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Reinstallation and performance of the Belle II Silicon Vertex Detector

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At the beginning of 2024, the data taking of the Belle II experiment resumed after the long-shutdown 1, required to install a new two-layer DEPFET detector (PXD) and upgrade accelerator components. The whole silicon tracker (VXD) was extracted, the two halves of the outer strip detector (SVD) were split for the PXD insertion and reconnected again. The new VXD was commissioned for the start of the new run. We will describe the challenges of this VXD upgrade and report on the operational experience and the SVD performance obtained with this first-year data. We then introduce the various improvements in the reconstruction procedure, that exploit the excellent SVD hit-time resolution to enhance beam-induced background rejection and reduce track fake-rate, crucial aspects for the higher luminosity regime.

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1. Introduction

Belle II [1] is a high-intensity frontier experiment that operates at the SuperKEKB e^+e^- asymmetric-energy collider [2]. On June 2022, SuperKEKB delivered the luminosity of 4.7×10^{34} cm^{-2}s^{-1}, while the target luminosity is 6×10^{35} cm^{-2}s^{-1}. The Belle II detector consists of several sub-detectors arranged in a cylindrical structure around the e^+e^- interaction point (IP). The closest sub-detector to the IP is the vertex detector (VXD), which consists of two inner layers of pixel detector (PXD) made of DEPFET sensors, and four layers of silicon vertex detector (SVD) [3] made of double-sided silicon strip detectors (DSSD), whose main tasks are the extrapolation of the reconstructed charged particle trajectories (tracks) to PXD, and the standalone tracking and particle identification of low-p_T tracks. Diamond sensors, used both in the beam abort system and to measure the radiation dose on SVD, are installed on the beam pipe and SVD support cones [4].

Since the beginning of the operation in March 2019, Belle II integrated a luminosity of 531 fb^{-1}, with 427 fb^{-1} collected in Run 1 (2019–2022) and 104 fb^{-1} collected in Run 2 (2024–ongoing). Following the Run 1, from June 2022 to January 2024, there was a period of long shutdown (LS1) dedicated to maintenance and upgrades to both accelerator and detector; the main detector improvement was to complete the VXD with two new layers of PXD.

2. The Belle II Silicon Vertex Detector

The SVD consists of four layers, named 3, 4, 5 and 6 from the inner to the outer, which are composed of 7, 10, 12 and 16 mechanically and electrically independent sensor modules (ladders), hosting 2 to 5 sensors, respectively. For the ladder design, SVD adopts the chip-on-sensor concept [3]. The sensors in the forward end of layers 4 to 6 are slanted to better match the inclination of the forward tracks. The averaged material budget per layer is 0.7% radiation lengths.

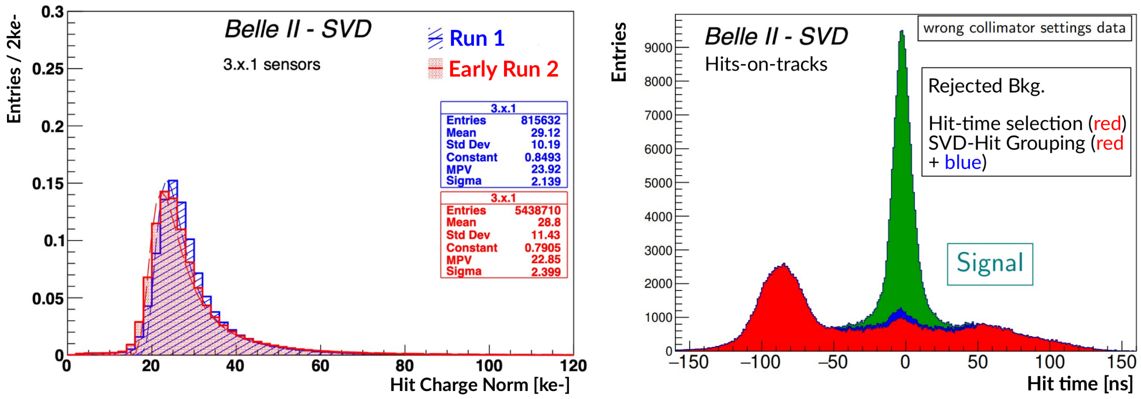
SVD has 172 DSSD sensors, covering a sensitive area of 1.2 m^2, with a total of 224k readout strips. The DSSD sensors are based on a n-type bulk, with p-doped strips on one side (p-side) and n-doped strips on the other (n-side). The p- and n-side strips are orthogonal, measuring the $r\phi$ position and the z coordinate respectively. Three types of sensors ~300 µm thick are used: small rectangular sensors for layer-3, trapezoidal sensors for the slanted sensors, and large rectangular sensors for the remaining. There are 768 (512) readout strips on the p-side of all three sensor types and on the n-side of small (large and trapezoidal) sensors. A floating strip is located between two adjacent readout strips to improve the hit-position resolution. On the n-side, the strip-pitches are 160 µm for small sensors, and 240 µm for large and trapezoidal sensors, while on the p-side they are 50 µm, 75 µm and 50–75 µm for small, large, and trapezoidal sensors, respectively.

