Operation Experience of the DEPFET based Pixel Vertex Detector of the Belle II Experiment

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Björn Spruck on behalf of the Belle II PXD Collaboration

Belle II

JENNIFER2
EU grant n.822070

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

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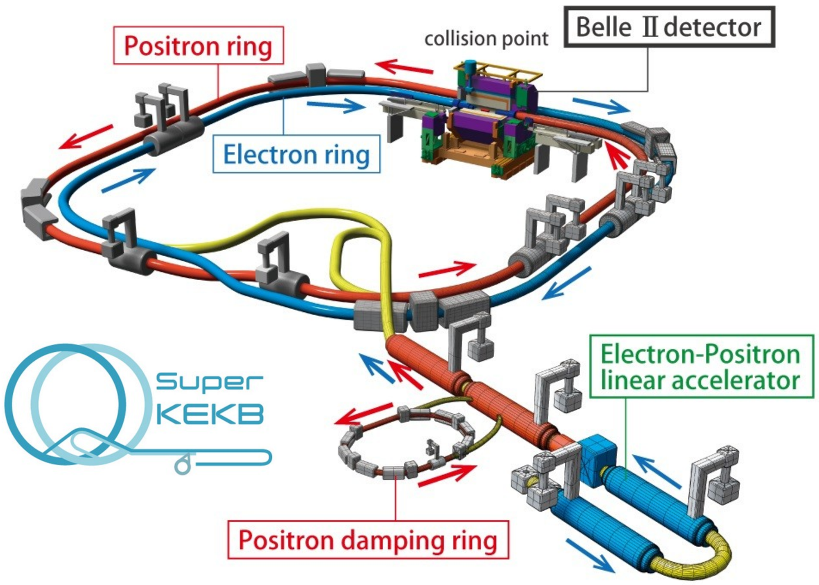
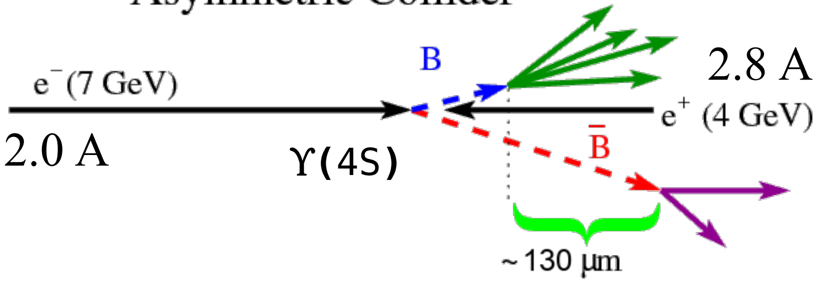
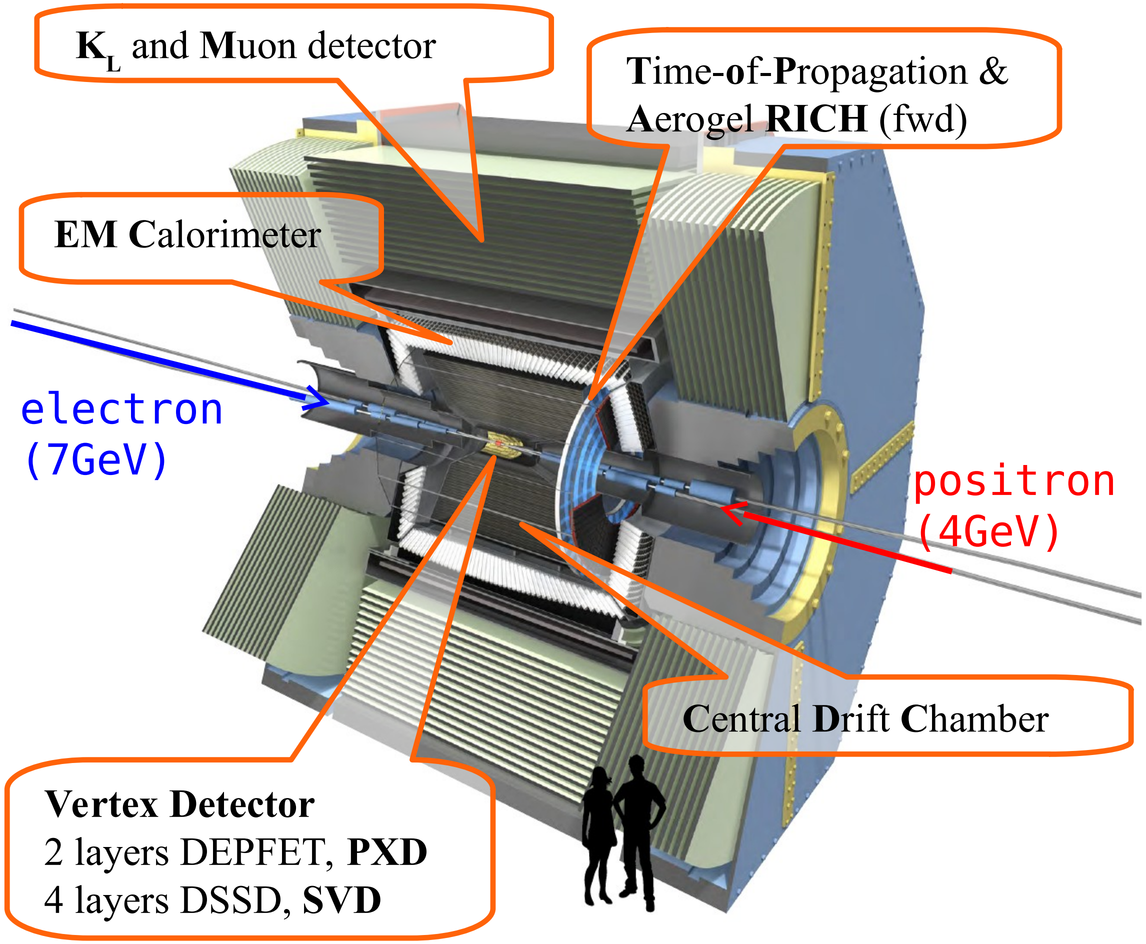
DEPFET
Active Pixel Detector

Belle II @ SuperKEKB



Asymmetric Collider





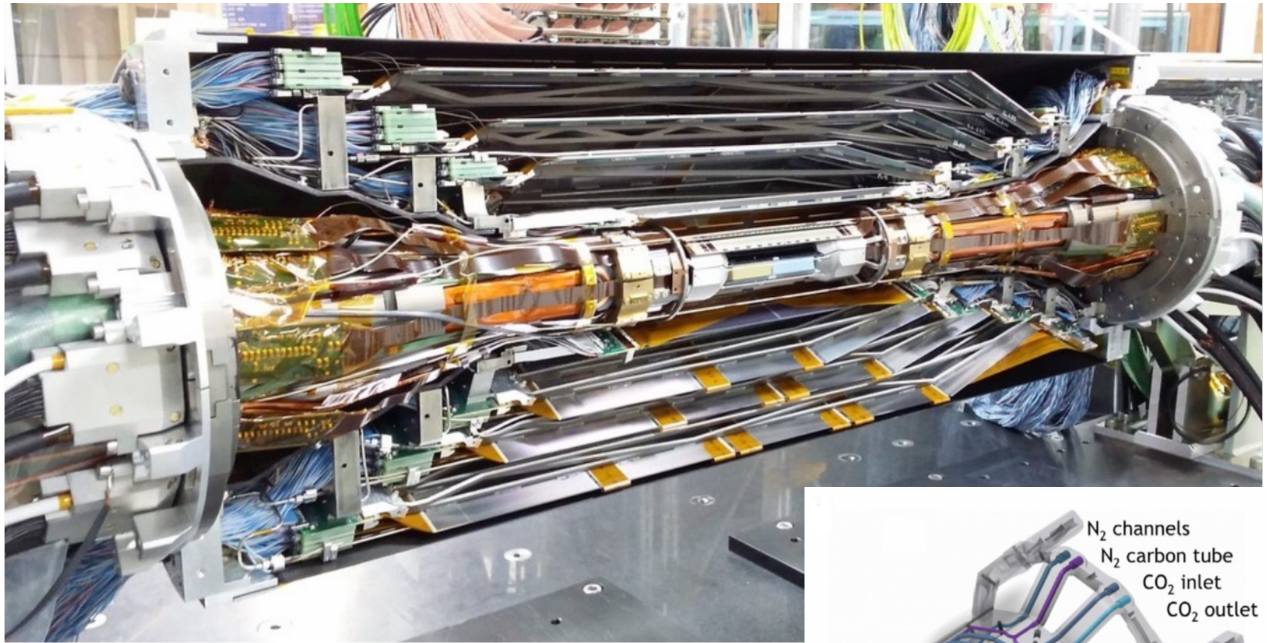
- B factory: $E_{cm} = M_{\Upsilon(4S)} \approx 10.58$ GeV
- Goal: $L = 6 \cdot 10^{35}\ cm^{-2}\ s^{-1}$
- Record by now: $3.8 \cdot 10^{34}\ cm^{-2}\ s^{-1}$
- Target: $L_{int} = 50\ ab^{-1}$

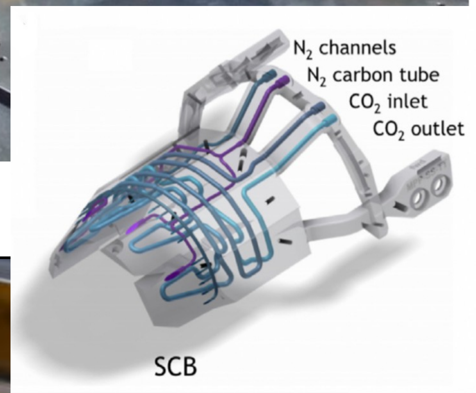
- Maximum trigger rate 30 kHz
- Less boost than KEKB/Belle, need ~2 times better vertex detector resolution

