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Performance Studies of Belle II Silicon Vertex Detector

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The Belle II experiment at the SuperKEKB asymmetric-energy e^+e^- collider in KEK, Japan will operate at an instantaneous luminosity of 8×10^{35} cm^{-2}s^{-1}, which is about 40 times larger than that of its predecessor, Belle. It is built with the aim of collecting a huge amount of data corresponding to an integrated luminosity of about 50 ab^{-1} by 2025 for precise measurements of *CP* violation and searches for new physics, such as flavor-changing neutral currents, probing charged Higgs, new sources of *CP* violation, lepton-flavour violating decays, and searches for a dark photon. At this high luminosity, Belle II will face harsh backgrounds. To validate the performance of a key component of Belle II, the silicon vertex detector (SVD), in such a high rate and background environment, a detailed systematic performance study is essential using the offline reconstruction software. In this work, the performance of the Belle II SVD is validated using commissioning data for each double-sided silicon strip sensor. These studies help us to optimize the operation parameters of the SVD.

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1. Introduction

The Belle II experiment [1] operates at the intensity frontier; its main goal is to search for physics beyond the Standard Model (BSM) through indirect means. The Belle II experiment is installed at an interaction point of the SuperKEKB [2] collider at KEK, Tsukuba, Japan. SuperKEKB is an asymmetric e^+e^- collider, which will operate at, or near, a center-of-mass energy of 10.58 GeV, which corresponds to the mass of $\Upsilon(4S)$ resonance. The collider is designed to operate at an instantaneous luminosity of 8×10^{35} cm^{-2}s^{-1}, which is 40 times larger than the previous KEKB collider. The Belle II experiment is expected to collect data corresponding to an integrated luminosity of 50 ab^{-1}, which is 50 times larger than the data sample collected by the previous experiment, Belle [3]. At such a high luminosity, Belle II will operate in a harsh background environment. Therefore it is extremely important to validate the performance of the Silicon Vertex Detector (SVD), which is a key element of the Belle II detector, using the offline-reconstruction software. The excellent performance of the SVD will provide time-dependent measurements of *CP* asymmetries in the *B*-meson system with higher precision. In order to achieve this and other physics goals, the reconstruction of tracks with high efficiency and good resolution is required. The reconstruction of charged particle positions close to the interaction point is provided by the Vertex Detector (VXD), which is further composed of two sub-detectors: the Pixel Detector (PXD) [4], made of two layers of sensors based on DEPFET pixels, and the Silicon Vertex Detector (SVD) [5], composed of four layers of double-sided silicon strip detectors. In this paper, our aim is to validate the performance of the SVD using the commissioning data, which will allow us to optimize the operation parameters of the SVD in offline-reconstruction software.

2. Overview of the Belle II SVD

The SVD is one of the main track-finding devices of the Belle II detector. It consists of four layers, namely, L3, L4, L5 and L6, which are made of ladders. These ladders are further comprised of several double-sided silicon strip detectors (DSSDs). The two sides of the silicon provide orthogonal position measurements, with the radial coordinate defined by the sensor position.

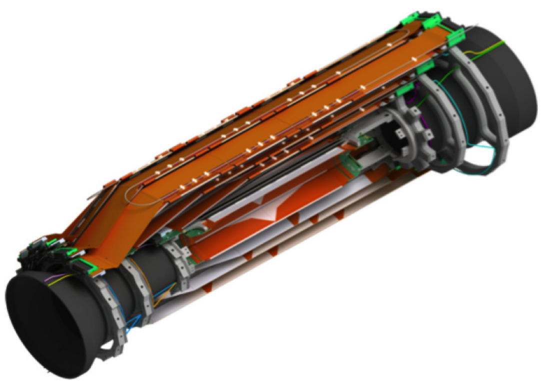

Figure 1: A three-dimensional section of the Belle II SVD.

The four SVD layers are placed at different radii of 39 mm, 80 mm, 104 mm and 135 mm and cover the polar angular range of 17° to 150° with respect to the e^- beam direction.

No. of Strips	Rectangular sensor	Trapezoidal sensor
# of p-strips	768	768
p-strip pitch (μm)	75 (L3: 50)	50...75
# of n-strips	512 (L3: 768)	512
n-strip pitch (μm)	240(L3: 160)	240
Active area (mm^2)	7030 (L3: 4738)	5890

Table 1: Specifications of DSSDs.

This asymmetry in angular coverage improves the acceptance and precision of forward-boosted particles in the experiment. Figure 1 shows the three-dimensional section of the SVD. The sensors in the SVD have differing dimensions. The innermost layer (L3) is made of small rectangular sensors of thickness 320 μm and width 3.8 cm, while other layers are composed of two types of sensors: (a) large rectangular sensors of thickness 320 μm and width 5.8 cm and (b) trapezoidal sensors of thickness 300 μm and width that varies from 3.8 cm to 5.8 cm. The specifications of the SVD sensors are listed in Table 1.

