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The Silicon Vertex Detector of the Belle II Experiment

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The Belle II experiment operating on the asymmetric e^+e^- SuperKEKB collider, located in Tsukuba (Japan), has been collecting data since March 2019. Its excellent vertexing abilities are provided by Vertex Detector (VXD), part of which is Silicon Vertex Detector (SVD) playing a crucial role in the tracking close to the interaction point. SVD operates very successfully and efficiently over the whole period of data taking so far. In this article we briefly discuss its purpose, structure and basic description of the front-end electronics. The main variables related to the SVD performance (Cluster Charge, Signal-to-Noise ratio, sensor efficiency, spatial and time resolution) are presented. We elaborate on the challenges concerning the increase of the SuperKEKB luminosity and related impact on the SVD performance in the high background environment. The quick overview of the radiation campaign is presented to show the predicted behaviour of the sensors subjected to the high radiation, whose level is constantly monitored. We also discuss the ongoing effort in the software development to account for the expected high occupancy in the SVD detector in the future. In particular, the utilization of the SVD hit time information is presented as a very important quantity to suppress off-time background hits and tracks. Finally, the Long Shutdown 1 is briefly overviewed, during which the major upgrade of the Pixel Detector (PXD) has been successfully done. Resume of the beam operation is expected in early 2024.

Keywords: Silicon strip detector, Vertex detector, Tracking detector, Belle II

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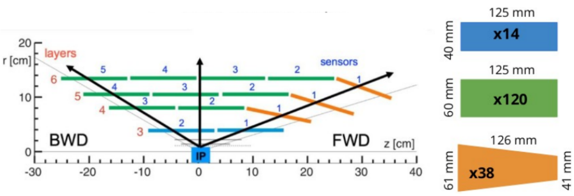
1. Introduction

The Belle II [1] experiment is dedicated to search physics beyond the Standard Model in the flavour frontier. It operates on the SuperKEKB collider located in KEK, Tsukuba (Japan), providing asymmetric beams of 7 GeV electrons and 4 GeV positrons. In the default accelerator's operation regime, the center-of-mass energy is set to the $\Upsilon(4S)$ resonance, hence it serves as a source of huge sample of B mesons via $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ process. So far, SuperKEKB achieved the highest instantaneous luminosity of 4.7×10^{34} cm^{-2}s^{-1}, which is the current world record. The Belle II detector is a multi-purpose spectrometer characterized by excellent vertexing capability and good hermeticity, which accumulated 424 fb^{-1} to date, and its final goal is to collect the data sample of 50 ab^{-1}, that will be possible with the constant increase of the SuperKEKB instantaneous luminosity up to our final goal of 6×10^{35} cm^{-2}s^{-1}.

Belle II is composed of various sub-detectors with the Vertex Detector (VXD) as the closest one to the beam interaction point, which divides into two further subsystems. First is the Pixel Detector (PXD), which is the innermost part and is based on depleted field effect transistor (DEPFET) pixel sensors. PXD consists of two layers and its main goal is the precise determination of the decay vertices. The second sub-system is the Silicon Vertex Detector (SVD) [2] with four layers (numbered 4-6) that predominantly extrapolates the measured tracks to the PXD, defining so-called Region of Interest (ROI), which allows to significantly reduce the amount of data recorded by PXD. SVD also performs standalone tracking for low momentum particles and contributes to the particle identification by providing energy loss (dE/dx) information.

2. SVD structure

Each layer of SVD is composed of Double-Sided Silicon Strip Detectors (DSSD) that are manufactured on an n-type bulk wafer with a thickness of about 300 m. One side of the bulk is covered by the p-type silicon strips placed in parallel to the beam axis that determine the $\phi - r$ coordinates (azimuthal angle and distance from the z-axis, respectively), and the n-type strips are placed perpendicularly on the other side of the bulk measuring z coordinate (along the beams). Figure 1 (left) shows the schematic picture of SVD layers and associated sensors with increasing numbering from the forward (FWD) to the backward (BWD) region. Such structure is repeated along the azimuthal angle forming different Ladders and so-called windmill geometry of the SVD. The sensors differ depending on the layer and the region in which they are placed in the SVD. In the FWD part for layers 4-6 they have the trapezoid shape and are bent to provide better coverage in the



