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

28th Vertex Conference, 13-18 October 2019

B. Spruck for the Belle II and DEPFET Collaborations

Belle II

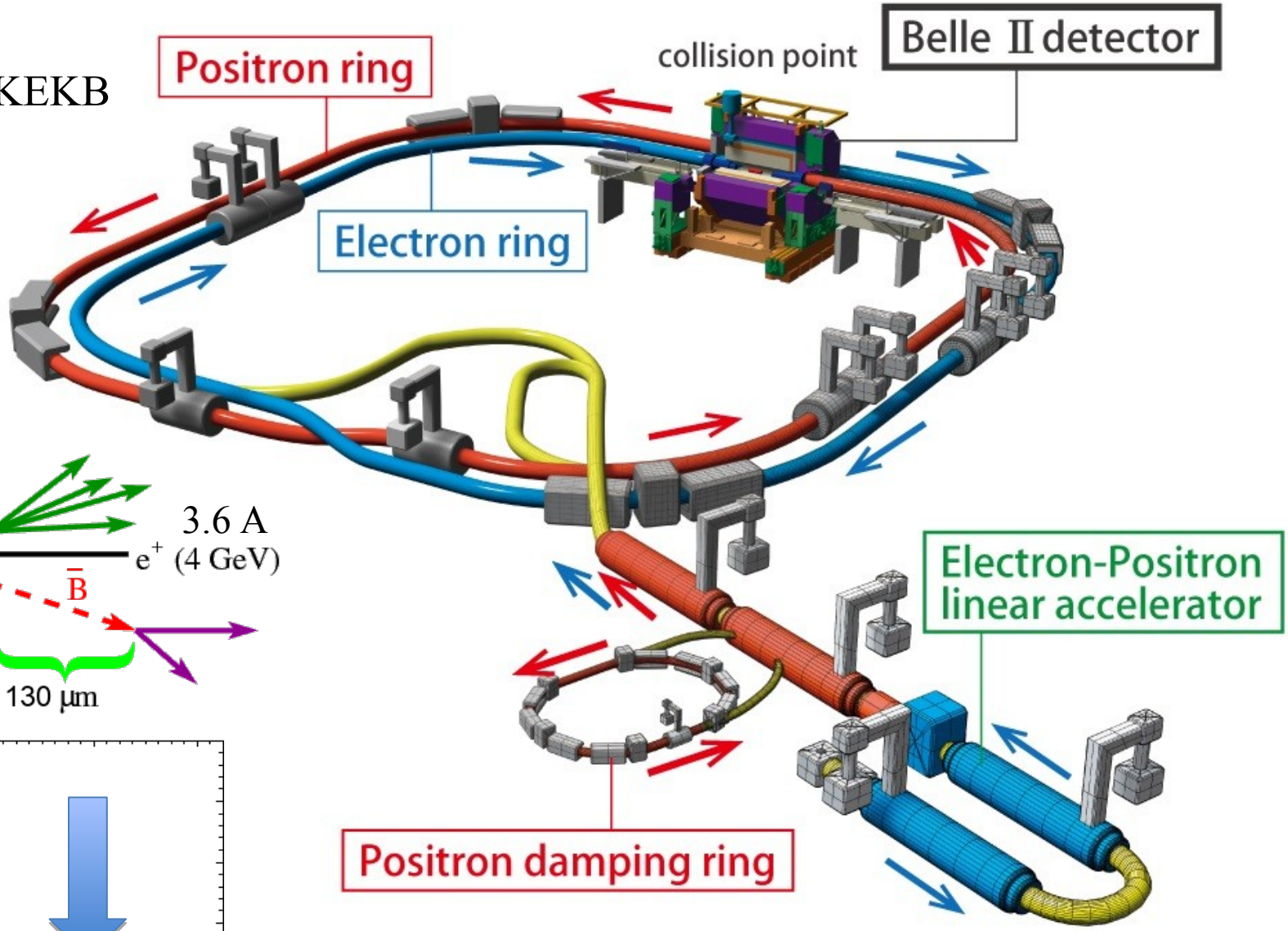
JENNIFER 2
EU grant n.822070

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

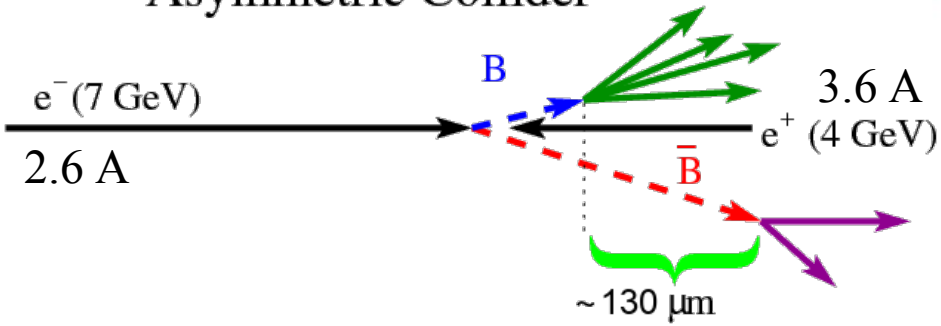
SPONSORED BY THE
Federal Ministry of Education and Research

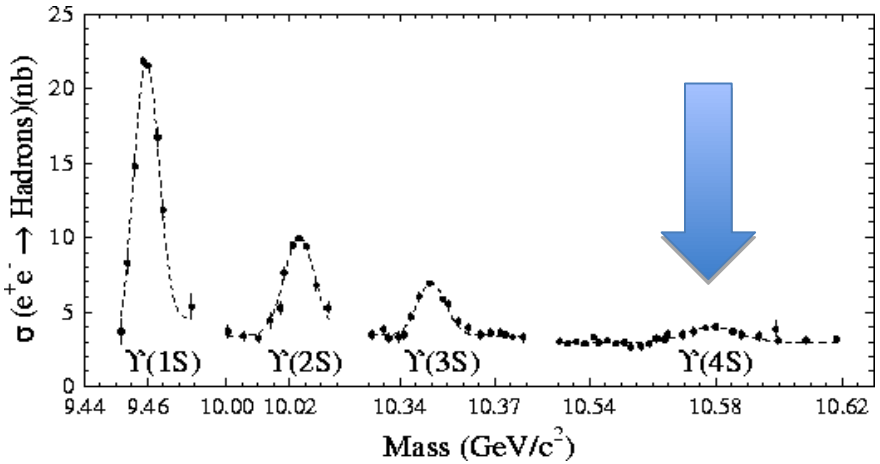
DEPFET
Active Pixel Detector

Goal: $L=8\cdot10^{35}cm^{-2}s^{-1}$
40 times the luminosity of KEKB

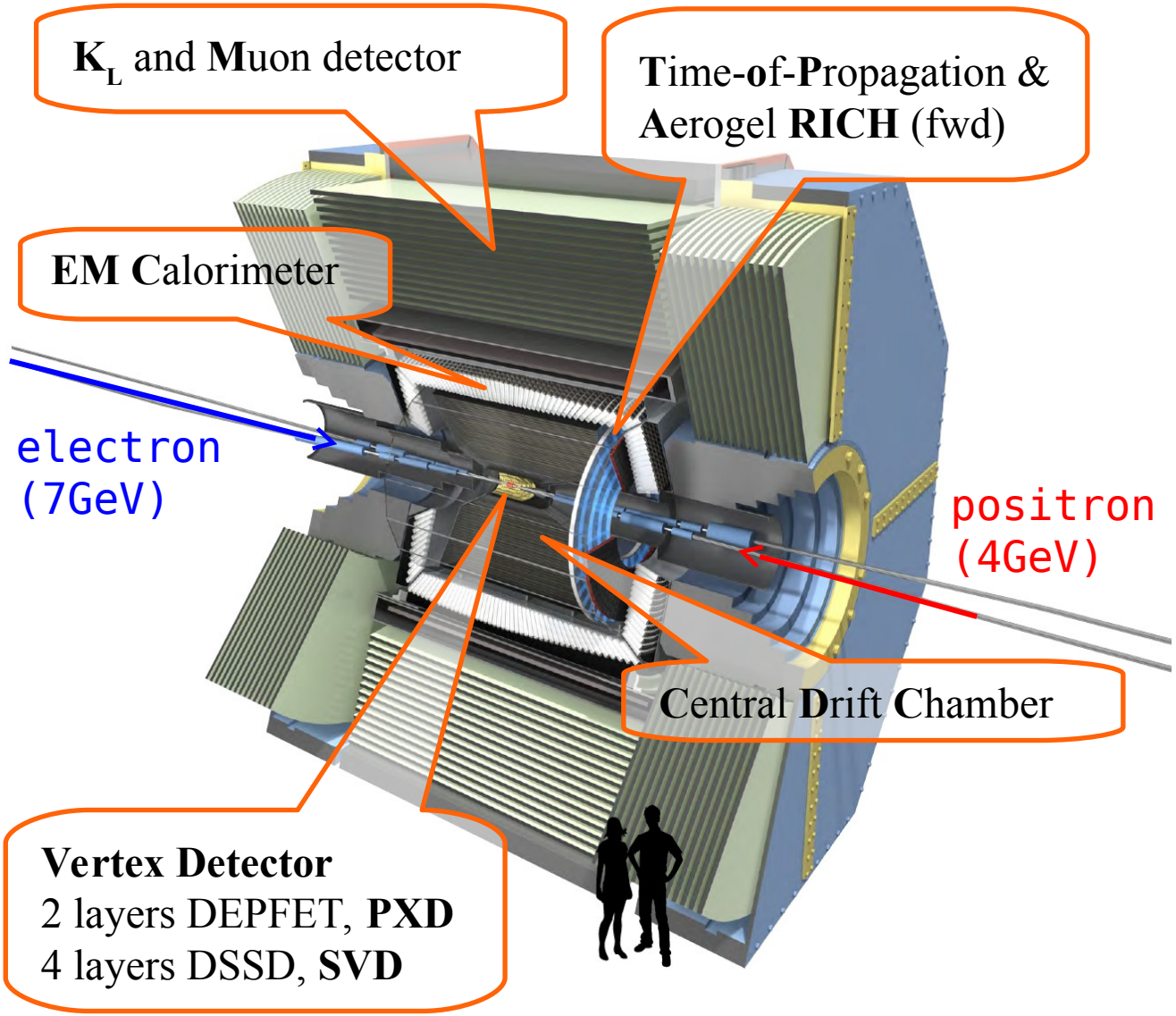


Asymmetric Collider

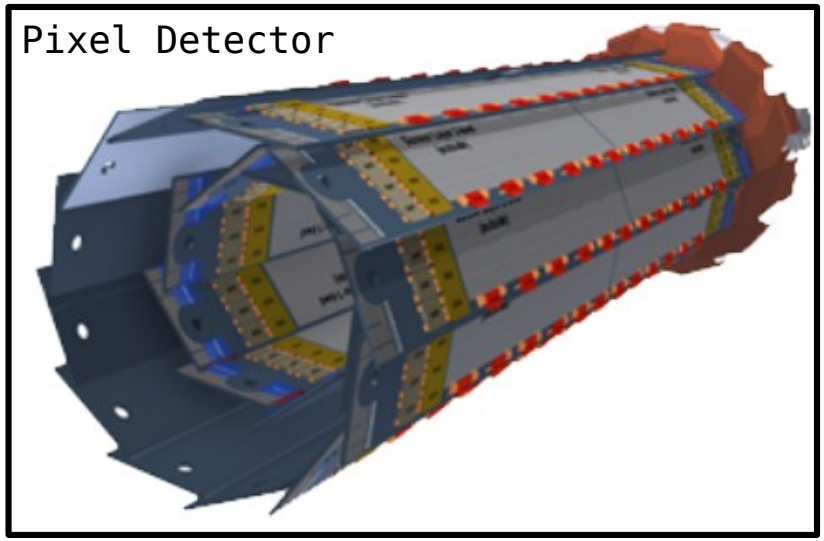




$$L = \frac{N_+ N_- f}{4\pi\sigma_x^* \sigma_y^*} R_L$$



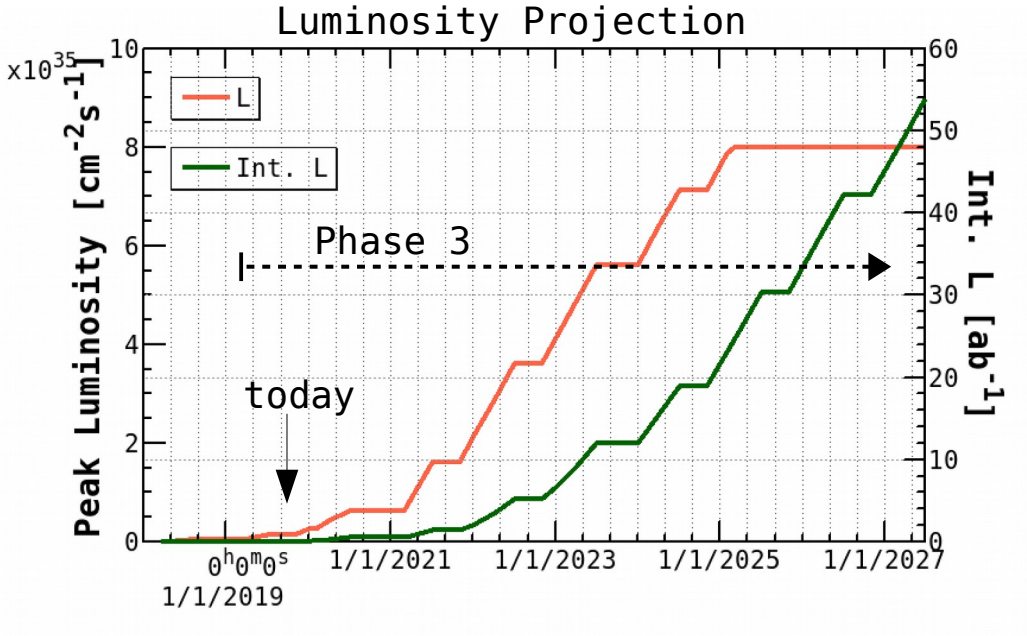
- Excellent vertexing and tracking down to low p_T (<100 MeV/c)
- Very low material budget for vertex detectors
- Inner layer only 14mm away from interaction point
- Impact parameter res. $\sigma_z < 20\mu m$
- Operate in high background environment
- Trigger rate 30 kHz

