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The Belle II DEPFET Pixel Detector and Cluster Shape Dependent Improvement of Spatial Resolution

Paola Avella[1](presenter), Peter Kodyš[2]

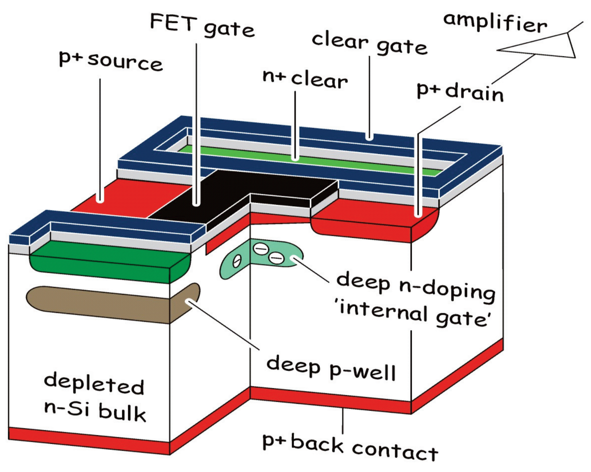
On behalf of the DEPFET Collaboration

[1]Max Planck for Physics and Semiconductor Laboratory of the Max Planck Society, Munich (Germany)
[2]Faculty of Mathematics and Physics, Charles University, Prague (Czech Republic)

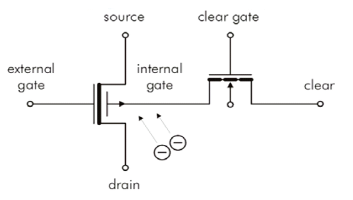
DEPFET sensors at Belle II

The Belle II experiment is a particle physics experiment currently being set up at the site of the High Energy Accelerator Research Organization (KEK) in Tsukuba, Japan, and is expected to take its first physics data in 2016. It will exploit the unprecedented luminosity (8×10^{35} Hz/cm^2) of the SuperKEKB accelerator. The experiment requires excellent vertexing performance in the vicinity of the primary interaction region. For precise vertex reconstruction, highly granular pixel detectors are needed in the innermost layers, featuring fast readout and minimum material budget to reduce the impact of multiple Coulomb scattering on measurement. This severely constrains sensor thickness, power consumption, and the design of detector services.

The DEPFET technology of active pixel sensors is among the frontier detector concepts for high energy physics at high luminosities. It has been chosen for the innermost 2 layers of the new Belle II vertex (VXD) detector, together with four layers of strip detectors (SVD). The in-pixel amplification of the DEPFET technology allows for 75 micron thin low-noise sensors which do not require additional support or cooling structures in the active region of the detector. Spatial point resolutions below 10 μm are expected. A unique gated data acquisition mode allows to suspend data readout for time periods with high noise occupancy; over this period, acquired charge is frozen and kept for later readout. The front end electronics and the data acquisition schemes supporting the integration into Belle II are finalized and the two-layer pixel vertex detector (PXD) will be ready for data acquisition from its 7.6 million pixels in 2016.

