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SI LAB
Silizium Labor Bonn

Belle II
Germany

The New and Complete Belle II DEPFET Pixel Detector: Comissioning and Previous Operational Experience

Jannes Schmitz on behalf of the PXD collaboration

13th International 'Hiroshima' Symposium

Vancouver, December 06, 2023

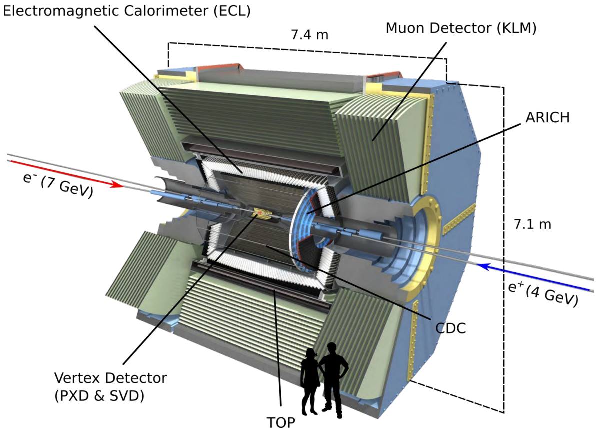
bmb+f - Förderschwerpunkt
Elementarteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

JENNIFER²
EU grant n.822070

DEPFET
Active Pixel Detector

SUPERKEKB ACCELERATOR & BELLE II DETECTOR

- Asymmetric e^+e^- collider in Tsukuba , Japan
- $E_{CM} = M_{\Upsilon(4S)} \approx 10.58$ GeV → "B factory"
- Physics data-taking March 2019 – July 2022
- Recorded a total physics data set of $L_{int} \approx 424\ fb^{-1}$
- $L_{peak} = 4.7 \times 10^{34}\ cm^{-2}s^{-1}$ (June 2022)
- Ongoing long shutdown (LS1) since July 2022
  - ~1.5 years for accelerator and detector improvements



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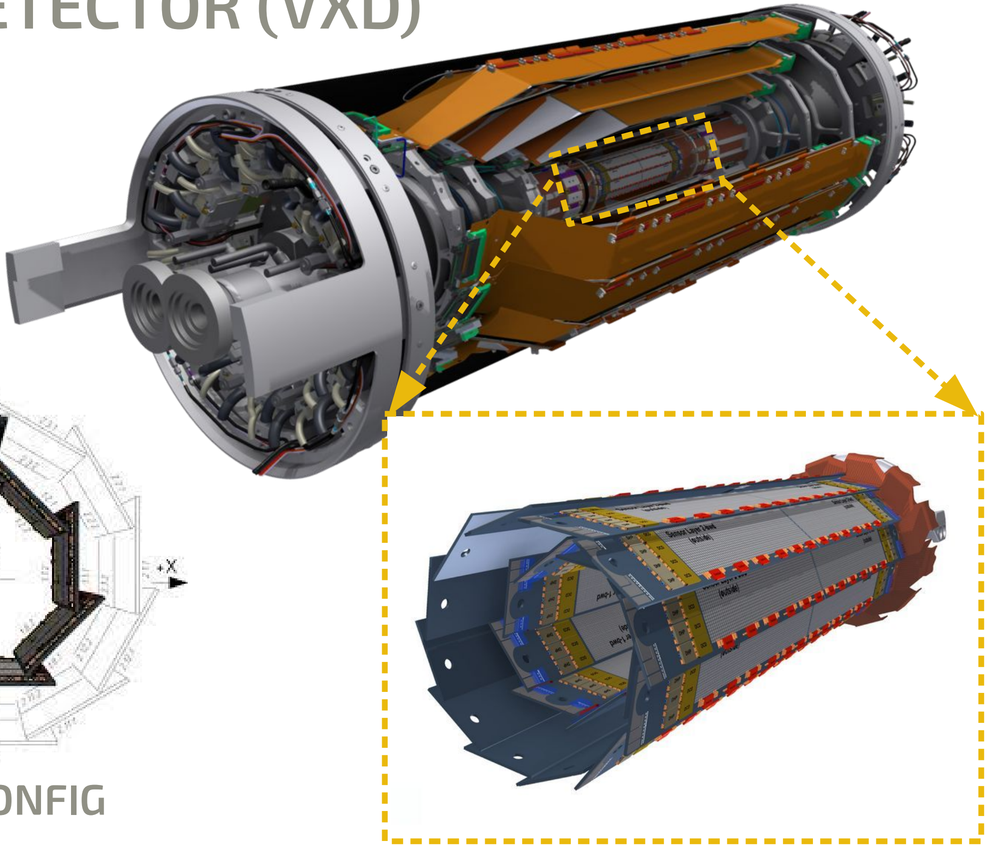
THE VERTEX DETECTOR (VXD)



SILICON VERTEX DETECTOR (SVD)

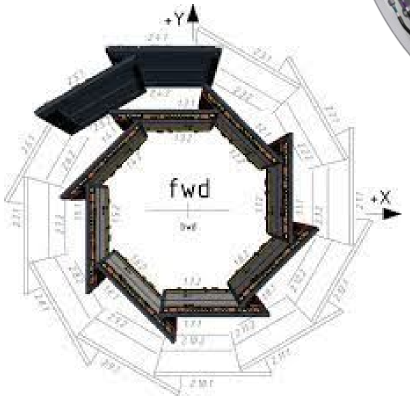
- Talk by Alice Gabrielli
- 4 layers double-sided silicon strips
- $R \leq 140$mm

PIXEL VERTEX DETECTOR (PXD)

- 2-layer DEPFET
  PXD1 2019-2022 incomplete
  PXD2 from 2023 full 2-layer
- $r_1 = 14$mm , $r_2 = 22$ mm

ACCEPTANCE

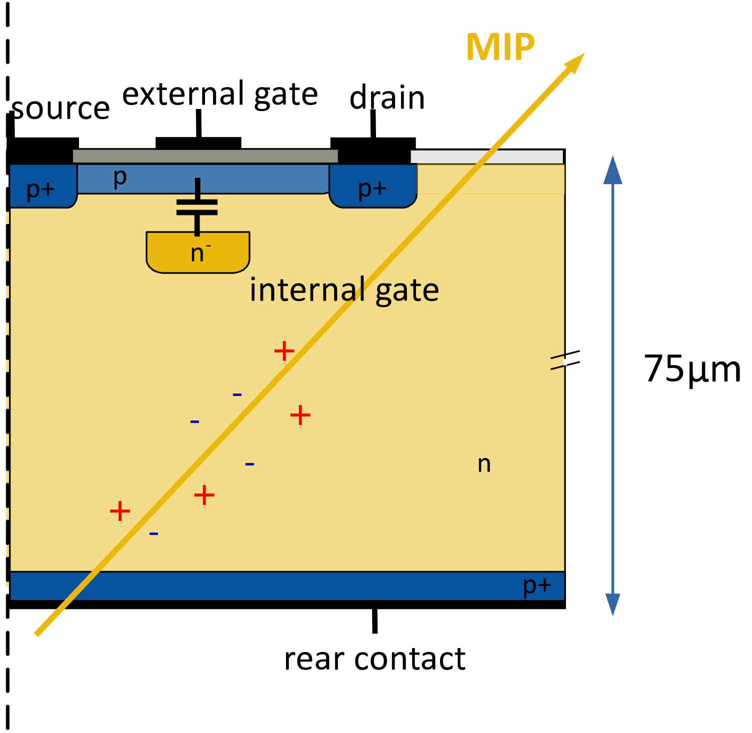
- $17° < \Theta < 150°$
- $p_t \geq 40$ MeV



PXD1 CONFIG

DEPFET PIXEL PRINCIPLE

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



DEPFET PIXEL OPERATION

- Matrix readout steered by gate and clear voltages

CHARGE COLLECTION

gate off, clear off:

- Charges drift to internal gate
- No drain current

SAMPLING

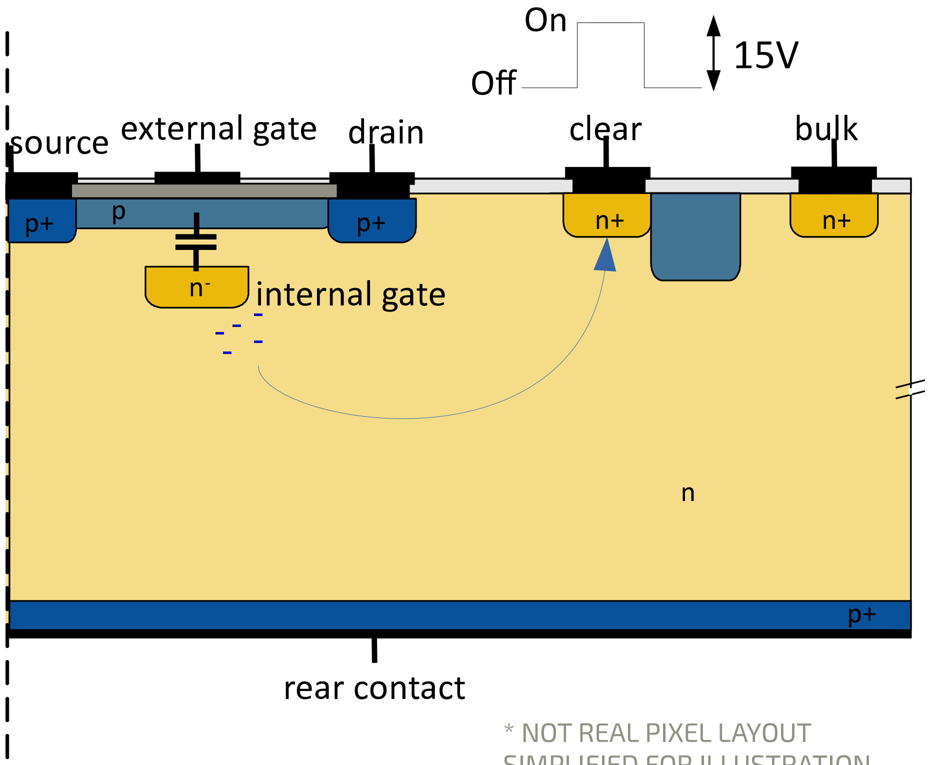
gate on, clear off:

- Readout of stable drain current

CLEARING

gate on, clear on:

- Charges drift from internal gate to clear implant



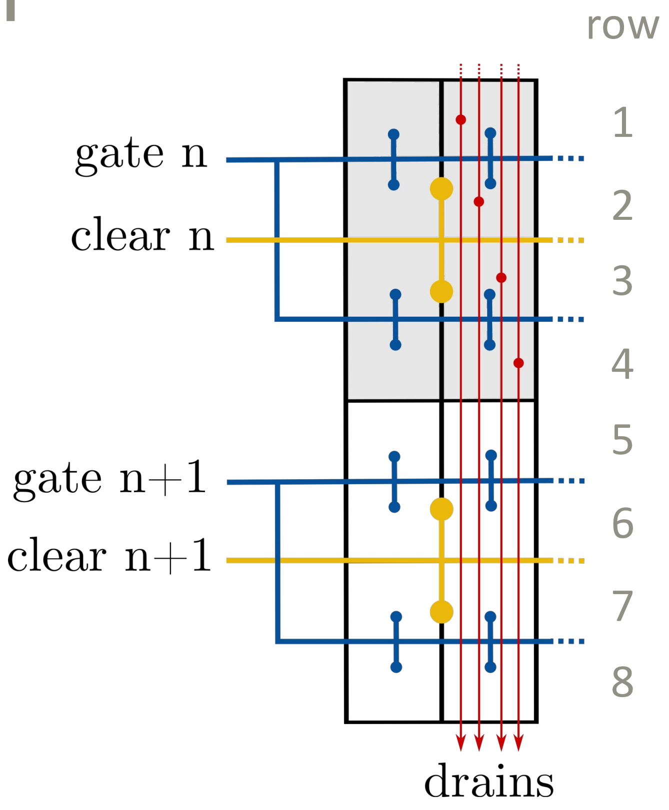
* NOT REAL PIXEL LAYOUT
SIMPLIFIED FOR ILLUSTRATION

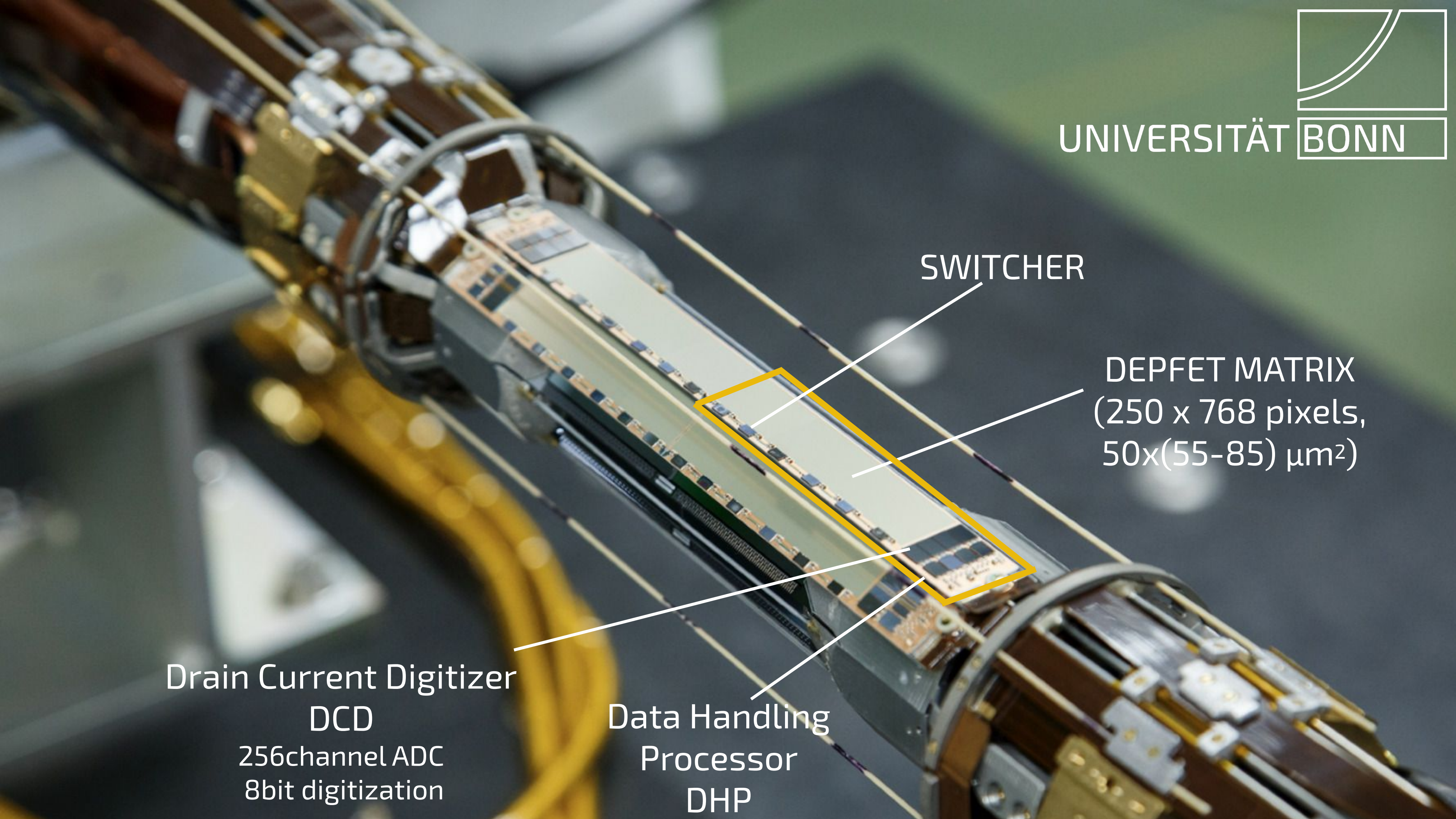
DEPFET PIXEL READOUT

- Rolling shutter readout mode with four active matrix rows at once

  → low power consumption

  – Control signals are shared among pixels
  – 20µs integration time (2x beam revolution)
- Modulated drain current processed via drain lines
- Different ASICs for row control and signal processing

