PROCEEDINGS OF SCIENCE

SuperKEKB, BEAST, and Belle II prospects

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The goal of the SuperKEKB collider is to provide 50 times higher integrated luminosity and 40 times higher instantaneous luminosity than that of the KEKB collider. Both KEKB and the Belle detector are being upgraded to the SuperKEKB collider and the Belle II detector to deliver and collect much more luminosity for precision measurements and search for rare behavior in the heavy flavor sector. The overarching goal is to seek and explain physics beyond the Standard Model. This contribution gives the status of SuperKEKB, the commissioning detector, BEAST II, and the construction status and schedule of the Belle II experiment.

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1. Introduction

The Belle detector operating at the collision point of the asymmetric e^+e^- collider at KEKB with an integrated luminosity of 1000 fb^{-1} was very successful in explaining Kobayashi-Maskawa mechanism of *CP* violation in the Standard Model [1]. This led to the 2008 Nobel Prize in physics to M. Kobayashi and T. Maskawa for their theory of *CP* violation. It also provided many exciting results in B-physics, charm physics, and tau physics. Many interesting measurements remain statistically limited. To improve statistical precision and search for physics beyond the standard model, both the KEKB collider and the Belle detector are being upgraded to the SuperKEKB collider and the Belle II detector. The goal is to deliver and record 50 ab^{-1} of integrated luminosity. The commissioning of SuperKEKB has already begun, and physics data taken with the full detector is planned to start in 2018.

2. SuperKEKB collider

In order to achieve 40 times higher luminosity, the KEKB collider is being upgraded to SuperKEKB collider [2]. The major improvements from KEKB to SuperKEKB are reduced beam size, crab crossing at a larger crossing angle, and increased beam current in both the Low Energy Ring (LER) and High Energy Ring (HER) beam. Other upgrades include new damping rings for low emittance positrons, a new beam pipe, the replacement of shorter dipole magnets with longer ones in the LER, and new final focusing superconducting quadrupole magnets near the interaction point. The LER beam energy is increased from 3.5 GeV to 4 GeV to reduce Touschek background. For lower emittance, the HER beam energy is reduced from 8 GeV to 7 GeV. The formula used to describe the luminosity of SuperKEKB is:

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right) \tag{2.1}$$

where γ, e and r_e are the Lorentz factor, the elementary electric charge and the classical radius of electron, respectively. The suffix $\pm$ specifies the positron $(+)$ or the electron $(-)$ beam. R_L and R_{ξ_y} are the geometrical reduction factors for the luminosity and the vertical beam-beam parameter which arise from crossing angle and hourglass effect. Since $\frac{R_L}{R_{\xi_y}} \sim 1$, the luminosity is mainly determined by the total beam current (I), the vertical beam-beam parameter (ξ_y) and the vertical beta function at the IP (β_y^*). In order to achieve a luminosity of 8×10^{35} $cm^{-2}s^{-1}$, the beam current has been doubled compared to KEKB, and using nano beam scheme, the vertical beta function at the IP (β_y^*) has been reduced by a factor of twenty. Figure 1 shows the expected instantaneous and integrated luminosity of SuperKEKB/Belle II as a function of time.

3. Schedule and commissioning

The commissioning of SuperKEKB has already begun in February 2016. Beam has successfully circulated and been stored in SuperKEKB. As shown in Figure 2, the whole operation schedule has been divided into three phases: phase 1, phase 2 and phase 3. SuperKEKB finished its phase 1 operation without final focusing quadrupoles and the Belle II detector on June 28th. During the

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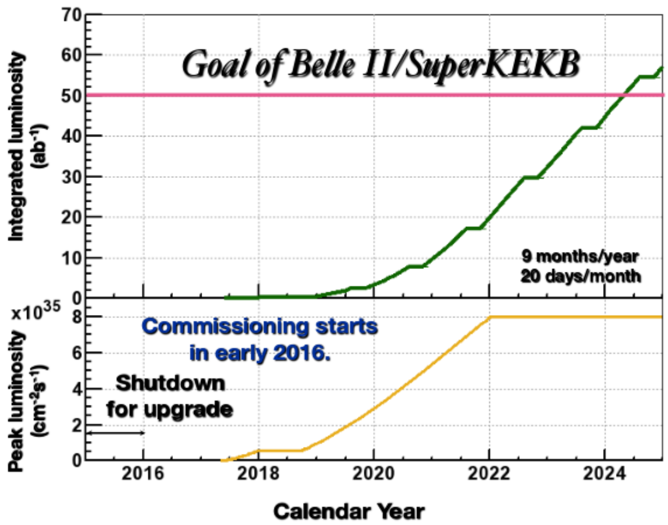

