The DEPFET Active Pixels for Belle II - Resolution in 50 micron Thinned Sensor

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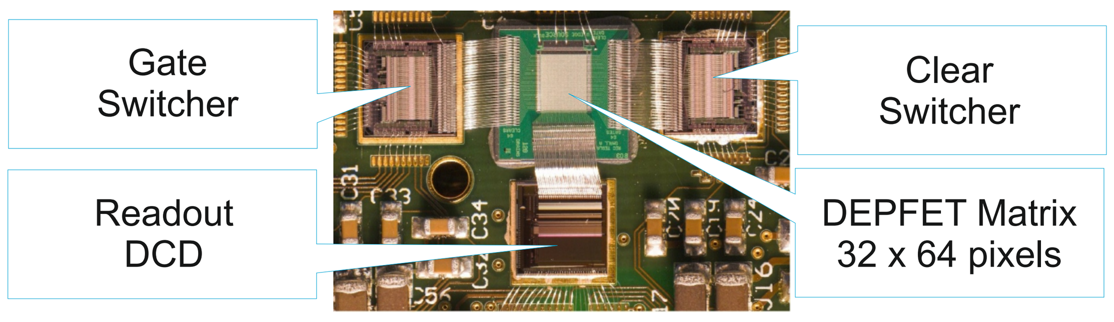
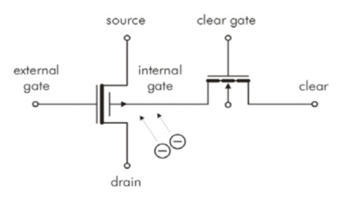
The DEPFET

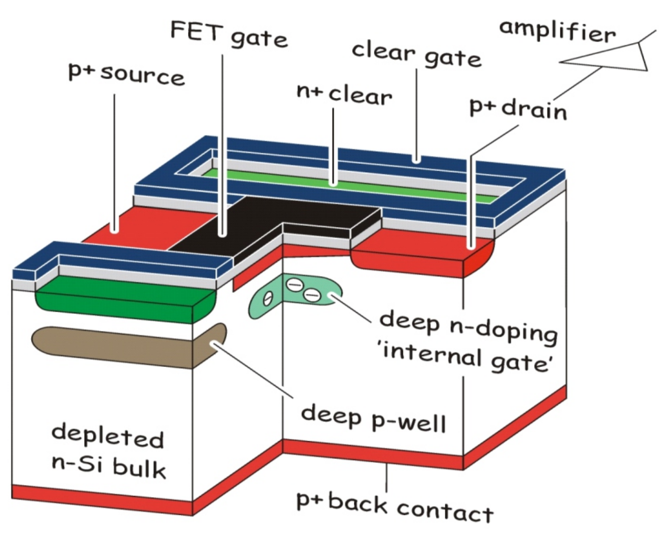
Detectors for experiments at future colliders - e.g. the Super B-factories or the ILC - require excellent vertexing performance for the layers close to primary interaction region. For precise vertex reconstruction, highly granular pixel detectors are needed, together with fast readout and minimum material budget to reduce the impact on the measurement due to multiple Coulomb scattering. The latter requirement severely constrains the sensor thickness, power consumption, and the design of the 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 new Belle II experiment at the SuperKEKB collider in Japan. The in-pixel amplification of the DEPFET technology allows for very thin low-noise sensors. The front end electronics and the data acquisition concepts supporting the integration into Belle II are finalized and the two-layer detector (PXD) will be ready for acquiring data from 7.6 million pixels in 2015.

The vertex detector of Belle II (PXD) uses DEPFET monolithic silicon active pixel sensors which do not require additional support or cooling structures in the active region of the detector. Spatial point resolutions (leave out the 50 degrees) below 10 μm are expected.