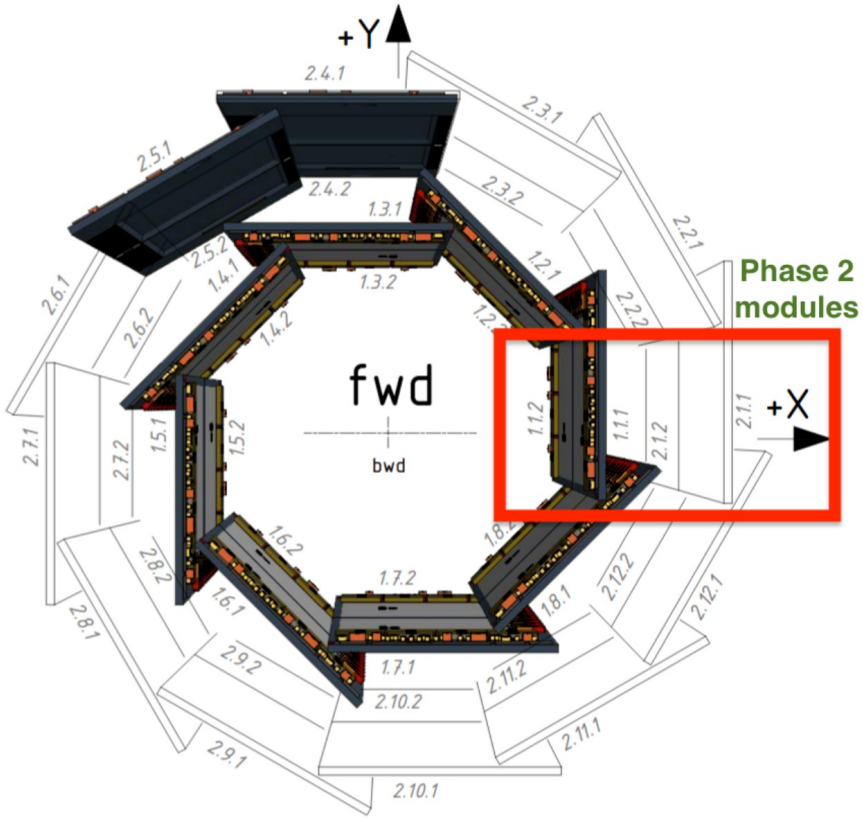


Physics data taking with full detector started this year

Time Line

- Phase 1 (2016) – only accelerator commissioning, no Belle II
- Phase 2 (2018) – 1/10 of PXD (1 slice of VXD), “Beast II”
  - Goals: commissioning, safety (beam abort), background, first physics
- Phase 3 (2019) – full VXD (besides PXD, full PXD from 2021)
  - Production delay due to low yield in ladder assembly (solved)
  - Only inner layer + 2 outer ladders were mounted



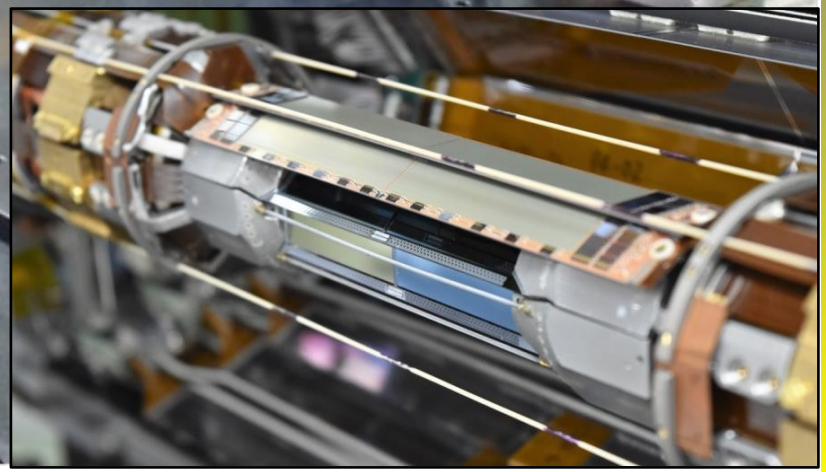


One bad quality module, excluded from DAQ

Combining Vertex Detector (One Half Shell)

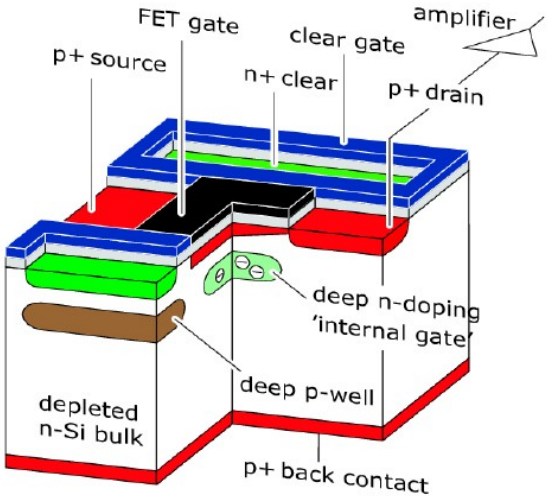
Belle II

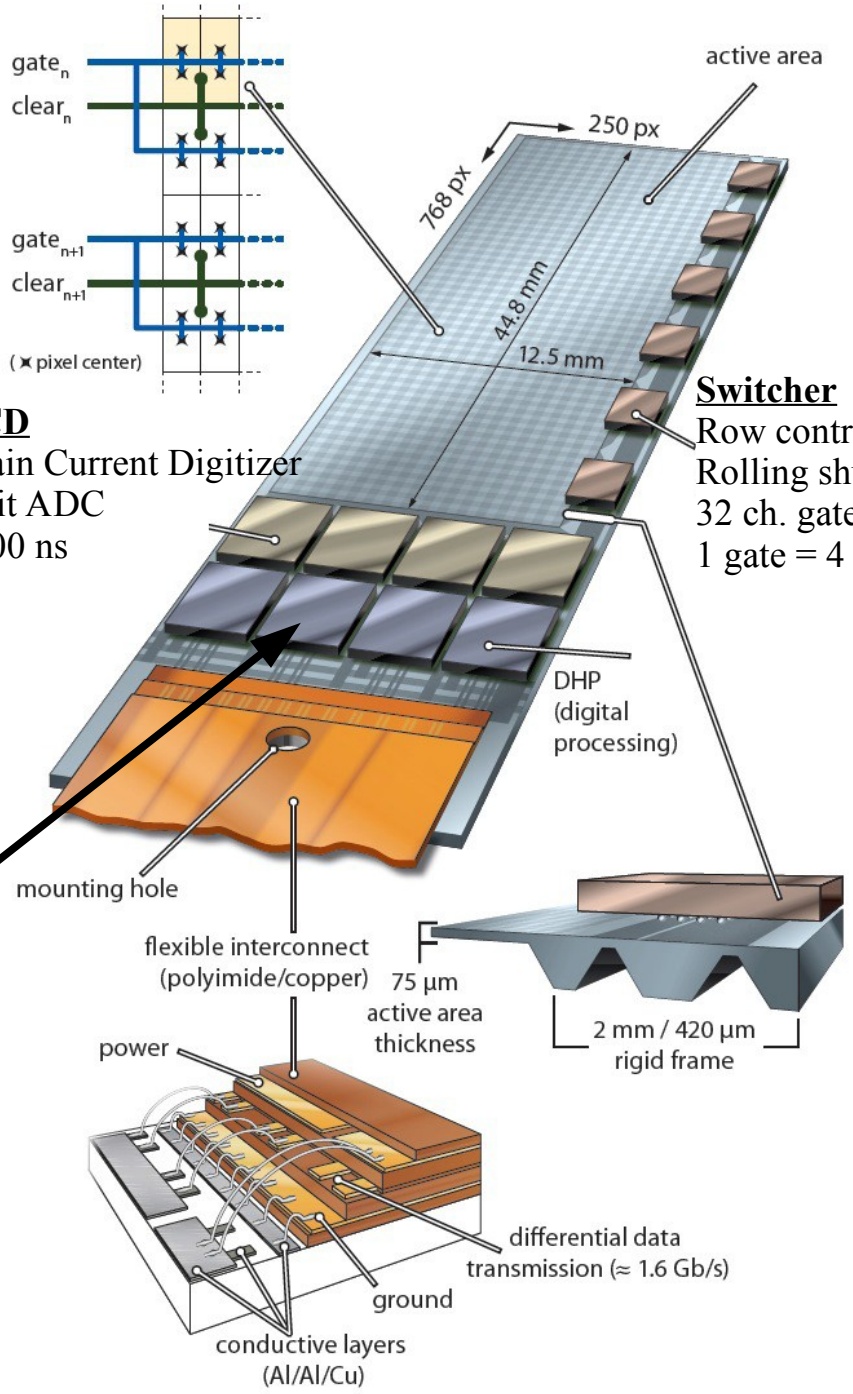
Oct 3
2018



PXD Sensors

- DEPFET active pixels
- 75µm thin sensors
- Pixel size down to 50x55µm²
- Rolling shutter read-out → low power
  - 50kHz → 20 µs integration time
- Design: 1% occupancy in layer 1
  - 3% occupancy limit (DHP, DAQ, tracking)
- Rad. hard sensor and ASICSs
- 40 sensors, 250x768 pixels each



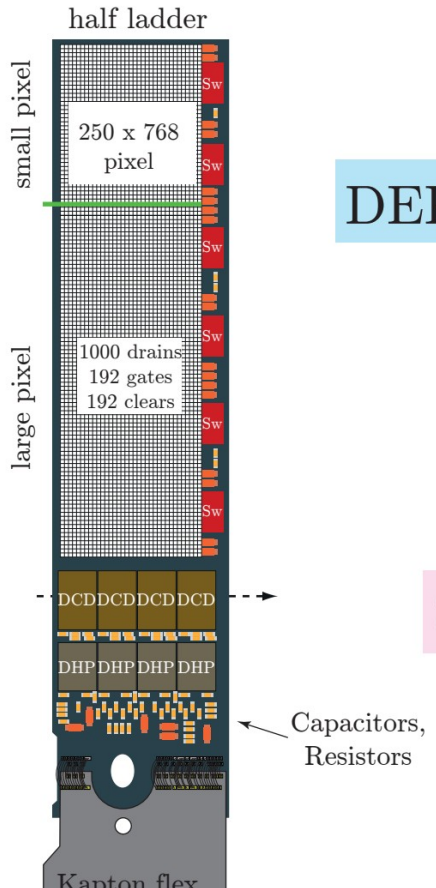


DCD
Drain Current Digitizer
8 bit ADC
~100 ns

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

System Layout



Data Readout Chain

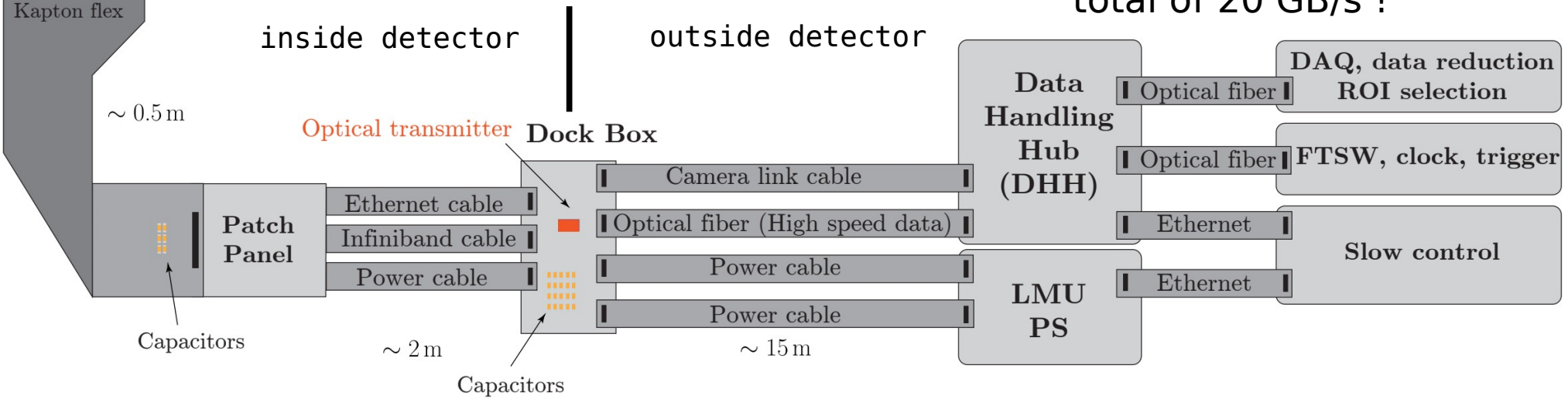
DEPFET → DCD → DHP → DHH → ONSEN → Belle II DAQ

Module control

Slow Control GUI → DHH → DHP → DCD, Switcher

Slow Control GUI → PS

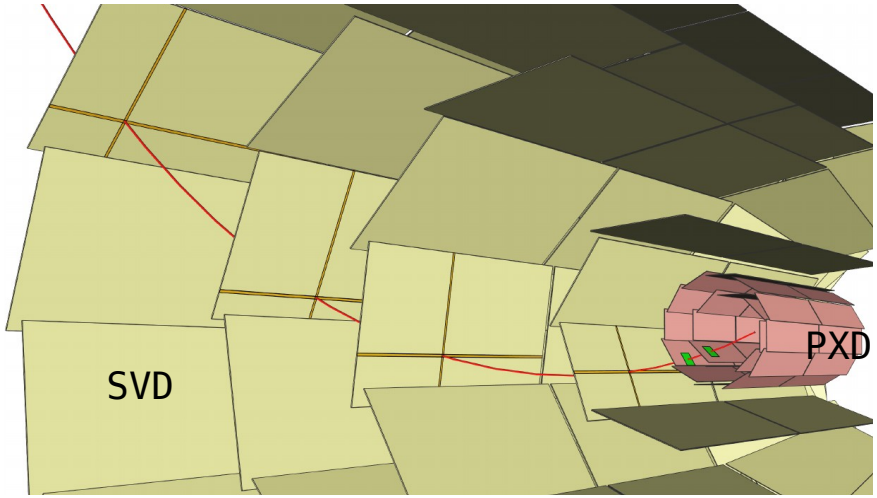
total of 20 GB/s !

