PROCEEDINGS OF SCIENCE

Commissioning of the Belle II Pixel Vertex Detector

Hua Ye[*]
On behalf of the DEPFET and Belle II PXD collaboration
Deutsches Elektronen–Synchrotron, 22607 Hamburg, Germany
E-mail: `hua.ye@desy.de`

As an upgrade of the asymmetric e^+e^- collider KEKB, SuperKEKB aims to increase the peak luminosity by a factor of 40 to 8×10^{35} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The upgraded Belle II detector allows the experiment to handle the much increased data rates, with the goal to explore new physics beyond the Standard Model at the intensity frontier. Belle II is expected to accumulate a dataset of 50 ab^{-1} by 2027. The Belle II pixel detector (PXD) has been developed using the **DE**pleted **P**-channel **F**ield **E**ffect **T**ransistor (DEPFET) technology, which combines low power consumption in the active pixel area and low intrinsic noise with a very small material budget. In this proceedings, commissioning and performance of this novel detector measured with first collision data are presented.

EPS-HEP 2019, Ghent, Belgium

PoS(EPS-HEP2019)122

---

[*] Speaker.

1. Introduction

The asymmetric e^+e^- collider, SuperKEKB, has been upgraded with the goal of increasing the peaking luminosity by a factor of 40 to 8×10^{35} $cm^{-2}s^{-1}$. In the meantime, the complex Belle II detector has accomplished a series of upgrades to improve the overall performance [1, 2]. The experiment started physics data taking in Mar. 2019, aiming to accumulate a data sample of 50 ab^{-1} in the next decade to study flavour physics and explore new physics beyond the standard model (SM).

Comparing to its predecessor KEKB, SuperKEKB has reduced the beam energy asymmetry from 3.5 GeV e^+ $\times$ 8 GeV e^- to 4 GeV e^+ $\times$ 7 GeV e^-, which results in a smaller boost of 0.28 instead of the previous 0.43. In order to achieve the same physics performance for instance in CP violation observables measurements, the impact parameter resolution of the detector has to be improved, in the mean time, the Belle II detector has to cope with the much increased beam background, occupancy and trigger rate. To meet these challenges, Belle II has employed a novel double-layer pixel detector (PXD) close to the beam pipe. PXD is indispensable for determining the decay vertices of B or D mesons. It employs the advanced pixel concept, DEPFET [3], since it offers ultra-low mass sensor and short integration time, which fits the requirements of the experiment.

2. DEPFET pixel detector

The DEPFET concept combines the detection together with the in-pixel amplification by integrating, on each pixel, a FET into a fully depleted silicon bulk. A deep n-doping implantation made few microns under the FET channel creates a potential minimum, named 'internal gate'. In detection, the electrons created in the bulk by ionizing particles, are accumulated in internal gate and modulate the transistor's drain current, then the firing pixels can be sensed by comparing the current of a pixel to its known pedestal. After the firing pixels are detected, the gathered charge will be removed from internal gate by applying a positive voltage to a n^+ contact, named clear, so that the pixels are reset and ready for the next event. In Belle II, the DEPFET based PXD provides an internal amplification of $g_d \sim 500$ pA/e^-, as well as ultra-low noise thus achieving a good signal to noise ratio (S/N) even for very thin sensors. A sketch of DEPFET pixels is shown in Fig. 1.

The PXD module is made from one monolithic piece of silicon with three metal layers (2 Al and 1 Cu) for signal routing and power. The sensitive region is comprised of a matrix with 250 $\times$ 768 DEPFET pixels, which covers an area of 12.5 $\times$ 44.80 (61.44) mm^2 for the module in inner (outer) layer. The matrix is thinned down to 75μm to reduce material budget. Surrounding the matrix is the 525 μm thick silicon frame to retain mechanical stability, making the module a self-supporting structure. The pitch size of PXD module is 50 $\times$ (50 - 85) μm^2, the $1/3$ of matrix closer to the interaction point adopts smaller pixel size to improve resolution in forward direction around 45° incident angle.

In the PXD readout scheme, a four-fold readout in the rolling shutter mode is employed. Three types of ASICs, which are directly bump bonded on the bump pads of the copper layer, serve to readout the signal. The row-wise steering for the DEPFET voltages are controlled by 6 Switcher chips, arranged on the balcony along a long edge of module stave. Drain signals are read out by

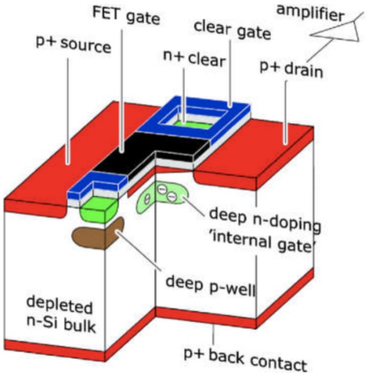

Figure 1: Schematic view of DEPFET pixel, which provides detection and internal amplification at the same time.

