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Review

The silicon vertex detector of the Belle II experiment

A. Gabrielli [l,m,*], K. Adamczyk [r], H. Aihara [p], S. Bacher [r], S. Bahinipati [e], J. Baudot [d], P.K. Behera [f], S. Bettarini [j,k], T. Bilka [b], A. Bozek [r], F. Buchsteiner [a], G. Casarosa [j,k], L. Corona [k], S.B. Das [g], G. Dujany [d], C. Finck [d], F. Forti [j,k], M. Friedl [a], B. Gobbo [m], S. Halder [i], K. Hara [q,n], S. Hazra [i], T. Higuchi [o], C. Irmler [a], A. Ishikawa [q,n], Y. Jin [m], M. Kaleta [r], A.B. Kaliyar [a], J. Kandra [b], K.H. Kang [o], P. Kodyš [b], T. Kohriki [q], R. Kumar [h], K. Lalwani [g], K. Lautenbach [c], R. Leboucher [c], J. Libby [f], L. Martel [d], L. Massaccesi [j,k], G.B. Mohanty [i], S. Mondal [j,k], K.R. Nakamura [q,n], Z. Natkaniec [r], Y. Onuki [p], F. Otani [o], A. Paladino [j,k,1], E. Paoloni [j,k], K.K. Rao [i], I. Ripp-Baudot [d], G. Rizzo [j,k], Y. Sato [q], C. Schwanda [a], J. Serrano [c], T. Shimasaki [o], J. Suzuki [q], S. Tanaka [q,n], F. Tenchini [j,k], R. Thalmeier [a], R. Tiwary [i], T. Tsuboyama [q], Y. Uematsu [p], L. Vitale [l,m], Z. Wang [p], J. Wiechczynski [r], H. Yin [a], L. Zani [c,2], F. Zeng [o], Belle-II SVD Collaboration

[a] *Institute of High Energy Physics, Austrian Academy of Sciences, 1050 Vienna, Austria*
[b] *Faculty of Mathematics and Physics, Charles University, 121 16 Prague, Czech Republic*
[c] *Aix Marseille Université, CNRS/IN2P3, CPPM, 13288 Marseille, France*
[d] *IPHC, UMR 7178, Université de Strasbourg, CNRS, 67037 Strasbourg, France*
[e] *Indian Institute of Technology Bhubaneswar, Bhubaneswar 752050, India*
[f] *Indian Institute of Technology Madras, Chennai 600036, India*
[g] *Malaviya National Institute of Technology Jaipur, Jaipur 302017, India*
[h] *Punjab Agricultural University, Ludhiana 141004, India*
[i] *Tata Institute of Fundamental Research, Mumbai 400005, India*
[j] *Dipartimento di Fisica, Università di Pisa, I-56127 Pisa, Italy*
[k] *INFN Sezione di Pisa, I-56127 Pisa, Italy*
[l] *Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy*
[m] *INFN Sezione di Trieste, I-34127 Trieste, Italy*
[n] *The Graduate University for Advanced Studies (SOKENDAI), Hayama 240-0193, Japan*
[o] *Kavli Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwa 277-8583, Japan*
[p] *Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*
[q] *High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*
[r] *H. Niewodniczanski Institute of Nuclear Physics, Krakow 31-342, Poland*

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ABSTRACT

The silicon vertex detector (SVD) is a four-layer double-sided strip detector installed at the heart of the Belle II experiment, taking data at the high-luminosity *B*-Factory SuperKEKB since 2019. SVD has been operating smoothly and reliably, showing a stable and above-99% hit efficiency, and a large signal-to-noise ratio in all sensors. In June 2022 the data-taking of the Belle II experiment was stopped for the Long Shutdown 1, primarily required to complete the vertex detector (VXD) with the inner two-layer DEPFET detector and to upgrade several components of the accelerator. This article reports on the excellent performance of SVD in terms of the signal-to-noise ratio, the hit position resolution, as well as the hit-time resolution. We briefly describe the challenges and delicate phases of the VXD re-installation and the SVD status for operation starting in early 2024. In SVD layer 3, which is closest to the interaction point, the average occupancy has been less 0.5%, well below the estimated limit for acceptable tracking performance. However, higher machine backgrounds are expected at increased luminosity, and so also increased hit occupancy. To enhance the robustness of offline software in a high-background environment, new algorithms of background suppression using the excellent

* Corresponding author at: Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy.
E-mail address: alice.gabrielli@ts.infn.it (A. Gabrielli).
1 Presently at INFN Sezione di Bologna, I-40127 Bologna, Italy.
2 Presently at INFN Sezione di Roma Tre, I-00185 Roma, Italy

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SVD hit-time information have been developed, which allows a significant reduction of the fake rate, while preserving the tracking efficiency.

