Belle II Silicon Vertex Detector (SVD)

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Abstract. The Belle II experiment at the SuperKEKB collider in Japan will operate at an unprecedented luminosity of 8×10^{35} cm^{-2}s^{-1}, about 40 times larger than its predecessor, Belle. Its vertex detector is composed of a two-layer DEPFET pixel detector (PXD) and a four layer double-sided silicon microstrip detector (SVD). To achieve a precise decay-vertex position determination and excellent low-momentum tracking under a harsh background condition and high trigger rate of 10 kHz, the SVD employs several innovative techniques. In order to minimize the parasitic capacitance in the signal path, 1748 APV25 ASIC chips, which read out signal from 224k strip channels, are directly mounted on the modules with the novel Origami concept. The analog signal from APV25 are digitized by a flash ADC system, and sent to the central DAQ as well as to online tracking system based on SVD hits to provide region of interests to the PXD for reducing the latter's data size to achieve the required bandwidth and data storage space. Furthermore, the state-of-the-art dual phase CO_2 cooling solution has been chosen for a combined thermal management of the PXD and SVD system. In this proceedings, we present key design principles, module construction and integration status of the Belle II SVD.

1 Introduction

1.1 SuperKEKB

The Belle II experiment [2] is an intensity frontier flavor-factory experiment that will operate at the SuperKEKB e^+e^- collider [1] at the KEK laboratory in Tsukuba, Japan. The primary goals of the experiment are to search for new sources of CP violation in decays of B and D mesons, which in turn requires precise determination of decay vertices of B mesons and tagging of D mesons from the charge of low-momentum pions in $D^{*\pm} \rightarrow D^0\pi^{\pm}$, and to indirectly look for physics beyond the standard model by studying super-rare decays [3]. The accelerator facility of KEKB will be upgraded to SuperKEKB, that will run at the same centre-of-mass energy of 10.58 GeV, with a reduced boost of 0.28 as compared to KEKB. In order to achieve the desired physics goals, Belle II envisions to collect an integrated luminosity of 50 ab^{-1}. The design peak luminosity 8×10^{35}cm^{-2}s^{-1} is 40 times larger than the world record achieved by Belle. The Belle II detector was successfully "rolled-in" without the vertex detector happened on April 11, 2017. The commissioning of the main ring of SuperKEKB started in February 2016.

1.2 Belle II

Belle II detector [4] is a multipurpose instrument, which covers a large solid angle and has capability for a precise vertex reconstruction and momentum determination, good pion-kaon separation, and excellent neutral particle identification. Since high luminosity will warrant high backgrounds and event rates, Belle II detector has to run under harsh conditions. Therefore, all its sub-detectors need to be upgraded in order to be able to function at these conditions. The upgraded detector includes a vertex detector with two pixel and four strip layers, a drift chamber with long lever arm and small cells, a particle identification system based on Cherenkov detectors, a fast electromagnetic calorimeter and a muon detector. Belle II expects to have its first physics run in Fall 2018.

2 SVD Overview

Similar to its predecessor, SuperKEKB will be an asymmetric e^+e^- collider that will operate at the $\Upsilon(4S)$ resonance. This will help in the precise measurement of CP violation in $B^0\bar{B}^0$-pairs, produced close to the interaction point. The two B-meson decay vertices have to be separable, hence, requiring an excellent impact parameter resolution. Therefore, in order to cope with high event rate and cater to the requirement of providing high tracking resolution to reconstruct B-meson decay vertices, a new vertex detector (VXD) [5] is being built (Figure 1). The VXD [3] is composed of two systems: a four-layer double-sided strip detector (SVD) [4] at higher radii around the beam-pipe and a two-layer DEPFET-based pixel detector (PXD) [5] as the innermost sensing device.

In order to minimize multiple scattering and the energy loss of particles crossing the detectors, the material budget has to be below $0.2\%X_0$ ($0.6\%X_0$) per layer for the PXD (SVD), including the sensors, readout electronics, support structures and services. The PXD sensors have pixel pitches ranging from $50 \times 50\mu m^2$ up to $50 \times 85\mu m^2$ that, together with SVD strip pitches from 50-75 μm (160-240 μm) on the p-side (n-side), results in a combined impact parameter resolution $\sigma_{d0} \approx 15\mu m$. For low track momenta the impact parameter resolution is up to three times better than Belle. This improvement decreases for higher track momenta leading to ≈ 1.2 times better d_0 and 1.7 times better z_0 impact parameter resolution [6].

3 Origami Concept

The Belle II SVD is made by four layers of double sided silicon strip detectors (DSSD) organised in a cylindrical geometry with a polar angle coverage from 17° in the forward region to 150° in the backward region and with a radius going from 39 mm for the inner layer to 140 mm for the outer layer.

