SUPERKEKB BACKGROUND SIMULATION, INCLUDING ISSUES FOR DETECTOR SHIELDING

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Abstract

The Belle experiment, operated on the KEKB accelerator in KEK, had accumulated a data sample with an integrated luminosity of more than 1 ab^{-1} before the shutdown in 2010. We are preparing upgraded accelerator and detector, called SuperKEKB and Belle-II, to achieve the target luminosity of $8 \times 10^{35} \text{cm}^{-1}\text{s}^{-1}$. With the increased luminosity, we expect more beam background which might damage our detector components, hide event signals under noise hits, max out readout bandwidth, etc.

Detector shielding is a key to cope with the increased background and protect Belle-II detector. We present how we estimate the impact from each beam background sources at SuperKEKB, such as Touschek-scattering, beam-gas scattering, radiative Bhabha process, etc. We also present our countermeasures to mitigate the beam background, such as tungsten shields installed in the detector to stop shower particles, beam collimators to stop stray beam particles before they reach interaction region, dedicated beam pipe design around interaction point to stop synchrotron radiation, and so on.

INTRODUCTION

The Belle experiment, operating at an asymmetric electron positron collider KEKB, finished its operation in June 2010. The Belle experiment had accumulated a data sample corresponding to an integrated luminosity of 1 ab^{-1}. KEKB recorded the world's highest peak luminosity, $2.1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$. Numerous results of the Belle experiment have confirmed the theoretical predictions of the Standard Model. Especially, measurement of large CP violation in the B meson system has demonstrated that the Kobayashi-Maskawa (KM) mechanism is the dominant source of CP-violation in the standard model,

SuperKEKB, an upgraded of the KEKB collider, will provide a prove to search for new physics beyond the Standard Model, thanks to much larger data sample. The target luminosity of SuperKEKB, $80 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, is 40 times higher than that of KEKB. The upgrade is based on so-called "Nano-beam scheme", which is first proposed by SuperB project planned in Italy [1]. The basic idea of this scheme is to squeeze the vertical beta function at the interaction point (IP). The luminosity of the collider is expressed by the following formula, assuming flat beams and equal horizontal and vertical beam size for two beams at IP:

$$L = \frac{\gamma_\pm}{2er_e}\left(\frac{I_\pm \xi_{y\pm}}{\beta^*_{y}\pm}\right)\frac{R_L}{R_{\xi_y}}, \qquad (1)$$

where $\gamma, e, andr_e$ are the Lorentz factor, the elementary electric charge and the electron classical radius, respectively. I, ξ_y, β^*_y are the beam current, the beam-beam parameter and the vertical beta function at IP. The suffix ± specifies the positron (+) or the electron (-) beam. The parameters R_L and R_{ξ_y} represent reduction factors for the luminosity and the vertical beam-beam parameter, which arise from the crossing angle and the hourglass effect. At SuperKEKB, the vertical beta function at IP is 20 times smaller than KEKB in the Nano-beam scheme. In addition, the total beam currents will be doubled to achieve 40 times higher luminosity. The basic parameter of SuperKEKB is summarized in Table 1.

Belle II detector, an upgrade of the Belle detector, has better vertex resolution with new pixel detector, better particle identification performance with new type sensors, and better tolerance for the background particles. Details of the Belle II detector are described in [2].

Table 1: Basic parameters of SuperKEKB and KEKB. The former number is for the Low Energy Ring(LER) and the latter for the High Energy Ring(HER).

	KEKB achieved	SuperKEKB
Energy [GeV]	3.5/8.0	4.0/7.007
Beam current [A]	1.637/1.188	3.6/2.62
Number of bunch	1584	2503
ξ_y	0.129/0.090	0.0869/0.0807
σ^*_y [nm]	940/940	48/63
β^*_y [mm]	5.9/5.9	0.27/0.30
σ^*_x [μm]	147/170	10/10
β^*_x [mm]	1200/1200	32/25
Luminosity [$\text{cm}^{-2}\text{s}^{-1}$]	2.1×10^{34}	80×10^{34}

BEAM BACKGROUND SOURCES

At SuperKEKB with higher luminosity, the beam-induced background will also increase. Major background sources at SuperKEKB are shown in this section.

Touschek Effect

The first background source is Touschek effect, which is one of dangerous background sources at SuperKEKB with "Nano-beam" scheme. Touschek effect is an intra-bunch scattering. Coulomb scattering between two particles in a same beam bunch changes their energy to deviate from the beam bunch, one with too much and the other with too little energy. The scattering rate of the Touschek effect is proportional to the inverse beam size, third power of the beam energy, the number of bunches and second power of the bunch current. Since the beam size of SuperKEKB is much smaller than that of KEKB, background from the Touschek effect will become much higher. At SuperKEKB, simple extrapolation using the machine parameters predicts that Touschek background will increase by factor of ~20 compared to that of KEKB. However, Touschek background is reduced than this prediction because we introduce improved countermeasures to reduce the background. Touschek-scattered particles are lost by hitting the beam pipe inner wall while they propagate around the ring. If their loss position is close to the detector, generated shower might reach the detector. Fake hits generated by the background shower particles deteriorate the detector's physics resolution. Radiation dose by gammas or neutrons in the background shower damage the Silicon devices used in the detector.