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SWITCHER
DEPFET MATRIX
(250 x 768 pixels,
50x(55-85) µm2)
Drain Current Digitizer
DCD
256channel ADC
8bit digitization
Data Handling
Processor
DHP

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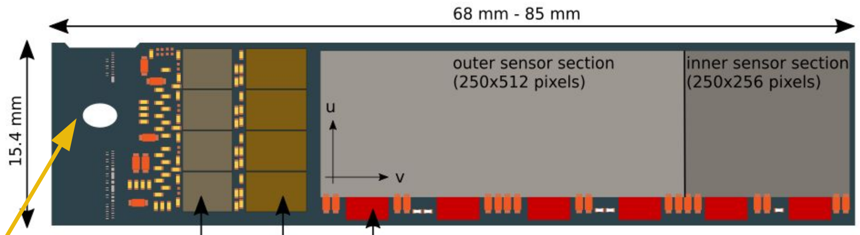
THE PIXEL VERTEX DETECTOR (PXD) MODULE

PROPERTIES

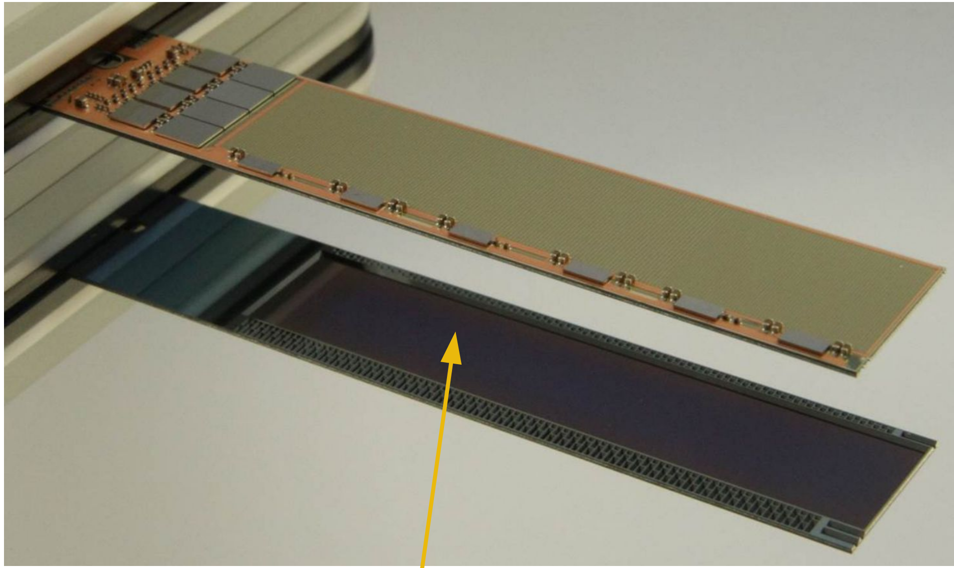
- Self-supporting **all-silicon** design
  - 450-525µm thick support frame
  - Active region thinned to 75µm

    → small total material budget ~0.21% X_0
- Pixel size 50 x (55-85) µm²



Elongated hole for sensor gliding

DHP DCD Switcher



Thinned backside at active sensor area

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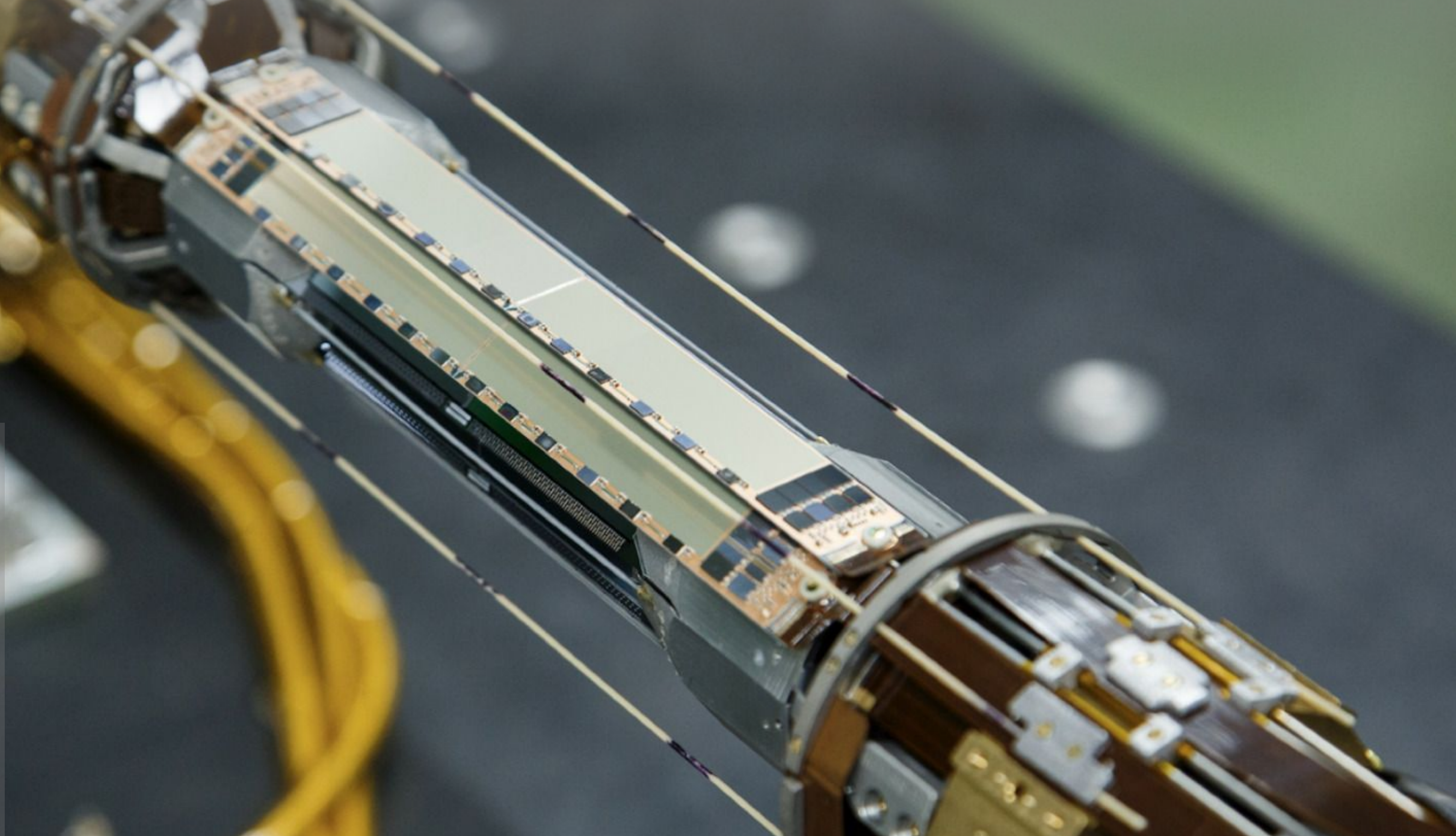
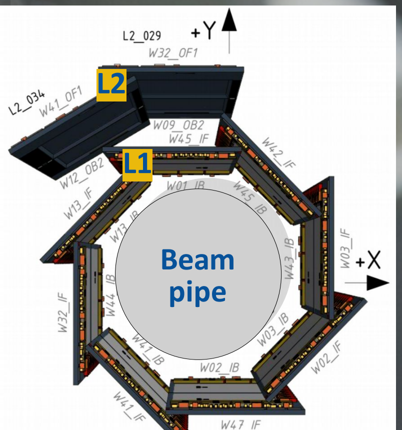
PXD1

PREVIOUS OPERATIONAL EXPERIENCE

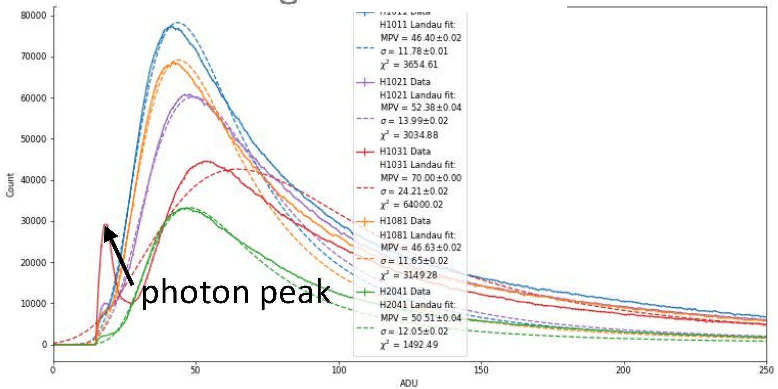




PXD1 PERFORMANCE

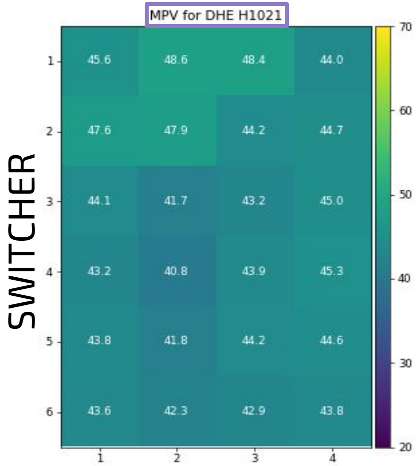
- Homogeneous signal and noise response across module matrix
- Noise performance < 1 ADU (~200e-) at SNR of ~30-50 (noise slightly increasing with DCD irradiation)
- Stable throughout 2019-2022

cluster charge distribution



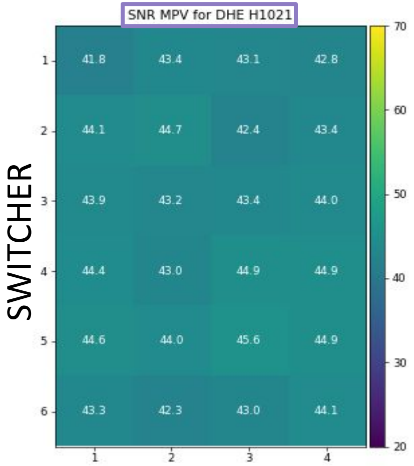
multi pixel cluster ADU

cluster charge MPV



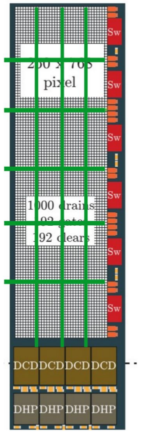
DCD/DHP

SNR MPV

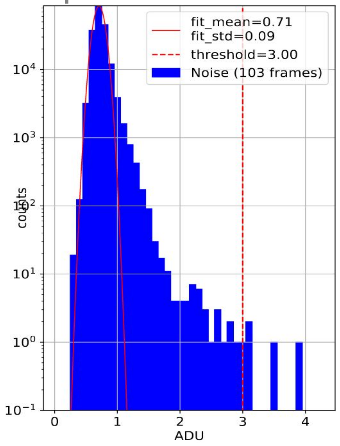


DCD/DHP

half ladder



pedestal noise



PXD1 EFFICIENCY

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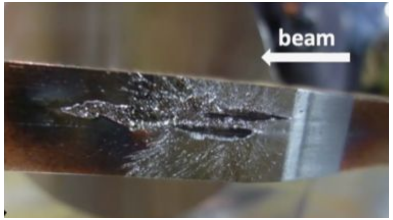
DI-MUON HIT EFFICIENCY

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

BEAM LOSS EVENTS

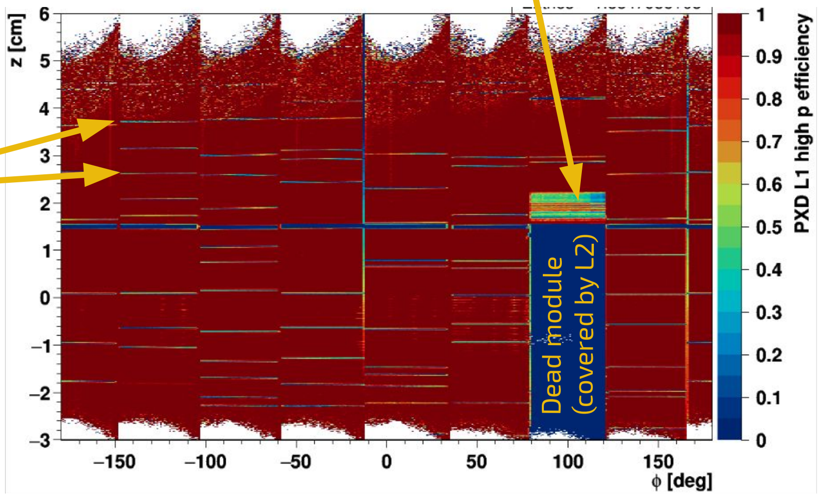
- Radiation bursts to PXD up to 3Gy in 40µs
- Permanent Switcher damage after beam incidents
  - → Inefficient/dead readout rows
  - → ~3% drop in efficiency
- Mitigation efforts in LS1:
  - Accelerator : - earlier detection
    - faster beam dump
  - PXD: - safe in OFF/STANDBY
    - → faster emergency shutdown