With the increasing luminosity also the radiation levels are expected to increase, with possible deterioration of the sensor performance. The SVD integrated dose is estimated by the correlation of the SVD occupancy with the dose rate measured by the diamonds of the radiation monitor and beam-abort system.

The effects of radiation damage are starting and in good agreement with our expectations. So far, no harmful impact due to the radiation damage on the detector performance has been observed.

1. Introduction

The Belle II experiment [1] is a B-factory dedicated to the search for new physics beyond the Standard Model at the intensity frontier, aiming at high-precision measurements of the properties of the heavy quarks and the tau lepton. It operates at the SuperKEKB collider [2], which provides asymmetric collisions with 7 GeV electrons and 4 GeV positrons. The majority of the collisions take place at the centre-of-mass energy of the $\Upsilon(4S)$ resonance. By July 2022, Belle II has accumulated collision data corresponding to 424 fb^{-1}, and SuperKEKB has reached the world's highest luminosity of $4.7 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. To reach the target instantaneous luminosity of $6\times10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, the operation of the machine will be further improved, with the target that Belle II collects $50\,\mathrm{ab}^{-1}$ of data in the next decade. The Belle II vertex detector (VXD) is the tracking detector closest to the interaction point. It consists of 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].

SVD extrapolates the measured tracks to the PXD, defining the so-called region of interest, which significantly reduces the amount of data recorded by PXD, but it also performs standalone tracking for low momentum particles and contributes to the charged-particle identification by providing energy-loss information (dE/dx). PXD was only partially installed in 2018 and its second layer covered only 1/6th of the azimuthal angle. In 2022 the VXD was re-installed with a new complete PXD and the same SVD.

A detailed description of the SVD and its performance until 2022 is given in Sections 2 and 3, respectively. Section 4 outlines the main challenges and results of the VXD re-installation. Finally, in Section 5, the main software improvements and radiation studies towards an high luminosity scenario are summarised.

2. Belle II silicon vertex detector

The SVD consists of four detector layers, as shown in Fig. 1, 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 layer is made of ladders, which are mechanically and electrically independent sensor modules, hosting 2 to 5 sensors with their readout chips and cooling support. A total of 172 DSSDs are arranged around the beam direction with a windmill-like structure that allows a partial overlap of the sensor's active regions. To cope with the inclination of the forward tracks as well as to minimise the material traversed in the forward part, a lantern-like geometry was adopted for the forward end of the three outer layers of SVD, whose detectors are inclined with respect to the cylinder axis.

These DSSDs consist of an N-type silicon substrate ~300 μm thick with P-type strips implanted on one side, and orthogonal N-type strips implanted on the other side, providing two-dimensional spatial information. The strips on u/P side are orientated in parallel to the beam axis, measuring the $u = r\phi$ position, while the ones on v/N side are transverse to the beam axis and provide the $v = z$ coordinate. The readout strips are AC coupled and there is a floating strip between two adjacent readout strips to improve the resolution on the hit position. In layer 3 the DSSDs have a strip pitch of 50 μm on u/P side and 160 μm on v/N side, while in layers 4, 5 and 6 sensors with a pitch of 75 μm on u/P side and 240 μm on v/N side are used. The initial full depletion voltage ranges from 20 to 60 V and the operating voltage is typically 100 V.

The signals from a group of 128 strips are processed by the APV25 [5] front-end chip, which has a typical "preamplifier-shaper" architecture. This chip is characterised by short shaping time of 50 ns and radiation hardness up to 100 Mrad, which meets the requirements for the high particle rate from beam-induced background expected on the innermost layer 3. The pulse height of the shaper output is sampled at a clock frequency of 32 MHz, which is 1/8th of the SuperKEKB bunch-crossing frequency. By default, APV25 operates under the "multi-peak" mode, outputting six successive samples upon receiving a level-1 trigger, to reconstruct the signal-peak height and hit time. To reduce the readout time and data size in higher luminosity runs, a "3/6-mixed" acquisition mode that uses either three or six samples has been developed and tested.