Figure 1: Luminosity goal of SuperKEKB/Belle II.

phase 1 period tuning of the e^+/e^- Beam Transport Lines, commissioning the new LER and HER, beam storage, vacuum scrubbing, optics studies, and beam tuning have been successfully carried out. Expected currents of 1 A, both for LER and HER, have been achieved. The commissioning detector, BEAST II, was successfully operated during this phase. After phase 1 the main ring renovation for phase 2 will include the installation of the final focusing quadrupoles called QCS, the Belle II detector excluding its vertex detector, and commissioning of the damping rings. Phase 2 will start operation from October 2017 and will run for 5-6 months. After phase 2, phase 3 physics data taking with Belle II detector will start in mid-2018.

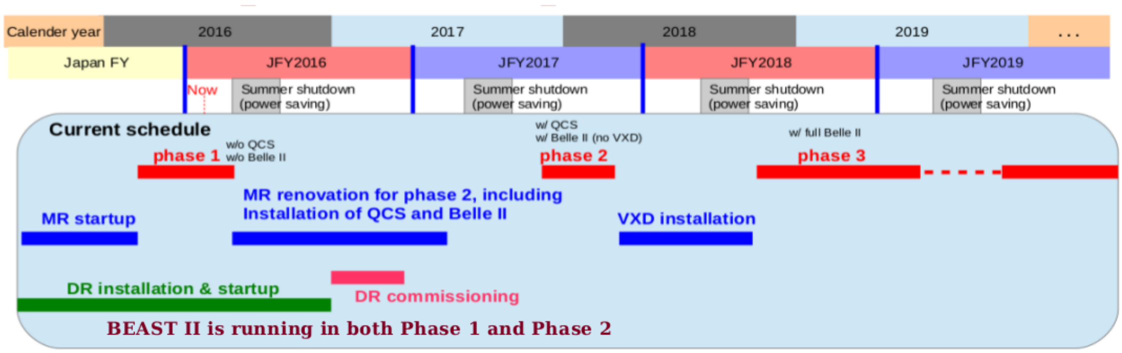

Figure 2: The Belle II commissioning schedule

4. SuperKEKB commissioning detector (BEAST II)

The commissioning detector, named BEAST II [3], consists of several sub-detectors to measure various beam backgrounds during phase 1 and phase 2 for safe roll-in of Belle II detector. BEAST II phase 1 without collision has successfully been completed. Figure 3 shows all BEAST sub-detectors positioned in the BEAST cage at the SuperKEKB interaction region (IR). Due to high beam currents, small beam size, and higher luminosity the predicted SuperKEKB beam background is forty times higher than at KEKB. Background can be reduced below this simple extrapolation by installing movable collimators and adding shielding near the QCS magnets. BEAST II provides feedback to SuperKEKB, and allows comparison between simulations and experimental data. During phase 1, the following BEAST sub-detectors were used to measure various beam backgrounds. To study injection background, we had eight sCintillation Light And Waveform Sensors (CLAWS). These detected minimum ionizing particles with timing resolution better than 1 ns and discriminated bunch-by-bunch injection background. Four diamond sensors installed near the IR measure ionizing radiation dose. 64 PIN diode sensors measure neutral and charged radiation dose at different positions around IR. Eight BGO crystals are able to monitor luminosity. Six CsI, six LYSO, and six Thalium dopped CsI crystals measure the electromagnetic energy spectrum of the background. Four He_3 tubes measure the thermal neutron flux and two micro-TPC measure the fast neutron flux.