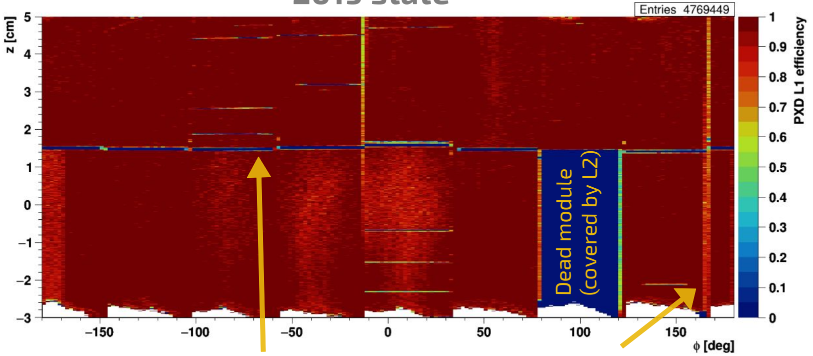
Lost beam hitting collimator
→ high inst. radiation

noisy Switcher

inefficient/dead readout channels



2019 state

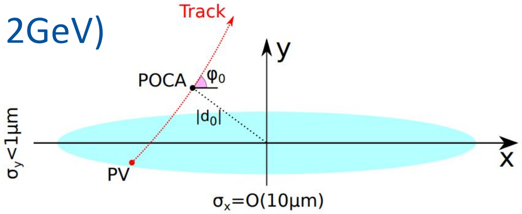


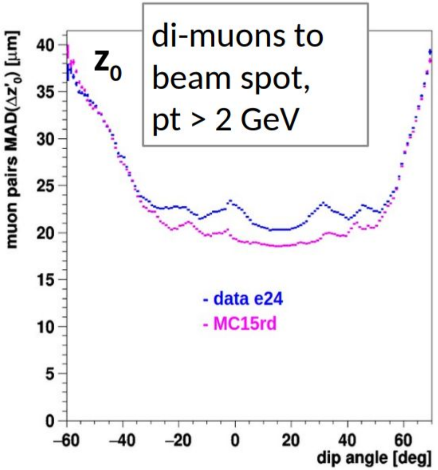
Glue gaps ~0.8mm   Half-shell gaps

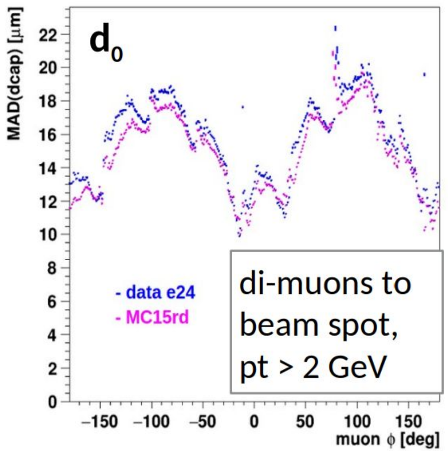
PXD1 PERFORMANCE

IMPACT PARAMETER RESOLUTION

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



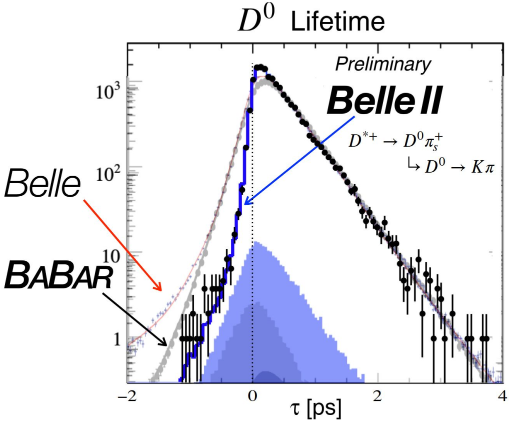




D^0 LIFETIME RESOLUTION

- 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)

PXD2

COMMISSIONING AND FIRST COSMIC DATA

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FULLY POPULATED 2-LAYER PXD2

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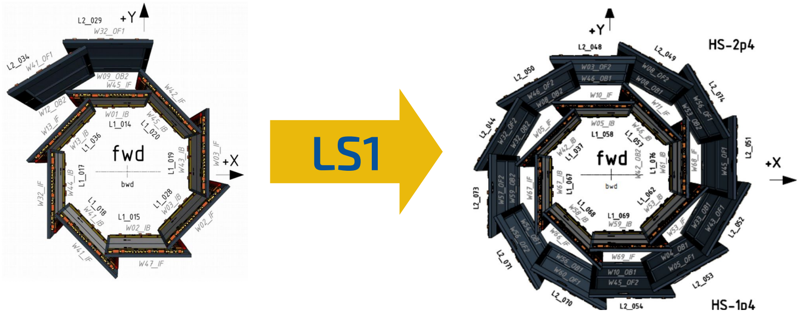
PXD1 WAS GOOD, PXD2 WILL BE BETTER

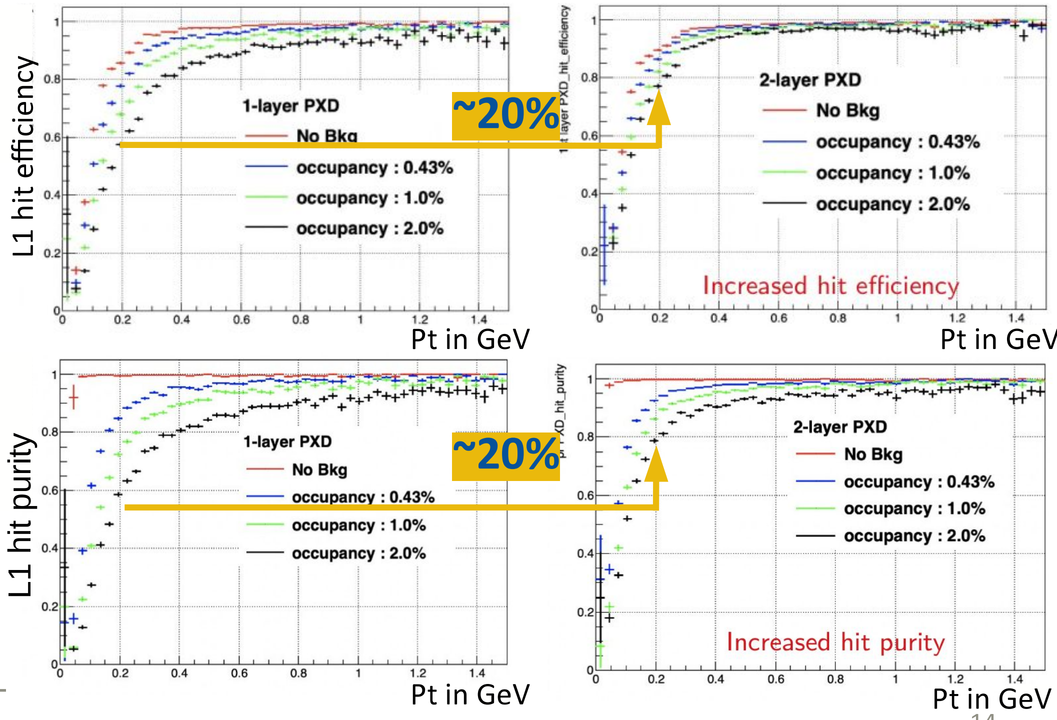
- Modest improvement of impact parameters (L1 highest impact)
- Higher probability to select correct PXD hits in 1st PXD layer at higher background levels
- Fraction of MC hits found in reconstructed track

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

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

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

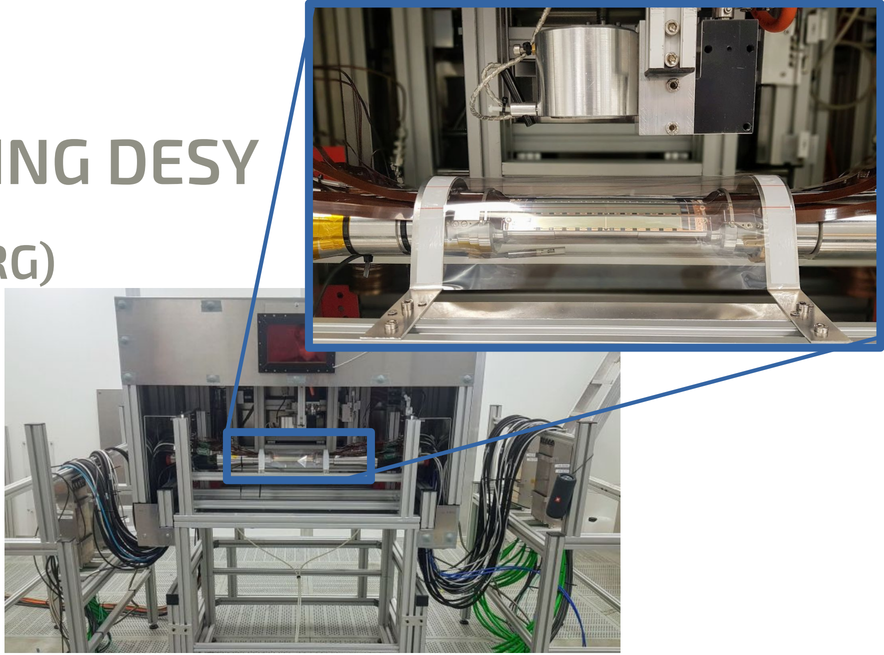




PXD2 COMMISSIONING DESY

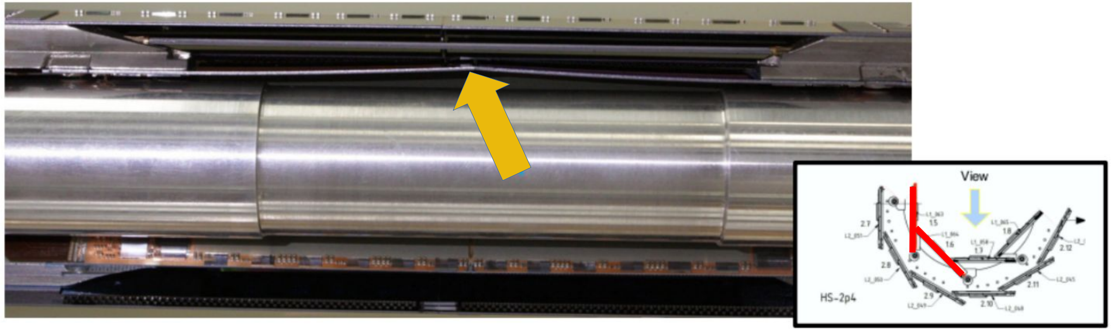
HALF-SHELL COMMISSIONING (DESY, HAMBURG)

- Pre-commissioning with full services, CO_2 (8W from DHP/DCD) and N_2 cooling (1W from sensor/Switcher)
- Half-shell mounted on aluminum dummy beampipe
- Movable ^{90}Sr for signal response tests
- 1st half-shell damaged during long-term operation



PROBLEMS FOUND

- Non optimal PXD ladder gliding
  - → Kink in 2 L1 ladders
  - → Repair & Reassambly
  - → Adjustment of screw torque to improve gliding



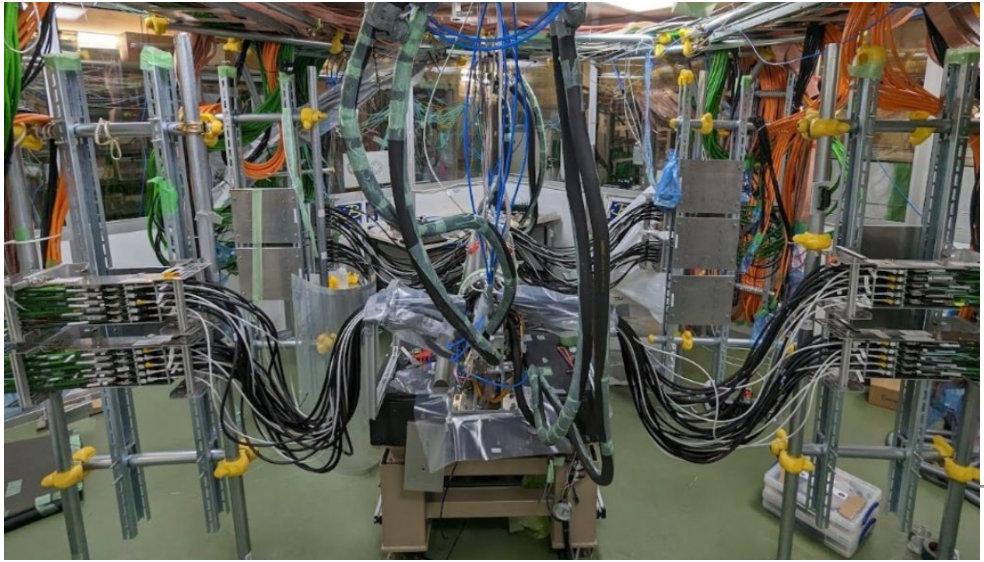
PXD2 COMMISSIONING KEK

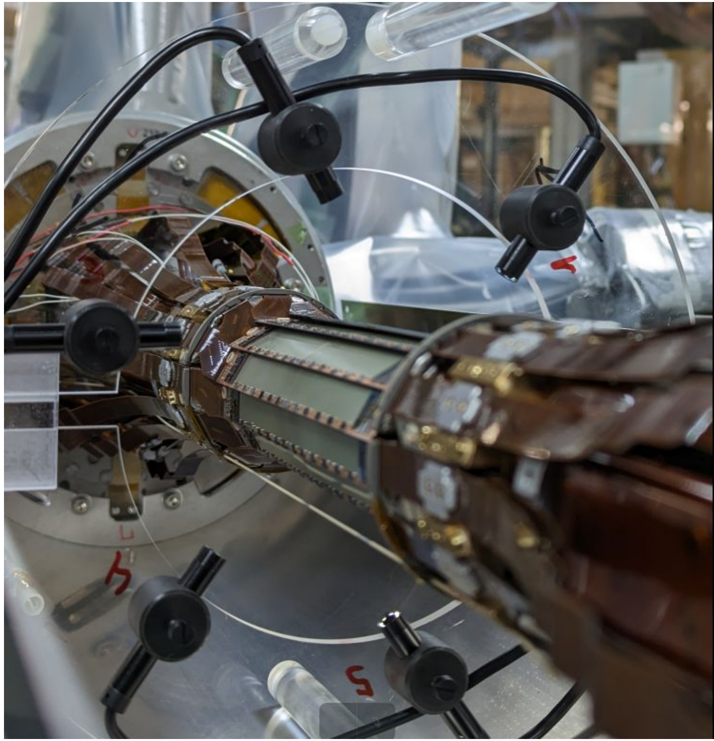
PXD2 STANDALONE TESTING

- Full optical & environmental monitoring in dry volume
- Step by step module operation with cooling adjustments