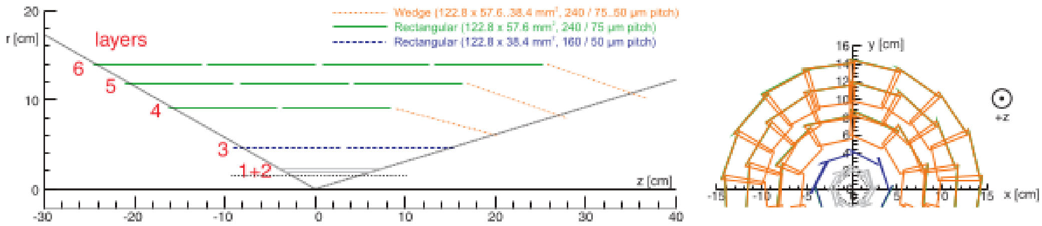

Figure 2: Cross section views of VXD, with emphasis on the SVD, in $r-z$ plane (left) and $x-y$ plane from positive z (right) [6].

In order to cope with the high particle rates expected, the DSSDs must be readout using electronics that have a short signal-shaping time. Therefore, APV25 readout chips are used. The two directions of the strips are defined: U side (parallel to the beam direction, with long strips and small pitch) and V side (perpendicular to the beam direction, with short strips and large pitch). Figure 2 shows cross-sectional views of VXD in $r-z$ plane and the $x-y$ plane. The Belle II SVD

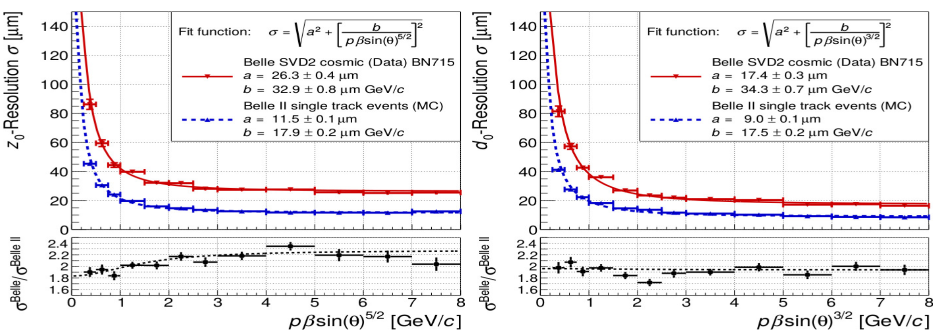

Figure 3: Impact parameter resolution (left) in the beam direction and (right) in the plane perpendicular to the beams [7].

will provide better vertex resolution, low-p$_T$ track finding efficiency and improved K_S^0 reconstruction efficiency compared to the Belle SVD. Along with the PXD, the SVD improves the impact parameter resolution in Belle II as compared to Belle [7], which is shown in Fig. 3.

3. Performance Studies of the SVD

The performance of the SVD is validated in the offline-reconstruction software (based on BASF2 [8]) using the commissioning data, taken at KEK, Japan. The set-up used for the commissioning data taking consists of two SVD half shells, which have been assembled at KEK. The testing of these SVD half shells was carried out with cosmic rays from July 2018 to September 2018. We collected a total of 30×10^6 cosmic events during the commissioning period. The complete SVD half shells are shown in Fig. 4, along with an event display of the first cosmic event taken on August 17, 2018.

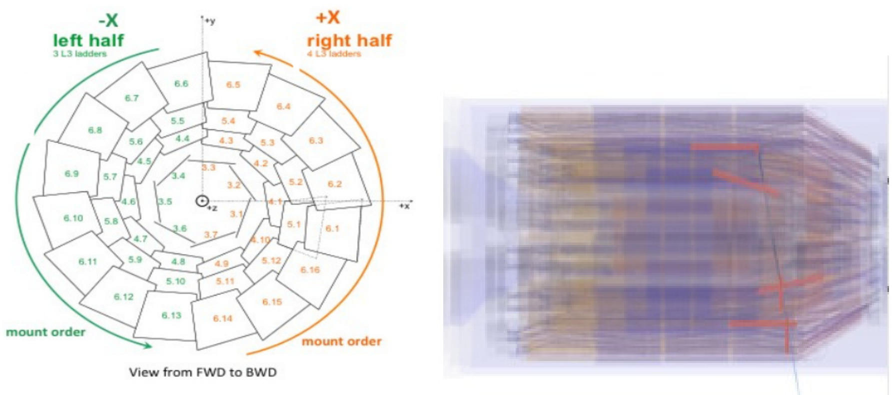

Figure 4: (Left) Schematic of the complete SVD half shells and (right) an event display of the first cosmic event recorded on August 17, 2018.

