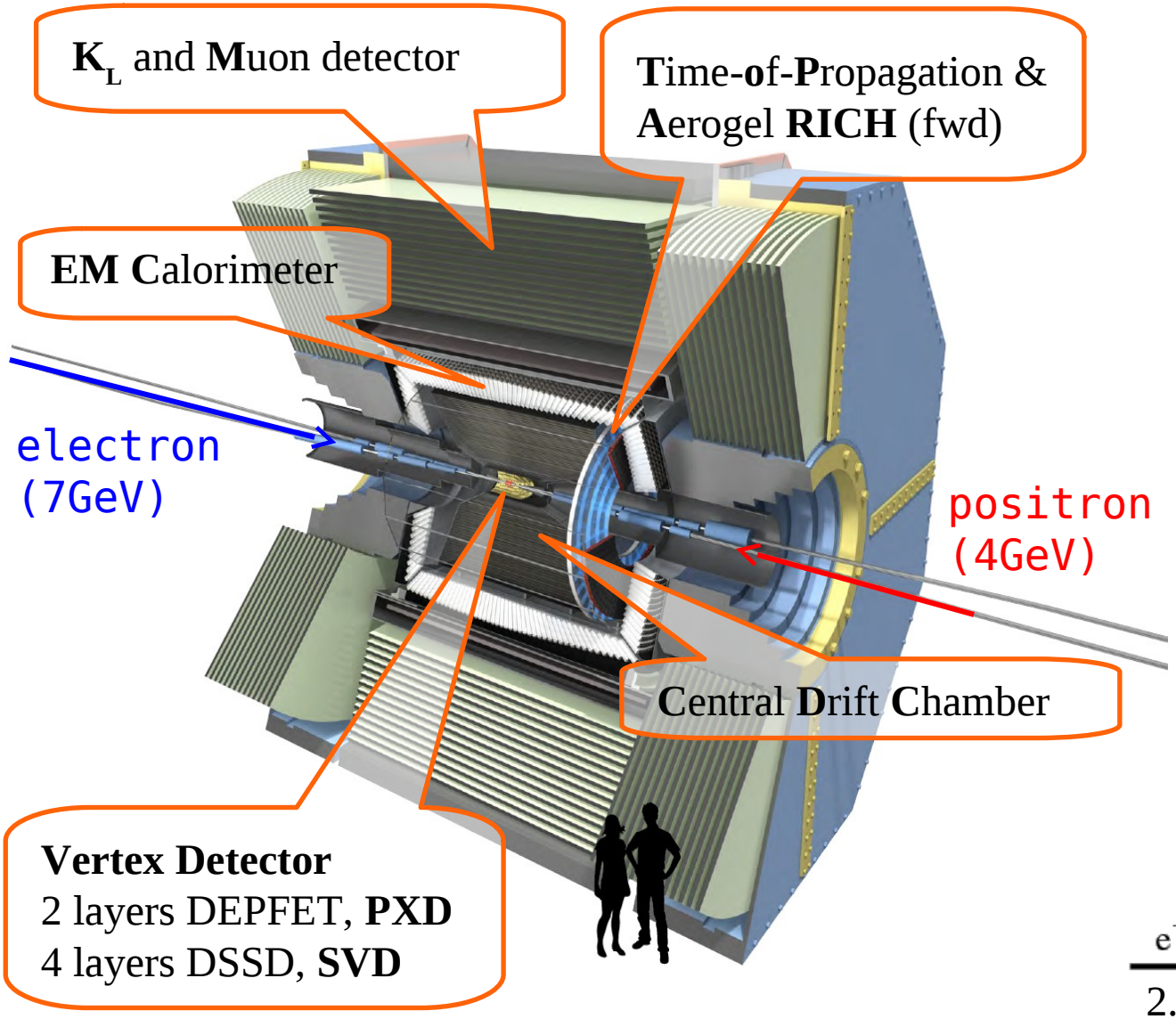
Belle 2 Pixel Detector (PXD) Status

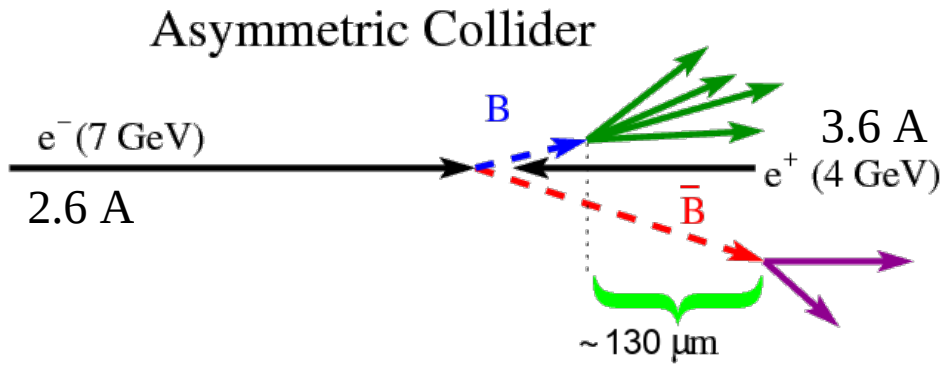
FSP Belle II Germany Meeting
14.9.2020

Bjoern Spruck, JGU Mainz

Belle II & Vertex Detectors



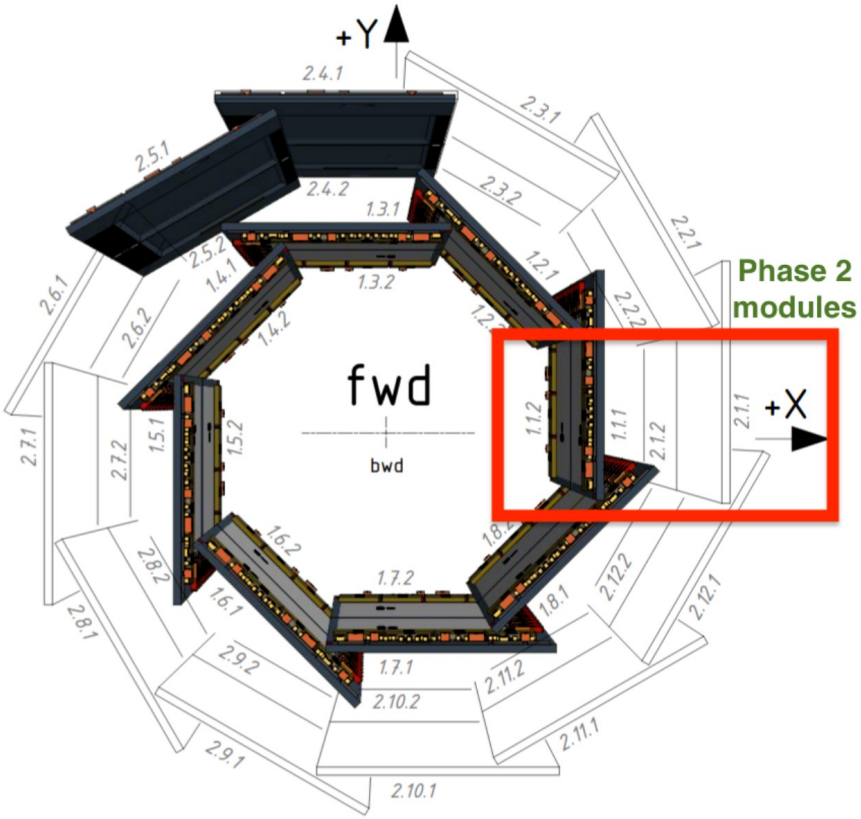
- Excellent vertexing and tracking down to low p_T (<100 MeV/c)
- Very low material budget for vertex detectors
- Inner layer only 14mm away from interaction point
- Impact parameter res. σ_z < 20µm
- Operate in high background environment
- Trigger rate 30 kHz



Secondary decay vertices for B and D mesons

A Little Bit of History

- Phase 1 (2016) – SuperKEKB 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
  - Currently only inner layer + 2 outer ladders due to production delay due to low yield in ladder assembly (solved by now)
  - Full PXD in Belle II in 2022