Type	Number of readout strips		Readout pitch (μm)		Thickness (μm)	Manufacture
	P side	N side	P side	N side		
Small	768	768	50	160	320	HPK
Large	768	512	75	240	320	HPK
Trapezoidal	768	512	50-75	240	300	Micron

Figure 1: *Schematic picture of SVD sensors forming different Layers (left) and the table summarizing the parameters for each type of sensor (right).*

region that, due to the asymmetric beams, is characterised by the highest multiplicity of the tracks. In addition, in Layer 3 the sensors are smaller and contain more n-type strips than the sensors in layers 4-6. This also implies the readout pitch (distance between two readout strips) to be much smaller for p-side strips with respect to the n-side. To improve spatial resolution, a floating strip is placed between two readout strips on both P-and N-sides. The charge induced in the floating strip is shared by the neighboring strips and the effective strip pitch is reduced to half of the readout pitch. The right table of the Fig. 1 summarises the sensor parameters. SVD consists of 224 thousand readout strips and 172 sensors in total that correspond to 1.2 m^2 of active area.

2.1 Fornt-end electronics

For the readout we use APV25 chips [3] that for the central part of SVD (except for Layer 3) are attached directly to the DSSD sensors via flex circuits bent over the DSSD edge (origami concept). The rest of the readout uses hybrid boards located outside the active volume. There are 128 channels per chip and the amplifiers provide shaping time of 50 ns. Radiation hardness exceeds 100 Mrad and the power consumption of the apparatus is around 0.4 W/chip. The sampling frequency is 32 MHz and after the trigger's arrival we can collect 6 consecutive signal samples in total in the multi-peak mode. To account for higher luminosity in the future we have introduced so-called "3/6 mixed acquisition mode", which allows switching between three and six samples recorded on an event basis, based on the trigger type (and hence its time accuracy) for a particular event. This tool, already prepared and tested, allows to significantly reduce the data size, which can be crucial in the high background conditions.

3. SVD performance

Since the start of the operation we observed very smooth performance of the SVD without major problems and with very little number of masked strips (less than 1%). Moreover, the environment has been stable and the evolution of the calibration constants was consistent with expectation. Also, the effects of radiation damage are well under control.

Several quantities related to the SVD performance - efficiency, signal-to-noise ratio and both spatial and time resolution - are constantly monitored and so far they are at the very satisfactory level. Regarding SVD sensor efficiency, the values for all the sensors are typically over 99% and they are also very stable over the whole period of data taking. Clusters are formed from adjacent fired strips and the charge collected in a given cluster strongly depends on the incident angle of the track. Over time, we observe very similar cluster charge in all the sensors after the normalization to the track's length. For the n-type strips we observe 10-30% loss of the signal due to larger pitch. Another important variable in Signal-to-Noise Ratio (SNR), which is at the satisfying level for all 172 sensors, however, a small degradation is observed for the p-side due to larger noise, which is a consequence of the longer strip lenght and hence larger inter-strip capacitance. Apart from that, we see a small deterioration of the SNR with time due to radiation damage. On Fig. 2 the distributions of Cluster Charge (left) and SNR (right) are presented, where histograms representing the data accumulated in 2020 and 2022 are superimposed.

Both position and time resolution are also very important quantities for the high SVD performance. The position resolution measurement is based on the residuals (the clusters' positions

