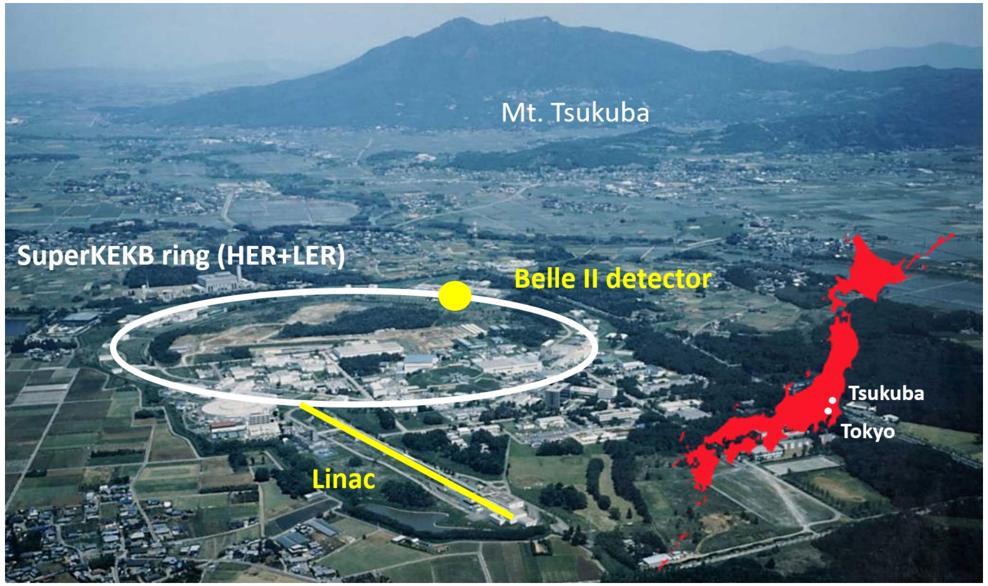
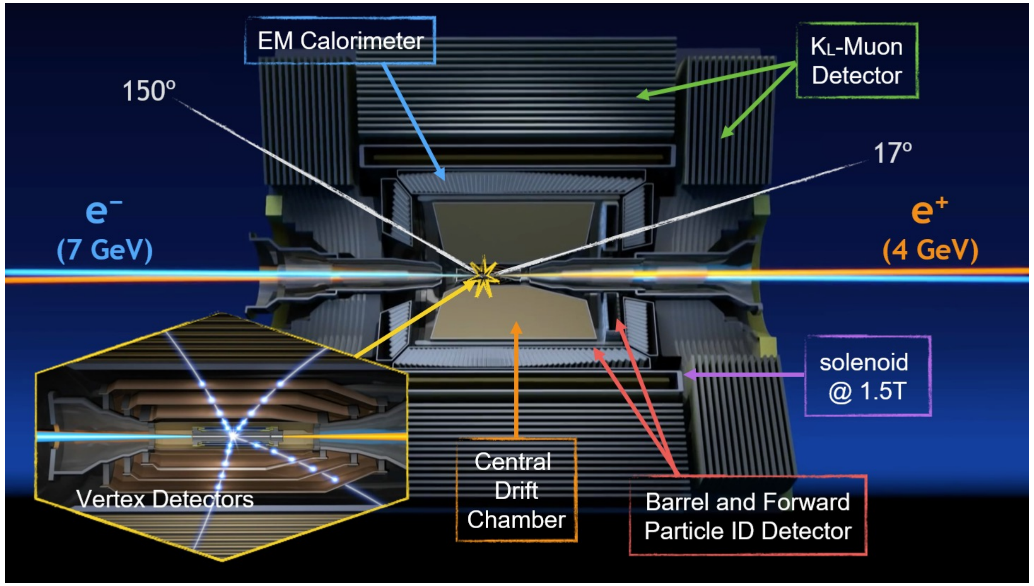
The DEPFET based all-silicon module for the Belle II Pixel Detector PXD

- ▷ PXD at Belle II
  - ↳ Construction, performance, and lessons learned
- ▷ Very brief outlook beyond HEP application

DEPFET PXD Collaboration
and the
team at the Semiconductor Laboratory of the Max Planck Society

SuperKEKB and Belle II

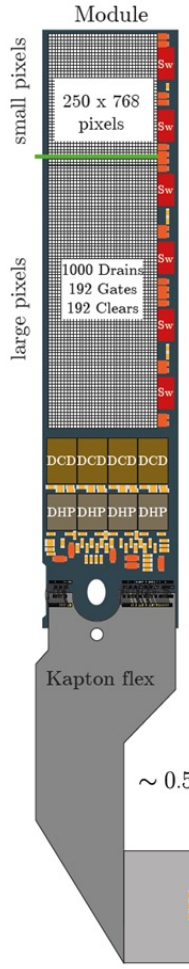




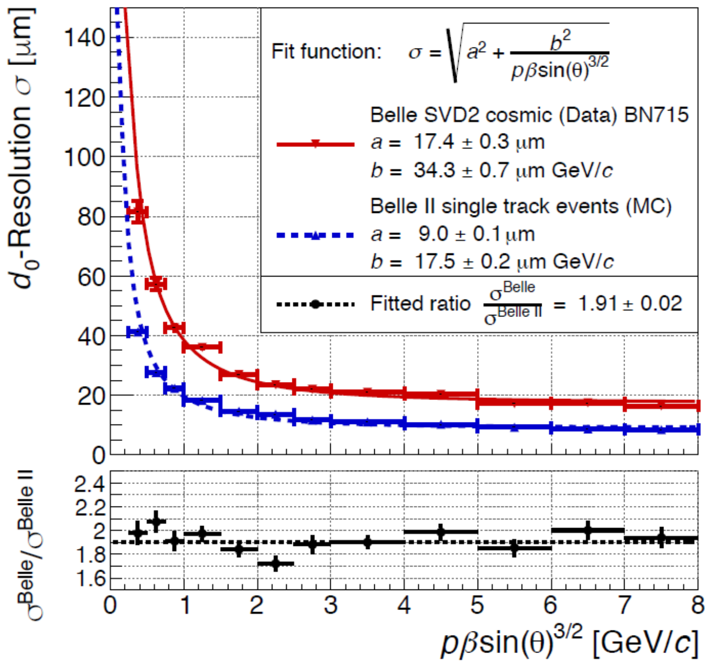
- ▷ Higher luminosity, KEKB → SuperKEKB "B factory"
  - ↳ goal Lumi 6 x 10^{35} $cm^{-2}s^{-1}$, achieved 4.7 x 10^{34} $cm^{-2}s^{-1}$ in June 2022
  - ↳ Higher event rate, higher background, higher radiation damage …
  - ↳ Ongoing long shutdown since July 2022 until end 2023

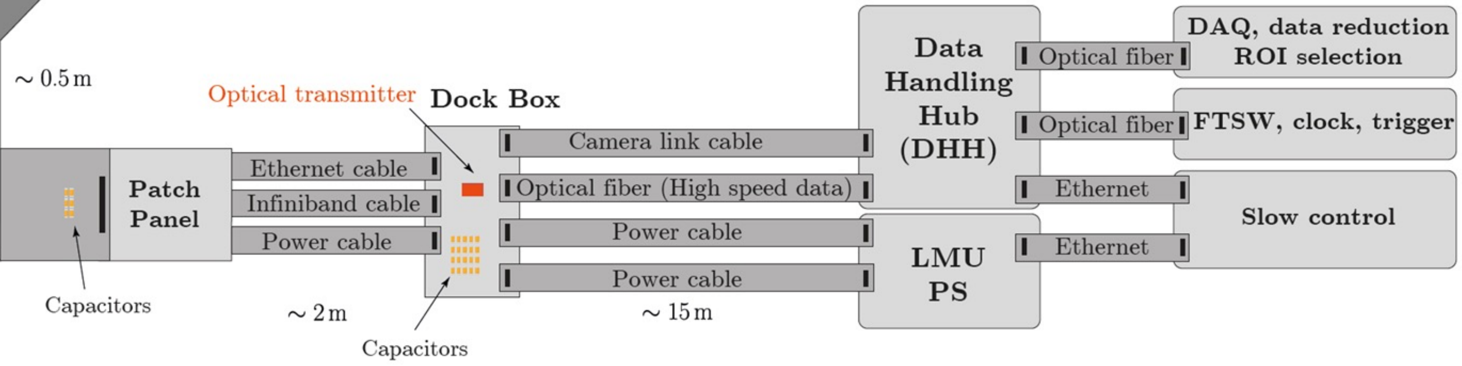
- ▷ Belle II
  - ↳ Upgraded detector
  - ↳ Physics data-taking since March 2019
    - ↳ 427.8 fb^{-1} recorded until June 2022
  - ↳ Goal is 50 ab^{-1} during lifetime (203x)

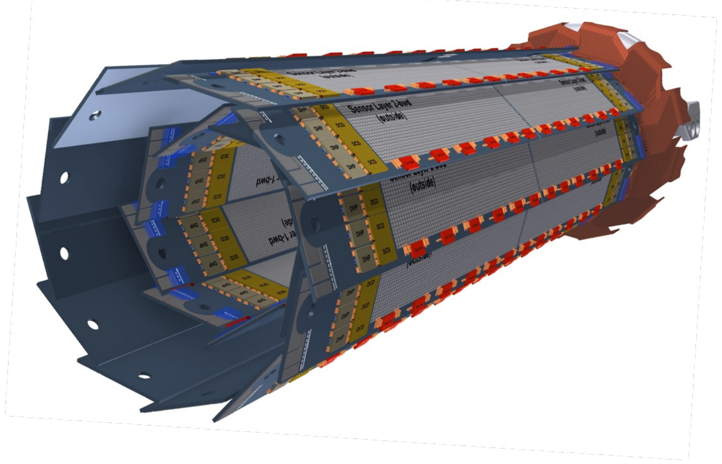
Belle II PXD



	L1	L2
# ladders (modules)	8 (16)	12 (24)
Distance from IP (cm)	1.4	2.2
Thickness (µm)	75	75
#pixels/module	768x250	768x250
#of address and r/o lines	192x1000	192x1000
Total no. of pixels	3.072×10^6	4.608×10^6
Pixel size (µm^2)	55x50 60x50	70x50 85x50
Frame/row rate	50kHz/10MHz	50kHz/10MHz
Sensitive Area (mm^2)	44.8x12.5	61.44x12.5







the DEPFET all-silicon module

DCDB (Drain Current Digitizer)