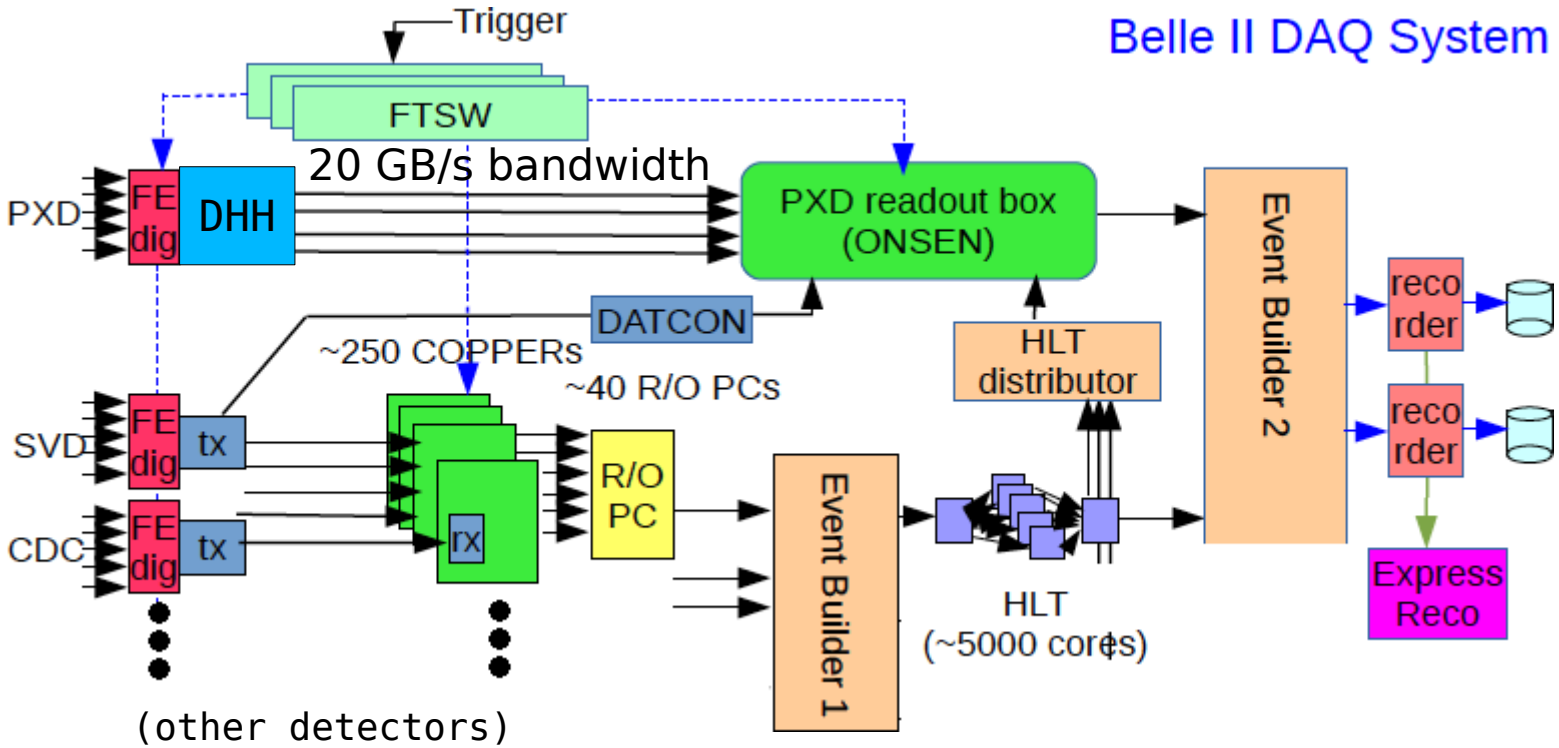


PXD DAQ Scheme

- PXD unfiltered data rate → 10x that of other Belle II detectors
  - Separate readout path
  - Remove data not belonging to a track
  - Data reduction to 1/10 by High Level Trigger based “Region Of Interest” calculation from CDC and SVD track information
  - Feedback to PXD readout
  - Selection of pixels within rectangular ROIs

ROI extrapolation on HLT

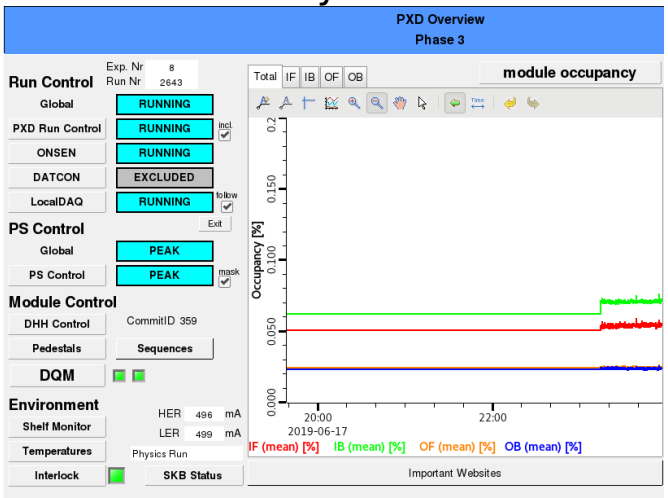




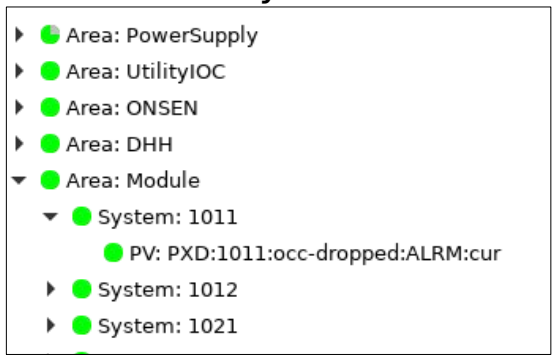
Slow Control and Monitoring

- PXD Slow Control uses EPICS
  - Interfaces to IPBus, IPMI, UNICOS, NSM2, …
- 20x200 PVs alone from Power Supply control
- Configuration from ConfigDB
  - Sophisticated sequences for powering the modules (ASICs)
- Archiver (13k PVs, 1.4 GB/day)
- Logging: DB with Elasticsearch, elog, Rocket.Chat
- Control and Monitoring GUI
  - Control System Studio
- Alarm System (BEAST)
- Scaled from 4 to 20 (40) modules from Phase 2 → 3

Control System Studio

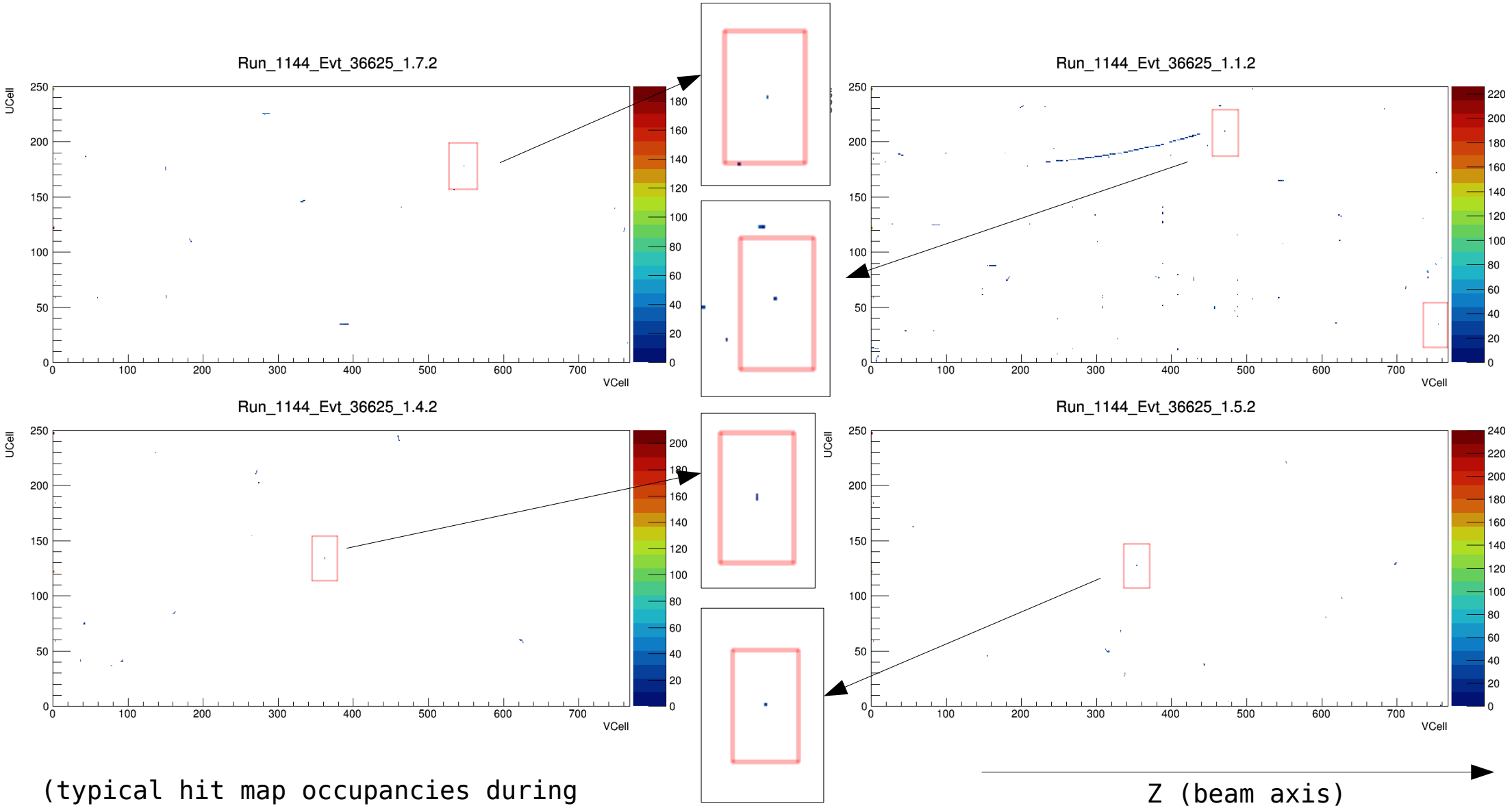


Alarm System Tree



Online ROI Selection

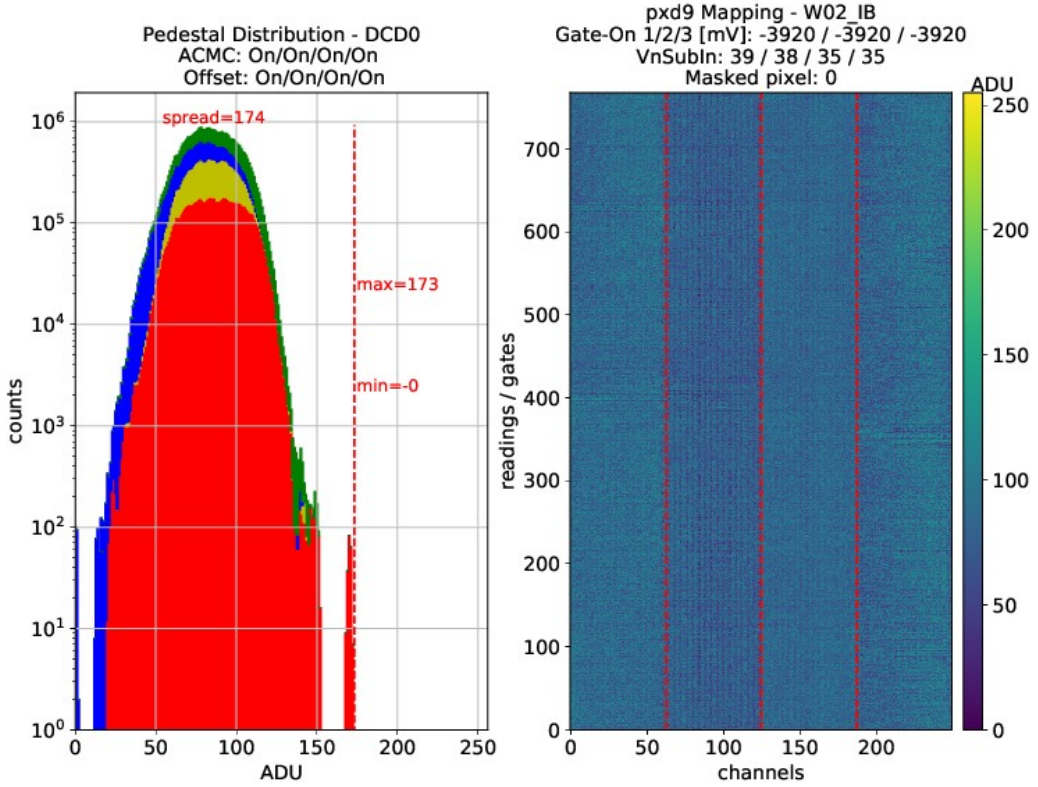
- Region Of Interest selection needs accurate ROI calculation on High Level Trigger
- Hit maps for different modules of same event: clusters fit to ROI computed on HLT



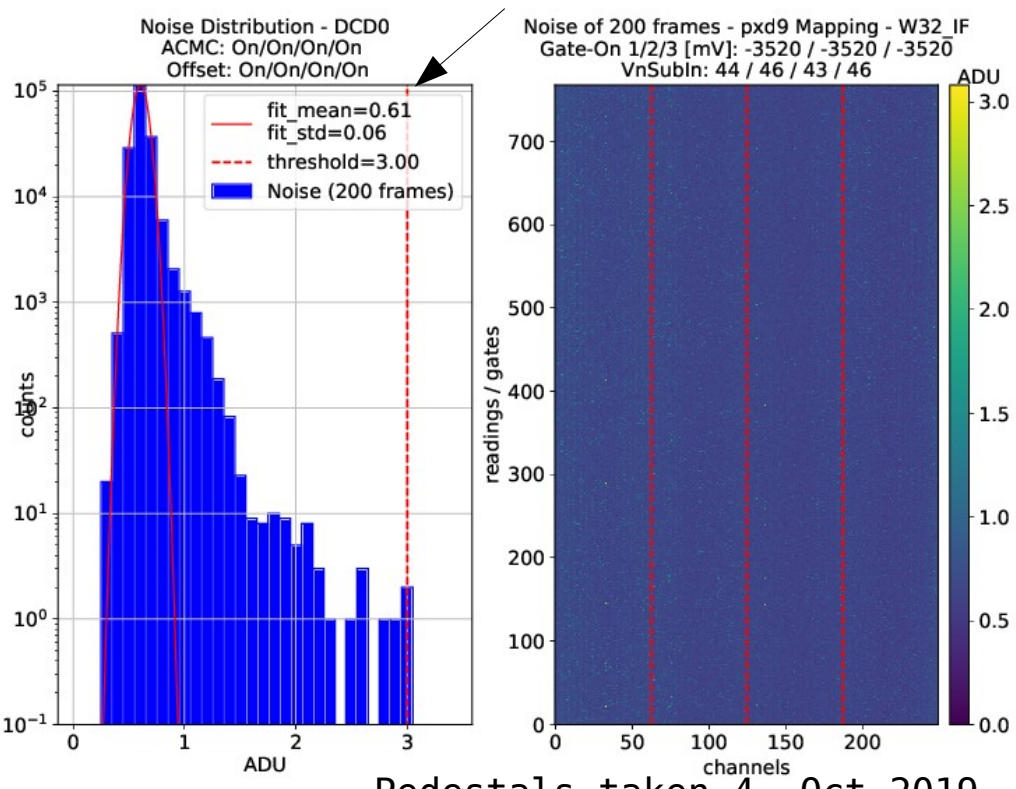
(typical hit map occupancies during spring 2019 run)