3. SVD operation and reconstruction performance

Since the beginning of operations in March 2019, SVD has operated smoothly and stably without any major issues, with a very good performance that has been continuously monitored and is in line with expectations. Less than 1% of the total strips are masked, mainly due to initial defects caused by the sensor production or the ladder assembly, and the hit efficiency exceeds 99% for all sensors and is stable over time.

Data collected in 2020 and 2022 show similar results, which are compatible and in line with expectations. Even if the first effects of radiation damage are observed, they are well under control and do not affect the reconstruction performance. The distribution of the cluster charge released in the sensors in layer 3 u/P-side and v/N-side, renormalised to the track length to account for the different track incident angle, is similar in all the sensor and with a most probable value of 21 ke^-. Taking into account the 15% uncertainty from the APV25 gain calibration, this result is consistent with the expected 24 ke^- for a minimum ionising particle signal in the 320 μm thick sensor.

The cluster signal-to-noise-ratio (SNR), defined as the total charge collected in the cluster divided by the square-root of the quadratic-sum of the noises in the strips associated with that cluster, has a most probable value (MPV) between 13 to 30, depending both on the sensor position, due to the different track incident angle, and the side, with u/P side's longer strips having higher noise.

A small reduction in the cluster SNR has been observed in the 2022 data, as shown in Fig. 2, due to increased noise of about 20%–30% in layer 3 caused by the irradiation damage. The noise value is consistent with the expectations from the irradiation campaigns described in Section 5 and shows a saturation.

The cluster position resolution is estimated from the residual of cluster position against unbiased track extrapolation using $e^-e^+ \rightarrow \mu^-\mu^+$ events [6]. The resolutions are 7 to 12 μm for u/P strips and 15 to 25 μm for v/N strips, which are in good agreement with expectations. The SVD offers an excellent hit time measurement of 2.9 ns (2.4 ns) for the u/P (v/N) side. The hit-time resolution is measured from the residuals of the hit time with respect to the time of the $e^-e^+ \rightarrow \mu^-\mu^+$ collision calculated by other detectors with very good time resolution ($\lesssim$1 ns).

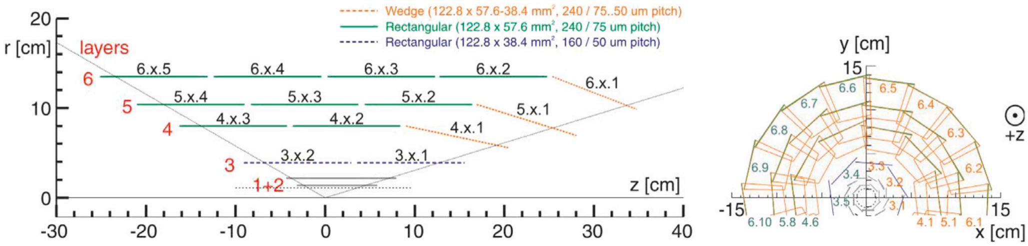

Fig. 1. Schematic view of the position of SVD layers and sensors.

