Commissioning of the Belle II Pixel Vertex Detector

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SuperKEKB and Belle II
The new generation of B-factory

- SuperKEKB: Asymmetric energy e⁺e⁻ collider
  - $E_{cm} = m(Y(4S)) = 10.58$ GeV
- Design instantaneous luminosity: $8 \times 10^{35}$ cm⁻²s⁻¹
  - x40 than KEKB
- Physics data taking started in Mar.2019, expected to accumulate 50 ab⁻¹ by 2027.
DEPFET PXD for Belle II

Depleted P-channel Field-Effect Transistor (DEPFET) combines detection and amplification within one device.

Each pixel is a p-channel FET on top of fully depleted silicon bulk

- Fast charge collection (~ns)
- Charges collected in the “internal gate”
- Readout of modulated drain current
  - internal amplification
    \[ g_q = \frac{\partial I}{\partial q} \approx 500 \ \text{pA/e}^- \]
- High Signal to Noise Ratio (SNR)
- Periodical clearing of “internal gate” required to reset the pixel
PXD Module Concept

- Pixel size: varies in z direction, 50 x 55-85 µm²
  - optimized to have the best resolution in forward direction around 45° incident angle
- 250 x 768 pixels per module
- By thinning the active sensor thickness can be reduced to as little as 50 µm.
- For optimal position resolution (COG) 75µm were chosen for PXD
- 3 Metal layers for circuitry
  - 2Al + 1Cu
- Mechanically self-supporting device
PXD Module Concept

❖ 3 types of ASICs are bump-bonded to the module
  ❖ Switcher: controls the gate and clear lines of the matrix.
  ❖ DCD: consists of 256 current mode pipeline 8-bit ADCs digitalize the inputs for drain lines.
  ❖ DHP: digital processor chips, 0- suppression & triggered readout.

❖ Rolling shutter mode
  ❖ Read signals row-by-row
  ❖ 4 rows in parallel
  ❖ Read-Clear cycle in ~100ns
    ❖ Full integration time is 20μs (twice the revolution time of SuperKEKB)
  ❖ Only ‘activated’ rows consume power
    ❖ Low sensor power consumption
  ❖ Max. Acceptable average occupancy <3%.
DEPFET Module Performance

- Soft components (<10keV) on calibrated cluster energy spectra.
  - Hint for synchrotron radiation

- SNR $\geq 50$ has been achieved
  - From PXD Phase3 module
Gated Mode Operation

- At design luminosity we have to inject at 2x25Hz (=> 20ms)
- Sensor can be periodically blinded with Gated Mode (GM)
  - Newly created charges are not collected
  - Charges in internal gate are preserved
- The principle was tested extensively in the lab
  - Pedestal fluctuation for several gates observed after returning to normal mode.
Belle II PXD for early Phase 3

- 2 layers of DEPFET sensors @ \( r = 14(22) \) mm
- Sensitive area per module: L1: 12.5mm x 44.8mm, L2: 12.5mm x 61.44mm
- Sensor thickness: 75 µm, 0.21% \( X_0 \) per layer
Each ladder is formed by a pair of mirrored DEPFET sensors
Due to problems in ladder gluing, only half of designed PXD (full L1+2 L2 ladders) was installed in 2018/2019, will be finalized in 2021.
Thermal Management

- The power consumption of full PXD is 420W, with 360W contributed from DCD/DHP, where the modules are located at the end of the stave.
  - Active 2 phase CO2 cooling is required there.
- Little power from matrix (0.5W per module) and Switchers (1W per module).
  - Air cooling is sufficient in the sensitive area.

2-phase CO2 cooling

2PACL: 2-Phase Accumulator Controlled Loop

Temperature along the PXD ladder
PXD Performance: Efficiency

- Projection on the $\phi_0$-$\tan(\lambda)$ plane.
- $\lambda \equiv \pi/2 - \theta$, : angle between a track and the plane $\perp$ to the beam.
- Gaps between fwd & bwd modules and between half shells
- Few modules not yet at optimal working point
PXD Performance: Efficiency

Ring structures indicate shift of working point
❖ The rings due to small scale variations in the bulk doping.
❖ Almost completely invisible if properly biased.

❖ Projection on the $\phi_0$-$\tan(\lambda)$ plane.
❖ $\lambda = \pi/2 - \theta$, : angle between a track and the plane $\perp$ to the beam.
❖ Gaps between fwd & bwd modules and between half shells.

Voltages were adjusted to cure the rings.
Transverse Impact Parameter ($d_0$) Resolution

- After correcting for the beam spot position, the $\phi$-dependent $\sigma(d_0)$ depends on the intrinsic VXD resolution and transverse size of the luminous region:
  \[
  \sigma_{d_0} = \sqrt{\sigma_x^2 + (\sigma_x \sin \phi_0)^2 + (\sigma_y \cos \phi_0)^2}
  \]
- In early phase 3, $\sigma_x = 14.8 \mu m$ and $\sigma_y = 1.5 \mu m$
- The intrinsic resolution is estimated by $\Delta d_0 = d_0(t_-) + d_0(t_+)$, from 2-track ($t_-$ and $t_+$) events, which are produced back-to-back.

- Good agreement observed between data and MC expectation
Summary

❖ The first real beam experience with a completely new detector type (DEPFET) and half of the full scale has been achieved.
  ❖ Challenging operating conditions close to the IP at a very ambitious machine like SuperKEKB
❖ PXD system is continuously being improved and optimized in the 2019 spring runs.
❖ Good PXD performance is demonstrated
  ❖ Efficiency -> further module optimisation possible
  ❖ Impact parameter resolution very close to MC expectation