DEPFET as physicist's measurement tool

Peter Kvasnicka
Charles University in Prague

for the DEPFET collaboration

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Outline

DEPFET Active Pixel Detector

Overview

DEPFET in Belle II

This talk is about DEPFET sensors in the vertex detector of Belle II, that is, about the Belle II pixel detector - PXD.
There are another two qualified talks on Belle II PXD at this conference,

The previous talk by Felix Mueller "DEPFET at Belle II", which covered

- Belle II and its DEPFET-based vertex detector,
- DEPFET technology and working principle
- DEPFET operation and readout
- and some experimental results,

Friday talk by David Muenchow "The Belle II Pxiel Detector DAQ", covering

- Belle II vertex detector (VXD) DAQ
- Data reduction and
- Beam test results

This talk is software-oriented, covering

- DEPFET simulation and reconstruction
- Challenges of the DEPFET-based Belle II PXD data processing
- In some aspects, the January Belle II VXD testbeam at DESY

KEKB and the Belle II detector

The Belle II experiment on Super-KEKB

- Luminosity 40× higher than Belle
- Nano-beam scheme
- 30 kHz trigger rate
- Beam energies 4(e^+) and 7(e^-) GeV

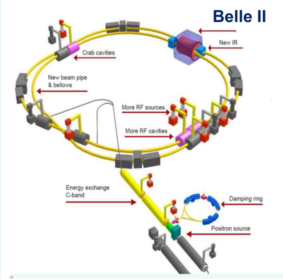


Figure: The KEKB accelerator

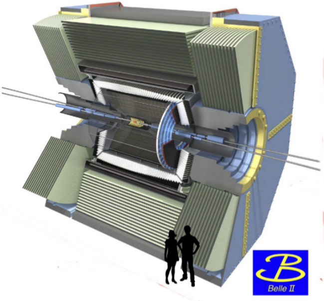
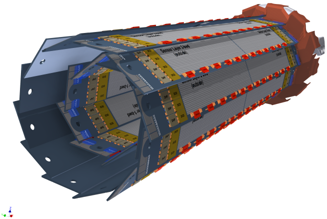


Figure: The Belle II detector

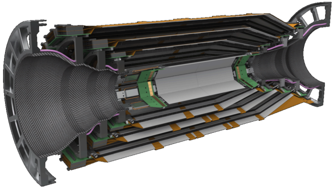
The vertex detector of Belle II

The pixel vertex detector - PXD



- 2 innermost layers of DEPFET pixel sensors
- 40 half-ladders 768 x 250 pixels, 8 MPix
- pixel size 50 $\times$ 50/60 μm^2 (inner layer), 50 $\times$ 70/85 μm^2 (outer layer), inner 512 / outer 256 pixels.
- thickness 75 μm

The strip vertex detector - SVD



- 4 layers of double-sided silicon strip sensors
- wedge sensors on outward side of outer 3 layers
- strips read by APV25 chips, 30 ns sampling time
- pitch 50-75 μm in R-ϕ (p-side), 160-240 μm in Z (n-side)
- thickness 320 μm

Belle II PXD simulation

Overview

- Simulation starts with the DEPFET sensor and its sensitive detector class that captures data from Geant4 simulation
- Digitization - simulation of detector response
  - Simulation of charge drift and diffusion
  - Simulation of Lorentz shift
- Simulation of readout chain - so far limited to 8 bit ADC discretization.
- Misalignment - *deferred to the next section*

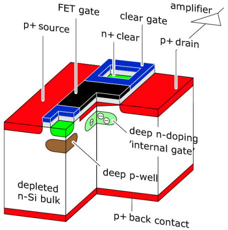


Figure: Schematic of a DEPFET pixel structure

Specific challenges of the PXD

- The 40 megapixels, which make DAQ people concerned about data rates, make software people concerned about management of and (fast) access to pixel data, such as noise or pixel gain maps, at reasonable computing costs.
- The 75 μm that make physicists happy about low material budget, mean that surface deformations of sensors must be taken into account in alignment.

DEPFET

DEPFET sensor simulation

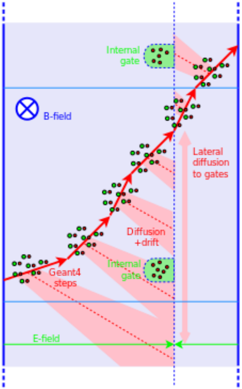


Figure: Simulation of charge drift and diffusion in a DEPFET sensor (B. Schwenker, Uni Goettingen).

- We use very small Geant4 steps in Si (5 μm).
- Velocity, diffusion and Lorentz shift are integrated along the track until the zero potential plane is reached.
- Lateral diffusion to internal gates is simulated as Brownian walk in a magnetic field.

