BEAM BACKGROUND AND MDI DESIGN FOR SUPERKEKB/BELLE-II

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Abstract

The Belle experiment, operated at the asymmetric electron-positron collider KEKB, had accumulated a data sample with an integrated luminosity of more than 1 ab^{-1} before the shutdown in June 2010. We have started upgrading both the accelerator and the detector, SuperKEKB and Belle-II, to achieve the target luminosity of $8 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. With the increased luminosity, the beam background will be severe. The development of Machine-Detector Interface (MDI) design is crucial to cope with the increased background and protect Belle-II detector. We will present the estimation of impact from each beam background sources at SuperKEKB and our countermeasures for them, such as collimators to stop Touschek-scattered beam particles, Tungsten shield to protect inner detectors from shower particles, and dedicated beam pipe design around interaction point to stop synchrotron radiation, etc.

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 worlds highest peak luminosity, $2.1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. 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, $80 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, 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:

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

where $\gamma, e, and r_e$ 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 $\pm$ 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 [$\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	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

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Touschek effect will become much higher. At SuperKEKB, simple extrapolation using the machine parameters predicts that Touschek background will increase by factor of $\sim$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 BG 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.

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 $\sim$ 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 have been expected the same order of magnitude (a few times higher) beam-gas background in the past publications[2]. However, our latest simulation study reveals that Coulomb scattering rate is higher by factor of $\sim$ 100 than that of KEKB, since 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. Transverse Mode Coupling (TMC) instability caused by the vertical collimator should be carefully examined since vertical beta function is larger than horizontal beta function. Details are explained in [3].

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 $\sim$ 2keV 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.

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 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 BG after installation of collimators. Beam intrinsic angular divergence at IP, angular diffusion by radiative Bhabha process, solenoid field kick, and leak field of the other ring's Q magnets (especially for electrons) play role for this radiative Bhabha background.

Two Photon Process

The fifth background source is very low momentum electron-positron pair backgrounds produced via the two-

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photon process: $ee \to eeee$. In SuperKEKB, the radius of the innermost detector is less than that of KEKB since we introduce the pixel detector close to the IP. The two-photon background rate increases roughly as $1/r^2$. MC simulations and machine studies at KEKB in 2010 has shown that the two-photon BG rate on the PXD is less than our requirement. As of Feb. 2012 we suffered from the discrepancy between SuperB's results. However, after the face-to-face discussion in joint BG Workshop in Vienna, this discrepancy has disappeared and we both agree that our number is correct.

Beam-beam Background

A beam bunch interacts with the electric field of the other bunch when they collide at the IP. A beam particle is kicked by this interaction and the kick force is almost proportional to the distance from the center of the bunch at $x/\sigma << 1$. Beam-beam interaction results in non-Gaussian shape of beam tail, therefore it might increase the background rate such as synchrotron radiation. Simulation study is performed using huge CPU power needed for a non-linear force calculation. Non-Gaussian tail is significant only for the vertical beam size, and the synchrotron background is not affected much.

LATEST BACKGROUND SIMULATION RESULTS

Figure 1 shows the latest background picture. Touschek and beam-gas background are rather localized, 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 $|z| < 4$ m. One can see now the radiative Bhabha background is the dominant, after the installation of optimized collimators to reduce Touschek and Beam-gas background.

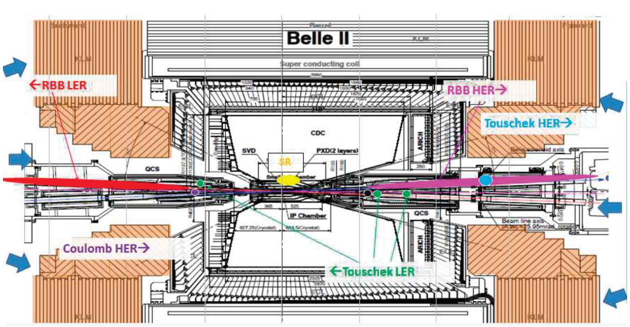

Figure 1: Latest background picture.

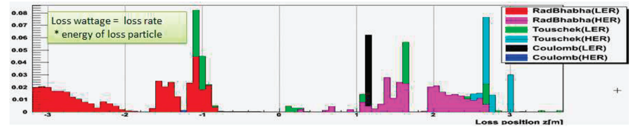

Figure 2: Loss wattage distribution along z position. Here loss wattage is defined as loss rate multiplied by energy of lost particles.

	LER (4GeV e+)	HER (7GeV e-)
Rad. Bhabha	0.45 W (eff. 0.7GHz)	0.25W (eff. 0.22GHz)
Touschek	0.14 W (0.22GHz)	0.11 W (0.10 GHz)
Coulomb	0.06 W (0.09GHz)	0.001W (0.001GHz)

Figure 3: Estimated loss rate and loss wattage within $|z| < 4$ m. Effective loss rate is calculated by scaling with beam energy.

GEANT4 FULL-DETECTOR SIMULATION

Using the estimated loss rate on each background shown in the previous section, we perform the full-detector simulation based on GEANT4. Not only the detector performance but also the radiation dose on detector or readout system are investigated.

Occupancy on PXD/SVD, PID K/π separation performance, etc.. were estimated to be OK, but the CDC hit rate and TOP PMT photocathode aging should be further mitigated. For this purpose we will adopt the new design of final-Q cryostat, with thick tungsten shield inside.

Radiation damage are OK for most of detector parts except for the neutron rates on CDC readout boards and ARICH HAPD, etc.. We will install additional neutron shields to mitigate neutron rate on them.

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