Using the commissioning data, the energy is reconstructed for clusters that are associated with tracks; this is done separately for the U and V side of the sensor. The left panel of Fig. 5 shows the reconstructed cluster energy in a single horizontal sensor. As the cosmic track is perpendicular to the horizontal sensors, the clusters are correctly reconstructed on both sides (U, V), hence the energy distributions are in agreement for both sides. As in SVD, cluster energy/cluster charge is sensitive to the interstrip capacitance depending on the strip pitch, therefore this study is useful to measure the actual interstrip capacitance of SVD sensors. In addition, we have also seen the dependency of the cluster energy on incident angle of cosmic rays on sensors. The right-side of Fig. 5 shows the cluster energy distributions for different sensors, which are positioned at different azimuthal angles with respect to the beam direction. Sensors with cosmic tracks with large incident angle with respect to the plane of sensor have a larger cluster energy due to the longer path length of the track in the sensor. In addition, the cluster signal-to-noise ratio (S/N) is also reconstructed for each side of a sensor and the distributions are shown in the left panel of Fig. 6. The S/N is measured to be larger than 25 for the N side and slightly lower on the P side due to the longer strips giving a larger capacitive load to the pre-amplifier. Further, the signal hit time is also reconstructed and results are shown in the right panel of Fig. 6. The study of S/N ratio helps to improve the

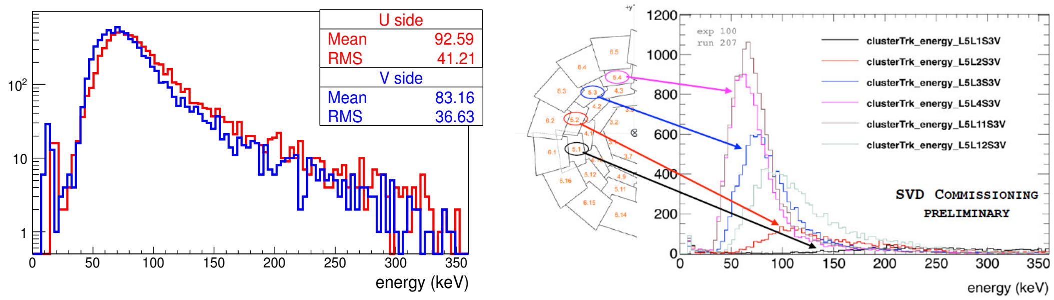

Figure 5: (Left) Distribution of cluster energy in L3, ladder 3, sensor 2 for clusters associated to tracks in the U (red) and V (blue) sides. Here different mean value of cluster energy on two sides is obtained due to the different contribution of the capacitance depending on the strip pitch on both side. (Right) Cluster energy in sensors at differing azimuthal angles.

energy resolution of SVD sensors. The RMS of signal hit time corresponding to a bunch crossing is found to be in the order of 5 ns, which is nicely matching with the design expectation. This study is useful to remove the off-time hits as well as to improve the tracking performance of the SVD.

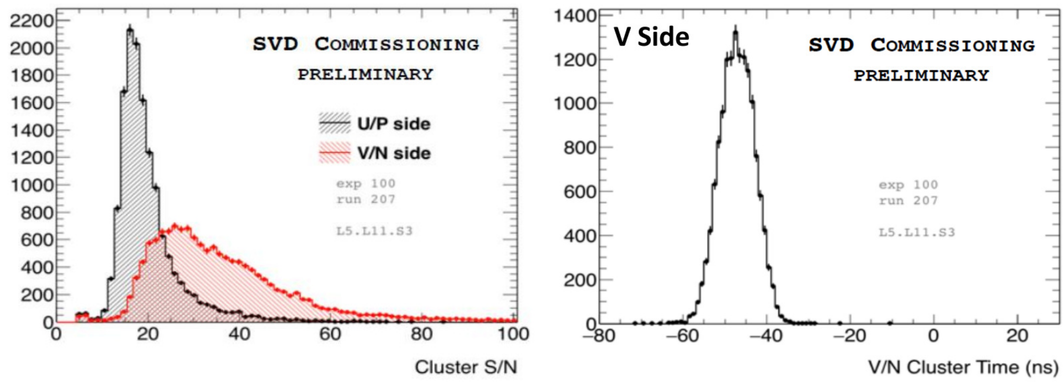

Figure 6: (Left) The U and V side cluster S/N ratio and (right) the signal hit time distribution in commissioning data.

4. Summary

The Belle II SVD is currently running smoothly during the commissioning period, where two SVD half shells are assembled at KEK. The performance of SVD is evaluated with cosmic runs for each side of the DSSD sensors in offline-reconstruction software and we have extracted the fundamental information from the SVD hits, for example, cluster energy, cluster S/N ratio and signal hit time. These studies provide the better energy resolution in SVD sensors. It is further demonstrated that the SVD is clearly able to distinguish bunch crossings of 5 ns apart. After analyzing the commissioning data, it is found that the SVD provides excellent performance. The first physics run at Belle II with the SVD installed is expected early in 2019.

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