ISBN: 978-3-95450-216-5 doi:10.18429/JACoW-eeFACT2018-WEXBA06

BEAM BACKGROUND AT SUPERKEKB DURING PHASE 2 OPERATIONS

A. Paladino* on behalf of the BEAST group, KEK - IPNS, Tsukuba, Japan

Abstract

The SuperKEKB accelerator, the upgrade of the KEKB machine, will operate at an unprecedented instantaneous luminosity of $8 \times 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$, providing the Belle II experiment an expected integrated luminosity of about $50\mathrm{ab}^{-1}$ in ten years of operation. With the increased luminosity, the beam background is expected to grow significantly with respect to KEKB, leading, among other effects, to possible damage of detector components and suppression of signal events. We present studies done during the Phase 2 operation of SuperKEKB to evaluate the contribution of each background source, including the Touschek effect, beam-gas scattering, synchrotron radiation, and injection background. We also present studies performed on collimators and other solutions adopted to mitigate beam backgrounds in the interaction region.

INTRODUCTION

The SuperKEKB [1] asymmetric e$^+$e$^-$ collider is an upgrade of the KEKB machine that will provide the Belle II experiment [2] an unprecedented instantaneous luminosity of $8 \times 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$, with an expected integrated luminosity of about $50\mathrm{ab}^{-1}$ 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 idea behind the nano-beam scheme is to squeeze as much as possible the vertical beta function of the beams at the IP, maximizing the luminosity, which is given by the following formula, assuming flat beams and equal horizontal and vertical beam sizes for the two beams:

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

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. + and - indices refer to positron and electron beams respectively. Squeezing the beta-function by a factor 20 with respect to KEKB and doubling the beam currents, a 40 times higher luminosity can be achieved. SuperKEKB basic parameters are summarized in Table 1.

The Belle II detector, an upgraded version of the Belle detector, is placed around the IP. Its vertex reconstruction performance will be improved thanks to the new VerteX Detector (VXD), whose readout electronics can tolerate the 10 Mrad dose expected for the whole period of operation. The purpose of the Phase 2 operation, together with the commissioning of SuperKEKB in its final configuration, is to verify that the level of backgrounds in the interaction region are compatible with the expectations.

Table 1: Basic parameters for SuperKEKB Phase 2 and Phase 3 operations. The former number refers to the Low Energy Ring (LER), the latter to the High Energy Ring (HER).

	Phase 2	**Phase 3**
Energy [GeV]	4.0/7.007	4.0/7.007
Beam current [A]	0.327/0.279	3.6/2.6
Number of bunches	789	2500
ε_x [nm]	1.7/4.6	3.2/4.6
$\xi_{y\pm}$	0.028/0.019	0.088/0.081
$\sigma^*_{y\pm}$ [nm]	692/486	48/62
$\beta^*_{y\pm}$ [mm]	3.0/3.0	0.27/0.30
$\beta^*_{x\pm}$ [mm]	200/100	32/25
Luminosity [$\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	2.62×10^{33}	8×10^{35}

BELLE II AND BEAST DETECTORS

For Phase 2, the Belle II detector was used in its final configuration, except for the VerteX Detector (VXD), where only one slice of the final silicon vertex tracker was used, as shown in Fig 1. The remaining volume was occupied by some of the BEAST II detectors:

- FANGS: hybrid silicon pixel detectors.
- CLAWS: plastic scintillators with SiPM readout.
- PLUME: double sided CMOS pixel sensors.

Outside of the VXD volume, other BEAST II detectors were used:

- Diamond sensors for ionizing radiation dose monitoring in the interaction region.
- PIN diodes for ionizing radiation dose monitoring around QCS magnets.
- ^{3}He detectors for thermal neutron flux measurements.
- TPC detectors for fast neutron flux and direction measurements.

BACKGROUND SOURCES

In this section, the most relevant beam background sources in SuperKEKB are described.