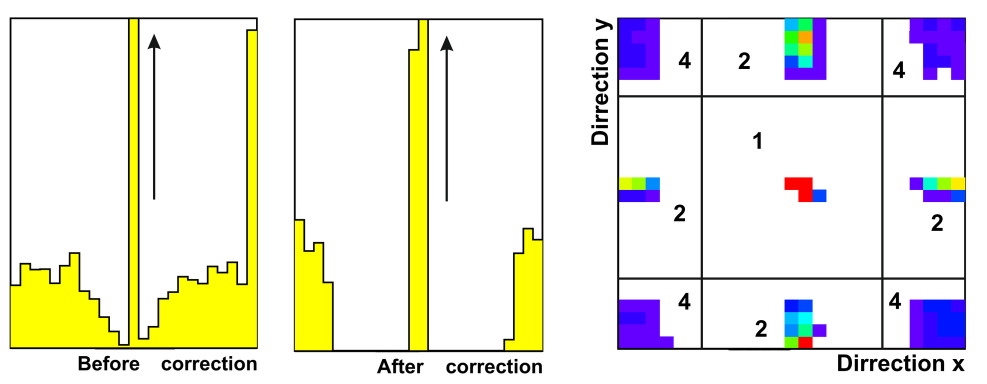


- Each pixel has an integrated p-FET transistor
- Sideward depletion creates a potential minimum for electrons under the channel
- Electrons are collected in the internal gate and modulate the transistor current
- Signal charge is removed via a clear contact
- DEPFET sensors with active readout structures located on the sensor surface
- Produced with high and medium energy implantation technology
- Common clear gate (CCG) and Clocked Common Clear Gate (CCCG) versions of DEPFET
- 32 x 64 pixels, thickness 50 μm, pixel size 50 μm.

Data processing and analysis results

The spatial resolution is largely affected by the cluster size achieved. However especially for tracks with normal incidence, thinned detectors have only a single pixel response over a large fraction of the pixel area, resulting in a cluster size for those tracks of mostly one. The response from most of the area has a cluster size of 1, close to pixels borders there are regions with a cluster size of 2, and at the pixel corners, the charge sharing is high enough to create response in up to 4 pixels. For the cluster size 2 and more the track intersection position can be calculated using well known methods like centre-of-gravity (COG) or head-and-tail. In the case of single-pixel response the hit is reconstructed in the pixel centre. The average resolution is better if the charge sharing is operational.

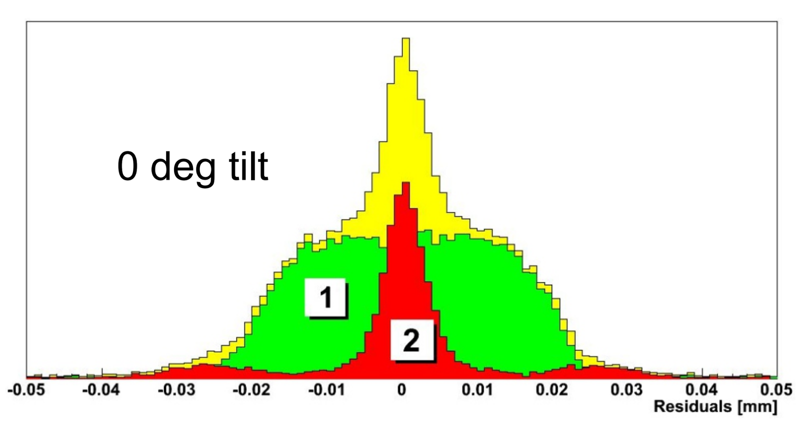
Data processing:
- Pedestal and common noise subtraction
- Cluster identification
- Cluster analysis (centre of gravity, signal, cluster size,...)
- Alignment of detectors
- η-correction of within-pixel response
- Residuals and resolutions analysis