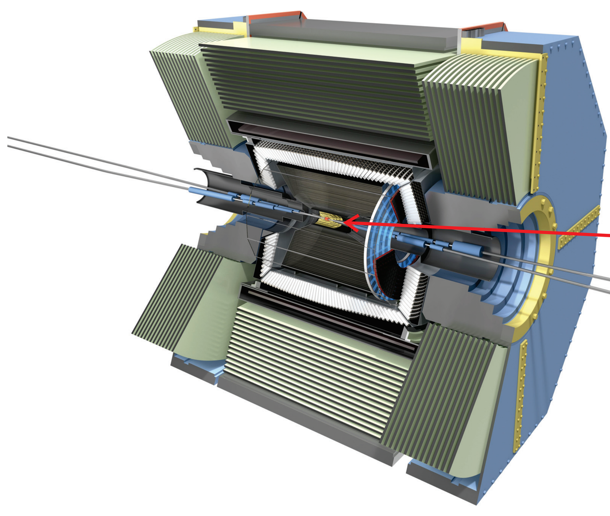


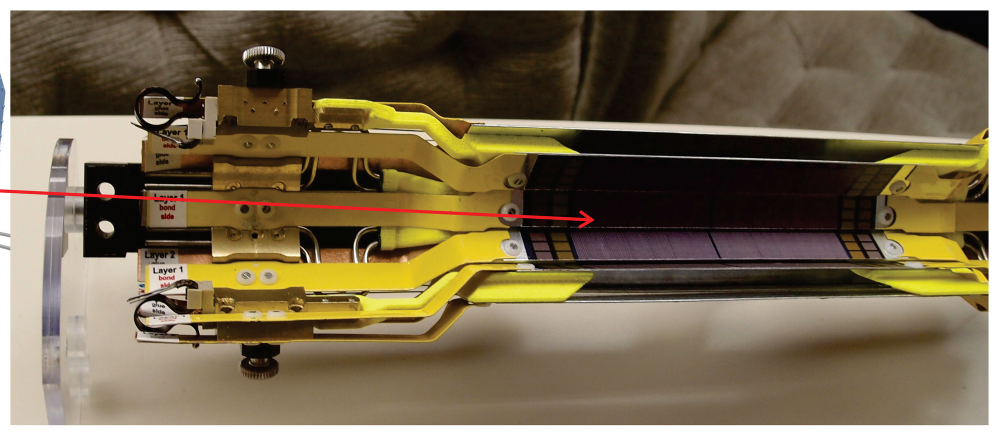
DEPFET pixel design



DEPFET pixel schema

- DEPFET sensors with active readout structures located on the sensor surface
- Produced with high and medium energy implantation technology
- Each pixel has an integrated p-FET transistor
- Sideward depletion creates a potential minimum for electrons under the channel
- Electrons are collected in the internal gate and modulate the transistor current
- Signal charge is removed via a clear contact

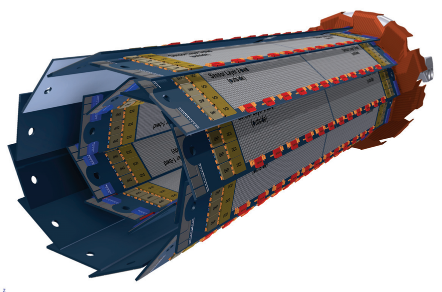

Arrangement of the vertex detector (DEPFET) within the inner tracker in Belle II experiment in KEK, Japan