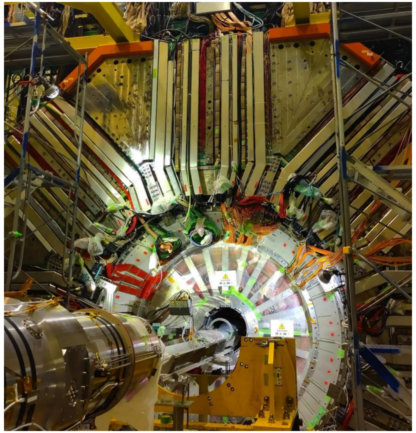
  → Successive full detector operation

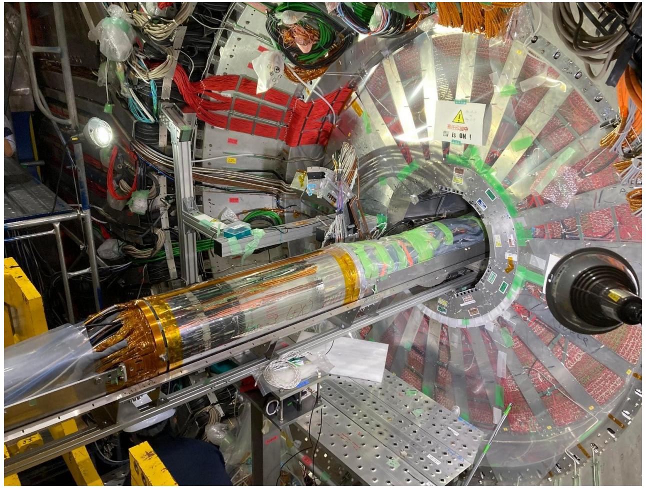
  → Significant bending (~1mm) in 2 outer ladders





COMMISSIONING OF THE NEW VERTEX DETECTOR (VXD)



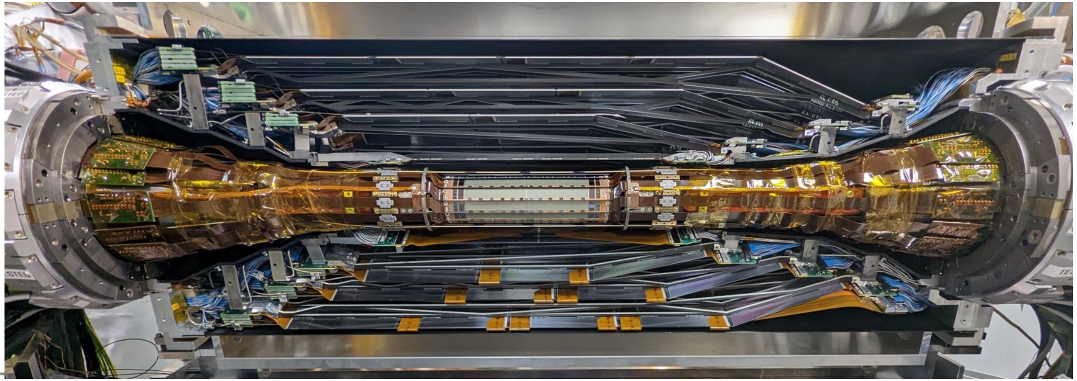


PXD1 EXTRACTION

- Old VXD extracted from Belle II in May
- Strip Vertex Detector (SVD) reused in new VXD
- PXD1 mechanical inspection did not show visible damage after 4 years operation

NEW VXD

- Extracted SVD halves installed around PXD2 on new beampipe
- Combined standalone testing
- Inserted back in August



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FIRST PXD2 COSMIC DATA SEPTEMBER23 (NO B-FIELD)

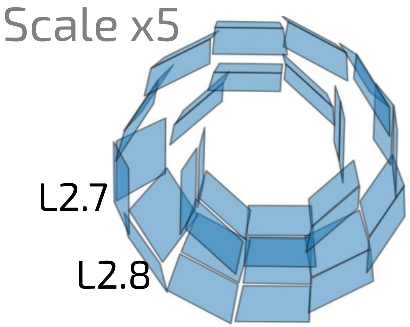
EFFICIENCY

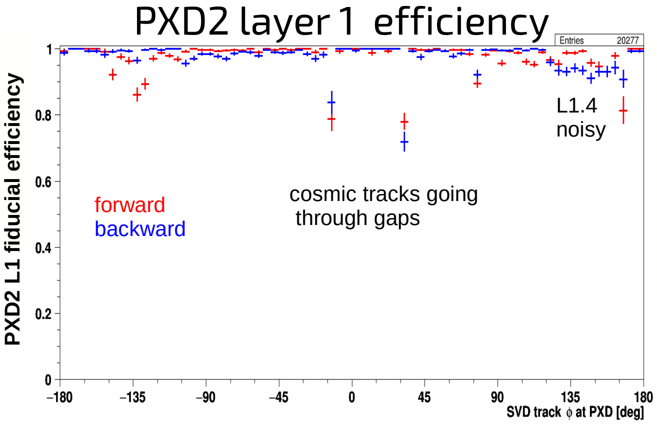
- Extrapolated SVD tracks
- Reaching > 98% in most regions
- Eff. Drops due to
  - Gaps for cosmics
  - Masked noisy pixels (esp. L2.12bwd)

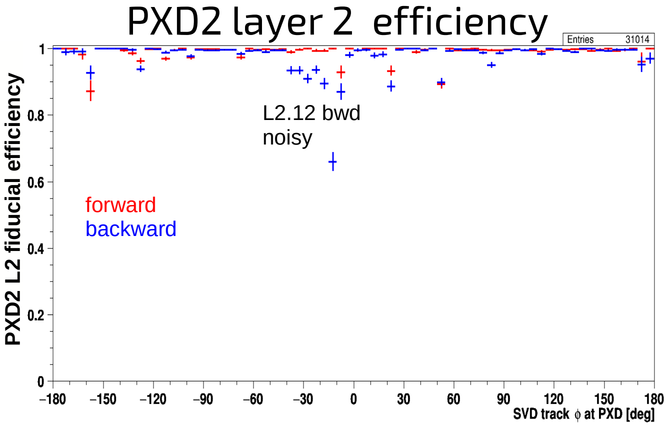
    → further module tuning ongoing

ALIGNMENT

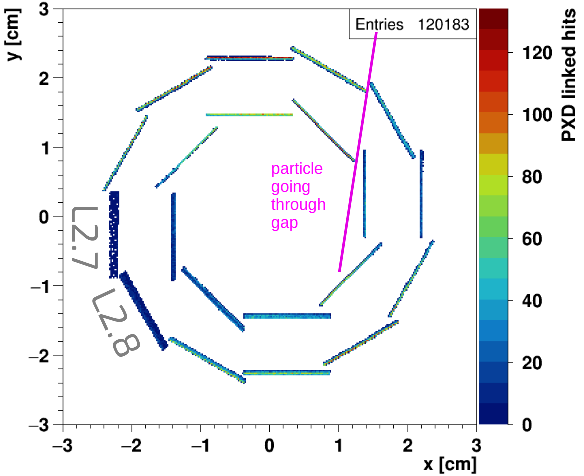
- Extrapolated CDC tracks
- Alignment done per module
  - 6 rigid body, 7 deformation parameters
- Ladder bowing visible
  - Up to ~1mm for L2.7/L2.8







xy-projection of spacial cosmic hits after alignment



thickness indicates ladder bowing

SUMMARY

PXD1 (2019-2022)

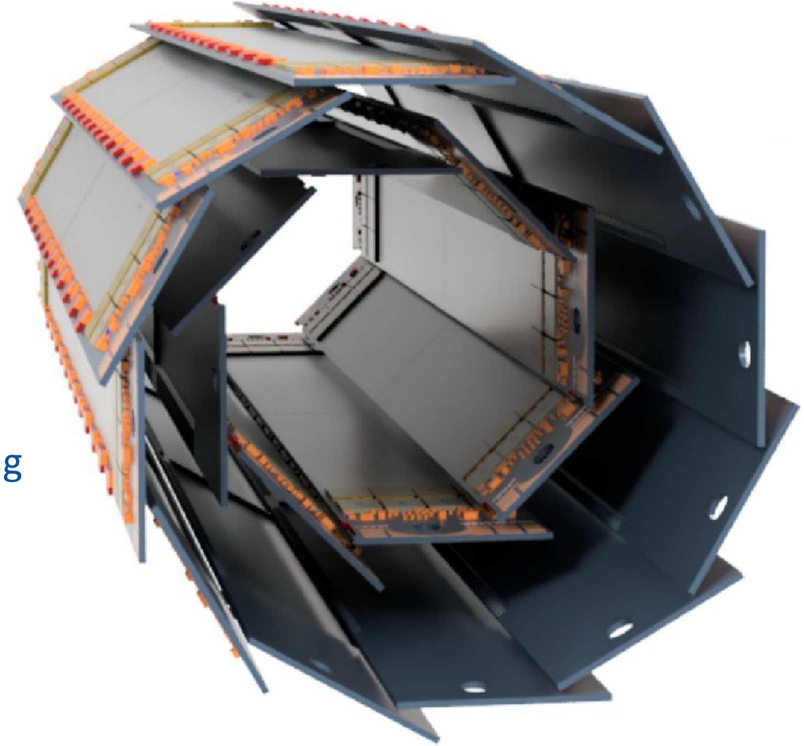
- 4 years successful operation with single layer
- Overall efficiency ~96 %
- 2x improvement of D^0 lifetime resolution
  (compared to previous experiment)
- Challenges: beam backgrounds and beam losses

PXD2 (SINCE 2023)

- All 40 modules operable after successful commissioning
- First cosmic data → efficiency mostly > 98 %
- Challenges : 2 ladders show significant bending
  → further investigations ongoing

OUTLOOK

- Resuming beam operation beginning of 2024
- PXD2 operation expected at least until LS2

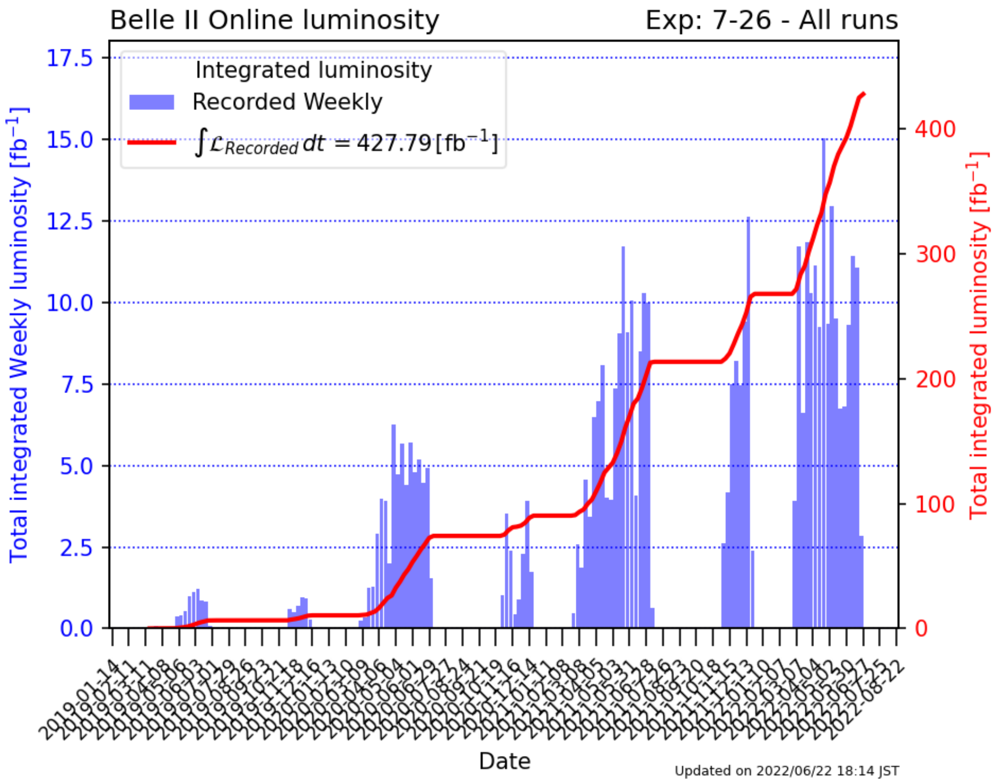


BACKUP

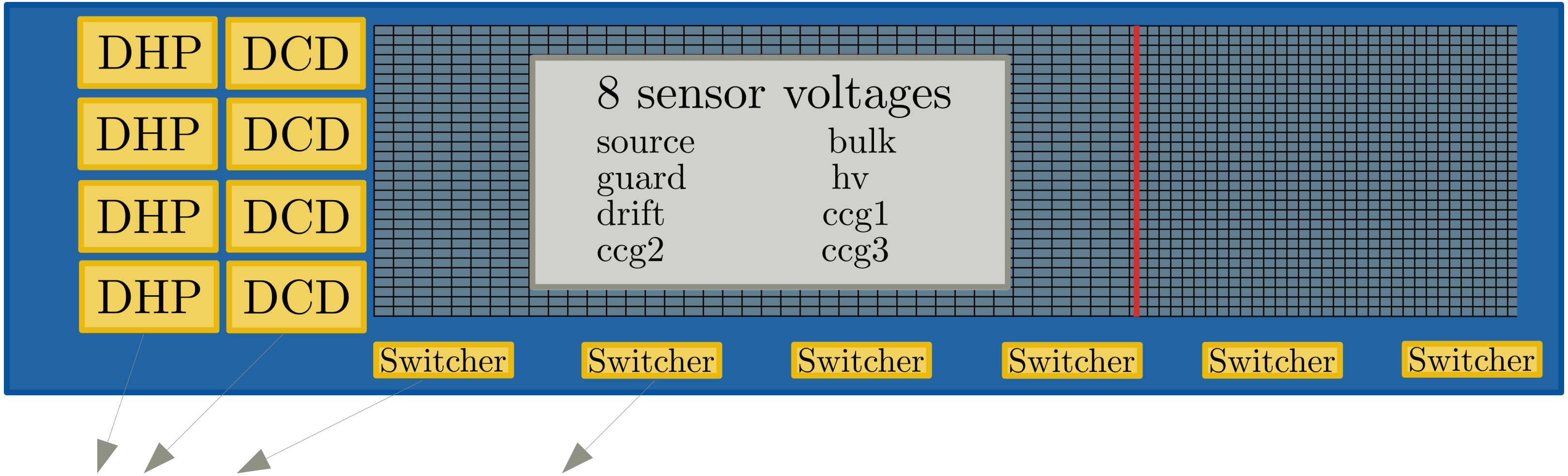
BELLE II LUMINOSITY

TOTAL INTEGRATED LUMINOSITY FOR GOOD RUNS

- Total L_{int} : 424 fb^{-1}
- Total L_{int} at Υ(4S) : 363 fb^{-1}
- Total L_{int} below Υ(4S) : 42 fb^{-1}
- Total L_{int} above Υ(4S) : 19 fb^{-1}



