The new two-layer Belle II Pixel Detector (PXD)

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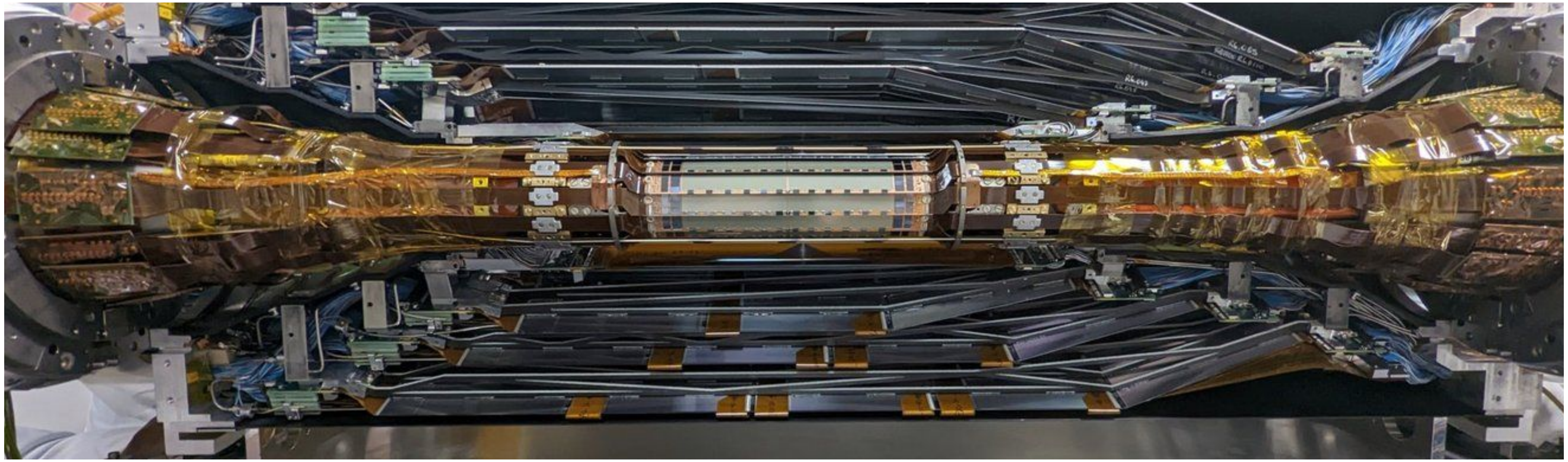
on behalf of the PXD collaboration

18.11.24
Pixel 2024, Strasbourg

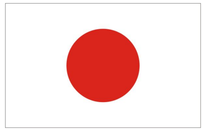


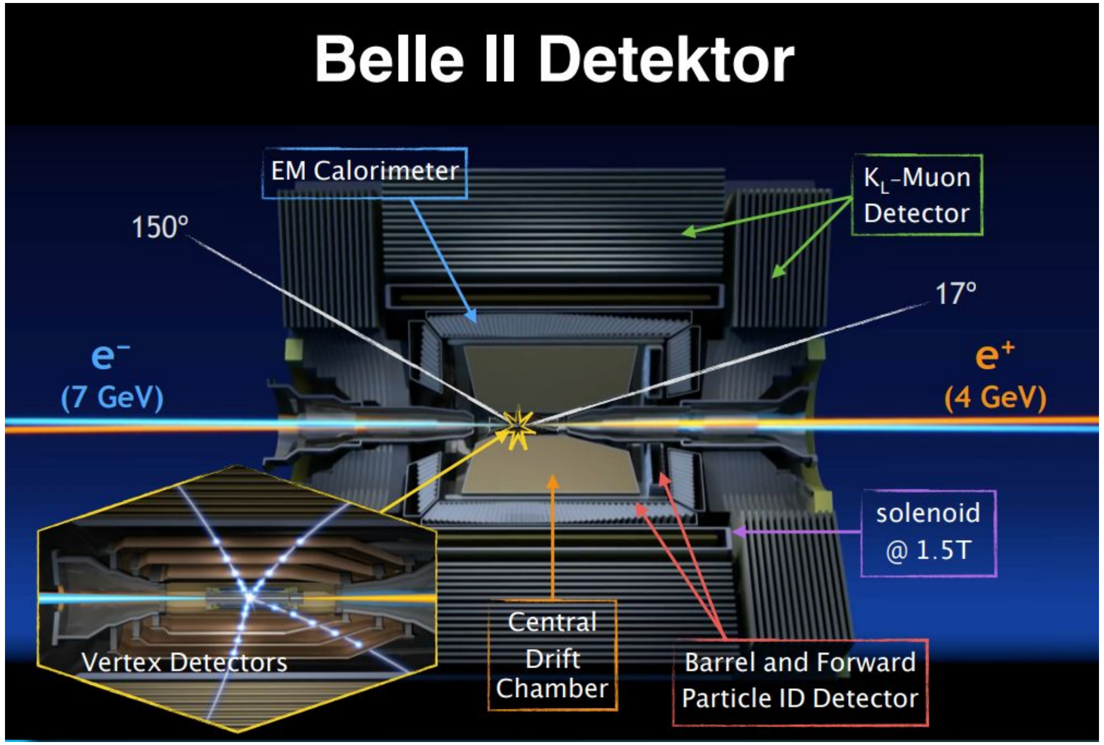
DEPFET
Active Pixel Detector

KEK
Insight through Accelerators.

HELMHOLTZ

SuperKEKB and Belle II



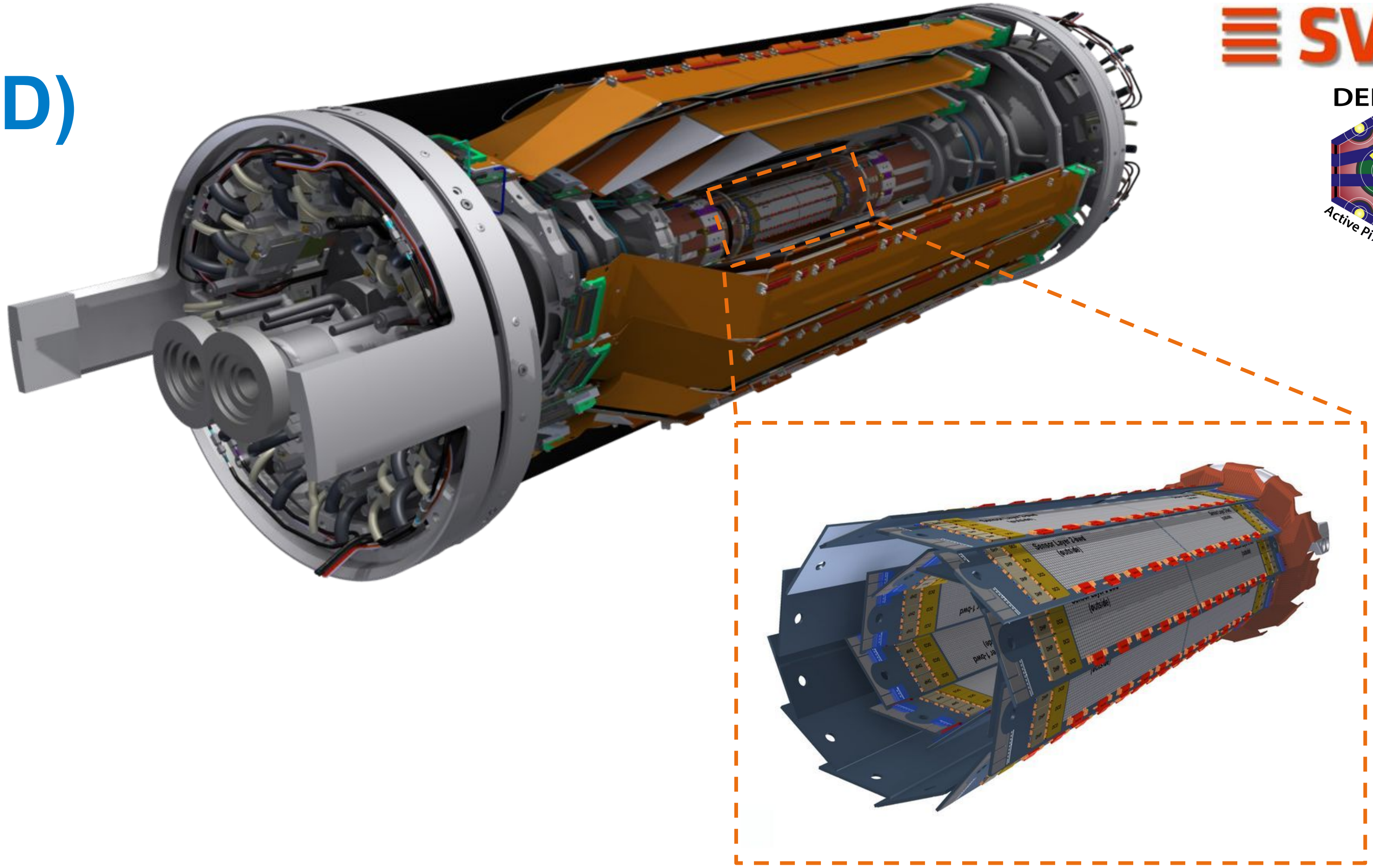


- Asymmetric electron-positron collider
- $E_{CM} \approx 10.6$ GeV ⇒ "B factory"
- Run 1: 2019 - 2022 with $L_{int} = 424$ fb^{-1}
- $L_{peak} = 4.7 \times 10^{34}$ cm^{-2}s^{-1} (world record)
- Long shutdown in 2022/23
- Run 2: Since 2024

- FWD - BWD asymmetric onion-shaped detector
  - K_L and Muon Detector
  - EM Calorimeter
  - Particle ID Detector
  - Central Drift chamber
  - Vertex Detector

The Vertex Detector (VXD)