PXD for Belle II - design and mockup by MPI Munich

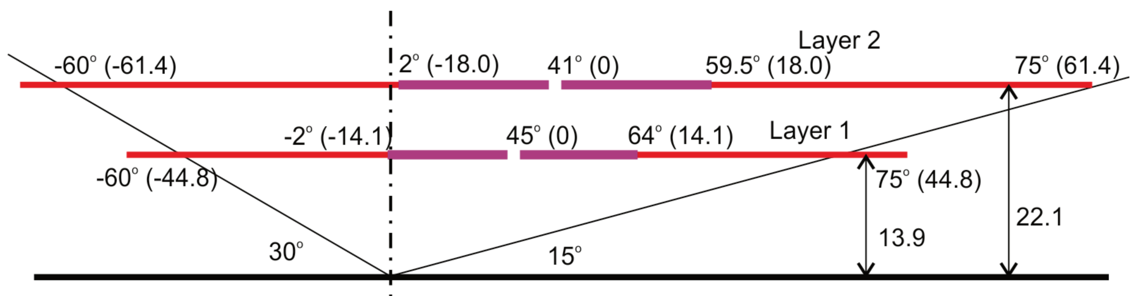
Design considerations

Current experiments use pixel detectors placed as close as possible to the collider interaction point. Such detectors face several design challenges: they have to combine low mass for non-intrusiveness with high granularity for high vertexing performance at high beam background exposure. The high granularity and beam background lead to huge data flows from the innermost layers, creating additional constraints related to reasonably achievable transmission and data processing bandwidths. A compromise between data flow and tracking/vertexing performance has to be sought, as well as improvements in noise suppression and data reconstruction that allow to push design optima within achievable limits. Increased charge-sharing between pixels is a typical example, allowing to increase pixel size and, consequently, decrease data flows, while keeping spatial resolution of a sensor.

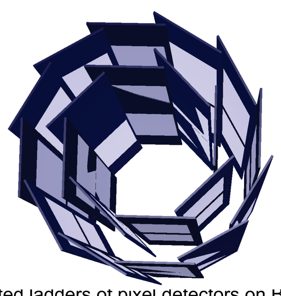
The DEPFET technology can produce matrices with a wide range of pixel sizes, from 20 microns to over 100 microns. Pixel sizes can even be optimized within sensor ladders to further reduce granularity and data flows.



	Inner Layer	Outer Layer
Modules	8	12
Thickness	75 microns	75 microns
Length	90 mm	123 mm
Sensitive	44.8 x 12.5 mm^2	61.44 x 12.5 mm^2
Pixel Size	55,60 x 50 μm^2	70,85 x 50 μm^2
Pixels	3.072 x 106	4.608 x 106
Frame Rate	50 kHz	50 kHz