Diffusion and drift in E and B field

$$
\begin{aligned}
v(z,t) &= \mu(E).E(z) \\
E(z) &= -\left(\frac{V + V_{dep}}{d} - \frac{2zV_{dep}}{d^2}\right) \\
\mu(E) &= \frac{v_{max}/E_c}{\left[1 + \left(\frac{E}{E_c}\right)^{\beta}\right]^{1/\beta}} \\
\tan(\theta_L) &= \langle \mu(E) \rangle_z r_H B
\end{aligned}
$$

Belle II PXD reconstruction

- Clustering and hit reconstruction
  - Identify connected groups of digits as traces of a particle hit
  - Identify the position of the hit from digit data
  - Calculate the precision of hit position estimate
- Correcting for Lorentz shift
  - Estimate the correction based on cluster data, local magnetic field, and charge mobilities in the sensor
  - We provide the midplane shift estimate, which is the median shift for particles that traverse the whole thickness of the sensor, but is off otherwise.
- Look-back reconstruction
  - Some estimates can be improved if a track hypothesis is available
  - Therefore, a mechanism allowing to make more precise estimates of hit position and its error, or of Lorentz shift correction is very useful.
  - The same mechanism is used in simulation to implement misalignment using MC track information.

Clustering

- Clusters formed from pixels with signals over a given (zero-suppression) threshold
- Fast 2D clustering (*Martin Ritter, MPI Munich*) uses a running buffer for digits of a single row.
  - Each pixel is visited once.
  - In generic case, probing consists in looking at 3 positions in the buffer and at the nearest cluster downstream of the current position.
  - Clusters are stored in a fast buffer

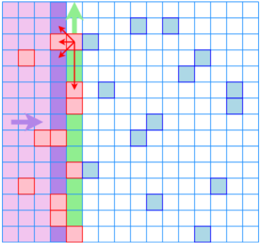


Figure: Fast 2D clustering of PXD

DEPFET Active Pixel Detector

Hit reconstruction

- Simple expressions based on the classical Turchetta's paper*.
  - "Unseen charge" formulas for cluster projections of size 1 and 2
  - Analog head-tail for projections of size 3 and more
  - Cluster shape taken into account in calculation of error covariance.
  - Based on simulations/real data, ad-hoc corrections will be applied.
- So far:
  - No η-corrections implemented
  - No special analysis / merging of large clusters

*Turchetta, R. : Spatial resolution of silicon microstrip detectors. NIM A335 (1993) 44-58

- The unseen charge method
  - Motinvation: Position error of size 1 cluster
  - Position estimate is clear - centre of the pixel
  - The trivial estimate of pitch/sqrt(12) is **wrong**.
  - Along with the signale of the one pixel, we have zero (below threshold) signals in neighbour pixels.

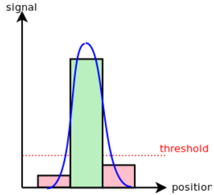


Figure: The unseen charge method

Hit reconstruction for various cluster sizes

Hit position: (u_c, v_c)	Hit position error $\begin{pmatrix} \sigma_u^2 & \rho\sigma_u\sigma_v \\ \rho\sigma_u\sigma_v & \sigma_v^2 \end{pmatrix}$
Positions and their errors are calculated separately from cluster projections to each direction. The correlation coefficient is calculated as $\rho = \frac{\sum_{pixels} S_i(u_i-u_c)(v_i-v_c)}{\left(\sum_{pixels} S_i[(u_i-u_c)^2+\epsilon_u^2]\right)^{1/2}\left(\sum_{pixels} S_i[(v_i-v_c)^2+\epsilon_v^2]\right)^{1/2}}$	(u_i, v_i) pixel positions; S_i pixel signals; $\epsilon_u = \frac{p_u}{\sqrt{12}}$ in-pixel spread; $\epsilon_v = \frac{p_v}{\sqrt{12}}$ in-pixel spread
size in u = 1 Center of pixel	$\sigma_u = p_u \frac{(n_v+2)S_{thr}}{S+(n_v+3)S_{thr}}$ n_v cluster size in v; S_{thr} 0-supp. threshold
size in u = 2 $u_c = \frac{S_1u_1+S_2u_2}{S}$	$\sigma_u = p_u \frac{(n_v+2)S_{thr}}{S+(n_v+3)S_{thr}}$ n_v cluster size in v; S_{thr} 0-supp. threshold
size in u > 2 $u_c = \frac{u_h+u_t}{2} + p_u\frac{S_h-S_t}{2S_0}, \; S_0 = \sum S_i$	$\sigma_u = \frac{p_u}{2}\left[2\left(\frac{S_{thr}}{S_0}\right)^2 + \frac{1}{2}\left(\frac{S_h}{S_0}\right)^2 + \frac{1}{2}\left(\frac{S_t}{S_0}\right)^2\right]^{1/2}$

The same formulas are used for v

Look-back reconstruction in Belle II

RecoHits and look-back reconstruction

- RecoHits pass reconstructed hit data to tracking.
  - They contain local coordinates of the hit in a sensor
  - Plus they contain the (local) sensor plane.
- Tracking software asks for hit position and hit error through RecoHit methods, and passes the current track status with the query.
- Thus it is possible to provide better estimates of hit position and its error covariance - this is, for example, critical for wedge strip sensors)

Misalignment

Misalignment uses a logically similar mechanism:

- Local hit position is shifted according to misalignment parameters and MC track information.