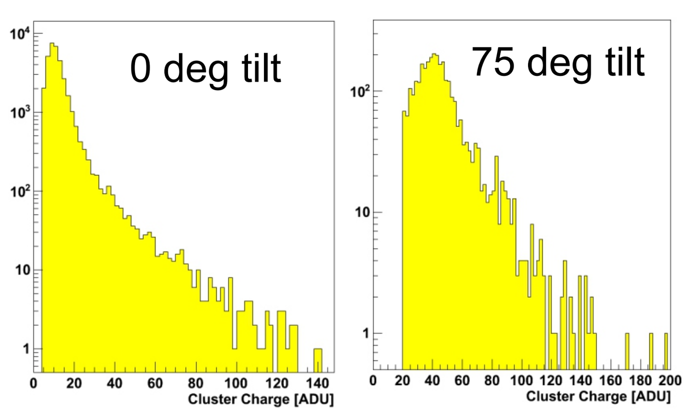
Distribution of hits over pixel area. The position reconstruction calculated using COG or head-tail method (left) was corrected with an η algorithm (middle). In 2-dimensional plot (right) the regions of various cluster sizes are shown: single-pixel response (1), with 2 pixels response (2) and with 3 to 4 pixels response in corners (4).

The spread of residuals is typically calculated from the histogram Gaussian fit. However for a large part of area 1 the residual distribution is not Gaussian and a different method should be used. It is useful to calculate the residual width separately for area 1 and the rest of the pixel.

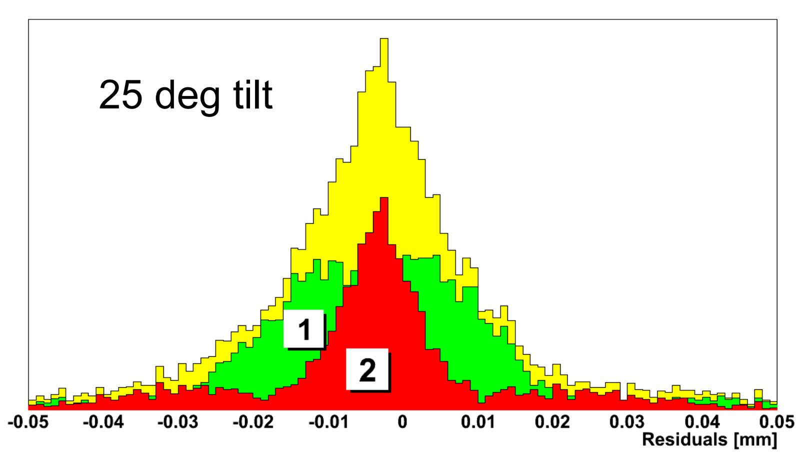
It is sometimes useful to use the full width at half maximum (FWHM) as a more stable value, especially for the fraction of area 1.



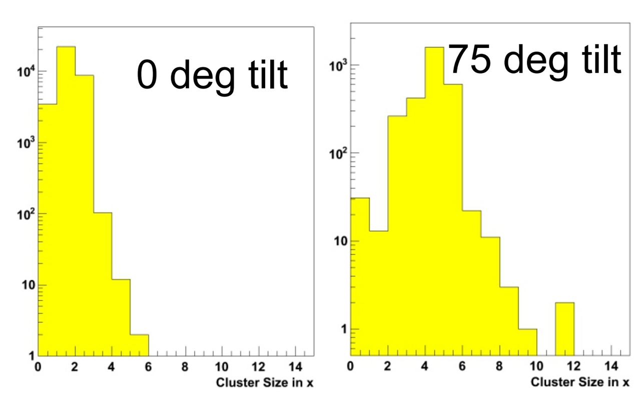
Residuals distribution for perpendicular tracks with single pixel response (1) and more than 1 pixel response (2) (linear vertical scale).