PXD Calibration and Optimization

- Phase 3 modules characterized before installation – still need further optimization
- 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, <100e ENC)



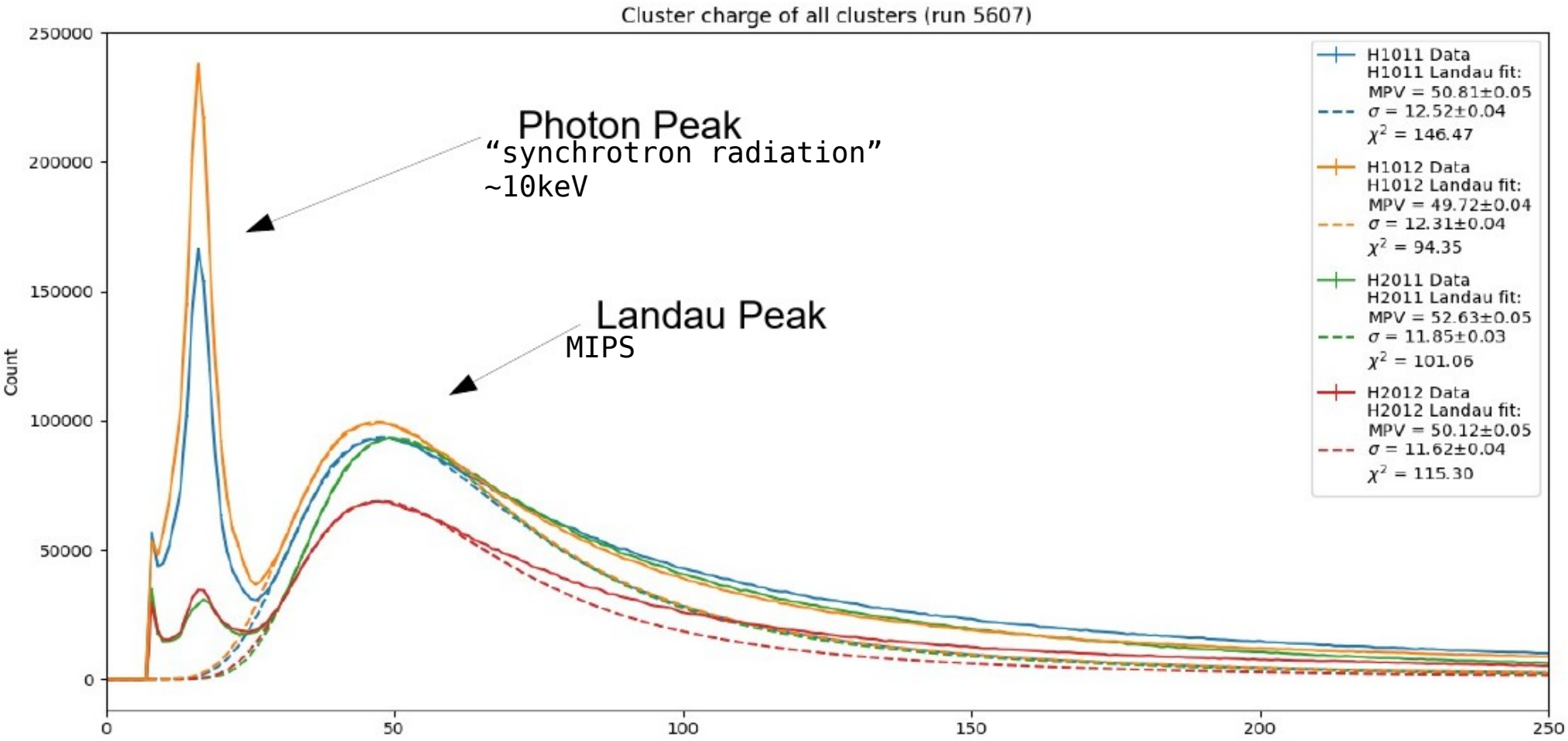
Noise of 0.6 ADU



Pedestals taken 4. Oct 2019

PXD Cluster Charge

Phase 2



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

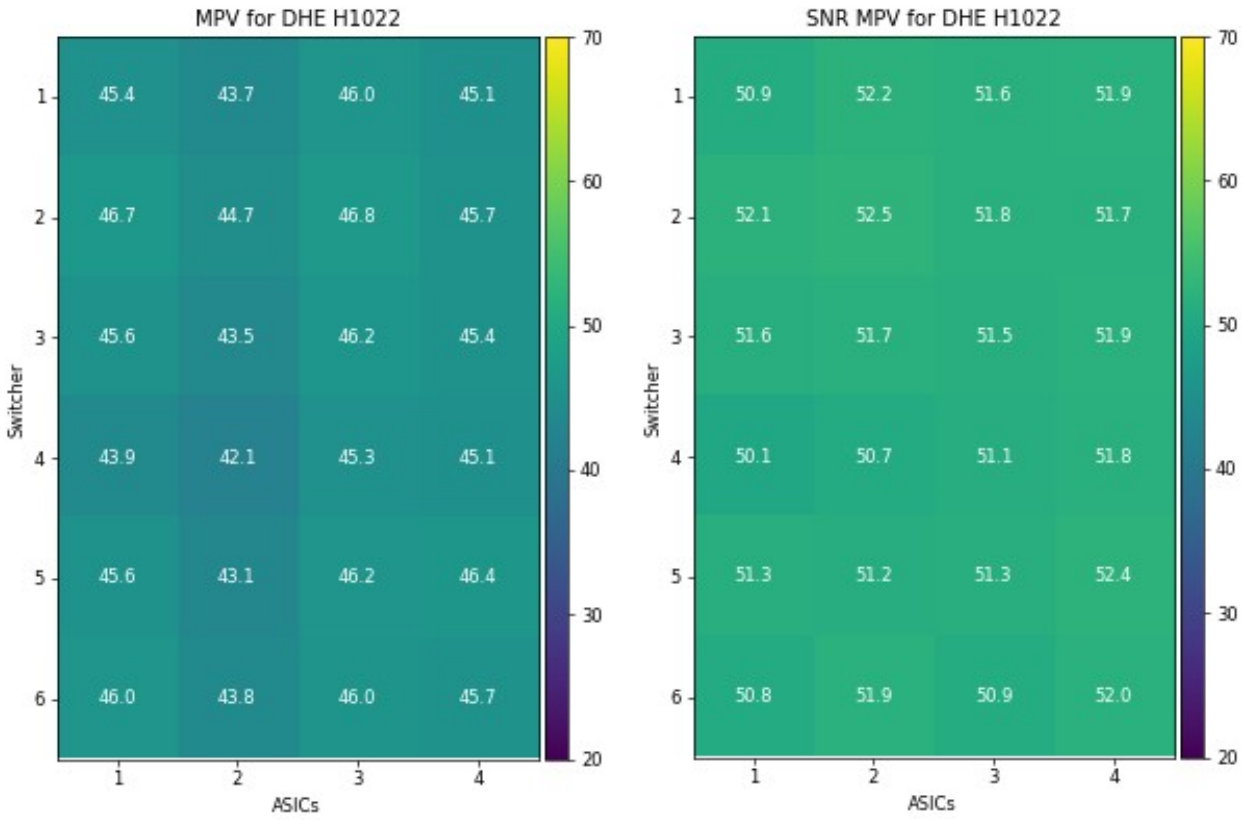
Changes by radiation damage

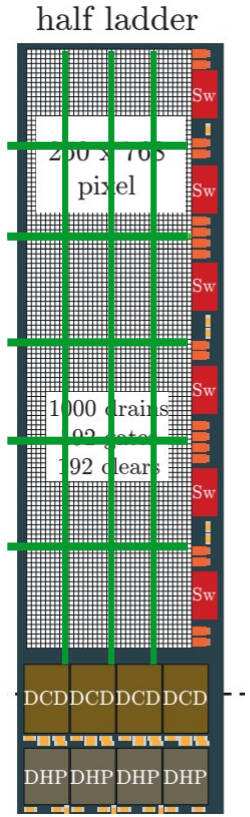
In Phase 3 photons peaks reduced, as Au layer inside beam pipe was thinner in Phase 2 (on purpose)

Gain Homogenity

- Uniform gain over sensor area can be achieved
- Signal to Noise Ratio ≈ 50
- Most probable value and SNR uniform over ASIC combinations

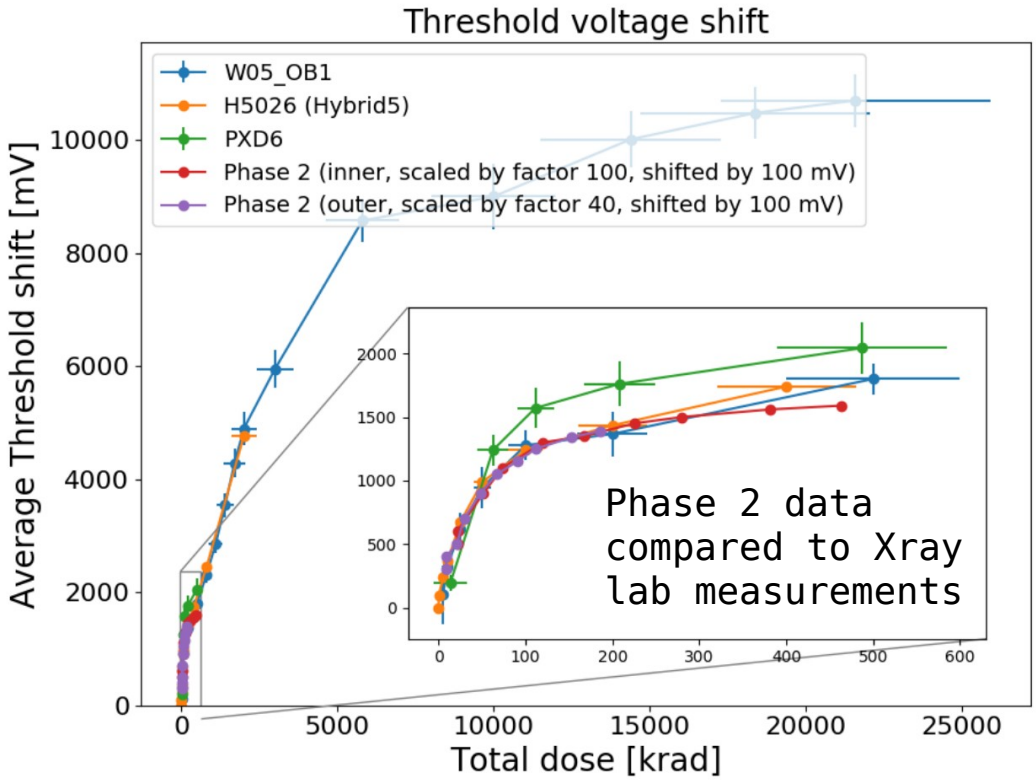
Phase 3, Run 2209 Exp 8

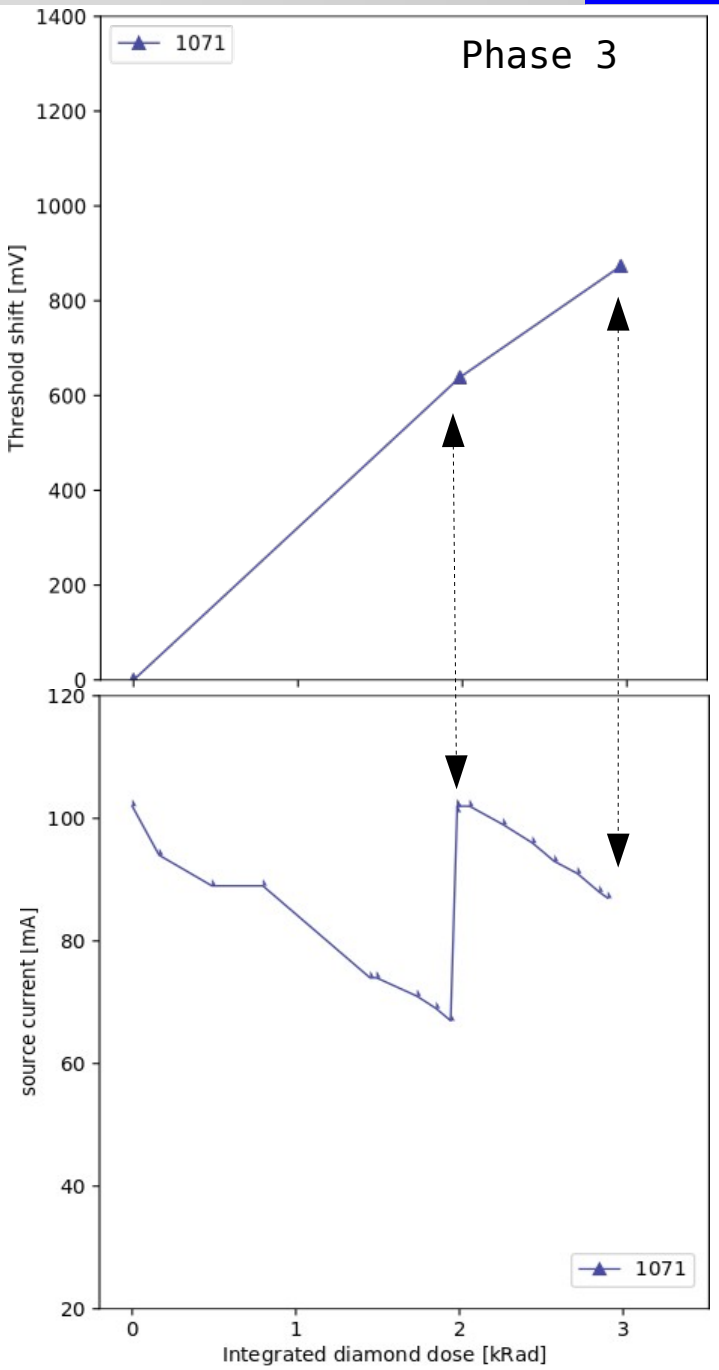




Compensation for Radiation Damage

- MPV for cluster changes with irradiation
- Expected, must be corrected for by increasing voltages
- Voltages adjusted to have same source current (100 mA) again
- Radiation dose from diamond sensors → scaling needed