---

[*] antonio.paladino@pi.infn.it

ISBN: 978-3-95450-216-5 doi:10.18429/JACoW-eeFACT2018-WEXBA06

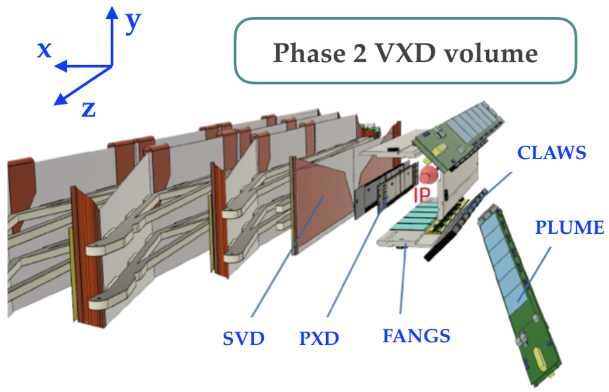

Figure 1: Detectors inside the VXD volume during Phase 2 operations.

Touschek Effect

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, one with too much energy, the other one with too less. 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, causing damage to silicon devices and contributing to generate fake hits that affect the performance of the detector.

The scattering rate of the Touschek effect is proportional to:

$$R_{Tou} \propto \frac{1}{\sigma} E^3 n_b I^2 \tag{2}$$

where σ is the beam size, E the beam energy, n_b the number of bunches, I the beam current.

During Phase 2 operations, beam size scans were performed to evaluate the Touschek component of the background levels. In single beam studies, the vertical beam size has been increased compared to the nominal one changing beam emittance, measuring the background level at each different beam size using BEAST detectors and some of the Belle II sub-detectors. At the beginning, increasing the beam size, a decrease in the background levels was observed, as expected since the Touschek effect is inversely proportional to the beam size. However going to bigger beam sizes during the HER study, an unexpected increase in the background was observed. This background increase could be due to a possible scraping of the beam tails on some structures of the beam pipe, but the hypothesis has to be verified with further studies.

Horizontal collimators are very effective to mitigate the Touschek background, and studies were performed during Phase 2 to find the optimal collimators setting. A description of these studies is given in the dedicated section on "Collimators studies".

Beam-gas Scattering

The second background source in SuperKEKB is the beam-gas scattering that occurs between particles and atoms of the residual gas in the beam pipe. The Coulomb scattering changes the trajectory of the particle, while the bremsstrahlung decreases the particle energy.

The rate of the beam-gas scattering is proportional to:

$$R_{bg} \propto IP \tag{3}$$

where P is the residual pressure inside the beam pipe. In the single beam background studies done during Phase 2, Touschek and beam-gas contributions were evaluated fitting the data with a two-parameters function:

$$P = T\frac{I^2}{\sigma_y n_b} + BIp \tag{4}$$

where T is the parameter for the Touschek component and B is the parameter for the beam-gas component. This function well represents the data of the HER and LER studies at small beam size, as shown in Fig. 2 and in Fig. 3, where the fit of the data taken with the PLUME detector for HER and LER respectively are shown.

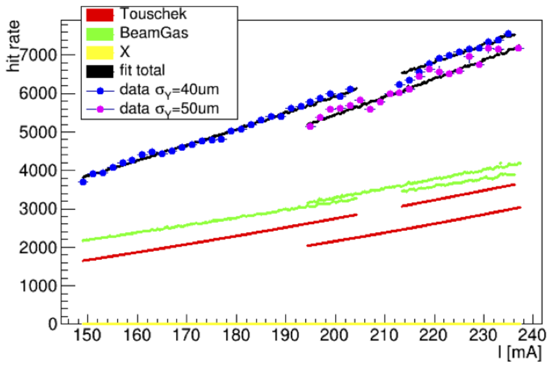

Figure 2: PLUME data of beam size study for HER with Touschek and beam-gas components.

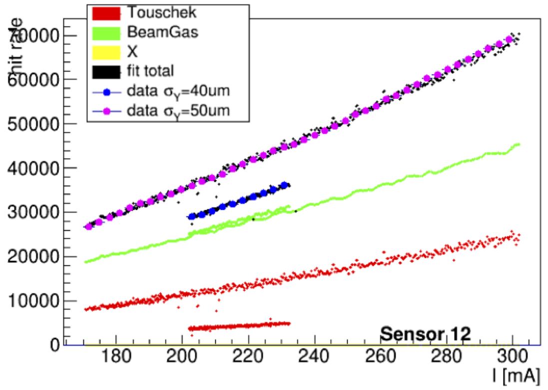

Figure 3: PLUME data of beam size study for LER with Touschek and beam-gas components.