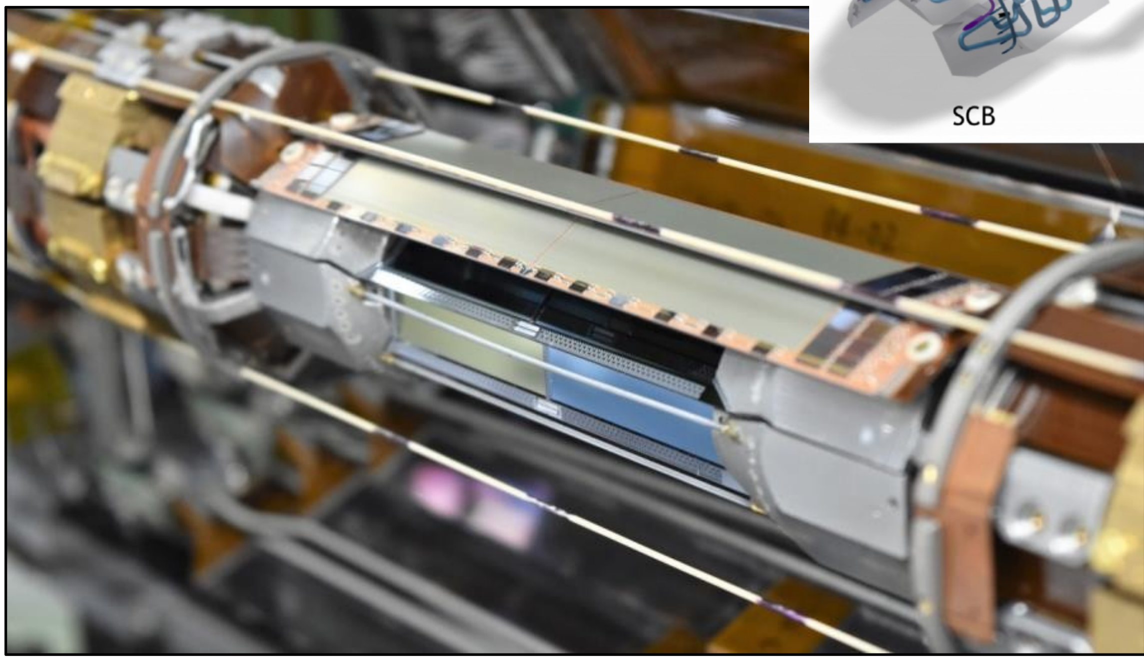
Physics data taking with full detector started 2019

Belle II Vertex Detectors

- Requirements:
  - Excellent vertexing and tracking down to low p_T (<100 MeV/c)
  - Very low material budget
  - Inner layer only 14mm away from interaction point
  - Impact parameter resolution $\sigma_z < 20\mu m$
  - Operate in high background environment
  - Trigger rate 30 kHz
- Pixel Vertex Detector (PXD)
  - 2 layers
  - DEPFET Pixel
- Silicon Vertex Detector (SVD)
  - 4 layers
  - 2-sided silicon strips
  - Covered by next speaker
- Shared 2-phase CO_2 cooling system

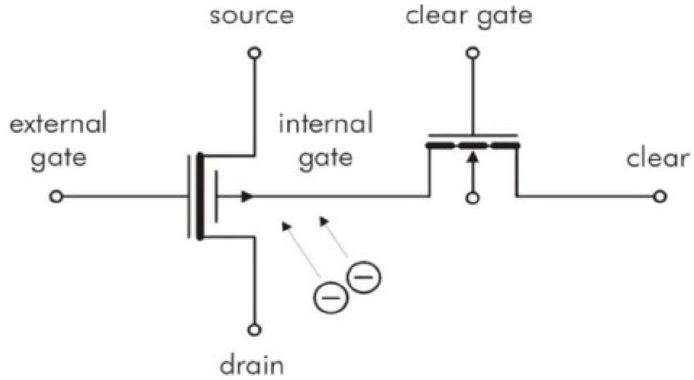




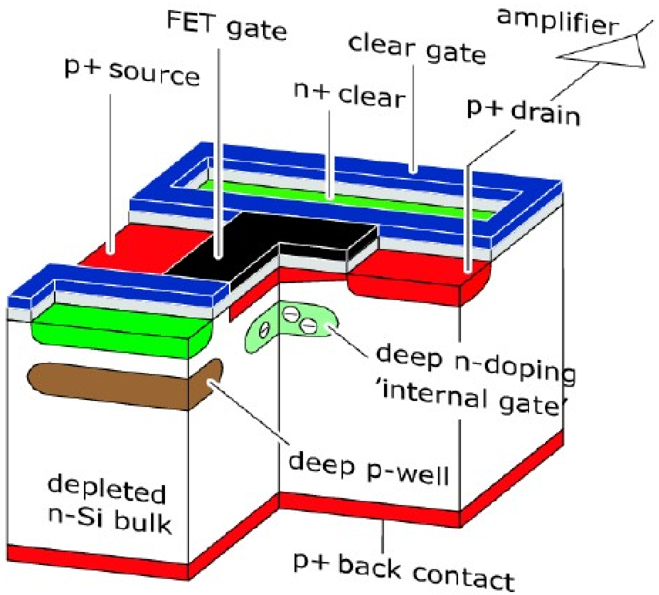


PXD Sensors Working Principle

- Depleted P-channel Field Effect Transistor (DEPFET) active pixels on fully depleted silicon bulk
- Fast charge collection (~ns) into internal gate
  - Non-destructive read-out, read-out current modulated by collected charge
  - Clear after read-out
- Internal amplification, large signal-to-noise ratio
- Low power consumption and heat dissipation
- Radiation hard
- 75µm thin sensors

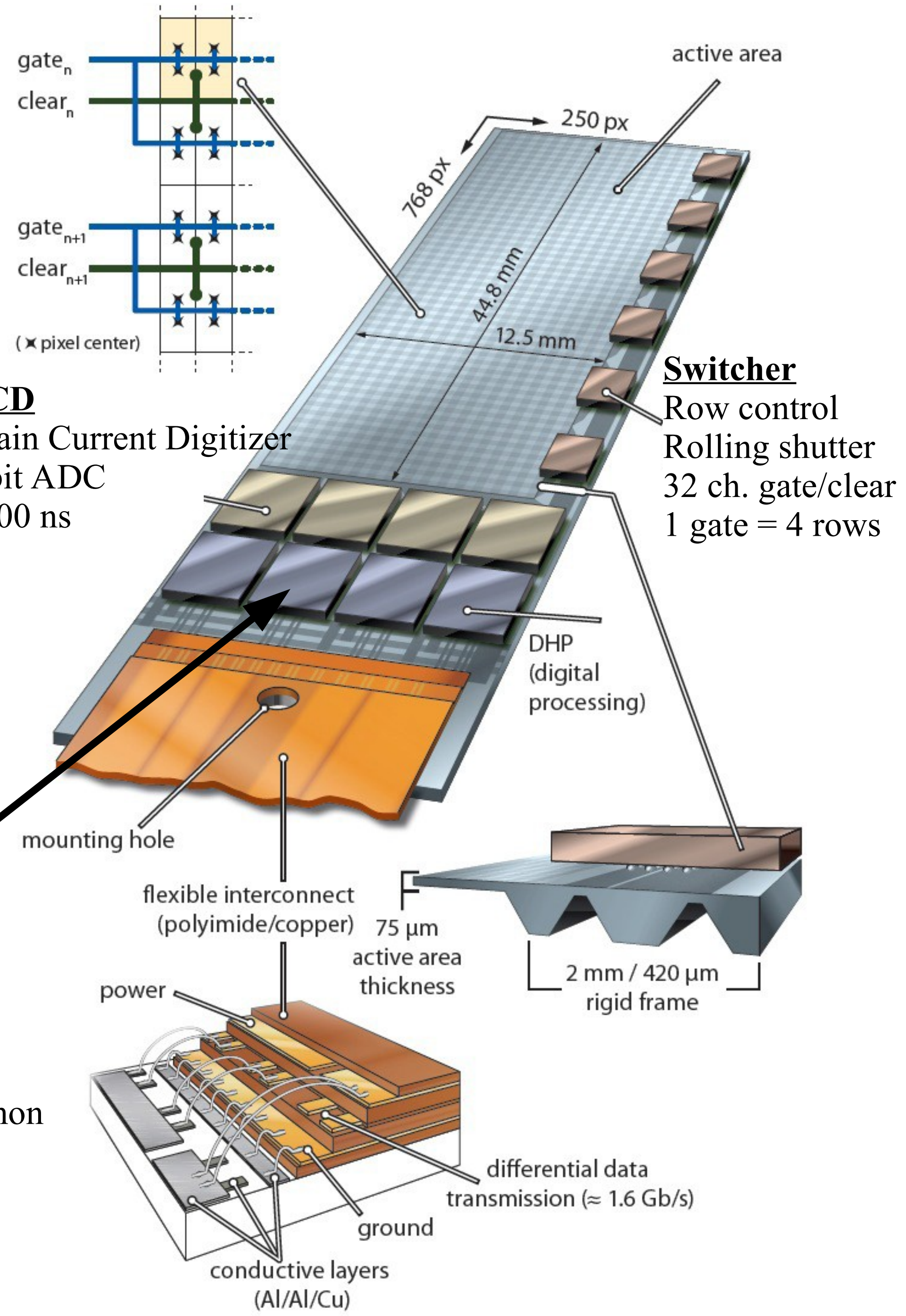


$$g_q = \frac{\partial I}{\partial q} \approx 500 \frac{pA}{e^-}$$



PXD Sensor Modules

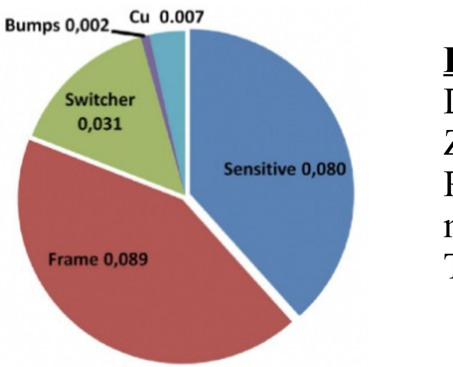
- Sensors thinned to 75µm in active region
  - Mechanically self supporting due to rigid frame
- Pixel sizes: 50x(55 – 85)μm^2
- Rolling shutter read-out → low power
  - 50kHz → 20 µs integration time
  - 192 gates, ~100ns per gate
- Design: 1% occupancy in layer 1
  - 3% occupancy limit (DHP, DAQ, tracking)
- 40 sensors, 250x768 pixels each = ~8 Mpixel
  - 2 sensor modules glued to one ladder
- Cooling:
  - 2-phase CO_2 cooling for ASICs at the end of stave.
  - N_2 gas for sensor and switchers.
- Radiation hard sensor and ASICs up to expected experiment lifetime