Three different kinds of sensors, fabricated on silicon wafers and with n-type substrate of 300 μm thickness, are used: two rectangular and one trapezoidal. The latter type is used in the forward region to optimise the angular coverage and the particle incidence angle. The two rectangular sensors are both around 120mm long, the larger one being 60 mm wide, the other one 39 mm wide, whereas the trapezoidal sensors are around 120 mm long, with the largest (shortest) edge around 60 (39) mm wide. The rectangular and trapezoidal sensors are made by Hamamatsu Photonics (Japan) and Micron Semiconductor Ltd. (UK), respectively. Further details on the sensors can be found in Refs. [7, 8]. Sensors are longitudinally organised in ladders, which are made of 2, 3, 4, 5 sensors for layer 3 (L3), 4 (L4), 5 (L5), 6 (L6) respectively. From the inner to the outer layer 7, 10, 12, 16 ladders will be used to build the barrel shape of every layer.

The peripheral sensors in the forward (FW) and backward (BW) region of the ladders will be read-out by front end electronics placed on hybrid circuits located outside of the SVD active region. It was decided to read-out sensors individually, in order to reduce the occupancy of the strips as well as to minimize the capacitive load on the front end electronics, keeping the signal-to-noise ratio high. This requires the read-out electronics for the inner sensors in layer 4, 5 and 6 to be placed inside the active area of the SVD, which in turn, led to some constraints for the read-out electronics. It must be radiation hard and have a short shaping time and low material budget. APV25 [9] fulfils these requirements since it is tolerant to radiation doses more than 100 MRad and the combination of short shaping time (50 ns) and the online pulse shape processing will keep the occupancies below the 1% level even under severe background conditions at the SuperKEKB design luminosity. APV25 chips have been thinned from the original 300 μm thickness down to 100 μm and placed on top of the sensors using the so called "Origami" chip-on-sensor concept [10,11]. Fig. 1 shows various components of the SVD in the left and the anatomy of one of the ladders, L6 with the Origami hybrid in the right.

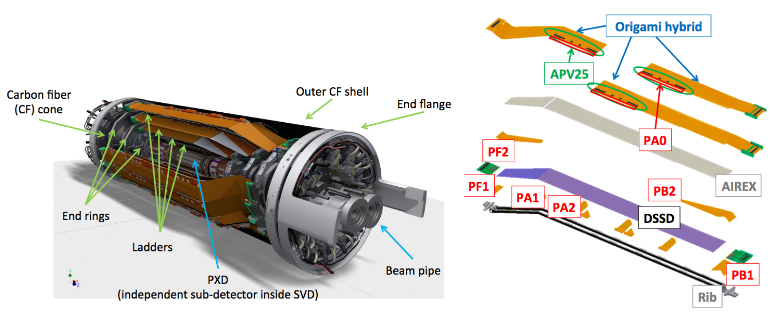

Fig. 1. (Left) Components of the Belle II SVD; (Right) Ladder anatomy of an L6 ladder, showing the Origami hybrid, which is a flexible circuit to transmit detector signals to the ladder ends. Here, FlexPA (PA/PF/PB) is flexible circuit to transmit detector signals to the APV25 and PA0 is flexible circuit glued on the Origami hybrid to transmit n-side detector signals to the APV25.

The Origami is a three layer kapton hybrid circuit on which all APV25 read-out chips of one sensor are placed and aligned. The Origami is then glued on the top side of the sensor, with a 1 mm thick layer of Airex [12] in between, to ensure electrical and thermal insulation. The sensor top side strips will be connected to the APV25 chips through a planar flexible pitch adapter circuit, while the bottom side strips will be routed to the other side of the sensor, toward the electronics, wrapping two different pitch adapters around the sensor edge, above the top side wire bondings. Two carbon fiber ribs are used as a support structure for the ladder.

4 CO_2 Cooling

The alignment of APV25 chips on top of the Origami allows the use of just one cooling channel, that consists of a 1.6 mm diameter pipe with dual phase CO_2 flowing inside. This ensure efficient read-out electronics cooling keeping low the material budget, that is in average 0.6% of a radiation length.

5 Performance Tests

In order to evaluate the performance of sensors, a beam test was performed in April 2016 at DESY in Germany, using a slice of the VXD that included all layers. The test was performed with an electron beam of energy 25 GeV and a solenoid magnetic field up to 1 T.

5.1 Sensor Performance

For the efficiency study, only the four SVD layer data are used to evaluate the efficiency: once that the layer under study is fixed, the other three layers are used as a reference, requiring one hit per layer and fitting a track passing through all 3 reference layers. The fitted track is used to estimate the position of the hit point on the fourth layer, then the number of hits within 300 μm from the estimated hit point is counted. The sensor efficiency, which is the ratio between the number of counted hits and the number of fitted tracks, is above 99.5% in both ϕ and z directions [13]. The same study was performed on the sensors of the other layers and the efficiencies show similar results for both strip directions.

