Recent Progress in Sensor- and Mechanics-R&D for the Belle II Silicon Vertex Detector

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Abstract

The Belle experiment at the KEKB electron/positron collider in Tsukuba (Japan) was successfully operating from 1999 to 2010 serving as a b-factory accelerator. Research Organization KEK (Tsukuba, Japan) was successfully operated from 1999 to 2010 serving as a b-factory with high intensity beams. After more than 10 years of operation, KEKB provided more than 1 ab\(^-1\) of integrated luminosity in total to the Belle experiment, whose measurements have offered important insights into the flavor structure of particles, especially in the violation of the CP symmetry among quarks. Results of the Belle collaboration, together with data from its counterpart BaBar at SLAC [1], led to the Nobel Prize in Physics awarded to M. Kobayashi and T. Maskawa for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature [2].

1. Introduction

The asymmetric \(e^-/e^+\) collider KEKB at the High Energy Accelerator Research Organization KEK (Tsukuba, Japan) was successfully operated from 1999 to 2010 serving as a b-factory with high intensity beams. After more than 10 years of operation, KEKB provided more than 1 ab\(^-1\) of integrated luminosity in total to the Belle experiment, whose measurements have offered important insights into the flavor structure of particles, especially in the violation of the CP symmetry among quarks. Results of the Belle collaboration, together with data from its counterpart BaBar at SLAC [1], led to the Nobel Prize in Physics awarded to M. Kobayashi and T. Maskawa for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature [2].

1.1. The Belle Experiment

The Belle experiment [3] was the only detector operating at the KEKB collider and stopped data taking after KEKB shutdown. It consisted of different subdetectors, which were arranged cylindrically around the interaction point. Since the accelerator provided asymmetric beams with 8 GeV electrons and 3.5 GeV positrons, the experiment was also constructed as mixture between a symmetric collider experiment and a forward-spectrometer with asymmetric acceptance angles.

2. The Belle II Silicon Vertex Detector

An elaborate upgrade program is currently ongoing to upgrade the KEKB collider to SuperKEKB, which will provide a super-high luminosity of \(8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}\) starting in 2015. The current Belle experiment cannot handle this 40-fold increase in luminosity and thus needs to be upgraded as well. The upgraded Belle detector is called the Belle II experiment, which is described in detail in its Technical Design Report (TDR) [4].
equipped with DEPFET-based pixel detectors [5]. Compared to the previous SVD, the Belle II SVD will have a slanted forward region. A drawing illustrating the four strip layers is shown in figure 1. The fully equipped SVD will consist of 7 ladders in layer 3 (the innermost SVD layer), 10 ladders in layer 4, 12 ladders in layer 5 and 16 ladders in the outermost layer 6. Each ladder is tilted in order to allow a windmill-style arrangement with a certain overlap between each other. The overlap is necessary for a proper track-based alignment during data taking. Section 2.5 will discuss this in more detail.

2.2. Double Sided Silicon Sensors

For an experiment at a low-energy $e^−/e^+$ collider, a low material budget is mandatory. To achieve this, the layout is entirely based on 6” DSSDs. A market survey was performed in order to find possible producers for such sensors. It was found that only Hamamatsu Photonics (HPK) and Micron Semiconductor are able to provide DSSDs with a thickness of 300 $\mu$m, AC coupling and poly-silicon bias resistors. HPK even started a new production line in order to be able to produce those detectors. As double-sided sensors involve a lot of processing steps, the yield is obviously lower than for single-sided detectors. Figure 2 shows the dark current behavior of prototype sensors from both vendors with comparable full-depletion voltages and dark currents.

The DSSDs are based on n-bulk substrate. To have a proper strip separation on the n-side, a p-stop pattern has to be applied. Baby sensors have been developed which feature three different p-stop layouts called atoll, common and combined, respectively, in order to determine the best layout of this pattern in terms of signal-to-noise ratio (SNR). Each layout comes in four geometries with different distances between the n-strip and the p-stop region (narrow, half-narrow, half-wide, wide). The detailed dimensions of the different layouts and geometries can be found in [6].

The baby sensors were tested in a 120 GeV/c pion beam at CERN’s SPS accelerator, where the SNR values were determined. Afterwards, they were irradiated with gammas from a $^{60}$Co source to 700 kGy. This is 7 times the expected fluence in Belle II. Immediately after, the sensors were re-tested in the same beam line to be able to properly compare the SNR figures before and after irradiation. It was found that the half-wide atoll geometry shows best performance in both un-irradiated and irradiated cases with SNR figures of 37 and 25, respectively [6]. These measurements were performed with Belle II SVD prototype readout electronics based on the APV25 readout chip.