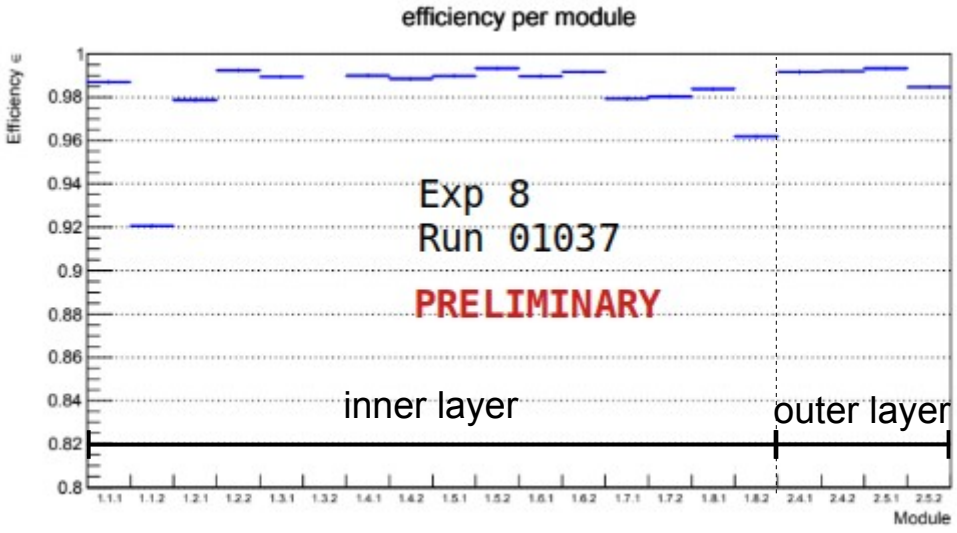


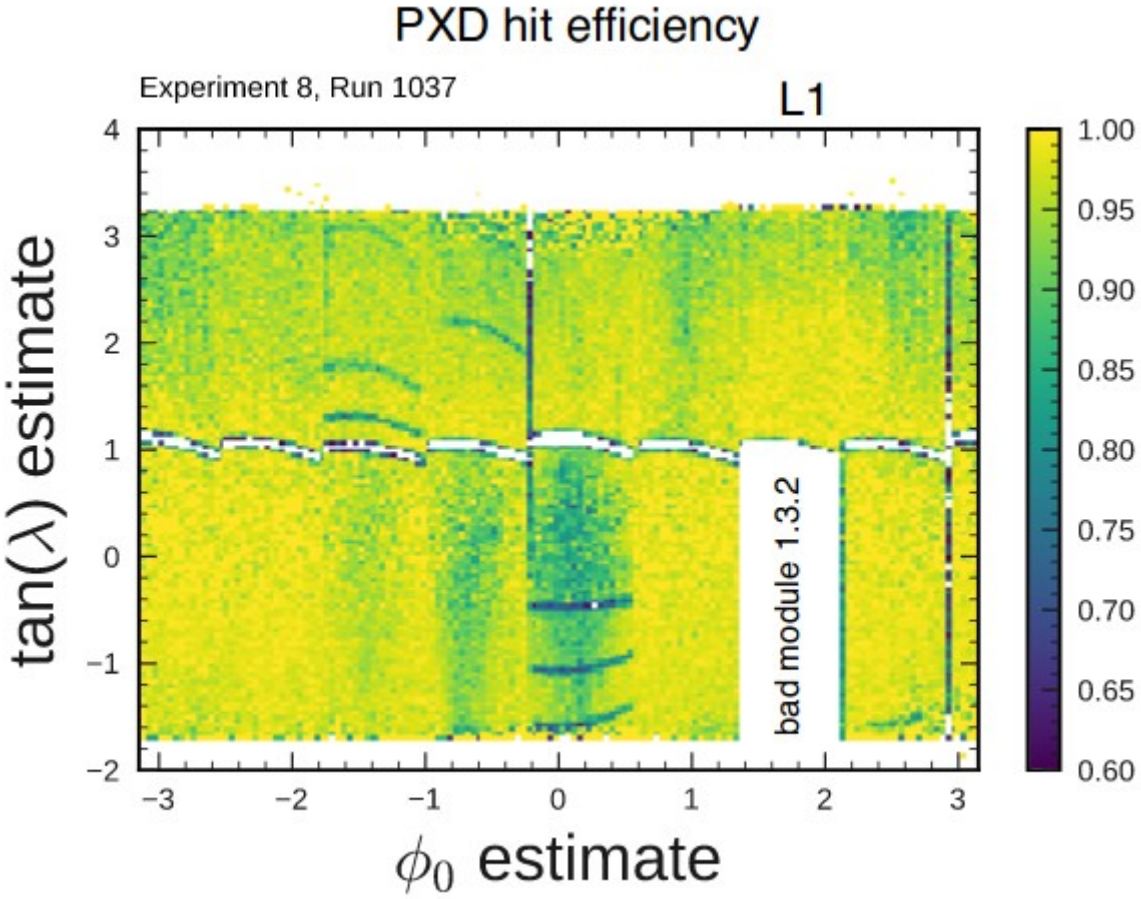


Efficiency

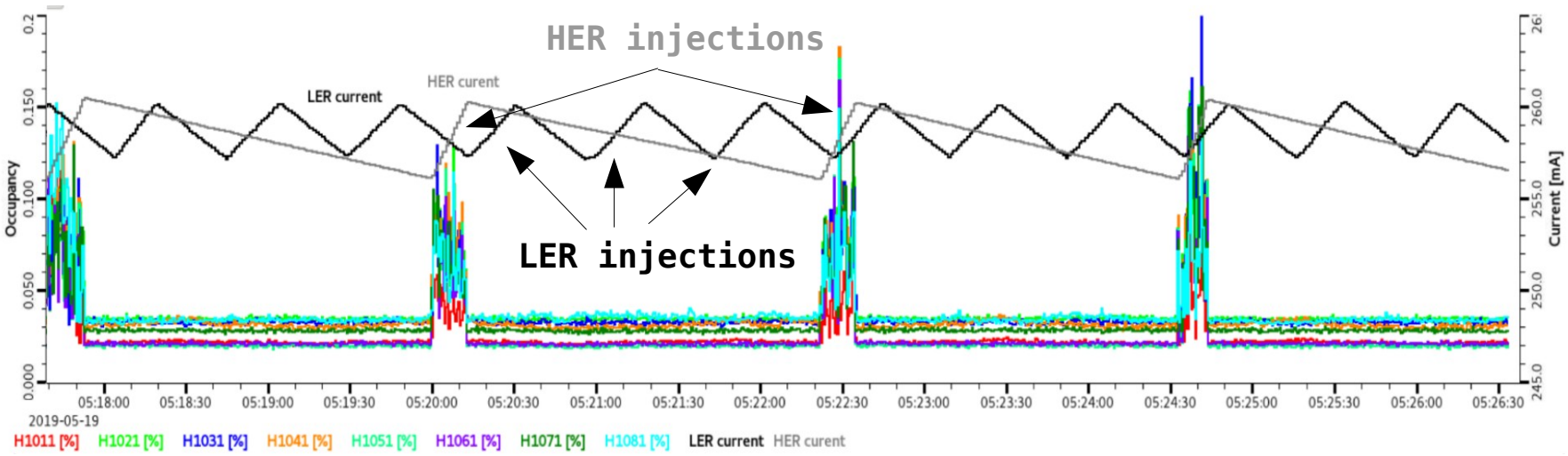
- Defined by hits found close to track intercepting points in modules
- Influenced by
  - Tracking quality
  - Alignment
- Take only tracks with good tracking
  - p_T>1 GeV/c

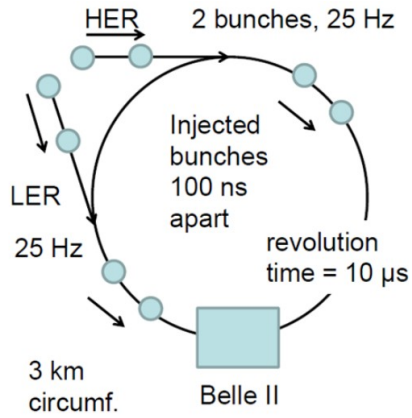
$$\epsilon = \frac{nr\ of\ tracks\ with\ hit\ near\ track\ intercept}{nr\ of\ good\ track\ intercepting\ a\ module}$$



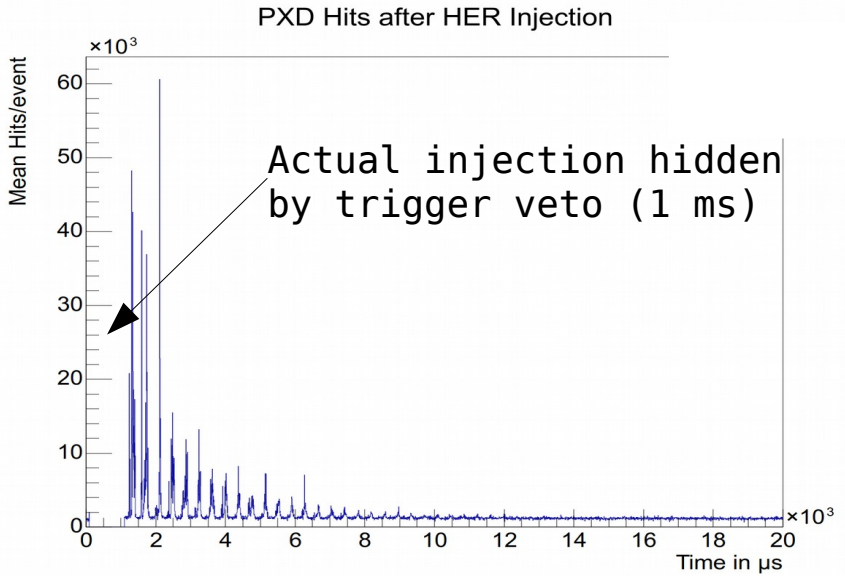


Continuous Injection Backgrounds





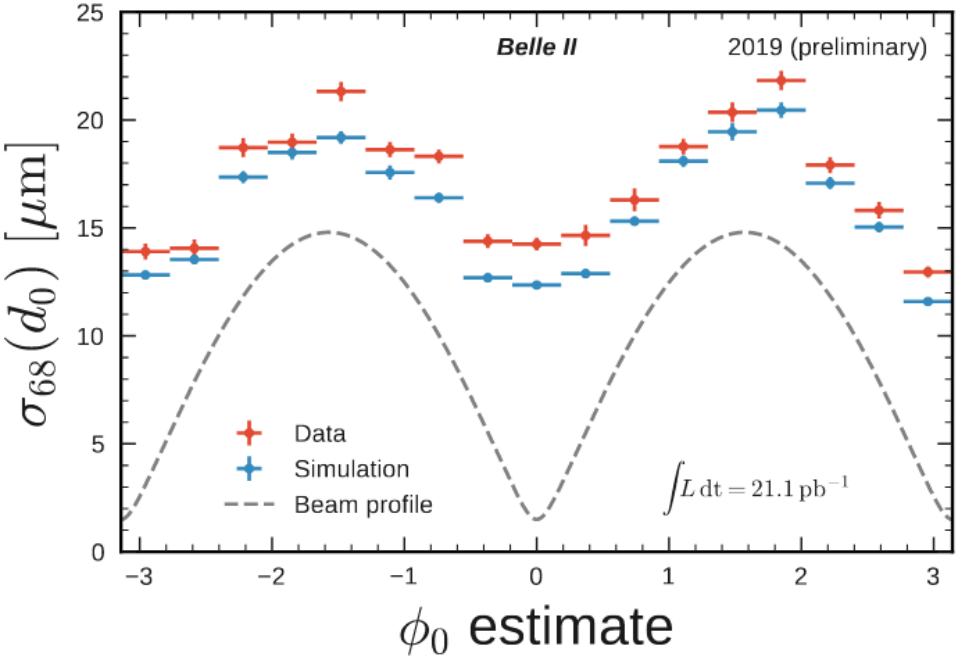
- Increased luminosity by continuous (top-up) injection, max 50 Hz
- Large background during HER injection (noisy bunch) → can lead to readout problems
- Belle II Trigger Veto (=no readout)
  - Full veto during injection (1-2 ms) and then for ~10 ms each time the bunch passes by (~2 µs)
- For PXD: Possible to blind detector while keeping stored charges (Gated Mode)
  - Deploy for upcoming autumn run

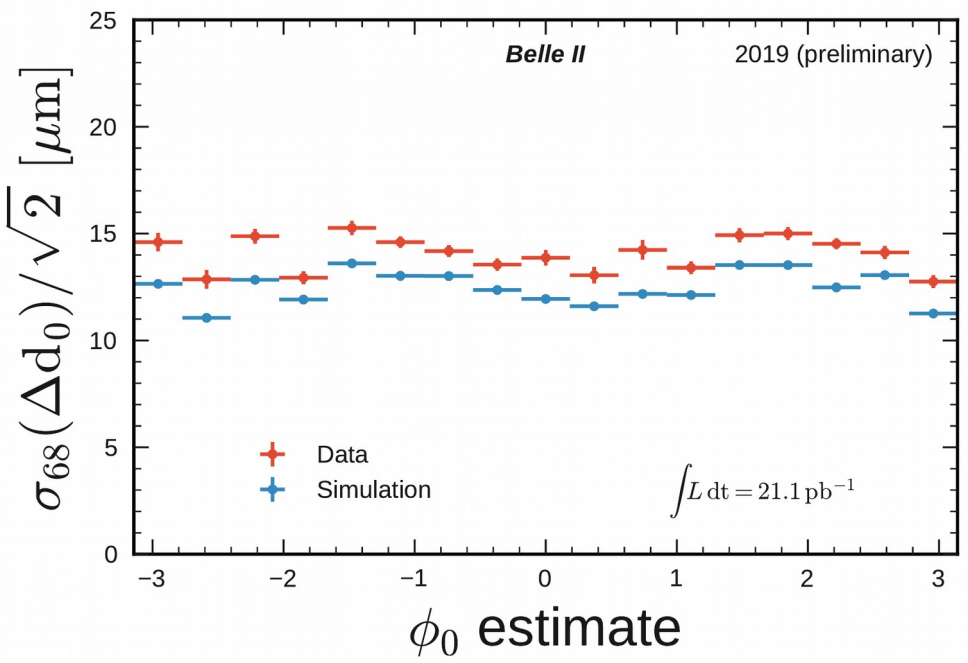


Rolling shutter! Integrated over 20 µs.