4 DCD (Drain Current Digitizer) chips housed at the end of stave (EOS). Each DCD consists of 256 current mode pipeline 8-bit ADCs which allow to digitalize the inputs from 4 rows of drain lines in parallel. Therefore, 192 readout cycles are required to read a complete frame. With a single read-clear cycle in approximately 100 ns, the total integration time for one frame takes 20 μs. Since only the activated rows of pixels consume power, the power consumption of operating DEPFET matrix is very low. Each DCD is followed by a DHP (Data Handling Processor) chip which performs zero-suppression and pedestal subtraction. It also controls steering signal to the other ASICs on the module, compensates common mode noise in data and manages operation modes. Another feature of DHP is providing an on chip temperature measurement to determine the operating condition. The maximum acceptable average occupancy of the readout scheme is 3%. The EOS also holds the passive Surface Mounted Device (SMD) components, as well as wire-bonding pads of a $\sim$ 40 cm long Kapton flex for power, control and readout.

3. Belle II PXD

Two layers of DEPFET sensors are installed close to the interaction point at radius of 14 and 22 mm. Benefiting from the low power consumption and self-supporting structure with 75 μm thick sensor, no extra cooling or supporting material is required inside of the physics acceptance of the detector, which makes PXD a ultra-light detector and minimizes the effect of multiple scattering. The average radiation length for each layer is determined as 0.2% X_0. Two mirrored PXD modules are glued face to face to form a ladder and combined with an additional ceramic mini-rod embedded for reinforcement. In the design of PXD layout, the inner layer holds 8 ladders and the outer holds 12, consisting of 40 DEPFET modules in total. Both layers are mounted on the so-called Support and Cooling Blocks (SCBs), which locate outside the acceptance region.

A moderate flow of nitrogen is necessary for cooling the active area of PXD inside of the physics acceptance. The DCD/DHPs contribute about 2W heat load per pair, and need to get active cooling from the SCBs underneath the stave. Two-phase CO_2 cooling method is adopted for detector cooling at the ends of PXD ladders. This cooling concept offers two major advantages of radiation tolerance and excellent thermo-mechanical behavior. The SCBs are manufactured from stainless steel by 3D laser sintering, which allows the integration of the meandering CO_2 channels to cool DCD/DHPs, and open N_2 channels to provide forced N_2 flow between the two PXD layers. 8 carbon tubes connect the backward and forward SCBs to guide N_2 through the holes along the tubes for the local cooling of inner layer Switchers. The SCBs are coated with a 15 μm thick Parylene layer to electrically isolate themselves from the sensors. Additionally, 20 μm thick Malyer foils are inserted in between modules and SCBs for about half of the PXD system to ensure the isolation. The carbon tubes are coated with silver paint for grounding purpose. The temperature in the gas atmosphere around PXD is determined with the fibre optical sensors (FOS), which are positioned a few millimetres away from the outer layer [4].

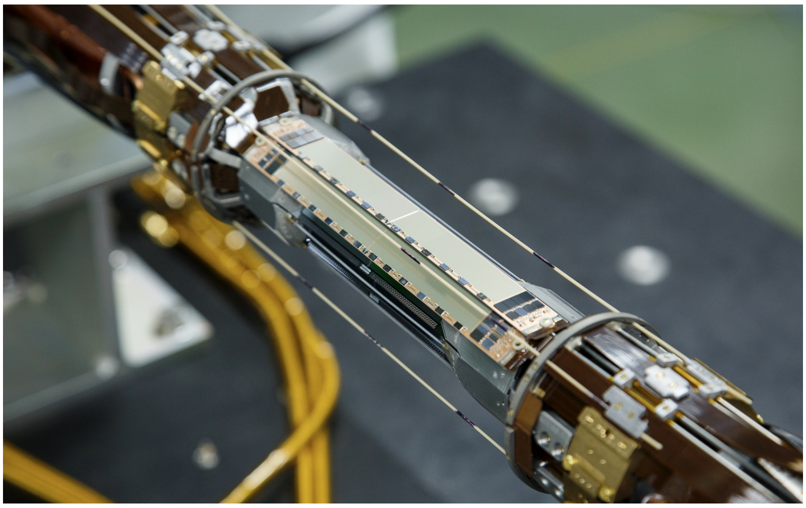

Figure 2: DEPFET based pixel detector for Belle II experiment. An de-scoped detector system had been installed closest to the central beam pipe in 2018 summer.

Due to some technical problems occurred in the ladder gluing procedure, only the full inner layer and two outer layer ladders (Fig. 2), *i.e.* half the the designed layout, were installed into Belle II and participated the data taking. The full PXD system is scheduled to be finalized in 2021.

4. PXD Commissioning and Performance

After the modules were produced, a series of tests were carried out for module characterization and ASICs tuning. Then the modules were glued to ladders and mounted onto SCBs. After investigating the performance of PXD in multi-modules scale, the detector was transported to KEK in the summer of 2018 and started commissioning there. In Nov. 2018, the vertex detector, including PXD and 4 layers of double sided silicon strip detectors (DSSDs) at larger radii, was installed into Belle II. The physics data taking with beam collisions started in Mar. 2019.

