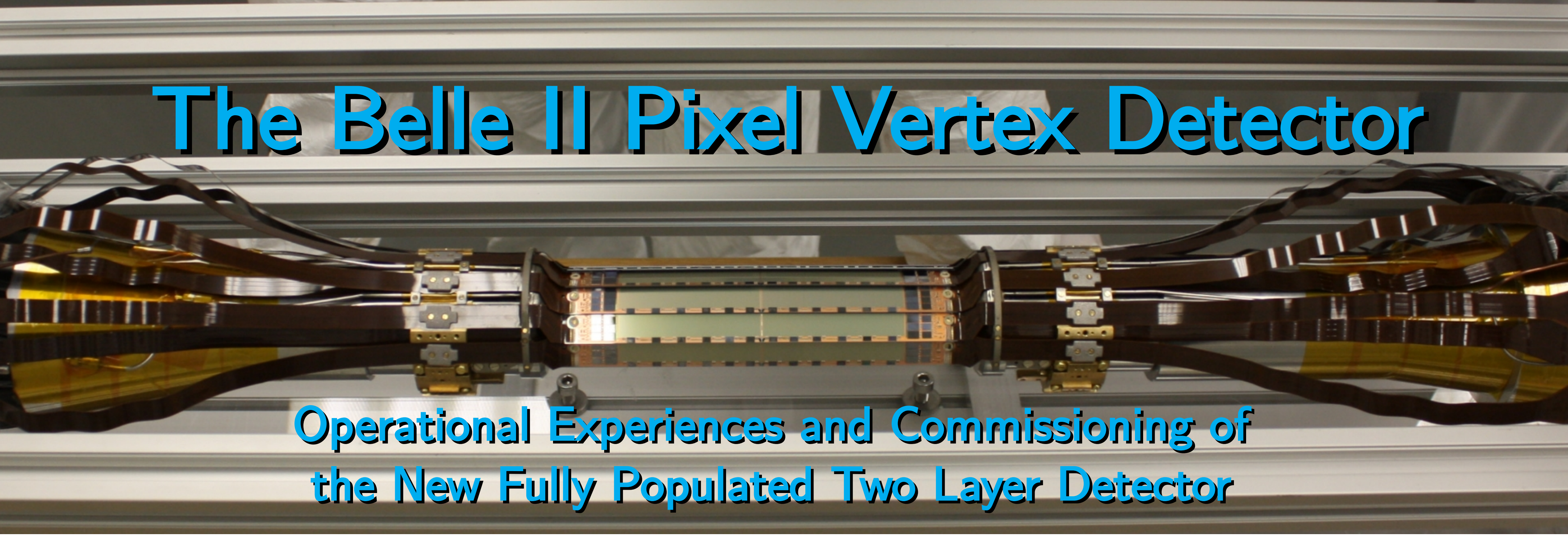


The Belle II Pixel Vertex Detector

Operational Experiences and Commissioning of the New Fully Populated Two Layer Detector

Anselm Baur (DESY) on behalf of the PXD collaboration

Sestri Levante (Italy), October 16th 2023

DESY. HELMHOLTZ RESEARCH FOR GRAND CHALLENGES JENNIFER² EU grant n.822070 VERTEX 2023 Belle II

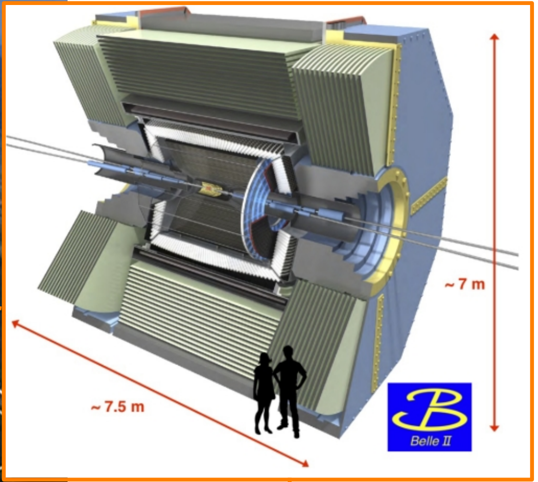
SuperKEKB Accelerator and Belle II Detector

SuperKEKB e^+e^- Collider:

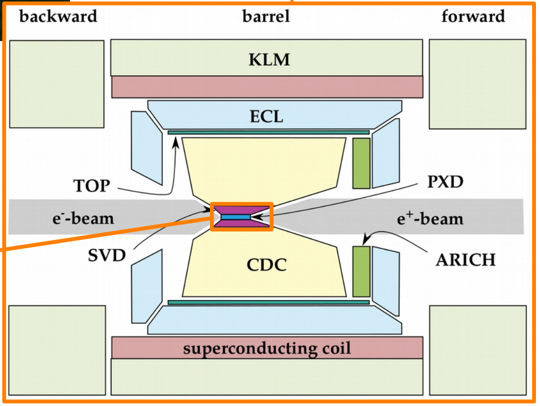
- Asymmetric beam energies
  e^+: 4 GeV, e^-: 7 GeV
- Υ(4S) resonance (10.58 GeV)
- Target lumi.: 6.3×10^{35} cm^{-2}s^{-1}
- 4 years with operation (2019-2022)

Belle II Detector:

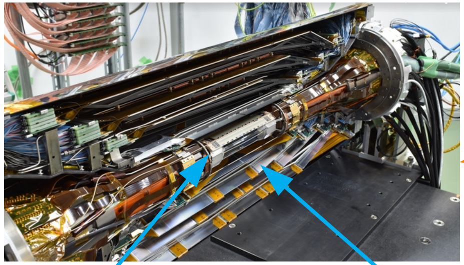
- Vertex detector (VXD)
- Tracking system (CDC)
- Identification of charged particles (TOP + ARICH)
- Electromagnetic calorimeter (ECL)
- K_L and Muon detector (KLM)



Belle II detector



VXD

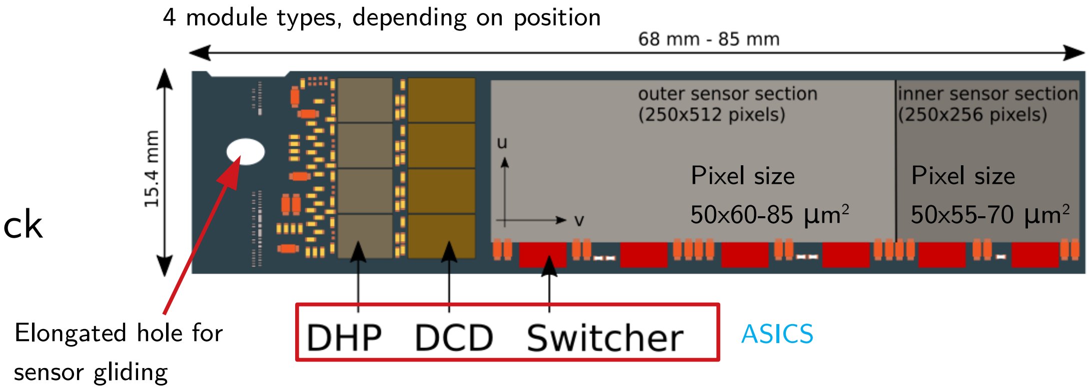


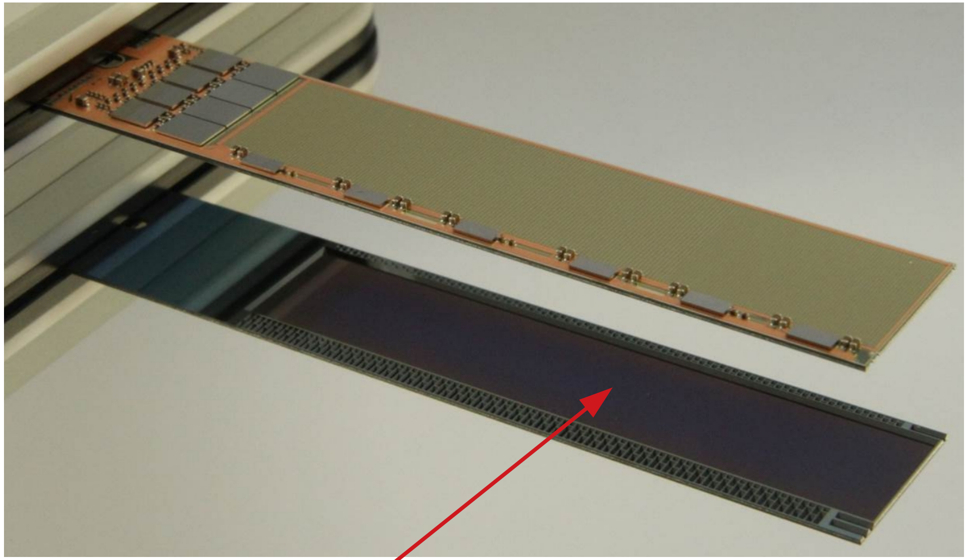
Pixel (PXD) Strip (SVD)

The Pixel Vertex Detector (PXD) Module

Properties:

- Self-supporting “**all-silicon**” structure
  - Support frame ~500 µm thick
  - **Monolithic** active area 75 µm thick
- **Low material budget** (~0.21% X_0)
- Pixel sizes 50 x 55-85 µm^2
  (250 x 768 pixels)





Thinned backside at active sensor area

Rolling Shutter Readout:

- **Switcher**: consecutive row selection for signal digitization of columns (10 MHz)
- **DCD**: 8-bit AD conversion of signal
- **DHP**: zero suppression, data formatting
- 20 µs integrated readout time
  (2x beam revolution)

The Pixel Vertex Detector (PXD)

2 Modules = 1 Ladder:

- Glued together
- In total 20 ladders

10 Ladders = 1 Half-Shell:

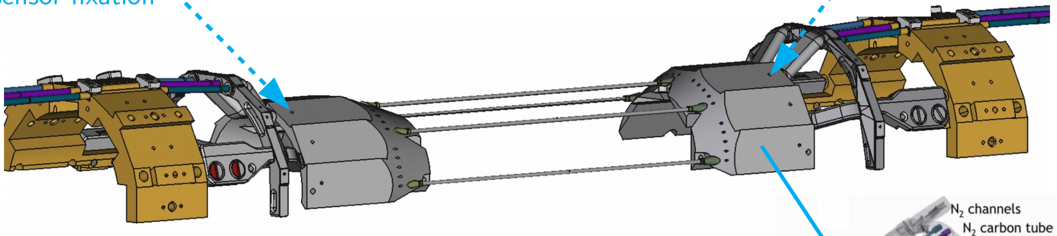
- Ladders screwed on cooling block
  - Radii: r_{L1}=14mm, r_{L2}=22mm
- Half-Shell mounted on beam pipe

Power Consumption:

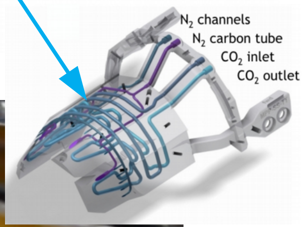
- ~9 W per module
  → ~360 W (full detector)
- Cooling
  - 2 phase CO_2: DHP/DCD (8W)
  - N_2 gas: sw.+sensor area (1W)

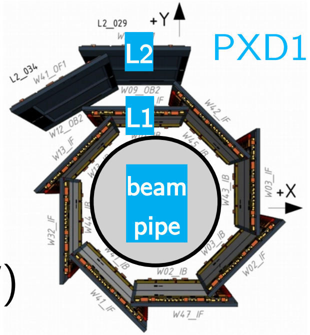
PXD1:

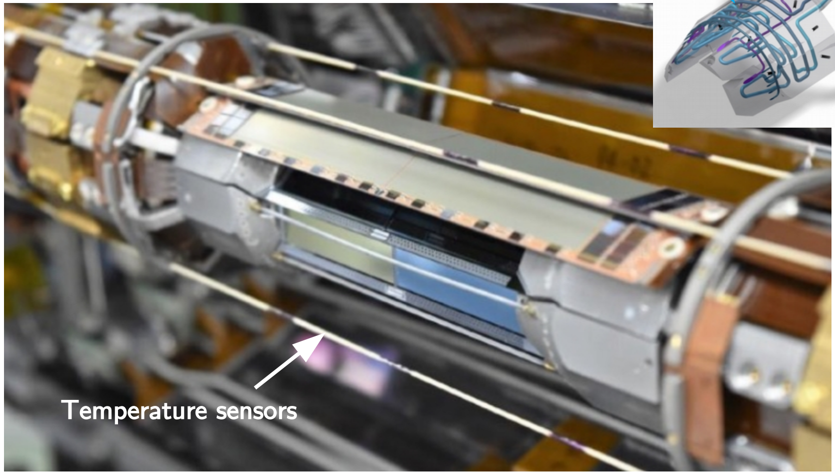
- PXD1 incomplete (effectively 1 layer)



PXD half-shell support and cooling block (SCB)







DEPFET Pixel Cell

DEPFET Working Principle

- **DE**pleted **P**-channel **F**ield **E**ffective **T**ransistor
- Field Effective Transistor (FET) on depleted Si bulk
- **Internal gate** charge modulates source-drain current
- Clear-mechanism to empty internal gate

Charge Collection

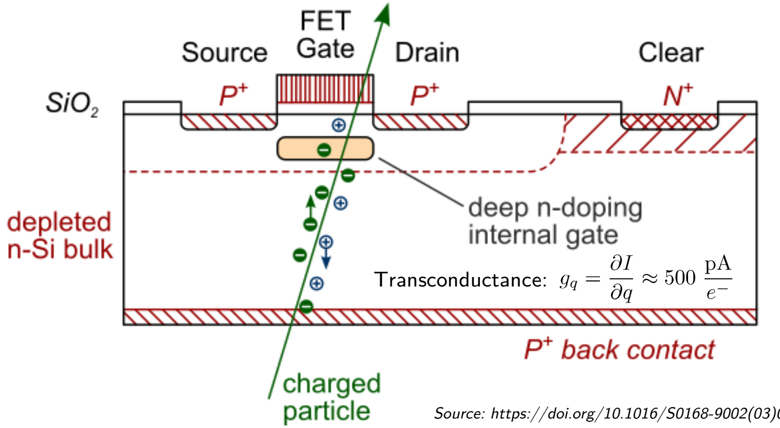
- Relevant voltages:

  V_{HV}, V_{drift}, and $V_{clear\text{-}off}$

Characteristics

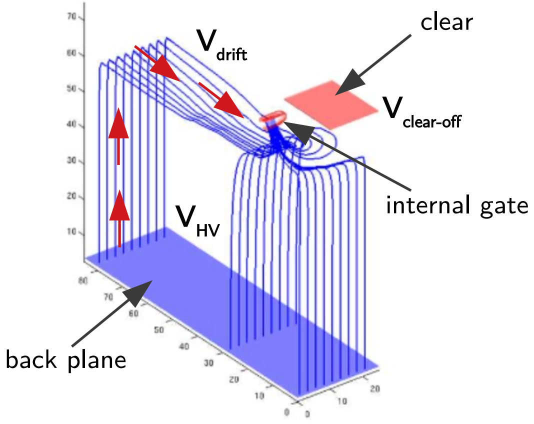
- High signal/noise ratio (low internal capacities)
- Internal charge integration
- Low power consumption
- Thin sensor (75 µm)
- **Low material budget**

Schematic of a DEPFET cell



Source: https://doi.org/10.1016/S0168-9002(03)01802-3

<u>Typical values:</u>
V_{HV}: -50V - -70V
V_{drift}: -3V - -6V
$V_{clear\text{-}off}$: 2V - 4V



PXD1 Efficiency

Di-Muon Hit Efficiency:

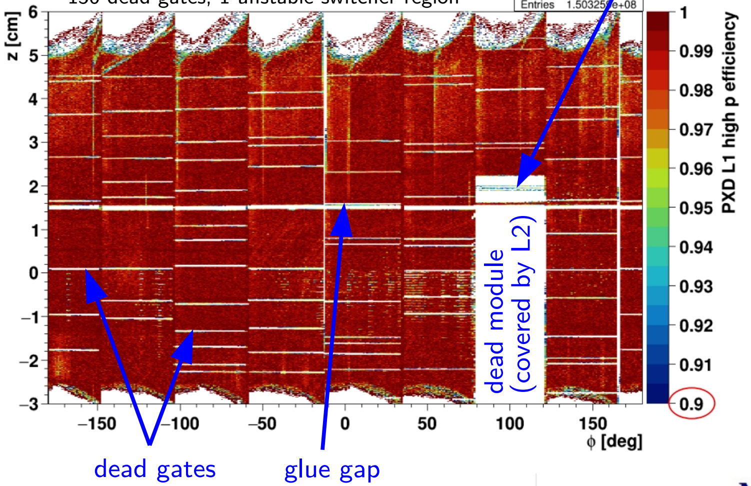
- ~99 % in fiducial regions
- ~96 % in physics region

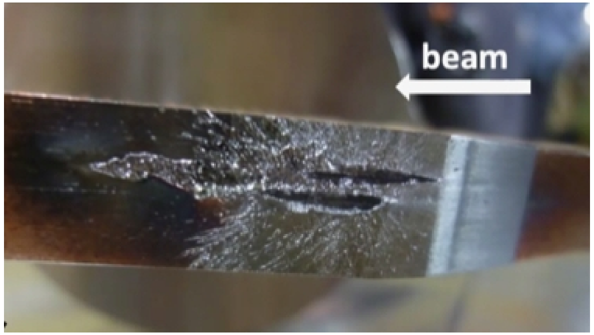
Sudden Beam Losses:

- Cause: unknown
- High instantaneous radiation doses (O(10) Gy in 40 μs)
- Can damage switchers
  - Verified at MAMI electron beam
- Improve detection and PXD power shutdown
  - Power off: switchers safe
- During LS1: focused by machine group

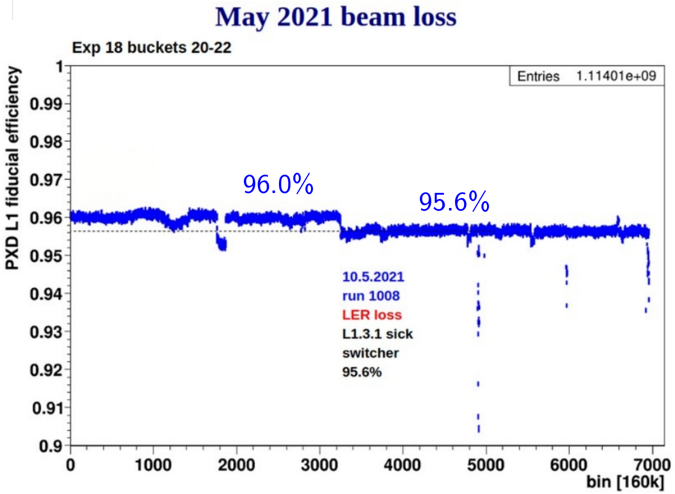
Efficiency map: rolled out inner layer (L1)

~ 150 dead gates, 1 unstable switcher region





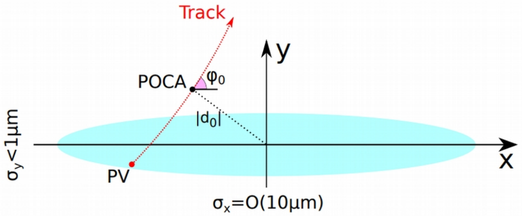
Lost beam hitting collimator
→ high inst. radiation

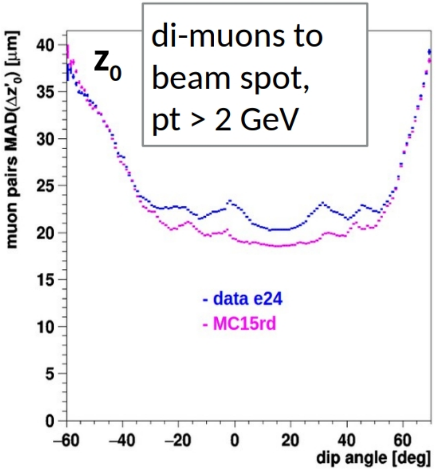


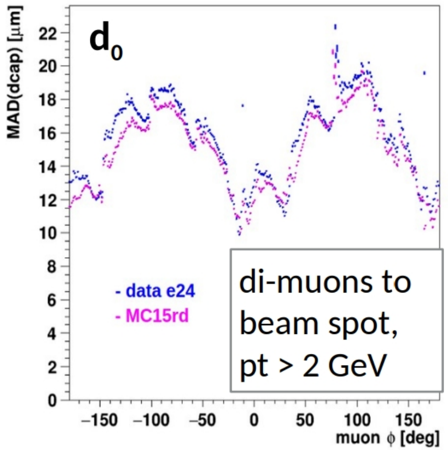
PXD1 Performance

Impact Parameter Resolution:

- Di-muon events (pt > 2 GeV)
  - z_0: 20 – 40 μm
  - d_0: 10 – 22 μm
- MC describes data
  - MC slightly too optimistic (z_0: ~3 μm, d_0: ~1.5 μm)
- ~1.5 – 2 times better than Belle

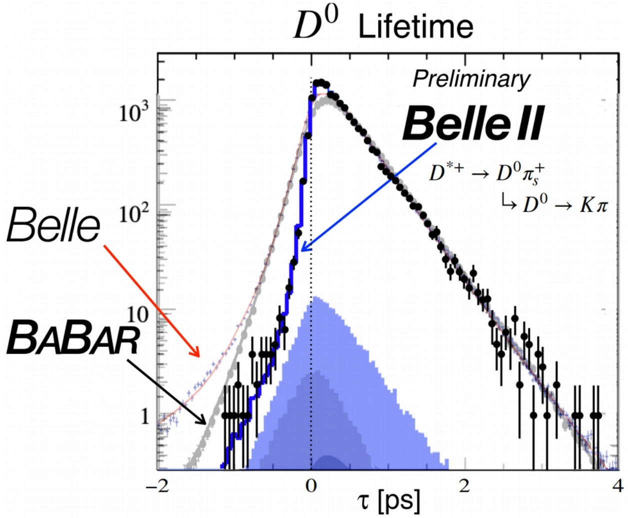






D^0 Lifetime Resolution:

- Impact of better vertex detector
- Belle II D^0 lifetime resolution ~2 times better



Belle II lifetime measurements with high PXD impact:

D_s^+: arXiv:2306.00365 → PRL
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)

Beam Background

Continuous Injection (25 Hz):

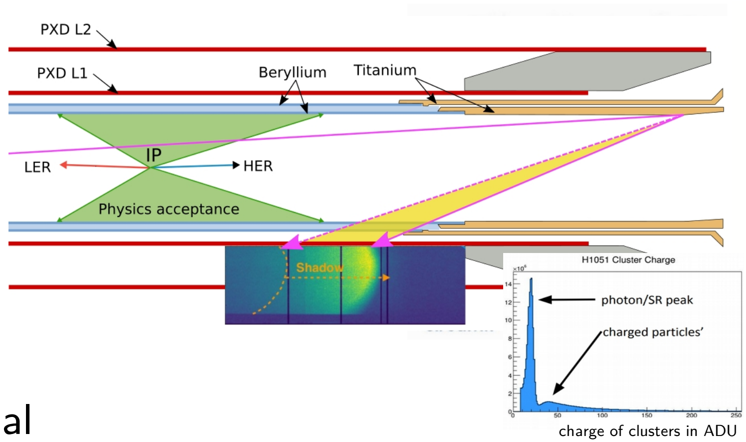
- **Synchrotron radiation**:
  betatron oscillations (HER)
  $\rightarrow$ full and gated **vetoes**