DCD
Drain Current Digitizer
8 bit ADC
~100 ns

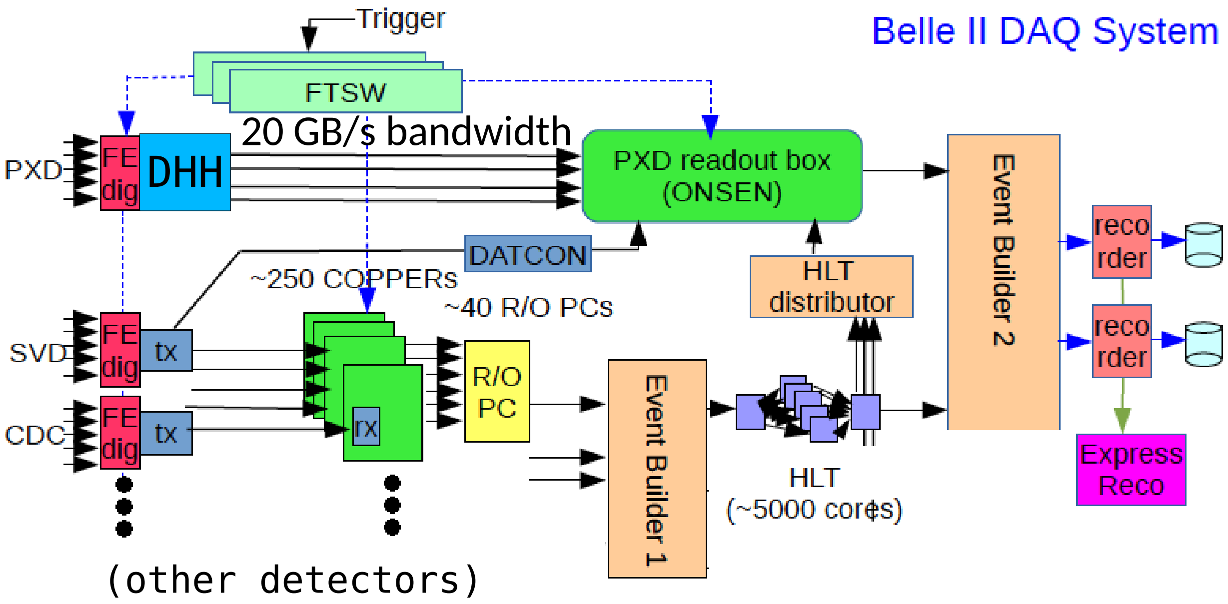
Switcher
Row control
Rolling shutter
32 ch. gate/clear
1 gate = 4 rows

DHP
Digital processing
Zero suppression
Pedestal and common mode correction
Trigger and timing

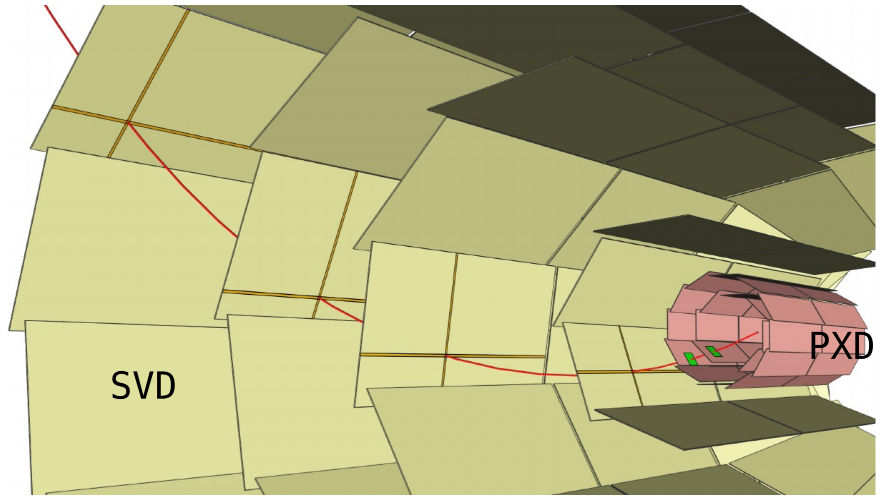


~0.21% X0 / layer material budget.

PXD DAQ Scheme

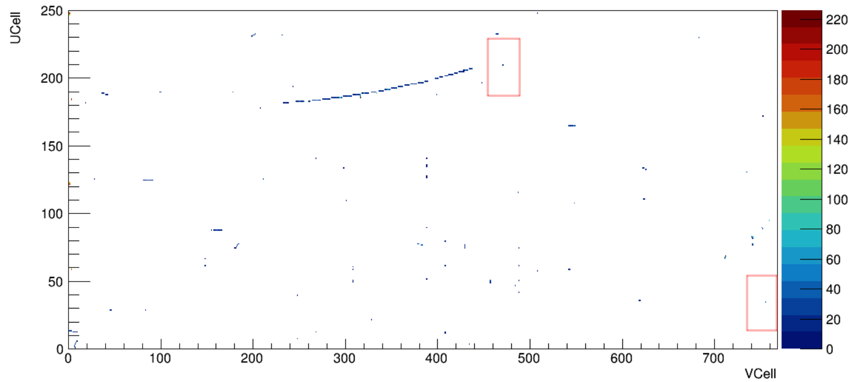


ROI extrapolation on HLT



- PXD unfiltered data rate → 10x that of other Belle II detectors at design luminosity
  - Dominated by beam and physics background
  - Separate readout path
  - Remove data not belonging to a track
  - Data reduction to 1/10 by High Level Trigger (HLT) based “Region Of Interest” calculation from CDC and SVD track information
  - Feedback to PXD readout: selection of pixels within rectangular ROIs and drop full events rejected by HLT
  - Currently not in use as overall data rate low enough