During Phase 1, all BEAST sub-detectors clearly measured beam gas background produced due to scattering of beam off the residual gas atoms in the beam pipe. They measured background produced at the IR due to pressure bumps at various locations around the rings. BEAST II clearly observed LER/HER baking as the beam-gas background decreased with growing integrated beam current. Touschek background, due to intra e^+/e^- bunch scattering that changes momenta of beam particles, proportional to inverse beam size, was clearly seen for both the LER and HER. The largest source of beam background in phase 1 are off-energy particles hitting the inner walls of beam pipe. Touschek background estimation is quite important as SuperKEKB beam size is 20 times smaller than at KEKB. For a beam size of 90 μm the Touschek background observed in the LER is around 3 times higher than HER. We are currently analyzing the estimation of various beam backgrounds. Figure 4 shows the Touschek background and background due to vacuum bumps observed by the PIN diode system in BEAST II.

Figure 3: BEAST II cage at IR

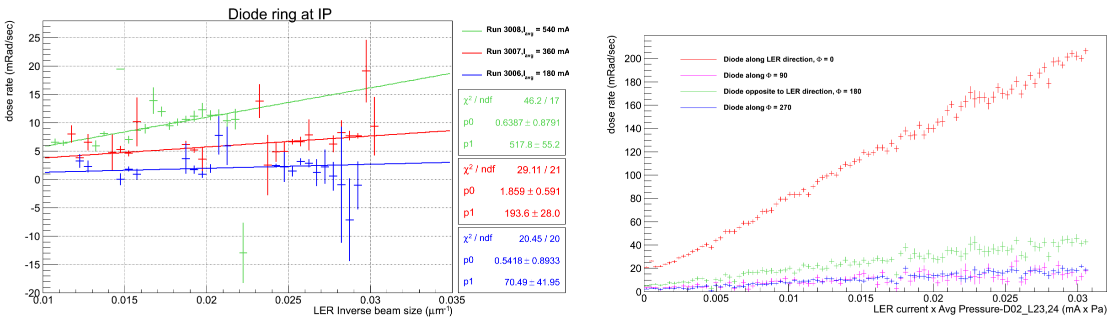

Figure 4: Left figure shows the Touschek background observed at IR as a function of LER inverse beam size. Right figure shows the level of background observed as a function of LER current multiplied by LER pressure.

5. Belle II detector

The Belle II detector upgrades or replaces all the sub-detectors of Belle to cope with the increased luminosity and increased beam background produced by SuperKEKB. The Belle II detector shown in Figure 5 consists of several sub-detectors. Full description of all the sub-detectors is available elsewhere ([2]). This contribution highlights the important improvements of Belle II over Belle detector, key design features, and recent developments.

The beam pipe radius has been reduced to 10 mm. This allows the innermost pixel detector (PXD) layer to be positioned closer to the interaction point (IP). This significantly improves the impact parameter resolution along the z direction. A large silicon tracker vertex detector (SVD) and central drift chamber (CDC) are there to provide tracking information, and to provide precise decay vertex information. Both of these improve flavor tagging. Time of Propagation (TOP) and Aerogel Ring Imaging CHerenkov (ARICH) detectors provide better K/π separation by covering the whole range momentum and cover both the Barrel and Endcap regions. Improvements in Electromagnetic Calorimeter (ECL) and K_L and muon (KLM) make them more robust versus beam induced backgrounds. Improved trigger and Data Acquisition (DAQ) systems also compensate for larger beam background. More details of each sub-detector are discussed in the following sections.

5.1 VXD

To provide precise measurement of the primary and secondary vertices of short- lived particles, the vertex detector consists of two parts: an inner PXD and an outer SVD. The PXD consists of two layers of DEPFET, DEPleted p-channel Field Effect Transistor, sensors with very thin (50 μm) pixels. The PXD provides excellent spatial granularity with resolution smaller than 15 microns. In simulation the performance of the combined PXD and SVD is shown in Figure 6.

The SVD consists of four layers of DSSD (Double Sided Strip Detectors) with an outer radius of 14 cm, more than twice Belle's SVD's of 6.05 cm, and an inner radius of 3.8 cm. It has excellent timing resolution of 2-3 ns. It covers the full Belle II angular acceptance of $17^{o} < \theta < 150^{o}$.

VXD and SVD construction are on-going, and both will be completed by early 2018 for phase 3 installation.