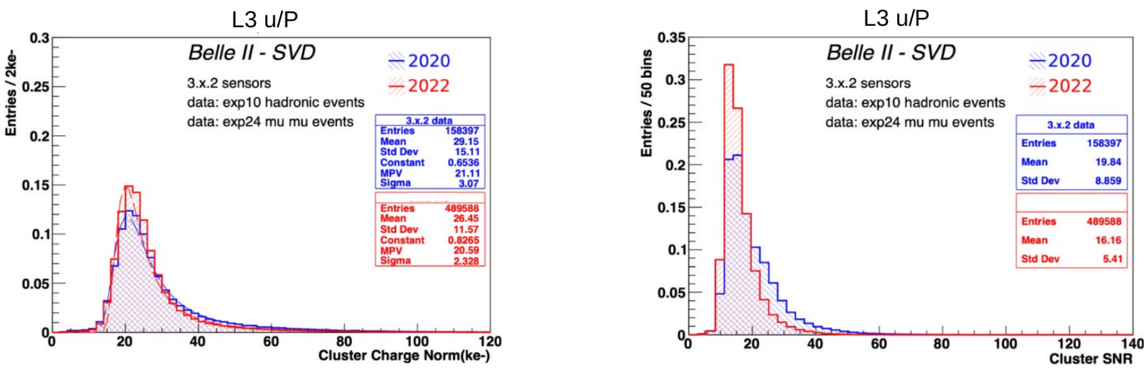


Figure 2: *Distribution of Cluster Charge (left) and Signal-to-Noise Ratio (right) for Layer 3 (p-side). Comparison between data taken in 2020 (blue) and 2022 (red) is presented.*

with respect to the intercept of the unbiased tracks' extrapolation) and it is evaluated with the large sample of $e^+e^- \rightarrow \mu^+\mu^-$ decays. As presented on Fig. 3, this variable depends on the incident angle and is very stable during the long period of the Belle II operation. As seen on the plot, the resolution for the n-side (left plot) is about two times worse with respect to the p-side, which is a result of different pitch.

Hit time resolution is measured with respect to the event time of the collision provided by Central Drift Chamber (CDC) and exhibits a very good resolution of less then 3 ns for the clusters associated to tracks. Using the average value of all the hits on a given track, so called "track-time" can be computed, slightly improving the time resolution. Furthermore, the "event-time" can be determined using all the clusters associated to selected tracks in the event. In such a way, the time of the event can be computed by the SVD with the resolution of the order of 1 ns, but around 2000 times faster with respect to the CDC. This feature is especially important in the higher luminosity environment, as it can significantly speed up the High Level Trigger (HLT) reconstruction process.

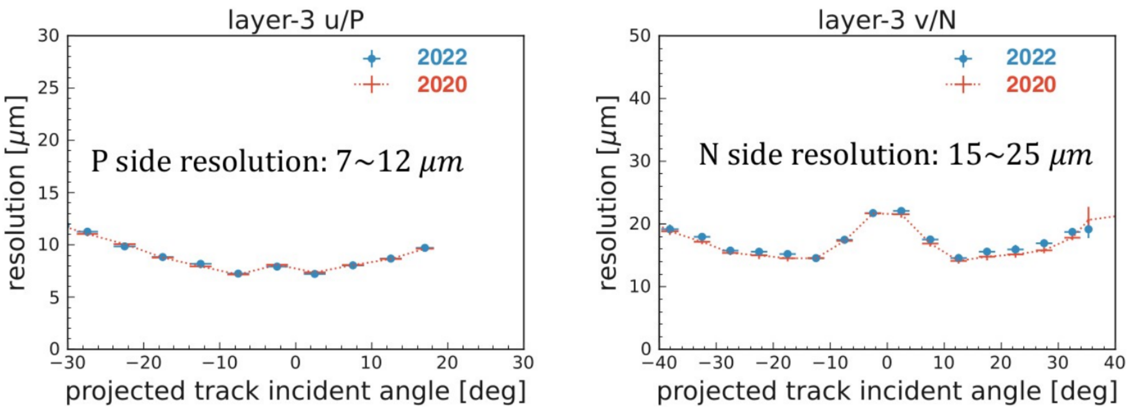


Figure 3: *Distribution of position resolution for p-side (left) and n-side (right) as a function of the incident angle. Comparison between data taken in 2020 (dots) and 2022 (dotted line) is presented.*