Two sub-detectors: PXD and SVD



SVD

DEPFET

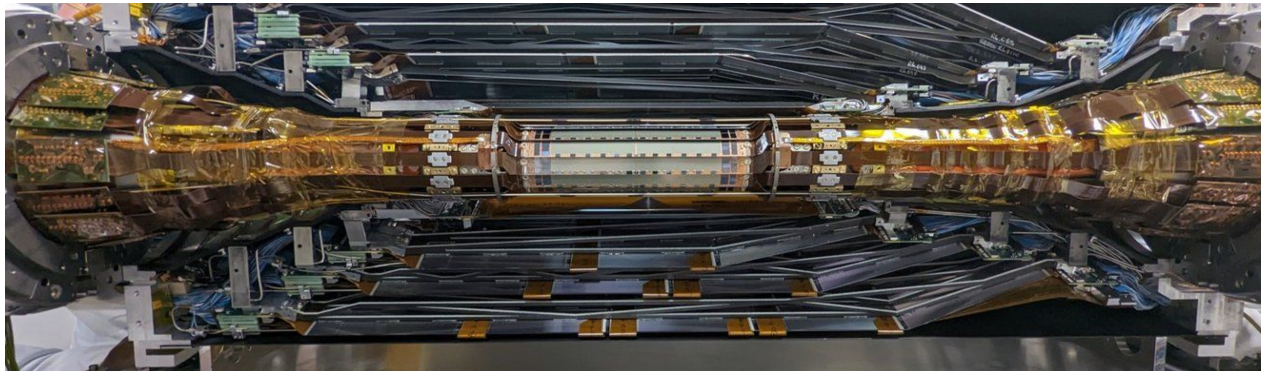
Active Pixel Detector

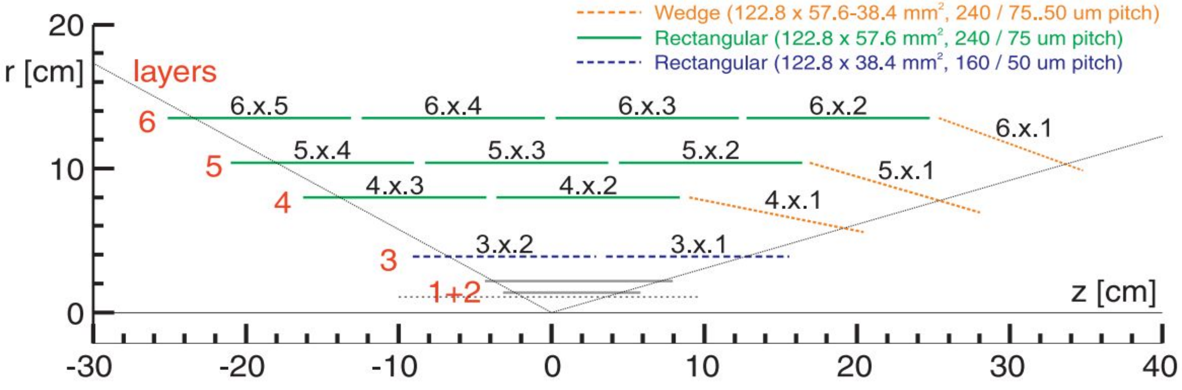
Silicon Vertex Detector (SVD)

- Four layers double-sided silicon strips
- $r \leq 140$ mm

Pixel Vertex Detector (PXD)

- 2-layers
  - $r_1 = 14$ mm and $r_2 = 22$ mm
- Coverage: $17^{\circ} < \boldsymbol{\theta} < 150^{\circ}$
- PXD 1: 2019 - 2022 incomplete 2-layer
- PXD 2: 2024 - 20XX complete



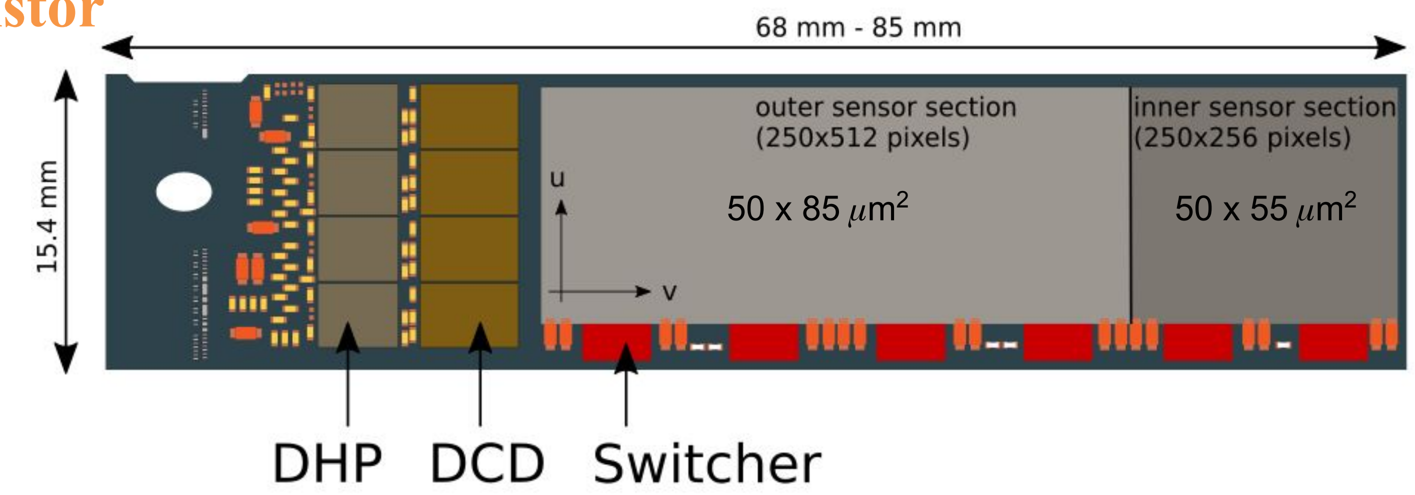


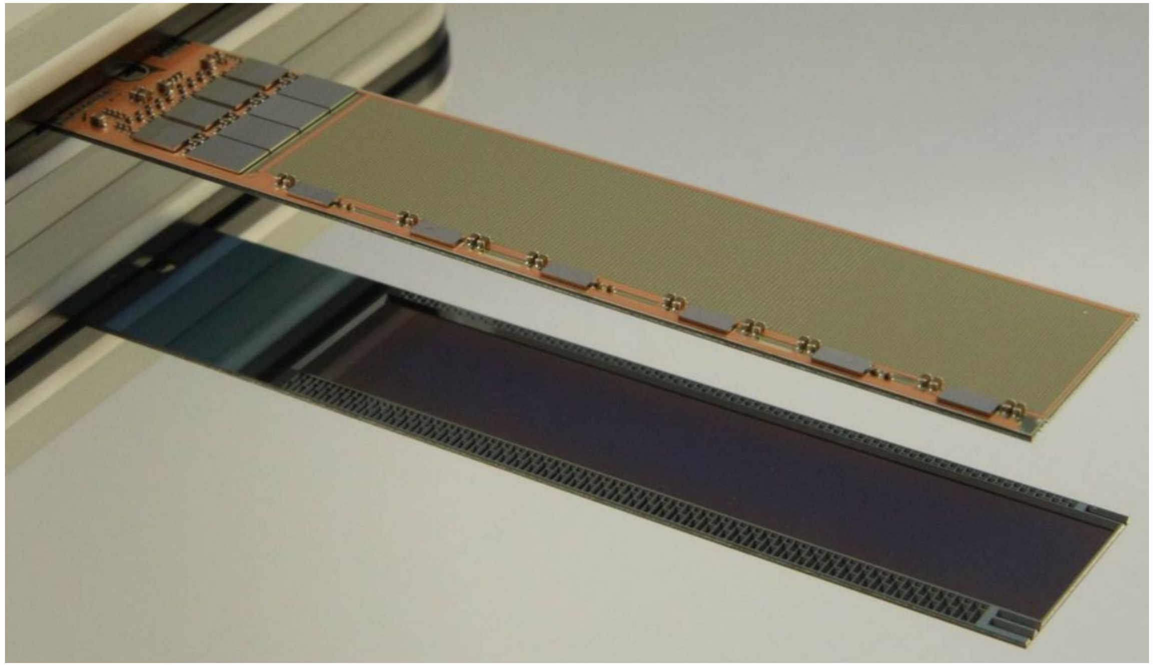
The Pixel Vertex Detector (PXD)

DEpleted P-channel Field Effect Transistor

Properties:

- Pixel detector based on DEPFET
  - Concept developed at Max-Planck-Institutes in Munich (MPI/HLL)
- Modules: Self-supporting “all-silicon” structure
  - Support frame ~ 500 μm thick
  - Monolithic active area 75 μm thick
- Low material budget (~ 0.21% average X_0)
- ASICs on module
  - Switcher:
    - Consecutive row selection for data readout
  - DCD: Drain Current Digitizer
    - Analog to digital conversion of signal
  - DHP: Data Handling Processor
    - Zero suppression, data formatting





PXD design

2 Modules = 1 Ladder

- Glued together
- In total 20 ladders

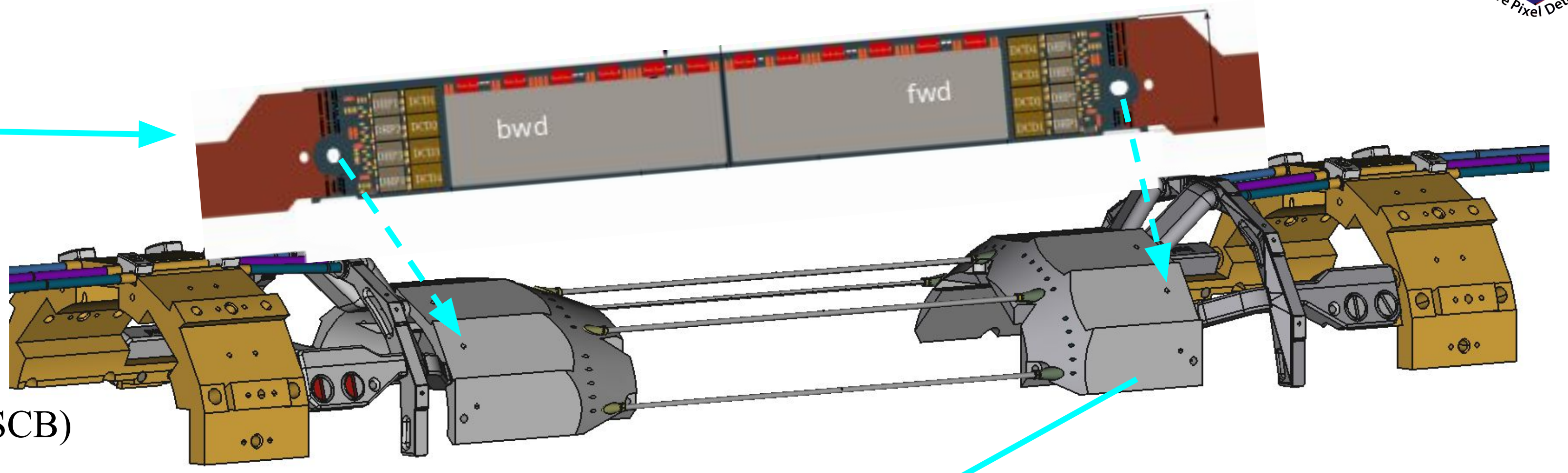
10 Ladders = 1 Half-Shell

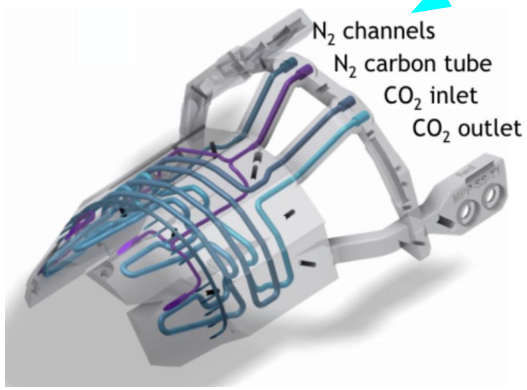
- Ladders screwed on support cooling block (SCB)
- Half-shell (HS) mounted on beam pipe

