PROCEEDINGS OF SCIENCE

The Belle II Silicon-strip Vertex Detector

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The Belle II experiment will make precision measurements and explore new physics in the flavor sector at the SuperKEKB asymmetric e^+e^- collider now under construction at the KEK laboratory (Tsukuba, Japan). All the Belle II sub-detectors have been redesigned to improve the performances with respect to its predecessor Belle and to cope with the expected luminosity increase. A large effort has been made to minimise the overall material budget for the VXD, the innermost tracking device of Belle II. The VXD will be composed of 2 layers of of DEPFET pixels (PXD) and 4 layers of double-sided silicon strips (SVD).

These proceedings describe the status of SVD construction and the progress since last year, like the development of the monitoring system of the SVD. Special care is needed to monitor all ambient parameters such as temperature, humidity and radiation levels. In addition to the radiation dose accumulated through the life of the experiment, also the instantaneous radiation rate has to be monitored, in order to be able to react quickly to sudden spikes for the purpose of protecting the detectors. A radiation monitoring and beam abort system based on single-crystal diamond sensors is now under development for the VXD.

The 23rd International Workshop on Vertex Detectors,
15-19 September 2014
Macha Lake, The Czech Republic

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PoS(Vertex2014)017

1. Introduction

The Belle II collaboration [1] has a comprehensive program in precision measurements of CP violation in the B meson sector, including violation in decays, in mixing and in the interference between mixing and decays. We will also search for CP violation in the D-meson sector, and for rare b, c and τ decays. The experiment will be performed at the SuperKEKB asymmetric e^+e^- collider [2] now under construction at the KEK laboratory (Tsukuba, Japan). SuperKEKB is a major upgrade of the KEKB collider, aiming to reach an unprecedented luminosity of 8×10^{35} cm^{2}s^{-1}, 40 times larger than the peak value achieved by KEKB, with a sizeable decrease of the beam size, larger crossing angle at the interaction region and just a moderate increase of the beam currents, thanks to the so called “nano beam” scheme originally proposed for the SuperB project [3].

The SuperKEKB accelerator is based on two separated rings, with 7 GeV energy for the electron beam and 4 GeV for the positron beam, corresponding to a center of mass energy around the $\Upsilon(4S)$ resonance. The $\Upsilon(4S)$ will thus be produced with a sizeable relativistic boost in the laboratory frame ($\beta\gamma = 0.28$), although significantly reduced with respect to KEKB ($\beta\gamma = 0.42$).

All the Belle II sub-detectors have been redesigned to improve the performances with respect to Belle and to cope with the expected increase of luminosity.

A large effort has been made to minimise the overall material budget for the VerteX Detector (VXD), the innermost tracking device of Belle II. The VXD will be composed of 2 layers (layers 1 and 2 in the following) of DEPFET pixels (PXD: PiXel Detector) at radii 1.4 and 2.2 cm, surrounded by 4 layers (layers 3, 4, 5, 6) of double-sided silicon strips (Silicon-strip Vertex Detector: SVD) at radii 3.8, 8.0, 10.4 and 13.5 cm. Each PXD layer will consist of only 75 μm of thickness in the active area (in average about 0.2% radiation length X_0 per layer) and SVD 0.6%X_0 per layer in average.

The DEPFET pixels have been presented separately [4], as well as the Belle II tracking [5]. Here I will concentrate on the SVD and on its recent progress. Section 2 gives a general overview of the SVD. Section 3 describes the progress since last year, the status of sensor production and tests, the ladder assembly procedure, electronics and read-out system tests, mechanics, cooling and the present status of the SVD construction. Finally, in the section 4 the development of the ambient monitoring system for the SVD and of the radiation monitoring and beam abort system for the VXD are described.