PXD POWER REQUIREMENTS



9 ASIC voltages

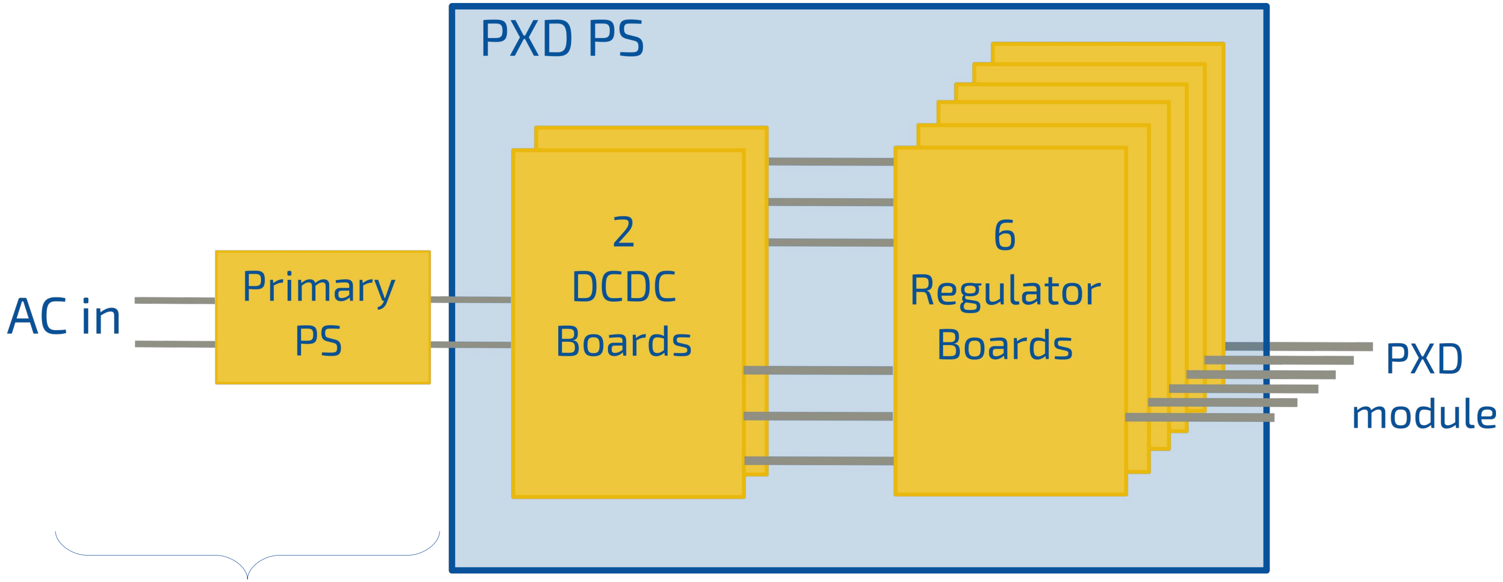
sw-dvdd / sw-sub / sw-refin
dcd-avdd / dcd-dvdd / dcd-refin / dcd-amplow
dhp-io / dhp-core

6 steering voltages

gate-on1 / gate-on2 / gate-on3 / gate-off
clear-on / clear-off

→ **23 voltages** must be supplied to each PXD module

PS SYSTEM ARCHITECTURE



- AC/DC conversion
- NetV → 24V LV

(Commercial component)

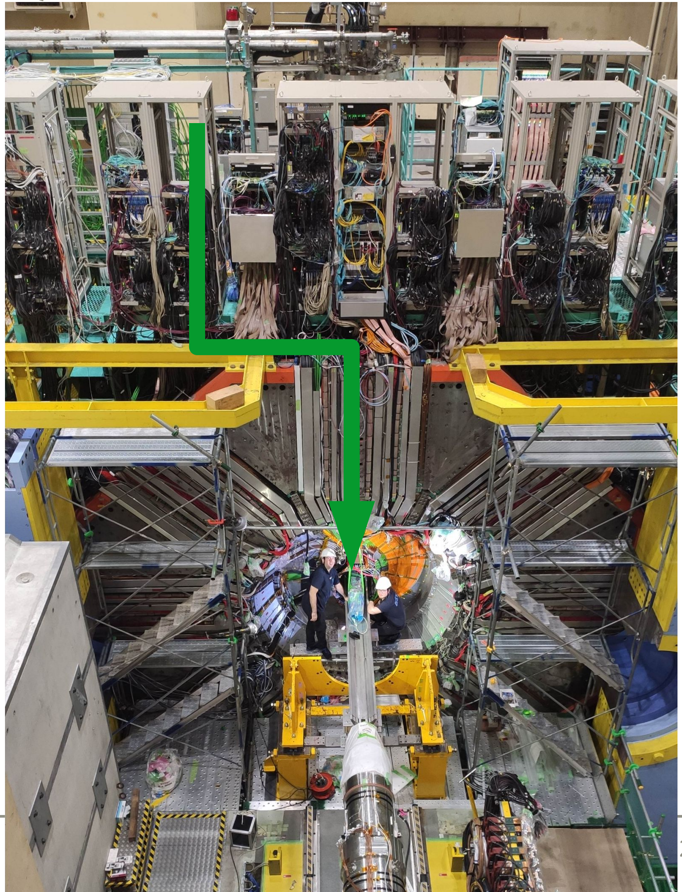
- DC/DC conversion for secondary voltages
- Electrical isolation

- Linear post regulation
- Readback of volt. & current
- Limiting of volt. & current

PXD POWERSUPPLY REQUIREMENTS

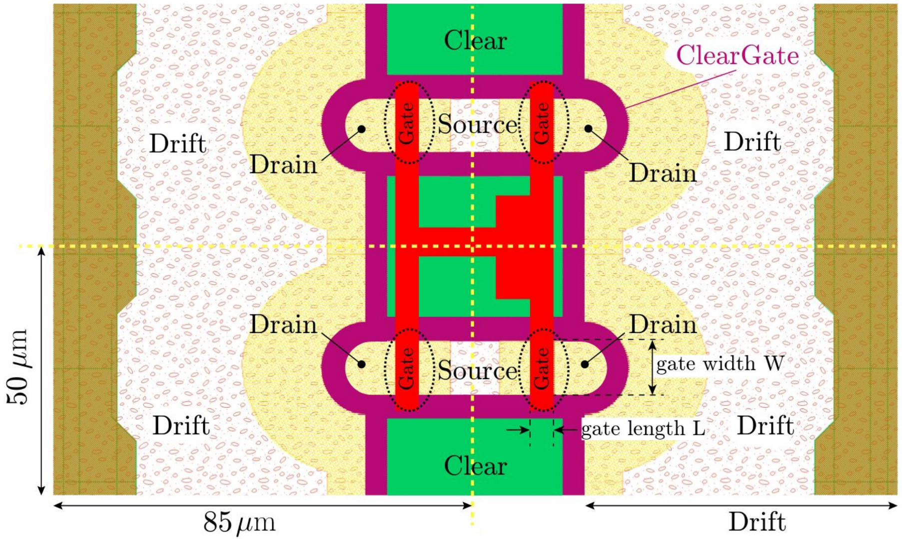
- Need 23 voltages, ranging from – 80V to + 20V with additional dependencies
- Currents up to 3A
- Enabling of hardware current limits
- Supplied via 15m long cables from top of Belle II
  - → Compensate for voltage drop
  - → 4-wire sensing and stable regulation

→ No commercial solution fulfilled all necessary features



DEPFET PIXEL DESIGN

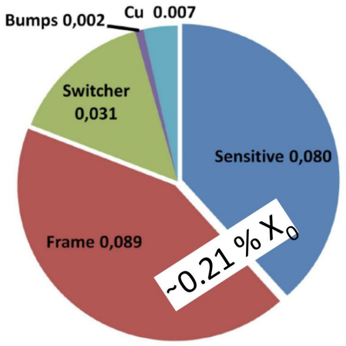
- Four-fold pixel design
  - Allows parallelization in metal routing
  - Source and Clear implant shared among multiple pixels
- Rolling shutter readout mode with four active matrix rows at once → low power
  - 50 kHz → 20 µs integration time (2x beam revo. cycle)
  - dead-time free except for 100 ns read-clear cycle

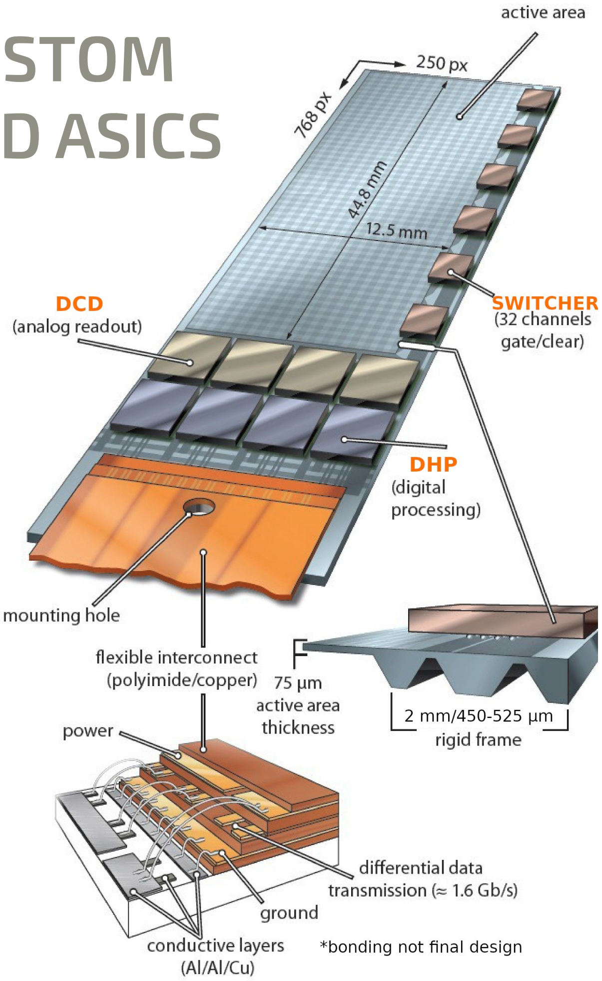


CUSTOM PXD ASICS

DCD
DRAIN CURRENT DIGITIZER

- pipeline 8-bit ADC per channel
- 256 input channels
- 92 ns sampling time
- UMC 180nm
- rad. hard proved (10 Mrad)





SWITCHER

- gate and clear signals for row control
  - 32 channels control 4 rows each
- fast HV ramping for clear
- AMS/IBM HV CMOS 180nm
- size 3.6 x 1.5 mm^2
- rad. hard proved (36 Mrad)

DHP
DATA HANDLING PROCESSOR

- data processing and transmission
  - pedestal correction
  - data reduction (zero suppression)
  - transmission at 1.6 Gbit/s
- TSMC 65nm
- size 4.0 x 3.2 mm^2
- rad. hard proved (100 Mrad)

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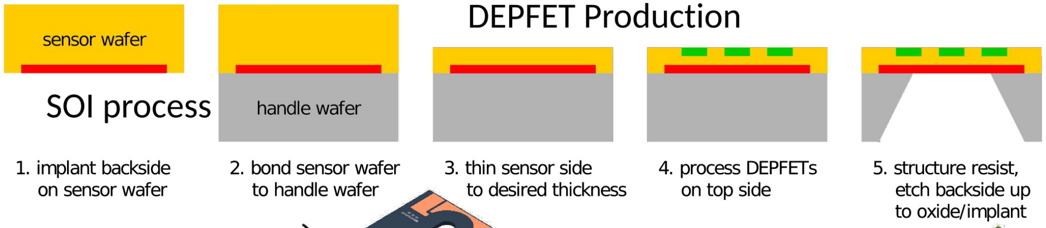
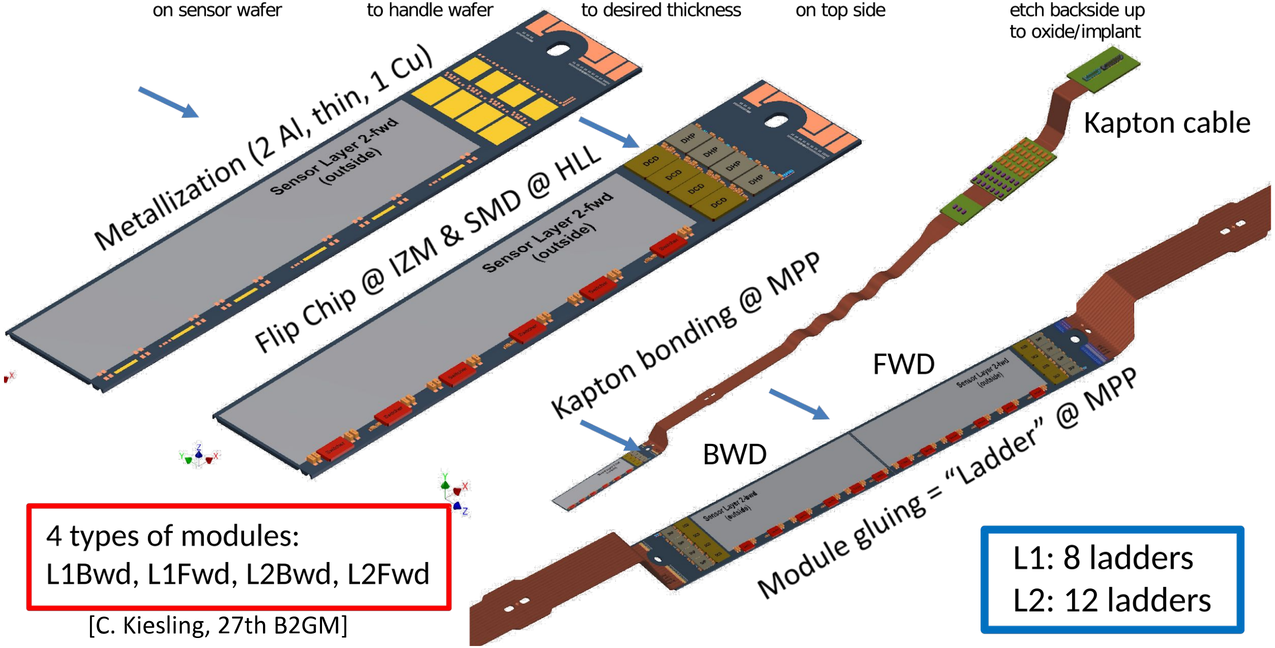
WAFER PROCESSING AND MODULE PRODUCTION