One bad quality module, excluded from DAQ

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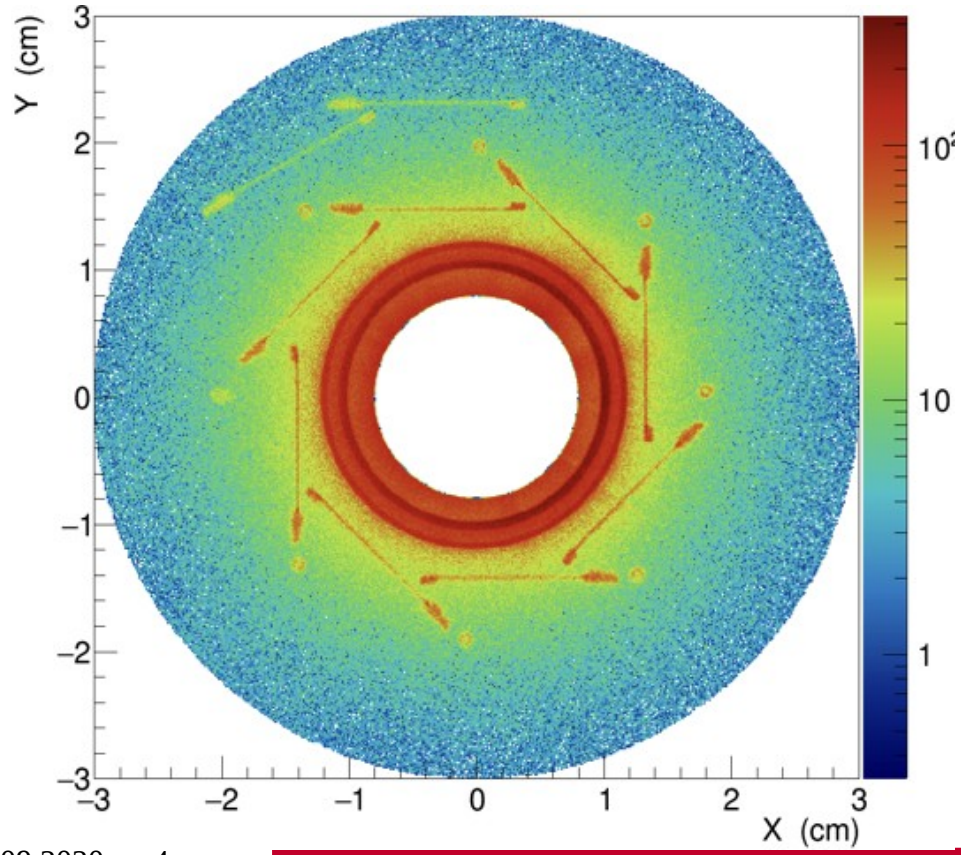
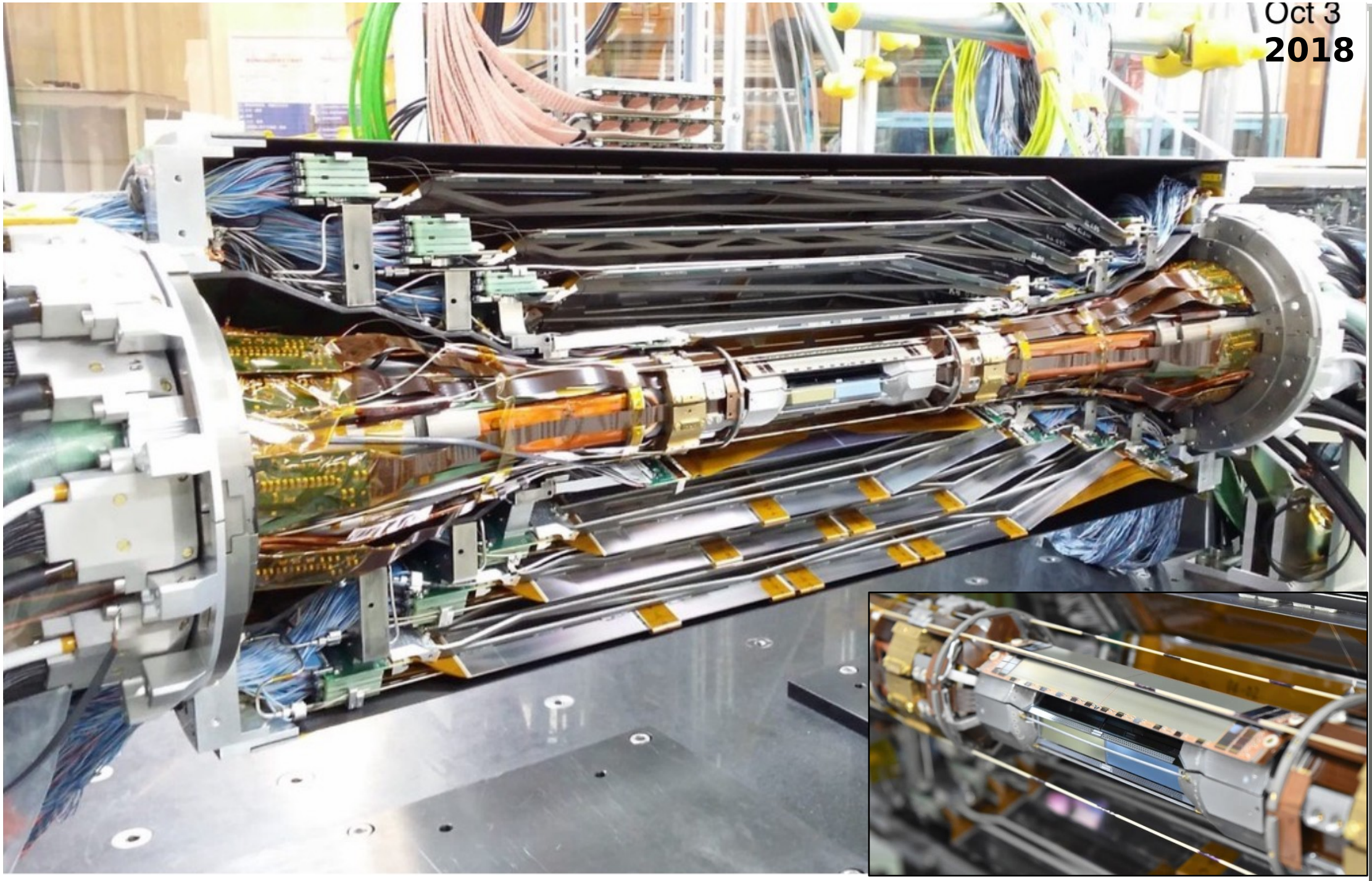
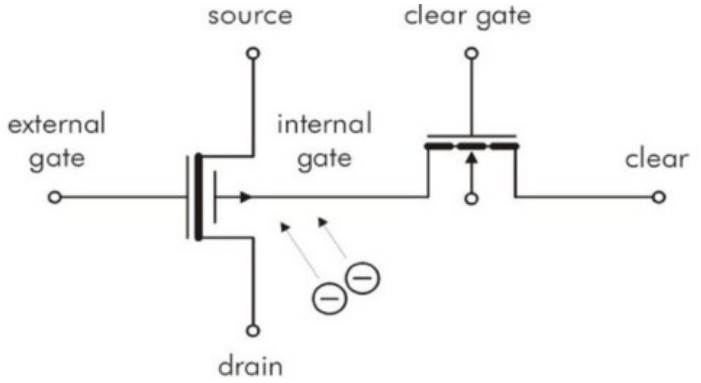


Combining Vertex Detector (One Half Shell)