Vertex Resolution

- Measuring the point of closest approach from particles from the interaction point in x, y
- Vertex resolution with PXD is close to MC expectations
  - d_0 resolution of 14.5 μm achieved
- Details → T. Bilka: Belle II Vertex Detector Performance



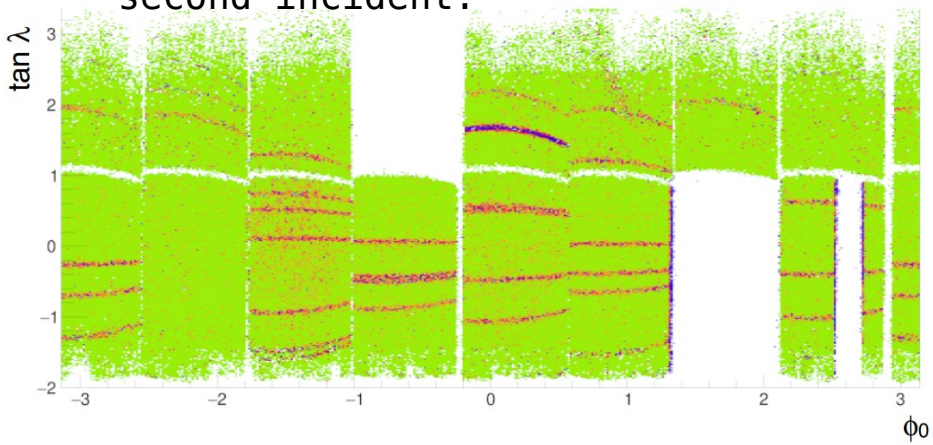


Beam Incidents

- Two major incidents:
  - QCS power supply failure
  - Beam dust particles event(?), collimator damaged
- Beam particles hitting QCS → magnet quench
  - Large instant radiation burst before beam was dumped (3 rad in <40us)
  - PXD modules in current limit → emergency shutdown
- Working point shifted
- Two modules could not be turned on (large currents)
  - One could be recovered after few days
  - Second module only after summer shutdown
- Permanent damage: “dead” gates
  - Single Event Effect (SEE)
  - → dedicated irradiation test for ASICs and sensor in November

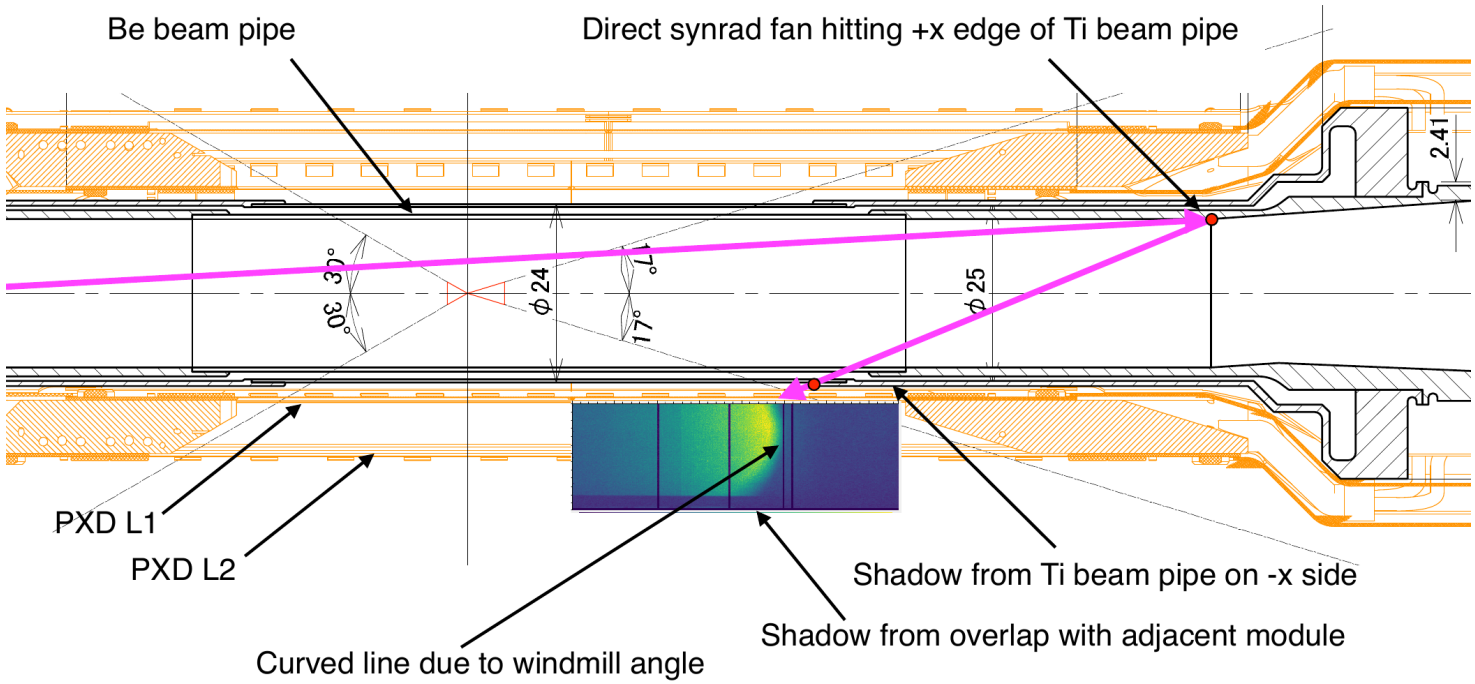
QCS:
Superconducting quadrupole coils close to interaction point

“Dead” gates in inner layer after second incident:



Sursprises – Synchrotron radiation

- Large photon background was observed for some runs in a few modules in -X
- IR designed such that no direct SR photons hit the central Be beam pipe
  - Secondary photons!
  - Single pixels, low energy
  - Problem: Inhomogeneous irradiation
  - Reason: Change in accelerator “tune”
  - We can only see this if the detector is on



Summary

- Belle II first particle physics experiment to use a DEPFET pixel vertex detector
- Good performance demonstrated
  - Some modules not at optimal working point yet
  - Vertex resolution close to MC expectations
- DAQ / ROI data reduction concept proven
- Suffering from damages due to radiation bursts

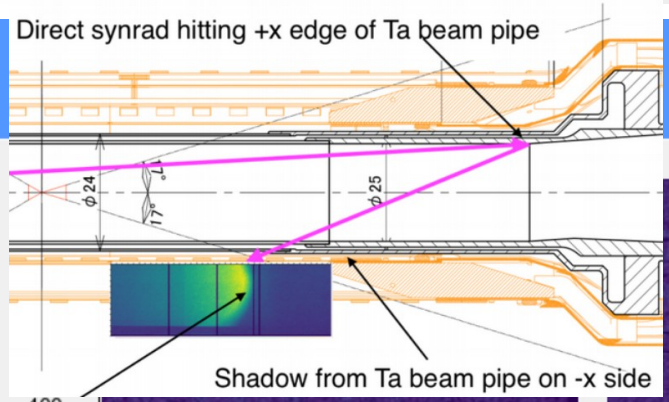
- Outlook
  - Understand and prevent damage by “beam incidents”
    - Add new collimators!
  - Complete PXD in 2021

Backups

Other talks

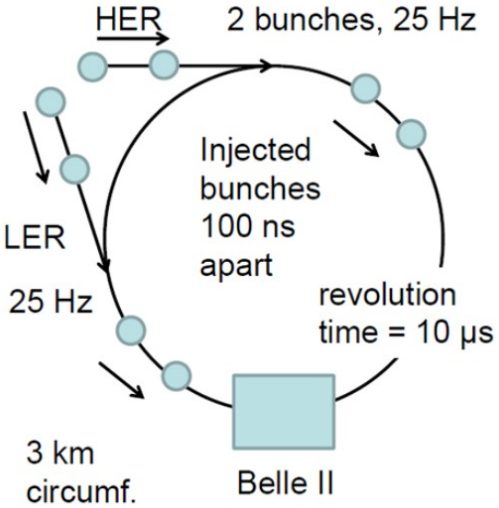
- Ch. Schwanda: Performance of the Belle II Silicon Vertex Detector
- T. Bilka: Belle II Vertex Detector Performance

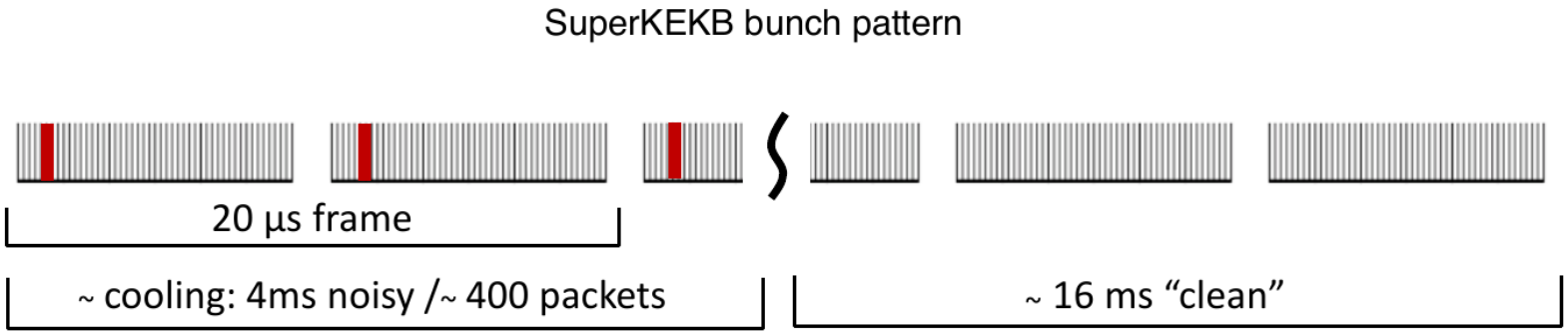
"Synchrotron" Radiation Problem



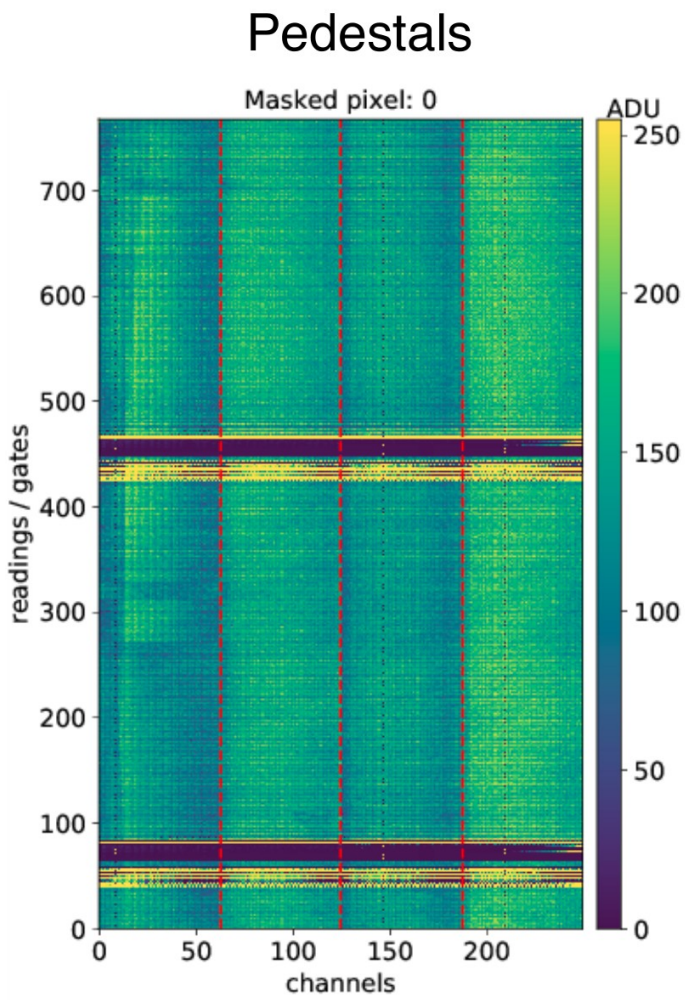
Problem: Cannot correct for non-uniform rad damage!
We get the damage even if we DO NOT see it because HV is off!!

