PROCEEDINGS OF SCIENCE

The Silicon Vertex Detector of the Belle II Experiment

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The Belle II experiment started data-taking in March 2019. The silicon vertex detector (SVD), part of the Belle II tracking system, has been operating smoothly and reliably. The data quality has been confirmed through various metrics such as a good signal-to-noise ratio and precise spatial resolution. The radiation damage effects have been continuously monitored, showing good agreement with our expectations. So far, no harmful impact due to the radiation damage on the detector performance has been observed. Additionally, the radiation tolerance of SVD sensors for future high-luminosity runs has been examined in a new irradiation campaign. In the high-luminosity runs, an increase in hit-occupancy is also expected due to the beam-induced backgrounds. To enhance the robustness of offline software in a high-background environment, new algorithms of background suppression using hit-time information have been developed.

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1. Introduction

The Belle II experiment [1] is a B-factory apparatus aiming at exploring new physics beyond the Standard Model of particle physics. It is operated at the SuperKEKB collider [2]. Most of the collision data are taken at the center-of-mass energy of the $\Upsilon(4S)$ resonance using asymmetric energy collision of 7 GeV electron and 4 GeV positron beams. By July 2022, Belle II has accumulated collision data corresponding to 424 fb^{-1}, and SuperKEKB has achieved the world's highest luminosity of $4.7 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. To reach the target instantaneous luminosity of $6 \times 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, machine operation continues to be improved.

The vertex detector (VXD) is the innermost tracking device of the Belle II detector. It consists of two inner layers of pixel detector (PXD) and four outer layers of silicon strip detector, known as the Silicon Vertex Detector (SVD) [3]. The primary purposes of the SVD are standalone tracking, particularly for low momentum tracks, extrapolation of tracks into the PXD, precise and efficient vertexing of K_S^0 and Λ^0, and charged-particle identification based on $\mathrm{d}E/\mathrm{d}x$. The SVD has been operating reliably and smoothly without major issues since its start of operation in 2019 by July 2022.

2. The Belle II Silicon Vertex Detector

The SVD consists of four detector layers, each equipped with double-sided silicon strip detectors (DSSDs) located at radii of 39, 80, 104, and 135 mm, referred to as Layer-3, 4, 5, and 6, respectively. Each detector layer comprises mechanically and electrically independent sensor modules known as ladders. The number of DSSDs on each ladder depends on the layer and ranges from two to five, resulting in a total of 172 DSSDs. These DSSDs have been fabricated on about 300 µm thick N-type bulk and readout strips are implemented orthogonally with either donors or acceptors on each sensor side, enabling them to provide two-dimensional spatial information. The strips on the side with acceptors, known as u/P strips, run parallel to the beam axis, while the strips with donors, v/N strips, are oriented transverse to the beam axis. The initial full depletion voltage ranges from 20 to 60 V and the operating voltage is typically 100 V.

The APV25 chip [4] is utilized for reading signals from a group of 128 strips. This chip is characterized by 50 ns shaping time and radiation hardness up to 100 Mrad, which meets the requirements for innermost Layer-3. In the SVD, the AVP25 chip operates at a clock frequency of 31.805 MHz, which is one-eighth of the SuperKEKB bunch-crossing frequency. In the present operation, six consecutive samples are read out upon the arrival of the Level-1 trigger to reconstruct the signal-peak height and hit-time. For the higher luminosity runs, a mixed-mode operation that uses either three or six samples has been developed to reduce the readout time and data size.

3. Detector Performance

The performance of SVD has been continuously monitored and consistent with expectations. The total fraction of masked strips due to defects is less than 1%. The hit efficiency exceeds 99% for all sensors.