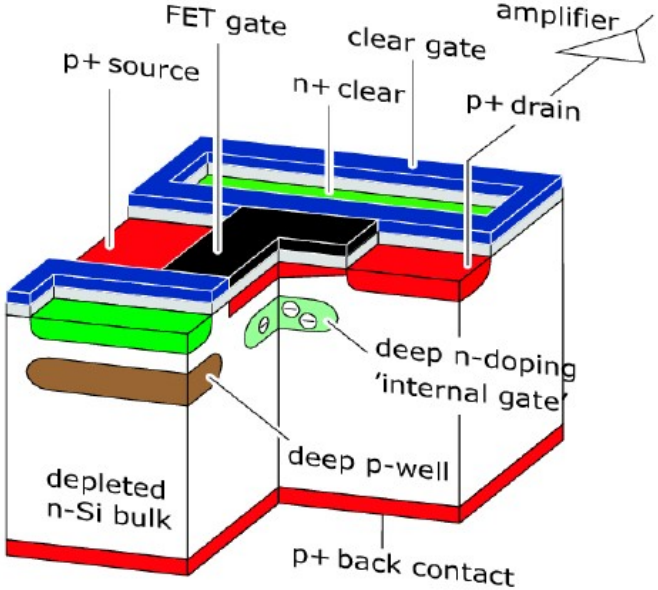


DEPFET Pixel Detector Concept

- Depleted P-channel Field-Effect Transistor pixels on fully depleted silicon bulk
- Fast charge collection (~ns) into internal gate
- Readout current is modulated by collected charge
  - Internal amplification, large Signal-to-Noise
- Gate must be cleared after readout
- Low energy consumption and heat dissipation