Pixel inner detector DEPFET layers on Belle II

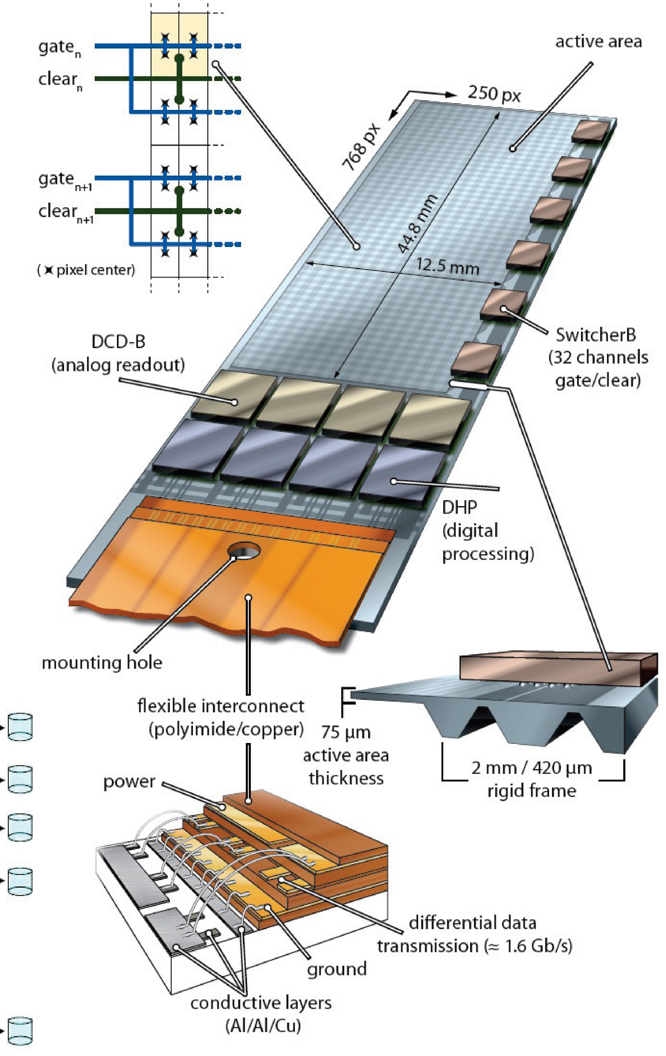

Tilted ladders of pixel detectors on Belle II

Data acquisition

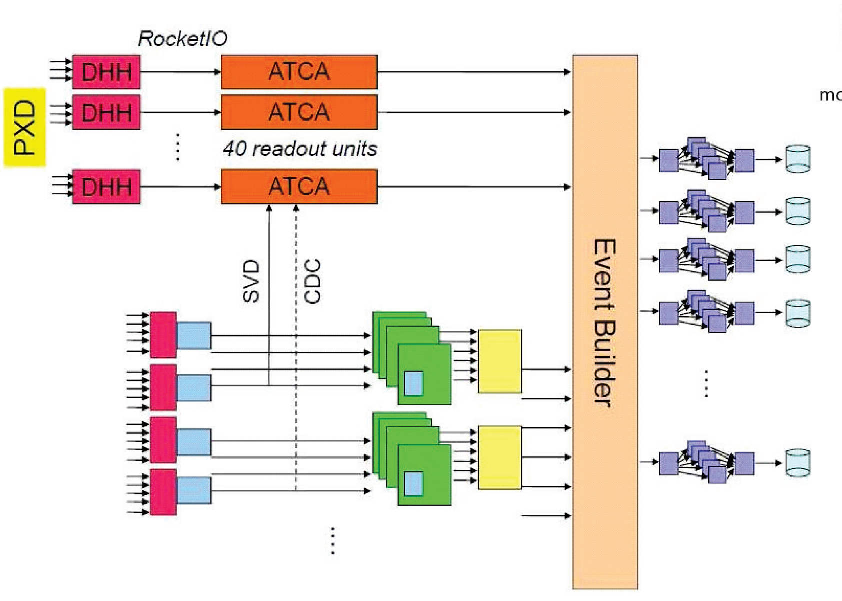
Belle II PXD produces 180 GB/s of raw data:

40 PXD half ladders with 250 x 768 pixels each and 8 x 106 pixels in total, expected occupancy up to 3 %, trigger rate of 30 kHz. To reach achievable data flow, data volume must be reduced by a factor of 10 before the PXD stream is combined with data from other subdetectors.

PXD module readout: Gate and Clear Switchers organize the readout sequence, DCD (Drain Current Digitizer) are readout chips and A/D converters, DHP (Digital Handling Processor) chips provide first-stage pre-processing and data reduction (pedestals, CMN correction, zero suppression, compression algorithm). From DHP to DHH (Data Handling Hybrid) 15 m line: kapton converted to twisted-pair in a passive patch panel, DHHs via optical links to ATCA Compute Nodes, ATCA CNs reduce data based on triggers, ATCA CNs compute fast tracking using SVD data to quickly identify regions of interest in the PXD.



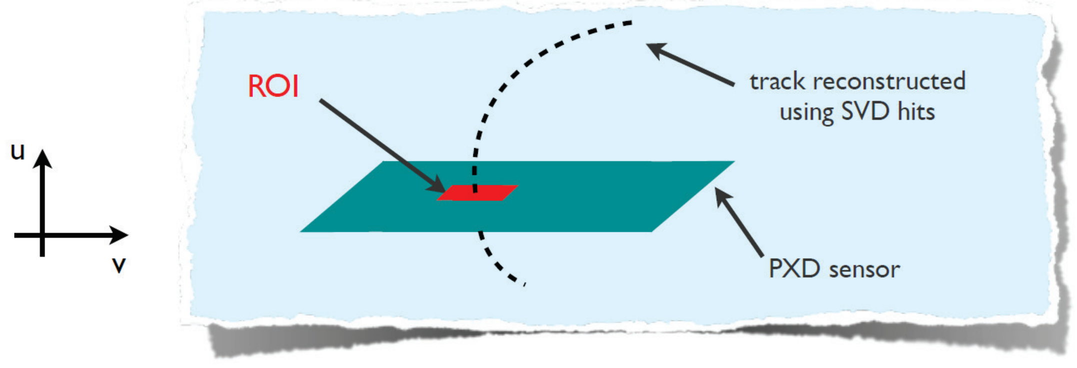
Pixel DEPFET ladders readout arrangement



