Operation Experience of the DEPFET based Pixel Vertex Detector of the Belle II Experiment

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Physics data taking with full detector started 2019

- **B factory:** $E_{\text{cm}} = M_{Y(4S)} \approx 10.58 \text{ GeV}$
- **Goal:** $L = 6 \cdot 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
- **Record by now:** $3.8 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- **Target:** $L_{\text{int}} = 50 \text{ ab}^{-1}$

- Maximum trigger rate 30 kHz
- Less boost than KEKB/Belle, need $\sim 2$ times better vertex detector resolution
Belle II Vertex Detectors

- Requirements:
  - Excellent vertexing and tracking down to low $p_T$ (<100 MeV/c)
  - Very low material budget
  - Inner layer only 14mm away from interaction point
  - Impact parameter resolution $\sigma_z < 20\mu m$
  - Operate in high background environment
  - Trigger rate 30 kHz

- Pixel Vertex Detector (PXD)
  - 2 layers
  - DEPFET Pixel

- Silicon Vertex Detector (SVD)
  - 4 layers
  - 2-sided silicon strips
  - Covered by next speaker
  - Shared 2-phase CO$_2$ cooling system
PXD Sensors Working Principle

- Depleted P-channel Field Effect Transistor (DEPFET)
  active pixels on fully depleted silicon bulk
- Fast charge collection (~ns) into internal gate
- Non-destructive read-out, read-out current modulated by collected charge
- Clear after read-out
- Internal amplification, large signal-to-noise ratio
- Low power consumption and heat dissipation
- Radiation hard
- 75μm thin sensors

\[ g_q = \frac{\partial I}{\partial q} \approx 500 \, \text{pA/e}^- \]
PXD Sensor Modules

- Sensors thinned to 75μm in active region
- Mechanically self supporting due to rigid frame
- Pixel sizes: 50x(55 – 85)μm²
- Rolling shutter read-out → low power
- 50kHz → 20 μs integration time
- 192 gates, ~100ns per gate
- Design: 1% occupancy in layer 1
- 3% occupancy limit (DHP, DAQ, tracking)
- 40 sensors, 250x768 pixels each = ~8 Mpixel
- 2 sensor modules glued to one ladder
- Cooling:
  - 2-phase CO₂ cooling for ASICs at the end of stave.
  - N₂ gas for sensor and switchers.
- Radiation hard sensor and ASICs up to expected experiment lifetime

![Diagram of PXD Sensor Modules](image)

**DCD**
Drain Current Digitizer
8 bit ADC
~100 ns

**DHP**
Digital processing
Zero suppression
Pedestal and common mode correction
Trigger and timing

~0.21% X₀ / layer material budget.
PXD DAQ Scheme

- PXD unfiltered data rate $\rightarrow$ 10x that of other Belle II detectors at design luminosity
- Dominated by beam and physics background
- Separate readout path
- Remove data not belonging to a track
- Data reduction to 1/10 by High Level Trigger (HLT) based “Region Of Interest” calculation from CDC and SVD track information
- Feedback to PXD readout: selection of pixels within rectangular ROIs and drop full events rejected by HLT
- Currently not in use as overall data rate low enough
PXD Calibration and Optimization

- Modules characterized before installation – working point shifting due to irradiation
- Signal on top of pixel dependent pedestals
- Analog Common Mode Correction
- Switchable currents at input of Drain Current Digitizer used to compress spread of drain currents from sensor
- Narrow and stable pedestals
- Low noise (<1ADU, <200e ENC)

Noise of 0.7 ADU
Gain Uniformity

- Most probable values of cluster charge rather uniform over all 24 ASIC combinations within one module
- Signal to Noise Ratio ~30 to 50 (module dependent)
- → Uniform gain over module area can be achieved
- Adjustment of Gate on/off voltages needed to compensate for FET threshold shift

\[ \text{MPV} \sim g_q \sim \sqrt{I_D} \sim (U_{\text{Gate}} - U_{\text{Threshold}}) \]

Sensitive to radiation damage (TID)
Radiation Effects

- Expected: threshold voltage shift
  - → need gate-on/off adjustment
- Slight increase of ASIC currents (expected)
- Emerging problem:
  - Pixel shift out of dynamic ADC range
  - → need (better) offset calibration/correction
- Several (19) SEU induced bit-flips in ASICs triple redundant configuration registers observed in 2020/21, may increase with higher luminosity
- Dose determination per module in progress
- Variation between modules (phi dependence)

[Graph showing dose determination per module with variation between modules (phi dependence)]

https://doi.org/10.1016/j.nima.2020.163522

[Graph showing trend for gate-on voltage with compensated threshold shift]

Preliminary!
Uncontrolled beam losses in 2019 – 2021 resulted in severe detector degradation (dead/noisy gates, broken Switcher ASICs).