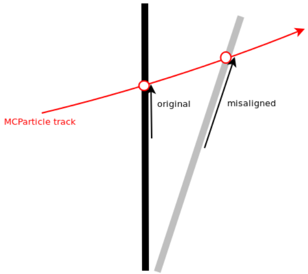


Figure: Misalignment of a planar sensor: displacement of *local* hit positions.

DEPFET
Active Pixel Detector

The January'14 Belle II VXD testbeam at DESY

Major test of Belle II vertex detector development maturity

- Sensors, readout, slow control
- DAQ, event building
- PXD ROI selection at two levels
- Test of DAQ, DQM, ExpressReco and off-line software
- Large dataset for analysis

Sensor setup

- 4 SVD DSSD planes
- 1 PXD plane
- 2 $\times$ 3 planes of AIDA pixel telescopes for triggering and tracking studies.

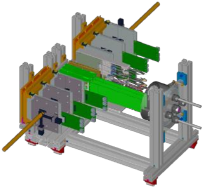


Figure: Telescope planes in the January 2014 DESY testbeam

Testbeam DAQ

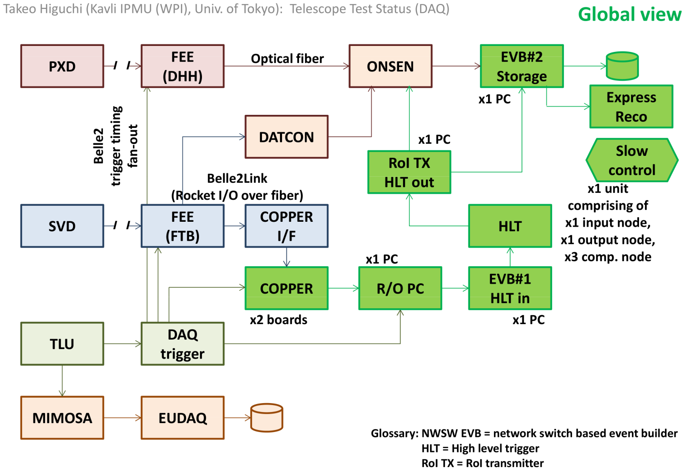


Figure: The January 2014 DESY testbeam DAQ system, credits Takeo Higuchi, Tokyo University

Testbeam setup and event views

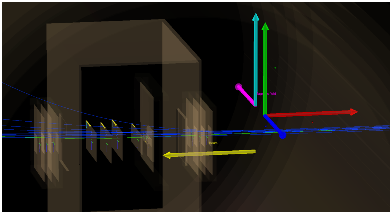


Figure: Global view of testbeam geometry

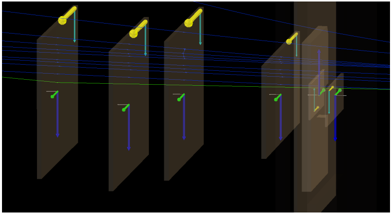


Figure: PXD and three AIDA telescope planes.

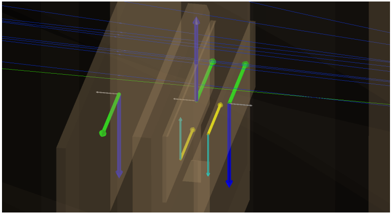


Figure: The PXD plane in testbeam event viewer

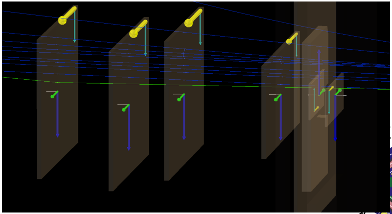


Figure: 4 SVD planes and the PXD plane.