Amplification and digitization

- UMC 180 nm
- 256 input channels
- 8-bit ADC per channel

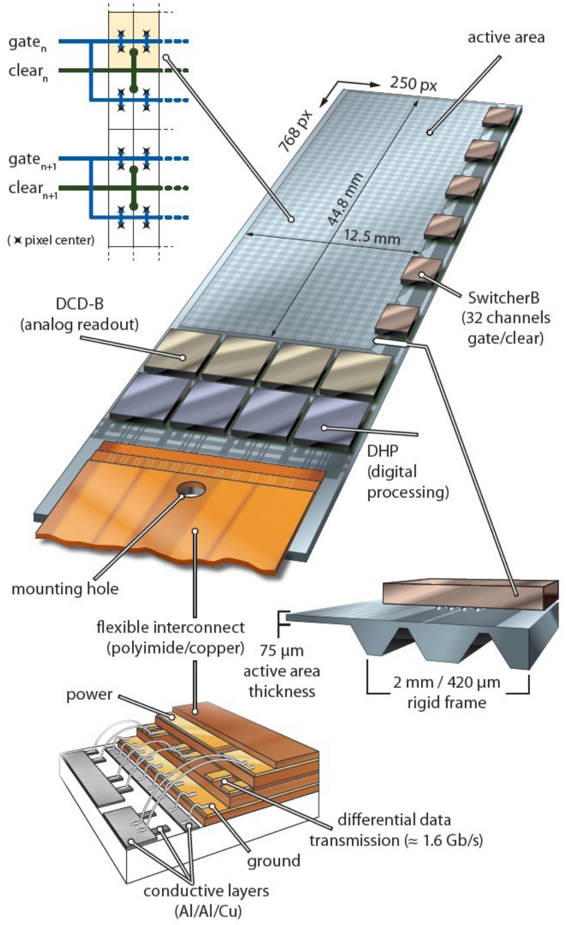
DHPT (Data Handling Processor)

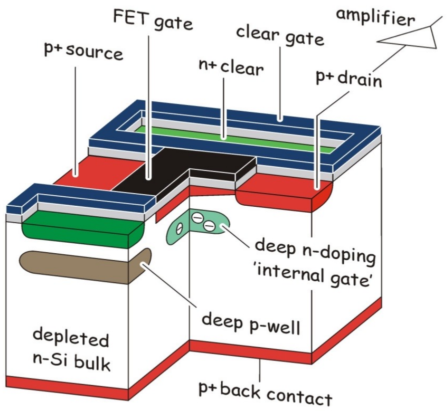
First data compression

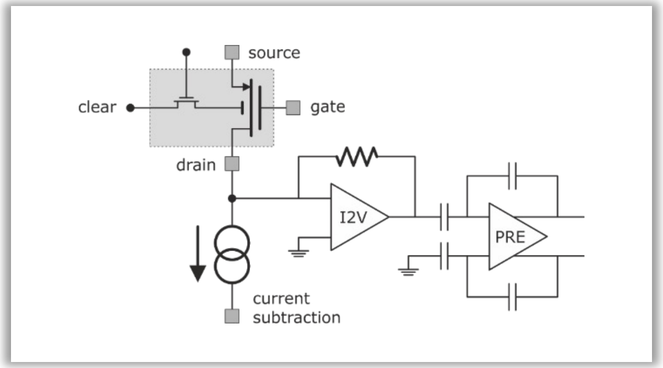
- TSMC 65 nm
- CM and pedestal correction
- Data reduction (zero suppression)
- Drives data link

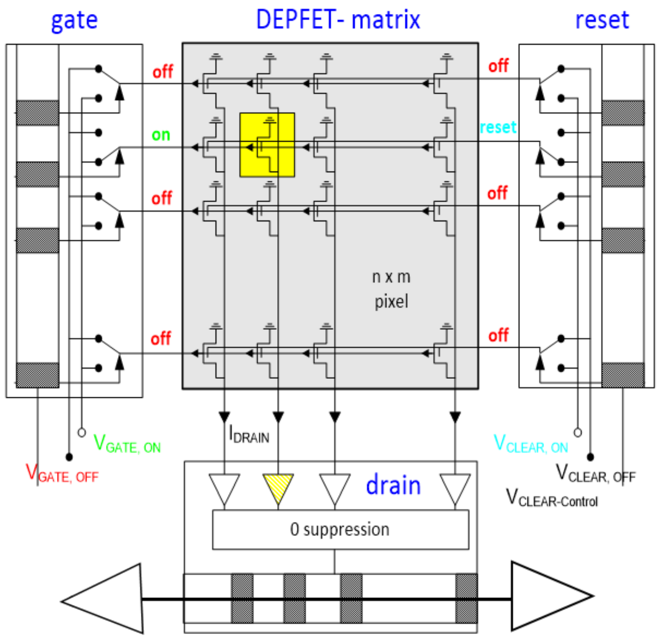
SwitcherB

- AMS/IBM HVCMOS 180 nm
- Gate and Clear signal
- 32x2 channels









▷ **Pixel array operated in „rolling shutter" mode, 20µs/f**

↳ **Only 4/768 rows active a time → low power in active area**

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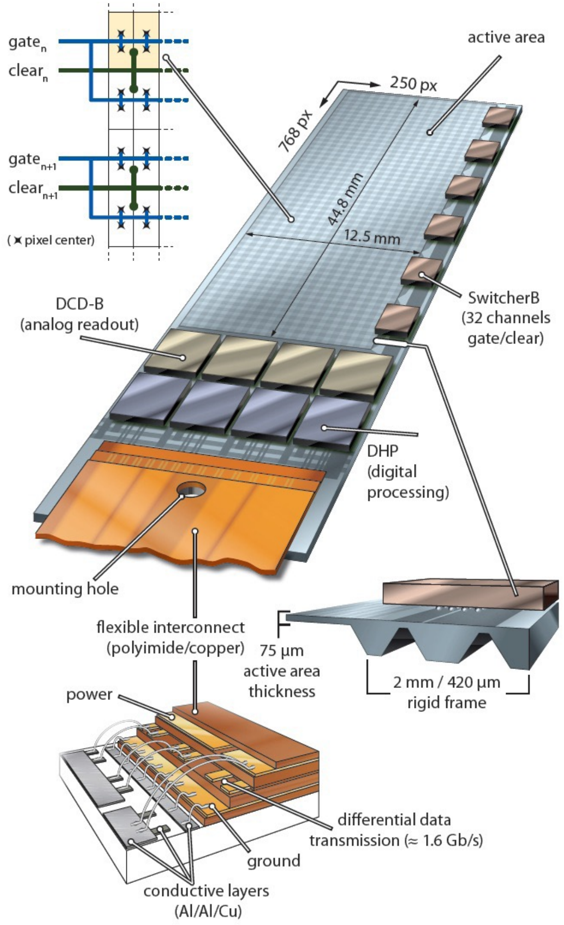