Gated Mode



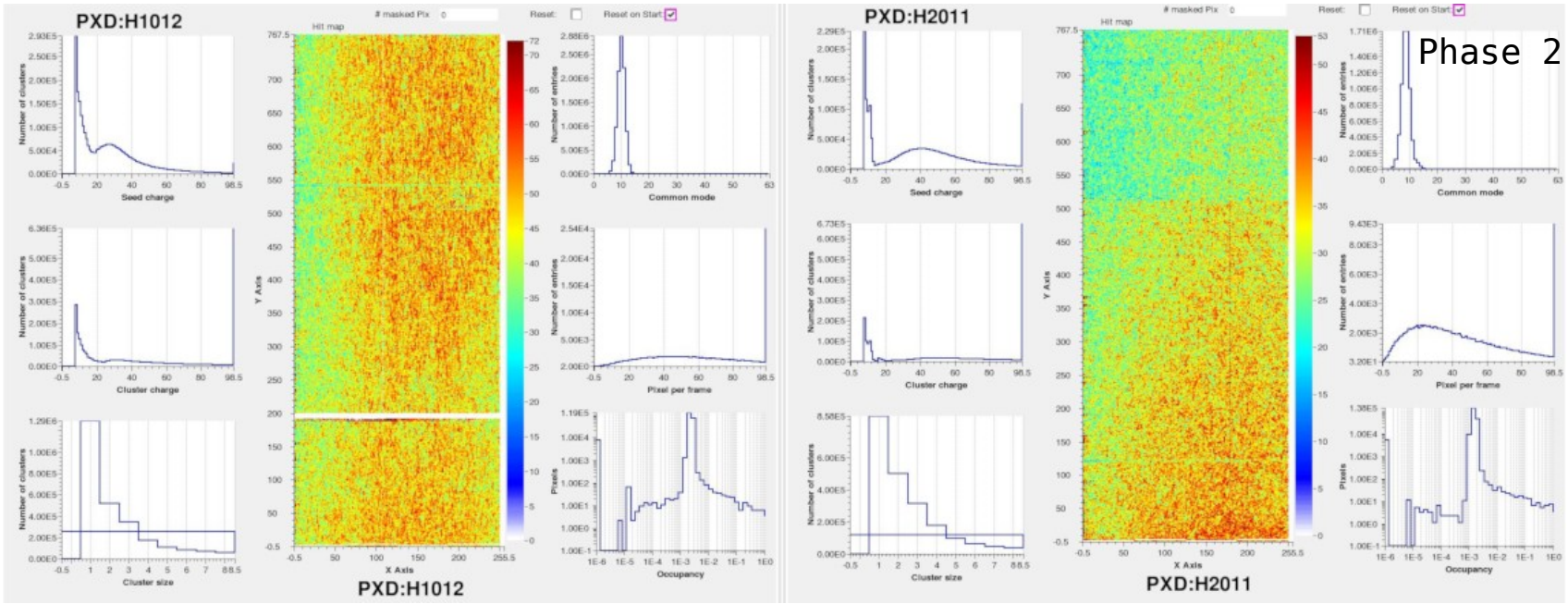


- Gating: change the voltages (potentials) such, that no new charge is collected while preserving the already stored charge.
- Gating two times per readout cycle
- Read out continuous during gating, but the data is unusable
- → fraction of the detector area is lost
- Large currents → pedestals change

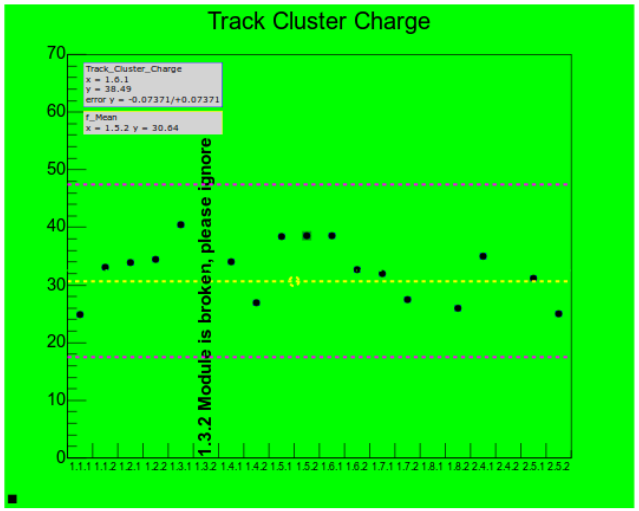


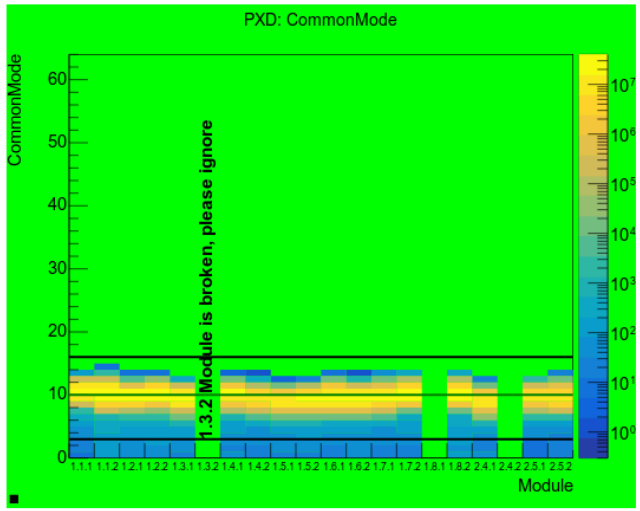
Online Monitoring

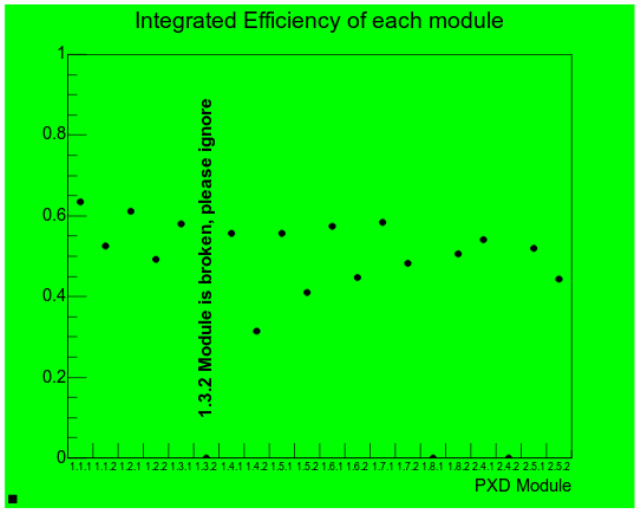
- Histograms from local DAQ



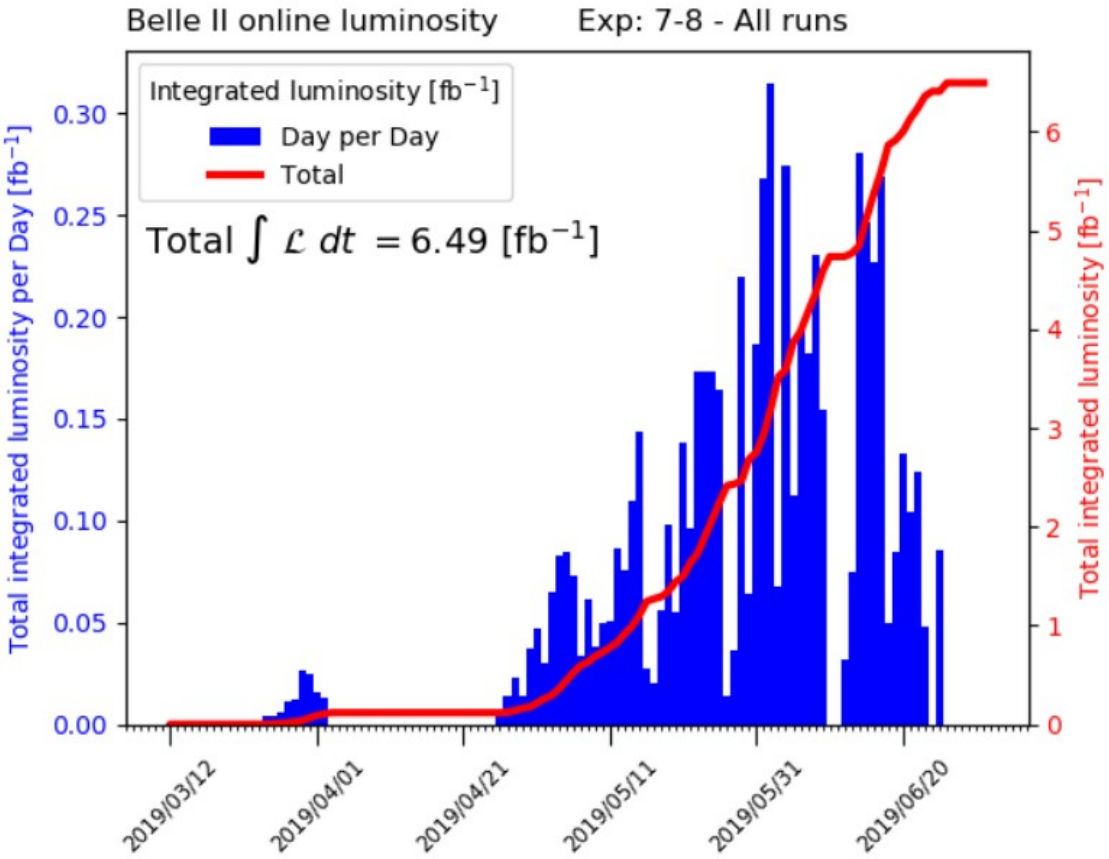
- Histograms from express reconstruction for online monitoring performance