Cooling system

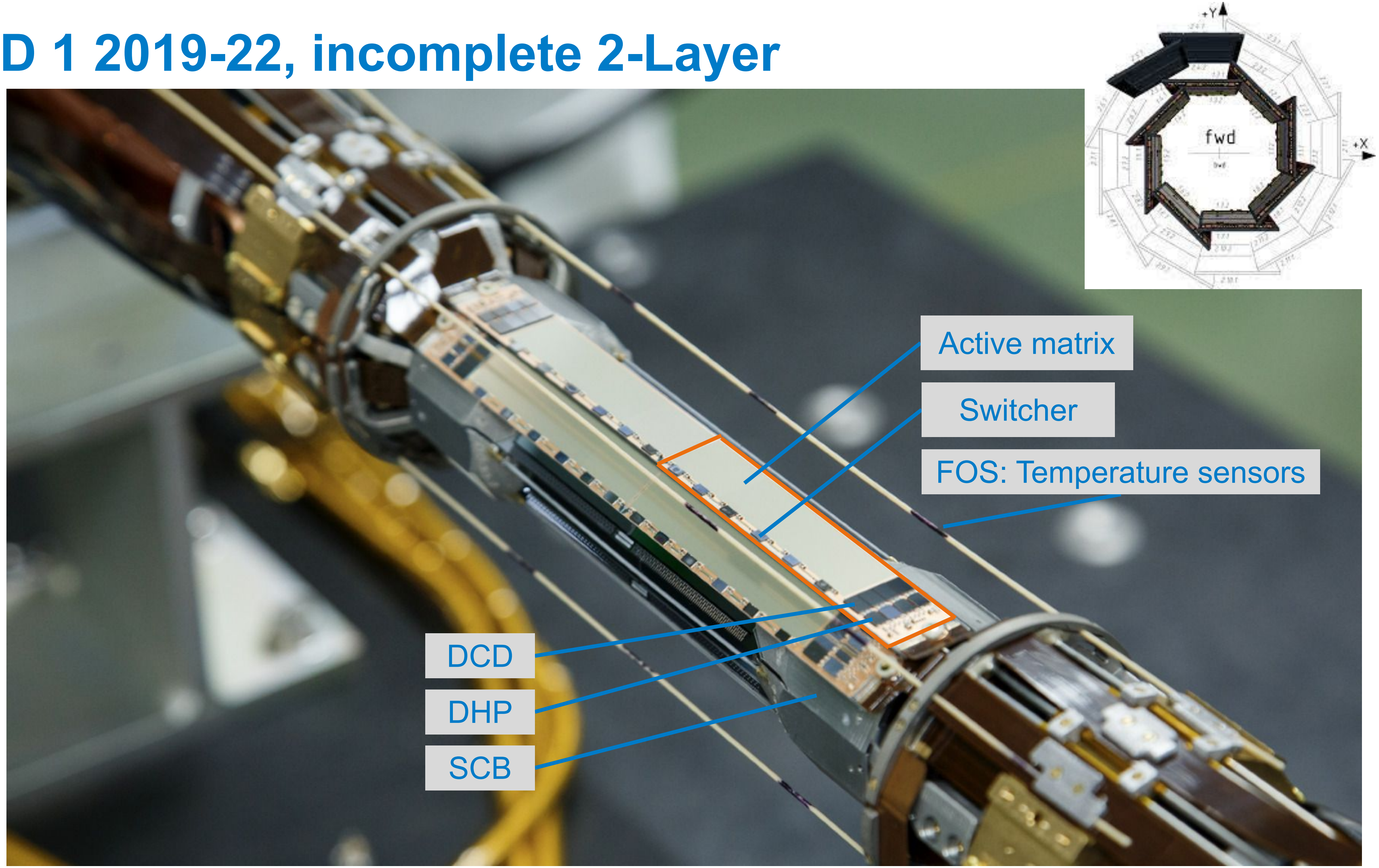
- ~ 9 W per module = ~ 360 W full detector
- 2-phase CO_2: DHP + DCD (8W)
- N_2 gas: Switcher + sensor (1W)

⇒ **Complex detector system**
⇒ **Challenging production, installation and operation**





PXD 1 2019-22, incomplete 2-Layer



PXD 1 Performance

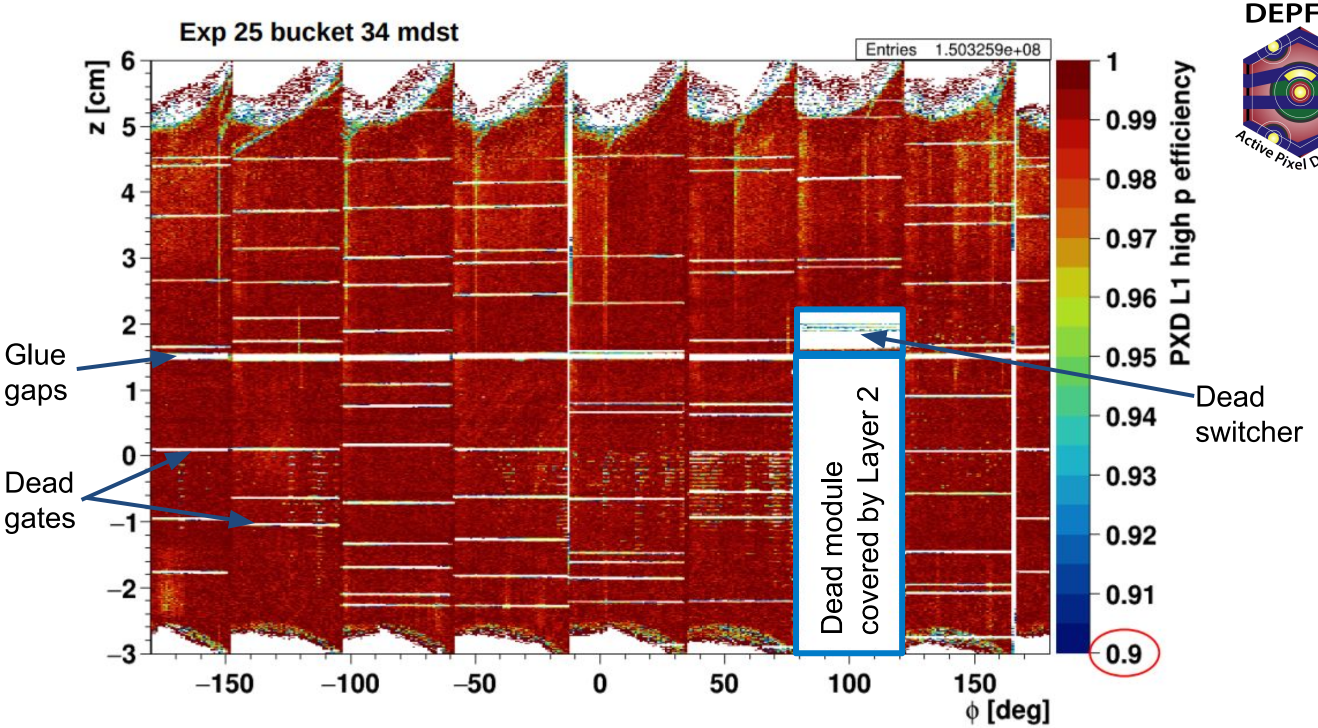
Efficiency and sudden beam losses

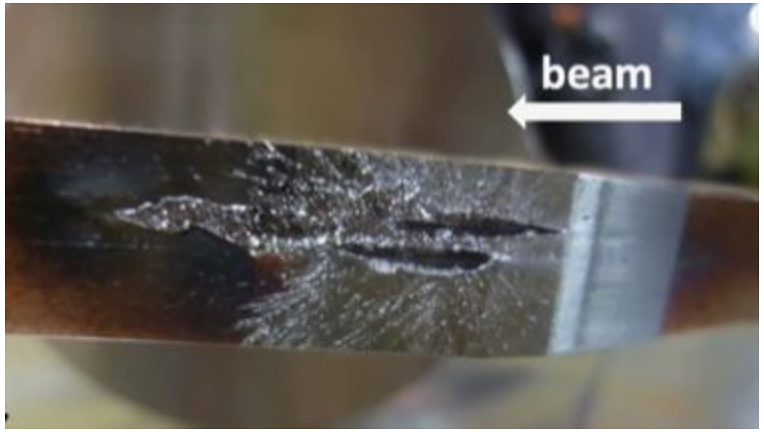
Di-muon hit efficiency

- ~ 99 % in fiducial region
- ~ 96 % in physics region

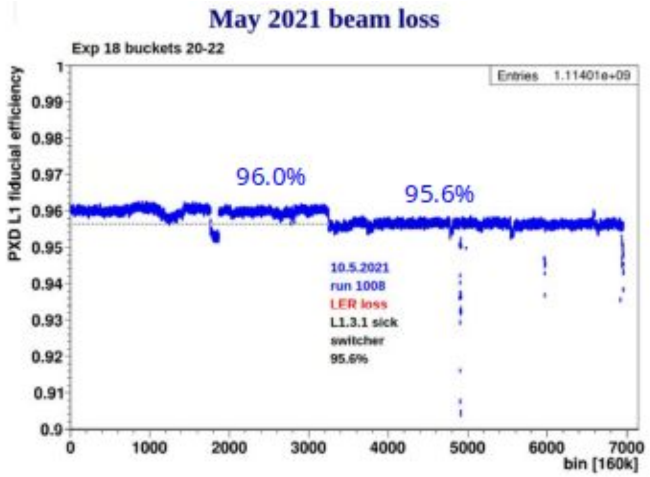
Sudden beam losses

- Cause: Dust particles (Hypothesis since this year)
- High instantaneous radiation doses (O(10) Gy in 40 µs)
- Can damage switchers if powered
  - Verified at MAMI electron beam
- Improve detection and PXD power shutdown
  - Power off: Switchers safe





