as much as possible. Despite the changes in the optics, reducing both horizontal and vertical betatron functions, that are supposed to cause an increase in beam backgrounds, Belle II has observed an overall reduction of background levels since the start of operations in 2019, thanks to improved injections, to progress in vacuum scrubbing and to collimators optimization and installation. Further reduction in the background levels are expected in 2020 due to the installation of a new vertical collimator in the LER and due to the use of crab waist sextupoles.

The background reduction achieved so far and the planned measures that will be be taken are promising for the future operations of the machine and the detector. The road towards design luminosity is challenging, however, with still a factor 3 of reduction in β_y^* and a factor 4 of increase in beam currents to achieve, while keeping low beam backgrounds.

Acknowledgments

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