The signal cluster charge and signal-to-noise ratio (SNR) are shown in Figure 1. The signal cluster charge is normalized by the track path length in the silicon to correct for the track's incidence angle. The most probable value (MPV) of the signal cluster charge for a minimum-ionising particle agrees with the expectation of approximately 24000 e^- within 15%, which is within the uncertainty from the APV25 gain calibration. The cluster SNR is an important figure-of-merit (FOM) defined as the total cluster charge divided by the quadratic sum of the noise from each strip in the cluster. All the 172 DSSDs exhibit excellent performance in the cluster SNR, with MPVs ranging from 13 to 30 depending on the incident angle using the 2022 data samples. Figure 1 further shows the stability between 2020 and 2022 data samples. Small changes in the cluster SNR are noticeable due to increased noise from the radiation damage, approximately 20-30% in Layer-3.

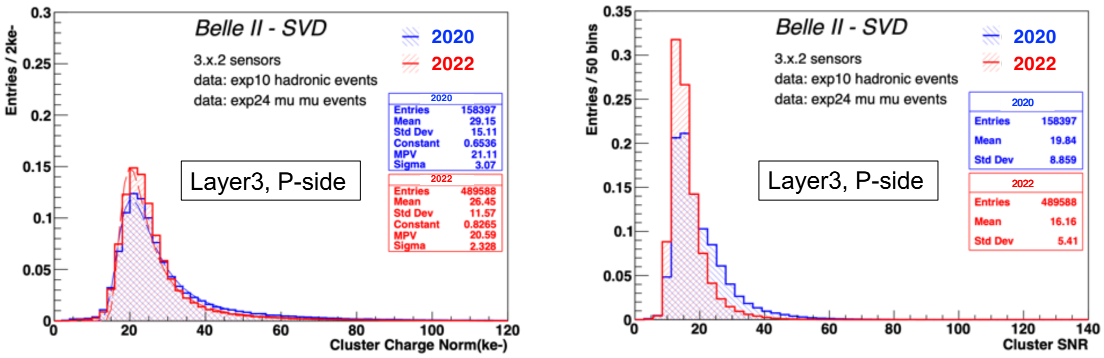

Figure 1: The signal cluster charge (left) and the cluster SNR (right) in u/P strips for one of Layer 3 sensors.

The cluster position resolution is estimated from the residual of the cluster position concerning unbiased track extrapolation, using $e^+e^- \to \mu^+\mu^-$ events. The resulting resolutions are within [7, 12] µm for u/P strips and [15, 25] µm for v/N strips, which are in good agreement with expectations. We have also confirmed the stability in the position resolution between 2020 and 2022 data samples.

4. Radiation damage

In this section, we discuss the radiation damage effect observed in the SVD sensors during the operation, as well as the results of an irradiation campaign on SVD sensors.

The radiation dose and sensor parameters are constantly monitored during the operation. The total integrated radiation dose on Layer-3 sensors is 70 krad, which corresponds to an equivalent 1-MeV neutron fluence of 1.6×10^{11} n_{eq}/cm^2, assuming the ratio of a neutron fluence to a radiation dose of 2.3×10^9 n_{eq}/cm^2/ krad based on MC simulation.

Furthermore, to evaluate the radiation tolerance of SVD sensors, we conducted a new irradiation campaign using a 90 MeV electron beam at the Research Center for Electron Photon Science (ELPH) at Tohoku University in Sendai, Japan. The maximum radiation dose reached 10 Mrad, equivalent to 3×10^{13} n_{eq}/cm^2. Considering the target luminosity of 6×10^{35} $cm^{-2}s^{-1}$, the expected radiation damage on Layer-3 sensors for one year is 0.35 Mrad and 8×10^{11} n_{eq}/cm^2. This expectation is still affected by a large uncertainty up to a factor of two, mainly due to the new design of the interaction region. Nevertheless, the radiation damage in this irradiation campaign corresponds to what the sensors will experience over many years of Belle II operation at the target luminosity.