Lost beam hitting collimator
⇒ high instantaneous radiation

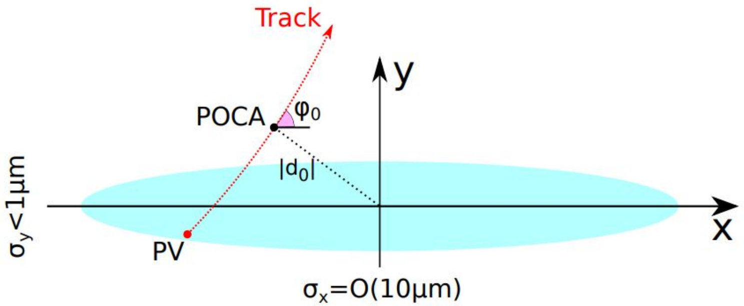


PXD 1 Resolution

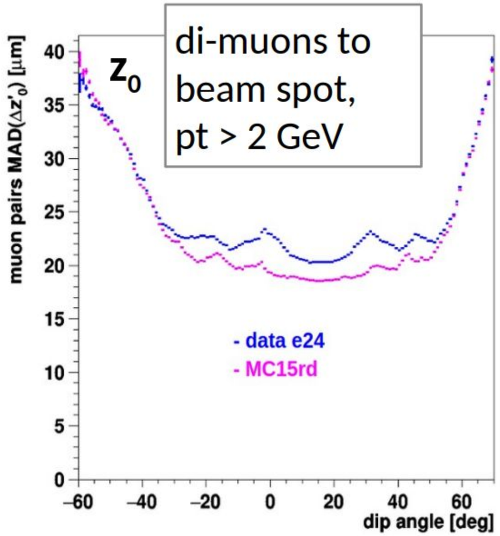
Comparison to Belle

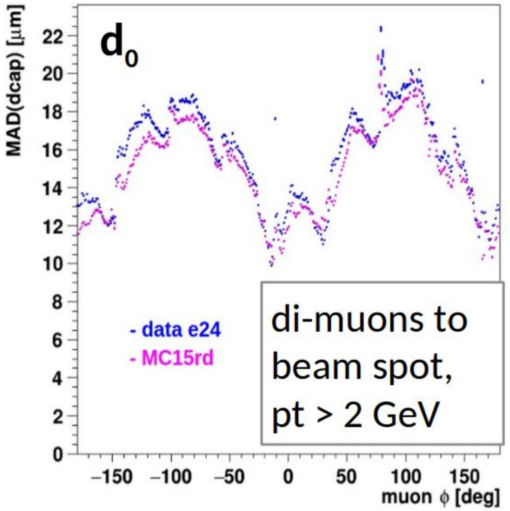
Impact parameter resolution

- Di-muon events (p_T > 2 GeV)
  - z_0: 20 - 40 µm
  - d_0: 10 - 22 µm
- MC describes data
  - MC slightly too optimistic
- **~1.5 - 2 times better than Belle**



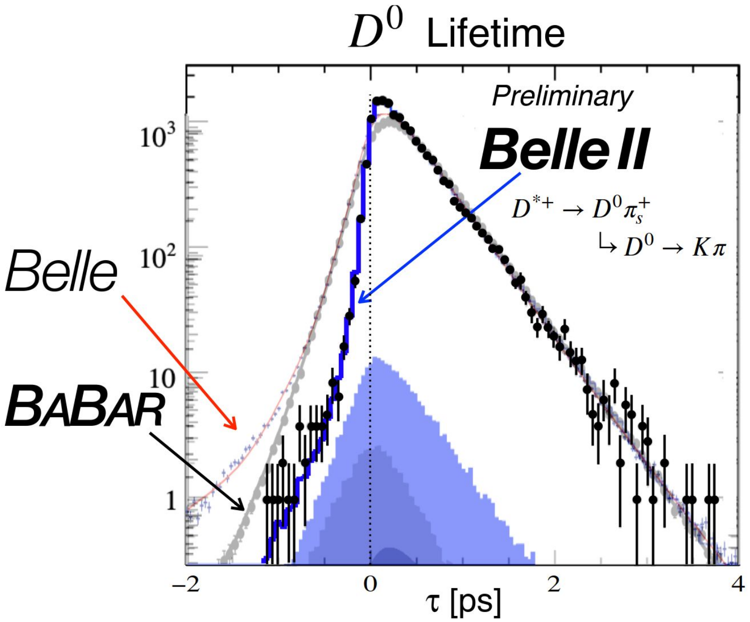
dip angle = 90 - θ





D^0 lifetime resolution

- Impact of better vertex estimation
- **2 times better than Belle**

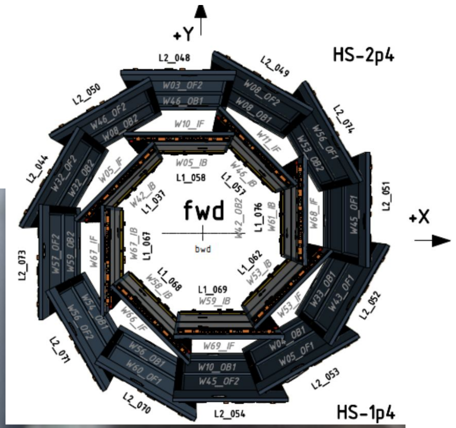


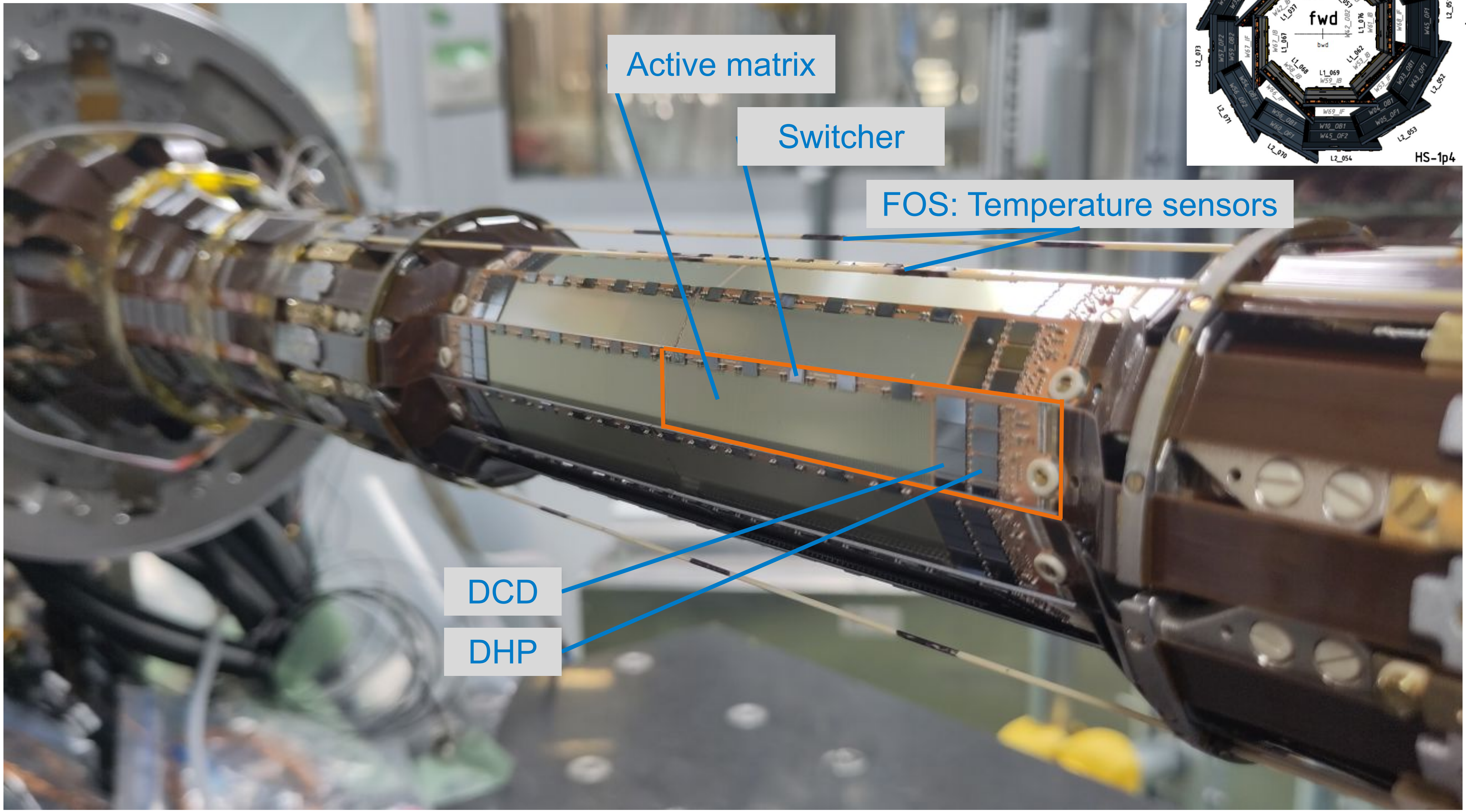
List of Belle II lifetime measurements with high PXD impact:

D_s^+: PRL 131, 171803 (2023)
B^0: PRD 107, L091102 (2023)
Ω_c^+: PRD 107, L031103 (2023)
Λ_c^+: PRL 130, 071802 (2023)
D_0/D^+: PRL 127, 211801 (2021)

PXD 2 2023-, complete 2-Layer

DEPFET
Active Pixel Detector



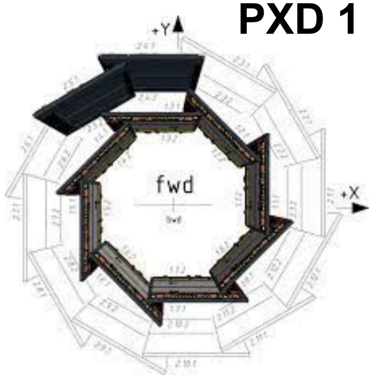


PXD 1 vs PXD 2

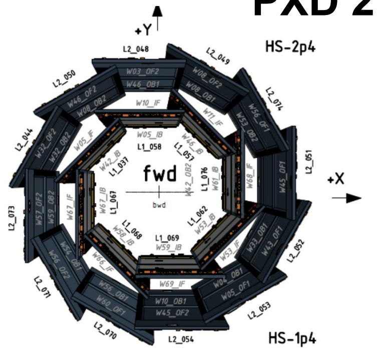
What will PXD 2 further improve?

DEPFET
Active Pixel Detector

PXD 1

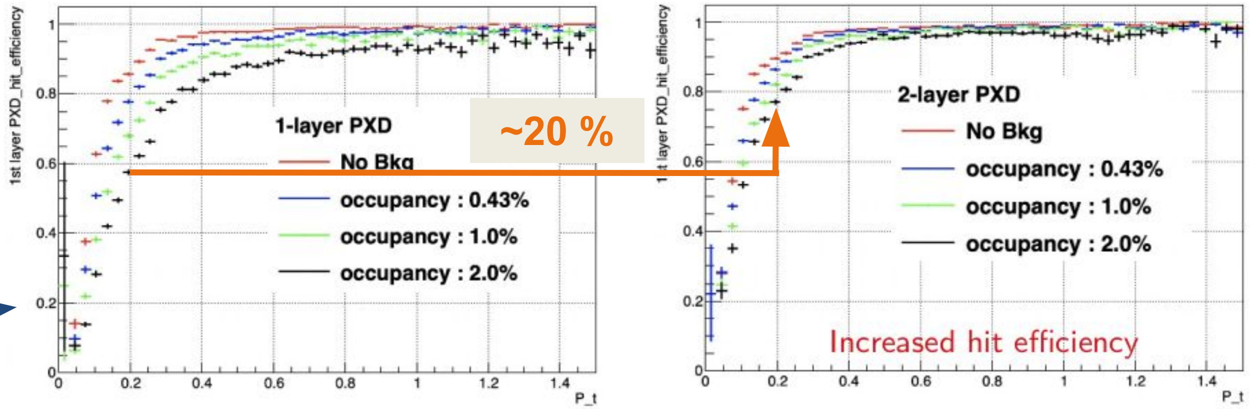


PXD 2



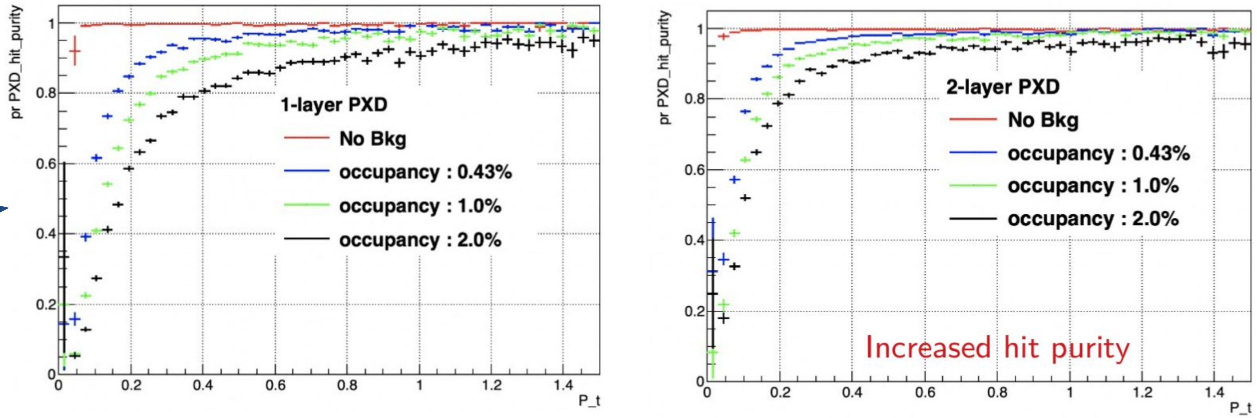
- Modest improvement of impact parameters (L1 has highest impact)
- Higher probability to select correct PXD hits in 1st PXD layer at higher background levels
- Fraction of MC hits found in reconstructed track