For higher beam sizes an additional term was necessary for HER to fit the data, to take into account the observed increase in background. Touschek and beam-gas components were found to be similar, with the fraction changing depending on the detector.

In Phase 3 the β_y function inside the Final Focus system will be ten times higher than it was at the end of Phase 2, so in Phase 3 we expect that the Coulomb lifetime will be shorter and beam-gas background very high, if not mitigated by good vertical beam collimation. Additional vertical collimators will be placed in the LER to improve the beam-gas background reduction. Some additional heavy-metal shielding are used around the interaction region to lower the effect of the losses due to beam-gas scattering.

Synchrotron Radiation

Another background source is the synchrotron radiation emitted from the beam. The rate of emission is proportional to:

$$R_{bg} \propto E^2 B^2 \tag{5}$$

where B is the magnetic field intensity. This means that the HER contribution to synchrotron radiation is expected to be the main source of this kind of background, with photon energies going from a few keV to tens of keV.

Some countermeasures were taken to protect the detector from synchrotron radiation: the beam pipe is coated with a Au layer (6.6 μm in Phase 2, 10.0 μm in Phase 3), the tapered shape of the beam pipes prevent from direct hits of photons inside the interaction region, and ridge structures are included in the beam pipe shape to prevent forward reflected photons to reach the interaction region.

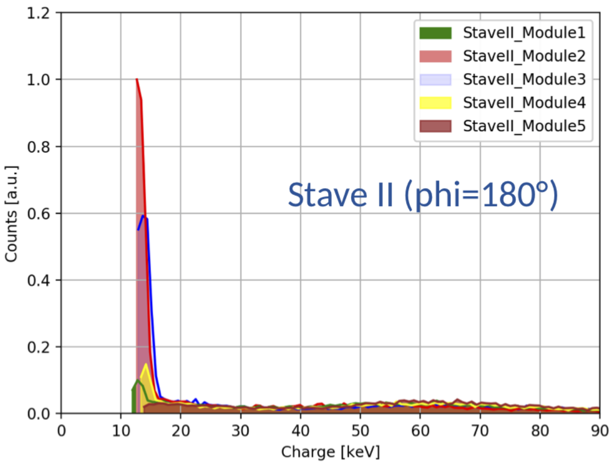

Figure 4: Synchrotron radiation peak observed by the stave n.2 of the FANGS detector, positioned at $\phi = 180°$

Despite the observation of synchrotron radiation was not expected in Phase 2, the PXD detector, located on the outer side of the ring ($\phi = 0°$), and the FANGS BEAST detector, with its Stave 2 located on the inner side of the ring ($\phi = 180°$), observed a peak in the energy spectrum at around 8-10 keV (see Fig 4), with longitudinal distributions that suggest the same mechanism of production for both rings. The origin of this synchrotron radiation peaks seems due to photons produced in the Final Focus region and then reflected by the Tantalum part of the beam pipe. The reflected photons can reach the IR beam pipe and, despite the presence of the Au layer, reach the inner detectors. The simulations has been revised and can now reproduce qualitatively the data, with still some differences in the ratio between the two layers of the PXD.

Luminosity Background

Other background sources comes from the interaction between the two beams, with a rate that is proportional to the luminosity:

1. Electron and positron energies decrease after the Bhabha process, so particles with too much energy difference with respect to the nominal one will be over bent by the Final Focus magnets and lost, hitting the beam pipe and generating electromagnetic showers. The process is mitigated by the fact that in SuperKEKB separate quadrupoles are used for each beam line and for incoming and outgoing beams, but with the very high luminosity of SuperKEKB, this background will still be the dominant one.
2. Photons from the Bhabha process propagate along the beam axis and interact with the iron of the magnets, producing neutrons via the photo-nuclear resonance mechanism. These neutrons are the main background source for the outermost sub-detectors of the experiment.
3. In the two-photon process, low momentum electron-positron pairs are produced and can hit the inner tracking detectors, affecting their tracking performance.