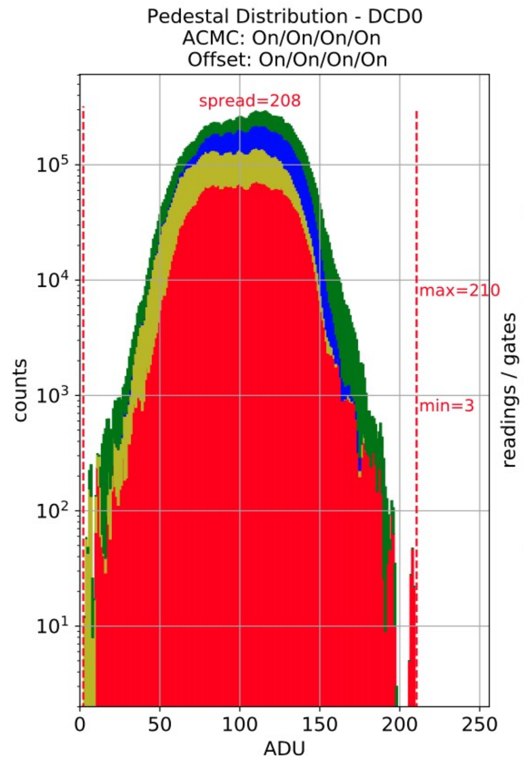
Hitmap of one sensor with ROIs

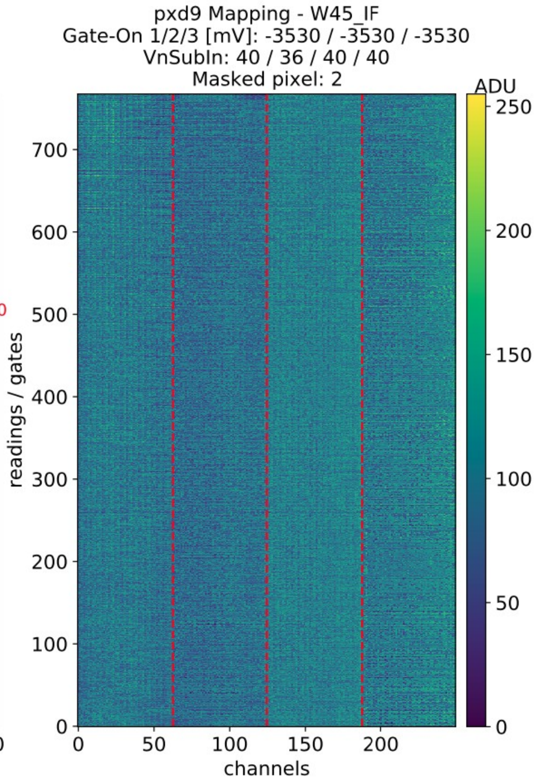


Beam axis

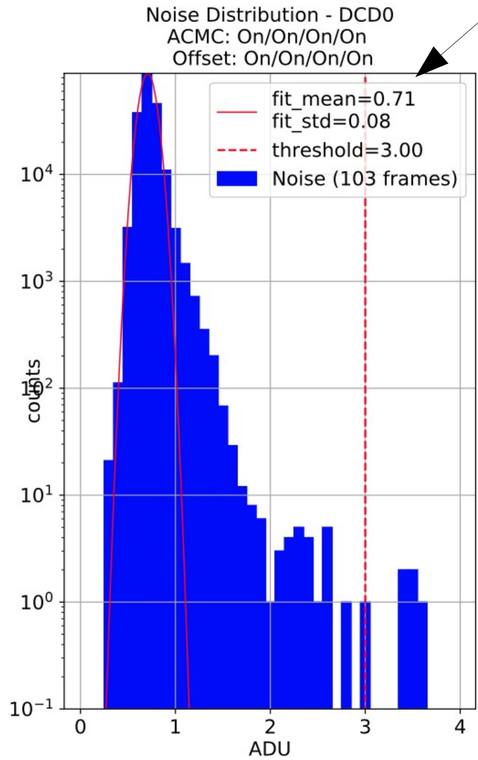
PXD Calibration and Optimization

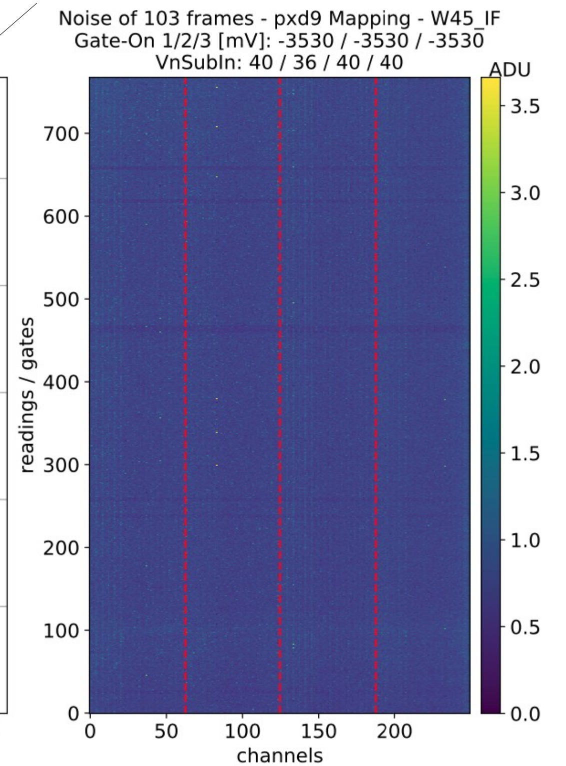
- Modules characterized before installation – working point shifting due to irradiation
- Signal on top of pixel dependent pedestals
- Analog Common Mode Correction
- Switchable currents at input of Drain Current Digitizer used to compress spread of drain currents from sensor
- Narrow and stable pedestals
- Low noise (<1ADU, <200e ENC)



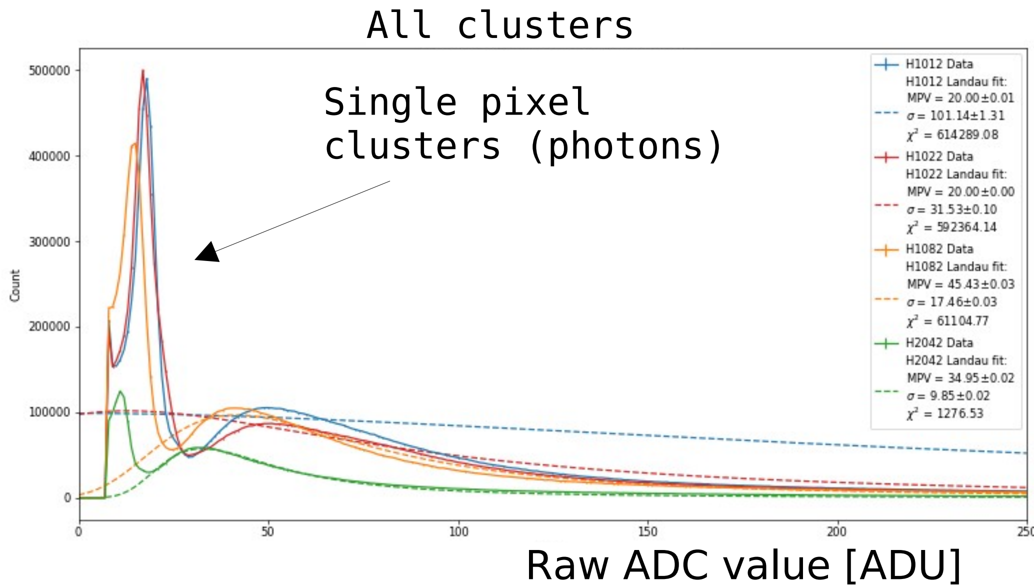


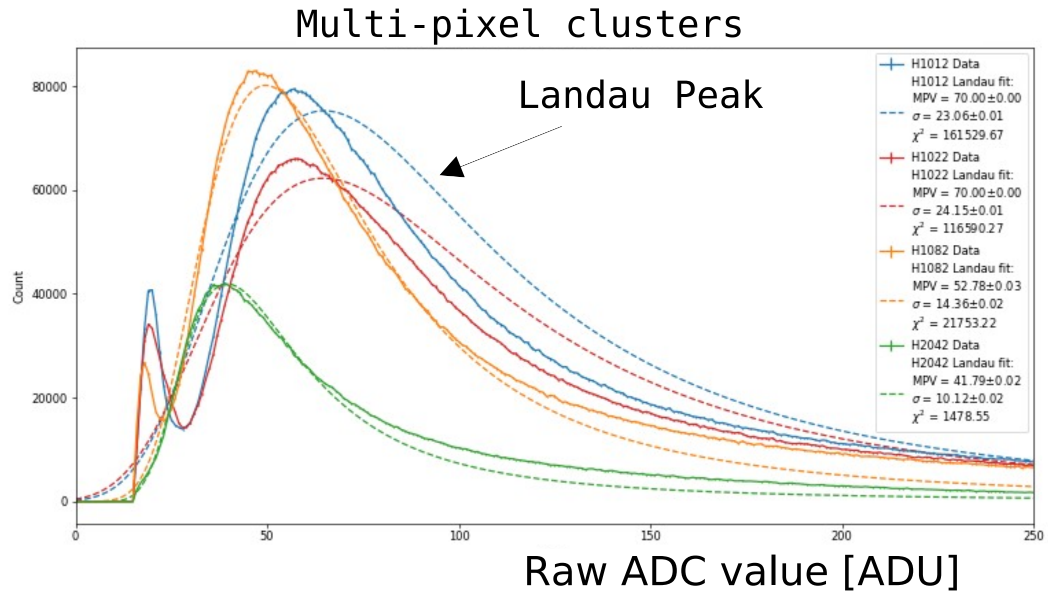
Noise of 0.7 ADU



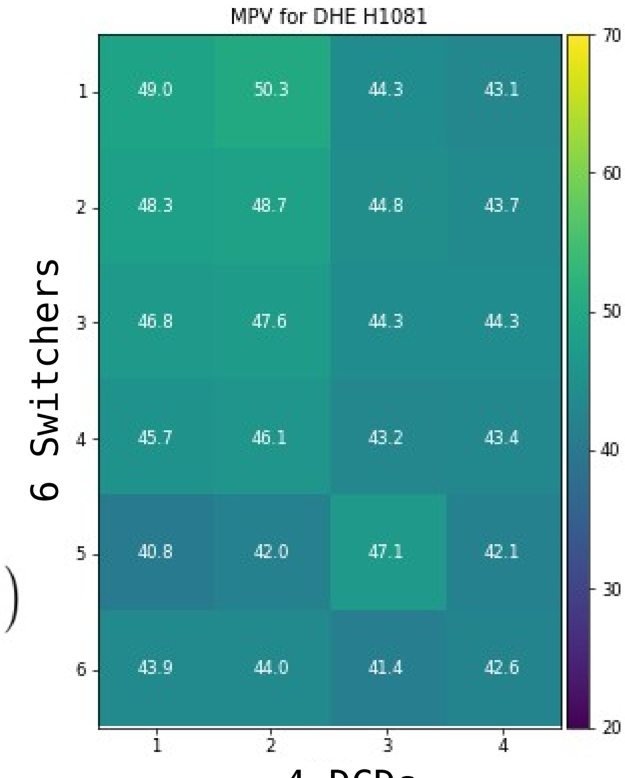


Gain Uniformity





- Most probable values of cluster charge rather uniform over all 24 ASIC combinations within one module
- Signal to Noise Ratio ~30 to 50 (module dependent)
- → Uniform gain over module area can be achieved
- Adjustment of Gate on/off voltages needed to compensate for FET threshold shift