2. SVD Overview

The Belle II SVD will consist of 4 layers of double-sided silicon strip sensors (DSSD) with a polar angle coverage up to 30° in the backward and 17° in the forward region. A 3D rendering is shown in Fig. 1. Compared to the strip detector of its predecessor (the so called “Belle SVD2”) it will extend to larger radii, it will have a slanted shape in the forward region with trapezoidal sensors to increase the angular coverage, optimising the particle incidence angle and the total detector length. All the sensors are fabricated on larger 150 mm silicon wafers, compared to the 100 mm ones used for the previous detectors. The number of sensor types has been minimized by having only three different sensor designs, two rectangular and one trapezoidal, all with AC coupled read-

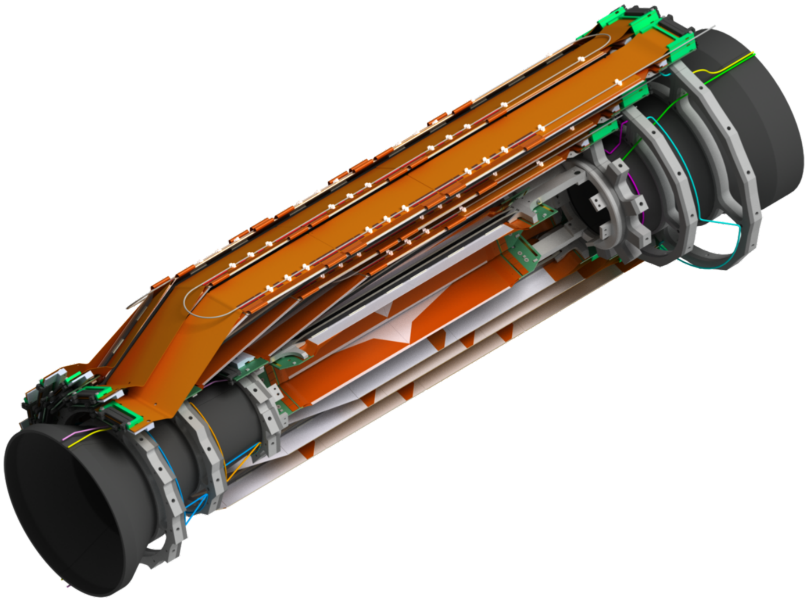

Figure 1: 3D rendering of the Belle II SVD design with part of the ladders mounted, its support structure and the thin CO_2 cooling pipes.

out, poly-silicon resistor biasing and perpendicular strips on the two sides. The rectangular sensors are manufactured by by Hamamatsu Photonics K.K. (Japan), while the trapezoidal sensors are made by Micron Semiconductor Ltd. (UK). The silicon substrate is n-type and has a thickness of 320 (300) μm for the Hamamatsu (Micron) sensors. More details about the sensors can be found in Ref. [1, 6, 7].

In Fig. 2 a longitudinal cross section of the sensor arrangement is shown as well as the sensor dimensions and the strip pitches. Sensors will be longitudinally combined in ladders, made of 2, 3, 4, 5 sensors in layers 3, 4, 5, 6 respectively. Every second strip of each sensor will be read-

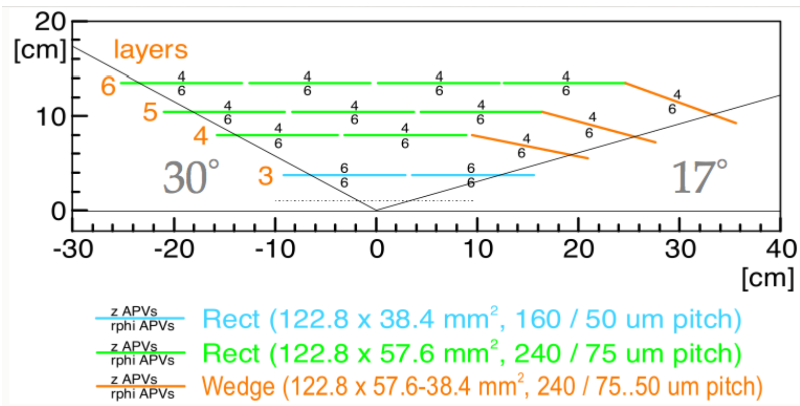

Figure 2: Longitudinal cross section of the sensor arrangement. The radius is shown in the vertical axis, the z coordinate horizontally . The origin is at the nominal interaction point. The colors distinguish the three different sensor types: in blue the small rectangular sensors, used for layer 3 only; in green the large rectangular sensors and in orange the slanted trapezoidal sensors. The numbers above and below each sensors correspond to the APV25 chips used to read-out the z and rphi strips on the n-side (top) and p-side (bottom) respectively. The sensor dimensions and read-out pitch per sensor are also shown in the legend.