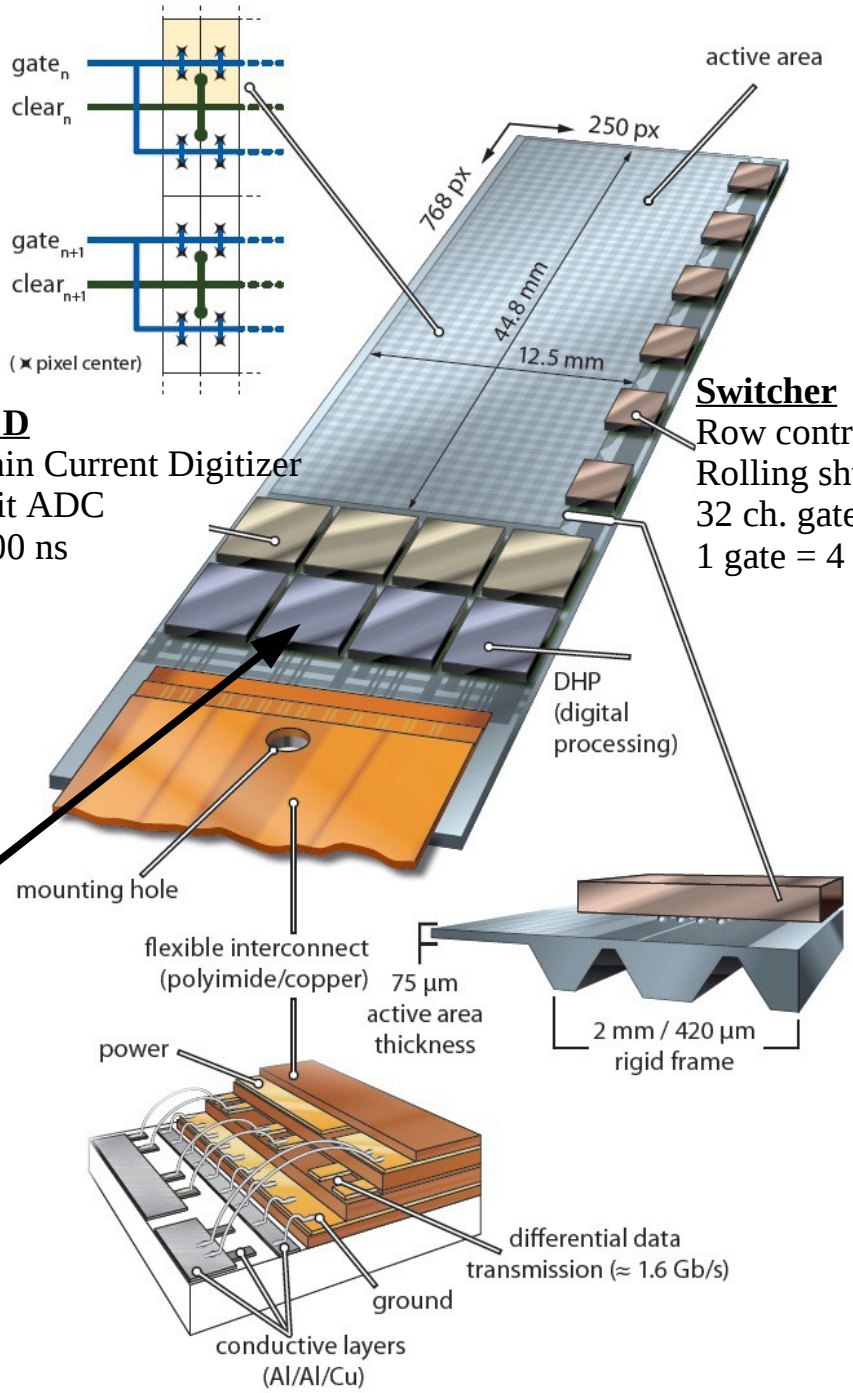


$$g_q = \frac{\partial I}{\partial q} \approx 500 \frac{pA}{e^-}$$



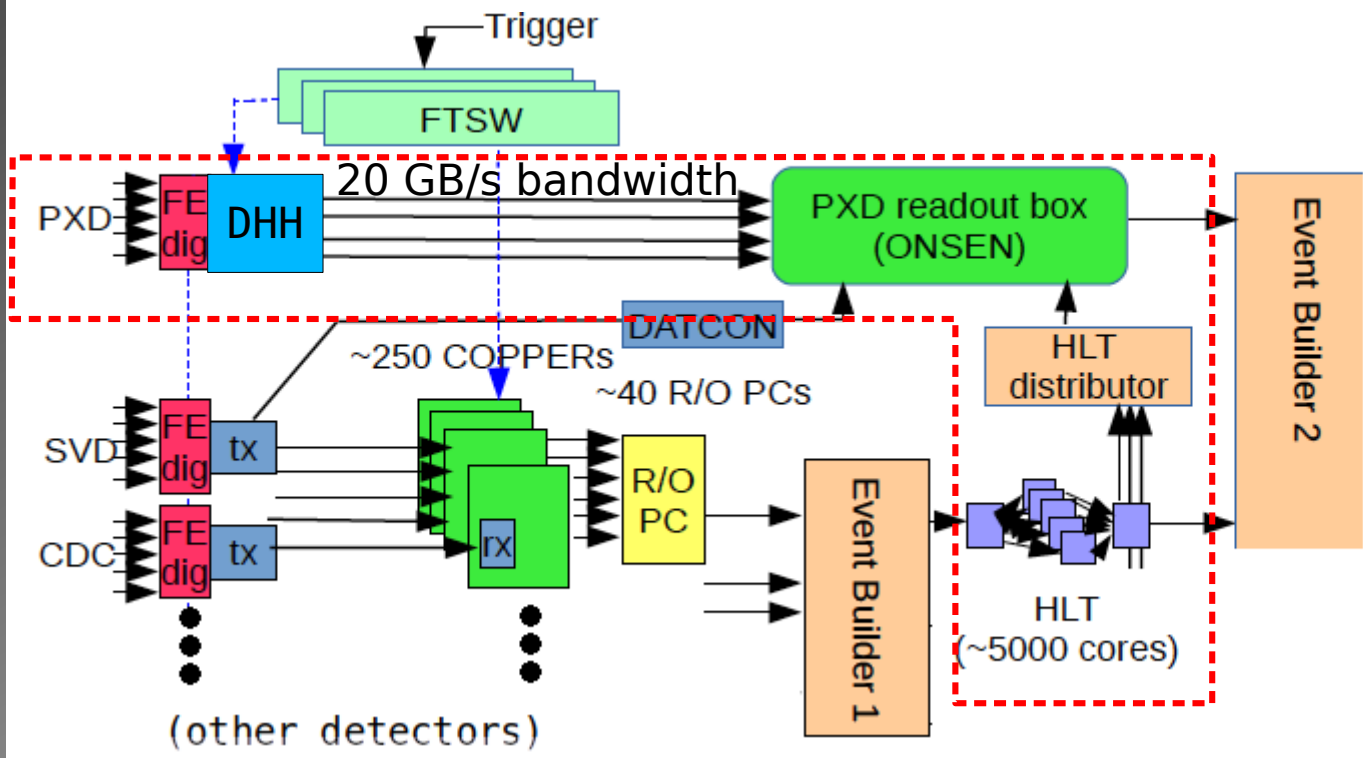
PXD Sensors

- Mechanically self-supporting 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 ASICs