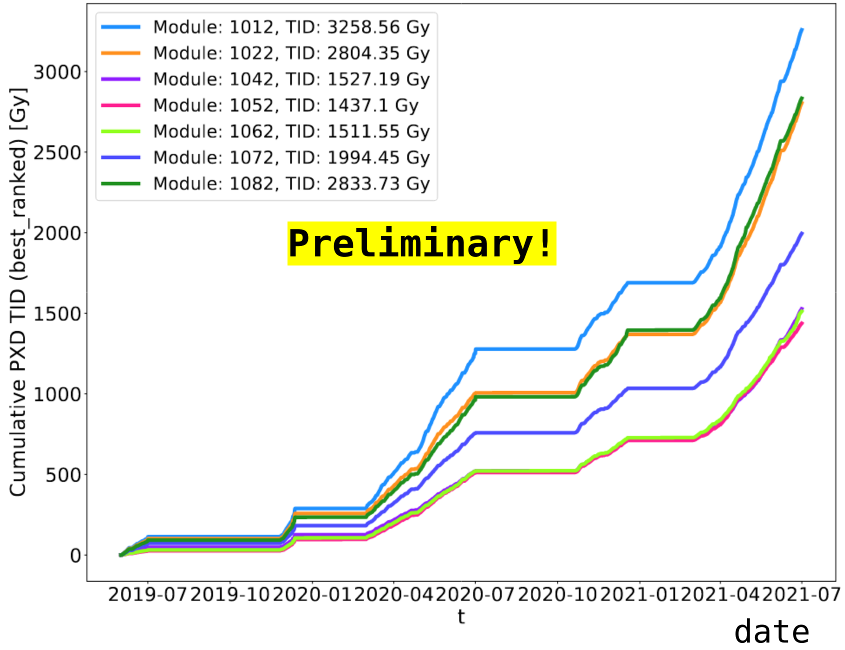


$$MPV \sim g_q \sim \sqrt{I_D} \sim \left(U_{Gate} - U_{Threshold}\right)$$

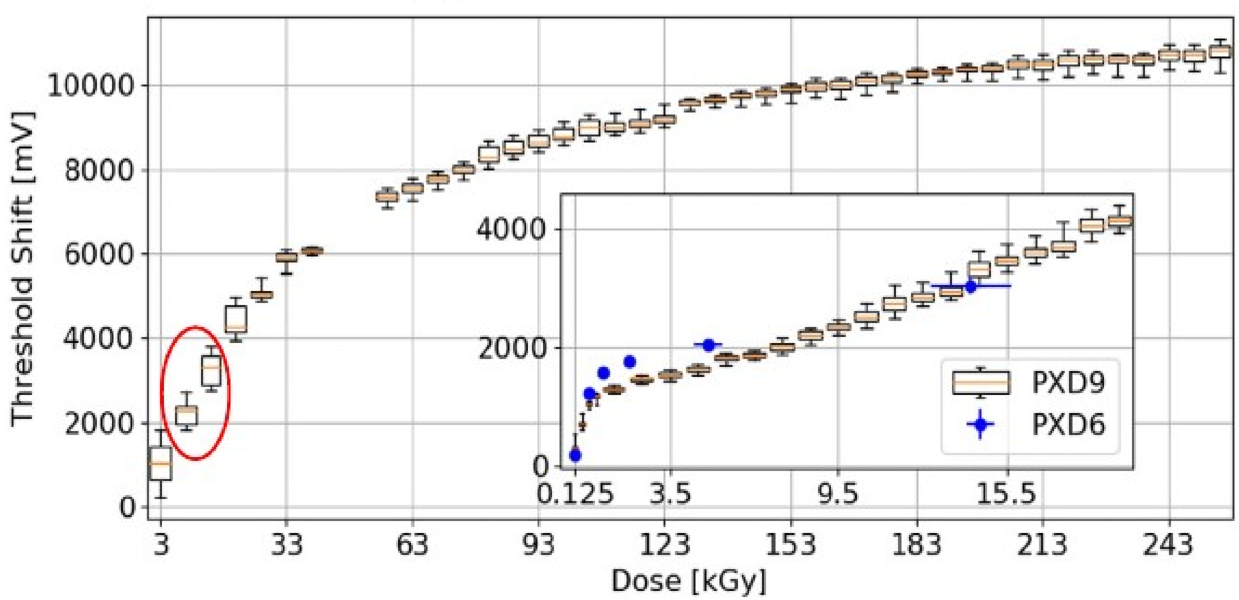
Sensitive to radiation damage (TID)

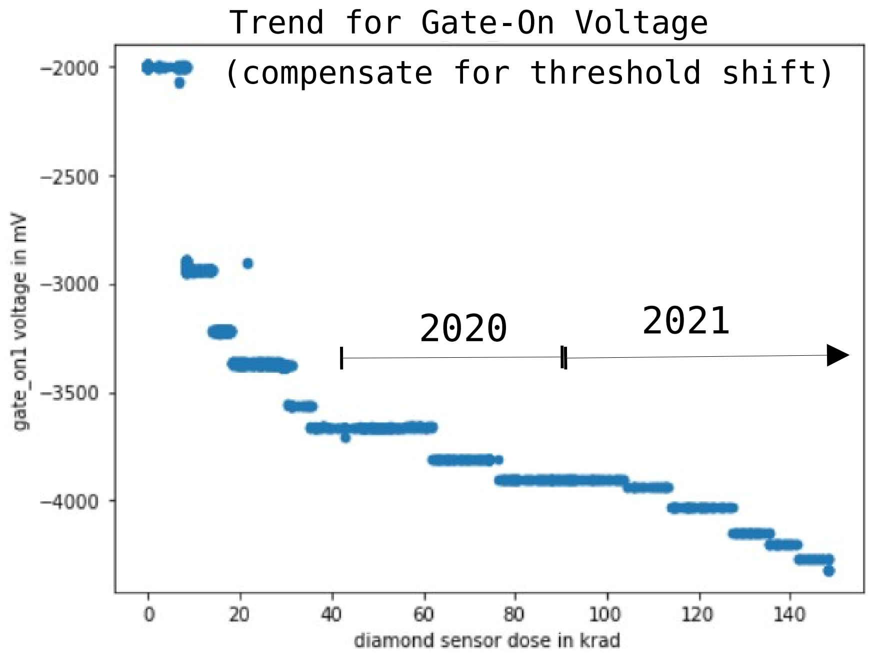
Radiation Effects

- Expected: threshold voltage shift
  - → need gate-on/off adjustment
- Slight increase of ASIC currents (expected)
- Emerging problem:
  - Pixel shift out of dynamic ADC range
  - → need (better) offset calibration/correction
  - Several (19) SEU induced bit-flips in ASICs triple redundant configuration registers observed in 2020/21, may increase with higher luminosity
- Dose determination per module in progress
  - Variation between modules (phi dependence)



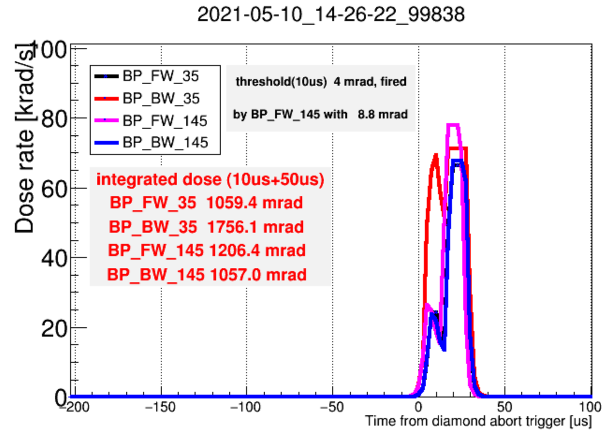
https://doi.org/10.1016/j.nima.2020.163522



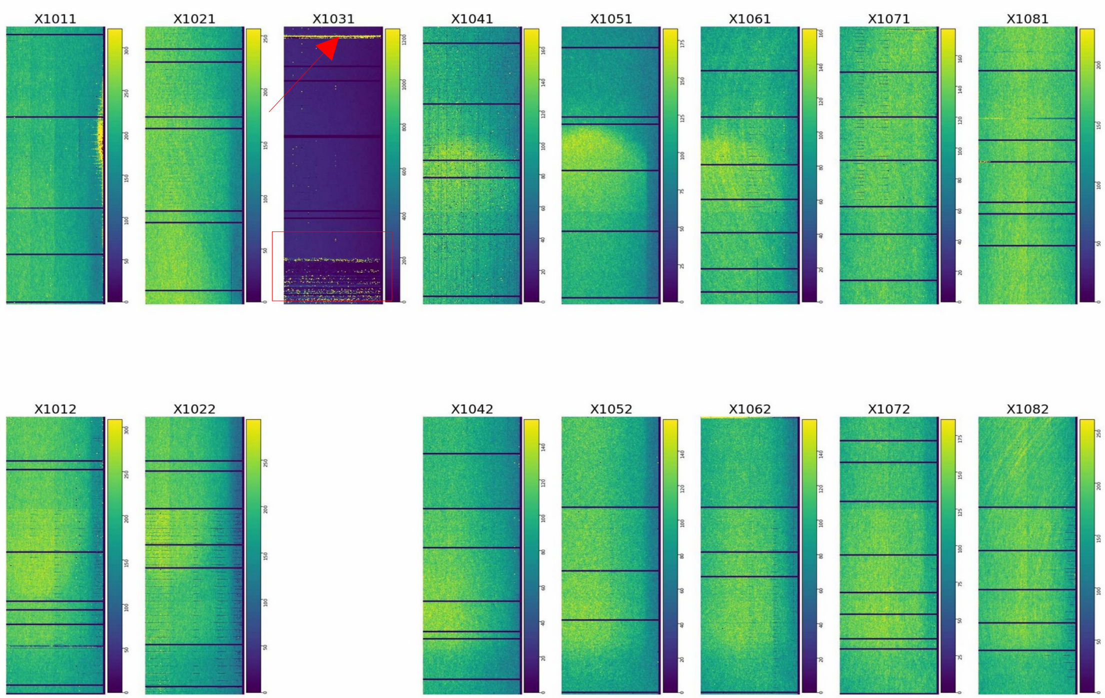


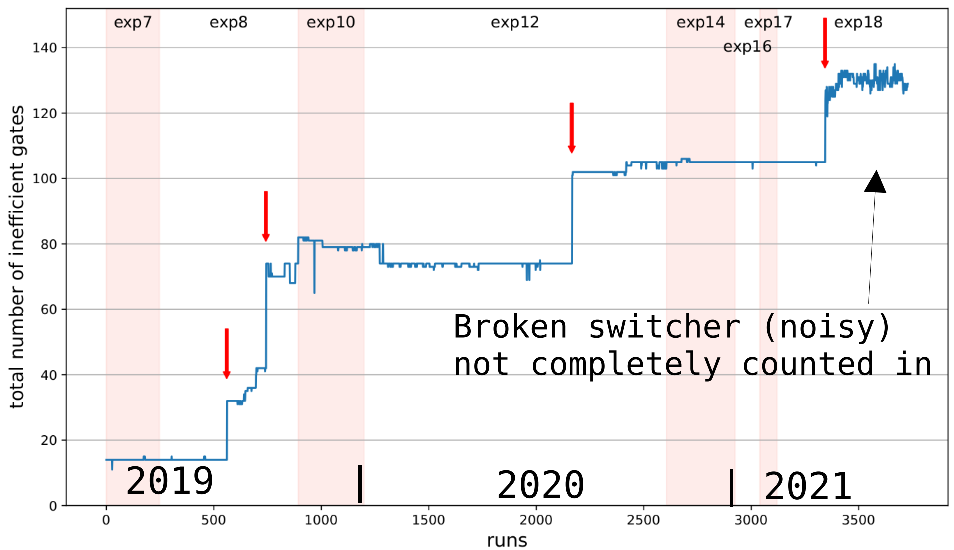
Damages by Beam Losses

- Uncontrolled beam losses in 2019 – 2021 resulted in severe detector degradation (dead/noisy gates, broken Switcher ASICs).
  - Broken gates lead to unstable behavior (pedestals, noise, occupancy)
  - Confirmed in irradiation tests that huge instant radiation dose can damage the Switcher output
- Dangerous for accelerator (damaged collimators)
- Improvements on beam abort (faster, more sensors)
- PXD emergency off triggered by additional sensors on the beam pipes
  - Ongoing work to make emergency off fast enough to prevent damage to ASICs
    - Clear on/off voltages shut down within O(100us)