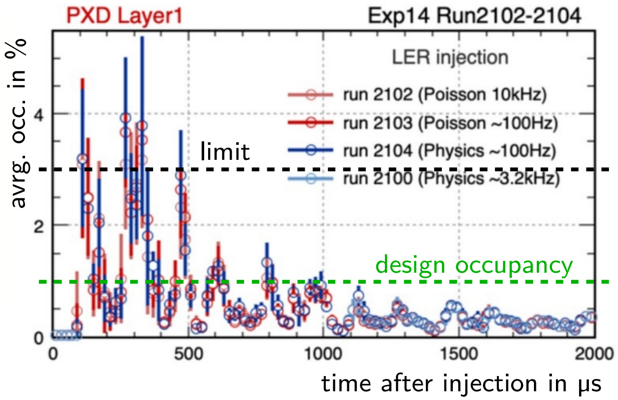
Beam Storage:

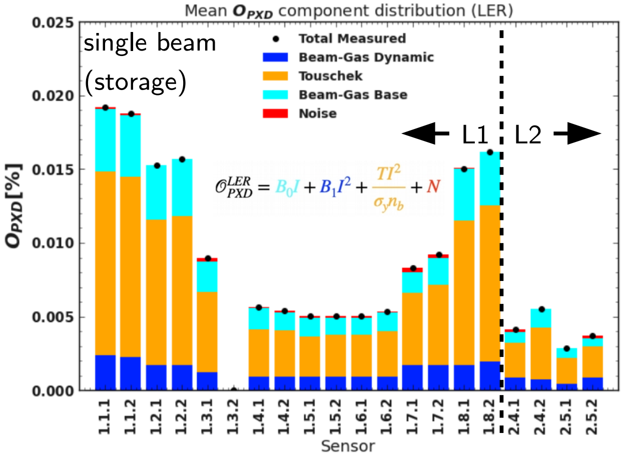
- **Beam-gas**:
  beam interaction with residual gas molecules
- **Touschek**:
  intra-bunch coulomb scat.

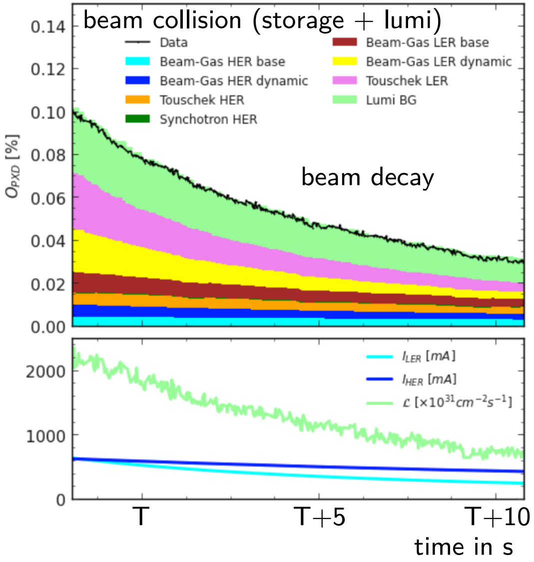
Luminosity (Beam Collisions at IP):

- **Two-photon interaction**
- **Radiative Bhabha**







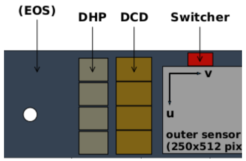


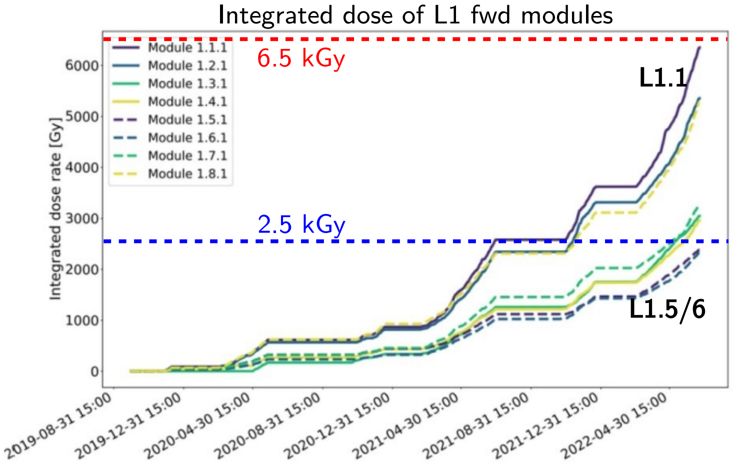
Measured and projected beam backgrounds in the Belle II experiment at the SuperKEKB collider: arXiv:2302.01566

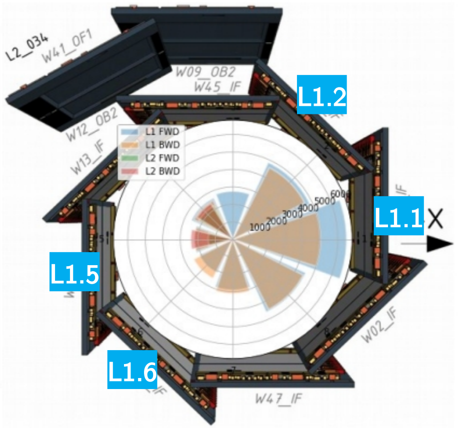
Radiation and Aging

Estimation Based on Module Occupancy:

- Module dependent TID
  → ~2.5-6.5 kGy (2019-2022)
- Expected lifetime exposure
  of PXD is ~200 kGy (10 years)
- Radiation tolerance limited by
  DCD and switcher

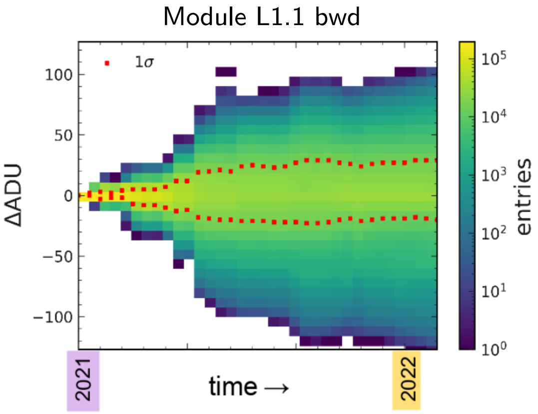


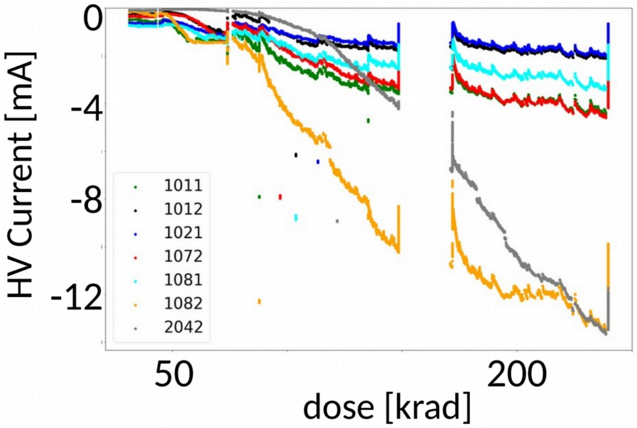




Detector Aging:

- **Trapped oxide charges**
  → DEPFET gate threshold shifts
- **Steadily increasing backside currents**
  - Leakage in guard ring structures
  - Performance not affected
- **Broadening of pedestal distribution**
- DCD irradiation: slight noise increase





Fully Populated 2 Layer Pixel Detector (PXD2)

PXD1 Was Good, PXD2 Will Be Better:

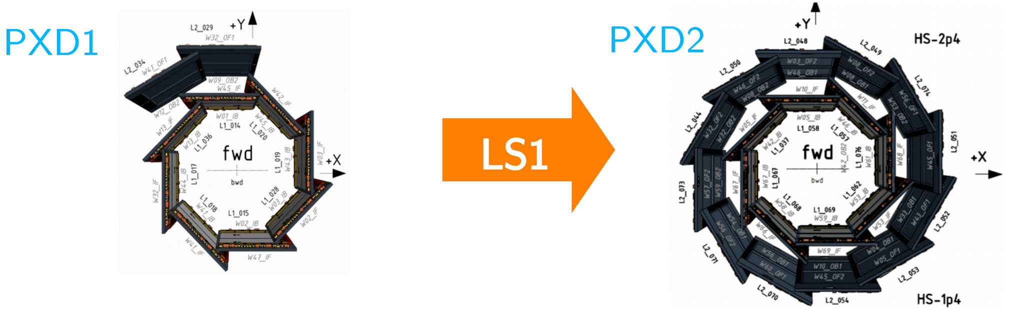
- Modest improvement of impact parameters (L1 highest impact)
- Higher probability to select correct PXD hits in 1st PXD layer at higher background levels
  - Fraction of MC hits found in the reconstructed track

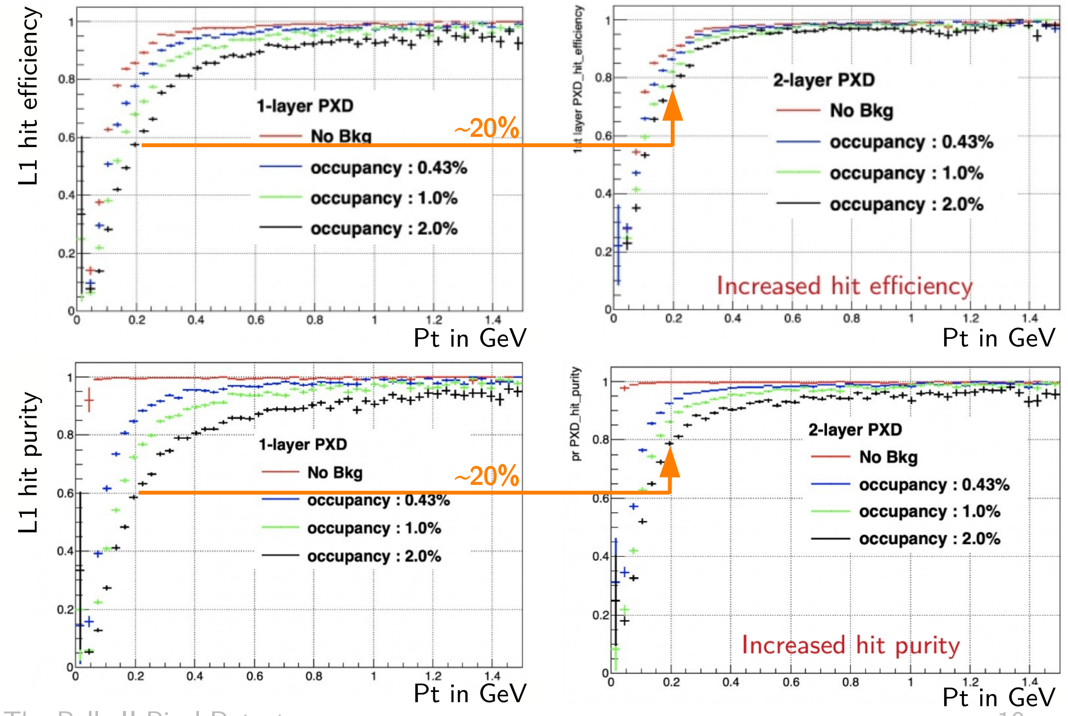
$$\text{hit efficiency} = \frac{N_{\text{mc\_hits\_in\_reco\_track}}}{N_{\text{hits,mc\_track}}}$$

  - Fraction of MC hits in the reconstructed track hits (how much background was picked up?)