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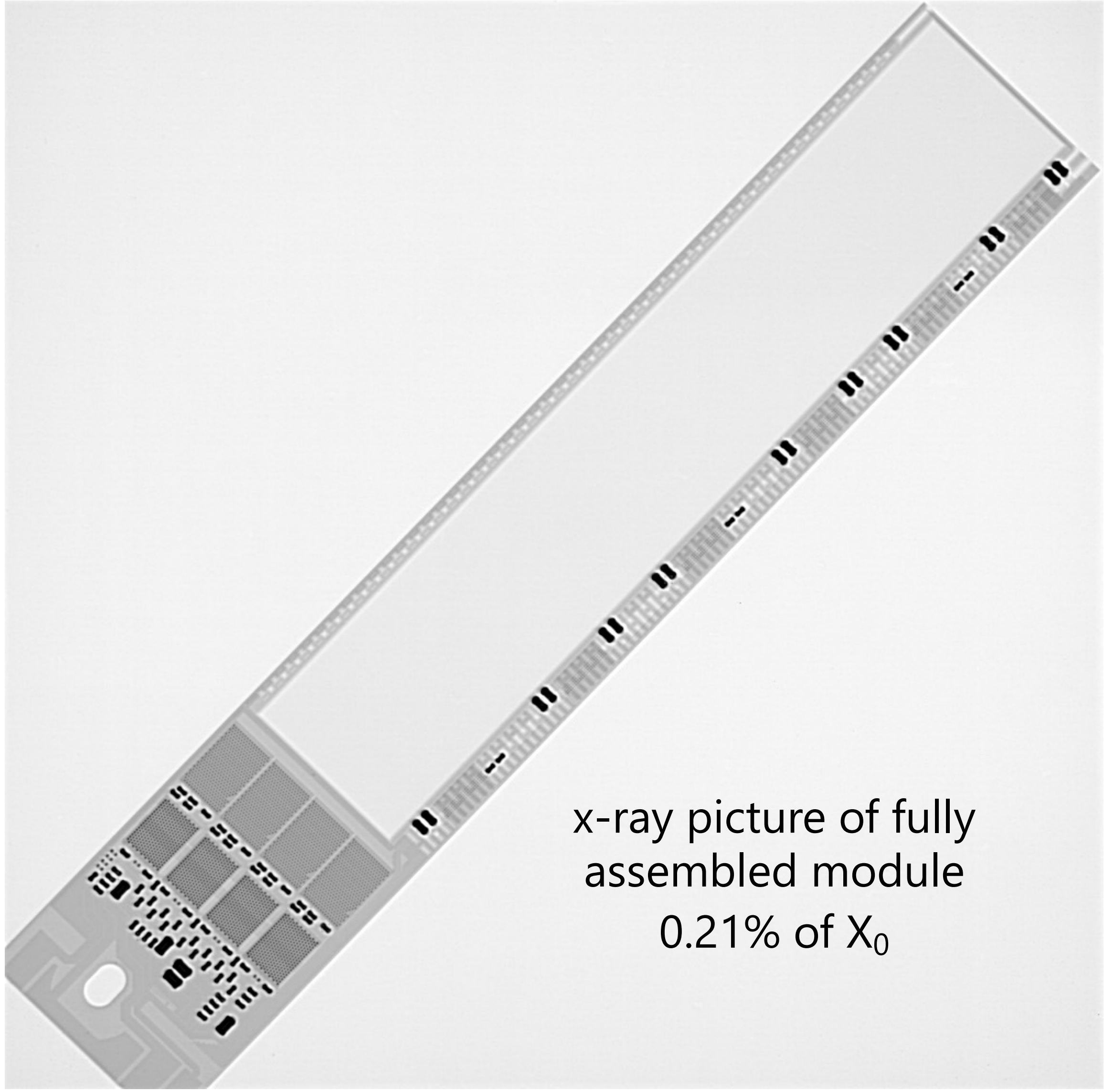
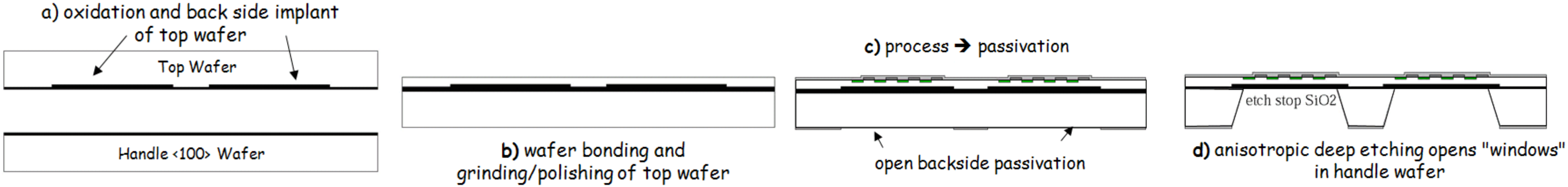
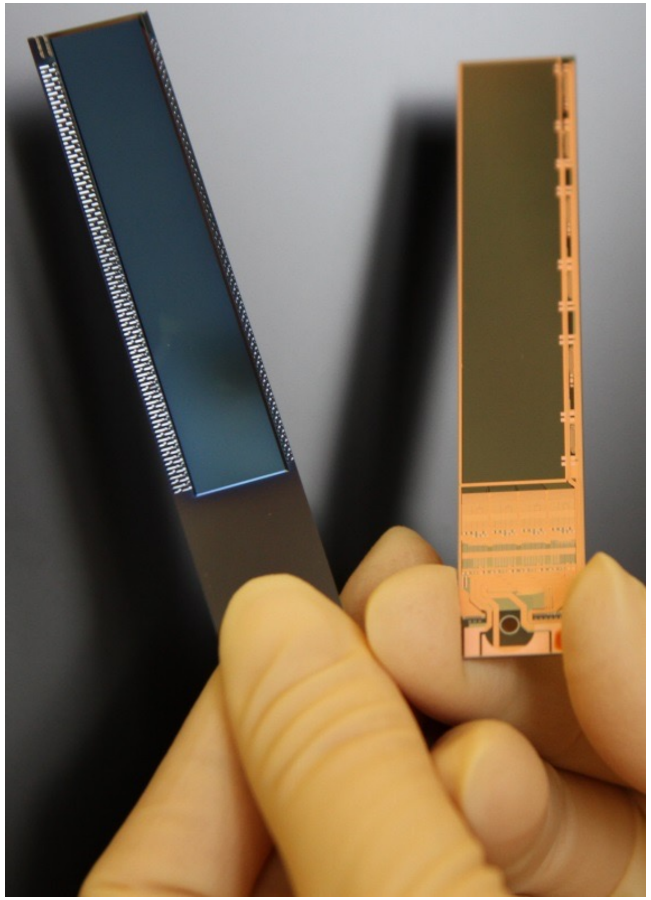


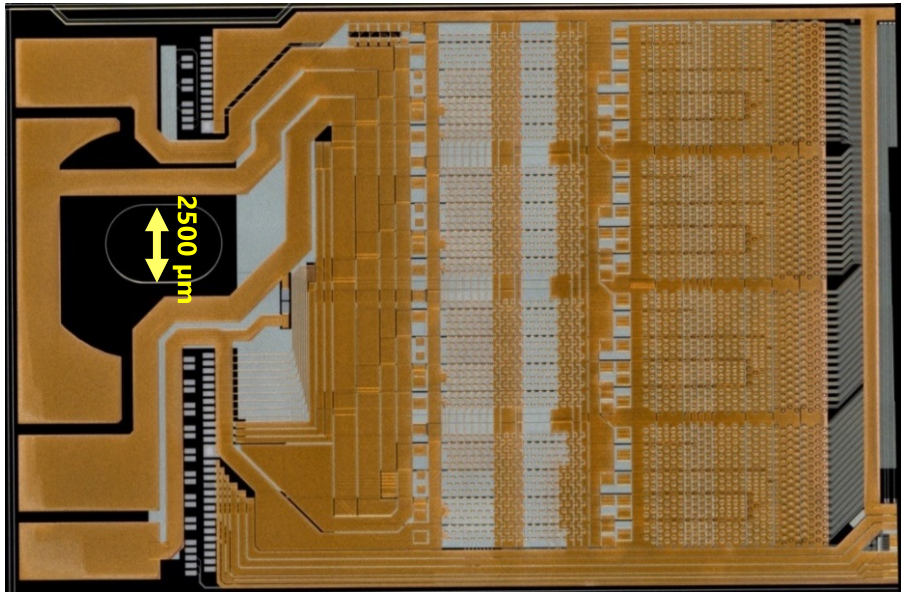
x-ray picture of fully assembled module

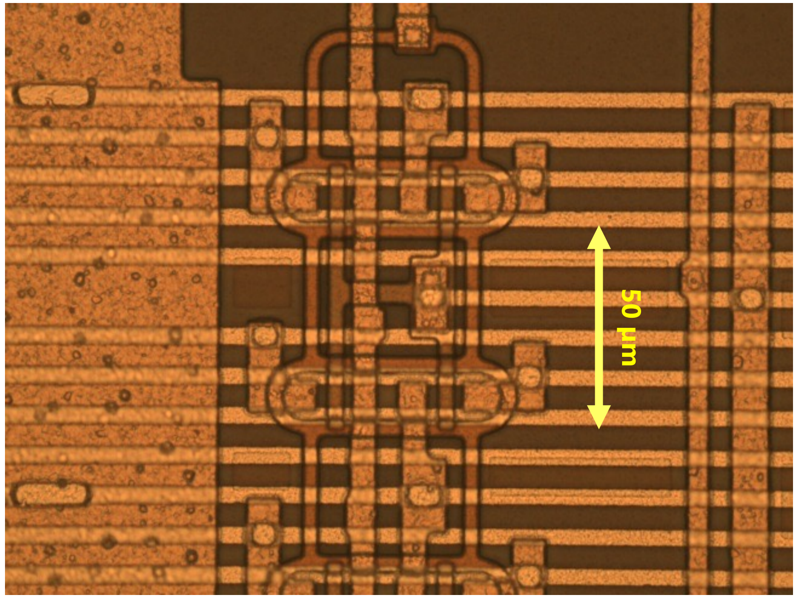
0.21% of X_0

Integrated sensor and module design









- thickness of the sensitive area is an almost free parameter
- full DEPFET technology in thin area
- thin area supported by a monolithically integrated silicon frame

module assembly overview

Flip Chip of ASICs (~240°C):

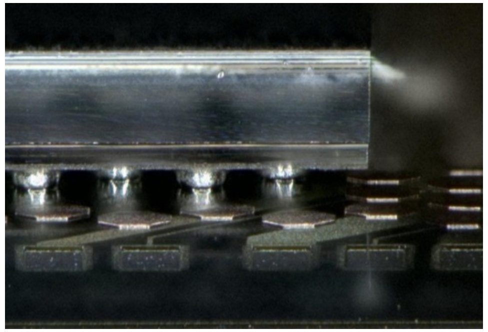
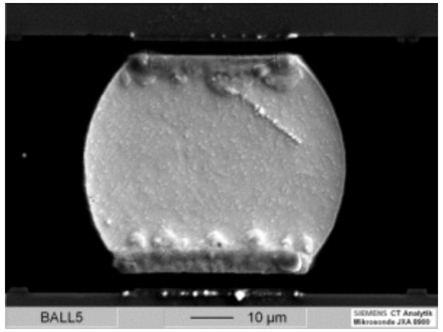
- ▷ Bumped ASICs have the same solder balls (SnAg)
  - ↳ DHP bumping at TSMC, DCD bumping via Europractice
  - ↳ SWB bumping on chip level
- ▷ Flip Chip of PXD modules on custom made support plates