DEPFET Production





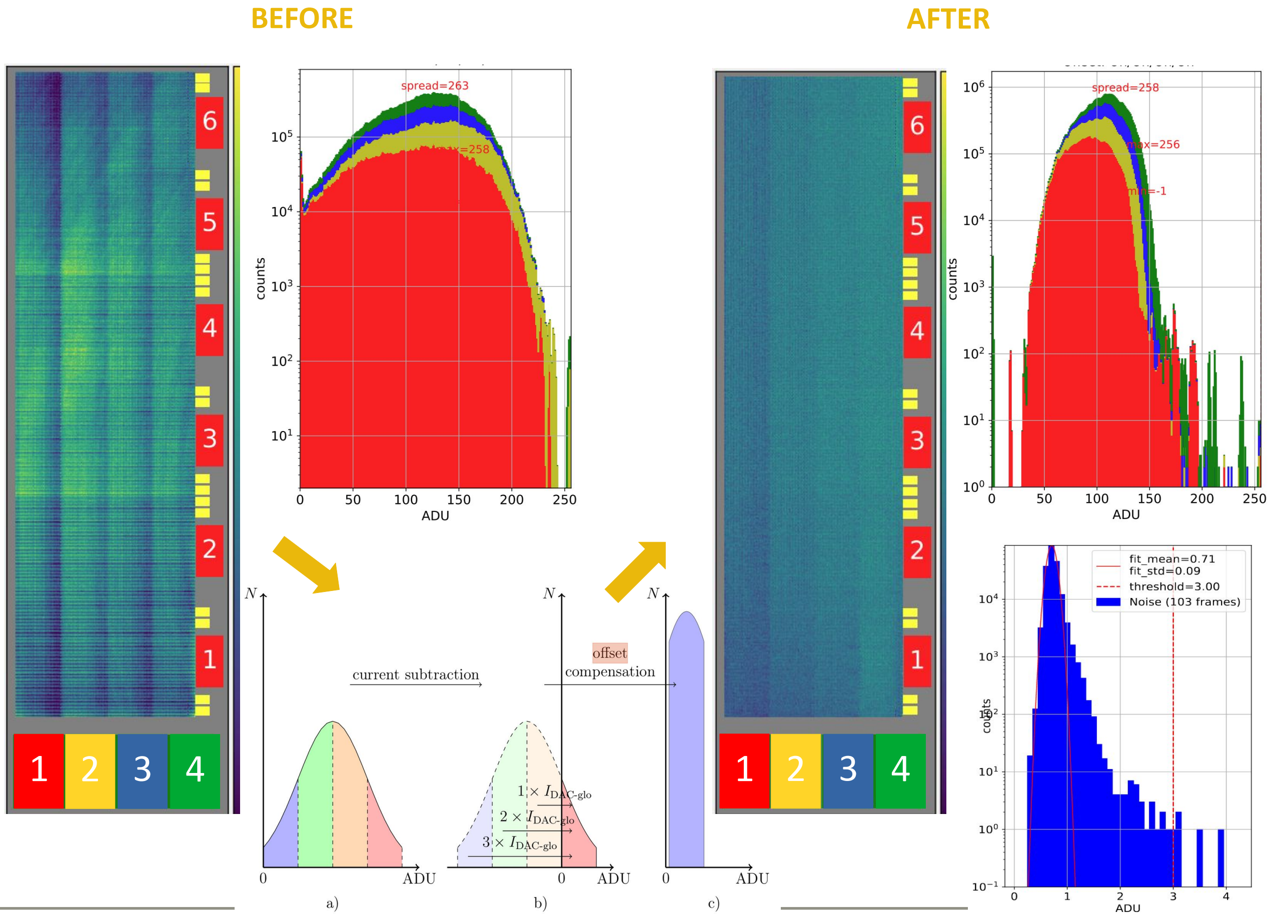
4 types of modules:
L1Bwd, L1Fwd, L2Bwd, L2Fwd

[C. Kiesling, 27th B2GM]

L1: 8 ladders
L2: 12 ladders

PXD CALIBRATION

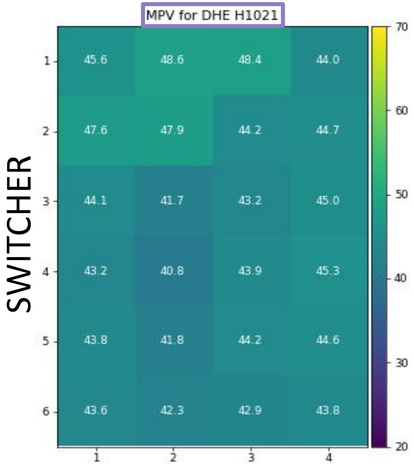
- Characterized modules before installation
- Further optimization during operation
- Improved/automated operation, monitoring and calibration procedures
- DCD calibration
- Biasing optimization
- Pedestal optimization on DCD
  - Pedestal compression via 2-bit DAC
  - Analog Common Mode Correction (ACMC)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



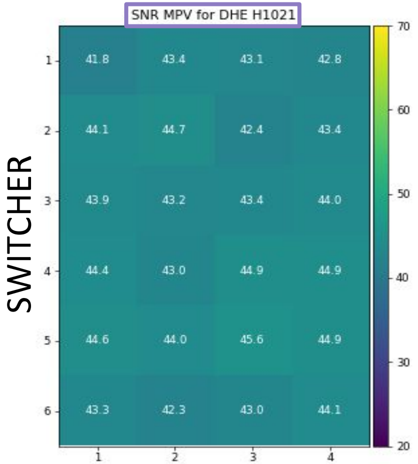
PXD1 PERFORMANCE

- 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

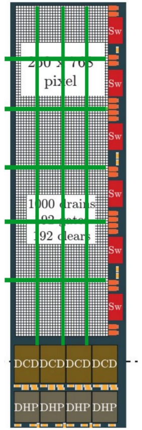
cluster charge MPV



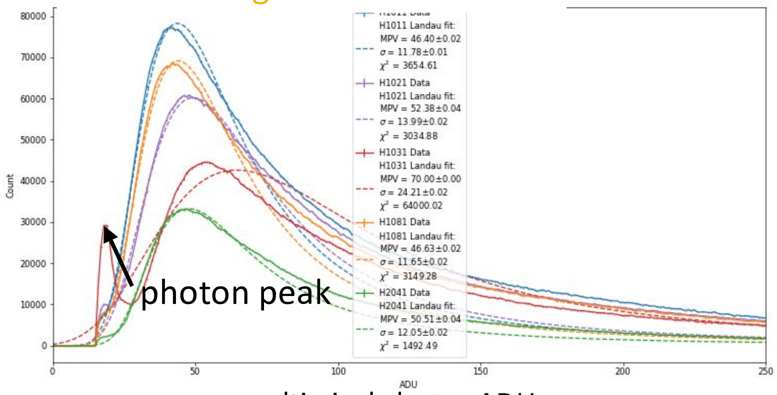
SNR MPV



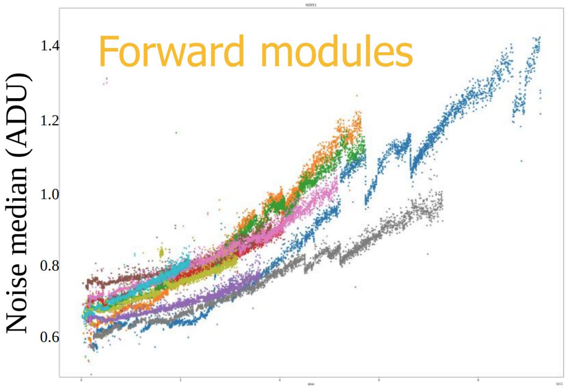
half ladder



cluster charge distribution

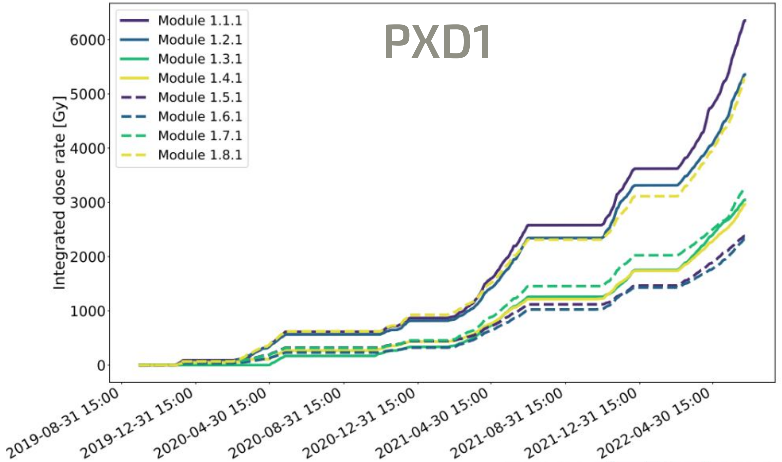


multi pixel cluster ADU

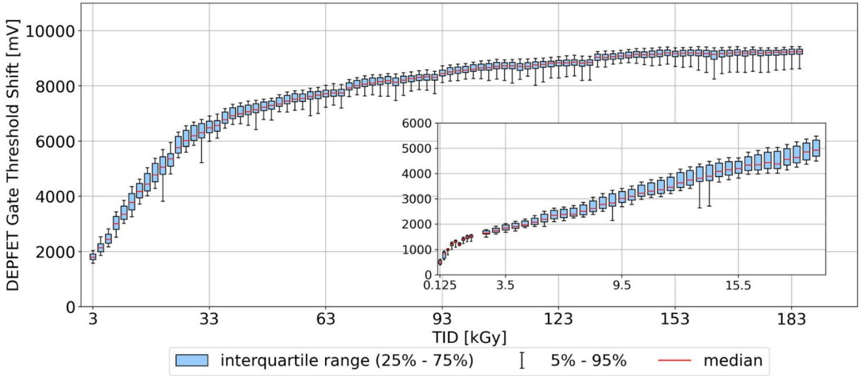


PXD1 RADIATION DOSE AND THRESHOLD SHIFT

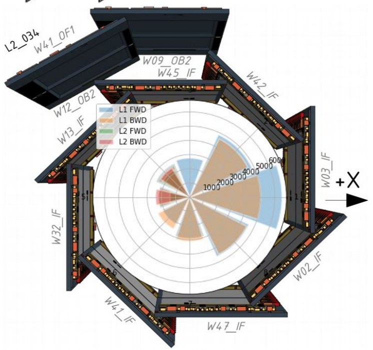
Integrated dose of L1 fwd modules



X-RAY LAB CAMPAIGN



$$MPV \sim g_q \sim \sqrt{I_{DS}} \sim (V_{GS} - V_{th})$$



- Dose estimation on module occupancy
- Module dependent TID
  → 2.5-6.5 kGy (2019-2022)
- Expected Lifetime exposure of PXD is ~200kGy in 10years

- Oxide damage → shift of MOSFET threshold V_{th}
- Compensated by regular adjustment of V_{GS}

  → keep g_q constant

- Lab results consistent with PXD experience

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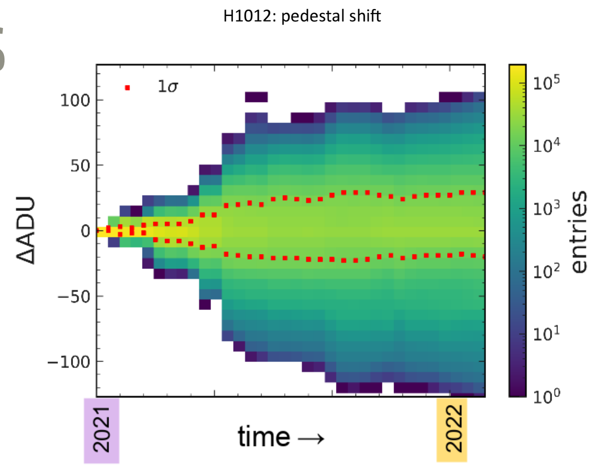
RADIATION AGING EFFECTS

TRAPPED OXIDE CHARGES

- Shift of DEPFET threshold voltage

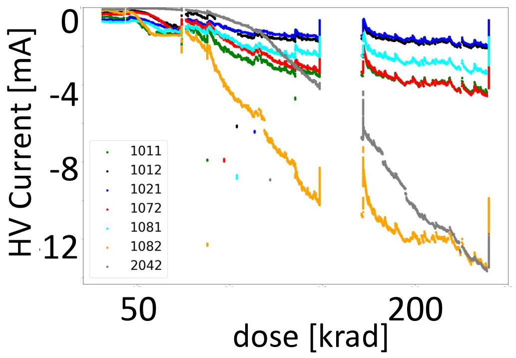


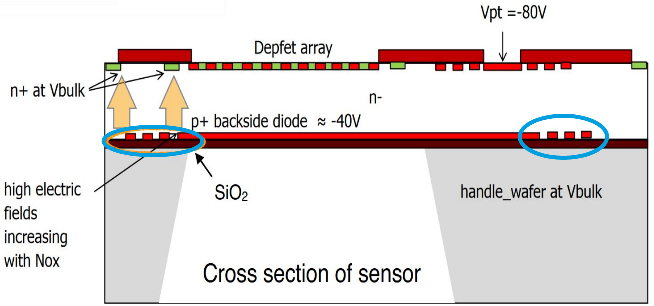
PEDESTAL AGING

- Broadening of pedestal distribution and noise increase
- Inhomogeneous across matrix
  → potential challenge for pedestal compression

INCREASING HV CURRENT

- Guard rings are (partially) shorted
- Burried oxide damage → high E-fields
  → avalanche current multipl. → High I_{HV}
- Modification of PS units
  → Performance not affected

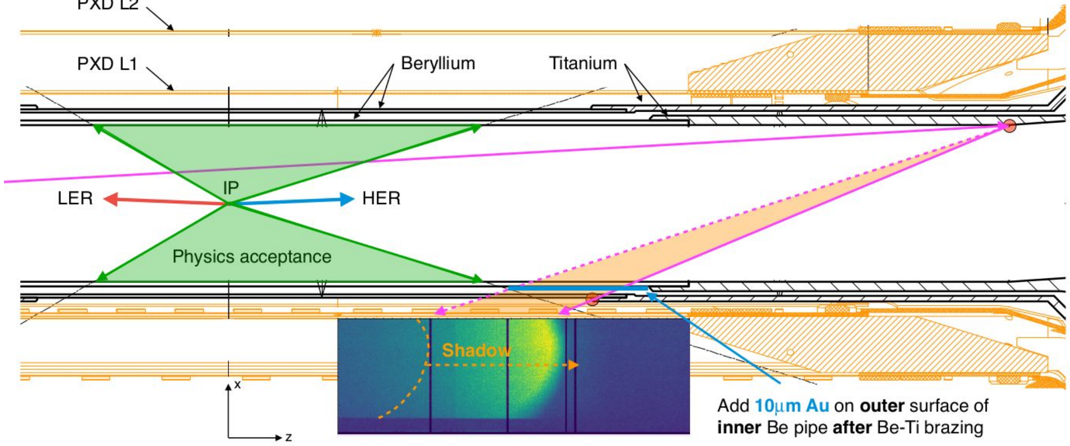




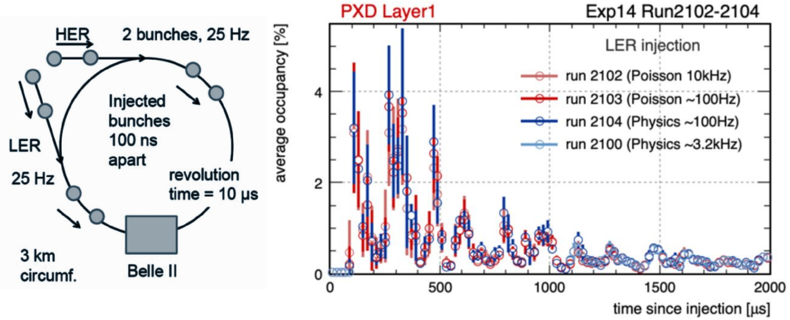
BACKGROUND CHALLENGES

SYNCHROTRON RAD. BACKGROUND

- From back-scattered SR fan photons on edge of Ti BP
- Appear during HER injections (large betatron osc. during cooldown)
  → inhomogeneous module irradiation
  → deterioration of clustering and tracking
- New modified BP with new geometry and add. gold plating