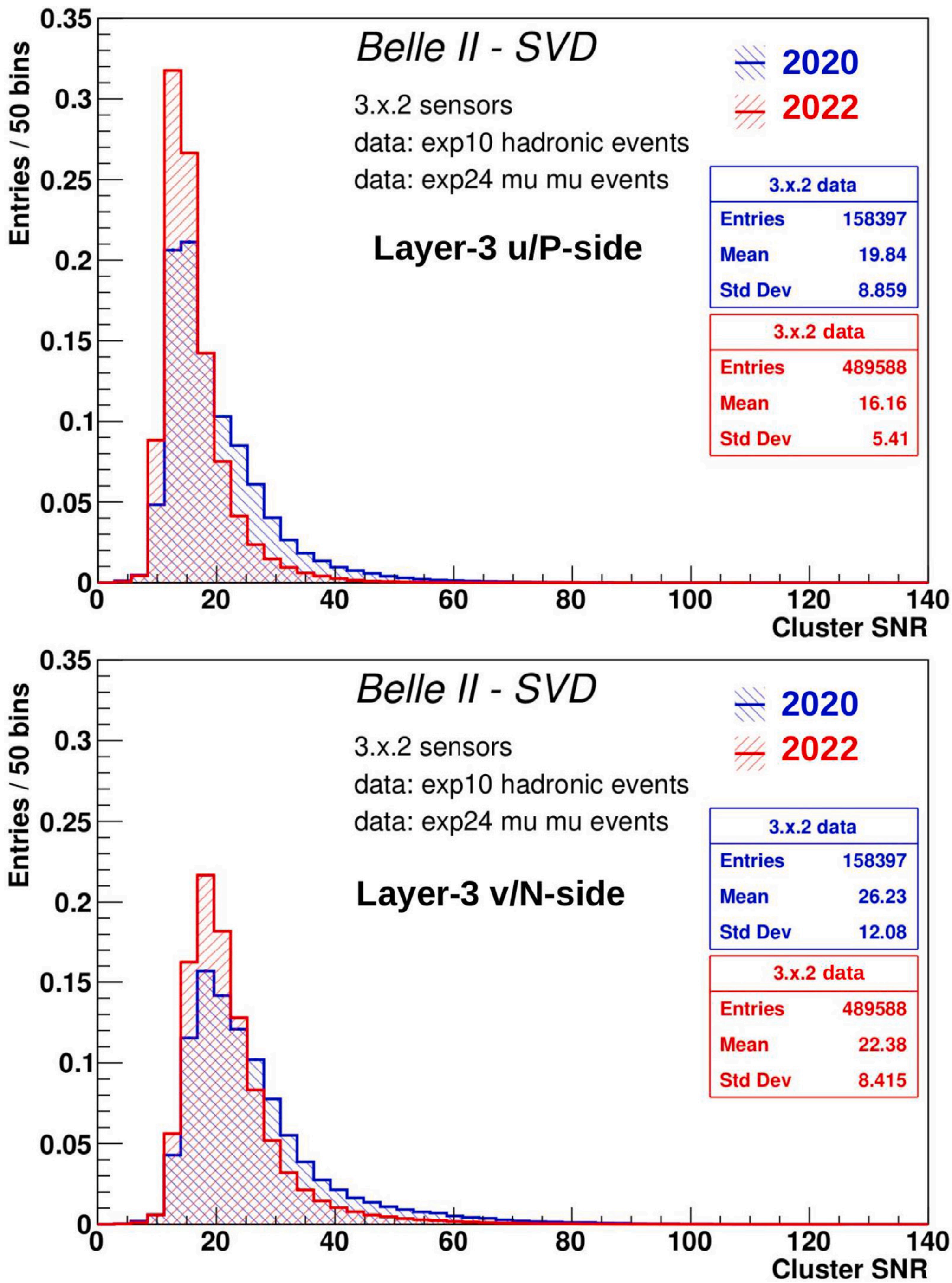

Fig. 2. Cluster SNR distribution for layer 3 u/P side (top) v/N side (bottom) for data collected in 2020 (exp10 data, in blue) and 2022 (exp24 data, in red). In the plots, the MPVs are approximately 15 (u/P side) and 18 (v/N side) for the 2020 data.

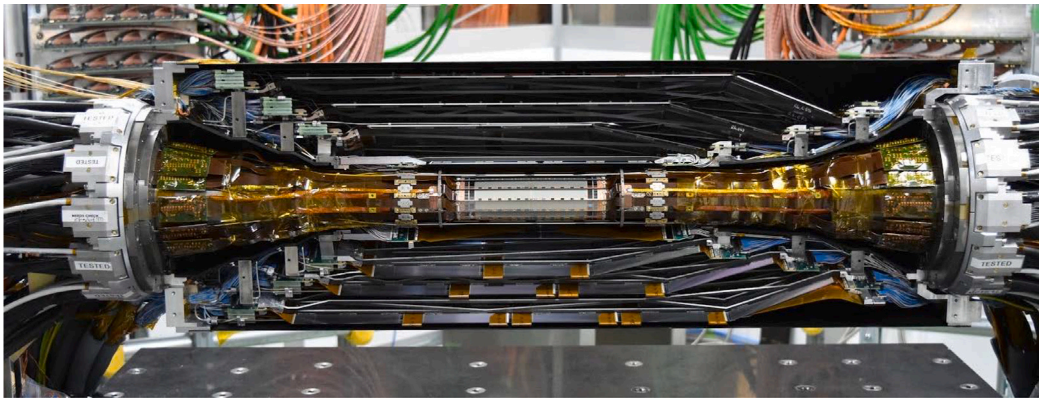

Fig. 3. Picture of the first SVD half-shell attached to PXD2.