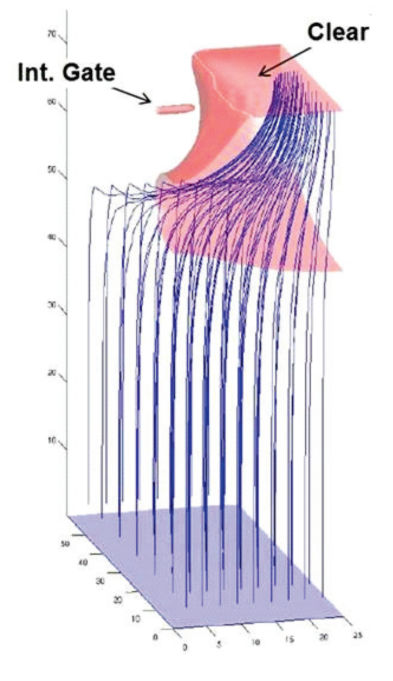
Data acquisition scheme of pixel detectors at Belle II

Hit position reconstruction

The point where a particle track crosses a sensor is reconstructed using pixel charges in a cluster, RMS pixel noises and clustering thresholds. These data are used to estimate hit position and its uncertainty. Tracking can provide a further improvement in accuracy and precision: when a hypothesis about a track in the sensor is available, information on incidence angle, particle type, etc. can be used to improve the estimates. Several methods are available to improve hit position reconstruction in the Belle II vertex detector:
1) Sensor design provide efficient charge transport from full bulk to internal gate of DEPFET.
2) Ladders are tilted to increase charge sharing between pixels in R-phi coordinate.
3) Data reduction based on regions of interest (ROIs) using an online track extrapolation from four strip layers - the motivation behind is to suppress noisy channels and high beam background.
4) Correction of position bias of reconstructed cluster position for non-symmetric small clusters.



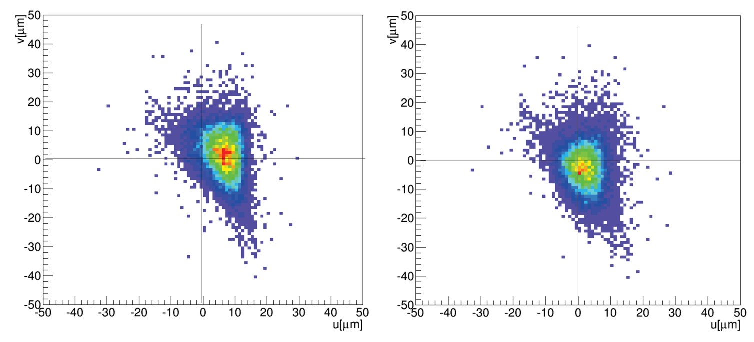
Region of interest recognition on DEPFET pixel layer



Charge drift lines in an individual DEPFET pixel cell (simulation) for an operation case called "gated mode" (Richter, MPI)

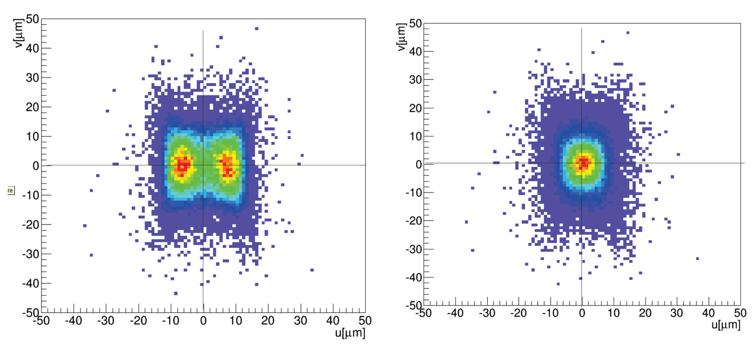
Using cluster shape to improve reconstruction of hit position estimates