The SVD front-end readout ASIC is the APV25, which is characterized by 128 input channels, a short shaping time of 50 ns, and a tolerance to radiation dose greater than 100 Mrad. APV25 chips are operated in multi-peak mode with a clock frequency of ~32 MHz, which is 1/8 of the SuperKEKB bunch-crossing frequency (254 MHz). Since the experiment is running at low luminosity and beam background levels, currently six subsequent analog samples are recorded to reconstruct the output waveform of each channel. To reduce bandwidth and data size with increased beam background expected at higher luminosity, a "3/6-mixed" acquisition mode that records either three or six samples has been developed and tested.

3. Operational experience and particle detection performance

The operation during both Run 1 and Run 2 has been reliable and smooth, without major problems. During Run 1, the total fraction of masked strips was less than 1%, mainly due to initial defects caused by the sensor production or the ladder assembly; the average occupancy in layer-3 was less than 0.5%; and the hit efficiency was greater than 99% and stable over time. Data collected in 2020 and 2022 confirmed the excellent SVD performance, showing a stable signal charge, signal-to-noise ratio (SNR) and position resolution, in agreement with the expectations. In particular, the signal charge distribution in layer-3 peaks at 21 ke^-, which is in agreement with the 24 ke^- expected for a minimum ionizing particle signal in a 320 μm thick sensor, taking into account an ∼15% of uncertainty in APV25 gain calibration. All SVD sensors show a SNR in the range 13–30, depending on the sensor position and side, with small changes observed due to the noise increase by radiation dose. The position resolution in layer-3 is within 7–12 μm on the p-side and 15–25 μm on the n-side, depending on the track incident angle and in line with the expectations due to the strip pitches. Finally, the SVD shows an excellent hit-time resolution in layer-3 of 2.9 ns and 2.4 ns for the p- and n-sides, respectively.

During the LS1, VXD was upgraded with a completely new two-layer PXD keeping the same SVD. This process required intense SVD-hardware activity with many crucial and delicate steps, in particular for the VXD deinstallation and reinstallation in the Belle II detector [5]. After each step, SVD test campaigns were performed to promptly spot problems, sanity check the detector performance, check the effect of temperature increase due to the complete PXD power consumption, and optimize the cooling condition to maintain the excellent SVD performance. The SVD performance observed in Run 1 has been confirmed with Run 2 data: no significant changes in signal charge and SNR have been observed, as shown in Figure 1a; and the hit efficiency remains greater than 99%. In Run 2 the background level is similar to Run 1. However, due to different trigger configurations, a higher SVD occupancy, less than 1%, has been observed.



(a) (b)

Figure 1: (a) Comparison of the signal charge normalized with the track path length and scaled to the sensor thickness obtained with Run 1 and Run 2 data, for all forward sensors of layer-3. (b) Hit-time distribution in data with particularly high background due to wrong collimator settings. Only the hits in the green peak are used for tracking, while the hits in the red and blue regions are rejected by the hit-time selections.

4. Offline software developments towards high luminosity

Over the next years, SuperKEKB instantaneous luminosity is expected to increase to target luminosity. This will result in a larger beam background, thus in a larger SVD occupancy that can deteriorate the tracking performance. From the simulation of the different contributions to the beam background [6], we can extrapolate the SVD occupancy for different future scenarios. At target luminosity, the SVD occupancy limit, above which the tracking performance significantly deteriorates, is 4.7% in layer-3. However, in the most conservative scenario, the occupancy level could reach 8.7% in layer-3, which is far beyond the limit. For this reason, considerable efforts have been made to improve SVD reconstruction software by exploiting the excellent SVD hit-time resolution.