4. VXD re-installation during LS1

Following the data taking period called *Phase 3 run 1* (2019–2022), a long-term shutdown period, LS1, began in July 2022, during which the completeness and robustness of present Belle II of the accelerator has been improved. The PXD installed for *run 1* was only partially completed. The main reason for this long shutdown was to complete the vertex detector with two full layers of pixel detectors and the same SVD.

This complex process spanned several months and involved a multitude of sequential steps and extensive testing of the detectors and the environmental monitoring system, to ensure the healthiness of the system after each step. The milestones are reported in Table 1. The VXD was extracted from Belle II in May 2023, after the successful installation of PXD2 on a new beam pipe, and moved to the clean room. Then the SVD was detached from the old PXD and a standalone SVD commissioning was performed to ensure the healthiness of all the sensors. Subsequently the SVD was attached to the new PXD2. Fig. 3 shows a photo of the SVD half-shell and the full PXD2 after the attachment of the first half-shell.

After the installation of the new VXD in Belle II in July 2023, a commissioning was performed to confirm the performance of the PXD and SVD and check the effect of the increased power consumption of the PXD and the possible increase in temperature on the sensor leakage current. Starting in September, several cosmic runs were made without a magnetic field to check performance and compare with data samples from the 2022 cosmic run. No problems were observed, and both noise and SNR distribution remain essentially unchanged. Also the same good efficiency as before LS1 is still observed for all sensors. The entire re-installation was successfully completed without any major problems or damage, and the beam operation resumed in January 2024.

Table 1
Summary of the main VXD re-installation and commissioning activities during 2023's LS1.

Start date	Activity	
May, 10th	VXD extraction	Belle II
May, 17th	SVD detachment	
June, 1st	SVD commissioning	clean
June, 28th	New VXD assembly	room
July, 14th	New VXD commissioning	
July, 28th	New VXD installation	
Sept, 22nd	VXD functional tests & commissioning with cosmic-ray	Belle II

5. Towards high luminosity scenario

Each increase in luminosity results in a larger beam background, thus higher occupancy in the SVD. The direct consequence is a deterioration in tracking performance. So far, the average hit occupancy is 0.5% for layer 3, which does not degrade tracking performance. The background extrapolation for different future scenarios is obtained from detailed simulations of the various contributions to the background (beam gas, Toushek, etc.) [7]. These simulations show that for the nominal luminosity we can reach an occupancy in layer 3 very close to the limit of 4.7%, above which the tracking performance deteriorates significantly.

One of the main challenges at high luminosity is to deal with the high detector occupancy, which affects the reconstruction performance. On the other hand, these predictions have large uncertainties due to the poorly known future evolution of the machine, with possible redesign of the interaction region. In the most conservative scenario, layer 3 occupancy can increase up to ~8.7%, which is far beyond reasonable tracking performance. For this reason, considerable effort has been put into the development of the SVD reconstruction software over the last months. A great effort is given by the use of the hit time information from the SVD. Even if the real signal hits come from well-triggered collisions, the SVD acquisition window (~100 ns) is much wider compared to the SuperKEKB bunch spacing (6 ns), and in this time window we have to deal with many off-time hits related to the beam-induced background or background from the other bunches. One way to reduce the off-time tracks is to apply a hit-time selection that takes advantage of the excellent hit-time resolution of SVD (<3 ns). With the current selection, which requires that the time difference between the P-side and N-side clusters, $|t_p - t_n| < 20$ ns, and a requirement on the absolute value of the cluster time, $|t_{p;n}| < 50$ ns, about 50% of the background hits are rejected while keeping the signal efficiency above 99%. This selection has been tested and allows the SVD occupancy limit for layer 3 to be set at 4.7%, but it is not yet used in real data reconstruction because the actual occupancy level is still low.

Another suppression method called “SVD grouping” has been developed to further increase the occupancy limit. The method consists of classifying the clusters event-by-event by their time: in this way, clusters belonging to tracks from the same collisions are collected in the same group, while clusters from different collisions or beam background are placed in the other groups. Thanks to this feature, it is possible to reduce the fake rate by 16% for the high background scenario. An additional fake rate reduction of a factor of 1.5 can be achieved by rejecting the off-time tracks by selecting the track time, *i.e.*, the time calculated by combining the hit time associated with the track. Thanks to these further improvements, the SVD occupancy limit for layer 3 can be increased from 4.7% to around 6%. However, due to the large uncertainties related to possible future developments of the machine and the interaction region, a conservative extrapolation of the occupancy level on layer 3 also exceeds the 6% level, opening the discussion about a possible upgrade of the vertex detector [8].

