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The Silicon Vertex Detector of the Belle II experiment

A.B. Kaliyar ,[a,*] K. Adamczyk,[b] L. Aggarwal,[c] H. Aihara,[d] T. Aziz,[e] S. Bacher,[b] S. Bahinipati,[f] G. Batignani,[g,h] J. Baudot,[i] P. K. Behera,[j] S. Bettarini,[g,h] T. Bilka,[k] A. Bozek,[b] F. Buchsteiner,[a] G. Casarosa,[g,h] L. Corona,[h] S. B. Das,[l] G. Dujany,[i] C. Finck,[i] F. Forti,[g,h] M. Friedl,[a] A. Gabrielli,[m,n] B. Gobbo,[n] S. Halder,[e] K. Hara,[o,p] S. Hazra,[e] T. Higuchi,[q] C. Irmler,[a] A. Ishikawa,[o,p] Y. Jin,[n] M. Kaleta,[b] J. Kandra,[k] K. H. Kang,[q] P. Kodyš,[k] T. Kohriki,[o] R. Kumar,[r] K. Lalwani,[l] K. Lautenbach,[t] R. Leboucher,[t] S. C. Lee,[s] J. Libby,[j] L. Martel,[i] L. Massaccesi,[g,h] G. B. Mohanty,[e] S. Mondal,[g,h] K. R. Nakamura,[o,p] Z. Natkaniec,[b] Y. Onuki,[d] F. Otani,[q] A. Paladino[A,],[g,h] E. Paoloni,[g,h] H. Park,[s] L. Polat,[t] K. K. Rao,[e] I. Ripp-Baudot,[i] G. Rizzo,[g,h] Y. Sato,[o] C. Schwanda,[a] J. Serrano,[t] T. Shimasaki,[q] J. Suzuki,[o] S. Tanaka,[o,p] H. Tanigawa,[d] F. Tenchini,[g,h] R. Thalmeier,[a] R. Tiwary,[e] T. Tsuboyama,[o] Y. Uematsu,[d] L. Vitale,[m,n] Z. Wang,[d] J. Webb,[u] O. Werbycka,[n] J. Wiechczynski,[b] H. Yin[a] and L. Zani[B,t]

[a] *Institute of High Energy Physics, Austrian Academy of Sciences, 1050 Vienna, Austria*
[b] *H. Niewodniczanski Institute of Nuclear Physics, Krakow 31-342, Poland*
[c] *Panjab University, Chandigarh 160014, India*
[d] *Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*
[e] *Tata Institute of Fundamental Research, Mumbai 400005, India*
[f] *Indian Institute of Technology Bhubaneswar, Bhubaneswar 752050, India*
[g] *Dipartimento di Fisica, Università di Pisa, I-56127 Pisa, Italy, [A]presently at INFN Sezione di Bologna, I-40127 Bologna, Italy*
[h] *INFN Sezione di Pisa, I-56127 Pisa, Italy*
[i] *IPHC, UMR 7178, Université de Strasbourg, CNRS, 67037 Strasbourg, France*
[j] *Indian Institute of Technology Madras, Chennai 600036, India*
[k] *Faculty of Mathematics and Physics, Charles University, 121 16 Prague, Czech Republic*
[l] *Malaviya National Institute of Technology Jaipur, Jaipur 302017, India*
[m] *Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy*
[n] *INFN Sezione di Trieste, I-34127 Trieste, Italy*
[o] *High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*
[p] *The Graduate University for Advanced Studies (SOKENDAI), Hayama 240-0193, Japan*
[q] *Kavli Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwa 277-8583, Japan*
[r] *Punjab Agricultural University, Ludhiana 141004, India*
[s] *Department of Physics, Kyungpook National University, Daegu 41566, Korea*

*Speaker

[t]*Aix Marseille Université , CNRS/IN2P3, CPPM, 13288 Marseille, France,* [B]*presently at INFN Sezione di Roma Tre, I-00185 Roma, Italy*

[u]*School of Physics, University of Melbourne, Melbourne, Victoria 3010, Australia*

E-mail: abdulbasith.kaliyar@oeaw.ac.at

The Belle II silicon vertex detector (SVD) is a four-layer double-sided silicon strip detector installed within the Belle II detector located at KEK, Japan. SVD has been operating smoothly and reliably since the start of data taking in March 2019. The data quality and radiation damage effects have been constantly monitored. In this article, we report the operational experience of SVD, reconstruction performance and effects of beam background and radiation damage. We also report some of the recent efforts to improve the software robustness targeting the high luminosity scenario and hardware activities performed during the first long shutdown of Belle II experiment.