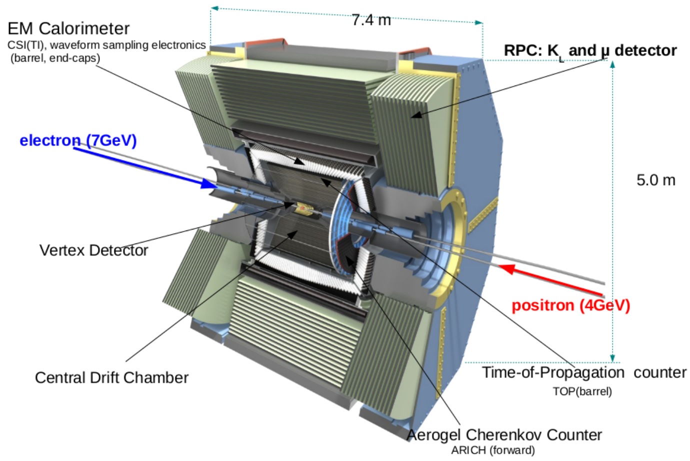

Figure 5: Belle II detector.

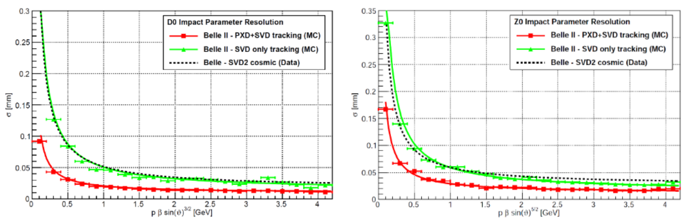

Figure 6: Impact parameter resolution in $r\phi$ direction (left) and z direction (right) for Belle II PXD+SVD simulation, Belle II SVD only simulation and Belle SVD2 cosmic events.

	Belle	Belle II
Radius of inner boundary (mm)	88	168
Radius of outer boundary (mm)	863	1111
Number of layers	50	56
Number of total sense wires	8400	14336
Gas	$\mathrm{He}-\mathrm{C_2H_6}$	$\mathrm{He}-\mathrm{C_2H_6}$
Diameter of sense wire (μm)	30	30

Table 1: Comparison between Belle and Belle II CDC

5.2 CDC

CDC is the main tracking device for charged track momenta. The Belle II CDC is larger than the CDC of Belle as shown in Figure 7. It has smaller drift cells, more layers, and faster electronics allowing better charged track reconstruction and dE/dx measurement compared to Belle. The comparison between Belle II and Belle CDC is given in Table 1. The new CDC will be installed this summer. Cosmic ray testing is currently being performed.

5.3 TOP

The TOP detector will be used for particle identification in the barrel region of Belle II cov-

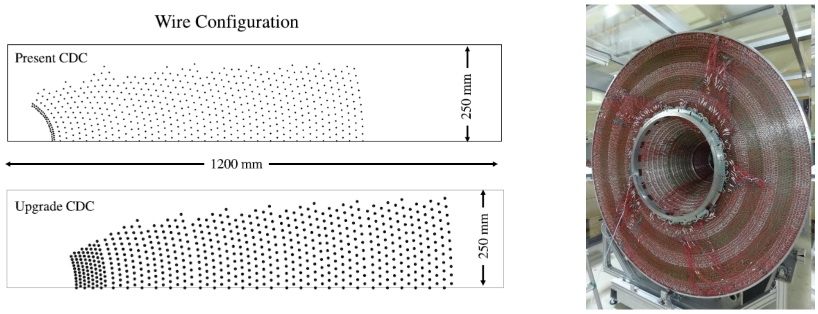

Figure 7: Left figure shows comparison of CDC wire configurations between Belle (top) and Belle II (bottom). Right figure is a picture of Belle II CDC.

ering the whole momentum range of interest. There are 16 20mm $\times$ 0.45m $\times$ 2.7m TOP modules. Each consists of two quartz bars, one focusing mirror, one prism, and an array of pixelated Micro-Channel Plate Photo-Multiplier Tubes (MCP-PMTs) to collect Cerenkov photons internally reflected inside the quartz radiator when charged tracks pass through the radiator. A module is shown in Figure 8. To distinguish between kaons and pions, the MCP-PMTs have excellent position and timing resolution with new waveform sampling electronics.