INJECTION BACKGROUND



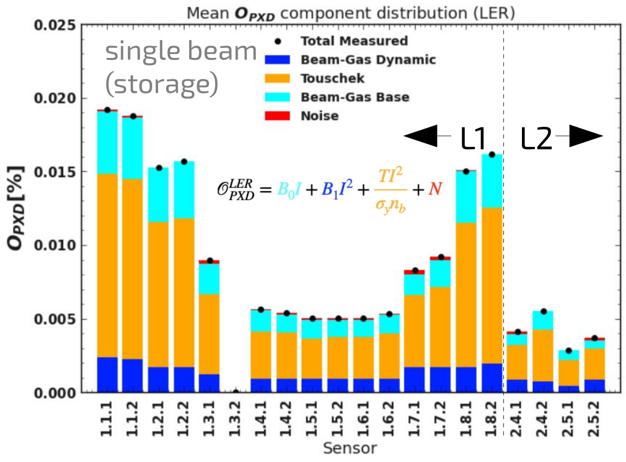
- From newly injected bunches (50Hz)
- Touschek effect limits beam lifetime to few mins → continuous injection
- 3% occupancy threshold in PXD
  → no problem so far
- Damping takes ~ms
  → Full and gated vetoes

BEAM BACKGROUNDS

BEAM STORAGE

- **Beam-gas scattering**
  beam interaction with residual gas molecules

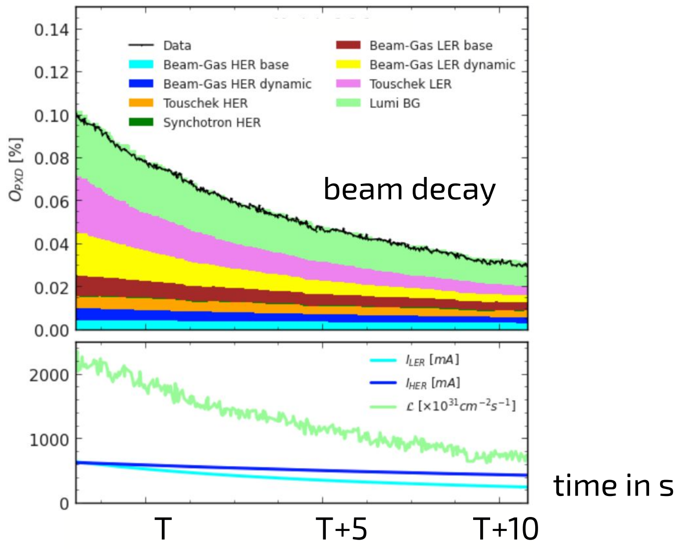
- **Touschek scattering**
  Coulomb scattering within bunch



LUMINOSITY (BEAM COLLISIONS AT IP)

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

beam collision (storage + lumi)



BEAM BACKGROUND EXTRAPOLATION

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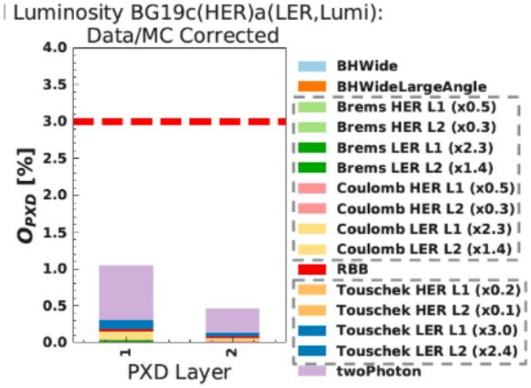
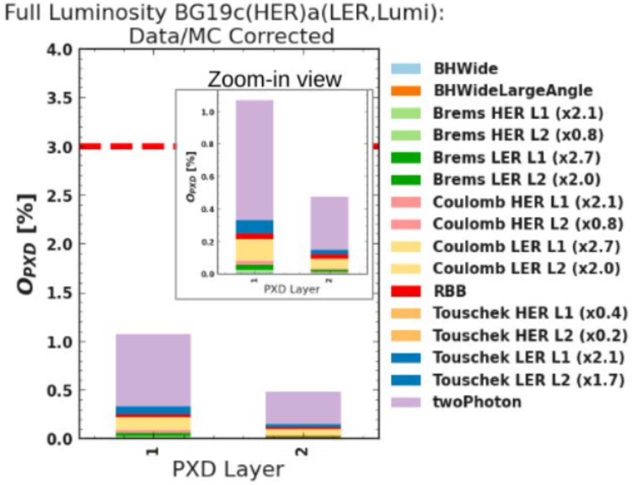
BASED ON SINGLE BEAM DATA/MC @ DEC 20 2021

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 total extrapolation
  → dominated by two-photon background

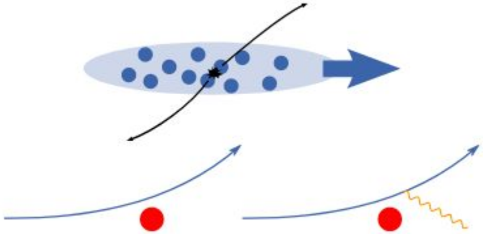


PXD BACKGROUNDS AT BELLE II

PXD Backgrounds @ Belle II

Single-beam backgrounds:

- **Touschek scattering** $\rightarrow$ scattering of particles within a bunch $\rightarrow$ **Touschek rate** $\propto N_{particles} \times \rho \rightarrow \mathbf{I} \times \frac{\mathbf{I}}{\sigma_y n_b}$
- **beam-gas scattering** $\rightarrow$ Coulomb scattering and Bremsstrahlung (scattering off gas molecules) $\rightarrow$ **Beam-gas rate** $\propto N_{gas\ molecules} \times N_{particles} \rightarrow \mathbf{P} \times \mathbf{I} \times \mathbf{Z}^2_{eff}$



- **synchrotron radiation background** $\rightarrow$ consequence of a radial acceleration of the beam's particles achieved in bending magnets and quadrupoles
- **injection background** $\rightarrow$ continuous injection of charge into beam bunch modifying the beam bunch

Single-beam backgrounds can be mitigated with beam-steering, collimators, and vacuum-scrubbing

Luminosity backgrounds:

- **two-photon background** $\rightarrow$ leading luminosity background ($e^+e^- \rightarrow e^+e^-\gamma\gamma \rightarrow e^+e^-e^+e^-$), unlike any of the backgrounds above cannot be reduced!

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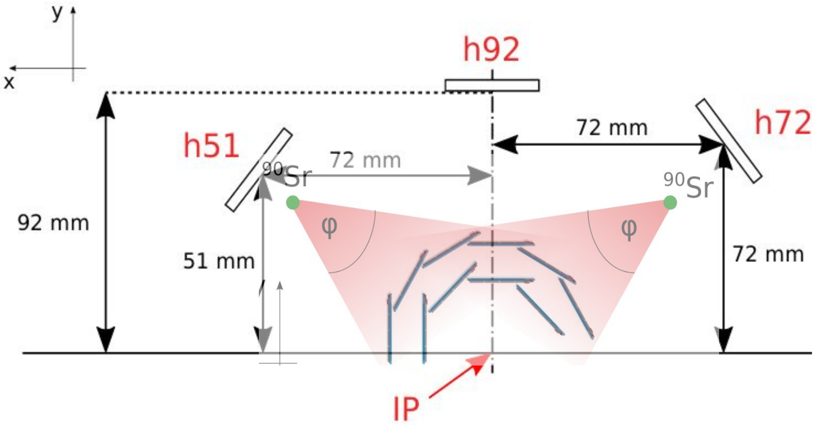
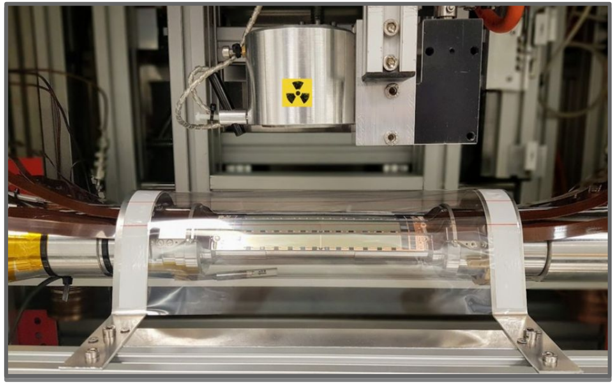
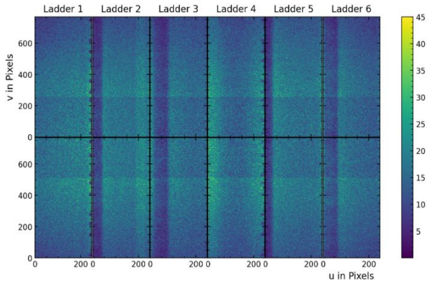
PXD2 BIAS OPTIMIZATION



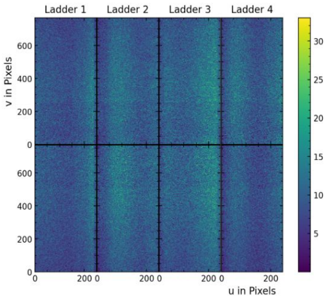


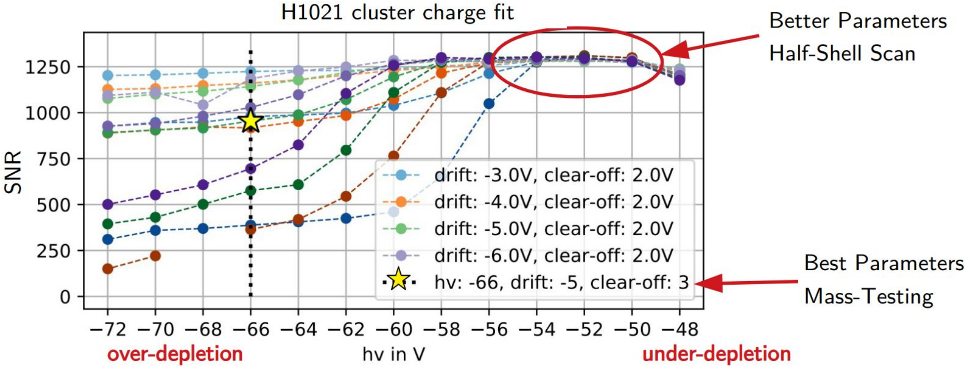
More than 200 voltage combinations, 15 minutes each

Layer 2:



Layer 1:





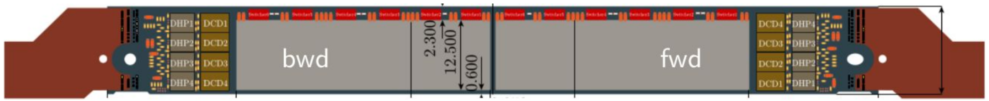
PXD2 MODULE STATUS

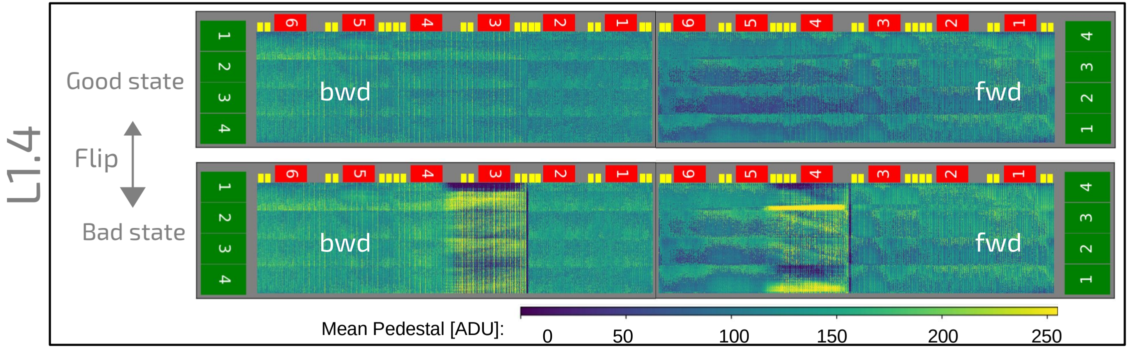
GENERAL

- All 40 modules operable

UNSTABLE SWITCHERS L1.4

- Two module states
- Problematic readout channel or broken switcher?
- Temporary solution: reduction of gate-on voltage

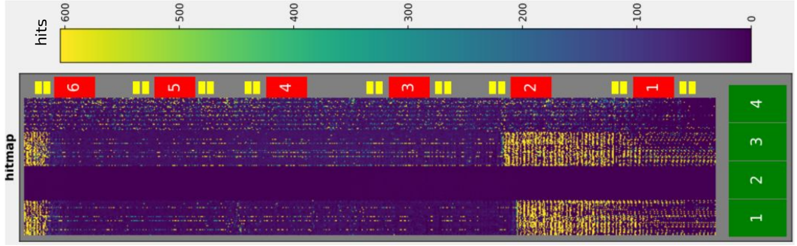




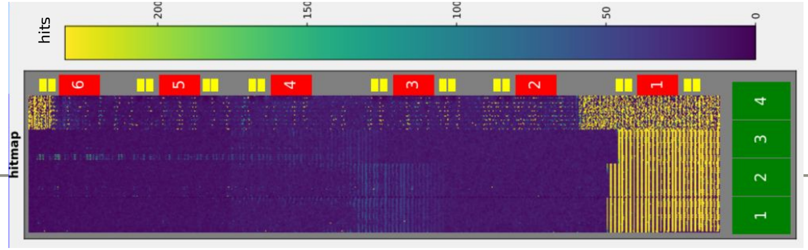
PEDESTAL GLITCHES

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

L2.12 bwd



L2.4 bwd

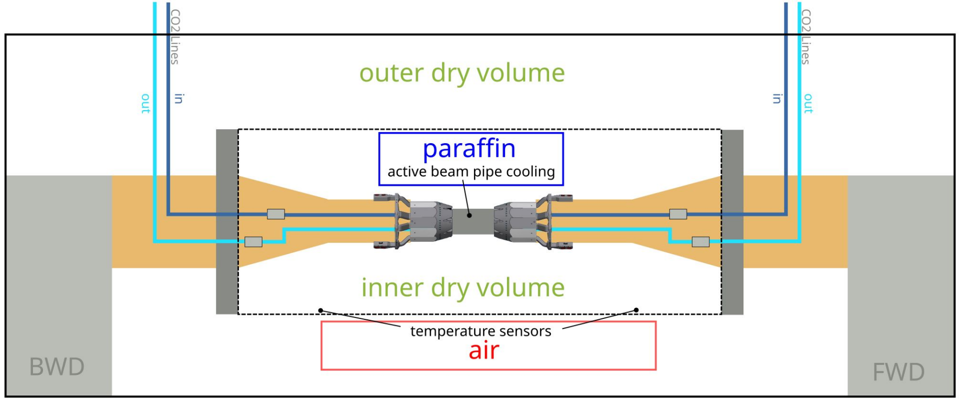


AIRTEMPERATURE INNER DRY VOLUME

PXD1 COOLING PARAMETERS

C02 : -20°C
N2 : 28l/min

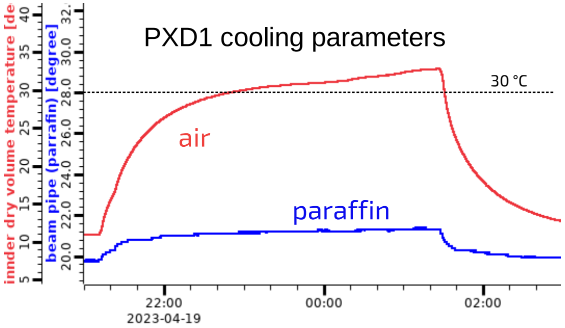
- Inner dry volume exceeded 30 °C
- No saturation observed → stopped
- Elevated temperatures and mechanical stress can be problematic for ladder glue joint