$$\text{hit efficiency} = \frac{N_{\text{mc\_hits\_in\_reco\_track}}}{N_{\text{hits, mc\_track}}}$$



- Fraction of MC hits in reconstructed track hits (Fraction of background in hits)

$$\text{hit purity} = \frac{N_{\text{mc\_hits\_in\_reco\_track}}}{N_{\text{hits, reco\_track}}}$$



PXD 2 commissioning at DESY

Source scan and system test

Half-shell test setup at DESY

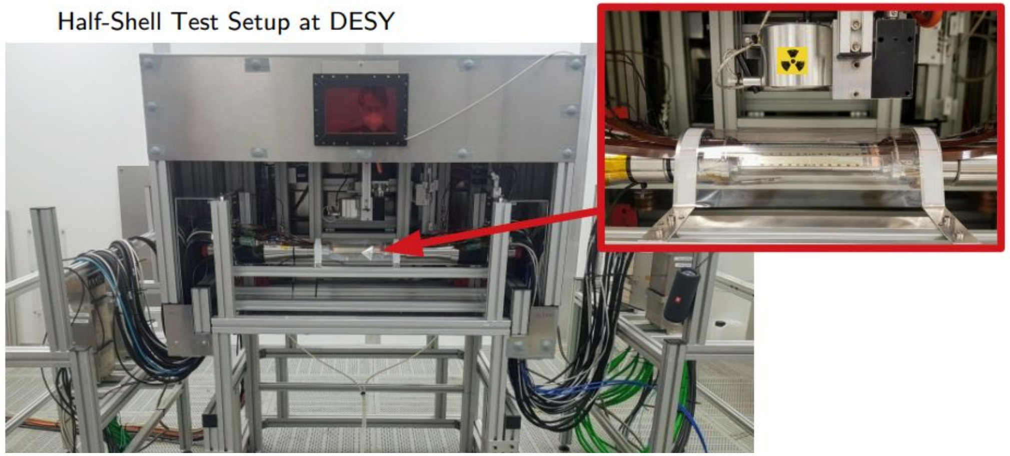
- Power supply and DAQ
- CO_2 and N_2 cooling
- Aluminium dummy beam pipe

Accident with 1st half-shell

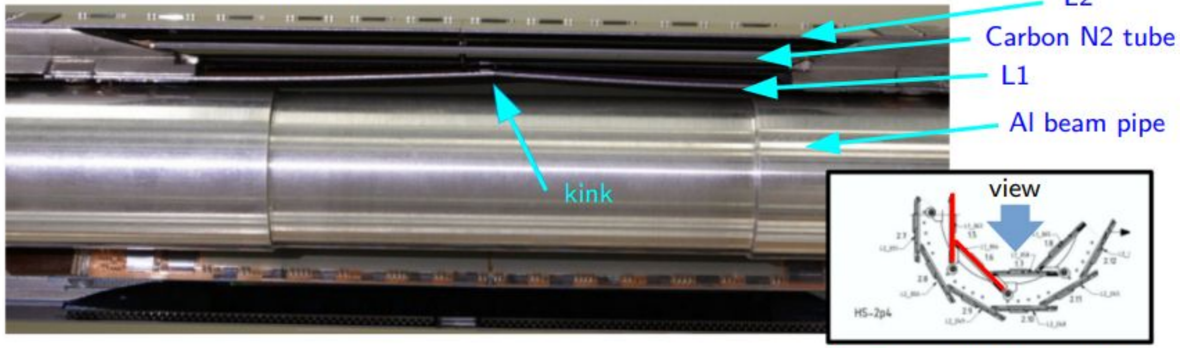
- Damaged during long-term operation (2 ladders with kink at glue gap)
- Studies to understand reason
  - Gliding of PXD ladders non optimal
  - Elevated air temperatures at test setup
  - Aluminum beam pipe (high expansion coefficient)
- Optimized gliding of ladders
- Performed endurance studies
  - Ladders quite robust against bowing
  - Elevated temperature plus bowing can open glue joint
    - Modules stay intact and connected with kink

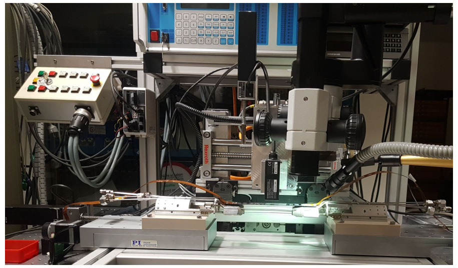
⇒ Carefully observe temperature and bowing during operation

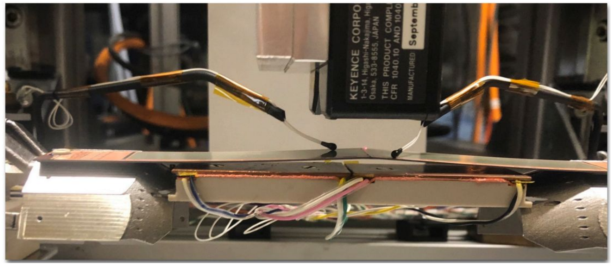
Half-Shell Test Setup at DESY



1st Half-Shell August 2022

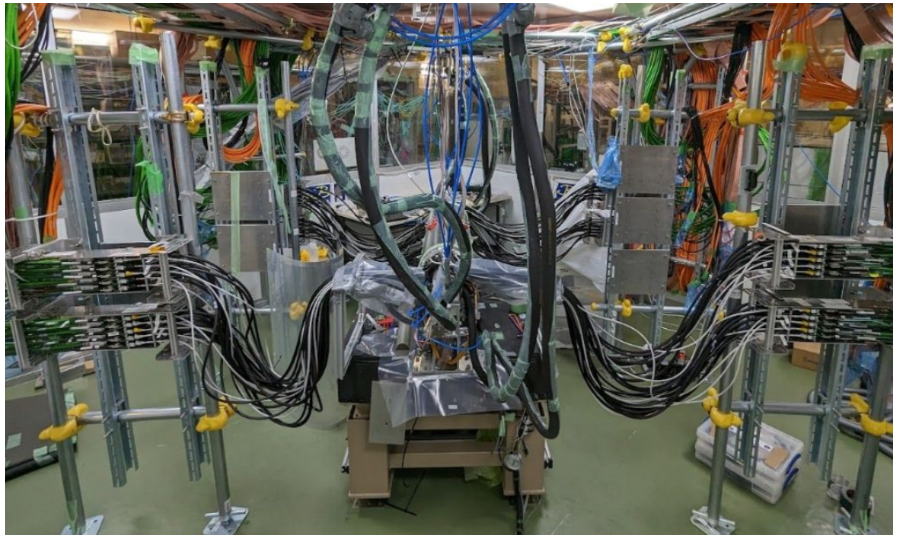






PXD 2 commissioning and installation at KEK

Full system test

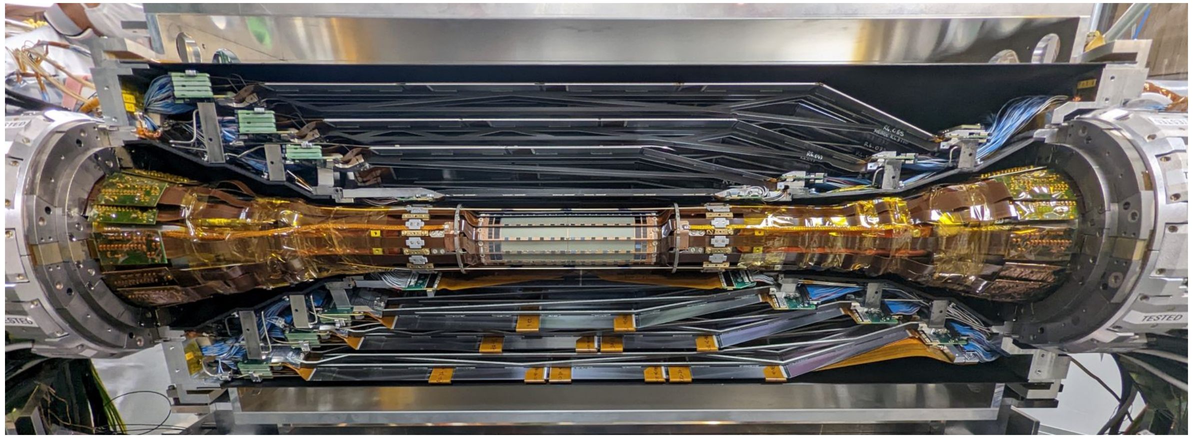


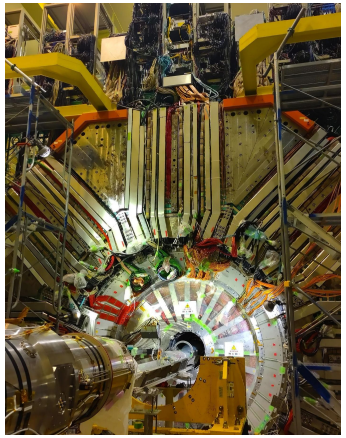
Commissioning at KEK

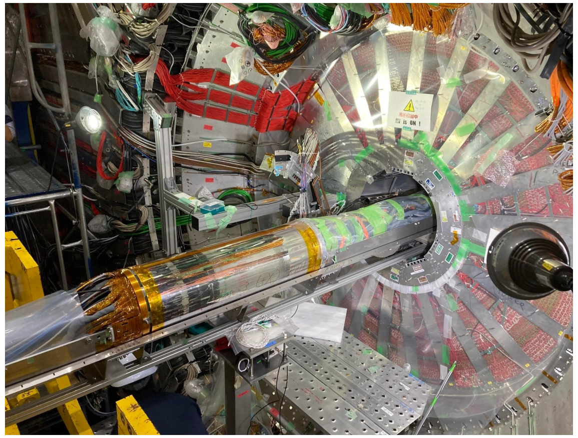
- First operation of full PXD 2
  - One L2 module showed high noise
- Optimized cooling to reduce air temperature
- Study ladder bending via cameras
  - Two Ladders showed increased bowing