An interesting effect has been observed on the narrow geometry of the atoll layout. Those sensors developed a virtual intermediate strip caused by charge-up during irradiation. This effect can be seen in the center peak in the eta distribution on figure 3. The passivation oxide, the metal and dielectric layers were then removed on this sensor. It was found by SRP measurements [7] that the charge-up vanished on the bare silicon. Thus, it must be caused by fixed oxide charges created during irradiation in the passivation of the sensor.

2.3. Front-End Readout

As mentioned earlier, the electronics chain must be upgraded to meet the Belle II requirements in respect of dead-time and fast shaping. The APV25 chip [8], originally developed for the CMS experiment at the LHC, was chosen for the Belle II SVD because it meets all those requirements. Moreover, it is very tolerant to radiation (much more than expected for Belle II) and is thoroughly tested. To minimize the material budget, the passive bulk of the chips was thinned to 100 $\mu$m.

The APV25 chip has a shaping time of 50 ns to meet the fast LHC bunch crossing frequency. This results in a time over
threshold of approximately 160 ns [9]. Compared to the 800 ns shaping time of the VA1TA chip used for Belle (with 2000 ns time over threshold), this new chip reduces the occupancy by a factor of approximately 12.5.

2.3.1. Hit time finding

To narrow down the effective shaping time and thus to reduce the occupancy even further, the shaped waveform is reconstructed to precisely determine its timing. This procedure called hit-time-finding can reduce the effective shaping time to approximately 3 ns with a time over threshold of only 20 ns [10]. Taking this feature into account, the total gain in terms of occupancy is about 100 compared to the previous experiment. This is summarized in figure 4.

2.4. Origami Chip-on-Sensor Concept

The drawback of fast shaping time is noise. The main noise source in a silicon detector and its readout chip is caused by the sensor capacitance. To keep this number on an acceptable level, daisy-chaining of several sensors is not possible and each sensor needs to be read out individually. To maintain a low material budget, a module and ladder concept was developed which features the readout chips on one side of the sensors only. This allows to reach all readout chips with a single cooling pipe per ladder. To contact the strips of the bottom of the module, fan-outs based on flexible Kapton material are used, which are wrapped around the sensor edges [11]. This module concept is shown in figure 5, while an actual picture of the module (before folding the two fan-outs) is shown in figure 6.

2.5. Mechanics

The mechanical design of the interaction region is currently being optimized. Figure 7 shows that the mounting of the ladders in layers 4 to 6 has been defined. For layer 3 (shown floating in the drawing) this work is currently ongoing.

Due to space constraints the radii of layers 5 and 6 had to be changed by 5 mm in respect to the TDR design. Table 1 shows the new radii of all SVD layers together with the number of ladders in each layer, the windmill angle and the resulting overlap between adjacent ladders. Since the number of ladders in each layer changed as well, there will now be 220 and 480 readout chips in layers 5 and 6, respectively. For layer 5 (6) the number of sensors changed to 36 (64) for rectangular and 12 (16)
for trapezoidal sensors. These changes result in a total number of 14 rectangular narrow sensors (for layer 3), 120 rectangular wide sensors (layers 4-6) and 38 (identical) trapezoidal sensors for the slanted forward part.

To verify the influence of these changes to the impact parameter resolution of the whole tracking system, a fast simulation was performed using the LDT simulation tool [12]. Figure 8 shows the results of this simulation. It was found that the impact parameter resolution deteriorates by a maximum of 1.5% in the transverse direction and 2.2% in forward direction with respect to the TDR design. For the dominant momentum region around 0.5 GeV/c, the change is only 1% in the transverse direction and can be neglected along the beam.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Layer # & Radius [mm] & No. of Ladders & Windmill-angle [deg] & Overlap [%] \\
\hline
6 & 135 & 16 & 7 & 15.2 \\
5 & 105 & 12 & 6 & 7.2 \\
4 & 80 & 10 & 6 & 21.6 \\
3 & 38 & 7 & 6 & 11.1 \\
\hline
\end{tabular}
\caption{Table summarizing the key parameters of the mechanical structure.}
\end{table}

3. Summary and Outlook

The R&D work on double-sided silicon sensors lead to a design which is optimized in terms of signal-to-noise-ratios for both, the un-irradiated and gamma-irradiated case. The readout system is using hit-time-finding to narrow down the effective shaping time of the APV25 readout chip to around 3 ns RMS. The necessity to have the readout chip close to the sensor lead to the chip-on-sensor concept called Origami scheme. Space constraints required a change in the mechanical design compared to the Technical Design Report. The outermost SVD layers have been moved inwards by 5 millimeters each. This change was verified by fast simulation, and it was found that no significant change in the impact parameter resolution of the Belle II SVD occurs.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{projected_impact_parameter_resolution.png}
\caption{Projected impact parameter resolution}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{impact_parameter_resolution_z.png}
\caption{Impact parameter resolution in z}
\end{figure}

References