out independently (i.e. without daisy chaining) by the APV25 front-end chip [8]. The peripheral sensors in the forward and backward region will be read-out by conventional hybrid circuits hosting the APV25. In order to read-out the inner sensors without long fanout circuits, the APV25 have been thinned to 100 μm and placed inside the active volume for the central sensor in layer 4 and two (three) central sensors of layer 5 (6), using the so-called “Origami” chip-on-sensor concept [1, 9]. For these central sensors all read-out chips will be placed on a single flexible PCB made of Polyimide and will be aligned on the external side of the sensor, allowing them to be cooled by a single cooling pipe. The top side strips will be connected to the chips through a planar fanout circuit. Signals from the strips on the inner side of the sensor will be routed to the APV25 chips on the outer side through thin, flexible fan out circuits wrapped around the sensor edge (hence the name “Origami”).

The Origami PCB will be glued onto the external side of the sensor, separated by a 1 mm thick layer of Airex, a very lightweight, but rigid foam, which serves as an electrical and thermal insulator between sensor and PCB. Two ribs, made of carbon fiber, will support the ladder from the bottom-side ([10, 11] and Fig. 3). The front-end chips will be cooled by CO_2 flowing inside thin, 1.6 mm diameter pipes, running along the outer side of the ladder (Fig. 1) directly on top of the Origami chips, ensuring efficiency at minimum material budget. The total material budget in the sensitive region will amount to $0.6\% X_0$ per layer in average. An exploded view of layer 5 and its components is visible in Fig. 3.

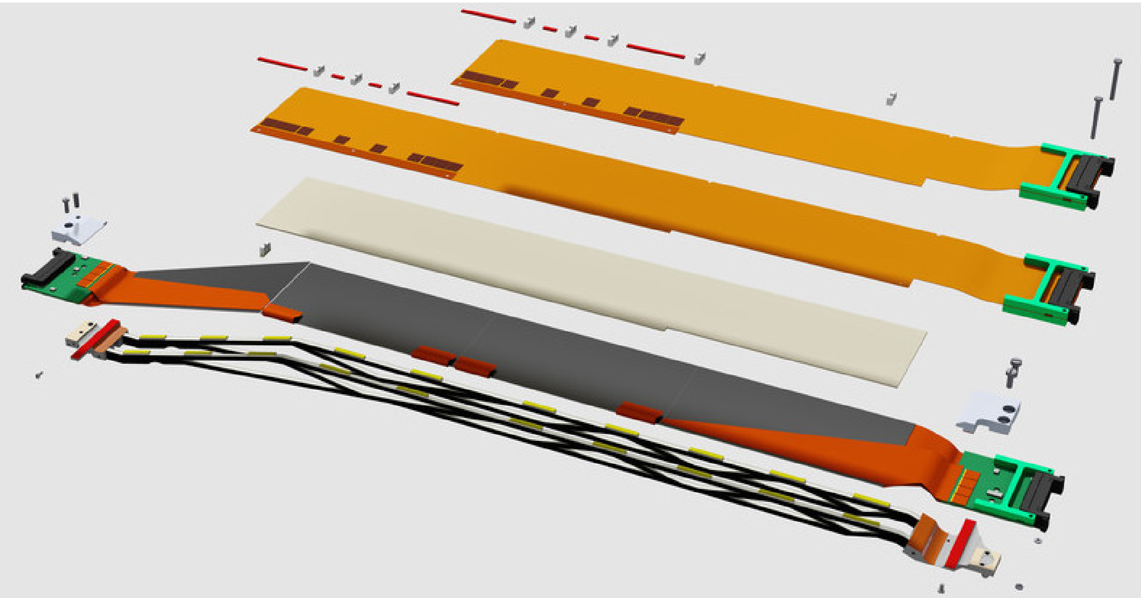

Figure 3: Exploded view of layer 5. From bottom to top: carbon fiber ribs (black), four sensors (gray), APV25 and flex circuits (red), hybrids (green), Airex foam (white), two Origami flexes (orange) with thinned APV25 (brown) and clips for the cooling pipes (grey).

Several single-sensor Origami modules were produced since 2008; moreover a prototype module with 2-DSSD, implementing the Origami concept, was fabricated in mid-2012 [10, 11] and then successfully tested.

Belle II is an international collaboration, but even the SVD group is quite an international enterprise with 16 institutions from 8 countries and 3 continents.