- Broken gates lead to unstable behavior (pedestals, noise, occupancy)
- Confirmed in irradiation tests that huge instant radiation dose can damage the Switcher output
- Dangerous for accelerator (damaged collimators)
- Improvements on beam abort (faster, more sensors)
- PXD emergency off triggered by additional sensors on the beam pipes
- Ongoing work to make emergency off fast enough to prevent damage to ASICs
- Clear on/off voltages shut down within O(100us)
Detector Efficiency

- Defined by hit clusters found close to track intercepting points in modules.
- Influenced by tracking quality and alignment.
- Different approaches (e.g. online/offline) with different cuts ($p_T$) and event samples. Take only tracks with good tracking.
- Bad switcher channels (4 rows each) degrade overall hit efficiency by $\sim$3% (good regions $\sim$ 98% hit efficiency).
- One partly broken/noisy switcher originating from a beam loss event.
- Module 1.03.2 was broken from beginning but covered by layer 2 module.
- Glue joint and gap between half-shells.

$$\epsilon = \frac{\text{nr of tracks with hit near track intercept}}{\text{nr of good track intercepting a module}}$$
High Voltage Currents

- Irradiation led to unexpected large currents in HV channel (60V – 75V), module dependent
- Saturation expected from irradiation campaign
- Suspected mechanism from simulation: avalanche generation at innermost backside guard ring (next to diode backside implant)
- Optical measurement on irradiated mini-matrix: avalanche appears to be at outermost guard ring
- Reason not fully understood, dedicated test structures prepared for more detailed studies

Phemos image of a test module

Cross section of sensor

X-ray irradiation measurement

HV current trend (2021)
Injection Backgrounds

- Storage beam background (Touchek, Beam-gas, 2-photon) no issue and well understood
- Both rings filled by continuous (top-up) injection, max 50 Hz
- Compensate short beam life time
- Large background during injection (noisy bunch), damping takes several ms
- Belle II Trigger Veto (=no readout)
  - Full veto during injection (1-2 ms) and then gated veto for ~10 ms each time the bunch passes by (~2 μs)
  - Gated veto not helpful for PXD (integrates 20μs)
- PXD readout affected due to instant high occupancy
- No issue for DAQ stability, only small fraction of events are truncated
- Possible to blind PXD while keeping stored charges (Gated Mode)
  - But: Gated Mode would result in extra noise and efficiency loss
  - To be balanced vs simple veto (Belle II or PXD internally)

Rolling shutter! Integrated over 20 μs.
Synchrotron Radiation

- Large photon background was observed in -X modules
- IR designed such that no direct SR photons hit the central Be beam pipe
- Secondary photons, diffuse scattering!
- Single pixels, low energy
- Problem: High local hit density
  - Inhomogeneous irradiation
  - Deterioration of clustering and tracking
- Mitigation:
  - HER beam orbit tuning (rotation)
  - New beam pipe design with additional plating (in production, install in 2023)
**Vertex Resolution**

- Vertex reconstruction essential for time dependent CP violation and lifetime measurements
- PXD and SVD play a key role
- Vertex resolution with PXD is close to MC expectations.
  - Measuring the point of closest approach from particles from the interaction point in x, y
  - Taking advantage of tiny interaction point
  - $d_0$ resolution of $13.64 \mu m$ (data), $12.05 \mu m$ (MC)
  - $z_0$ resolution of $14.92 \mu m$ (data), $14.35 \mu m$ (MC)

- Belle II $D^0$, $D^+$ life time measurement already topped world average
  - DOI: [10.1103/PhysRevLett.127.211801](https://doi.org/10.1103/PhysRevLett.127.211801)

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\tau(D^0) = 410.5 \pm 1.1 \text{ (stat)} \pm 0.8 \text{ (syst)} \text{ fs} \\
\tau(D^+) = 1030.4 \pm 4.7 \text{ (stat)} \pm 3.1 \text{ (syst)} \text{ fs}
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World average:

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\tau(D^0) = (410.1 \pm 1.5) \text{ fs} \\
\tau(D^+) = (1040 \pm 7) \text{ fs}
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- $D^0 \rightarrow K^- \pi^+$
- $D^+ \rightarrow K^- \pi^+ \pi^+$
PXD Replacement

- Currently PXD has 8/8 inner and 2/12 outer ladders installed
- Ladder assembly problems (low yield) in 2018
- Outer layer important for higher luminosities and occupancies
- Full PXD will be installed in first long shutdown (July 2022-August 2023)
- New beam pipe design (block synchrotron radiation)
- Replace full PXD detector, not just add missing parts
- Production in final stage of module assembly
Summary

- Belle II first particle physics experiment to use a DEPFET pixel vertex detector
- Nearly three years running, two under pandemic conditions
- Good performance demonstrated
- High efficiency
- Vertex resolution matches MC expectations → world leading D⁰ and D⁺ lifetime measurement
- DAQ / ROI data reduction concept proven
- Challenging operation close to IP in high radiation environment
- Suffering from damages due to radiation bursts from uncontrolled beam aborts
  - Understand and prevent damage by “beam incidents”
    - Add new collimators!
    - Faster detection → issue earlier beam abort and PXD emergency off
- Replace with a full detector in 2022/23
Thank you.