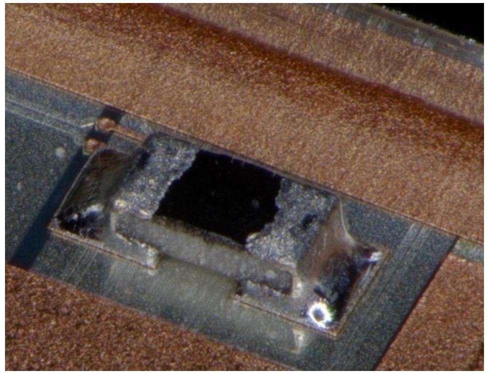
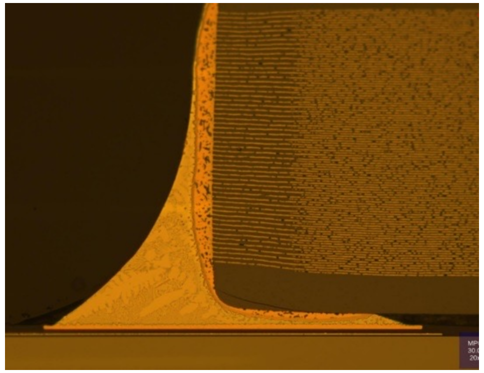
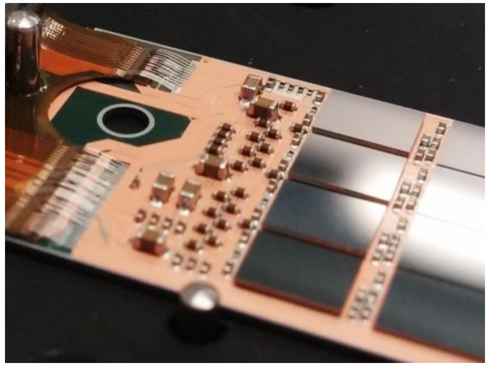
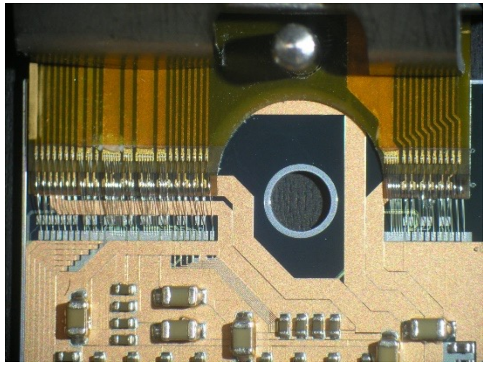
SMD placement (~200°C):

- ▷ Passive components (termination resistors, decoupling caps)
- ▷ Dispense solder paste, pick, place and reflow

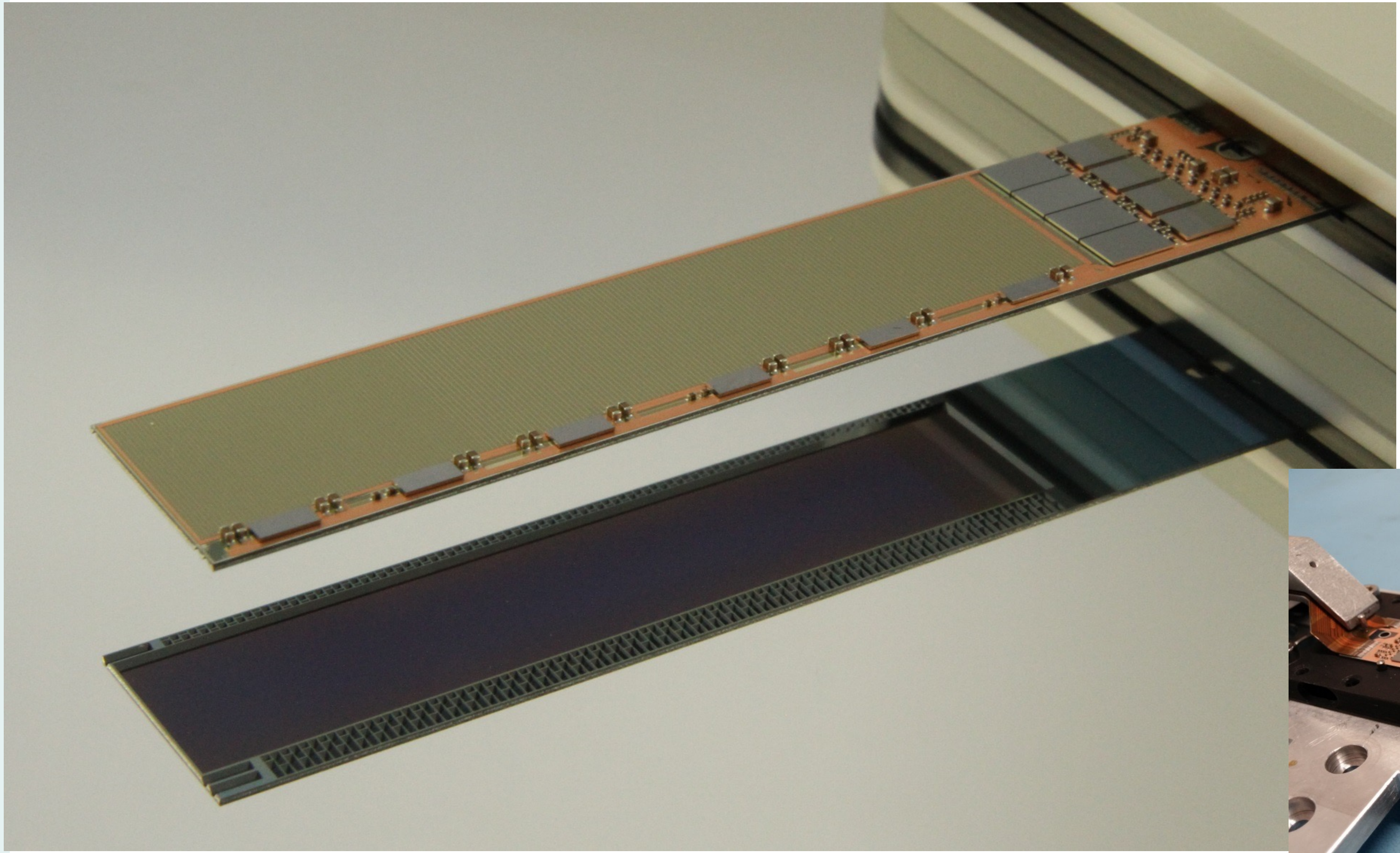
Kapton attachment (~170°C), wire bonding:

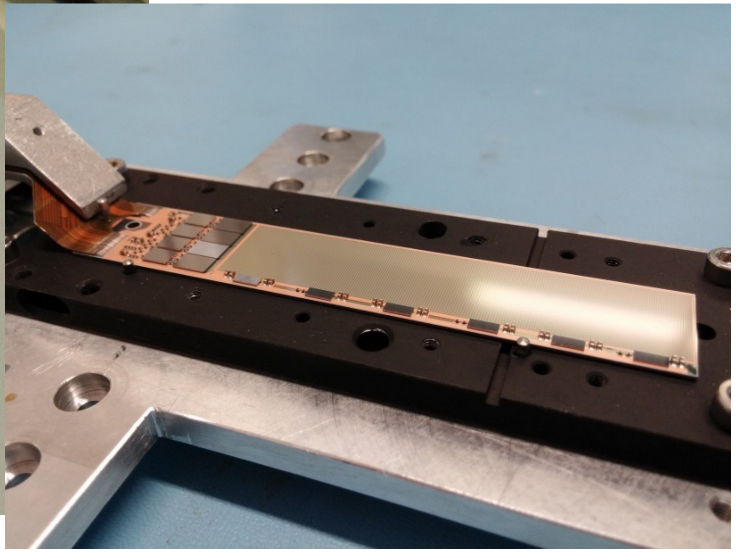
- ▷ Solder paste printing on kapton,
- ▷ Wire-bond, wedge-wedge, 32 μm Al bond wires

module 0



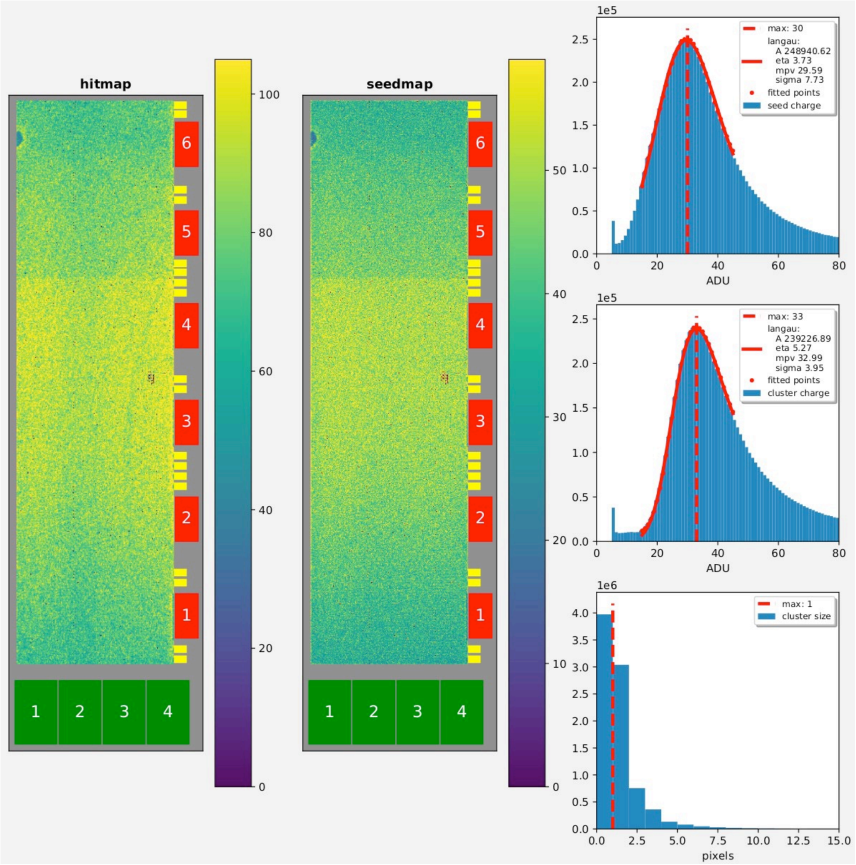


module characterization

- ▷ **71 modules (+46 for PXD2)** attached to pre-tested kapton cables
  - ↳ Module assembly yield ~96% (after rework)
  - ↳ ~50% contingency, both for PXD1 and PXD2