As expected from the bulk damage described by the NIEL model [6], a linear increase in leakage current as a function of radiation damage is observed in the sensors. The damage constant, quoted in [μA/ cm^2/Mrad], is extracted from the slope of this dependency. From the irradiation campaign, we obtained a damage constant of 2.2 μA/ cm^2/Mrad at 24°C after annealing at room temperature for 1000 hours, which is consistent with measurements from the BaBar experiment [5]. In the installed SVD sensors, the measured damage constants typically range from 4 to 8 at room temperature, with significant variations due to temperature differences in different layers and variations in dose among sensors within the same layer. Due to the fast shaping time of the APV25 chip, the contribution of strip noise from leakage current is expected not to degrade SVD performance up to 6 Mrad, which is the anticipated dose during about 17 years of operation.

5. Improvements in offline software

One of the main challenges in SVD operation at high-luminosity is hit-occupancy. The current average hit-occupancy in Layer-3 is less than 0.5%. However, at the target luminosity, the average hit-occupancy is expected to be 4.7% due to an increase in beam-induced backgrounds.

The precise timing of hits is crucial for background suppression. The SVD hit-time resolution is less than 3 ns, which is much smaller than the time interval of beam-induced background events that typically occur at intervals of around 100 ns. Selections of SVD space-points, formed by combining clusters on u/P and v/N sides, based on the hit-time are effective in reducing the backgrounds. By requiring each cluster's hit-time to be within 50 ns of the event time and a hit-time difference between u/P and v/N clusters within 20 ns, it is possible to discard half of the background hits while retaining 99% of signal hits. The hit-occupancy limit after the selections is 4.7%, which is almost the same as the estimated values at the target luminosity. However, these selections provide no safety margin.

Two new algorithms exploit the hit-time information to enhance offline software robustness in the high-background environment. One method involves grouping SVD clusters using the hit-time information. Figure 2 shows the cluster time distribution in an event taken in 2022. 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. Notably, many background hits are within the 50 ns range, which cannot be eliminated with the hit-time selection. The cluster grouping method allows event-by-event classification and further background elimination. Another algorithm 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. These new algorithms allow us to set the hit-occupancy limit at around 6%. Further software improvement and optimization are planned. In addition to these software enhancements, a future upgrade of the detector is under study to improve tolerance to hit rates, considering the large uncertainty on background extrapolation, and to accommodate a possible new design of the interaction region that is currently under evaluation.

6. Conclusions

The Belle II SVD has been operating smoothly with excellent detector performance since March 2019. The first effects of radiation damage have been observed at the expected level, and the radiation tolerance of SVD sensors for the high integrated dose has been confirmed through a new

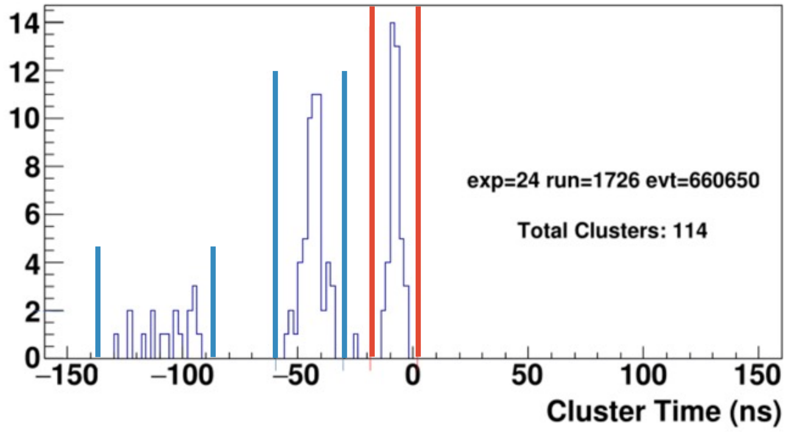

Figure 2: Cluster time distribution in an event taken in 2022.

irradiation campaign. In preparation for high-luminosity runs, efforts are underway to enhance the offline software robustness for high-hit occupancy.

During the Long Shutdown since July 2022, the VXD was upgraded. A new PXD, with a complete second layer, is installed within the existing SVD. The commissioning of the new VXD with cosmic rays began in September with the aim of resuming beam operation in December.

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