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1. Introduction

The Belle II experiment [1] aims to make precise measurements of weak interaction parameters, study exotic hadrons, and search for new physics beyond the Standard Model of particle physics. The experiment is currently underway at the SuperKEKB accelerator research center located in Tsukuba, Japan. The SuperKEKB [2] is an asymmetric energy e^- (7 GeV) e^+ (4 GeV) collider operates near the $\Upsilon(4S)$ resonance (10.58 GeV). The instantaneous peak luminosity achieved so far is $4.7 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, which is the world record and more than twice that of KEKB accelerator, the predecessor of SuperKEKB. The ultimate target is to reach a peak luminosity of $6 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$. The Belle II detector is positioned around the interaction point of the SuperKEKB and has so far collected 430 fb^{-1} of data.The eventual goal is to collect 50ab^{1} of data in the next decade.

The Vertex Detector (VXD) is the innermost subdetector in the Belle II detector system located closest to the interaction point. Comprising six layers, it includes two inner layers of pixel detector (PXD) [3], based on depleted field effect transistor (DEPFET) sensors, and four outer layers of silicon strip detector, known as the silicon vertex detector (SVD) [4]. The SVD is crucial for extrapolating the measured tracks to the PXD and point at a region-of-interest that helps to significantly reduce the amount of data recorded by PXD. Besides, SVD also performs standalone tracking of low-momentum particles, vertex detection of K_S^0 and Λ particles, and contributes to the charged-particle identification by providing energy-loss information (dE/dx).

In July 2022, Belle II temporally paused operation for the first long shutdown (LS1) to allow the maintenance work of the accelerator and improvements in detector. VXD was re-installed during this time with a new complete PXD and the same SVD. In this report we present a detailed description of the SVD , its performance until July 2022, effects of radiation damage and the software improvements towards high luminosity scenario and the main challenges and results of the VXD re-installation during LS1.

2. Belle II Silicon Vertex Detector

The Belle II SVD is composed of four layers of Double-Sided Silicon Strip Detector (DSSD), namely layer 3, 4, 5 and 6, placed at a radii of 39, 80, 104, and 135 mm, respectively, from the beam pipe. The material budget is about 0.7% of a radiation length per layer. In total, there are 172 sensors with a sensor area of 1.2 m^2 and 224 thousand readout strips. There are three types of DSSDs: “small” rectangular sensors in layer 3, “large” rectangular sensors in the barrel region of layers 4, 5, and 6, and “trapezoidal” sensors in the forward region of layers 4, 5, and 6, that are slanted. These sensors are made from an N-type bulk 6-inch wafer with a thickness of about 300 μm. To provide two-dimensional spacial information, P side strips of the sensors are placed parallel to the beam axis while the N side strips are placed transverse to the beam axis. The details of the DSSDs are summarized in Table 1. The readout strips are AC coupled and there is one intermediate floating strip between two readout implants. The full depletion voltage ranges from 20 – 60 V, and the operating voltage is 100 V. The radiation hardness of SVD sensors is about 6 Mrad.

The front-end readout ASIC used in SVD is APV25 [5] chips, with 128 input channels. The signals from the strips are collected by APV25 chips and provide analog readout. APV25 chip has

Table 1: Details of the three types of DSSDs used in the SVD.

	Small rectangular	Large rectangular	Trapezoidal
Sensor active area (mm^2)	122.90×38.55	122.90×57.52	$122.76 \times (38.42 - 57.59)$
Number of P-strips	768	768	768
P-strip readout pitch (μm)	50	75	$50 - 75$
Number of n-strips	768	512	512
N-strip readout pitch (μm)	160	240	240
Thickness (μm)	320	320	300
Manufacturer	Hamamatsu	Hamamatsu	Micron

a fast 50 ns shaping time and a radiation hardness up to 100 Mrad. By default, the chip operates in multi-peak mode at a clock frequency of 31.8 MHz which is 1/8 of the SuperKEKB bunch-crossing frequency. Six consecutive samples are read out upon the arrival of a global hardware trigger to reconstruct the signal pulses. To save the data transmission bandwidth at the high luminosity runs, a 3/6-mixed operation mode is also developed, where three or six samples are acquired depending on the timing precision of the hardware trigger. The 3/6-mixed mode operation mode has been tested and is ready to use in the future.