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

- Important: **physical redundancy**





Commissioning of PXD2 (DESY)

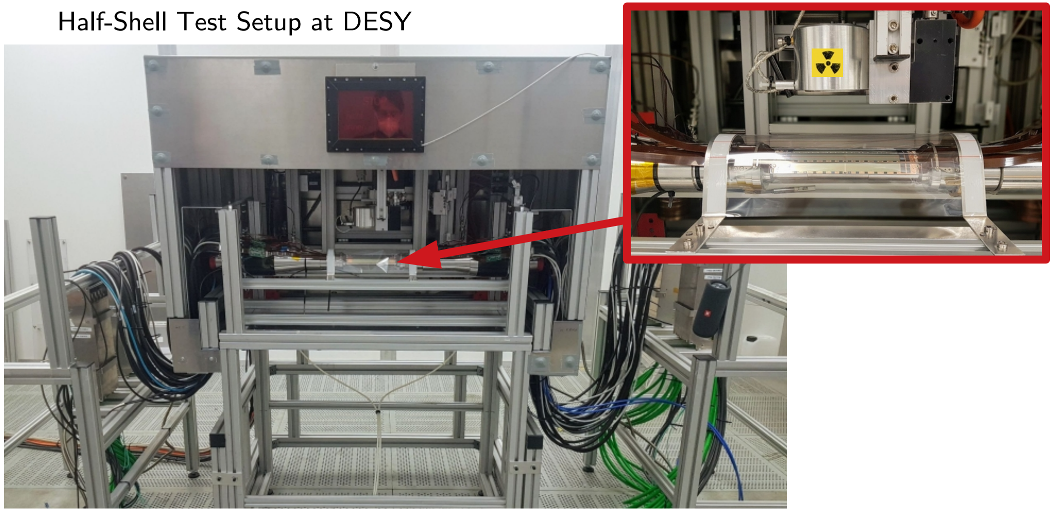
Half-Shell Test Setup at DESY:

- Power Supply + DAQ
- CO2 and N2 cooling
- Movable ^{90}Sr source holder
- Aluminum dummy beam pipe
- 1st half-shell damaged during long-term operation

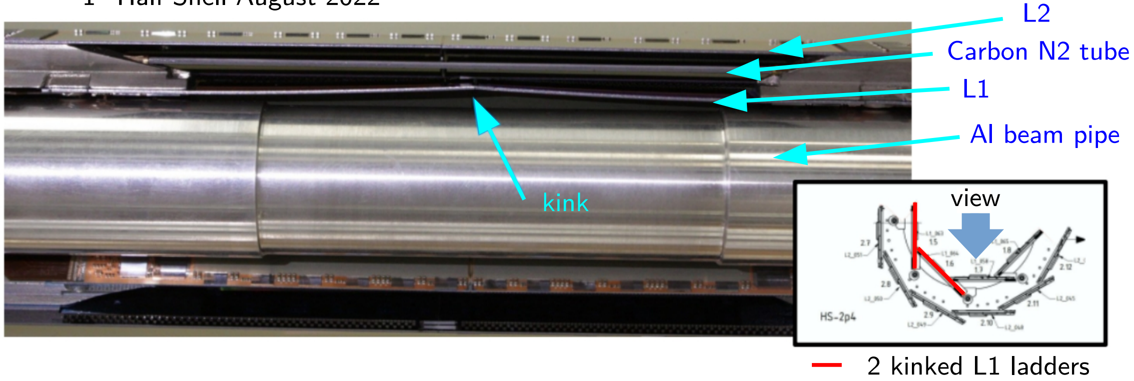
Problems Found After Investigations:

- No optimal PXD ladder gliding
- Elevated air temperatures
  $\rightarrow$ expansion Al beam pipe

Half-Shell Test Setup at DESY



1st Half-Shell August 2022



Commissioning of PXD2

Repair and Improvements of PXD2:

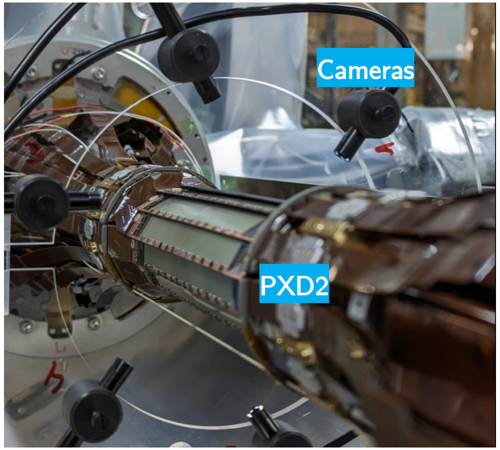
- Fully reassembled 1st half-shell
- Improved gliding mechanics

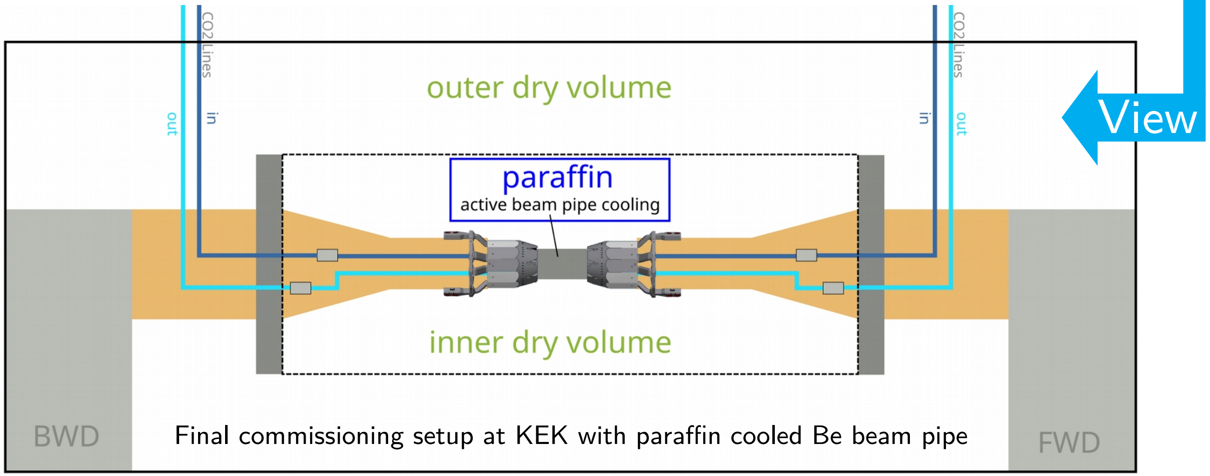
Monitor Ladder Bending:

- Improved monitoring setup
- Careful cooling operation
- Step by step module operation
- Successive full detector operation
- Observed significant bending in 2 L2 ladders

PXD2: Higher Power Consumption:

- PXD2 2x more modules than PXD1
- Needed adjustment of cooling





Final commissioning setup at KEK with paraffin cooled Be beam pipe

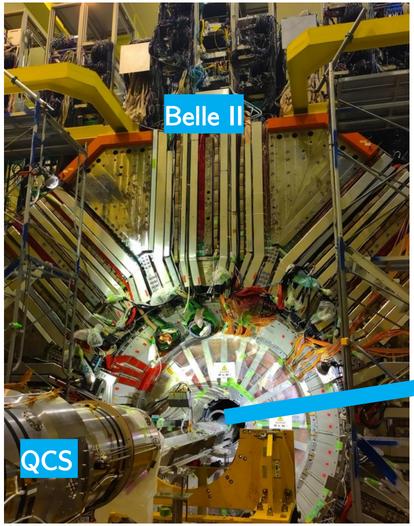
Commissioning of The New Vertex Detector (VXD)

PXD1 Extraction:

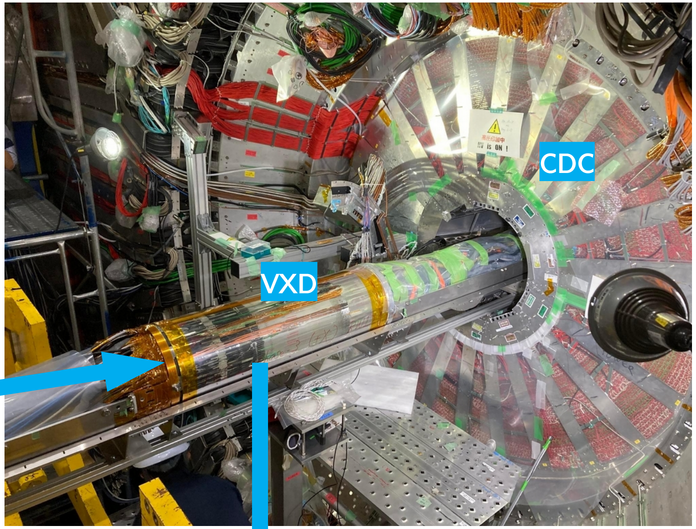
- Old VXD extracted from Belle II
- Strip Vertex Detector (SVD) reused in new VXD
- PXD1 inspection (mechanical state) $\rightarrow$ No visible damage after 4 years of operation

New VXD:

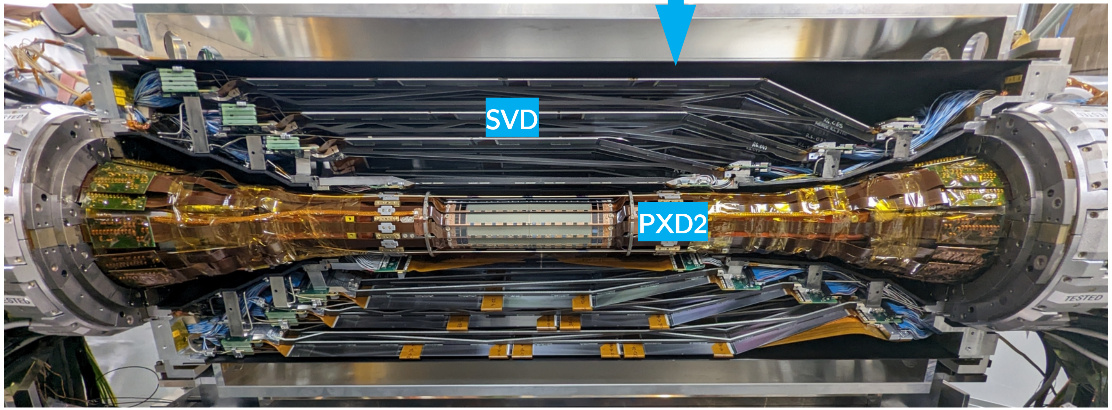
- Extracted SVD halves installed around PXD2
- Combined standalone VXD test
- Installation in Belle II
- First data: cosmic particles



QCS: Final Focus Quadrupole Magnet



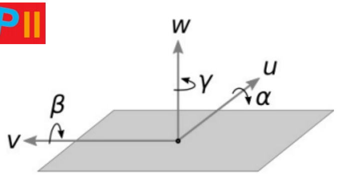
CDC: Central Drift Chamber

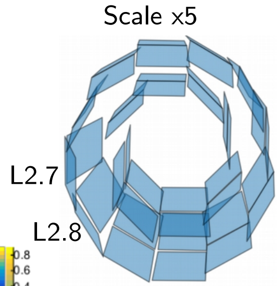


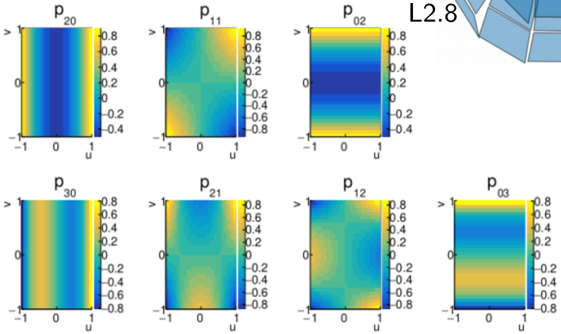
First PXD2 Cosmic Data in September 23 (B-Field Off)