The distribution of signal in DEPFET shows higher response for tilted detector



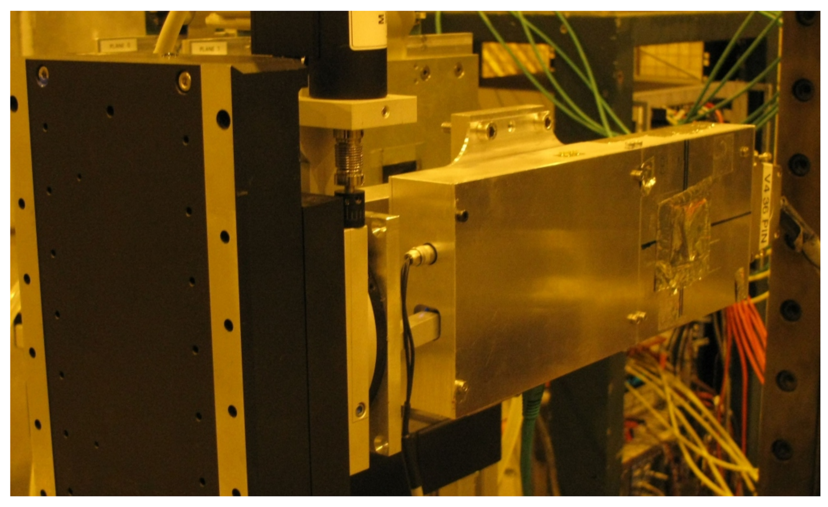
Residuals distribution for 25 degree tilted tracks with single pixel response (1) and more than 1 pixel response (2) (linear vertical scale).

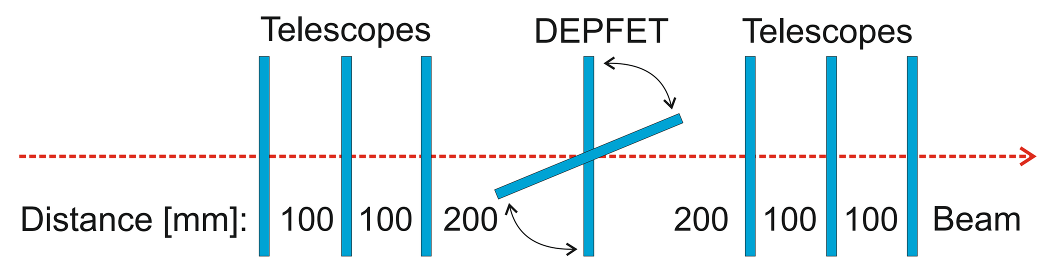


Cluster size for tilted detector is higher within expectation

The 2011 DEPFET beam test

450 μm thick ILC type prototypes were tested using high-energy beams during previous years. The first DEPFET sensors with a geometry design close to the Belle II vertex detector were tested at the CERN SPS in October 2011 pion beams with an energy of 120 GeV. The sensors tested were 50 μm thick with pixel sizes of 50 x 50 μm, gate length of 6 μm, depleted by punch-through and operated at 100 MHz. For tracking, 3 + 3 EUTEL telescope planes with Mimosa26 pixel sensors were used. The DEPFET matrix could be rotated relative to the beam direction in a wide range up to 75 degrees.

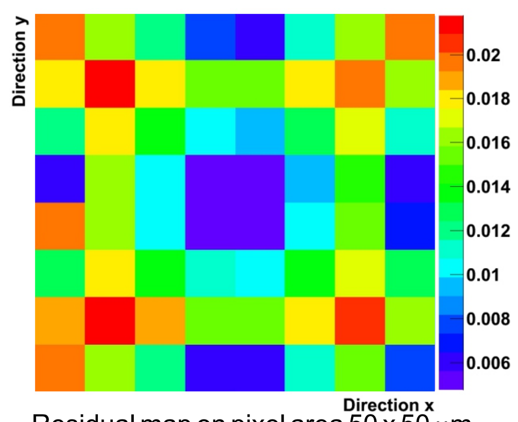




Beam test 2011 of thinned DEPFET detector with EUTEL telescopes in the beam test at the CERN SPS H6B area