3. Operation and performance

The SVD has been operating smoothly and reliably since its installation in 2019. The total fraction of masked strips due to defects is less than 1% and only one out of 1748 APV25 chip was temporarily disabled. Temperature and calibration constants are evolving in the expected ranges due to radiation damage. The hit efficiency exceeds above 99% for all the sensors. Figure 1 shows example distributions of cluster charge and cluster signal-to-noise ratio (SNR) measured in 2022 and 2020. The signal cluster charge is normalized to the track path length in the silicon to correct for the track's incidence angle. The normalized cluster charge is found to be in good agreement with expectations and similar in all sensors. The charge matches with the expected minimum ionizing particle (MIP) value of approximately 24000 e^- within 15%, which is the uncertainty in the absolute APV25 gain calibration. The cluster SNR is defined as the total cluster charge divided by the quadratic sum of the noise values from each strip in the cluster. A small decrease of cluster SNR is observed in 2022 data, due to increased noise from radiation damage ($\sim$ 20% $-$ 30%). In general, very good SNR is measured across all 172 DSSD sensors, with most probable value typically falling within the range of 13 to 30, varying based on sensor side and position.

The cluster position resolution is crucial in vertexing and track reconstruction performance. The position resolution of the SVD is estimated from the residual of cluster positions with respect to unbiased track extrapolation after subtracting the effect of the track extrapolation uncertainty [6]. Studies using dimuon ($e^+e^- \to \mu^+\mu^-$) events shows a resolution of $7 - 12$ μm for the P side and $15 - 25$ μm for the N side. These are in fair agreement with expectations from the sensor pitch. Good stability of position resolution over the time is also confirmed by comparing measurements from 2022 to 2020.

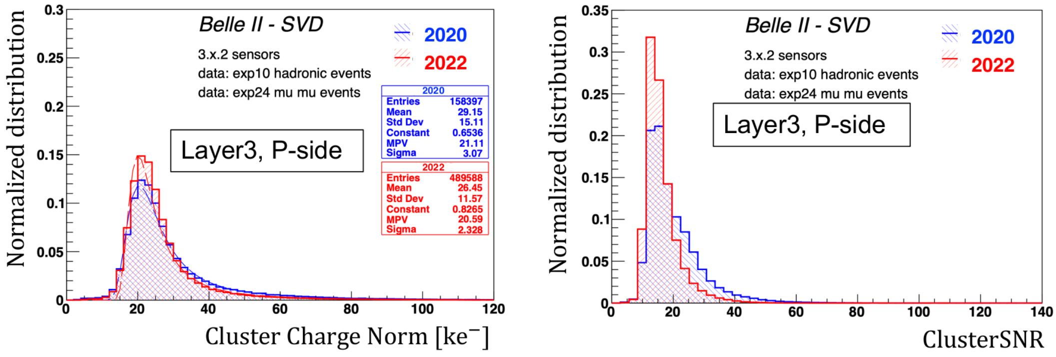

Figure 1: The signal cluster charge (left) and the cluster SNR (right) in P strips for one of Layer 3 sensors.

The SVD also offers an excellent hit time resolution. It is measured from the residuals of the hit time with respect to the time of the e^+e^- collision (EventT0) provided by the central drift chamber (CDC) of the Belle II detector. The measured hit time resolution is 2.9 ns (2.4 ns) for the P (N) side. The hit time information is also used to remove the machine related background, which is typically unassociated with the e^+e^- collisions. These off time hit background enters the triggered data acquisition window and increase the strip occupancy. Background occupancy above a certain threshold can cause tracking performance degradation. Time difference between the P and N side clusters can also be used to suppress the wrong combination of P and N side clusters when there are more than one particle crossing one piece of sensor. By requiring the cluster time within 50 ns of the event time and time difference between P and N side cluster within 20 ns, 50% off-time background hits can be rejected while keeping 99% tracking efficiency. This allows us to set the hit occupancy limit at layer 3 to 4.7% without tracking performance deterioration.