All these background sources depend on the luminosity, so a change in luminosity should decrease the total background level observed by the detectors. Two luminosity studies were performed during Phase 2: in the first one the vertical offset between the beams was changed until luminosity was reduced to zero; in the second study the fill pattern was changed so that the bunches were shifted in time and did not collide. During the first study, when the beams were shifted enough to have no luminosity, an increase of background levels was observed, which is unexpected if collisions do not occur. The origin of the increasing background is still under study. It was challenging to extract the luminosity component of the background from these studies, because the background conditions were not stable between luminosity studies and single beam background studies, making difficult to disentangle the Touschek and beam-gas components from the luminosity one.

Injection Background

During particles injection in the main ring, the injected bunch is perturbed, resulting in particle losses.

ISBN: 978-3-95450-216-5 doi:10.18429/JACoW-eeFACT2018-WEXBA06

During Phase 2, two detector systems were mainly used to monitor injection background: diamond sensors, located in the forward and backward regions of the IR beam pipe, and CLAWS. The diamond sensors provided a measurement of the radiation dose deposited by the background radiation, while CLAWS provided a rate of background hits as a function of time after injection. There are two requirements coming from the inner tracking detectors, PXD and SVD: for PXD there is a limit of 3% in occupancy, that means a limit of 150 MIPs/800ns; for SVD there is a safety limit in occupancy, that means a limit of 5 mRad/s on diamond sensors. The goal during the injection was to stay always below the limit of the diamond sensors, and to stay below the PXD limit at least after about one millisecond from injection, to avoid affecting the tracking performance of the VerteX Detector. Moreover the Belle II detector uses a trigger VETO for high-background periods after injection, so keeping these periods shorter allows longer data taking for the detector. An example of a good injection is shown in Fig 5. In addition, high injection background can cause the quench of Final Focus magnets.

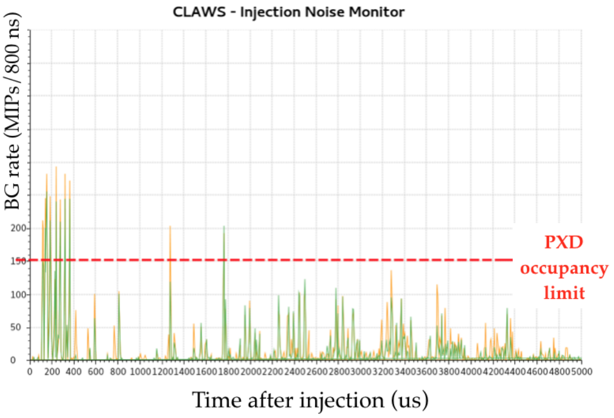

Figure 5: An example of a good injection background level in the CLAWS detector, with high-background period limited to less than 1 ms.

To reduce injection background, horizontal and vertical collimators are used, together with the tuning of the injector parameters. In addition, a new Damping Ring for positrons has been commissioned and successfully used in Phase 2. The injection background changed every time the optics were changed, so collimators and injector parameters had to be re-optimized every time, making it difficult to keep always low the background levels throughout Phase 2. On average, the HER injection background was always higher than LER one.

COLLIMATORS STUDIES

To mitigate Touschek and Beam-gas background contributions, horizontal and vertical movable collimators are installed along the two rings. Some of the collimators, the newest ones, can be moved both on the inner and outer sides (or top and bottom sides for vertical collimators), so particles with less or more energy can be stopped on the collimators avoiding shower production. The design of the movable collimators is described in [4].

The position of the vertical collimators is determined by two different conditions [5]. The first one is given by the local beam size σ_y: the physical aperture of the collimator should not be larger than the minimum aperture of the beam pipe in the IR; the second condition comes from the so called Transverse Mode Coupling Instability (TMCI), or fast head-tail instability. These two conditions give a dependence respectively of the maximum and minimum collimator aperture as a function of β_y:

$$d_{max} \propto \beta_y^{1/2}, d_{min} \propto \beta_y^{2/3} \tag{6}$$

To satisfy both conditions, the collimators must be placed where β_y is small. Collimators position for Phase 2 is shown in Fig. 6.