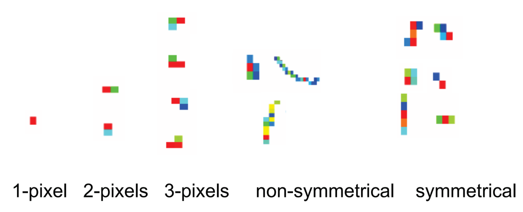
Cluster shape analysis are based on full Geant4 simulation in the basf2 (simulation and reconstruction framework developed for the Belle II experiment). The accuracy and precision of hit position estimates strongly depends on cluster size. There are five basic types of clusters for four different pitch in v direction: single, double and triple pixel clusters, rest of symmetrical and nonsymmetrical clusters. In Belle II geometry for particles shot of 0.05 – 3.0 GeV electrons and positrons in uniformly distributed directions from the interaction point and in range phi 17 – 150 deg, 25 % form single-pixel clusters, 15 % form 2-pixel clusters along the R-phi coordinate, and 26 % along the z-coordinate. 12 % form non-symmetric "L"-shaped three-pixel clusters, 16 % form larger non-symmetrical clusters, and rest 6 % form symmetrical clusters (like 2x2 clusters).


Residual plot of "L" shape in one orientation before (left) and after (right) correction

For single-pixel clusters, the obvious hit position estimate is the center of the pixel. For larger clusters, hit position is estimated separately for the u-coordinate (R-phi) and v- coordinate (z-direction), using center-of-gravity estimates for clusters size 2 and the analog head-tail method for size 3 and more. Generally, the average resolution is best for small clusters of size 2 and 3.

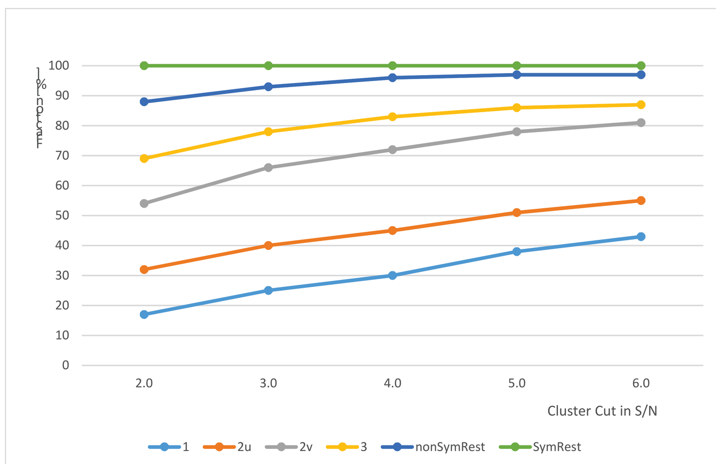
For one-pixel clusters, hit position uncertainty is given by the area where a given energy deposition is mostly contained within the single pixel - it therefore depends on pixel charge and clustering threshold. With particles arriving at different (and unknown) directions, the standard eta-correction algorithms are not usable. Therefore, simple bias-correcting methods for center-of-gravity and head-tail estimates are desirable, that would only use measurable quantities to correct for bias. The 3-pixel "L"-shaped clusters are the simplest and most common case where such a bias correction would be desirable. For these clusters, the center-of-gravity estimate is biased by about 10% of pixel size, comparable to the typical RMS error of the position estimate. Therefore, correction of the bias highly desirable.