3. Progress

In this section I describe the recent progress towards the mass production of ladders and the final SVD assembly, foreseen in 2015, in particular the finalisation of sensor production and tests, the ladder assembly procedure, electronics and read-out system tests, mechanics, cooling and the present status of the SVD construction.

3.1 Sensor production and tests

To date all required sensors were produced and delivered. The rectangular sensors were tested by HPK before delivery. Detailed verification and characterization testing and has been performed by Trieste and Vienna on two of these sensors.

For the trapezoidal Micron sensors, 44 are required and 60 were ordered. The bottleneck of the delivery was the detailed testing by the supplier, so in order to speed up production, complete testing (I-V, C-V, AC and DC strip scan and long-term current stability test) has been done in Vienna and Trieste. 56 DSSDs were delivered and tested with a very good overall quality, only 10 DSSDs were rejected. Further 24 sensors were delivered in September 2014 and now are under test in Trieste.

3.2 Ladder assembly procedure

The ladder assembly procedure is rather complex and requires a total of 23 jigs to align, glue, bond, mount and attach all the components of each ladder. A detailed description can be found in [7, 10] and a sketch of the mounting sequence in [12].

The SVD will be assembled at several sites in parallel; for instance INFN Pisa is in charge of the forward and backward sub-assemblies and each one of Melbourne, TIFR India, HEPHY Vienna, IPMU Tokyo will assemble layers 3, 4, 5, 6, respectively.

Set-up and tuning of the assembly procedure is now underway at all sites. All steps have been tested, addressing the various issues: mechanical precision, gluing procedure, pitch adapter flexibility and wirebonding. Almost all components and all jigs are available. Mechanical prototypes of the ladders have been already realized. Now fully functioning prototypes with few defects are under construction. The final prototypes will be assembled at the beginning of 2015 and then the production will start and it will continue for the full 2015. The ladder mount is foreseen starting from the end of 2015.

3.3 Electronics and read-out system tests

The heart of the front-end electronics of the SVD is APV25 chip [8], developed for the CMS experiment at CERN and successfully operated in large scale. It is tolerant to high radiation doses (>100 MRad) and the combination of short shaping time of APV25 (50 ns) and the online pulse shape processing (reducing by a factor 8 the effective time window) will keep the occupancies below the 1% level even under the severe background conditions at the SuperKEKB design luminosity. The analog outputs from the APV25s are transmitted to Flash Analog-to-Digital Converter

(FADC). An FADC board receives up to 48 APV25 analog outputs and performs flash analog-to-digital conversion with 31.8 MHz clock to obtain digitized DSSD signals. The digital data are decoded and processed on an FPGA, and propagated to Finesse Transmitter Board (FTB). The FTB sends the data to the COmmon Pipelined Platform for Electronics Read-out (COPPER) which is a Belle II DAQ interface through an optical fiber, using Belle II unified high-speed serial protocol (belle2link). In the Belle II experiment, 48 FADC boards and 48 FTBs will be installed. A description of the read-out electronics can be found in [13, 14, 15] and the recent progress in Ref. [16, 17]. All the components in the SVD read-out system are being developed and the first prototypes for these components have been successfully produced and tested.

In January 2014 a beam test of a significant VXD subset was performed with 2-6 GeV electrons at DESY and inside a 1 T magnetic field in a direction perpendicular to the beam line. The setup included two DEPFET modules, four SVD modules (with one large rectangular DSSD each), FADC and FTB boards, CO_2 cooling, slow control and environmental sensors based on Fiber Optical Sensors (FOS) [18]. This can be considered as a complete system test for the Belle II VXD, since all the components (sensors, front-end and back-end electronics, the DAQ interface and even the cooling, slow control and environmental sensors) are very close (or prototypes similar) to the ones that will be used in the final experiment. Several aspects have been thus checked, for instance the SVD cluster hit efficiency were measured to be above 99.4% for tracks in the fiducial volume. From the resulting high efficiency, we confirmed our Common Mode Correction and zero-suppression do not deteriorate the SVD hit efficiency [16, 17].

3.4 Mechanics and cooling

As mentioned above and shown in Fig. 3, the ladders are supported by two ribs and an end mount structure in aluminum on each side. The ribs have 3 mm of Airex core with 0.15 mm of laminated carbon fiber sheets to ensure a very stiff framework, but yet lightweight thanks to the sandwich construction and the truss structure.