In addition to the higher hit occupancy expected at the nominal luminosity, also the radiation level will increase, with an estimated radiation level of 0.35 Mrad/yr, corresponding to an equivalent neutron fluence of 8×10^{11} $n_{eq}/cm^2/yr$. The SVD dose is constantly monitored by 28 diamond detectors installed on the VXD and by the SVD hit occupancy. However the integrated radiation dose can deteriorate the sensor performance with time, such as an increase of the leakage current and strip noise, and a changing of the depletion voltage. Since the beginning of operations in 2019, the total integrated dose on layer 3 is less than 70 krad (1.6×10^{11} n_{eq}/cm^2) and the first effects of radiation damage are observed. The strip noise, which is expected to be saturated, is dominated by the inter-strip capacitance and increased by around 20% (30%) for N-side (P-side) during operation. 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 both the still small leakage current and short APV25 shaping time. However, a deterioration in SNR is expected for the dose of about 6 Mrad. No changes to the depletion voltage are measured so far, suggesting that bulk damaged effects are not observed.

In-depth studies on the effects of radiation damage on our sensors have been carried out with several irradiation campaigns. In July 2022, an irradiation campaign was performed at ELPH, Tohoku University, with a 90 MeV electron beam, for an integrated dose up to 10 Mrad (equivalent neutron fluence of 3×10^{13} n_{eq}/cm^2). The depletion voltage was observed to decrease up to the point of type inversion at 2 Mrad (6×10^{12} n_{eq}/cm^2), after which the depletion voltage started to increase again. The tests confirmed that the sensors continue to work well after type inversion, which is in line with expectations for these types of silicon detectors. These results provide a large safety margin for SVD even after 10 years of operation at target luminosity.

6. Conclusions

Since the starting of operation in March 2019, SVD has consistently delivered high-quality data for Belle II. With exceptional performance characterised by high SNR, precise position resolution and accurate time resolution, the SVD has met and exceeded expectations. Despite the expected effects of radiation damage, the observed effects remain within expected parameters, with no significant degradation in SVD tracking performance so far. In 2023, during the first long shutdown, a new VXD was successfully re-installed, incorporating the full PXD2 together with the existing SVD. Despite the many delicate steps in this operation, the post-installation commissioning of this upgraded VXD, validated by cosmic ray studies, was successfully completed and operations resumed in January 2024. Over the next few years, it is expected that the luminosity will increase to the target value, thereby increasing the background level at which the detector will operate. The extrapolated background level from simulations indicates that the occupancy in the SVD may exceed the current limit that ensures good tracking performance. Extensive improvements to the reconstruction software and radiation hardness studies have been carried out to prepare for the high luminosity scenario. New background rejection methods that exploit the good time resolution of SVD and new event-by-event grouping classification of clusters, improve the software robustness against high background data, setting the occupancy limit for layer 3 up to ∼6%. Moreover, the results of irradiation campaign show that the SVD is safe even after 10-years' operation regarding the radiation damage. Despite the robustness of the system, a VXD upgrade during the second long shutdown of Belle II is under discussion due to possible future machine evolution and redesign of the interaction region.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] T. Abe, et al., Belle-II Collaboration, Belle II Technical Design Report, 2010, arXiv:1011.0352.
[2] Y. Ohnishi, et al., PTEP 2013 (2013) 03A011.
[3] P. Avella, in: P. Govoni, P.S. Marrocchesi, F.-L. Navarria, M. Paganoni, A. Perrotta, T. Rovelli (Eds.), JINST 9 (01) (2014) C01057.
[4] K. Adamczyk, et al., Belle-II SVD Collaboration, JINST 17 (11) (2022) P11042, arXiv:2201.09824.
[5] M.J. French, et al., in: T. Ohsugi, Y. Unno, H.F.W. Sadrozinski, I. Nakano (Eds.), Nucl. Instrum. Methods A 466 (2001) 359–365.
[6] R. Leboucher, et al., Belle-II SVD Collaboration, Nucl. Instrum. Methods A 1033 (2022) 166746, arXiv:2209.03006.
[7] A. Natochii, et al., Nucl. Instrum. Methods A 1055 (2023) 168550, arXiv:2302.01566.
[8] M. Babeluk, et al., Belle II VTX Collaboration, Nucl. Instrum. Methods A 1048 (2023) 168015.