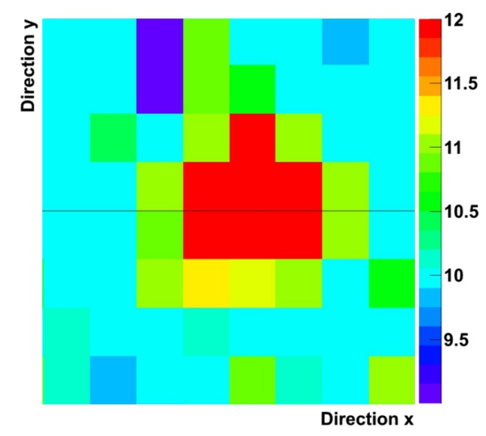
Residual distributions

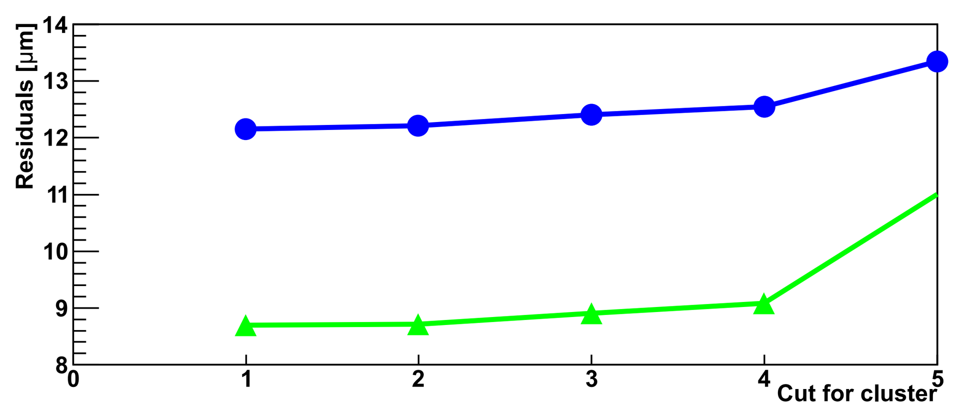
Distribution of residual width over pixel area shows best values at the pixel edges and corners where the charge sharing allows for weighting several cell response. Single-pixel response in the rest of the area leads to residual width corresponding to binary readout. For the tilted tracks the charge sharing higher and the residual width is improved. One can also observe the highest collected charge in the middle of the pixel. This is due to the fact that the whole charge is read out by one pixel.



Residual map on pixel area 50 x 50 μm

Collected charge map on pixel area 50 x 50 μm

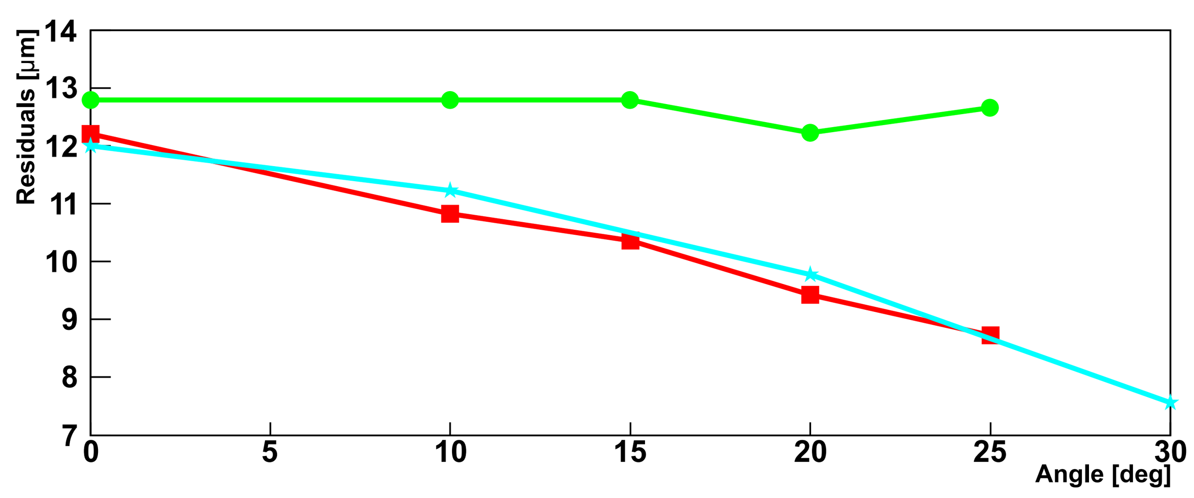




The sensitivity of analysis to clustering cuts is low for cluster charge cut as high as 30 per cent of most probable value: the reconstruction efficiency degrades, but the effect on residual distributions is below 3 % with normal incidence.