Two new algorithms are currently being developed that exploit the SVD time information to further relax the hit-occupancy limit and enhance the offline software robustness in the high-background environment. One method involves the selection of track-time, which is computed by combining the hit-time of SVD clusters associated with a track. This reduces the fake-track rate, thus relaxing the hit-occupancy limit. The second algorithm involves grouping SVD clusters using the hit-time information. The cluster time distribution has clear grouping structure since clusters from different bunches are collected within the acquisition time window of the triggered event. Signal clusters are located in a group around the event-time, $T = 0$, while other background hits form other groups, which are caused by other beam-bunches. Since many background hits are within the 50 ns range, it cannot be eliminated completely with a hit-time selection alone. The cluster grouping method allows event-by-event classification and further background elimination. The addition of these two new algorithms allow us to set the hit-occupancy limit at around 6%. Further software improvement and optimization are currently ongoing before incorporating these features to the actual data processing.

4. Beam Background and Radiation Effects

In this section we discuss the effects of radiation damage on the SVD sensors during its operation. The beam-induced background increases the hit occupancy and causes radiation damage to the sensors. The radiation damage affects the strip noise, leakage current, and full depletion voltage of sensors and it is constantly monitored during the operation . Current average hit occupancy on layer 3 sensors is less than 0.5% and well under control. Radiation dose in the SVD is estimated based on the data from diamond sensors that are mounted on the beam pipe and the bellows pipes outside of the VXD. The total integrated radiation dose on Layer-3 sensors is 70 krad, which corresponds to an equivalent 1 − MeV neutron fluence of $1.6 \times 10^{11} \mathrm{n_{eq}/cm^2}$, assuming the ratio of a neutron fluence to a radiation dose of $2.3 \times 10^{9} \mathrm{n_{eq}/cm^2/krad}$ based on MC simulation.

The strip noise, which is dominated by the inter-strip capacitance, during the operation increased about 20% (30%) for N-side (P-side), which is expected to be saturated. The leakage current is gradually increasing and, in general, its value shows a linear dependence on the accumulated dose, as expected from NIEL model. So far, this increase has negligible contribution to the noise because of small leakage current and short APV25 shaping time. However, after 6 Mrad the leakage current contribution to noise might become significant and reduces the SNR in the layer 3 below 10. So far no changes in full depletion voltage are observed in the operating sensors.

Further studies have been carried out with several irradiation campaigns to better evaluate the radiation tolerance of SVD sensors even after bulk type inversion. In July 2022, a new irradiation campaign of SVD sensors was performed with 90 MeV e^- beam at ELPH, Tohoku University, with a radiation dose up to 10 Mrad (corresponding to $3 \times 10^{13} \mathrm{n_{eq}/cm^2}$ of neutron fluence). The type inversion of the sensor bulk is confirmed after 2 Mrad of radiation. The tests confirm that the SVD sensor works well even after the bulk type inversion which is expected from previous experience of silicon detectors of similar type. These results provide a large safety margin for SVD even after 10 years of operation at target luminosity.

5. VXD reinstallation during Long Shutdown 1

In July 2022, Belle II paused it's operation for the first long shutdown to allow the maintenance work of the accelerator and implement upgrades to the detector. A brand new pixel detector (PXD2) with fully installed second layer was installed in the VXD volume along with the current SVD. Very intense hardware activities were carried out involving the SVD crew during the de-installation and re-installation of VXD. On 10 May, 2023, the VXD was safely extracted from the Belle II detector, followed by dismounting two SVD half-shells from the old PXD and mounting them on PXD2. All these delicate operations involved several steps with extensive testing of the detector and the environmental monitoring system, to ensure the healthiness of the system after each step. The healthiness of all SVD sensors were confirmed during the commissioning of the new VXD in the clean room. On 28 July, 2023, the new VXD was successfully reinstalled into the Belle II detector. Additional tests including cosmic ray runs were performed before the start of the actual beam operations. After LS1, Belle II officially restarted data taking in January 2024, and so far SVD is performing smoothly as before.

6. Conclusion

The Belle SVD has been taking high-quality data since March 2019. Operation is stable and reliable with excellent detector performance. Effects from radiation damage are observed at the expected level, however their contribution does not cause any degradation to the SVD tracking performance so far. During the first long shutdown, a new VXD was successfully re-installed into the Belle II detector incorporating the full PXD2 together with the existing SVD.

Background extrapolation to the target luminosity as well as the results of irradiation campaign show that the SVD is safe even after 10-years operation. However, the high background environment in the future may deteriorate tracking performance of the SVD as indicated by the simulation. To enhance the robustness against high background, as well as matching the possible new interaction region, technology assessment is ongoing for a possible VXD upgrade during the second long shutdown of the Belle II operation [7–9].

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