The total SVD (Origami) power dissipation is estimated to be 688(328) W. The APV25 chips of the edge hybrids will be cooled by the CO_2 at -20° C flowing inside the end rings. A thin pre-bent cooling pipe will be clipped onto the ladders on top of the Origami APVs.

The Belle II strips and pixels will share the same volume and the PXD contributes to other 360 W to the power dissipated in the VXD. Nitrogen at 20° C will be flown to the VXD volume to keep stable temperature and low humidity. Given the system complexity, a PXD+SVD thermal mock-up is in preparation at DESY and will be ready at the beginning of 2015. It will be crucial for understanding several aspects and setting the exact location for the ambient sensors.

4. Monitoring

As mention in the introduction, the design luminosity of SuperKEKB, 40 times higher than that of KEKB, will be achieved by higher beam currents and smaller beams size at the interaction point. As a consequence, higher beam-induced backgrounds and radiation doses are expected. The main background sources will be Touscheck scattering, radiative Bhabha scattering, electron-positron pair production in photon-photon scattering, and off-momentum particles from beam-gas interactions. Synchrotron-radiation induced backgrounds are expected to be smaller and will be kept under control by appropriate shielding.

These backgrounds are strongly dependent on the beam optics; simulations are in progress. According to preliminary estimates the PXD total integrated doses may range from about 150 to about 180 kGy (15 to 18 Mrad) during the projected lifetime of Belle II at the design integrated luminosity (50 ab^{-1}). For the inner layers of the SVD, less exposed, a dose of about 90 krad per ab^{-1} would approximately integrate to about 4.5 Mrad during the projected lifetime of Belle II.

To protect the detector against excessive radiation doses, the radiation monitoring system will be able to detect a sudden large increase in backgrounds, or a lesser increase, an unacceptable integrated dose over some longer time period. In the first case an immediate trigger signal will be sent to the SuperKEKB beam-abort system; in the second case a warning signal followed after some time by a beam-abort trigger signal. The system will also provide continuous monitoring and recording of radiation doses at sensitive spots in the PXD+SVD detector volume.

Radiation-hard single-crystal diamond sensors, realized by the Chemical Vapour Deposition technique (scCVD), will provide the dose rate measurements. A set of $4+4$ sensor will be located on an empty groove behind the beam pipe cooling manifold, upstream and downstream of the PXD; $6+6$ will be located close to the support rings of the inner SVD layers. The read-out electronics, presently in the design stage, includes current digitizers and FPGAs with digital filtering, data buffering, and programmable thresholds for the beam abort triggers.

Concerning the ambient monitoring system, the temperature close to the heat sources will be monitored with an accuracy lower than 1° C by FOS, optical fibers equipped with sensors realized by Bragg gratings coated with temperature-sensitive acrylate [18]. They will be inserted in the Airex foam of the SVD ladders. A complementary set of NTC thermistors will provide both a precise cross-calibration and a hardware temperature interlock.

To avoid humidity condensation on the cooling pipes, the whole volume of the PXD/SVD will be kept dry by a flux of nitrogen. Some FOS fibers, with humidity-sensitive coating, will measure the relative humidity. Sniffing pipes will sample the VXD atmosphere; more bulky instruments, located outside, will provide alarms and interlock signals whenever the dew point should exceed about -30° C with an accuracy of about 1° C.

5. Conclusions

The Belle II SVD will be made of 4 layers of double-sided AC-coupled silicon strip sensors from 150 mm silicon wafers. The outer 3 layers will have a partially slanted geometry to reduce the material budget and optimize the track incidence angle. Each silicon sensor will be individually read by APV25 chips and the outer 3 layers will use the novel Origami technique. The short shaping time and the FPGA online processing will keep the occupancies below the 1% level under severe background conditions. All sensors needed have been delivered and tested. The Origami chip-on-sensor concept has been successfully tested. SVD ladder mass production will start soon. Moreover an ambient and radiation monitoring system will be integrated in the VXD.

PoS(Vertex2014)017

Acknowledgments

I would like to thank my SVD colleagues; in particular Luciano Bosisio, Markus Friedl, Christian Irmler, Livio Lanceri, Katsuro Nakamura for the help in preparing my talk and proceedings.

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