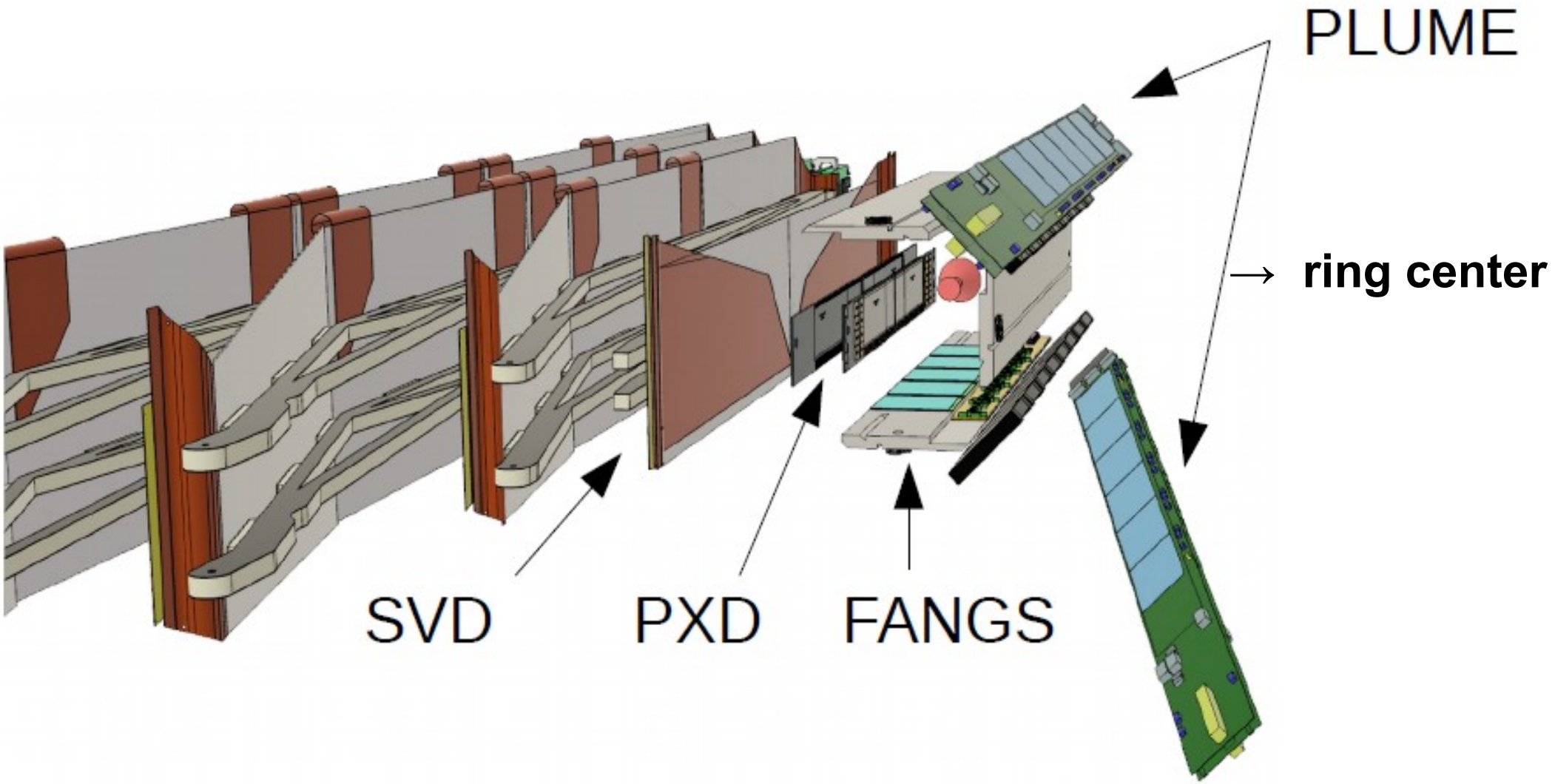


Collected Luminosity in Spring 2019



VXD Installation

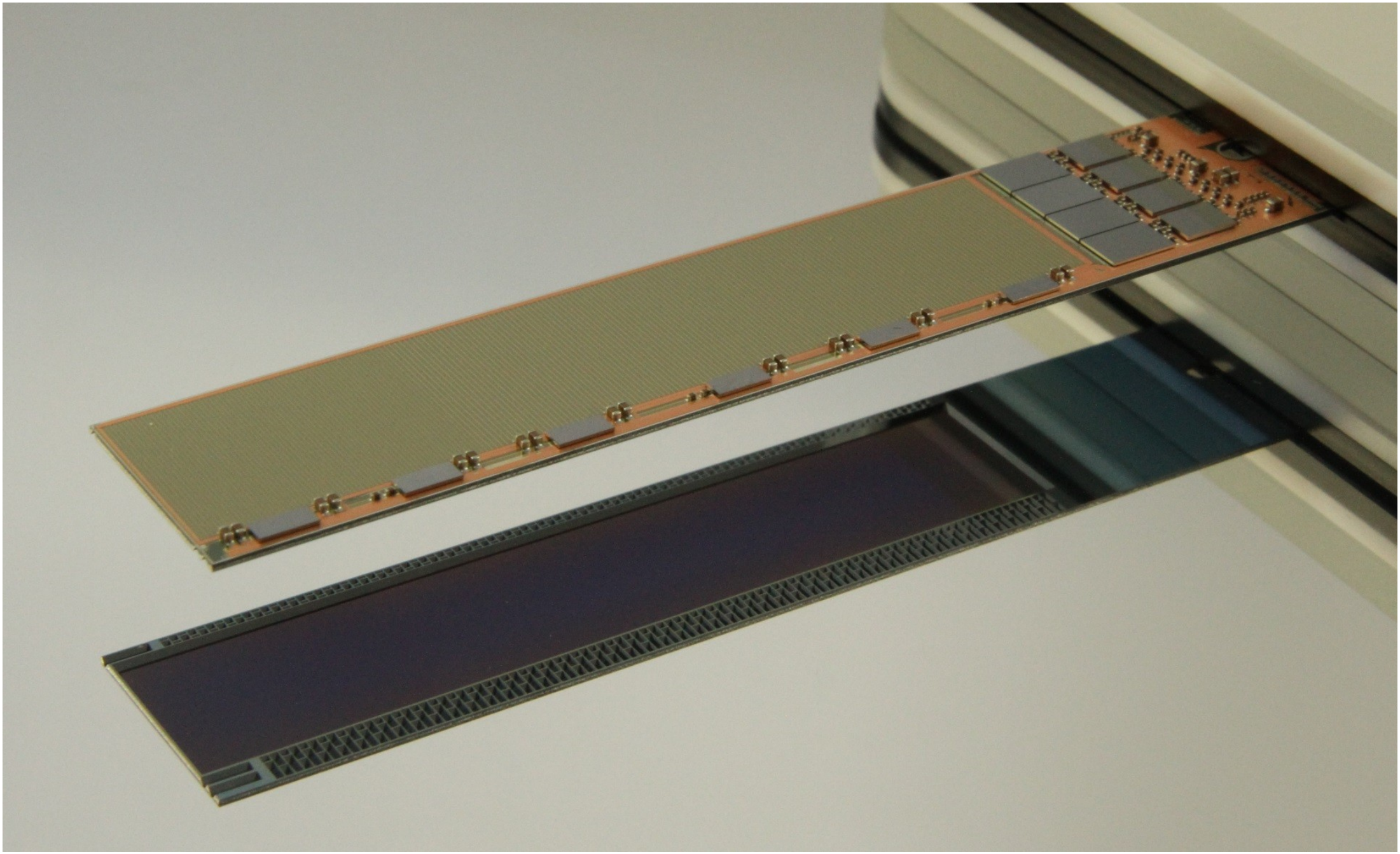
Phase 2 VXD and BEAST II



Background in Pixel detector

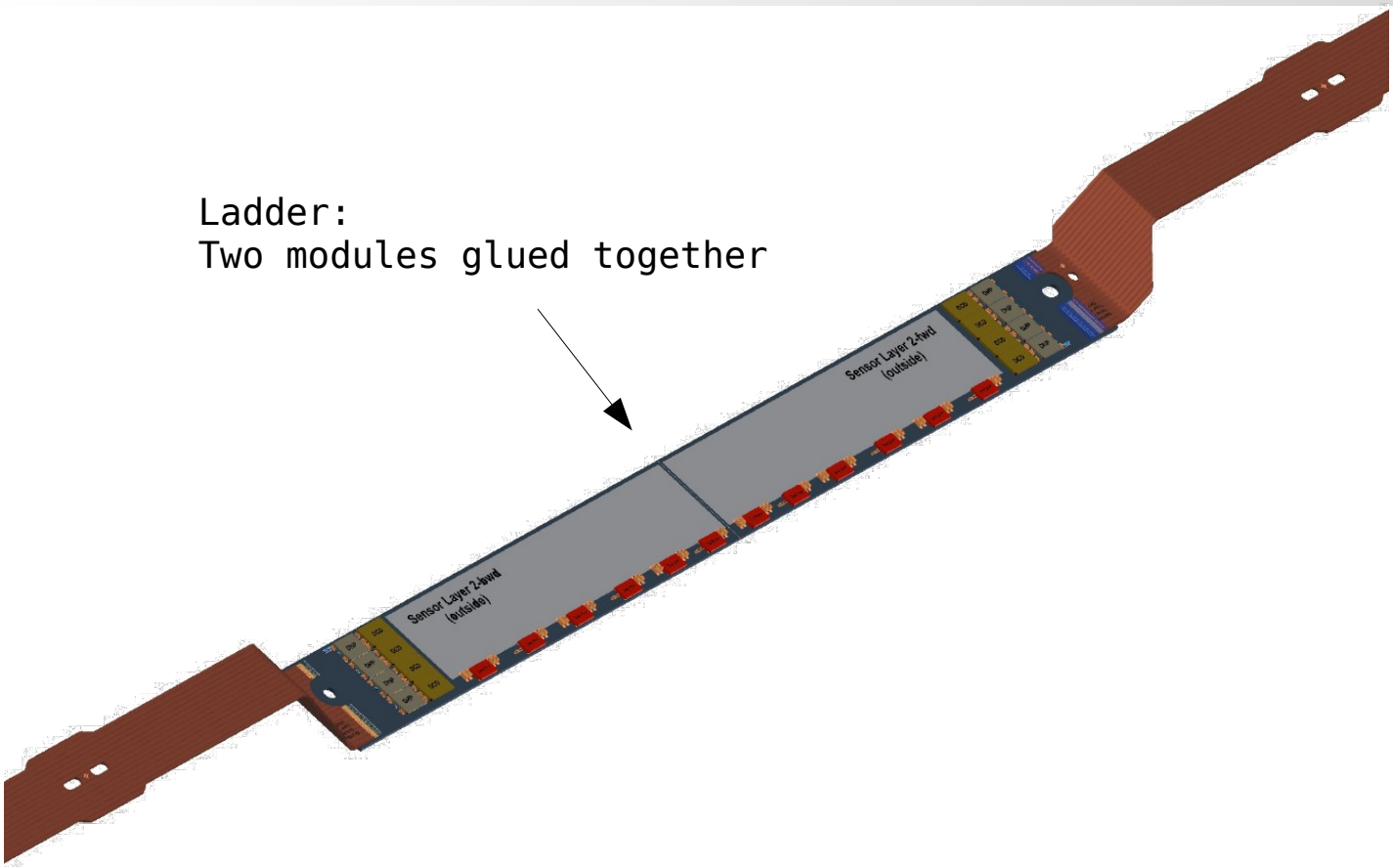
- Occupancy of PXD dominated by background
  - physics <1% occupancy
- Beam related background by
  - Synchrotron radiation
  - Beam - gas reactions
  - Touschek effect – intra-beam scattering because of high particle density
- Interaction background
  - Radiative QED, two photon processes
- Can be studied and decomposed with single beams and varying currents
- Big uncertainty in extrapolations
  - Backgrounds much too high (not only in PXD!)
  - LER background dominates
  - Mitigation needed

PXD Module

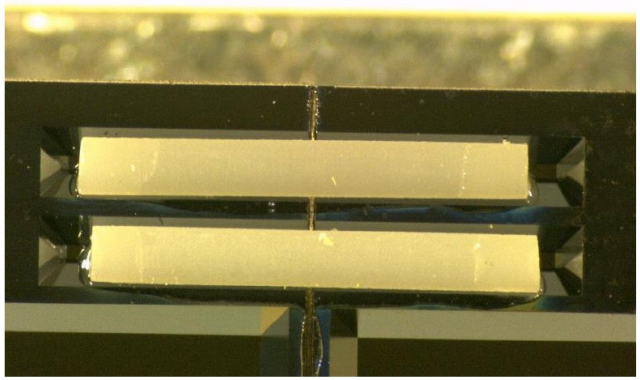


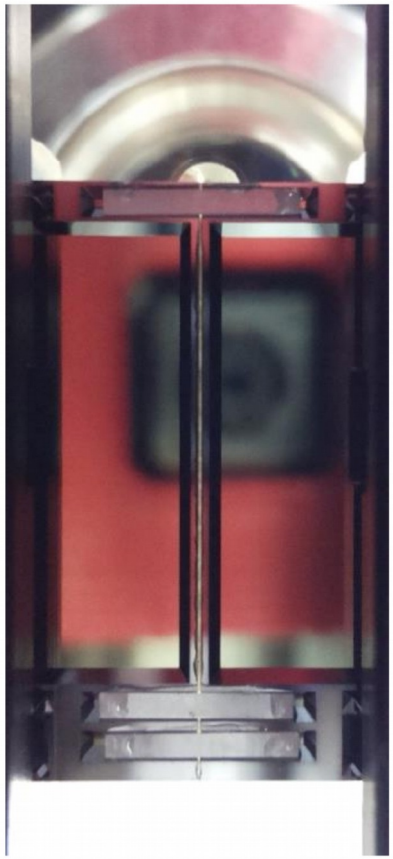
Ladder Gluing

Ladder:
Two modules glued together

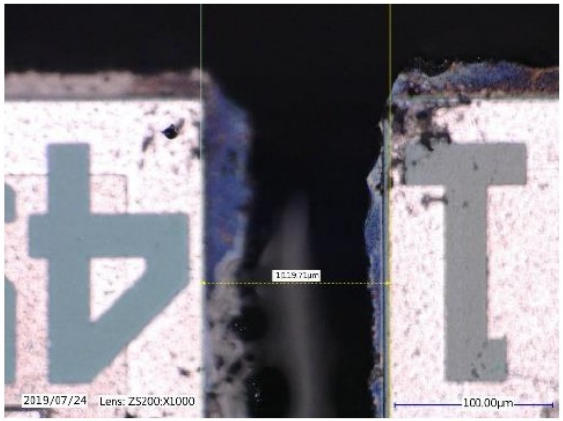


Stiffeners

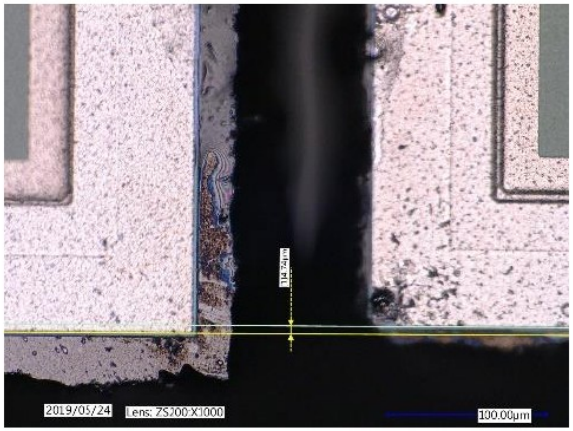




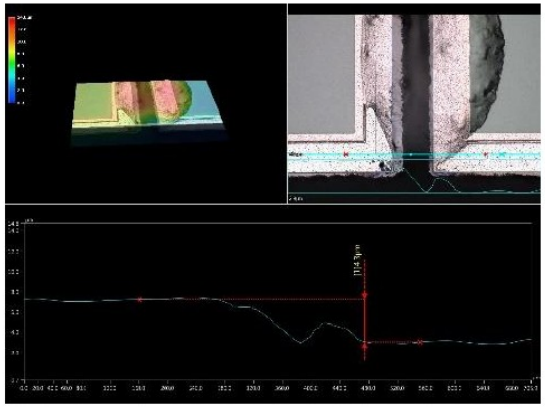
gap: glue gap between Al



dx: lateral displacement



dH: step between modules

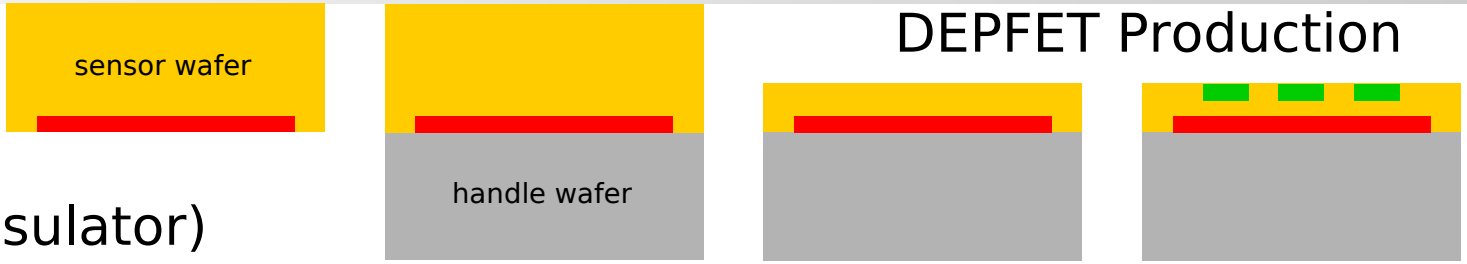


DEPFET Module Production

DEPFET

Active Pixel Detector

SOI process
(silicon on insulator)



1. implant backside on sensor wafer
2. bond sensor wafer to handle wafer
3. thin sensor side to desired thickness
4. process DEPFETs on top side

Phase II, Phase III
Metallization (2 Al, thinning & Cu)

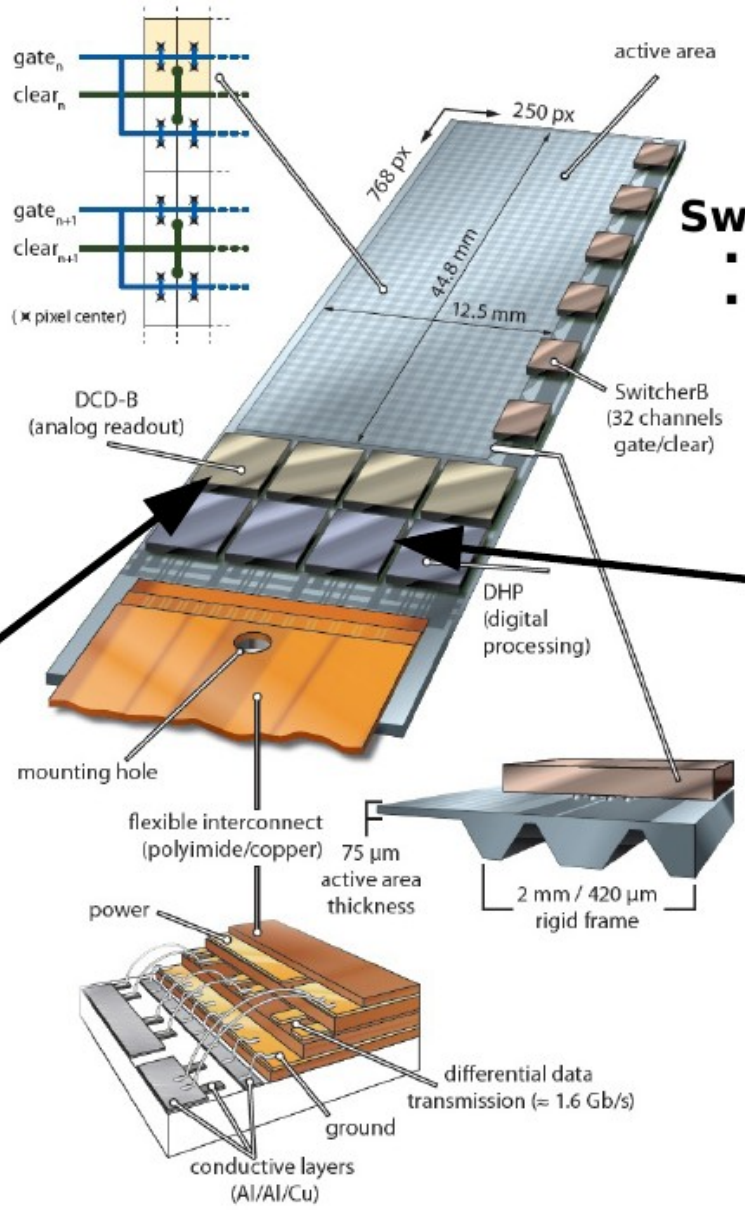
Flip Chip ASICs & mount SMD

Kapton bonding

Module gluing = "Ladder"

4 types of Kapton

4 types of modules



SwitcherB - Row Control

- Gate and Clear signal
- Rad. hard proved (36 Mrad)

DHP - Data Handling Processor

- Common mode and pedestal correction
- Data reduction (zero suppression)
- Timing and trigger control
- Rad. Hard proved (100 Mrad)

DCDB - Drain Current Digitizer

Amplification and digitization of DEPFET signals.

- 256 input channels
- 8-bit ADC per channel
- 92 ns sampling time
- Rad. hard proved (10 Mrad)