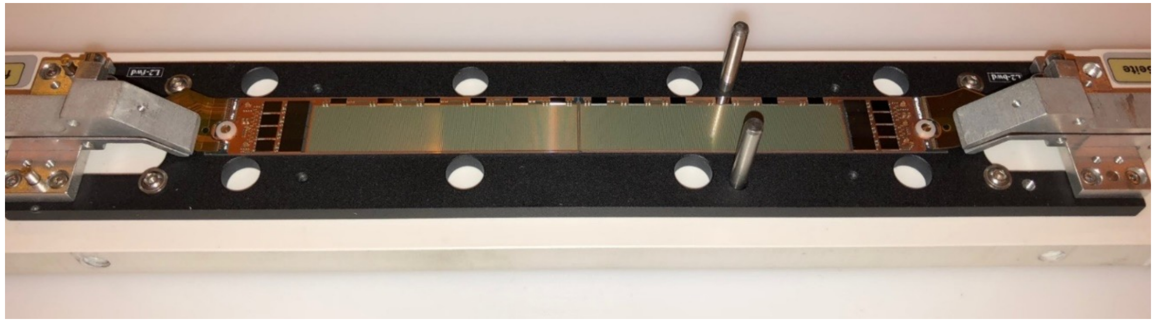
- ▷ collaborative effort (Bonn, Göttingen, HLL, MPP, IFIC, DESY)
  - ↳ script based, automated procedure
  - ↳ optimize/confirm ASIC and DEPFET parameters
    - ↳ linear response of the ADC, pedestal compression
    - ↳ Off-module link of DHP
  - ↳ charge collection (DEPFET voltages: Drift, HV, Clear-Off)

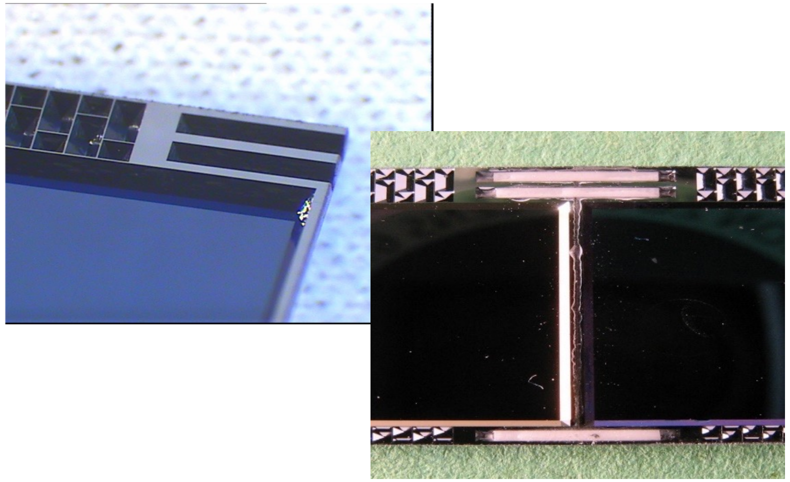
- ▷ Damage and repair after testing (PXD1 and PXD2)
  - ↳ 2 x kapton cables revealed shorts (modules ok after kapton exchange)
  - ↳ 1 x module: mechanically damaged (can not be depleted)
  - ↳ 2 x modules: SwitcherB damaged at test
  - ↳ 4 x modules suffered from cooling malfunction (condensation)



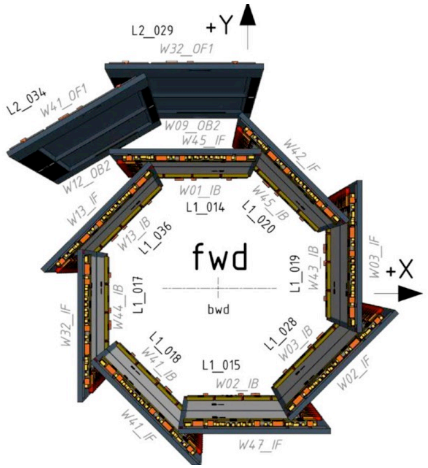
After characterization: Sr90 spectrum *(Bonn Uni)*

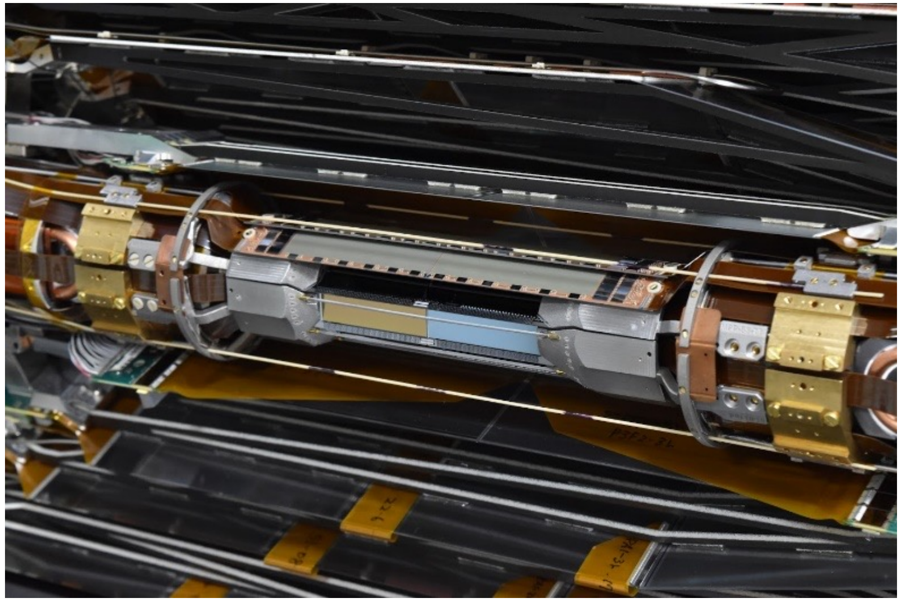
- ✓ 291 unresponsive single pixels
- ✓ 251 noisy pixels
- ✓ 99.85% active pixels





- ▷ Join two modules to a ladder → “ladder gluing”
  - ↳ v-grooves for small ceramic inserts on the back side → Reinforcement of the joint
- ▷ **Yield issue**: out of 17 assembled ladders, 5 were lost due to damage at assembly
  - ↳ Resolved for PXD2
- ▷ **Install de-scoped PXD1** to meet the schedule for the start of data taking (March 2019)
  - ↳ Full L1 (8 ladders) and 2/12 ladders in L2

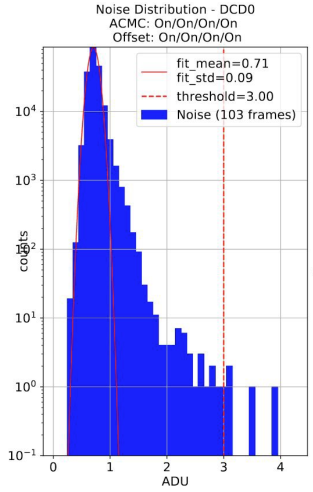


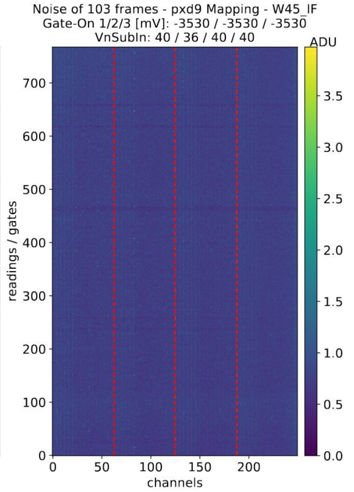


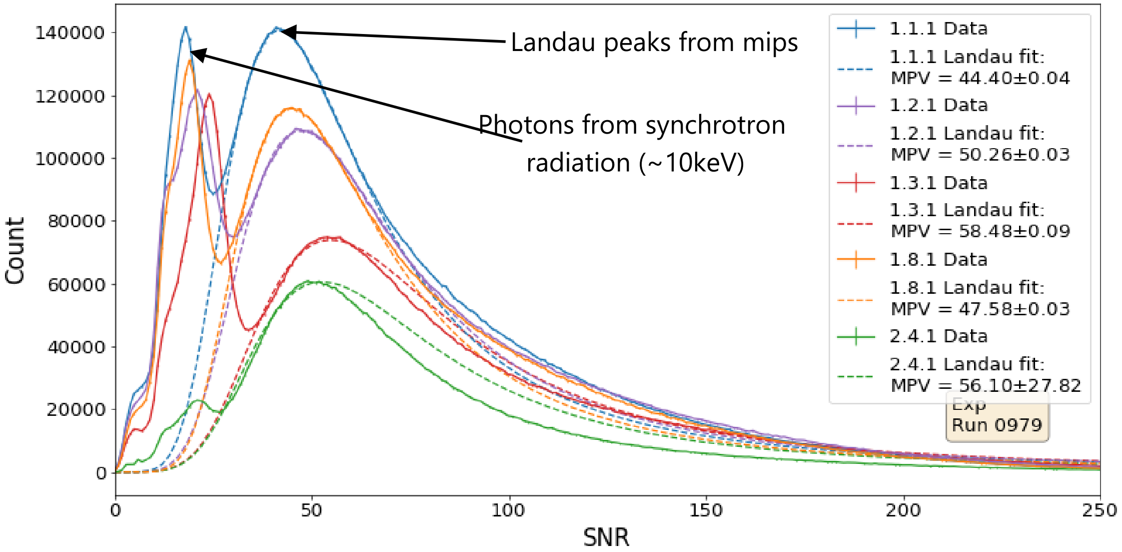
- ▷ **Completion of PXD (“PXD2”) with new modules accomplished 2023**