Installation in Belle II

- After confirming stable operation installation was performed
  - Connect SVD
  - Insert into Belle II
  - Setup all service connection
  - Perform cosmics to study bending more precise





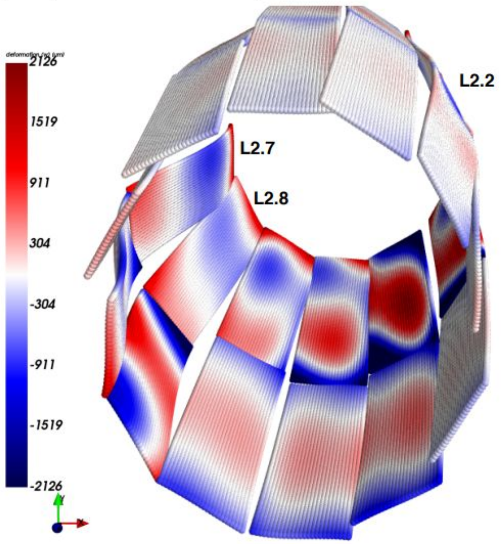


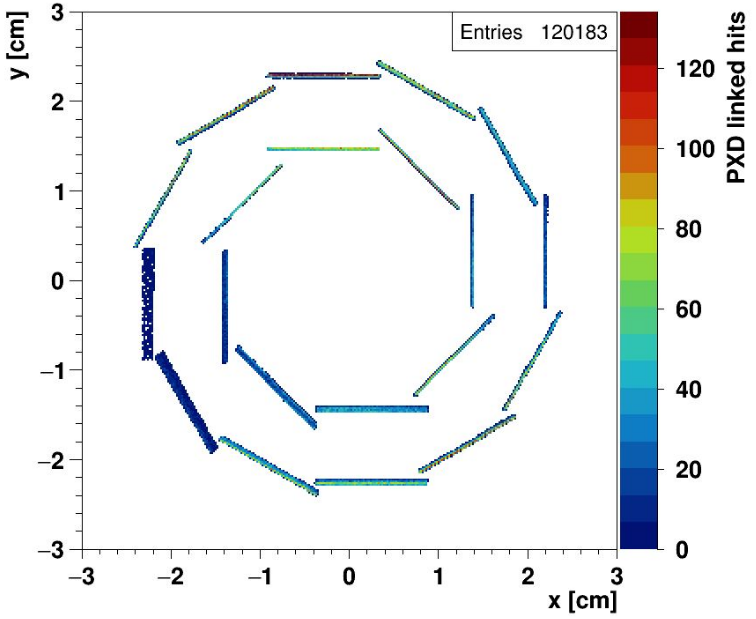
PXD 2 cosmic data taking

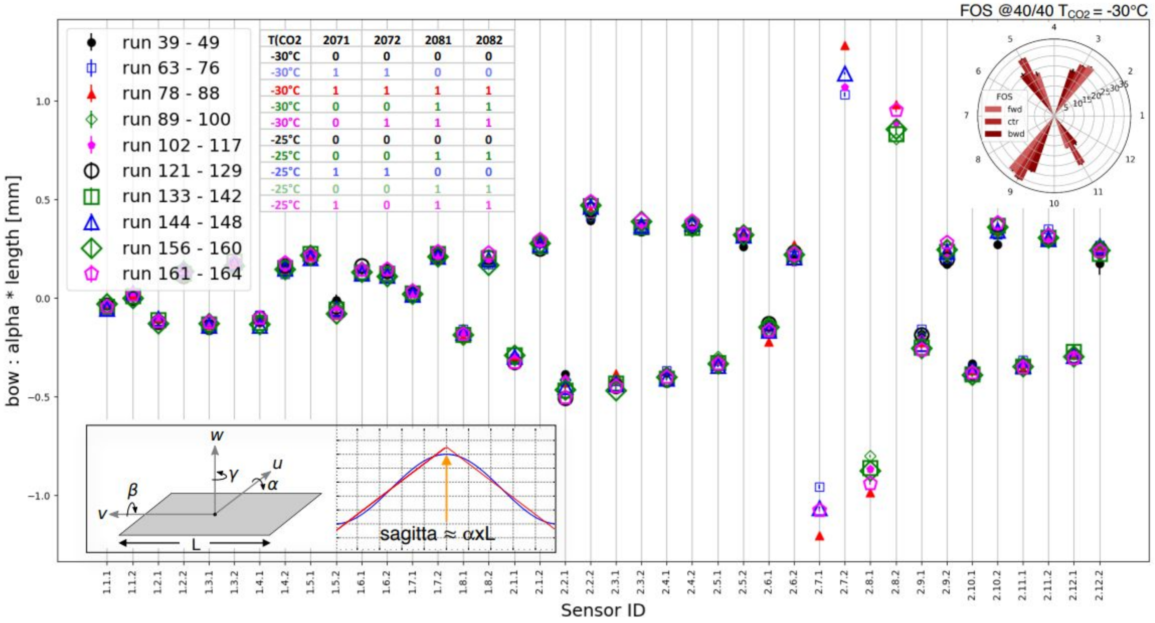
Study bending of ladders

- Study ladder alignment with cosmic data
  - Test different cooling setup
- Studies confirmed stronger bending for two ladders
  - ~ 1 mm sagitta
  - Bowing still less than tested in endurance studies
- 2 ladders = 4 modules
  - Partially turned off some of the modules
  - Slightly reduces bending of the two ladders
- Decided to keep both ladders off during operation start
  - Observe bending further during operation
  - With beam operation alignment possible even for non-powered ladders

Here: All misalignment parameters in payloads multiplied by 10. Sensor 3D surface plotted point by point (+ color for w-coordinate)





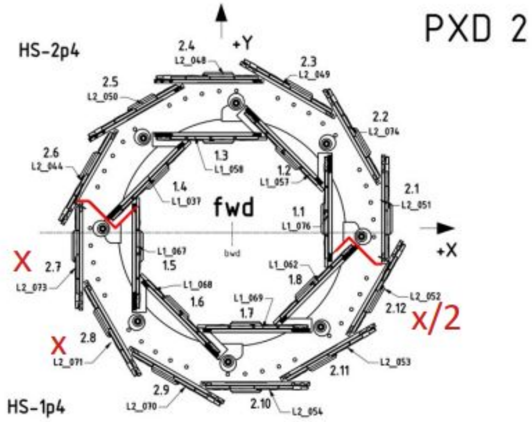


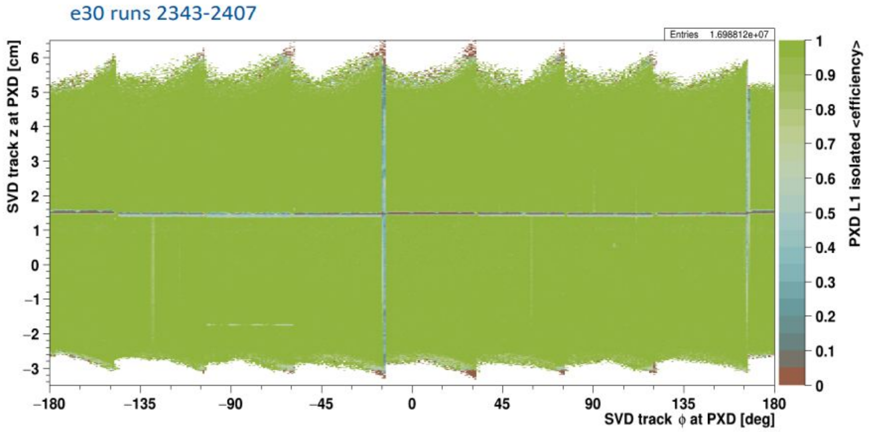
PXD 2 performance

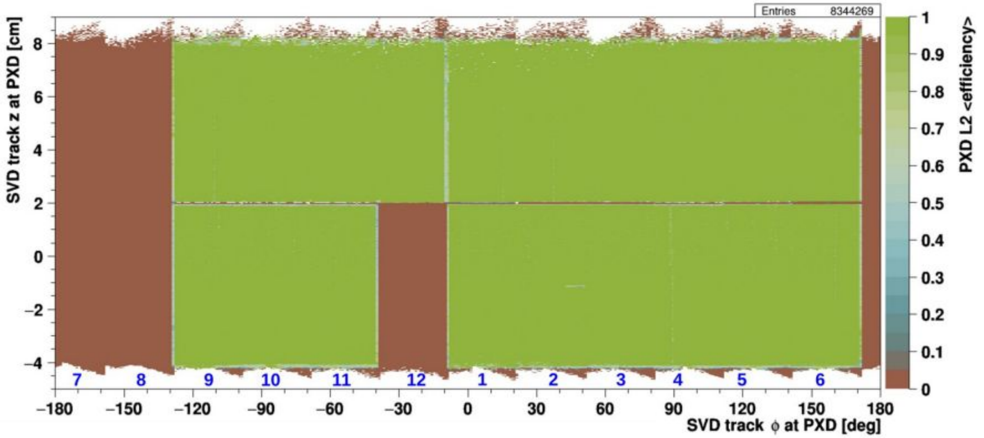
Operation in 2024

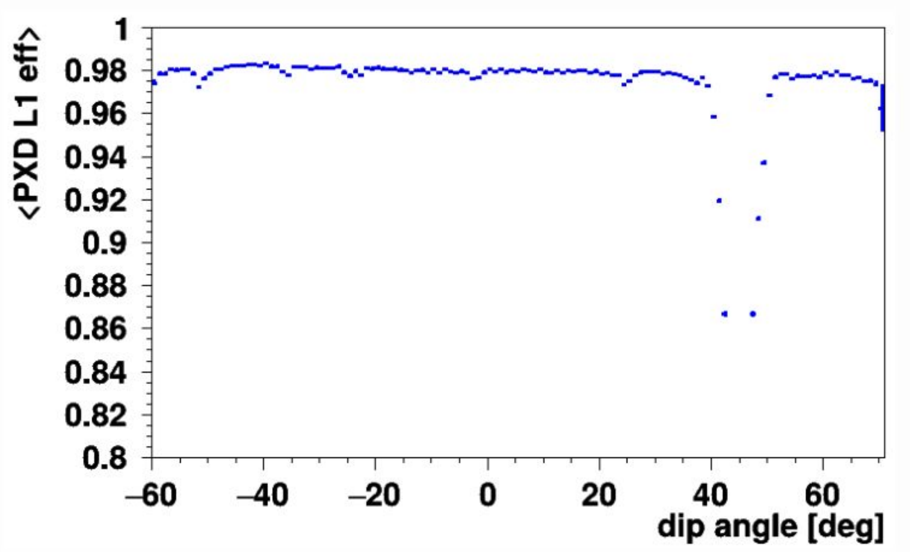
- Running with 35 / 40 modules
    - 4 Modules off because of bowing
    - 1 Module off because of noise