To cope with Touschek background, we install horizontal and vertical movable collimators. The movable collimators located along the ring can stop the deviated particles before they reach close to the detector. Touschek background can be reduced effectively by collimating the beam horizontally from both inner and outer sides, since Touschek-scattered particles have more or less energy. At KEKB, we had horizontal collimation only from inner side.

The horizontal collimators are located at the positions where horizontal beta function or the dispersion become local-maximum. The horizontal collimators located just before to the interaction region play important role to minimize the beam loss rate inside the detector. The nearest collimator is only 18 m upstream of IP for LER.

The vertical collimator in LER, which is originally installed to reduce the beam-gas Coulomb background explained in the next subsection, also stops the vertically oscillating Touschek scattered particles. Particles scattered in Fuji-area, which is opposite side of IP in the ring, where LER beam orbit is vertically bending to pass under the HER ring.

The particle loss with various momentum deviations due to the Touschek effect can be evaluated by particle-tracking simulations along each location in the whole ring. The scattering probability is calculated using Bruck's formula, as described in [3].

Beam-Gas Scattering

The second background source is the beam-gas scattering by the residual gas atoms. Coulomb scattering changes the direction of the beam particle, and bremsstrahlung scattering decrease the energy of the beam particles. Scattering rate of the beam-gas scattering is proportional to the vacuum level and the beam current. At SuperKEKB, the beam currents will be ~ 2 times higher than that of KEKB, and the vacuum level except for the interaction region will be the same level as KEKB. Therefore we expected the same order of magnitude (a few times higher) beam-gas background in the past publications [2].

Beam-gas bremsstrahlung loss rate in the detector is well suppressed by horizontal collimators and it is negligible compared to the Touschek loss rate in the detector. However, beam-gas Coulomb scattering rate is found [4] to be higher by factor of ~ 100 than that of KEKB, since Interaction Region (IR) beam pipe aperture is smaller and the maximum vertical beta function is larger. Beam-gas scattered particles are lost by hitting the beam pipe inner wall while they propagate around the ring, just like Touschek-scattered particles. The countermeasures used for Touschek background, movable collimators and the heavy-metal shield, are also effective to reduce beam-gas background. Especially, vertical movable collimator is essential to reduce Coulomb scattering background. However, Transverse Mode Coupling (TMC) instability caused by the vertical collimator should be carefully examined, since vertical beta function is larger than horizontal beta function. Therefore, collimator width should satisfy two conditions at the same time:

- narrow enough to avoid beam loss in the detector
- wide enough to avoid TMC instability

The only way to achieve this is to use the collimator with ~2 mm width. More detailed discussion can be found in [4].

Beam-gas Coulomb scattering probability for given scattering angle is calculated as shown in [3]. The particle loss distribution inside the detector is obtained by particle-tracking simulations along each scattering location in the whole ring, as did in case of Touschek effect.

Synchrotron Radiation

The third background source is synchrotron radiation (SR) emitted from the beam. Since the SR power is proportional to the beam energy squared and magnetic field squared, the HER beam is the main source of this type of background. The energy of SR is few keV to tens of keV. At the first stage of Belle, the inner layer SVD was severely damaged by x-rays with E ~ 2 keV from HER. To absorb the synchrotron radiations before they reach the inner detector (PXD/SVD), the inner surface of the beryllium beam pipe are coated with gold plate. The shape of IR beam pipe is designed to avoid direct SR hits at the detector. Ridge structures on the inner surface of incoming pipes prevent scattered photons to reach interaction point.

Synchrotron radiation is simulated by the physics model implemented in Geant4. We estimate the impact on our inner detectors is tolerable.

Radiative Bhabha Process

The fourth background source is Radiative Bhabha process. Photons from the radiative Bhabha process propagate along the beam axis direction and interact with the iron of the magnets. In these interactions, neutrons are copiously produced via the giant photo-nuclear resonance mechanism. These neutrons are the main background source for the outermost detector, the KL and muon detector (KLM) instrumented in the return yoke of the spectrometer. The rate of neutron production by the radiative Bhabha events is proportional to the luminosity, which is 40 times higher than that of

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KEKB. Additional neutron shield in the tunnel to stop those neutrons is necessary. Both electron and positron energies decrease after radiative Bhabha process. If we employ the shared QCS magnets for incoming and outgoing beams as in KEKB, the scattered particles are over-bent by the QCS magnets. The particles then hit the wall of magnets and electromagnetic showers are generated. In the SuperKEKB case, we use two separate quadrupole magnets and both orbits for incoming and outgoing beams are centered in the Q-magnets. We therefore expect the radiative Bhabha background due to over-bent electrons and positrons will be small and only small fraction of them with very large energy loss(ΔE) are lost inside the detector. However, since the luminosity gets 40 times higher, those large ΔE particles are not negligible and will be comparable to Touschek and Beam-gas background after installation of collimators. Kick from solenoid field due to finite crossing angle is crucial and inevitable cause of those beam loss. Beam intrinsic angular divergence at IP, angular diffusion by radiative Bhabha process, and leak field of the other ring's Q magnets also play a role, but less crucial than solenoid kick.