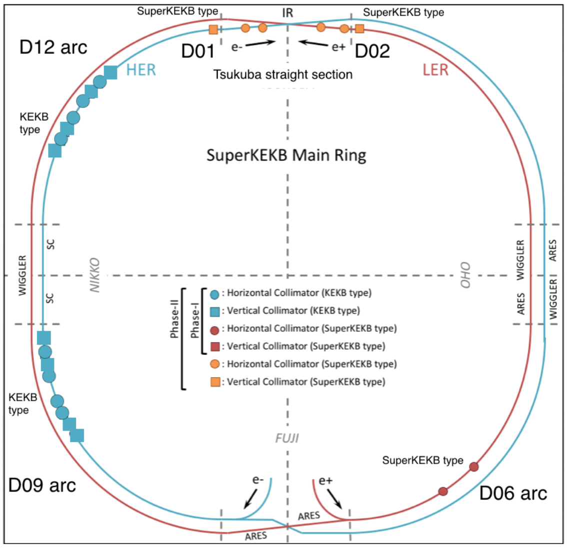

Figure 6: Collimators positioning during Phase 2 operations.

During Phase 2 operation, the effect of collimators on the IR background has been evaluated with collimators studies performed with single beams. Starting from an open collimator configuration with a low impact on the background reduction, each horizontal collimator has been closed individually in steps of 0.5 mm. After each step, when the current reached a certain value, injection was done up to the current limit, monitoring the injection background with the diamond sensors and the CLAWS detector. After injection, the storage background level was observed with the BEAST detectors. Then the collimator was closed by another step, and the full procedure was repeated again for each step until visible effects were seen in background level and beam lifetime. The optimal collimator aperture was chosen as a compromise between background level and beam lifetime. The same procedure was applied for all horizontal collimators in LER and HER. With the optimized collimators settings obtained with these studies the background levels in the IR were sensibly reduced. For the LER, a second collimator study was performed, using the first optimised collimators configuration as a starting point, to see if it was possible to further reduce the background levels. In some cases, like for D06H3 and D06H4, it was possible to further reduce the IR background level. More similar studies are planned for the beginning of Phase 3, especially for horizontal collimators, that are more effective against Touschek background.

A similar study on collimators was done with machine simulation, starting from the fully open configuration and closing one collimator at a time with different steps. A collimator study for Phase 3 using simulation is ongoing, including the collimators that will be added in the early stage of Phase 3.

CONCLUSIONS

BEAST II and BELLE II detectors have been successfully used to study the beam background during the Phase 2 commissioning of SuperKEKB. The studies for Touschek, beam-gas and synchrotron radiation have given useful results, although more investigation is needed to explain some observations. For luminosity background, more effort is needed for Phase 2 data to disentangle the single beam background components and extract the luminosity one.

A general overview of Phase 2 data indicates that the background levels were higher than expected, with LER storage background around five times HER ones and with HER injection background always higher than LER one. More time should be dedicated at the beginning of Phase 3 to improve background reduction.

ACKNOWLEDGEMENTS

The BEAST group thanks the Belle II collaboration and the SuperKEKB collaboration.

REFERENCES

[1] Y. Ohnishi *et al.*, “Accelerator design at SuperKEKB”, *PTEP 2013*, 03A011, DOI: 10.1093/ptep/pts083

[2] T. Abe *et al.* [Belle-II Collaboration], “Belle II Technical Design Report,” arXiv:1011.0352 [physics.ins-det].

[3] M. Baszczyk *et al.* [SuperB Collaboration], “SuperB Technical Design Report,” arXiv:1306.5655 [physics.ins-det].

[4] T. Ishibashi, Y. Suetsugu and S. Terui, “Collimators for SuperKEKB Main Ring,”, in *Proc.IPAC’17*, paper WEPIL009, doi:10.18429/JACoW-IPAC2017-WEPIK009

[5] H. Nakayama, K. Ohmi, Y. Ohnishi, K. Kanazawa, Y. Suetsugu, H. Nakano and Y. Funakoshi, “Small-Beta Collimation at SuperKEKB to Stop Beam-Gas Scattered Particles and to Avoid Transverse Mode Coupling Instability,” *Conf. Proc. C* **1205201**, 1104 (2012).