Inner layer hit map

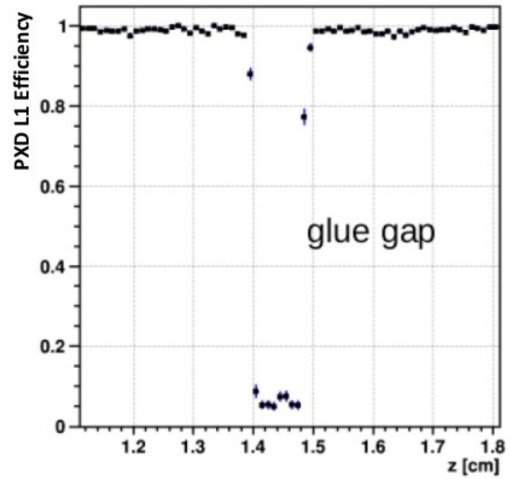


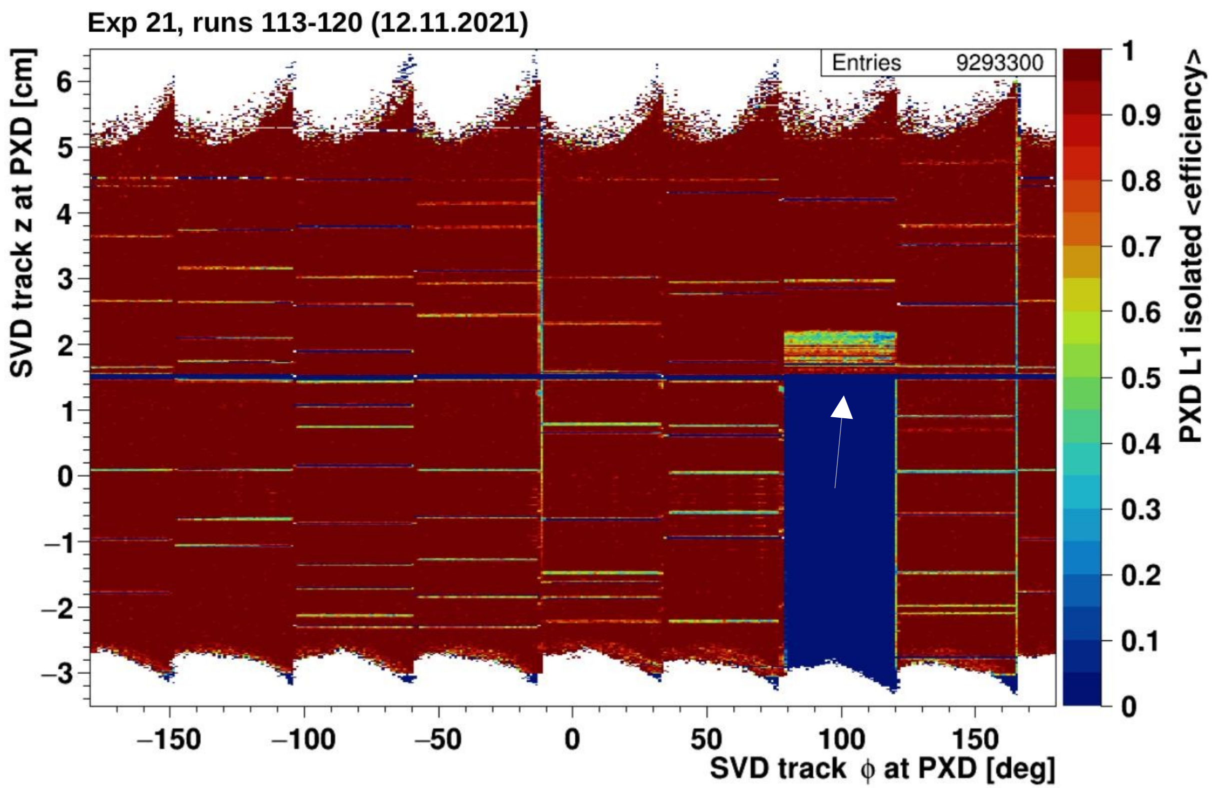


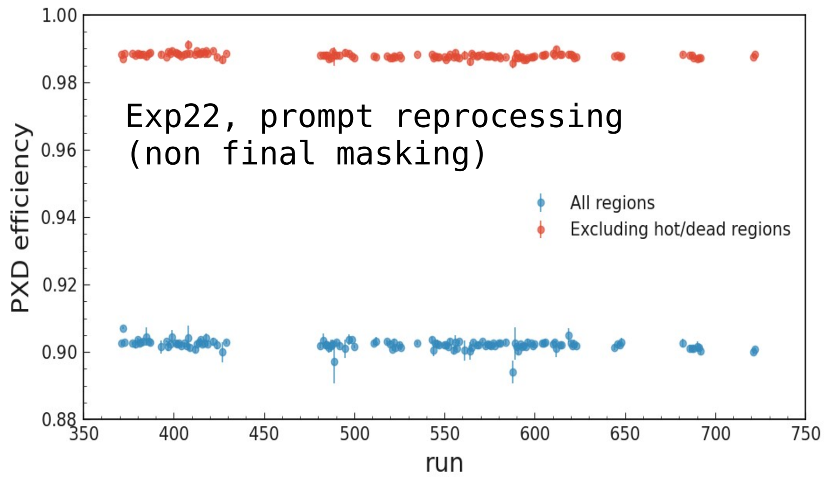
Detector Efficiency

$$\epsilon = \frac{\text{nr of tracks with hit near track intercept}}{\text{nr of good track intercepting a module}}$$

- Defined by hit clusters found close to track intercepting points in modules.
  - Influenced by tracking quality and alignment.
  - Different approaches (e.g. online/offline) with different cuts (p_T) and event samples. Take only tracks with good tracking
  - Bad switcher channels (4 rows each) degrade overall hit efficiency by ~3% (good regions ~ 98% hit efficiency).
- One partly broken/noisy switcher originating from a beam loss event
- Module 1.03.2 was broken from beginning but covered by layer 2 module.
- Glue joint and gap between half-shells