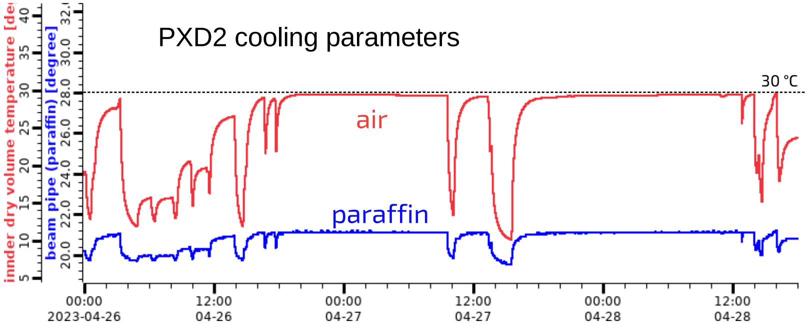


PXD2 COOLING PARAMETERS

C02 : -25°C
N2 : 32l/min

- ~20h permanent operation
- Air temp. saturated at 29 °C
- Paraffin (beam pipe) temp. stable at 21 °C

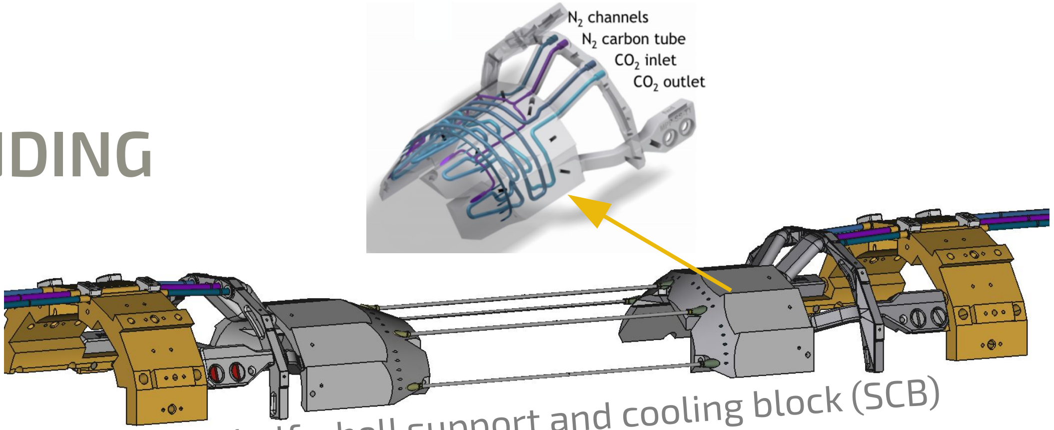




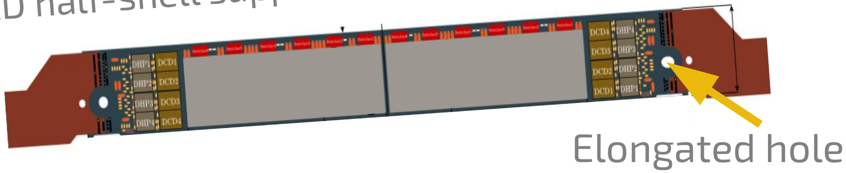
LADDER BENDING

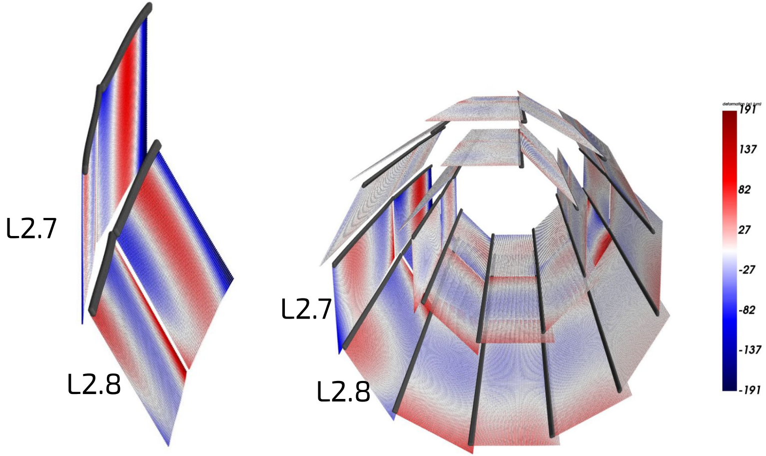
COOLING PROPERTIES

- Power consumption ~9W per module
  → 360 W for full detector
  - 2-phase CO_2 for DHP/DCD (8W)
  - N_2 gas for sensor + switchers (1W)



PXD half-shell support and cooling block (SCB)





- Thermal stress should be prevented by ladder gliding
- Problem of unsatisfactory gliding known from commissioning
- Dedicated bending study: ladder & glue joint still intact even after 90k cycles with sagitta ≥1mm (up to 2mm)
- **BUT** : If L2.7 turned off, could potentially touch L2.8

  → Implementation of interlock condition to prevent this condition

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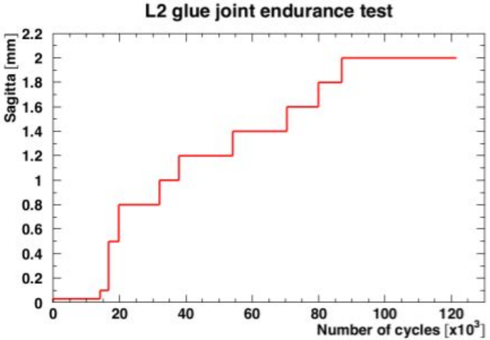
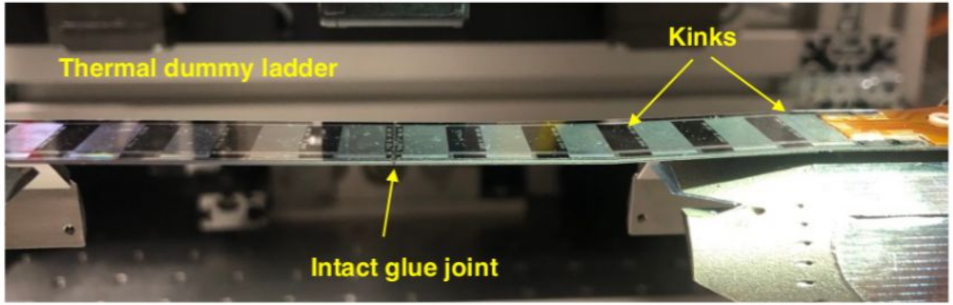
LADDER BENDING STUDIES AT DESY

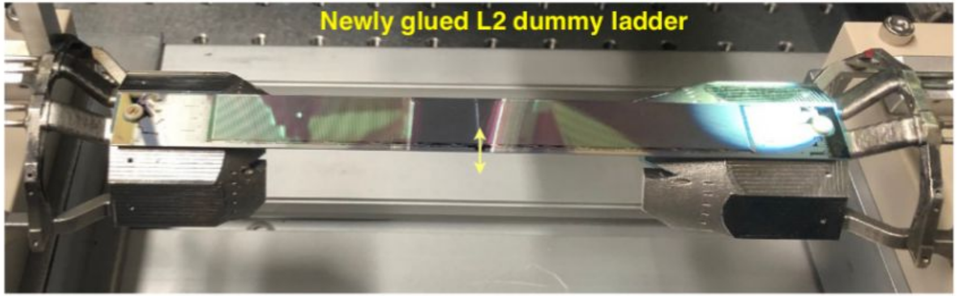
Thermal dummy L2 ladder bent with gradually increasing sagitta

- $\sim$ 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

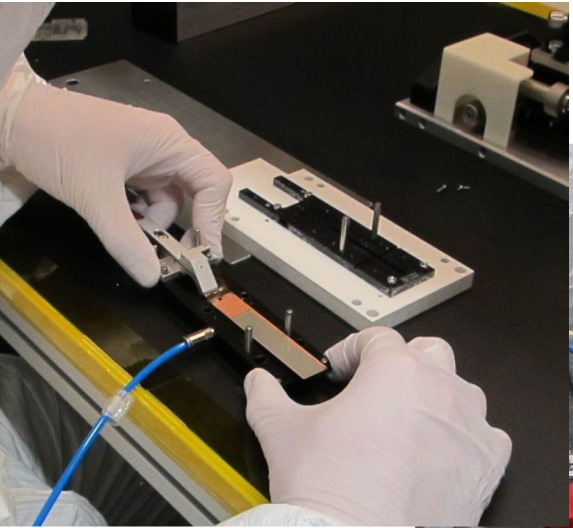


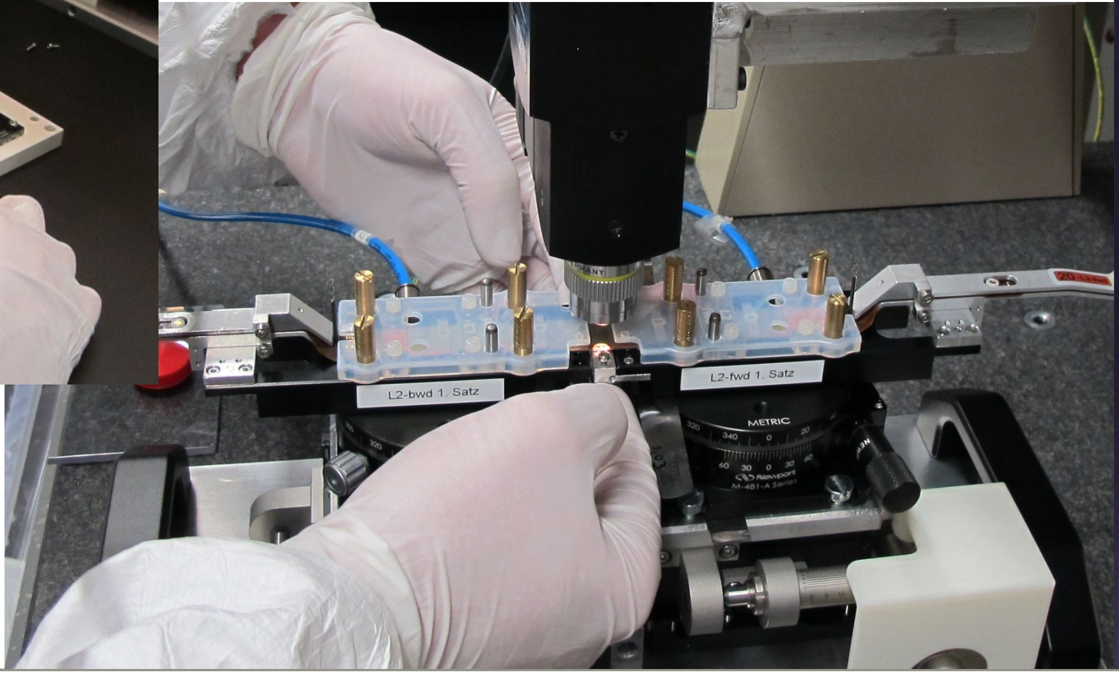




After more than two months with more than 90k cycles with sagitta $>$1mm $\rightarrow$ Ladder still intact

HANDLING, LADDER ALIGNMENT & GLUING





TRACKING AT BELLE II

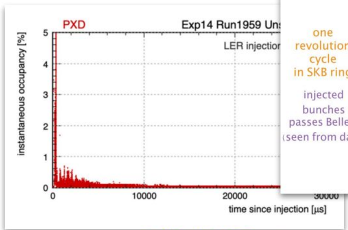
Tracking at SuperKEKB

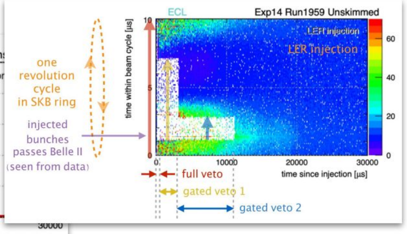
Challenges

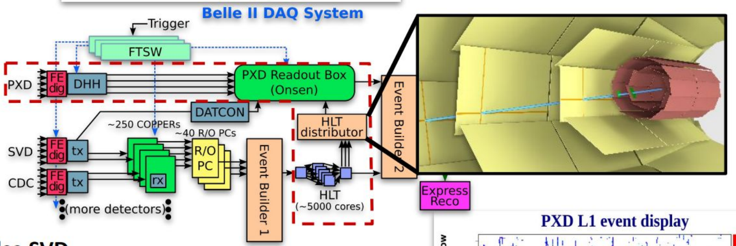
- **increased backgrounds** with instantaneous lumi
  - beam lifetime only few minutes
    ⇒ continuous “top up” injection (for 2400 bunches)
    (50 Hz @ 4 ms cooldown ⇒ 4 ms damping time with particle losses)
  - “Synchrotron”, “Touschek intra-bunch scattering”, “Bhabha”, “2 photon”…
  - challenge 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

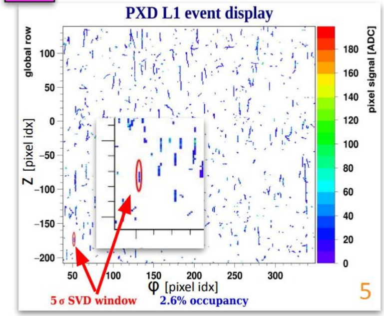
Track reconstruction and PXD role

- (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*









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