A high S/N ratio of ~ 50 for DEPFET PXD modules is extracted from a Landau fit to the cluster signal distribution. A prominent peak in the low energy region ($<$10 keV) on cluster energy spectra is originated from synchrotron radiation, which is featured more significantly in the inner layer modules. During operating PXD in collisions, the ionizing dose received by the sensor lowers the FET thresholds and decreases pedestal currents and transistor gains, which can be compensated by applying more negative gate voltages for the FETs [5]. The hit efficiency of modules is determined by tracking the charged particles passing through the outer trackers and extrapolating to PXD. The averaged efficiency is better than 95 % for all PXD modules, in which a portion is still under optimization. Further improved hit efficiency is foreseen with an optimal working configuration.

The thermal performance of Belle II vertex detector was studied with a full size mock-up, where dummy silicon sensors were manufactured exactly in the same way as for the real PXD module. Instead of using real front-end electronics, resistors are equipped for dissipating nominal power loads. It was determined the temperature along the full loaded PXD sensors stays below 33°C in nominal operating condition [4].

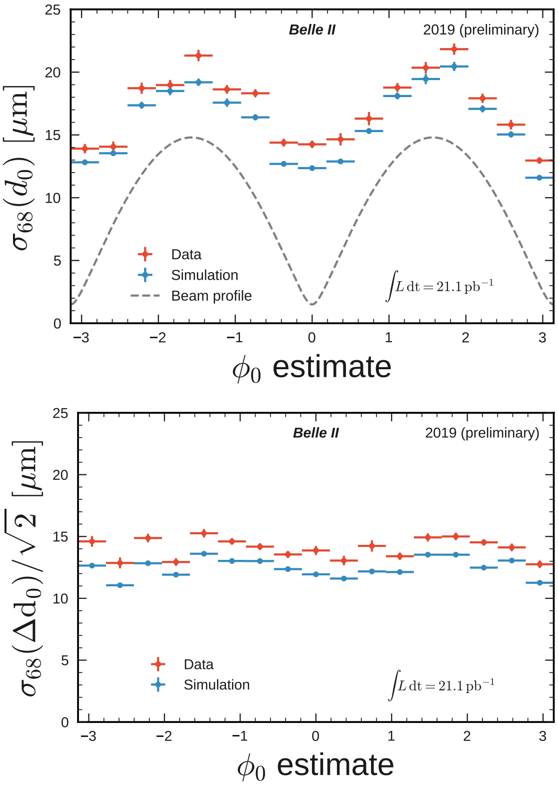

Figure 3: Width of the d_0 (left) and $\Delta d_0/\sqrt{2}$ (right) distribution in bins of ϕ_0 for the data and simulation. A beam profile is drawn in gray, it's described by $\sqrt{(sin\phi_0 \cdot \sigma_x)^2 + (cos\phi_0 \cdot \sigma_y)^2}$ where σ_y = 1.5 μm is fixed in fit. σ_{68} means the width are measured according to the 68% coverage.

Tracks from Bhabha scattering events close to be vertical to the beam-axis are selected to study the transverse impact parameter (d_0) resolution. The width of d_0 depends not only on the intrinsic detector resolution but also on the beam profile because d_0 is defined with respect to the origin instead of the beam spot position. This beam profile dependence can be described by $\sqrt{(sin\phi_0 \cdot \sigma_x)^2 + (cos\phi_0 \cdot \sigma_y)^2}$. In practice, σ_y is very small with respect to σ_x. For the back-to-back generated tracks (denoted as t_+ and t_-), the definition of d_0 implies that $d_0(t_+)$ and $d_0(t_-)$ have opposite signs, so the difference $\Delta d_0/\sqrt{2} \equiv (d_0(t_+) + d_0(t_-))/\sqrt{2}$ is a more direct estimation of the d_0 resolution. Fig. 3 shows the width of the d_0 and $\Delta d_0/\sqrt{2}$ distributions in bins of ϕ_0. The d_0 resolution is estimated to be $\sim$ 14 μm. The discrepancy between data and simulation may arise from the too optimistic expectation of outer trackers resolution in simulation.

5. Summary

The first real beam experience with a completely new pixel detector for Belle II, based on the DEPFET technology have been achieved. Half of the full scaled PXD had been installed and participated the physics data taking in 2019 spring, the full system is scheduled to be finalized in 2021. Good PXD performance has been demonstrated and is continuously being optimized.

References

[1] K. Akai, K. Furukawa et al., Nuclear Instruments and Methods in Physics Research, A 907 (2018) 188-199

[2] I. Adachi, T.E. Browder et al., Nuclear Instruments and Methods in Physics Research, A 907 (2018) 46-59

[3] J. Kemmer, G. Lutz, Nuclear Instruments and Methods in Physics Research Section, A 253 (1987) 365.

[4] H. Ye, C. Niebuhr et al., Nuclear Instruments and Methods in Physics Research, A 896 (2018) 82-89

[5] B. Paschen, F. Abudinen et al., Belle II pixel detector: Performance of final DEPFET modules, Nuclear Inst. and Methods in Physics Research, A (2019), https://doi.org/10.1016/j.nima.2019.05.063.