- 40 sensors, 250x768 pixels each
- Power is dissipated mainly in the ASICs at the end of stave
  - 2 phase CO_2 cooling

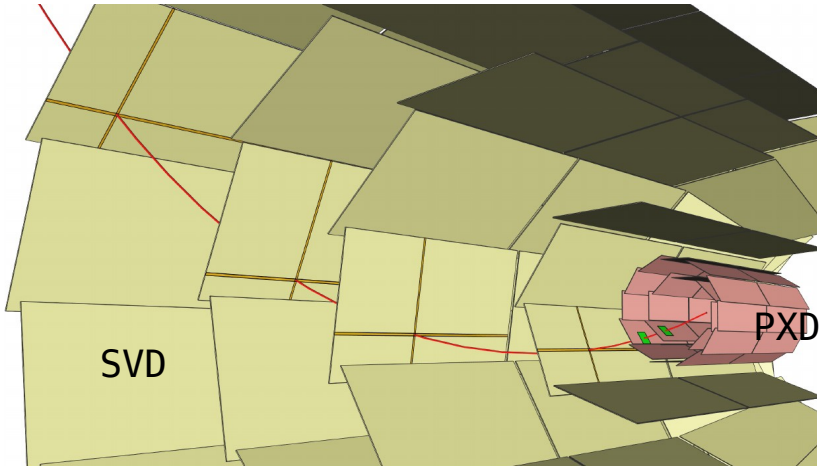


DHP
Digital processing
Zero suppression
Pedestal and common mode correction
Trigger and timing