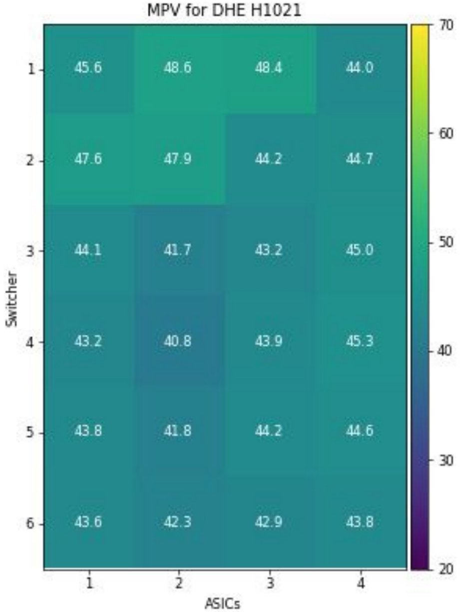
PXD1: operation in Belle II

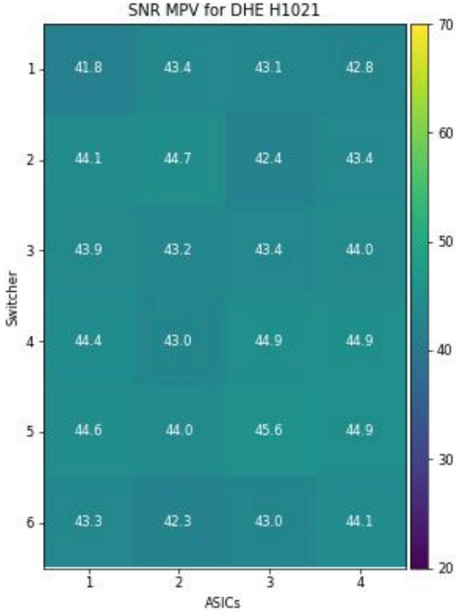
- ▷ PXD in operation in Belle II March 2019 until June 2022 with good performance
  - ↳ First application of DEPFET sensors in HEP!
- ▷ S/N around 40, stable over time and with good homogeneity
  - ↳ Narrow and stable pedestals and noise
- ▷ Efficiency to find in L1 or L2 ~ 96%
  - ↳ ~99% efficiency in fiducial region
- ▷ Impact parameter resolution close to expectations
  - ↳ data: $\sigma(d_0)$ = 14.2 μm → about 2x better than Belle







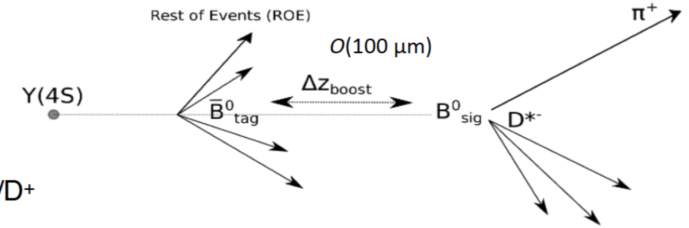


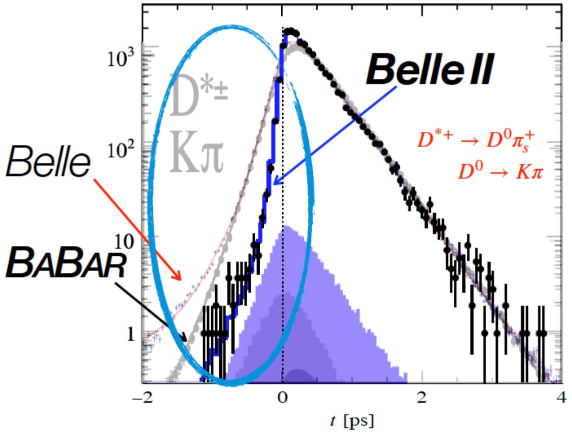


PXD1: Physics Performance

VXD Physics Performance

- Precise measurements of decay vertices crucial for time dependent measurements
  - Belle II proper time resolution ~2x better than Belle
  - thanks to PXD precision and smaller beam pipe diameter
- Belle II published world-leading lifetime measurements on charmed mesons: D^0/D^+





Factor 2 improved t-resolution at Belle II compared to Belle and BaBar

15.12.22, HLL Project Review, Ringberg: **Belle II PXD**

- **New**: lifetime measurements of charmed baryons: Λ_c and Ω^0_c
  - further measurements, eg on time-dependent CP violation in the pipeline

$\boxed{\tau(\Lambda_c):\ 203.20 \pm 0.89\,(\mathrm{stat}) \pm 0.77\,(\mathrm{syst})\ \mathrm{fs}}$

$\boxed{\tau(\Omega_c^0) = 243 \pm 48\,(\mathrm{stat}) \pm 11\,(\mathrm{syst})\ \mathrm{fs}}$

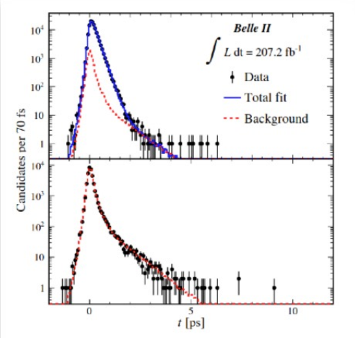
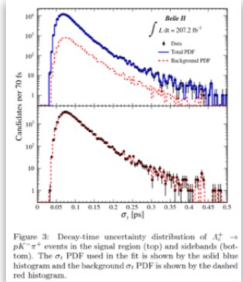
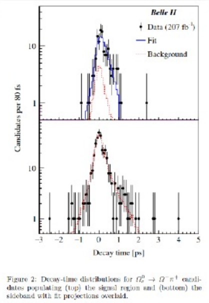


Figure 2: Decay-time distribution of $\Lambda_c^+ \to pK^-\pi^+$ events in the signal region (top) and sidebands (bottom) with fit projections overlaid.



- Confirming LHCb results of 3σ tension with pre-LHC world average



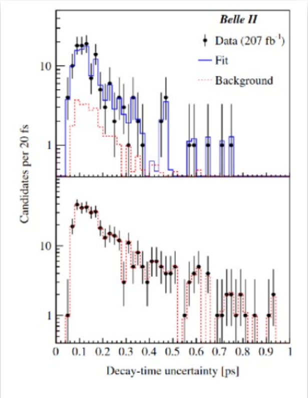


Figure 3: Decay-time-uncertainty distributions for $\Omega_c^0 \to \Omega^-\pi^+$ candidates populating (top) the signal region and (bottom) the sideband with fit projections overlaid.

Ω_c: arXiv:2208.08573 → Physical Review D Letters
Λ_c: arXiv:2206.15227 → Physical Review Letters
D^0/D^+: Phys. Rev. Lett. 127, 211801 (2021)

15.12.22, HLL Project Review, Ringberg: **Belle II PXD** 11

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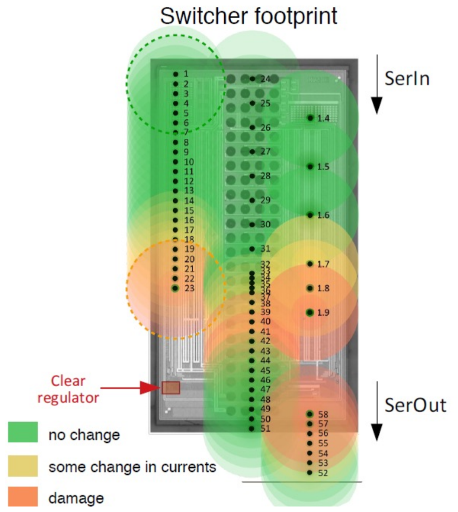
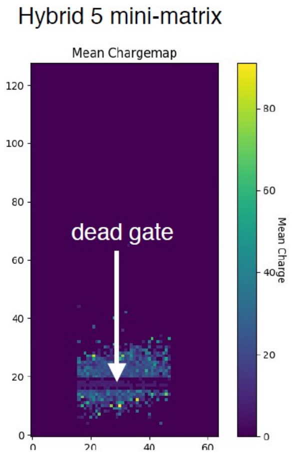
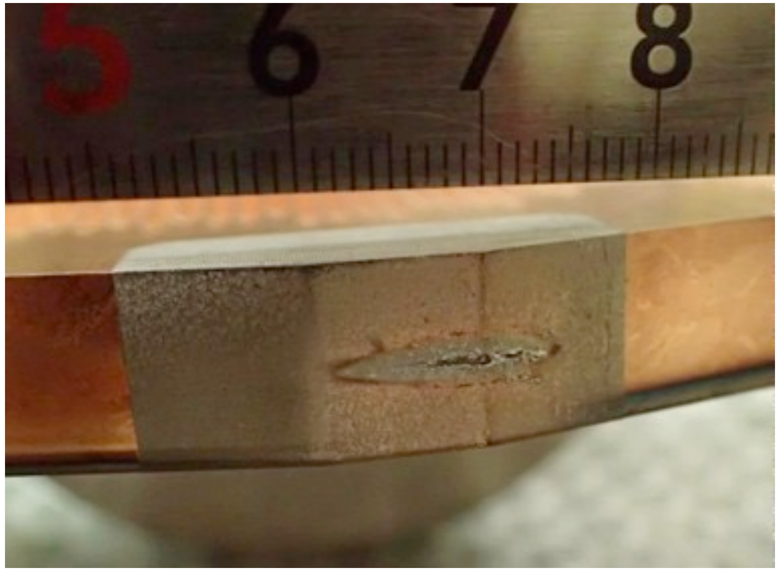
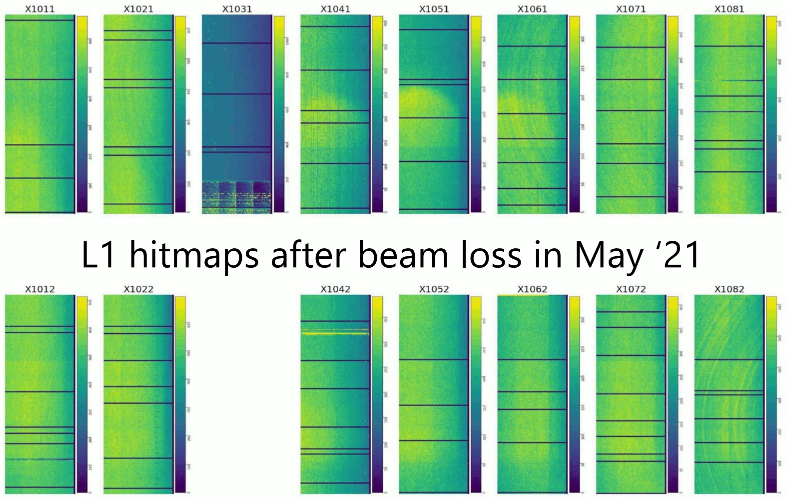
surprises I