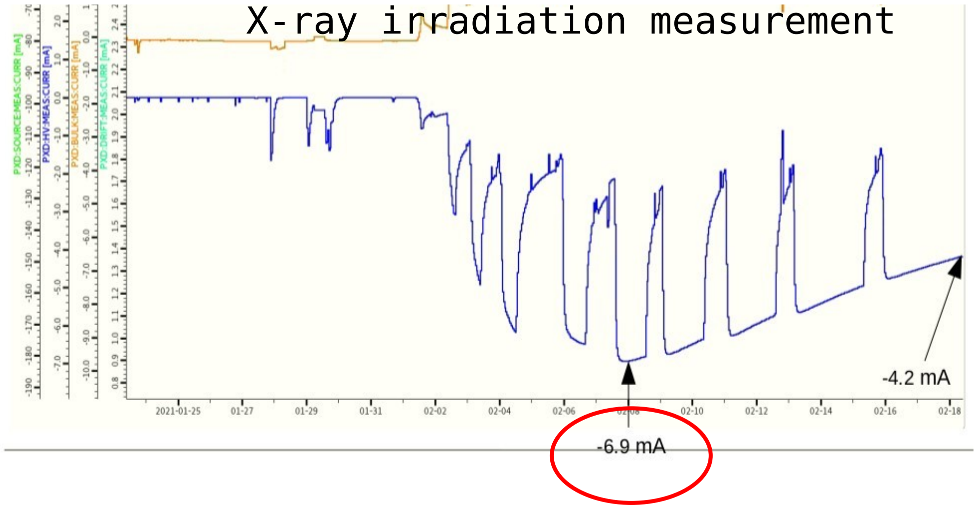


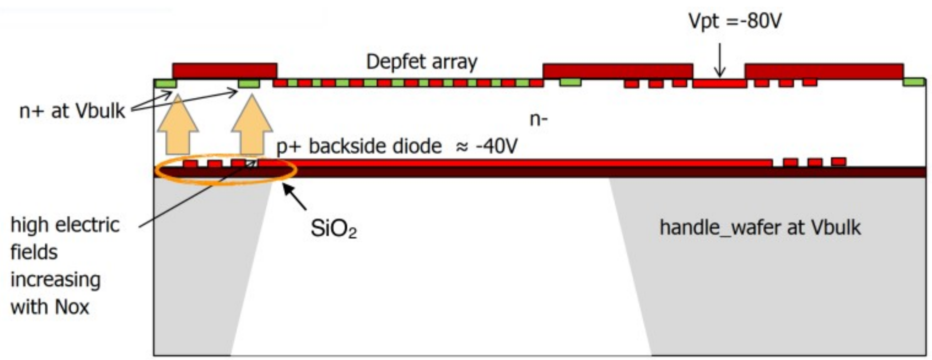




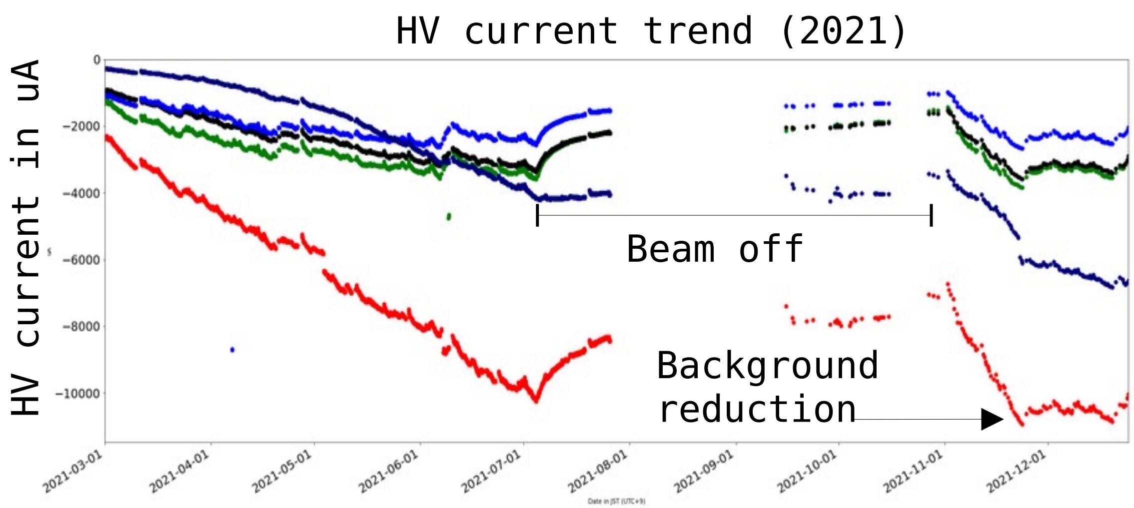
High Voltage Currents

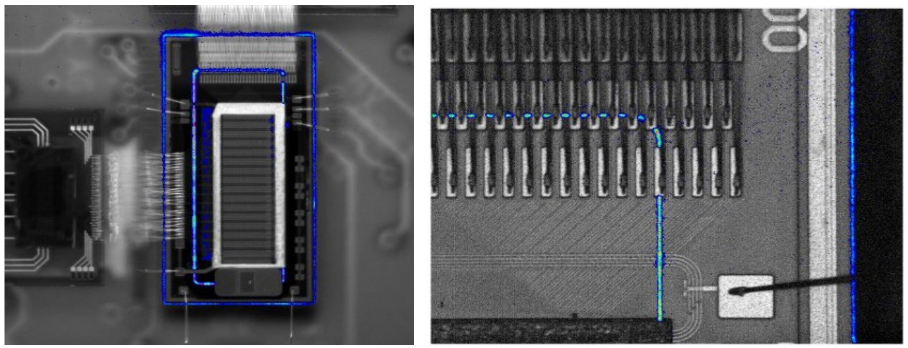
- Irradiation led to unexpected large currents in HV channel (60V – 75V), module dependent
- Saturation expected from irradiation campaign
- Suspected mechanism from simulation: avalanche generation at innermost backside guard ring (next to diode backside implant)
- Optical measurement on irradiated mini-matrix: avalanche appears to be at outermost guard ring
  - Reason not full understood, dedicated test structures prepared for more detailed studies





Cross section of sensor

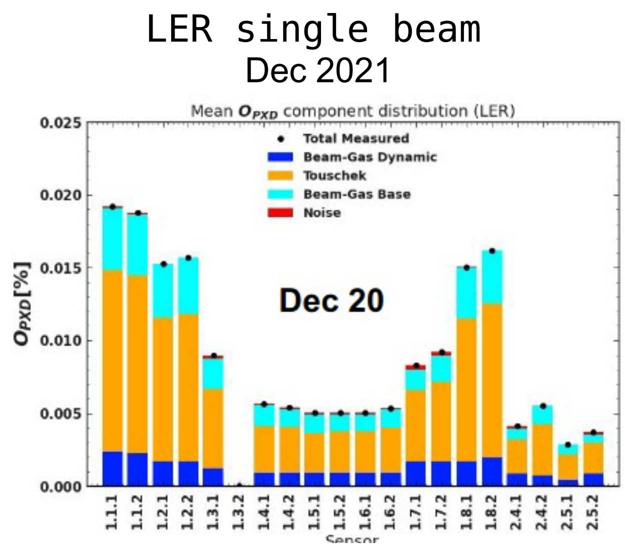


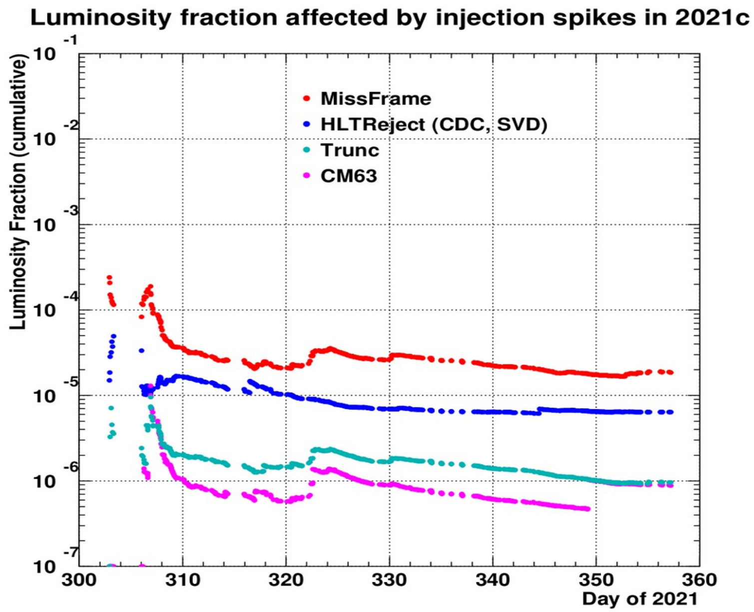


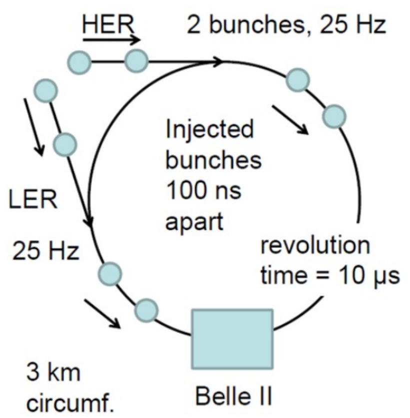
Phemos image of a test module

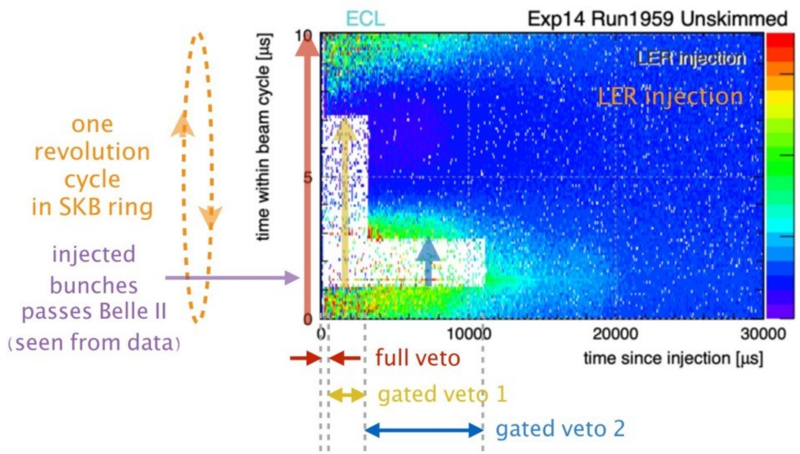
Injection Backgrounds

- Storage beam background (Touchek, Beam-gas, 2-photon) no issue and well understood
- Both rings filled by continuous (top-up) injection, max 50 Hz
  - Compensate short beam life time
- Large background during injection (noisy bunch), damping takes several ms
- Belle II Trigger Veto (=no readout)
  - Full veto during injection (1-2 ms) and then gated veto for ~10 ms each time the bunch passes by (~2 µs)
  - Gated veto not helpful for PXD (integrates 20µs)
- PXD readout affected due to instant high occupancy
  - No issue for DAQ stability, only small fraction of events are truncated
- Possible to blind PXD while keeping stored charges (Gated Mode)
  - But: Gated Mode would result in extra noise and efficiency loss
  - To be balanced vs simple veto (Belle II or PXD internally)