4. Radiation effects

In the high energy physics experiments, the radiation coming from the beams is a major factor that deteriorates the sensor performance with time, so the dose on SVD is constantly measured by, in particular, diamond sensors. There are several effects related to the radiation damage that have to be taken into account. Firstly, the leakage current is gradually increasing and, in general, its value shows a linear dependance on the accumulated dose (Fig. 4 left), that can be also expressed in the equivalent neutron fluence. So far, this increase has negligible contribution to the noise as the leakage current is still small and also due to short APV25 shaping time. This behaviour is consistent with the experience from the similar experiments (like BaBar) working with similar detectors and in comparable conditions. However, for the dose of ~6 Mrad we expect some impact on the strip noise and hence the deterioration in Signal-to-Noise ratio. The strip noise itself is dominated by the inter-strip capacitance and during the operation we have observed the increase of its value for about 20%(30%) for n-side(p-side), which is expected to be saturated (Fig. 4 center).

Another known effect of the radiation is an impact on depletion voltage. The high energy experiments usually carry out irradiation campaigns to observe the sensors' behavior after exposing them to high radiation. In case of Belle II such campaign has been conducted for SVD in July 2022 (ELPH, Tohoku University), where the effects of high radiation up to 10 Mrad (equivalent neutron fluence: $3 \times 10^{13} n_{eq}/cm^2$) have been checked. The decrease of the depletion voltage has been observed up to the point of type inversion, which occurred at 2 Mrad ($\sim 6 \times 10^{12} n_{eq}/cm^2$), after which the depletion voltage started to increase again (Fig. 4 right). It was confirmed that the sensors will still work well after the type inversion, which meets the expectation for these types of silicon detectors. Since the beginning of the detector operation we have not observed any change of the depletion voltage and we estimate the radiation levels to be of 0.35 Mrad/year ($8 \times 10^{11} n_{eq}/cm^2/year$) after extrapolating the background to the nominal luminosity. This ensures a wide safety margin for SVD even after 10 years of the operation at the target luminosity.

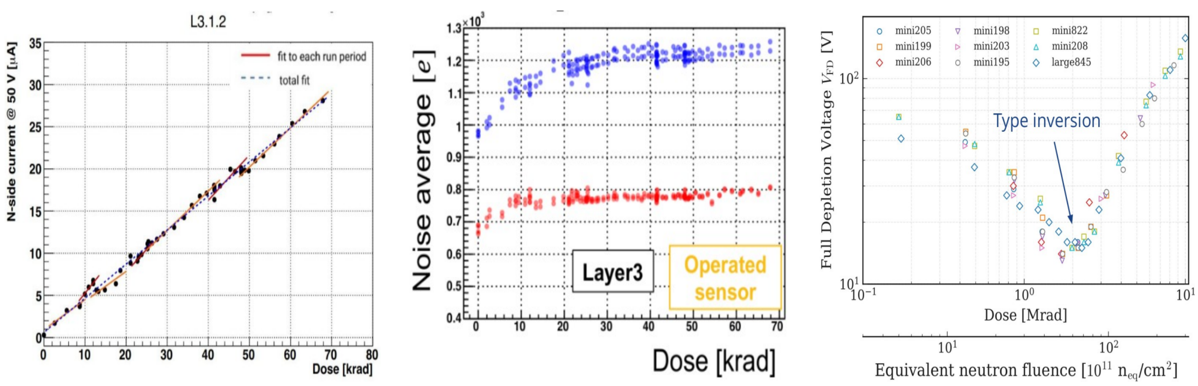


Figure 4: *Left plot: Leakage current as a function of the accumulated dose; Center plot: the average noise level as a function of accumulated dose for p-side (blue dots) and n-side (red dots); Right plot: full depletion voltage as a function of the accumulated dose with the type inversion observed at 2 Mrad.*