- ▷ Damage due to beam losses/incidents
  - ↳ Origin of beam losses not completely clear (beam-dust events? machine glitches?)
- ▷ Resulted in collimator damage, quench of the QCS magnet system …
- ▷ Huge instant radiation dose of about 300 rad in ~40 μs in the PXD
  - ↳ Permanent damage of entire rows → "dead", inefficient regions
  - ↳ Overall efficiency loss of about **3 percentage points** at the end of run1
- ▷ Origin of PXD damage traced back to SEE in the Switcher HV-CMOS chip
  - ↳ Reproduced at MAMI accelerator in Mainz
    - ↳ electron pencil beam scanned over DEPFET array and Switcher chip







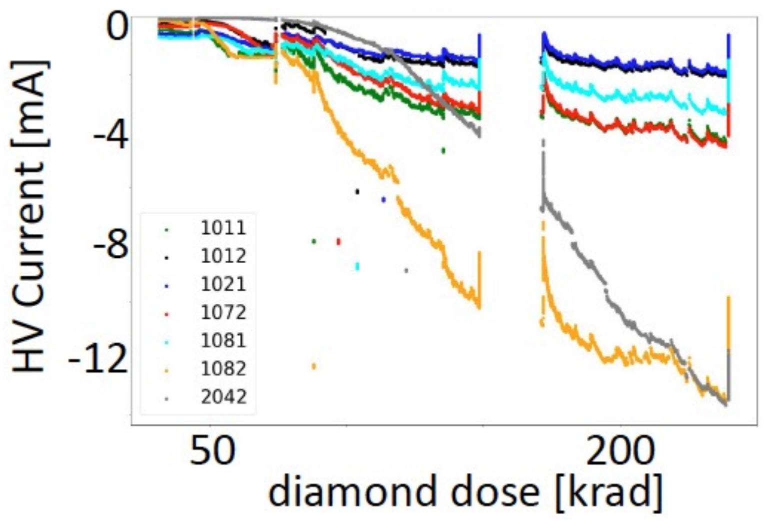


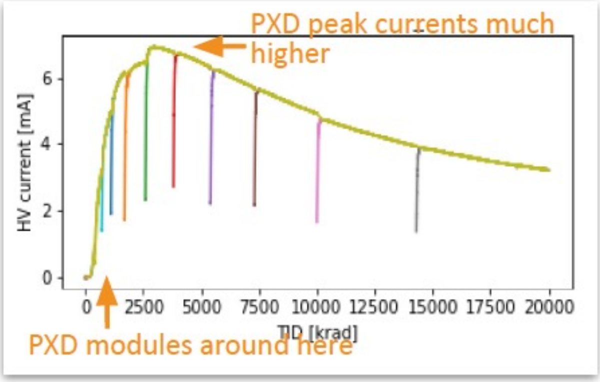
L1 hitmaps after beam loss in May '21

- ▷ Mitigation (from PXD side and SuperKEKB) ongoing
  - ↳ Accelerate beam abort signal and power-down of modules
  - ↳ Root cause in the switcher chip understood (new version under production, tests pending)

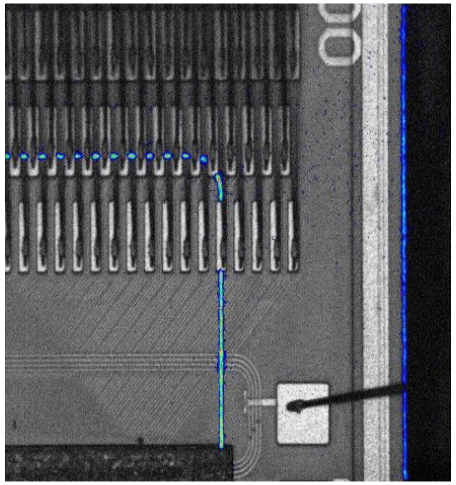
surprises II

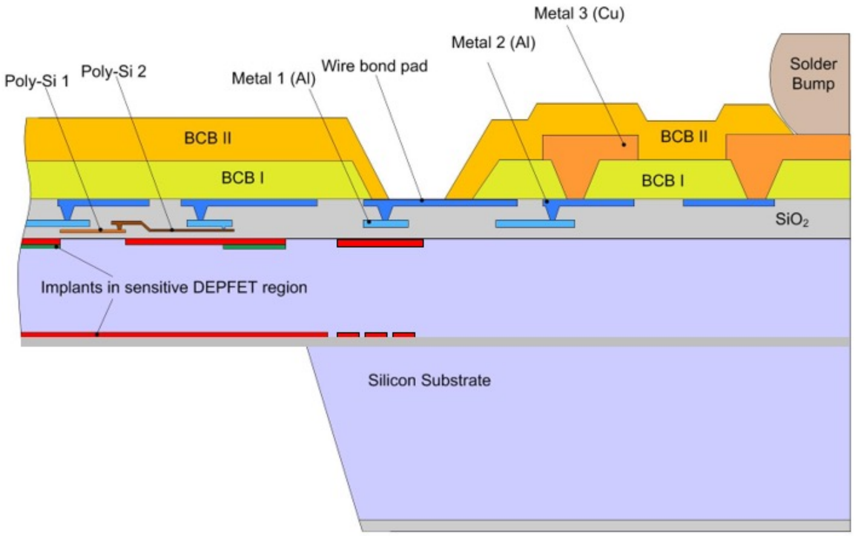
- ▷ Backplane (HV, depletion) is increasing from tens of µA to >1mA
  - ↳ Most affected modules are currently in +x direction
  - ↳ This is where the background is 2x higher …
- ▷ Module performance not affected, noise and signal stable
  - ↳ Also negligible contribution to overall power consumption
- ▷ Issue: the power supply system is not designed to supply that high current
  - ↳ Some PS upgraded already in PXD1, for PXD2 PS will be able to supply up to 28 mA
- ▷ Root cause
  - ↳ Guard rings on the back side not fully functional at higher radiation doses
- ▷ Confirmed by dedicated photon irradiations on test modules





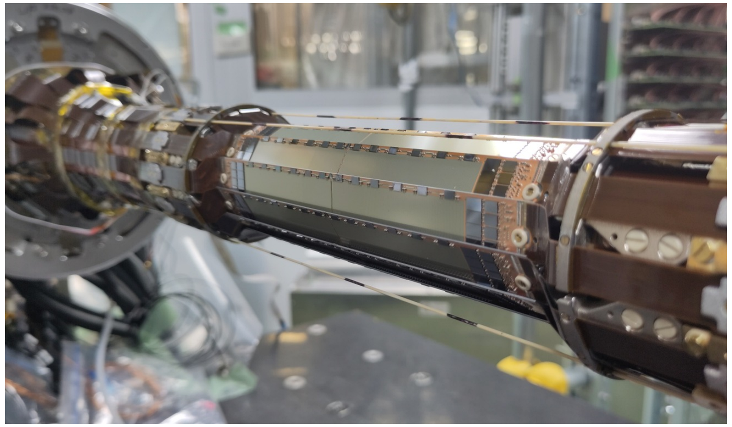
- x-ray lab campaigns: expect currents saturate at certain dose
- not observed in PXD yet

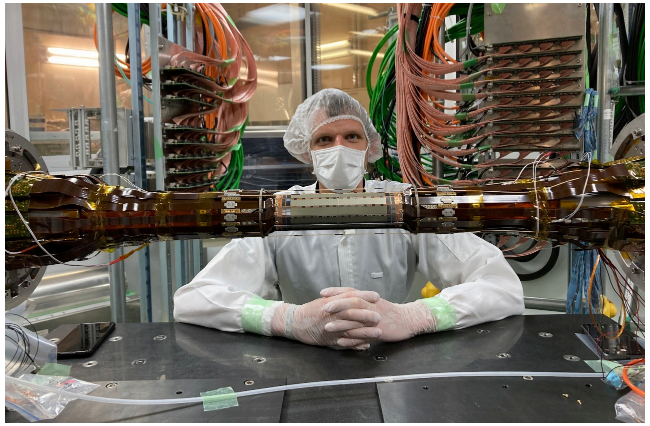


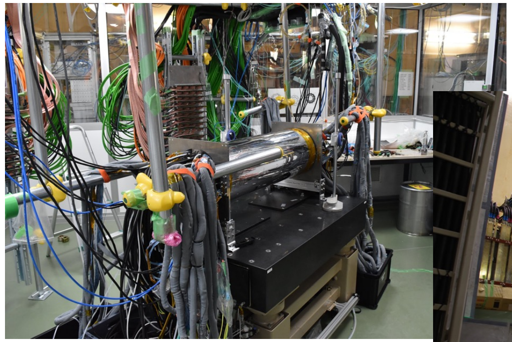


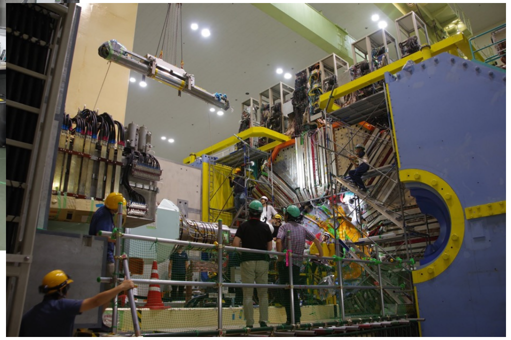
PXD1 → PXD2

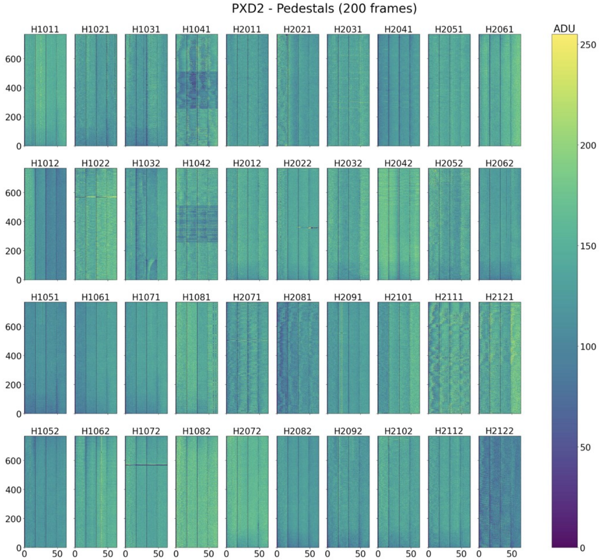
- (incomplete) PXD1 in operation from May 2019 until June 2022
- (complete) PXD2 assembled with leftover modules from PXD1 and newly produced sensors and assembled modules and ladders
- Installed in Belle July 2023, currently under commissioning, run2 start scheduled December 2023