In addition, radiative Bhabha loss within $|s| < 65$ cm from IP is very dangerous because we cannot put enough shielding in that region. Cryostat is located on $|s| > 65$cm.

Scattering is simulated using the generator called “BBBREM” [5]. The we perform particle-tracking until they hit beam pipes, to obtain loss distribution.

Two Photon Process

The fifth background source is very low momentum electron-positron pair backgrounds produced via the two-photon process: $ee \rightarrow eeee$. Those pairs might reach our inner detectors for vertex measurement.

Scattering is simulated using the generator called “BDK(Diag36)” [6].

LATEST BACKGROUND SIMULATION RESULTS

Figure 1 shows the latest background picture. Touschek and beam-gas background are rather localized on the position where beam pipe radius changes, while radiative Bhabha background is distributed over wider range in z direction.

Figure 2 shows the loss wattage distribution and Figure 3 summarizes the loss wattage and (effective) loss rate within $|s| < 4$ m. Loss wattage is defined as loss rate multiplied by energy of beam lost particles. One can see now the radiative Bhabha background is the dominant, after the installation of optimized collimators to reduce Touschek and beam-gas background.

GEANT4 FULL-DETECTOR SIMULATION

Using the estimated loss distribution of each background sources shown in the previous section, we perform the full-detector simulation based on GEANT4. Not only the impact on detector performance but also the radiation/neutron dose on detector components are investigated. Guided by the simulation, we have added tungsten shields inside the cryostat of the final focusing magnets to mitigate the beam background impact on detectors. We also installed several neutron shields to protect Silicon devices.

Assuming the beam background in case of the full design luminosity at SuperKEKB, occupancy on the inner vertex detectors, PXD and SVD, is estimated to be tolerable. Degradation on particle identification (K/π separation) performance is also acceptable.

Assuming 10 years of operation at the full luminosity, radiation damage are acceptable for most of detector components. Neutron flux on FPGAs of CDC readout board causes single event upset which needs FPGA reset, but the estimated frequency of the reset is tolerable.

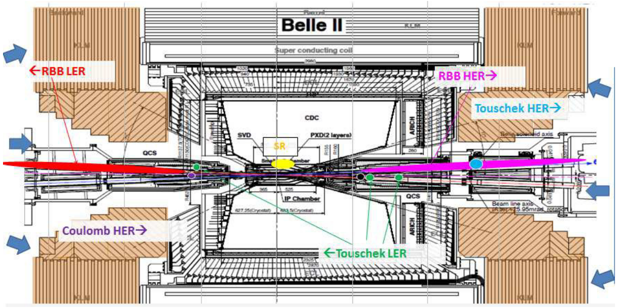


Figure 1: Latest background picture.

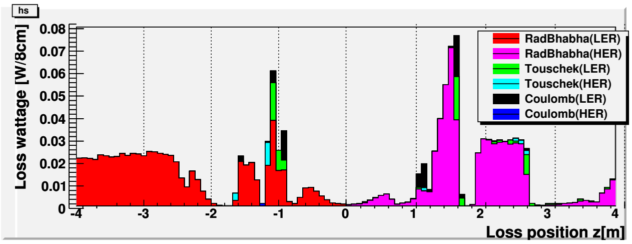
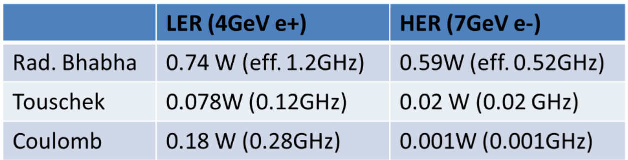


Figure 2: Loss wattage distribution along z position. Loss wattage is defined as loss rate multiplied by energy of lost beam particles.



	LER (4GeV e+)	HER (7GeV e-)
Rad. Bhabha	0.74 W (eff. 1.2GHz)	0.59W (eff. 0.52GHz)
Touschek	0.078W (0.12GHz)	0.02 W (0.02 GHz)
Coulomb	0.18 W (0.28GHz)	0.001W (0.001GHz)

Figure 3: Estimated loss rate and loss wattage within $|s| < 4$ m. Loss wattage is defined as loss rate multiplied by energy of lost beam particles. Effective loss rate is calculated by scaling loss rate by the energy of lost beam particles.

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The only problem we still suffer is TOP PMT photocathode aging issue. We have purchased PMTs with ∼1 C/cm^2 lifetime, which will be killed in few years of full luminosity operation. The recently developed PMTs has ∼7 C/cm^2 lifetime, but for now we have budget to buy new PMTs for only half of TOP PMTs. We plan to replace old PMTs after few years of operation.

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