PXD DAQ Scheme



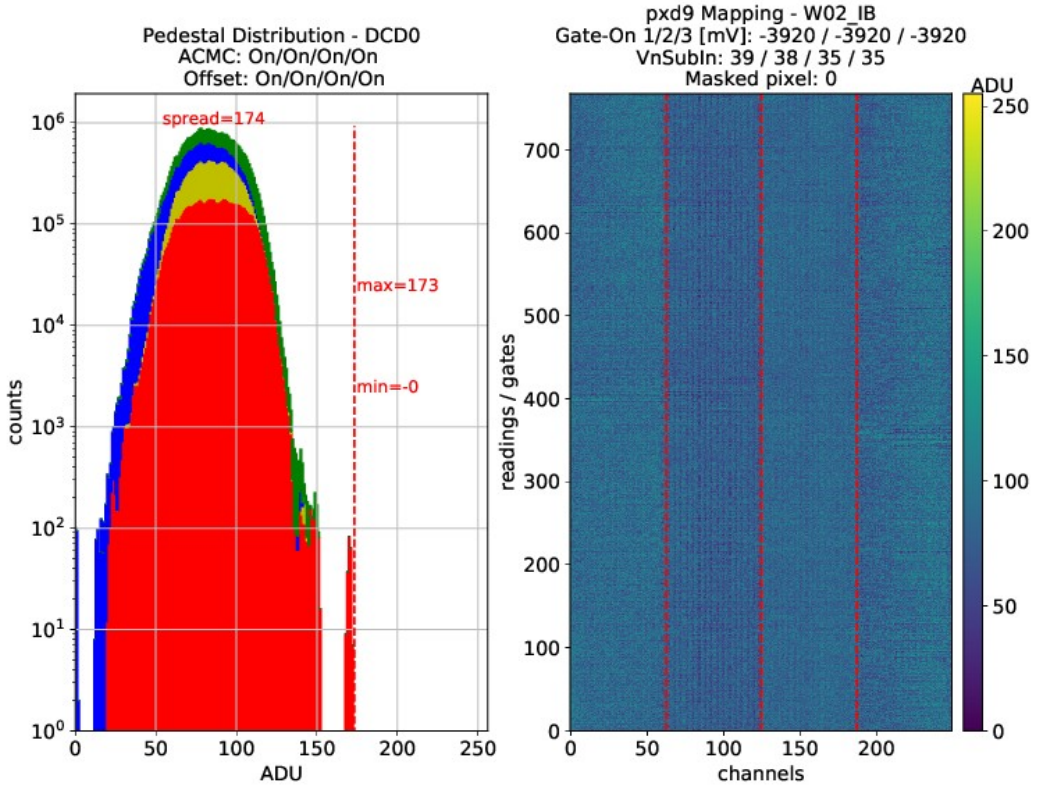
ROI extrapolation on HLT



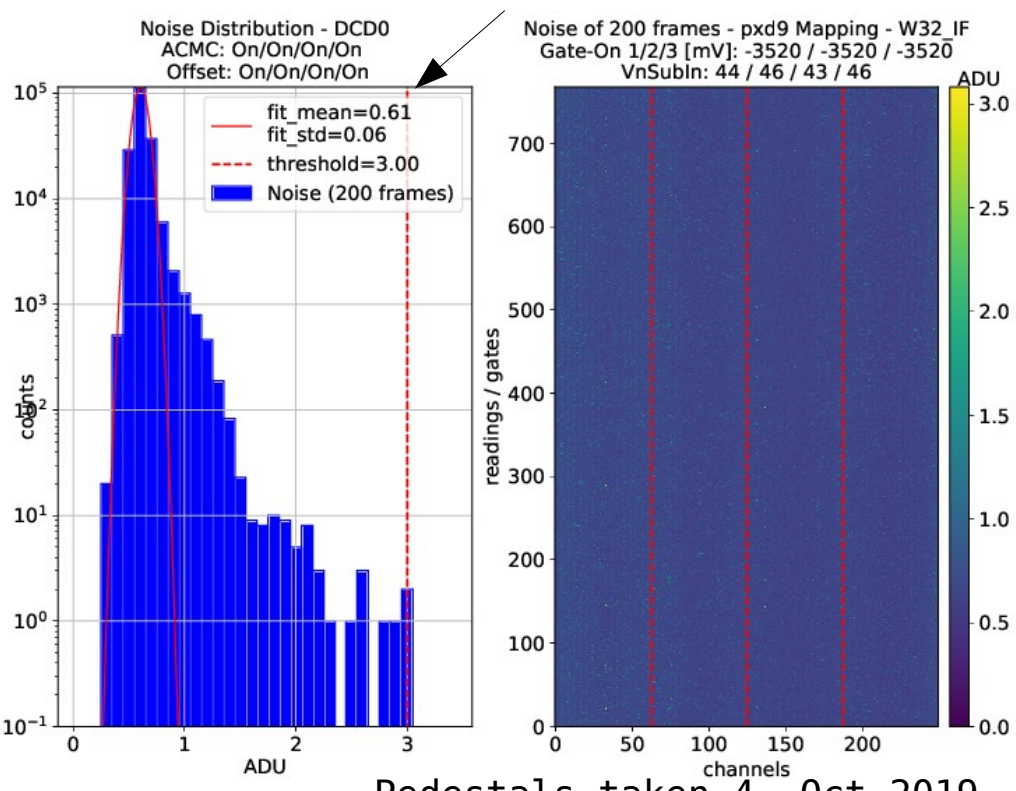
- PXD unfiltered raw data rate → 10x that of other Belle II detectors
  - Separate readout path
  - Goal: Remove data not belonging to tracks
  - Data reduction to 1/10 by High Level Trigger based “Region Of Interest” calculation from CDC and SVD track information
  - Feedback to PXD readout and selection of pixels within rectangular ROIs
- Proven to work: ROI calculation on HLT is always on but filtering is currently turned off as data rates are still low