When a collision is triggered, the samples obtained from the APV25 output waveform are recorded. The SVD acquisition window is ∼200 ns wide in the six-sample acquisition mode. SuperKEKB is a quasi-continuous machine, where a bunch crossing happens every ∼4 ns, while the maximum trigger frequency is 30 kHz, thus many bunch crossings happen before and inside the SVD acquisition window. The signal of the off-time particles hitting the SVD sensors before the triggered collision can stay over threshold for several bunch crossings due to the $\mathcal{O}\,(100)$ ns tail of the APV25 output waveform. In addition, background hits can also be produced by beam-induced background particles hitting the sensors randomly over time. The SVD hit time is obtained from the APV25 sampled response in the SVD acquisition window. Thanks to the excellent hit-time resolution, we can use it to reject off-time particle hits, which allows rejection of the corresponding off-time tracks thus improving track quality.

Figure 1b shows the distribution of the hit time $t_{\rm hit}$ in data with particularly high background. The hits from particles produced in the triggered collision are expected to accumulate at ∼0 ns, the hits of the particles produced in collisions that occurred before the triggered collision accumulate at approximately -80 ns, and the hits from beam-induced background are almost uniformly distributed. The current selection $|t_{\rm hit}| < 50$ ns and $|t^{p}_{\rm hit} - t^{n}_{\rm hit}| < 20$ ns, where $t^{p}_{\rm hit}$ and $t^{n}_{\rm hit}$ represent the hit time of p- and n-side hits respectively, rejects about 50% of the background hits while keeping the signal efficiency greater than 99%. This selection, which has been tested but not yet used in data reconstruction because the occupancy level is still low, allows the SVD occupancy limit for layer-3 to be set at 4.7%. Additional background rejection can be obtained by applying the SVD-hit *grouping* algorithm [7], which is an event-by-event classification of SVD hits into groups based on their time. Hits coming from the same collision are expected to have similar times and thus are associated to the same group, while hits coming from different collisions or beam background belong to different groups. Only groups of hits with a time compatible with the triggered collision are used in tracking reconstruction. The *grouping* algorithm reduces the fake-track rate by an additional 15% in the high-background scenario. In Figure 1b, the red region is the distribution of hits rejected by applying the current hit-time selection, while the sum of the red and blue regions is the distribution of hits rejected by applying the *grouping* algorithm. The green region is the distribution of hits used for tracking, obtained after applying the hit-time-based selections. Finally, the hit time can also be used to compute the track time, which is obtained combining the time of the SVD hits associated with the track. From preliminary studies, a selection based on the track time allows further reduction of the fake-track rate by a factor of 1.5 in high-background scenario. These improvements allow an increase of the SVD-occupancy limit in layer-3 from 4.7% to 6%. However, due to the large uncertainties in the possible future evolution of the machine and interaction region (IR), a conservative extrapolation of the occupancy level in layer-3 shows it would exceed 6%, which opens the discussion about a possible upgrade of the vertex detector [8].

5. Conclusions

Since March 2019, SVD is delivering high-quality data, showing excellent and stable performance: high SNR, precise position and time resolutions, and a high hit-efficiency greater than 99%. In 2023, during LS1, VXD has been upgraded with a completely new two-layer PXD. The excellent SVD performance observed in Run 1 has also been confirmed with Run 2 data, and the effects of radiation damage observed so far are in line with expectations without affecting the SVD performance. Over the next few years, the machine luminosity will increase, and so will do the background level at which the detectors will operate. Extrapolations of background level at target luminosity show that SVD occupancy could exceed the current limit that ensures good tracking performance. For this reason, the SVD reconstruction software has been made robust against background by exploiting the excellent hit-time resolution, which allows efficient rejection of off-time background hits, setting the layer-3 occupancy limit to ~6%. Despite the high performance and the robustness of the system, an upgrade of the VXD during a second long-shutdown is under study to account for possible future machine evolution and redesign of the interaction region.

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