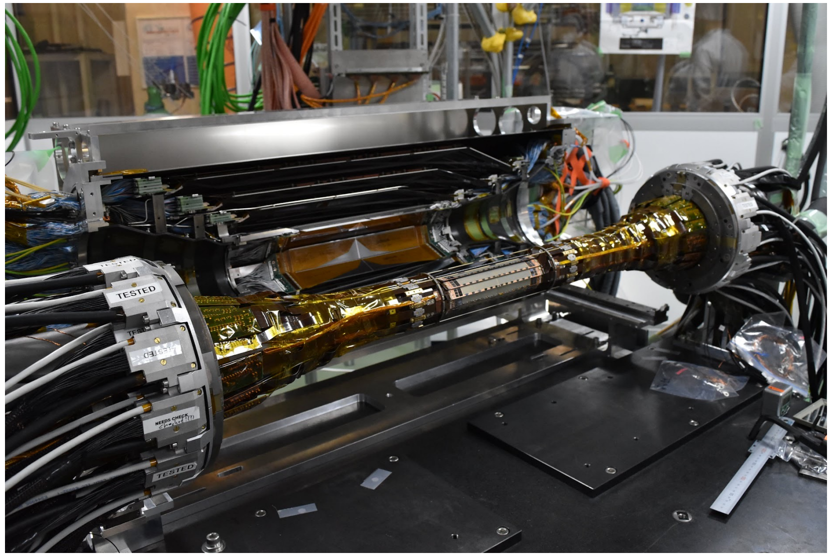


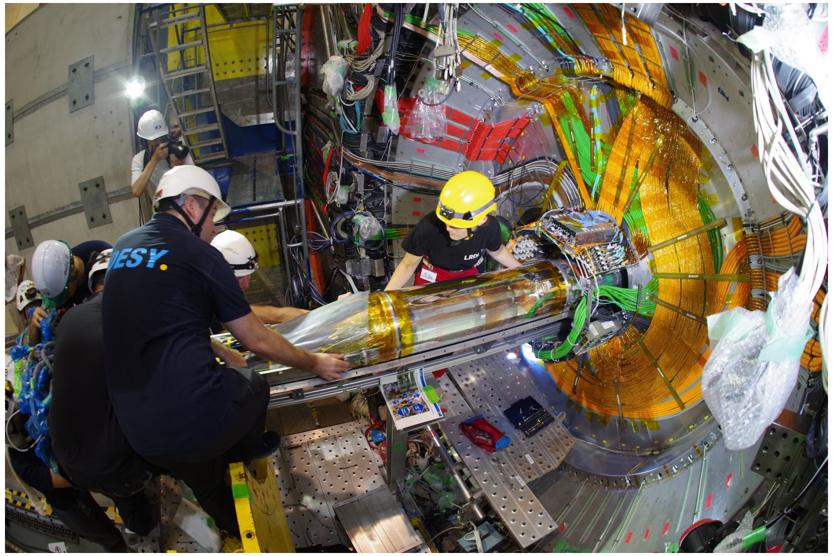






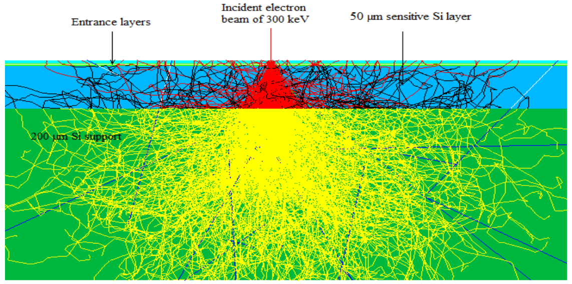


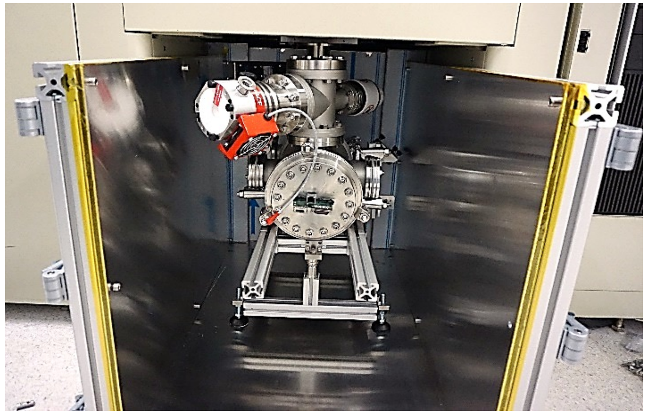


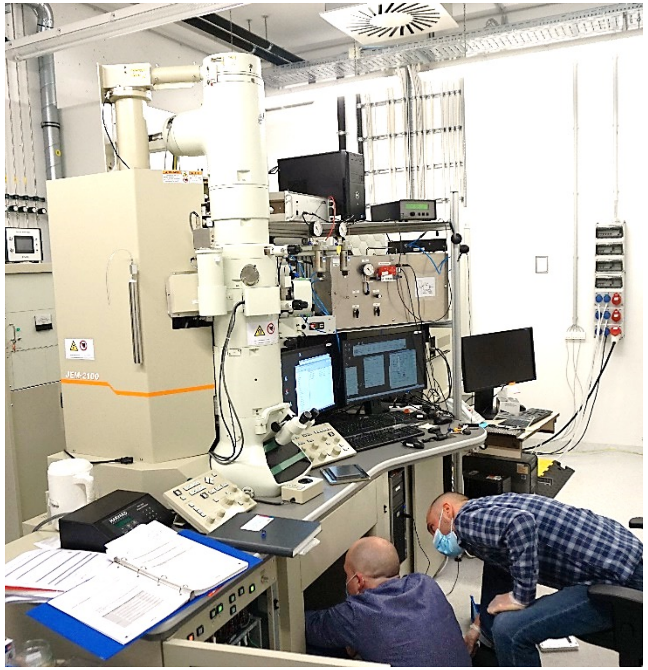


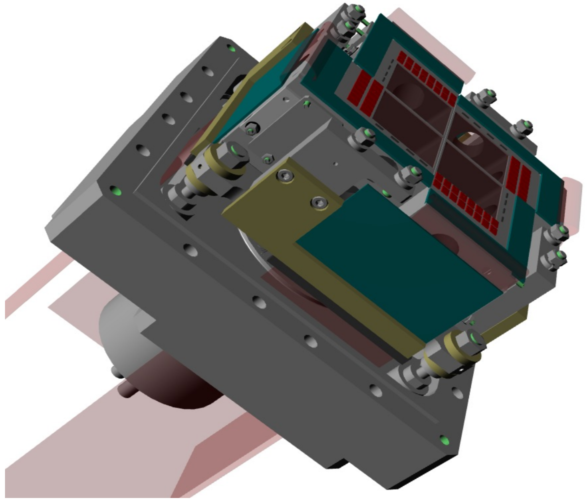
Same module concept, different application

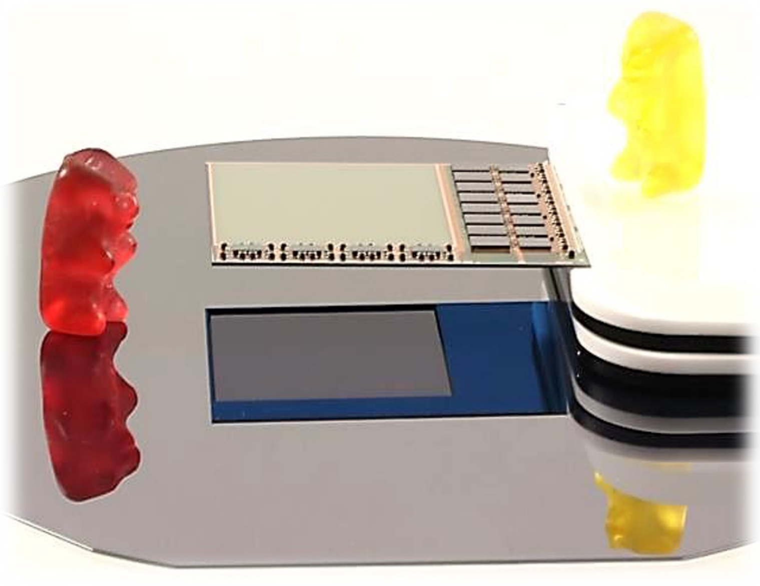
- ▷ Ultrafast direct electron detection for 300 keV TEM – 80 kHz frame rate for 1 Mpix camera
  - ↳ Sensor 50 μm (optionally 30 μm)
  - ↳ Optimized 60 μm DEPFET pixel cell with high dynamic range (800 k signal electrons)
  - ↳ Challenging operation in in very narrow UHV chamber











In Summary

- ▷ Belle II PXD: the first full vertex detector based on DEPFETs!
  - ↳ Overall performance of the modules meets the requirements at SuperKEKB
  - ↳ Run1 successfully finished with descoped PXD1
  - ↳ Run2 with complete PXD2 scheduled to start end 2023

  - ↳ There were a few surprises, many lessons learned
    - ↳ One of the most important ones: have to make the system more user friendly!

- ▷ The concept of the DEPFET all-silicon module finds now new applications in a different field

- ▷ This is not the end, there is more to come
  - ↳ Integration of micro-channels for cooling under way
  - ↳ New generation of DEPFETs with improved characteristics finished and being tested
    - ↳ Higher amplification, smaller pixels, high dynamic range, improved radiation tolerance ....