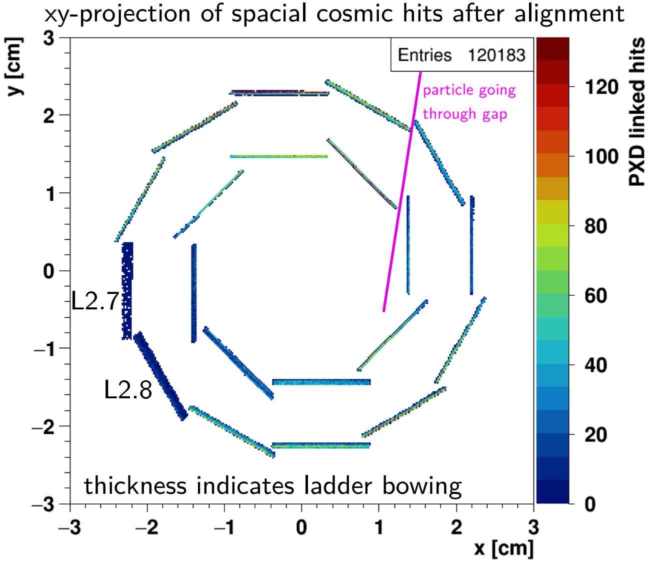
Alignment:

- Extrapolate CDC tracks
- Per module:
  - 6 rigid body alignment param.
  - 7 deformation parameters
- Ladder bowing visible
  - Up to ~1 mm



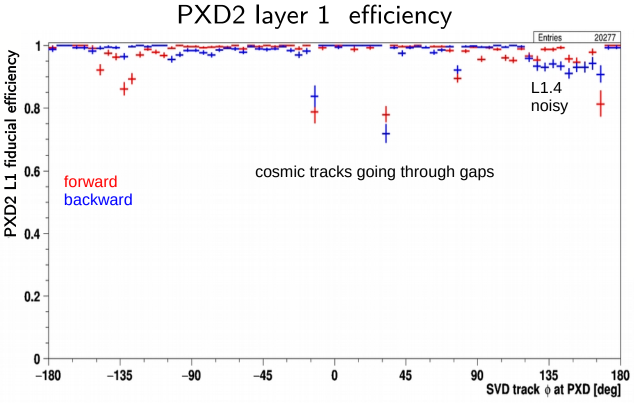


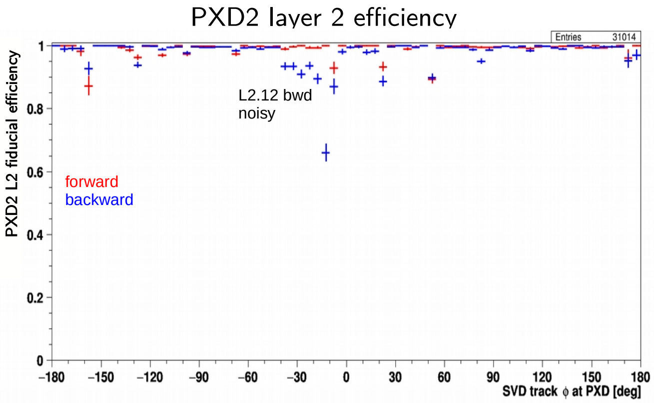




Efficiency:

- Extrapolate SVD tracks
- Efficiency drops
  - Gaps for external cosmics
  - Masked noisy pixels (esp. L2.12 bwd)
- Reaching >98 % in most regions
- Further module tuning ongoing





Summary and Outlook

PXD1 (2019 - 2022):

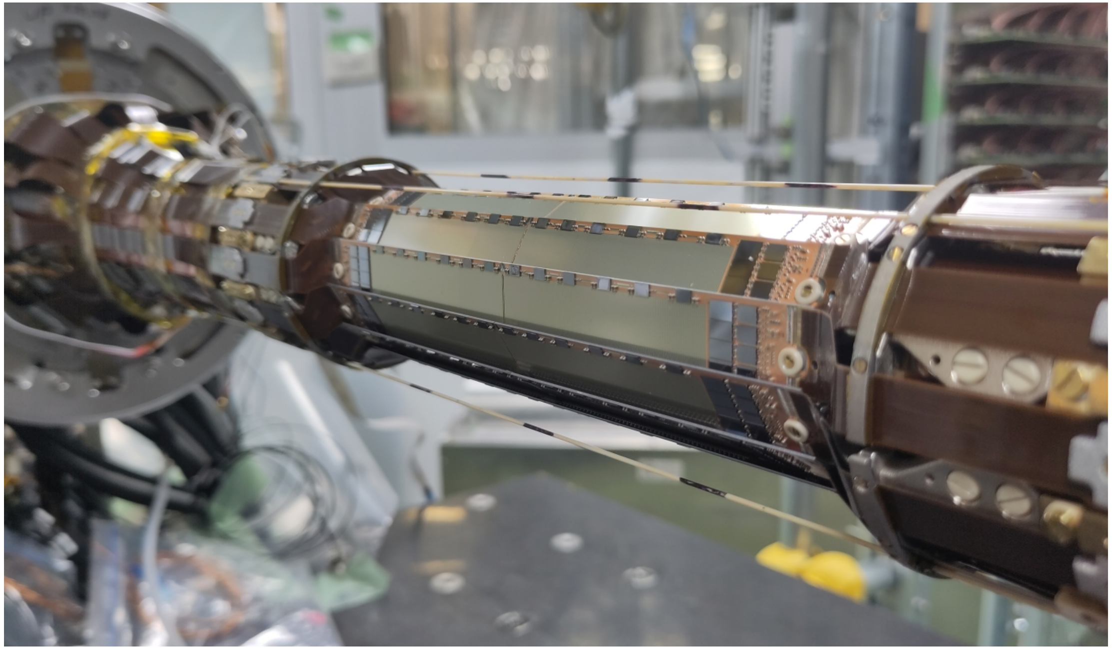
- Single layer
- 4 years successful operation
- Overall efficiency ~96 %
- D^0 lifetime resolution 2x better than previous experiments
- Challenges: beam backgrounds and beam losses

PXD2 (Since 2023):

- Successful commissioning after some throwbacks
- All 40 modules operable
- 4 modules need further tuning
- First cosmic data $\rightarrow$ mostly efficiency >98%
- 2 ladders show significant bending $\rightarrow$ optimize cooling
- PXD2 operation expected at least until LS2

Outlook:

- Belle II experiment under commissioning
- **Resume beam operation this winter**



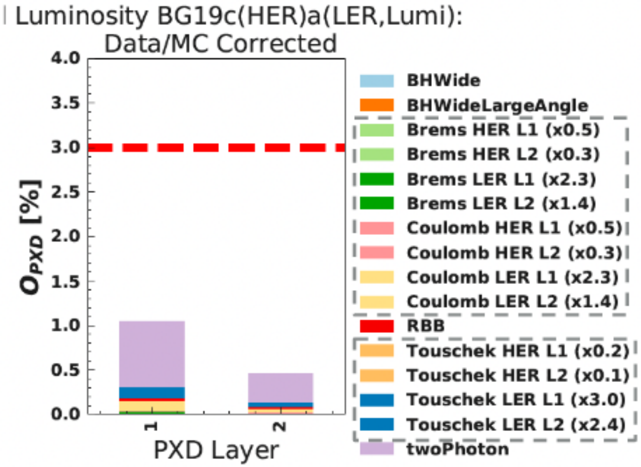
Thank You!

Backup

Backup: Background Extrapolation

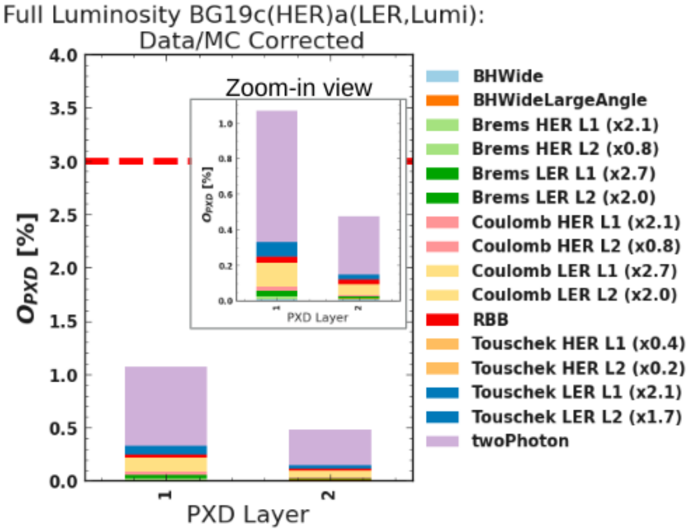
Based on single beam Data/MC @ Dec 20 2021

Parameters @ Original Design Optics	LER	HER
Beam current [A]	3.6	2.6
N. of bunches	2500	2500
Vertical beam size [um]	24	10
β_x^* / β_y^* at IP [mm]	32/0.27	25/0.30
Pressure [nTorr]	1	1



Use data/MC 27.06.2020 bugfix2 ratios to correct the BG19c sample [taken from Sally's talk @ PXD Background Workshop, 17.08.2021]

- Updated LER & HER components using current Data/MC factors
- **Small changes** expected for the total extrapolation → dominanted by **two-photon** background



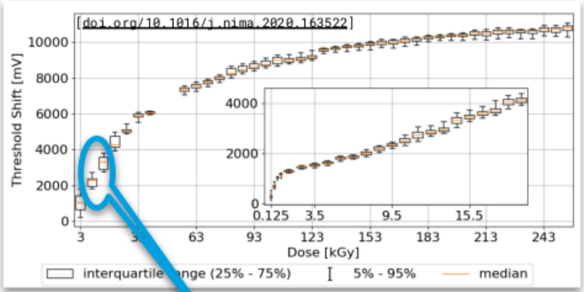
Backup: Aging

Operational Challenges

radiation effects and "aging"

threshold shift

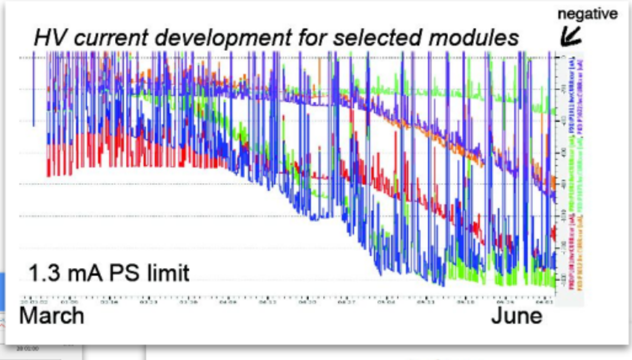
- radiation damages oxide layer
  - causes shift of MOSFET threshold voltage
  - can be compensated by continuous adjustment of gate voltage
- investigated / expected already from X-ray radiation campaign @ 200 krad/h:

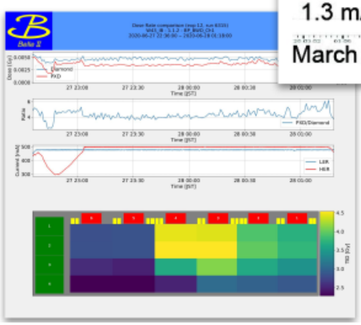


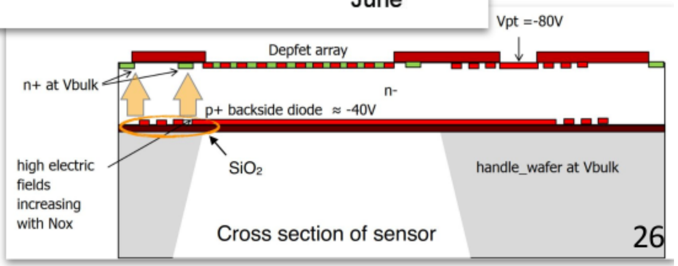
- integrated dose in PXD
  - rough estimate < 20 kGy until end of 2020
  - more precise measurements in progress

increasing HV currents

- observed increased HV currents
  - some modules reached power supply limits
  - can not reach set voltage → worse SNR and efficiency
- interpretation: charge-up effect at handle wafer bond oxide and avalanches at bulk
  - some annealing during beam off times
  - currents saturate at certain dose
- could be mitigated by modifying power supplies