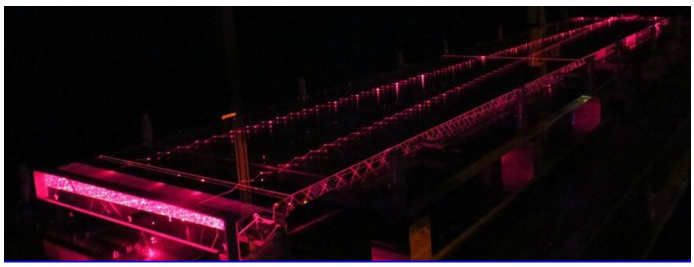

Figure 8: Total internal reflection of laser light inside the last TOP module

All 16 modules have been installed. Commissioning of all 16 modules is ongoing.

5.4 ARICH

ARICH identifies charged particles in the forward endcap. Two layers of aerogel with different refractive indices are used to provide better photon yield without affecting the resolution. The detector is shown in Figure 9. 420 Hybrid Avalanche Photo Detectors (HAPD), each with 144 channels, will be used for readout. The beam test results and simulations show excellent K identification efficiency with a low π mis-identification rate. The detector will be installed in this Autumn.

5.5 ECL

Belle ECL will be upgraded to compensate for the larger beam induced background in Belle II. The Belle CSI (TI) crystal calorimeter will be reused with improved back-end readout electronics with better waveform sampling. The Barrel ECL has already been installed, and cosmic ray testing

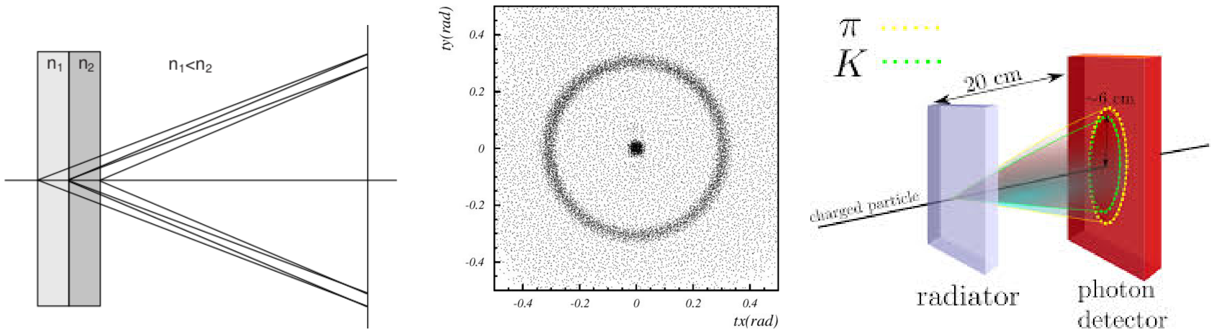

Figure 9: The focusing mechanism of ARICH.

Detector	$\varepsilon_{\rm phys}$	$\varepsilon_{\rm signal}$	$\varepsilon_{\rm bkg}$
Belle	99.42 %	88.70 %	10.72 %
Belle II	99.90 %	99.12 %	0.78 %

Table 2: Comparison in simulation of the Belle II ECL trigger efficiency and Belle ECL efficiency

is ongoing. Table 2 shows the simulated Belle II ECL trigger efficiency compared to Belle ECL efficiency.

5.6 KLM

Due to the expected high neutron background and to maintain the efficiency of the KLM detector, the endcaps and two innermost barrel RPC layers of Belle KLM were replaced with scintillators. The barrel KLM installation was completed in 2013 and endcap KLM was installed in 2014. Commissioning of the KLM is ongoing with cosmic rays.

6. Summary

SuperKEKB phase 1 commissioning has been completed. BEAST II phase 1 detectors studied beam backgrounds very successfully. BEAST II has seen charged particles, X-rays, thermal neutrons, and fast neutrons from beam-gas events clearly. Belle II is on schedule with the CDC complete, and KLM, ECL, TOP installed. Belle II will start operation in 2017 and start taking physics data with a complete detector in 2018. The project is well on its way to collecting 50 ab^{-1} of data, which will open new windows in many areas of flavor physics and have the potential for the observation of New Physics.

References

[1] M. Kobayashi, T. Maskawa, *CP Violation in the Renormalizable Theory of Weak Interaction, Prog.Theor.Phys.* **49** (1973) 652-657.

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

[3] BEAST II Technical Design Report.