Residual plot of "L" shape in all orientation before (left) and after (right) correction



Categorization of cluster shapes

We show that adding a fixed (pixel noise dependent) charge to the pixel with zero signal in the 2x2 matrix can significantly improve the center-of-gravity estimate of hit position for such clusters. Adding the fourth pixel with the signal of 1.3 x ENC improved position RMS error from 7.4 microns to 4.7 microns in R-phi, and reduced position from 5 to 2 microns. Bias and RMS error for different cuts and corrections are summarized in tables.



Fractions of cluster shape types for different clustering cuts.

clustering cuts 3xENC (default)

Cluster cut [ENC]	2	3	4	5	6
No correction R-phi	5.8	5.7	5.6	5.6	5.5
No correction Z	4.0	3.4	3.1	2.9	3.0
Correction R-phi	1.9	2.0	2.0	1.8	
Correction Z	-0.6	-1.3	-1.4	-1.9	

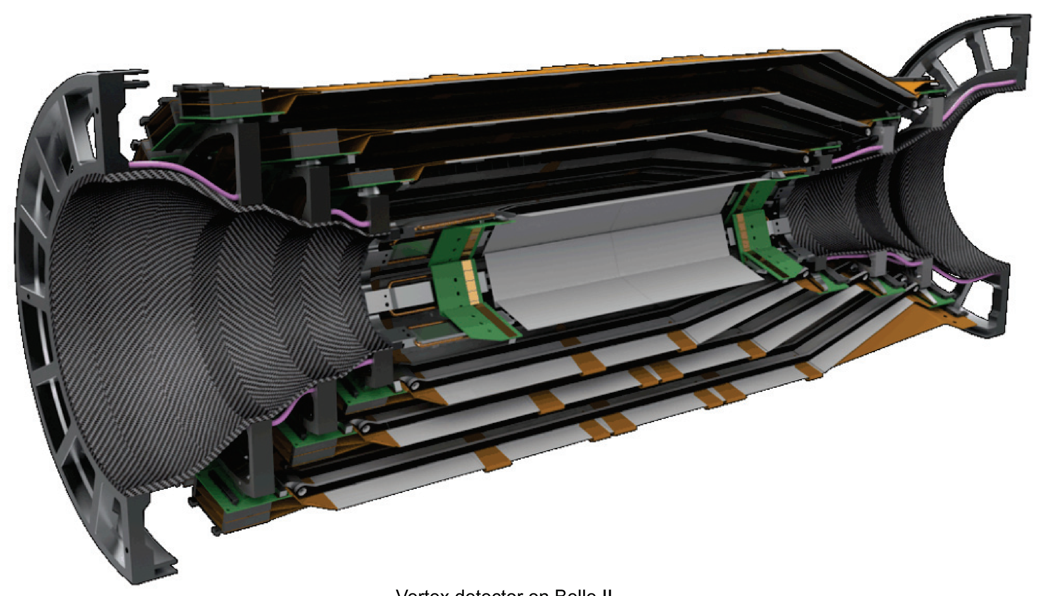
Table for hit position bias reconstructed from "L"-shaped clusters before and after correction for different clustering cuts

Cluster cut [ENC]	2	3	4	5	6
No correction R-phi	7.6	7.4	7.4	7.4	7.5
No correction Z	7.3	7.6	8.0	9.2	10.1
Correction R-phi	4.9	4.7	4.7	4.7	
Correction Z	6.6	7.4	8.0	9.6	

Table for RMS error reconstructed from "L"-shaped clusters before and after correction for different clustering cuts

Conclusions

The exciting Belle II experiment is under construction at KEK. The goal of the first physics run in 2016 seems realistic and the pixel detector will be ready with all specifications met. Improvement of hit position reconstruction is important for vertexing performance and new physics searches. Realistic estimates of hit position uncertainties and correction of reconstruction bias is equally important. We have shown that the most important reconstruction biases in small "L"-shaped clusters can be easily corrected by adding a constant charge in the missing pixel. This efficiently corrects for center-of-gravity bias and improves the distribution of residuals. Impact on physics analyses is under study.


Vertex detector on Belle II