- L1 and L2 efficiency > 98 % in fiducial region
- Smooth operation with minor down times
- Operation temperature high but within limits

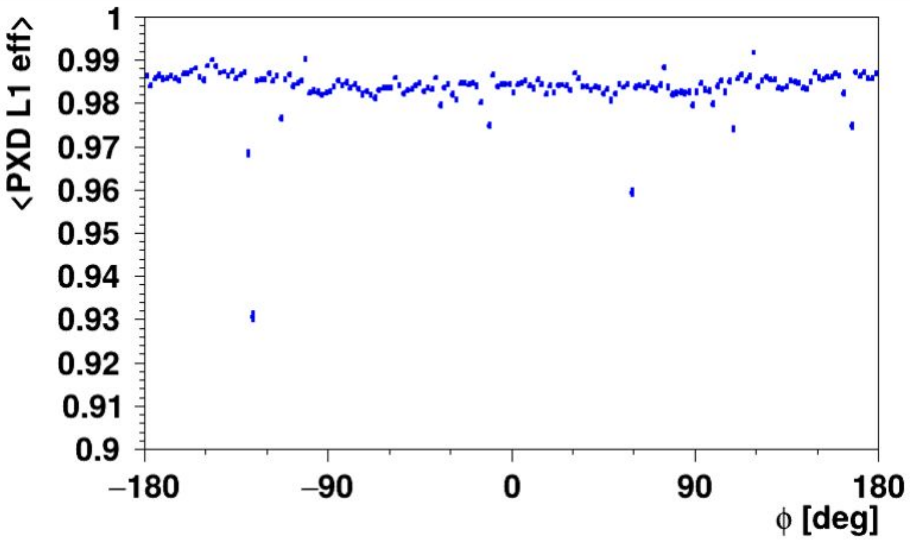








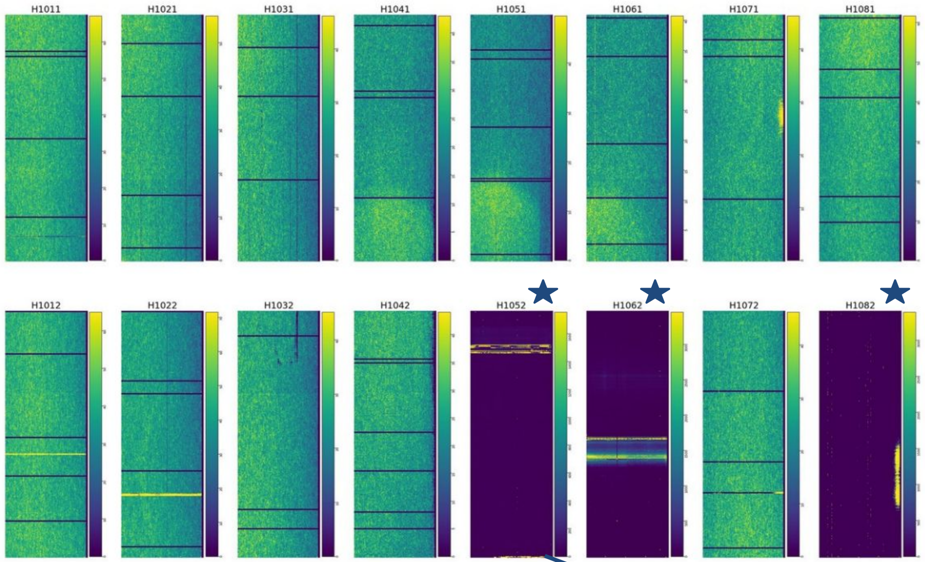
dip angle = 90 - θ

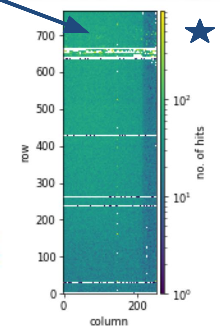


New sudden beam lose events (SBL)

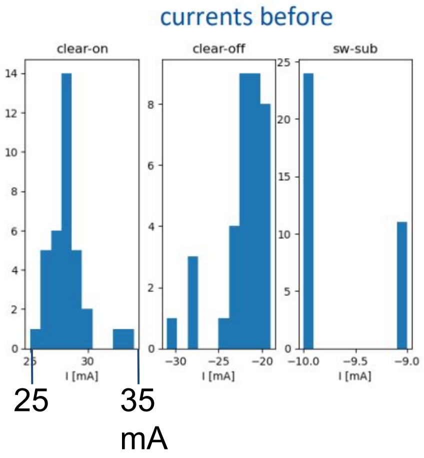
Two beam loses with high dose in PXD

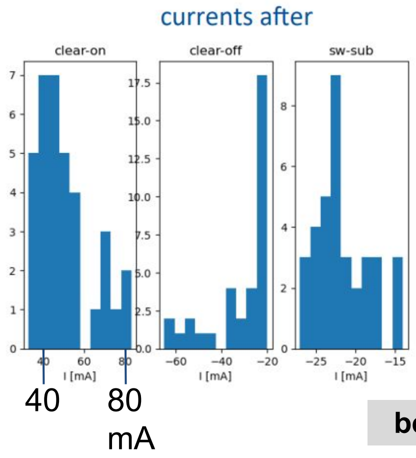
- After two beam loses similar effects as for PXD 1 observed
  - Dead gates and noisy switcher
- ~ 2 % of pixel lost after both SBL events
- PXD 2 still functional with good performance
  - Further SBLs events could damage PXD 2 severely
- Damage of switcher increases currents
  ⇒ Increased current increases temperature
- To ensure safe temperature turned off 3 additional modules in L2

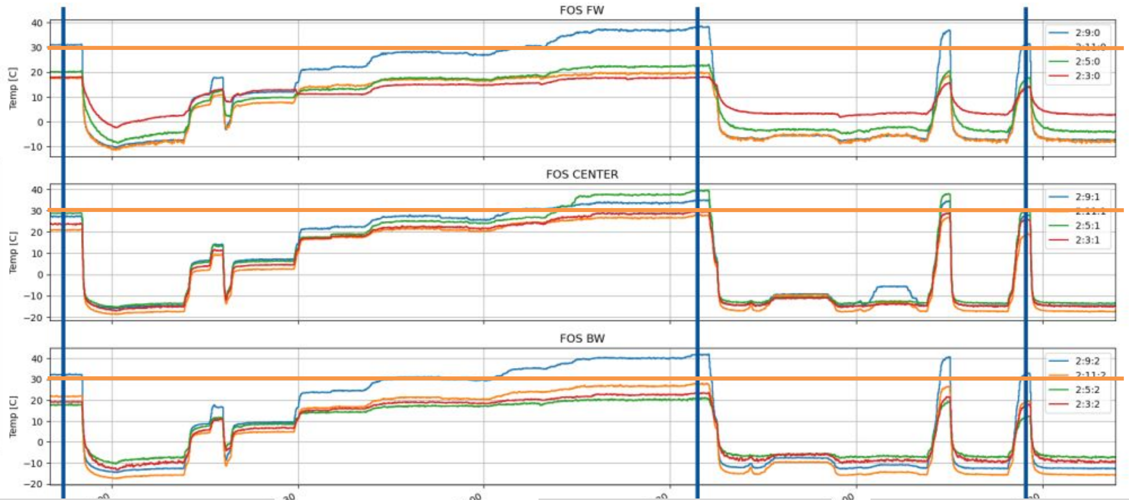


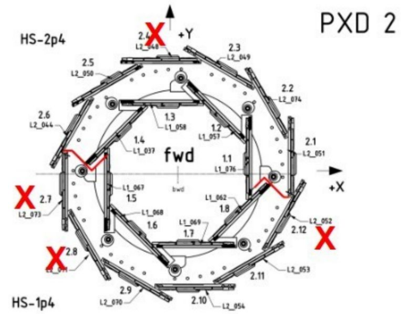


★ Scaling to highlight noisy areas ⇒ dark areas are not dead









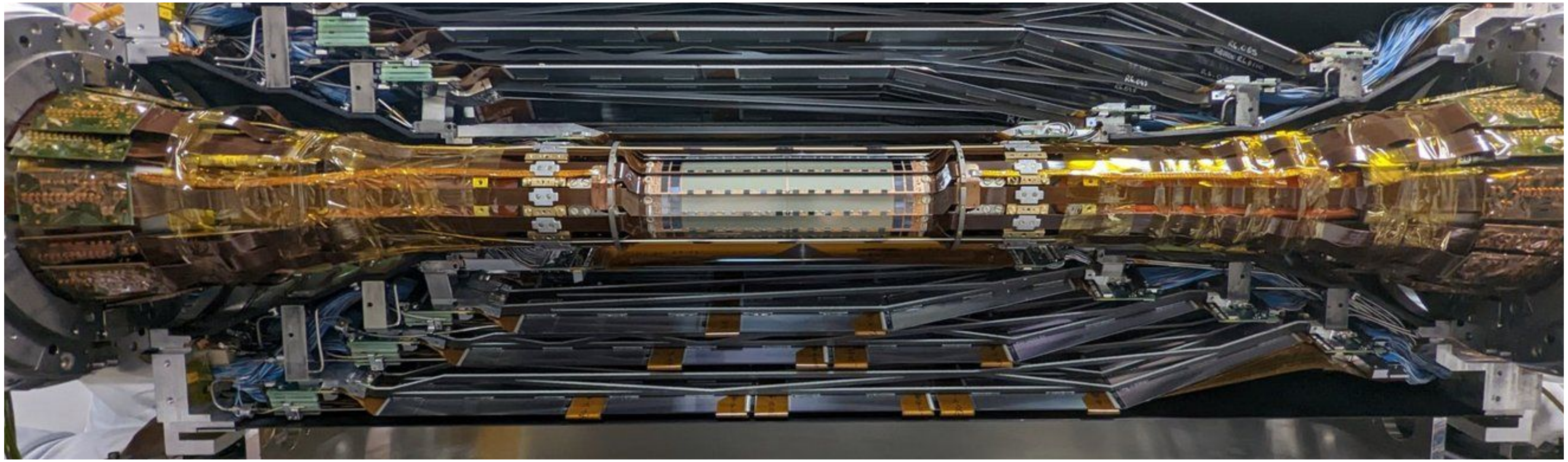
Summary and outlook

Summary

- Operation of **PXD 1 was successfu**l and ended in 2022
- **PXD 2 installed** and commissioned in 2023
  - Intensive studies on ladder bowing and temperature
  - Large sagitta and high temperature can open glue join
- In 2024 **data taking with PXD2 has been started**
  - **35 / 40** modules in operation
    - 4 larger bending
    - 1 large noise
  - L1 and L2 **efficiency > 98 %** in fiducial region
- **Two major SBL** events happened in 2024
  - Damage ~ 2 % of PXD 2 pixel
  - Increased operation temperature ⇒ 3 additional L2 modules turned off

Outlook

- Risk to lose PXD 2 after further SBLs is to large
  - PXD 2 especially needed for later runs with high luminosity and higher background
- Decided to **turn off PXD2 for now**
  - Gives accelerator group more freedom
    - To optimize beam operation
    - To solve origin of SBL events
  - Other sub-detectors robust against SBL events
- R&D ongoing for VXD successor called VTX
  - Talk by Alice Gabrielli on Thursday at 9am



Thank you!