The head-tail calculation gives the same residual distribution as COG for angles up to 25 degrees and the η correction improves the residual spread by 0.2 μm for perpendicular tracks ("the worst" case).

The angle scan analysis and comparisons with simulation show good agreement in the residuals. The simulation was carried out in a program to optimize the tracking capabilities of the Belle II detector. The beam test data contain telescope tracking errors estimated to about 4.5 microns. This contribution gives a slightly better result for the DEPFET properties than expected.

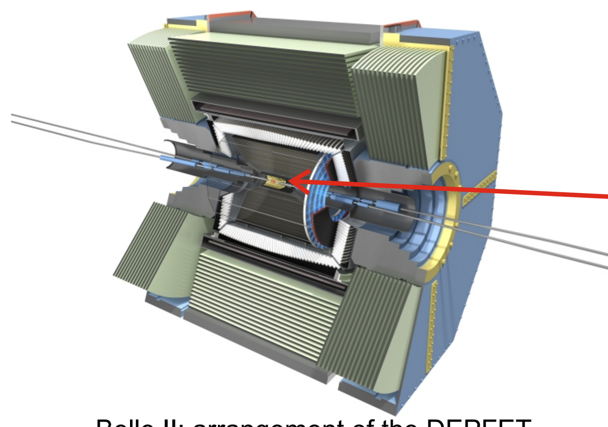


Residual width vs. incidence angle. Squares: test beam, x direction (tilted), circles: test beam, y direction (not tilted), asterisks: MC simulation for 50 μm thick silicon, x direction (tilted).

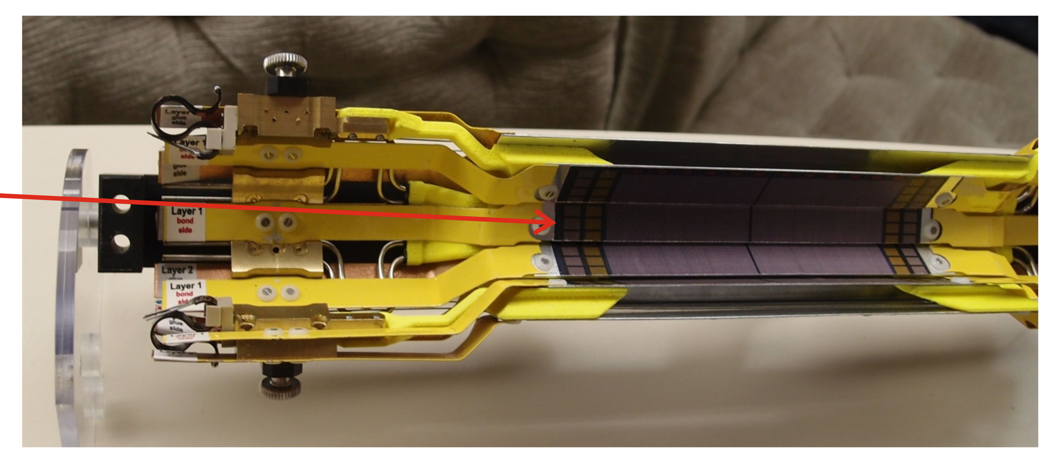
Conclusions

The exciting physics experiment Belle II is under preparation at KEK. The goal to start data acquisition in 2015 seems realistic and the pixel detector will be ready with all required properties. Beam tests and simulations are important in validating the detailed simulations, and convey a deep understanding of the properties of the real modules.

The predicted resolution of the DEPFET modules from simulations is now confirmed by a beam test analysis. The required precision of the Belle II PXD sensors seems to be realistic and feasible.



Belle II: arrangement of the DEPFET detector designed for the inner tracker in sBelle experiment in Japan



PXD for Belle II - design and mockup by MPI Munich