PXD Calibration and Optimization

- Sensors characterized before installation, but continuous optimization of working points needed
- 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)



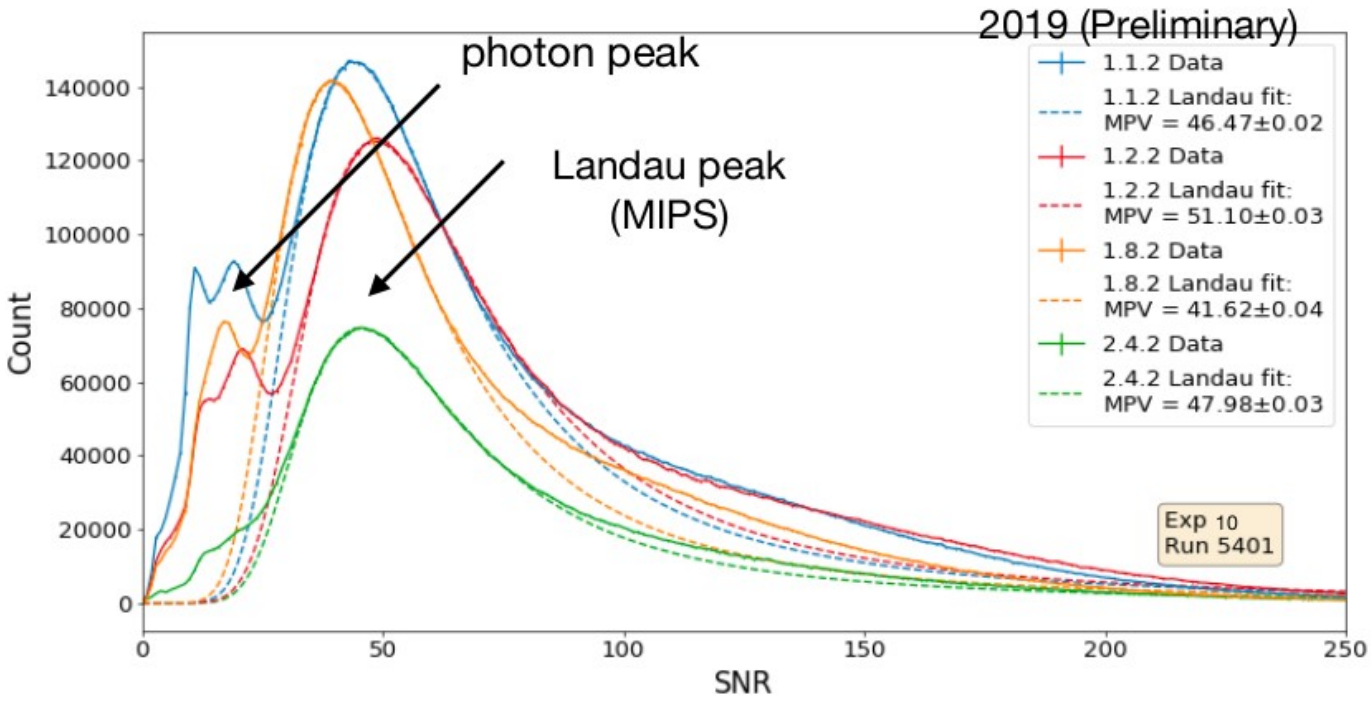
Noise of 0.6 ADU



Pedestals taken 4. Oct 2019

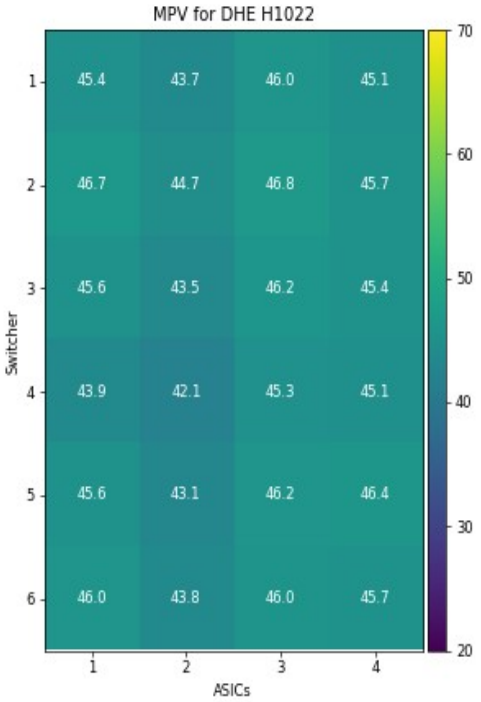
Signal to Noise and Gain Homogenity

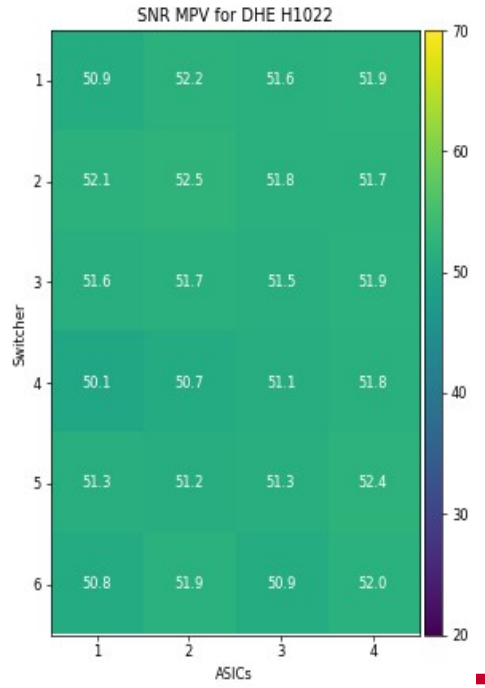
- Most probable value (MPV) and SNR uniform over ASIC combinations within one sensor
- Signal to Noise Ratio ≈ 50