Belle II-chan

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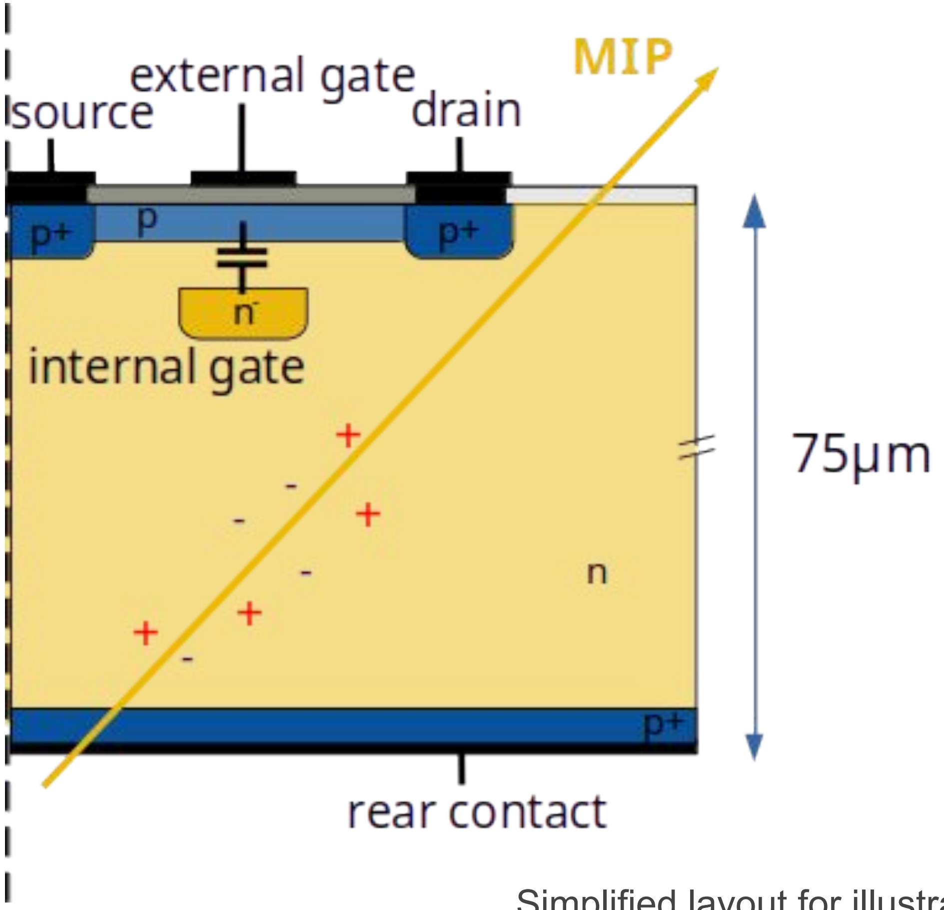
DEPFET Active Pixel Detector
HELMHOLTZ
PIXEL 2024
KEK Insight through Accelerators.
Belle II
SuperKEKB

DEPFET PIXEL Principle

*DE*pleted *P*-channel *F*ield *E*ffect *T*ransistor

- MOSFET on top of fully depleted silicon bulk
- Fast charge collection (~ns) in internal gate
- Charge in int. gate modulates drain-source current
- Internal amplification $g_q = \frac{\partial I_D}{\partial q} \approx 750 \frac{pA}{e^-}$
- High signal-to-noise ratio
- Periodic clearing required



Simplified layout for illustration

DEPFET PIXEL Operation

*DE*pleted *P*-channel *F*ield *E*ffect *T*ransistor

- Matrix readout steered by gate and clear voltages

Charge collection

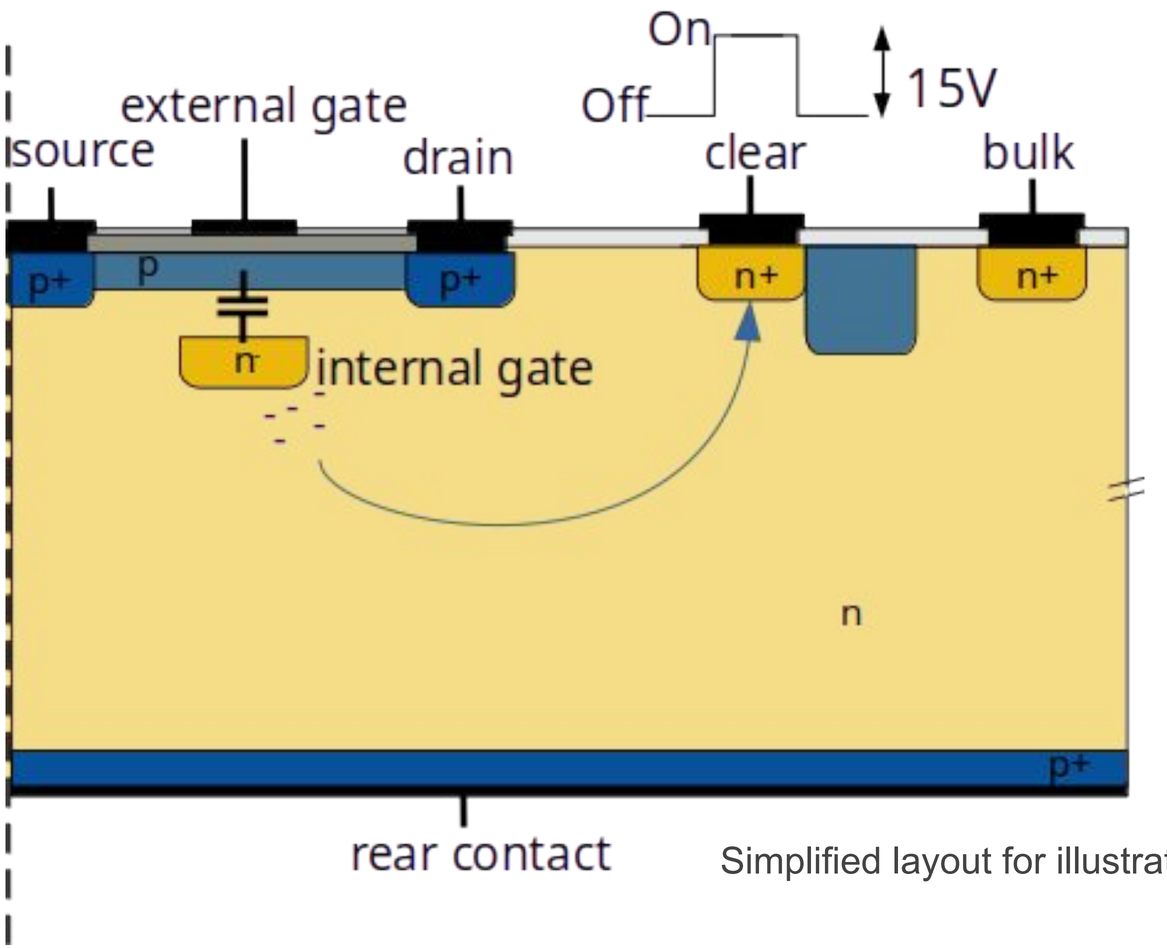
- Gate off and clear off
  - Charges drift to internal gate
  - No drain current

Sampling

- Gate on and clear off
  - Readout of stable drain current

Clearing

- Gate on and clear on
  - Charges drift from internal gate to clear implant

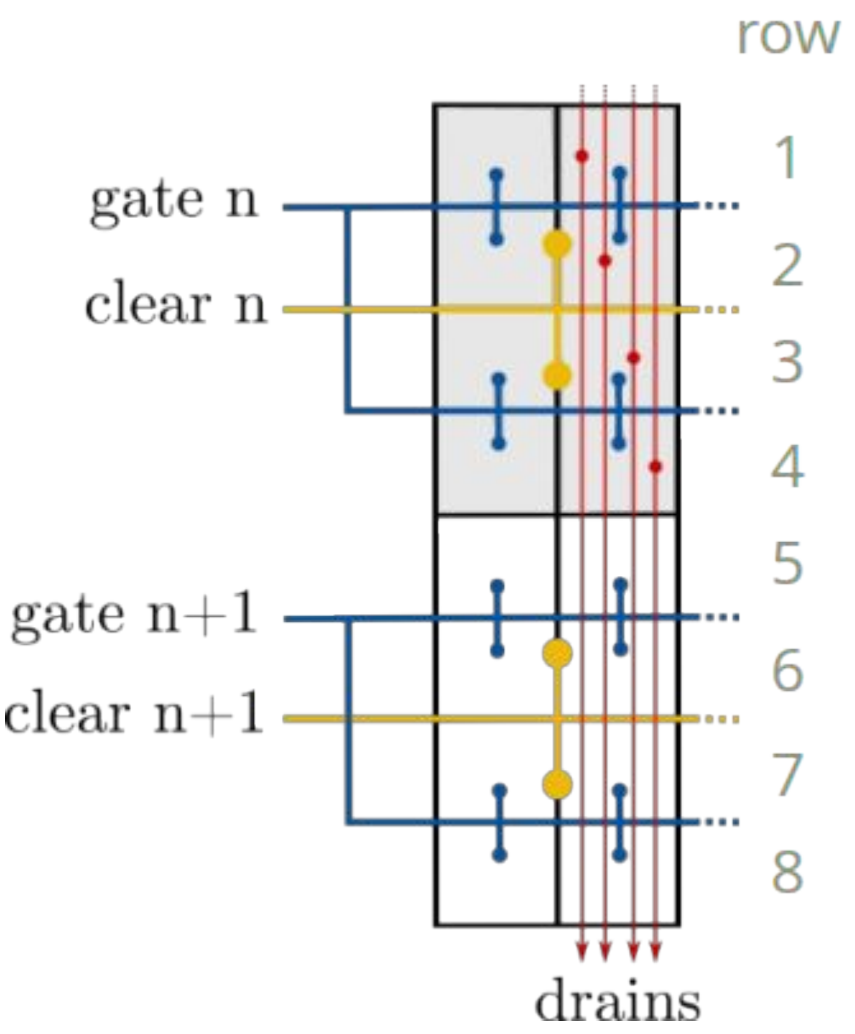


Simplified layout for illustration

DEPFET PIXEL Readout

Rolling shutter readout

- Four active matrix rows at once
  - Low power consumption
  - Control signals shared among pixels
  - 20 µm integration time (2x beam revolution)
- Modulated drain current processed via drain lines
- Different ASICs for row control and signal processing



DEPFET

PXD 2 optimization and tests at DESY

Gliding and endurance tests