Data acquired in the beam test

Data	VXD (TB)	Telescopes (TB)
Total acquired	2.50	0.093

Data	VXD (TB)	Merged Tel+VXD (TB)
For further processing	1.99	0.048

Data	VXD (kEvts)	Tel+VXD (kEvts)
Total	18,366	12,249
B = 1.0 T	2,399	1,482
B = 0.5 T	102	102
B = 0.2 T	313	0
B = 0.0 T	15,553	10,865
E = 5 GeV	1,397	1,376
E = 4 GeV	9,311	5,804
E = 3 GeV	9.311	3,563
E = 2 GeV	661	104

Table: Breakdown of testbeam dataset by magnetic field and beam energy

DEPFET Active Pixel Detector

Residuals after Millepede alignment using the 4 SVD planes

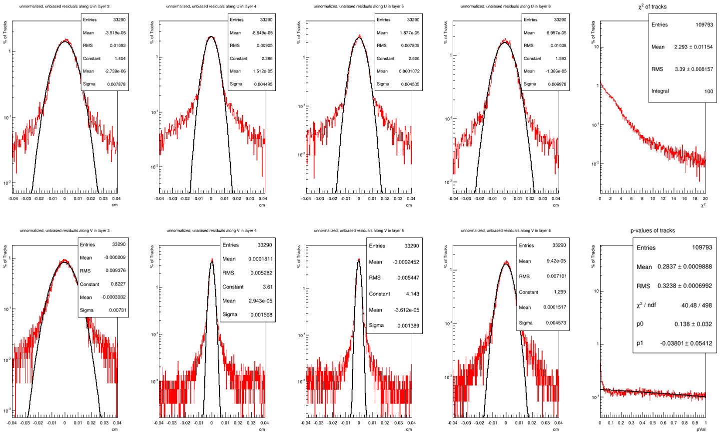


Figure: The plots show resiludals (track - measured) on 4 SVD planes after Millepede alignment. For such a small number of planes, the alignment is weak. The two plots on the right show χ^2 distribution and the distribution of p-values.

PXD alignment

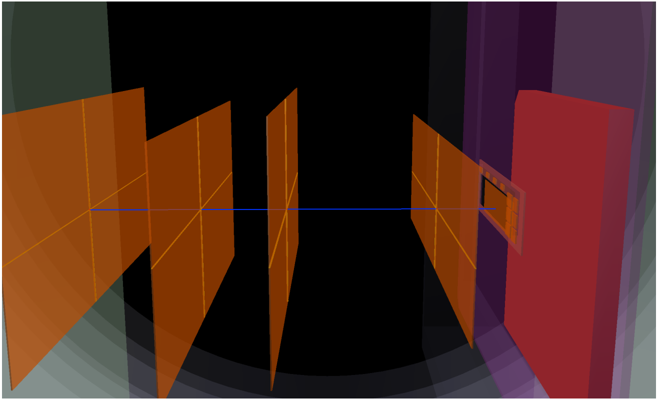


Figure: Alignment of PXD: Note the displacement of the active area wrt. the sensor frame.

PXD alignment 1

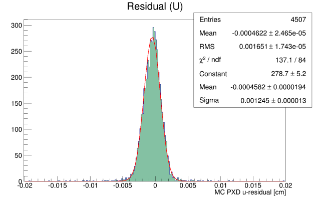


Figure: u-residuals in PXD, simulation

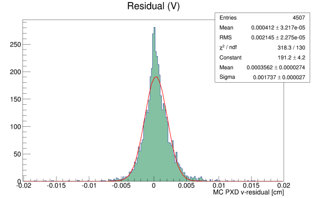


Figure: v-residuals in PXD, simulation

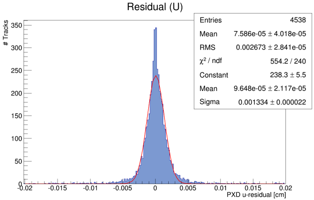


Figure: u-residuals in PXD, testbeam data

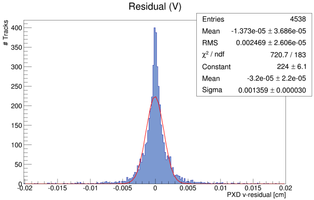


Figure: v-residuals in PXD, testbeam data

DEPFET Active Pixel Detector

PXD alignment 2

A different software chain, alignment with forward telescope arm

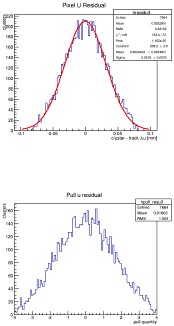


Figure: Residuals and pulls, PXD u-ccordinate

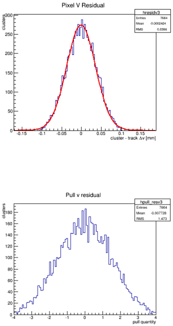


Figure: Residuals and pulls, PXD v-ccordinate

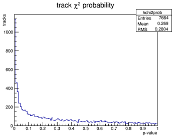


Figure: P-values

DEPFET

Conclusions

- The DEPFET-based vertex detector of Belle II is strongly constrained by high performance requirements and harsh operating conditions.
- The pixel sensors together with the whole readout chain planned for Belle II has been tested in the January 2014 testbeam at DESY.
- It was found to operate, and so was DQM and offline software, though some features are missing, and implementation of the missing features goes hand in hand with analysis of testbeam data.

Thanks

Thank you for attention.