5.2 Sensor Efficiency

For calculating resolution, a total of twelve layers that includes four SVD layers, two PXD layers and six layers of the EUDET telescope, three downstream and three upstream, are used. This is to avoid a biased estimation of the resolution. The tracks used to evaluate resolution are required to have at least 10 hits in the eleven layers used as a reference. The residuals for the sensor under investigation is calculated as the difference between the position of the extrapolated track and the hit on the sensor, on both ϕ and z directions [13]. The obtained resolution estimation is compatible with the digital resolution, which is 7.2(23.1) μm in $r-\phi(z)$ direction for L3 and 10.8(34.6) μm in $r-\phi(z)$ direction for L4, L5 and L6 ladders [13].

5.3 Ladder Assembly Status

Ladder assembly is a complex process [7, 11], that requires precision assembly jigs ($O(50\mu m)$), on which the sensors are fixed by vacuum chucking followed by gluing and wire-bonding. The FW and BW subassemblies for L4, L5 and L6 were produced at INFN Pisa, Italy. L3, L4, L5 and L6 production is done at Melbourne, Australia, TIFR, India, HEPHY, Vienna and Kavli-IPMU, Japan, respectively. As of May 2017, FW/BW subassembly is almost completed. For L3, ladder production has finished. For L4, 6 out of 10+2 ladder production is done. For L5, 12 out of 12+3 ladder production is done and for L6, 7 out of 16+4 ladder production is completed.

5.4 Mechanical Precision Measurement

Mechanical precision are measured with an optical coordinate measuring machine. A displacement of less than 150 μm (nominal value) in all directions for L4 is obtained. Similar results are obtained for the other three layers.

5.5 Humidity and Temperature Monitoring

During the beam test at DESY, one Dewpoint transmitter and few fibers were used [14]. The Fiber Optical Sensors (FOS) sensitive to humidity were installed close to PXD ladders. In the experiment, there will be 4 sniffing pipes, steadily sampling the dew point with external sensors, two in the cold VXD volume, two in the warm VXD volume. This work, both for PXD and SVD, will be carried out at Trieste, Italy. For low humidity/ dew point, these external sensors are much more precise than the FOS.

5.6 Background Monitoring

Due to the increased luminosity at Belle II, severe beam-induced backgrounds and integrated radiation doses are expected. The primary background sources will be Touscheck scattering, radiative Bhabha scattering, e^+e^- pair production in photon-photon scattering, and off-momentum particles from beam-gas interactions. Synchrotron-radiation induced backgrounds are expected to be smaller and can be kept under control by appropriate shielding. These backgrounds are strongly dependent on beam optics. Simulations show that the most affected Belle II sub-detector is the VXD with energy losses coming mainly from electrons and positrons. For the inner layers of the SVD, a dose of about 0.90 kGy/ab^{-1} (90 krad/ab^{-1}) would approximately integrate to 45 kGy (4.5 Mrad) [14]. The results from the 15th beam background simulation campaign are consistent with the results of the last ”stable” campaign. The results of the current background monitoring studies infer that SVD stays within safe limits. New version of SVD simulation/reconstruction settings for these studies are being prepared (strip capacitances, noises etc.).

6 Summary and Outlook

The Belle II SVD has a partially slanted geometry to reduce material budget while optimizing the track incidence angle. Novel Origami chip-on-sensor concept has been successfully tested and now in production. Ladder production is expected to be completed by early 2018. Ladder mount for first half-shell will be during August 2017. The SVD commissioning is foreseen in October 2018. Belle II physics run data taking is expected to begin during Fall 2018.

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References

1. Y. Ohnishi et al., Prog. Theor. Exp. Phys. (2013) 03A011; see also http://www-superkekb.kek.jp/
2. T. Abe et al., Z. Doleal and S.Uno (editors), Belle II Technical Design Report, KEK Report 2010-1, arXiv:1011.0352; see also http://belle2.org/
3. P. Urquijo, Nuclear and Particle Physics Proceedings, Volumes 263-264, June-July 2015, Pages 15-23.
4. C. Marinas et al., PoS DIS2016 (2016) 261.
5. G. Casarosa, PoS EPS -HEP2015 (2015) 255.
6. A. Paladino et al., PoS ICHEP2016 (2016) 248.
7. T. Bergauer, PoS (EPS-HEP 2013) 487.
8. T. Bergauer et al., Nucl. Instr. Meth. A 718 (2013) 279-282.
9. M. French et al., Nucl. Instr. Meth. A 466 (2001) 359-365.
10. M. Friedl et al., TWEPP-08, CERN-2008-008 (2008), 277-281.
11. C. Irmler, TWEPP-12, 2013 JINST 8 (TWEPP 2012 conference), C01014.
12. Airex AG (Switzerland), http://www.airexag.ch.
13. T. Luck et al., PoS Vertex2016 (2016) 057.
14. L. Vitale et al., PoS Vertex2016 (2016) 051.