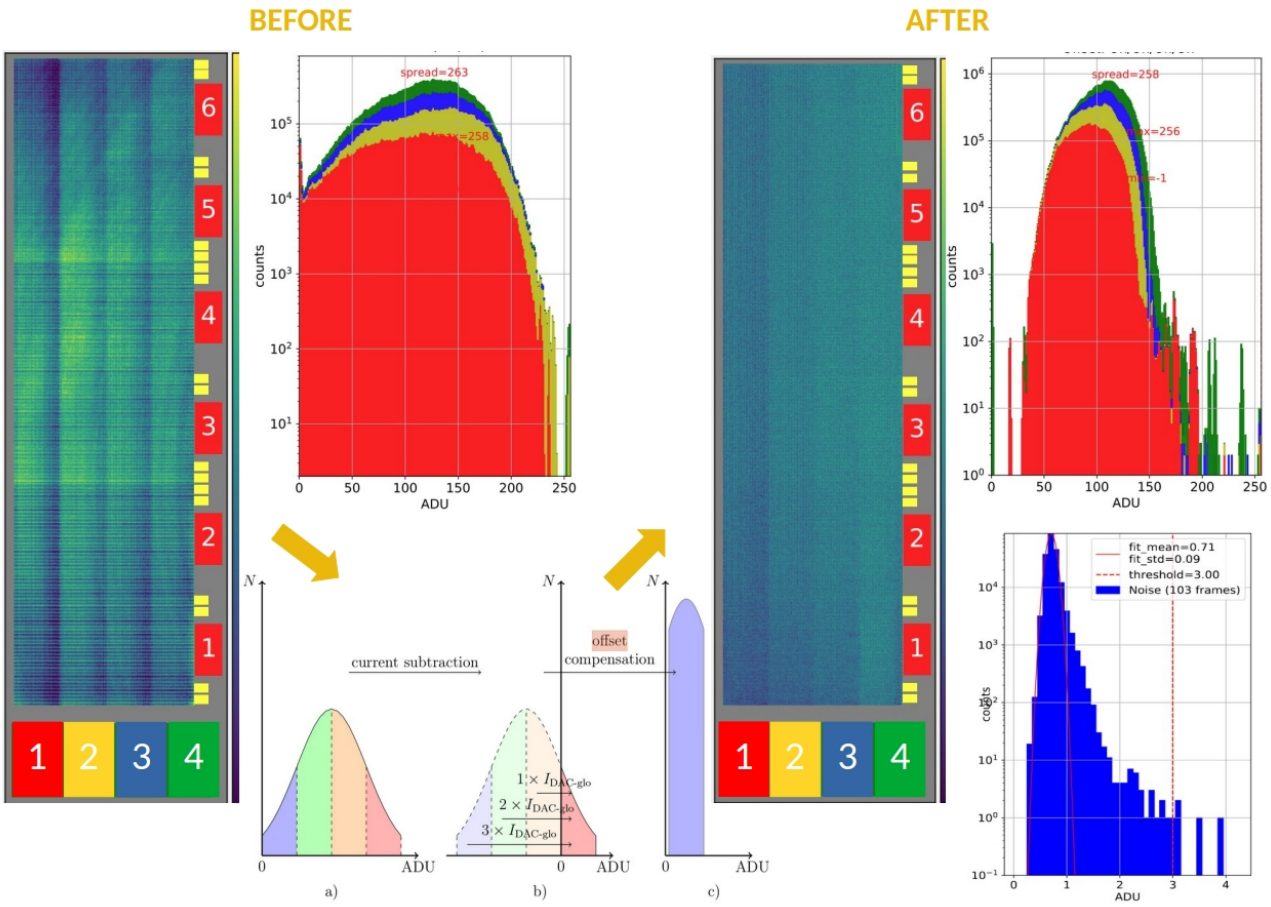




DESY.

Backup: PXD Calibration

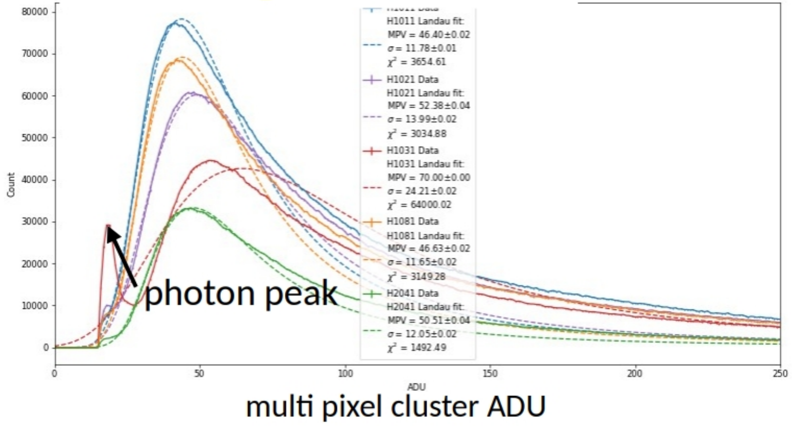
- Characterized modules before installation
  - Further optimization during operation
  - Improved/automated operation, monitoring and calibration procedures
- DCD calibration
- Biasing optimization
- Pedestal optimization on DCD
  - Pedestal compression via 2-bit DAC
  - Analog Common Mode Correction (ACMC) for noise reduction
  - Low noise $<1\,ADU \simeq 200\,ENC$
- Stress tests
  - Power cycling
  - Thermal cycling



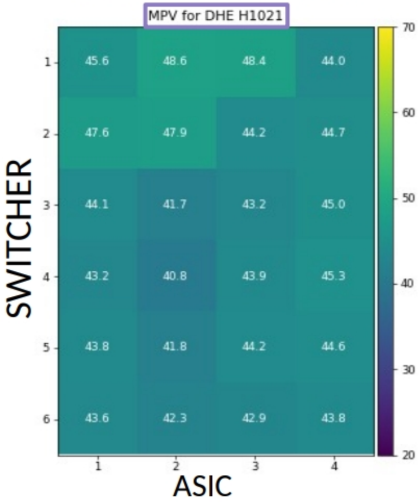
Backup: PXD Performance

- Homogeneous noise and signal response across the module matrix
- Stable throughout 2019-2022
- Slight increase in noise with DCD irradiation
  - Maybe more extensive DCD calibration is needed
  - Under investigation

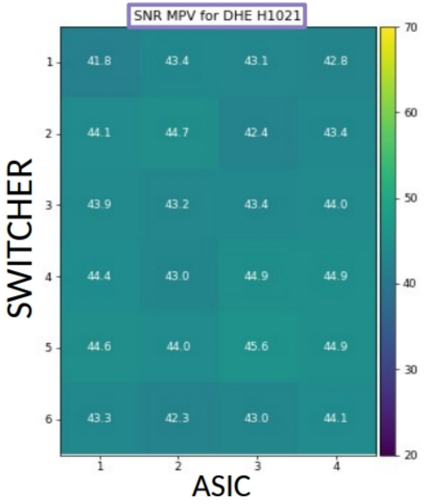
cluster charge distribution

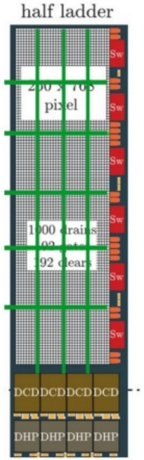


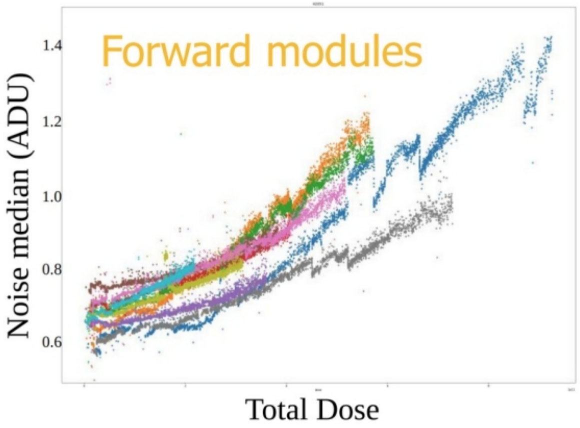
cluster charge MPV



SNR MPV







Backup: PXD2 Optimization of Charge Collection

Source Scan:

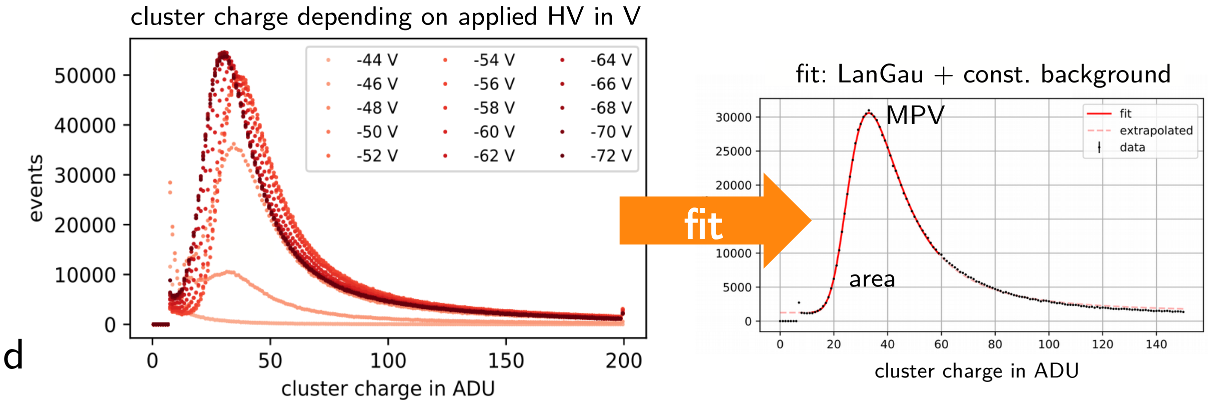
- Modules individually optimized (Mass-Testing)
  - Different test sites
  - Large time span (4 years)
  - Best parameters not always found
- Repeat source scan for each half-shell

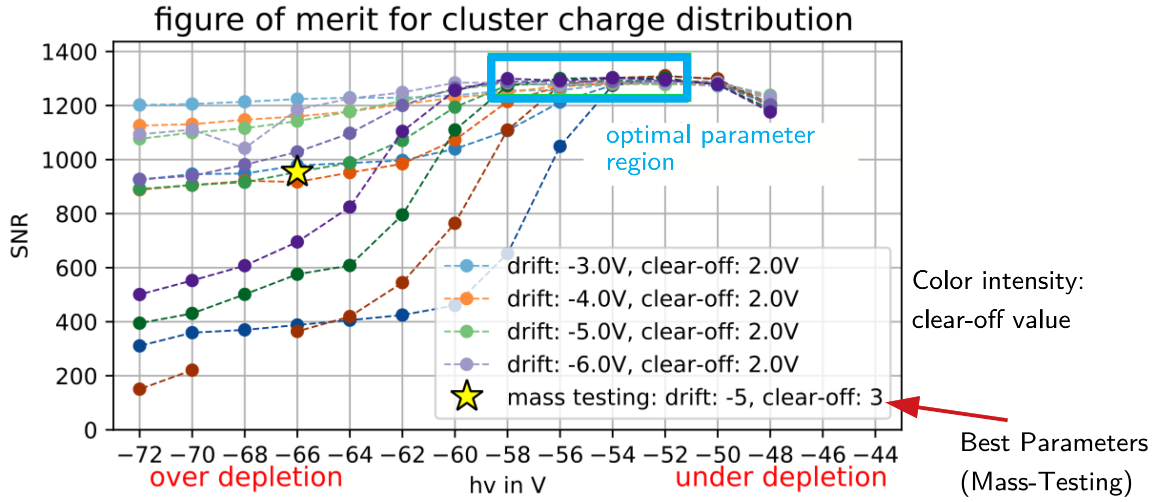
Figure of Merit:

- Based on signal to nose ratio (SNR)
  - $$SNR = \frac{\mathrm{MPV}}{\mathrm{noise}_{\mathrm{pedestal}}} \cdot \frac{\mathrm{area}}{1000}$$

Optimal Parameters:

- Stable plateau region
- Large HV variation between modules
  - -50 V – -70 V

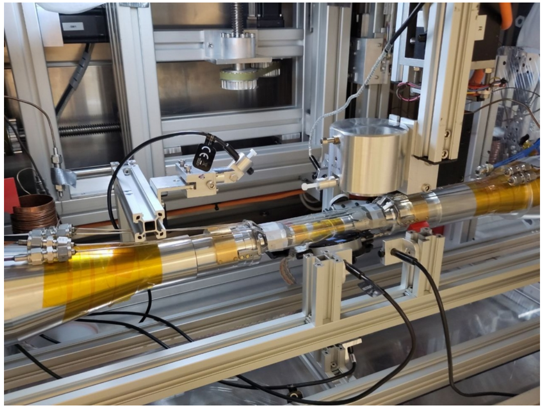


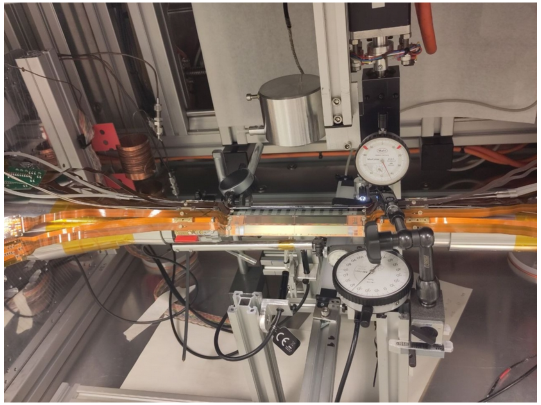


Backup: Camera Monitoring Setup

Understanding the Mechanical Behavior

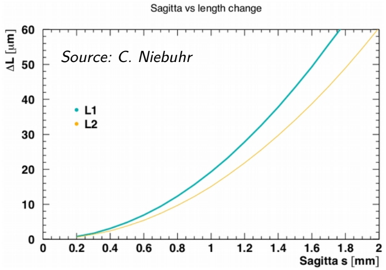
- Improved environmental/BP monitoring
- Installed dial gauges to measure BP deformation
- Installed cameras
- Observed large length change of the Al BP
  - 1-2 um/K
  - Reached extension up to 60 um





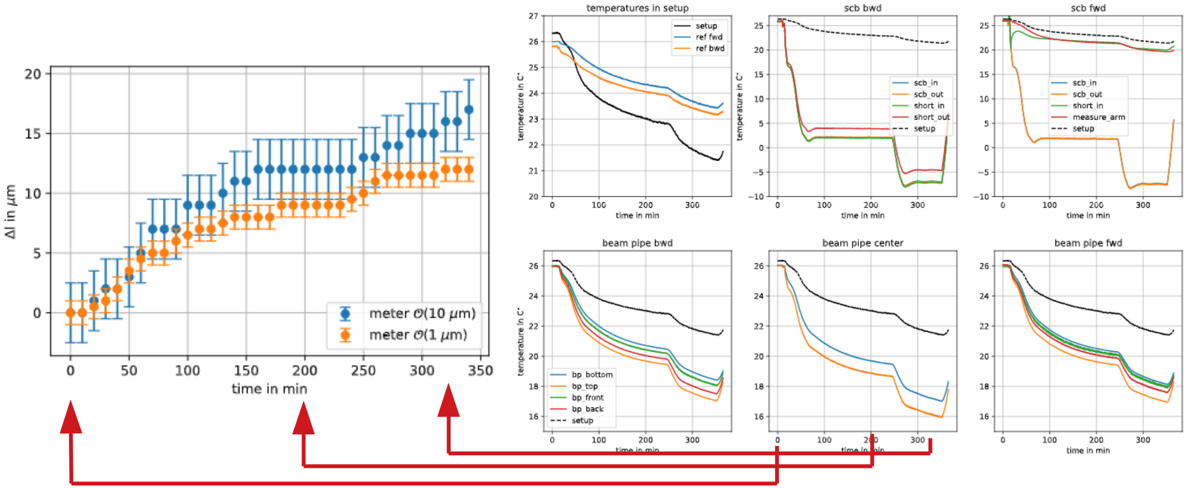
Using BP Length Change to Study PXD Mechanics

- SCB gliding
- Ladder gliding



Results

- Ladders glide
  - Good at room temperature
  - Worse at -10 °C
- Gave up on SCB gliding (probably contra productive)
- Some L2 ladders bent strong



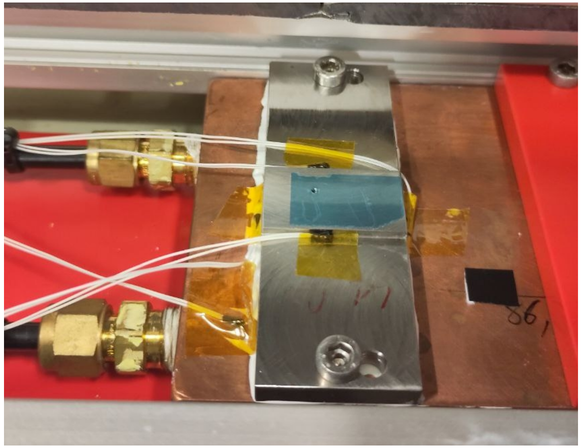
Thermal Torque Measurements

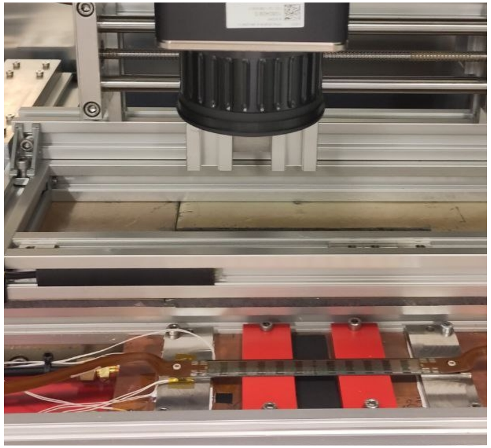
From the Thermal Mock-up

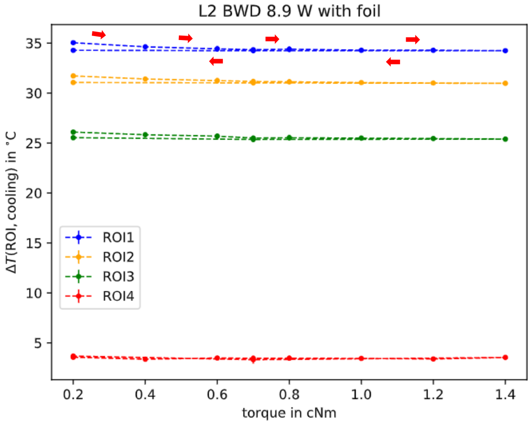
- Dummy Si ladder with resistors for heating
  - 8.9 W the design power consumption
  - 8 W DHP/DCD

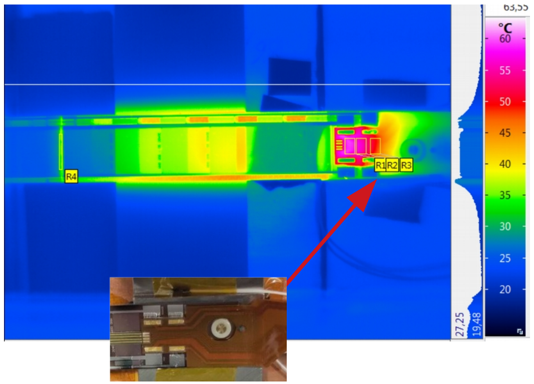
Thermal Impact of the Screw Torque

- Screwed Ladder to cooling block
  - 0.2 cNm → 1.4 cNm → 0.2 cNm
- IR camera:Temperature of DHP/DCD area
  - 4 ROIs: 3 DHP/DCD, 1 glue joint
  - Kapton: emission 0.9
- Impact observed: < 2 °C









Backup: Air Temperatures Inner Dry Volume

PXD1 Cooling Parameters:

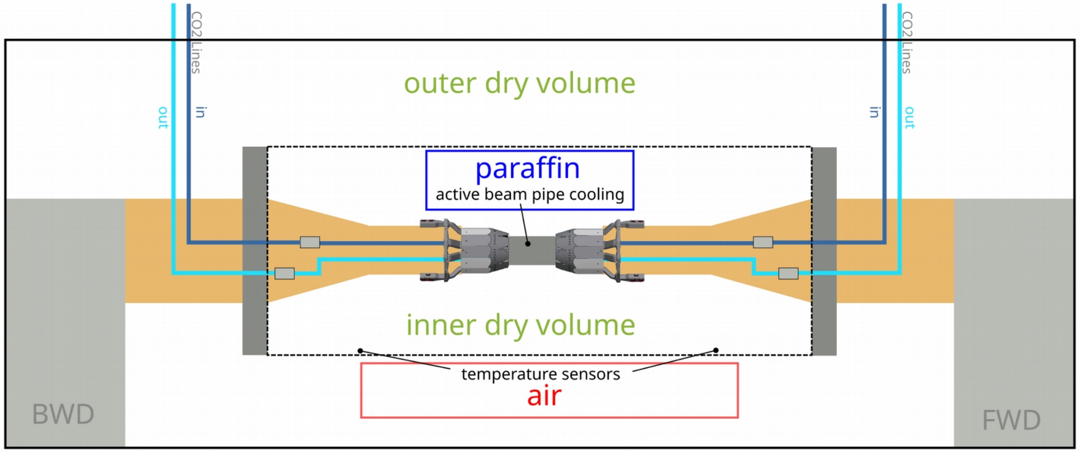
- CO_2: -20 °C
- N_2: 28 l/min

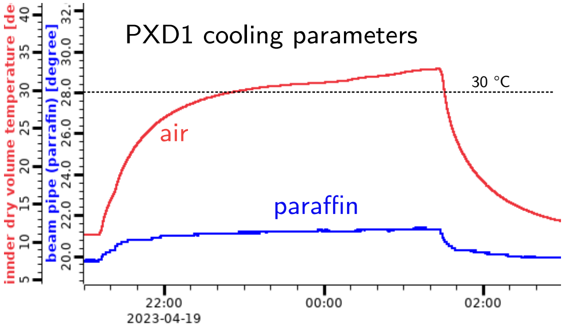
- Inner dry volume exceeded 30 °C
- No saturation observed → stop
- Elevated temperatures and mechanical stress can be problematic for ladder glue joint