5. High background scenario and related software/hardware developments

An increase of the luminosity gives the effect of an increasingly larger beam background and hence higher occupancy in the SVD, the direct consequence of which is the deterioration of the tracking performance. So far, the average hit occupancy is 0.5% for Layer 3 and it is well under control. However, the background extrapolation for different future scenarios has been performed based on detailed simulations of the various contributions to the background (Beam-Gas, Toushek, etc.) and applying data/MC scale factors [4]. These studies predict that for the nominal luminosity we can reach the occupancy in Layer 3 very close to the limit of 4.7%, which is the upper limit that ensures good tracking performance. On the other hand, these predictions have large uncertainties originating from not well known machine evolution in the future with possible re-design of the interaction region. In the most conservative scenario, the Layer 3 occupancy can increase up to ~8.7%, which is far beyond the reasonable tracking performance. This situation motivates us for constant development in SVD reconstruction software, and, on the other hand, the considerations of the vertex detector upgrade [5], as the safety factor might be finally too small to ensure the good quality data. The technology assessment related to this hardware upgrade is currently ongoing.

The most important effort related to the software development is the utilization of the hit time information for SVD. The real signal hits come from well-triggered collisions, but the SVD acquisition window (~ 100 ns) is much wider with respect to the SuperKEKB bunch spacing (6 ns). Therefore, we need to cope with many off-time hits related to the beam-induced background or background from the other bunches. The current selection is based on two requirements: a) time difference between u and v cluster: $| t_u - t_v | < 20$ ns, and b) cut on the absolute value of the cluster time: $| t_{u,v} | < 50$ ns. These conditions reject the majority of the background hits keeping above 99% of the signal, and based on them the SVD occupancy limit for Layer 3 can be set at 4.7%. Recently, a more effective background suppression method has been developed in the form of so-called "SVD Grouping". It is based on event-by-event classification of the clusters by their time, so the clusters belonging to tracks from the same collisions are collected in the same group. Clusters from the different collisions or beam background will be placed in the other groups, so finally only the clusters belonging to the priority group will be used for the tracking. This feature reduces the fake rate (fraction of the fake tracks) by 16% for the high-background scenario. An additional fake rate reduction can be achieved by utilizing the selection on the track-time to reject off-time tracks. Finally, these improvements allow to increase SVD occupancy limit for Layer 3 from 4.7% to around 6%.

6. Activities during the Long Shutdown 1

Long Shutdown 1 started in May 2022 and its main goal was to upgrade the VXD detector with a new PXD. During the first data taking period, the second Layer of PXD consisted of two ladders only, so 5/6 of the azimuthal angle remained uncovered. The new PXD detector provides the full coverage, beneficial for more precise vertexing procedure. There were intense hardware activities for the VXD uninstallation and reinstallation: after the VXD extraction form Belle II, the SVD has been detached from the old PXD (May 16-17th, 2023), then the new PXD has been attached to the SVD (20-21st June, 2023) and finally the complete VXD has been installed in Belle II detector.

The whole delicate procedure went successfully without major problems or damages. In the period of September 12th - October 1st, 2023, the VXD commissioning has been performed to confirm the PXD and SVD performance, and also to check the impact from the increased PXD power consumption (and possible increase of the temperature) on the sensor current. From September 21st, several cosmic runs with no magnetic field have been taken to check the important quantities and compare them with corresponding ones for 2022 data samples. We observed no issues, in particular the noise distributions over the readout channels remain basically unchanged as well as Signal-to-Noise Ratio for the clusters associated to the tracks. Also, an excellent efficiency (>99%) for all the sensors is still observed.

7. Conclusions

To conclude, SVD has successfully operated since March 2019 with very smooth performance and without major problems. Its good vertexing quality has been confirmed by many physics measurements, in particular those related to the lifetime analyses (D^0, D_s, B^0, Ω_c^0, Λ_c). Some radiation damage effects were observed, but without any impact on the performance so far.

However, the extrapolated background level indicates that the occupancy in the SVD can exceed the current limit that guaranties good tracking performance. Hence, several software improvements are being implemented to account for the high background conditions. In particular, exploitation of the SVD hit time is of a major importance. Alongside, the VXD upgrade is also under discussion to increase robustness against high background and matching possible new interaction region.

The VXD reinstallation at Belle II with complete PXD detector has been successfully done during the Long Shutdown 1, followed by successful VXD commissioning with cosmic data. The beam operation is planned to be resumed in early 2024.

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