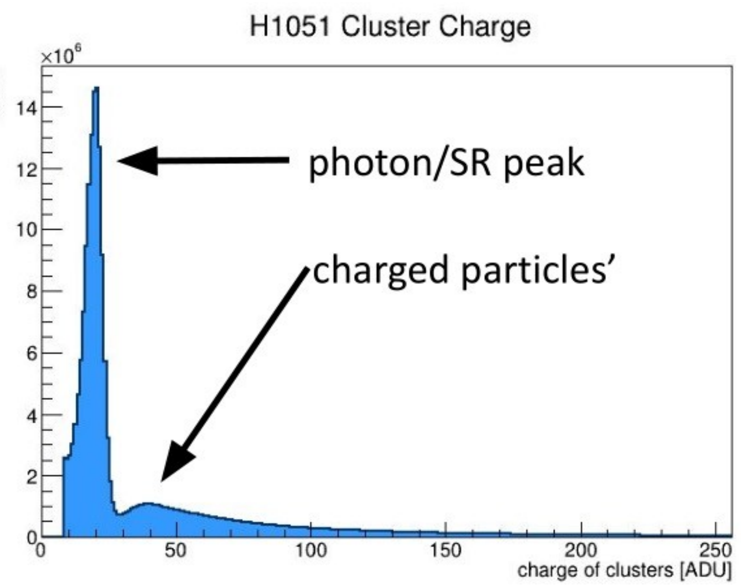


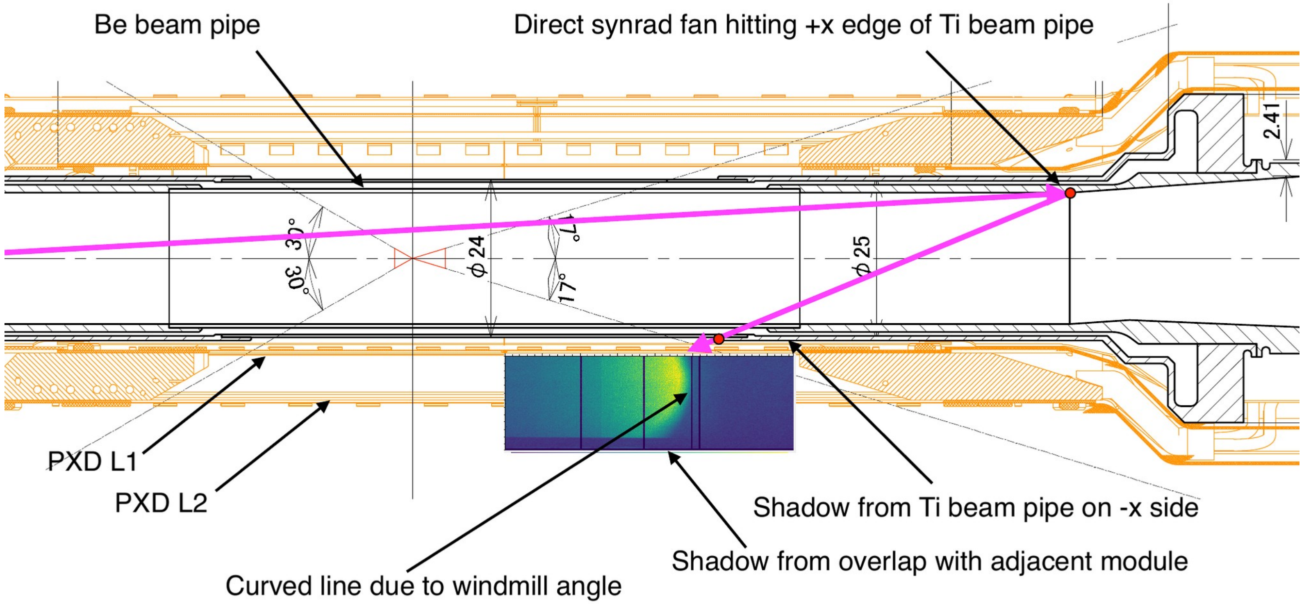


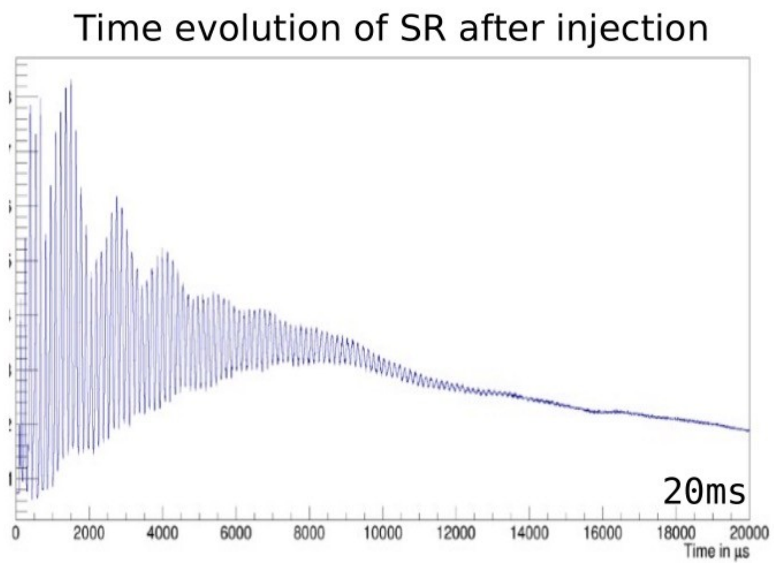
Rolling shutter! Integrated over 20 µs.

Synchrotron Radiation

- Large photon background was observed in -X modules
- IR designed such that no direct SR photons hit the central Be beam pipe
  - Secondary photons, diffuse scattering!
  - Single pixels, low energy
  - Problem: High local hit density
    - Inhomogeneous irradiation
    - Deterioration of clustering and tracking
- Mitigation:
  - HER beam orbit tuning (rotation)
  - New beam pipe design with additional plating (in production, install in 2023)





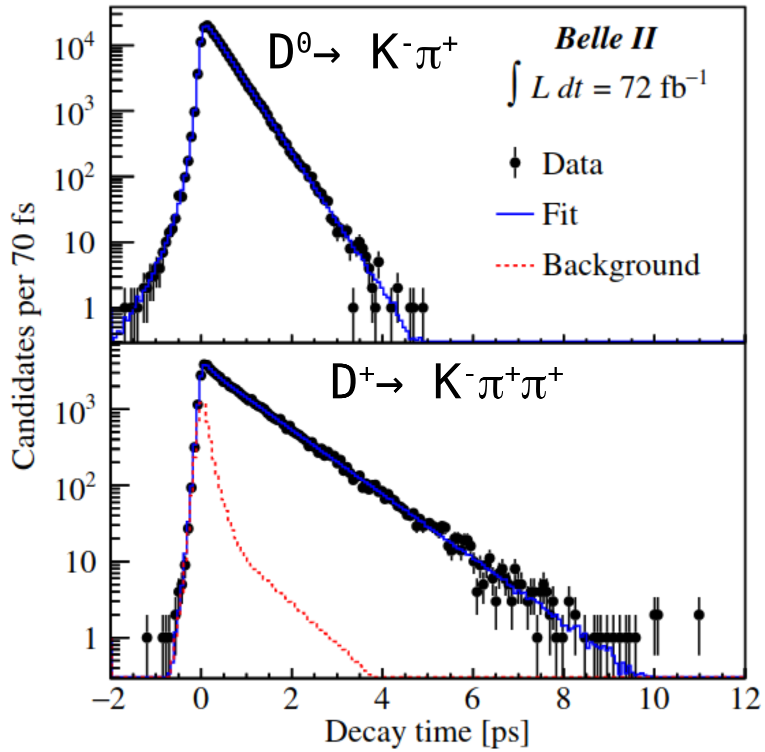


Vertex Resolution

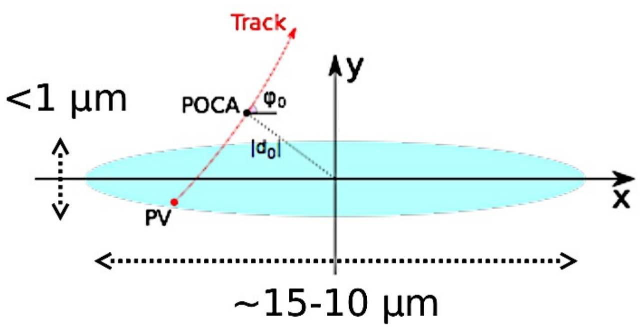
- Vertex reconstruction essential for time dependent CP violation and lifetime measurements
  - PXD and SVD play a key role
- Vertex resolution with PXD is close to MC expectations.
  - Measuring the point of closest approach from particles from the interaction point in x, y
  - Taking advantage of tiny interaction point
  - d_0 resolution of 13.64μm (data), 12.05μm (MC)
  - z_0 resolution of 14.92μm (data), 14.35μm (MC)

Belle II D^0, D^+ life time measurement already topped world average

DOI: 10.1103/PhysRevLett.127.211801

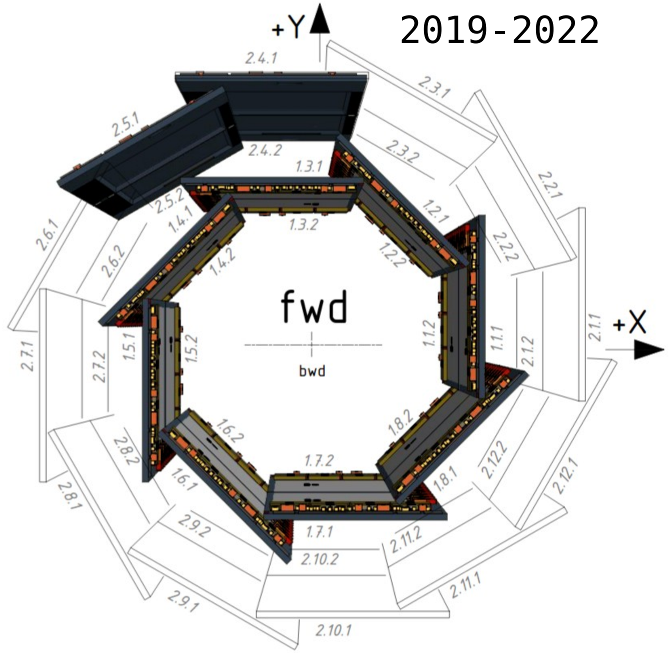


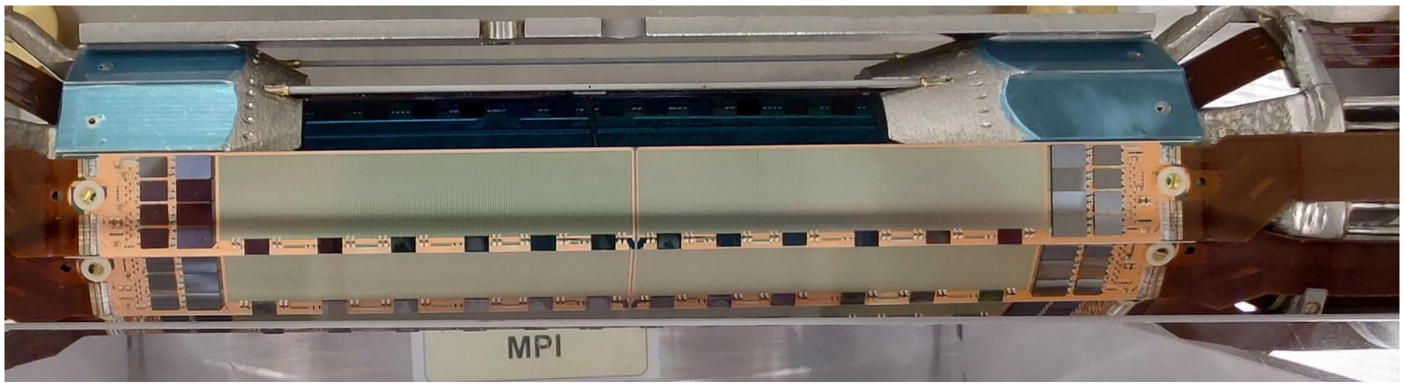
τ(D0) = 410.5 ± 1.1 (stat) ± 0.8 (syst) fs
τ(D+) = 1030.4 ± 4.7 (stat) ± 3.1 (syst) fs
World average:
τ(D0) = (410.1 ± 1.5) fs
τ(D+) = (1040 ± 7) fs



PXD Replacement

- Currently PXD has 8/8 inner and 2/12 outer ladders installed
  - Ladder assembly problems (low yield) in 2018
  - Outer layer important for higher luminosities and occupancies
- Full PXD will be installed in first long shutdown (July 2022-August 2023)
  - New beam pipe design (block synchrotron radiation)
  - Replace full PXD detector, not just add missing parts
- Production in final stage of module assembly





Summary

- Belle II first particle physics experiment to use a DEPFET pixel vertex detector
  - Nearly three years running, two under pandemic conditions
- Good performance demonstrated
  - High efficiency
  - Vertex resolution matches MC expectations → world leading D^0 and D^+ lifetime measurement
- DAQ / ROI data reduction concept proven
- Challenging operation close to IP in high radiation environment
- Suffering from damages due to radiation bursts from uncontrolled beam aborts
  - Understand and prevent damage by “beam incidents”
    - Add new collimators!
    - Faster detection → issue earlier beam abort and PXD emergency off
- Replace with a full detector in 2022/23

Thank you.