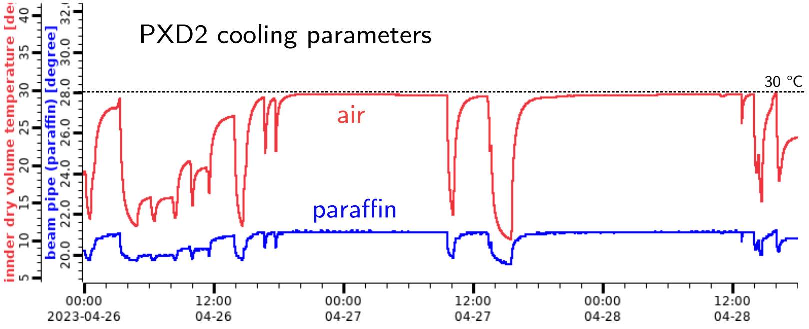
PXD2 Cooling Parameters:

- CO_2: **-25** °C
- N_2: **32** l/min

- ~20 h permanent operation
- Air temperature saturated at 29 °C
- Paraffin (beam pipe) temperature stable at 21 °C
- Verify during VXD combined test operation







PXD2 Module Status

General:

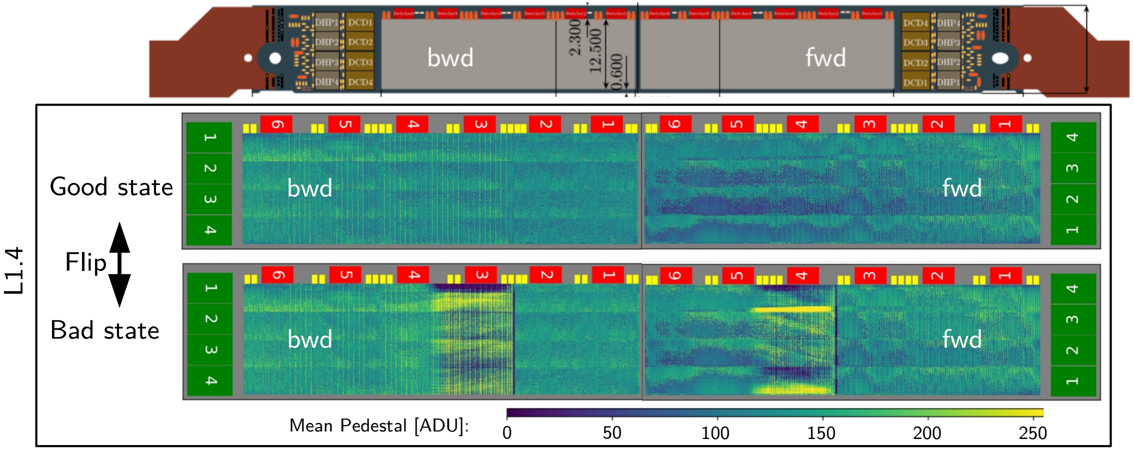
- All 40 modules operable

Unstable Switcher States in L1.4:

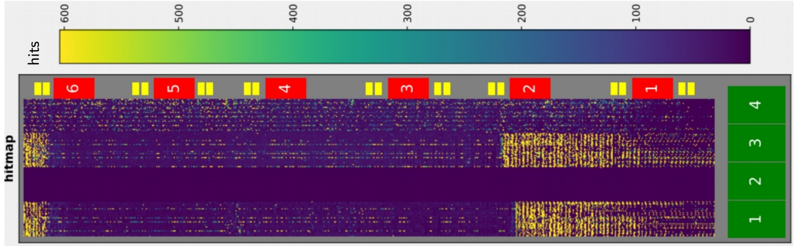
- Two module states: “good” or ”bad”
- Problematic gate(s) or broken switcher?
- Temporary solution: reducing gate-on voltage

Pedestal Glitches:

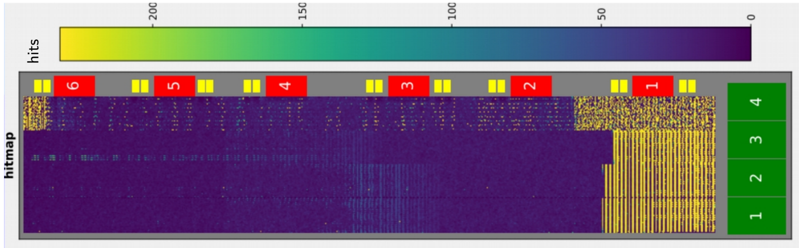
- 2 modules with regions of significant pedestal shifts within individual frames
- Dominant structures in L2.4 bwd, L2.12 bwd → mask these pixels



L2.12
bwd



L2.4
bwd

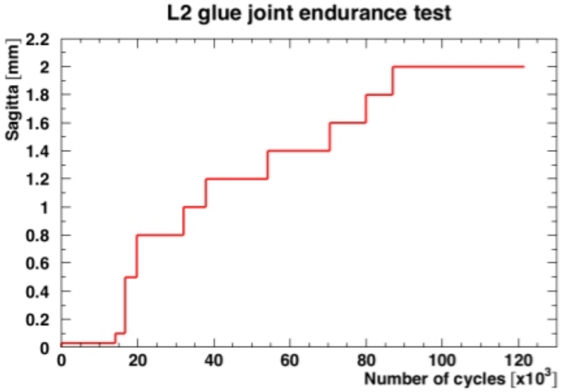


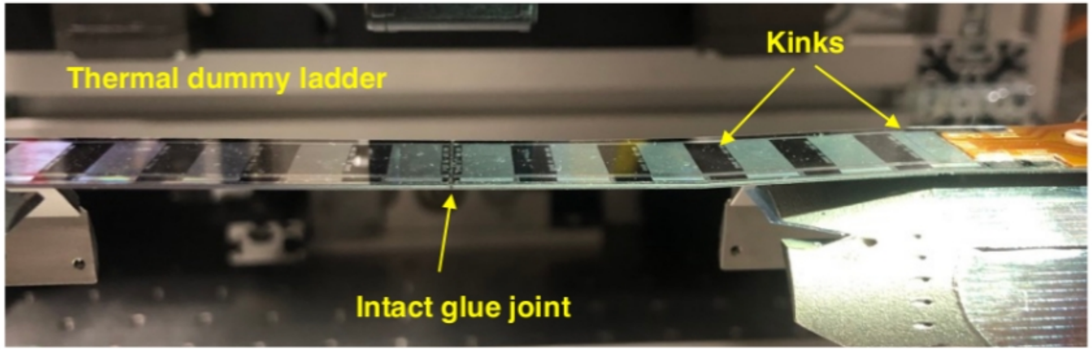
Ladder Bending Studies at DESY

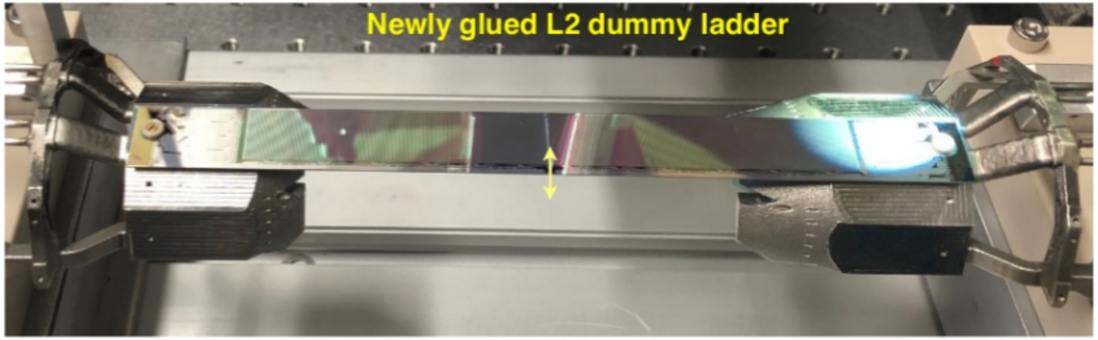
Thermal dummy L2 ladder bent with gradually increasing sagitta

- $\sim$ 4500 cycles at Δ 0.9 mm
- $\sim$ 2500 cycles at Δ 1.1 mm
- >100 cycles at 1.8 mm
  -> ladder developed two kinks

$\rightarrow$ Thermal dummy ladder mechanically different
$\rightarrow$ Both kinks at resistor lines
Repeat with recently glued L2 dummy ladder





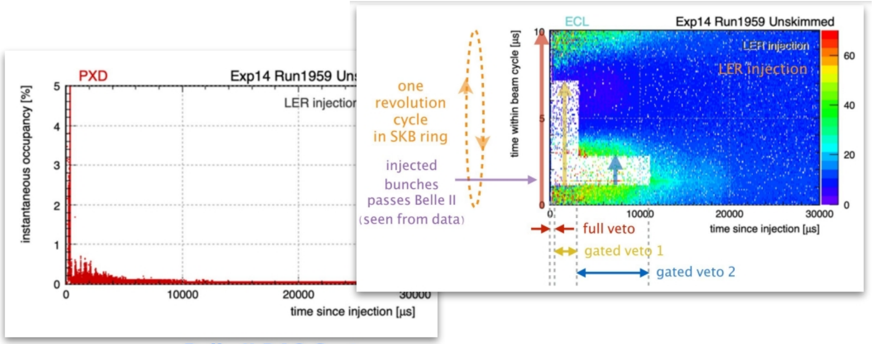


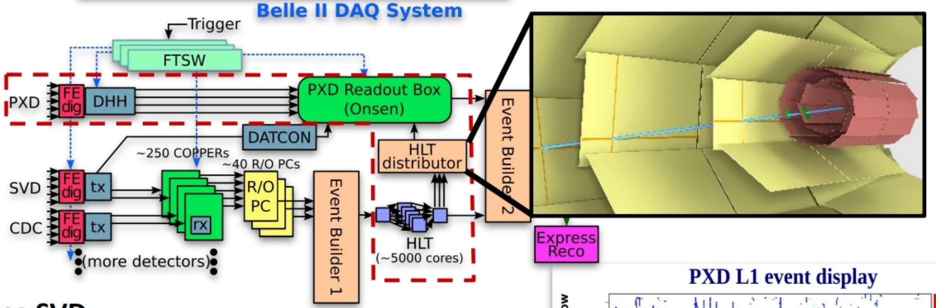
After more than two months with more than 90k cycles with sagitta $\geq$1mm $\rightarrow$ Ladder still intact

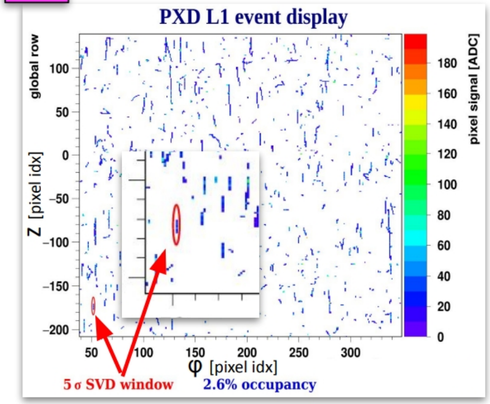
Backup: Tracking at Belle II

Challenges

- **increased backgrounds** with instantaneous lumi
  - beam lifetime only few minutes
    ⇒ continuous "top up" injection (for 2400 bunches)
    (50 Hz @ 4 ms cooldown ⇒ 4 ms damping time with particle losses)
  - "Synchrotron", "Touschek intra-bunch scattering", "Bhabha", "2 photon"...
  - challenge for detector/tracking overall
    (challenges for PXD discussed explicitly later)
- **smaller Lorentz boost** (for better beam lifetime at 4 GeV > 3.5 GeV)
  - critical for time dependent measurements







Track reconstruction and PXD role

- (HLT) **track finding seeded in CDC** (pT > 100 MeV) or else **SVD**
- **PXD** hits used in offline track fit → **improved vertex resolution**
- Regions of Interest (**ROI**) filtering:
  - HLT: extrapolates tracks to ROIs on PXD for readout to reduce data rate
    not needed yet
- PXD layer one crucial for *impact parameter resolution*
- PXD layer two (will be) important to retain performance at *higher backgrounds*