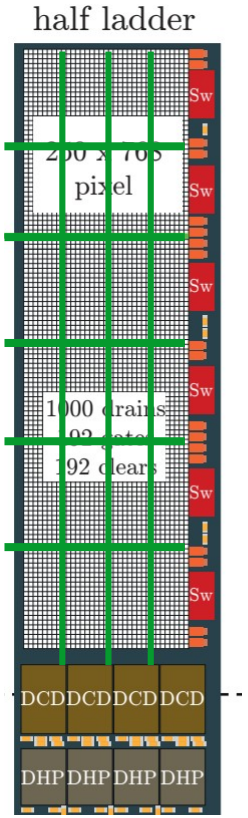


$$MPV \sim g_q \sim \sqrt{I_D} \sim (U_{Gate} - U_{Threshold})$$

Sensitive to radiation damage

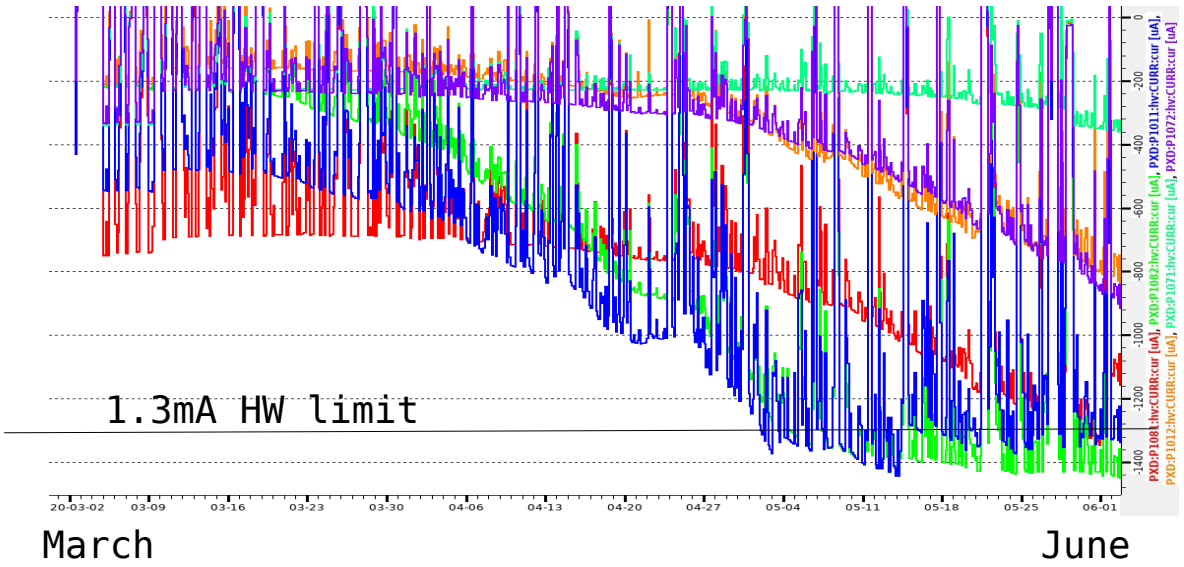




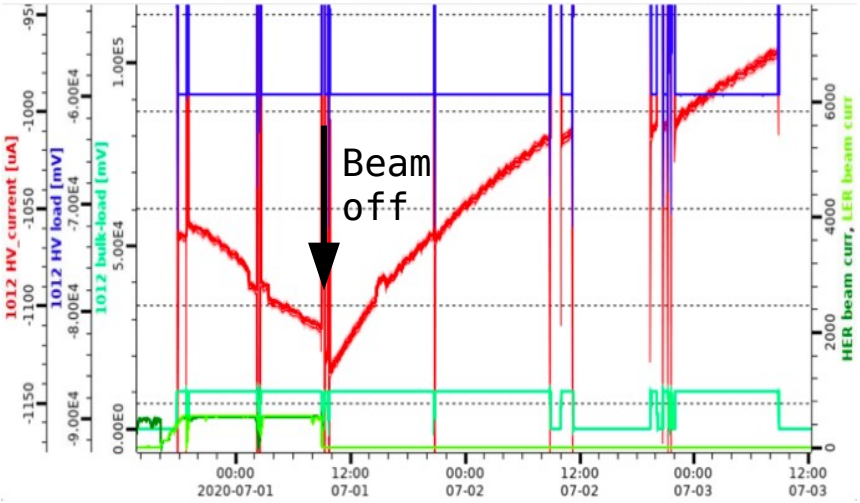


Irradiation Effects

Voltage trend for selected modules



Partly recovering after beam was off



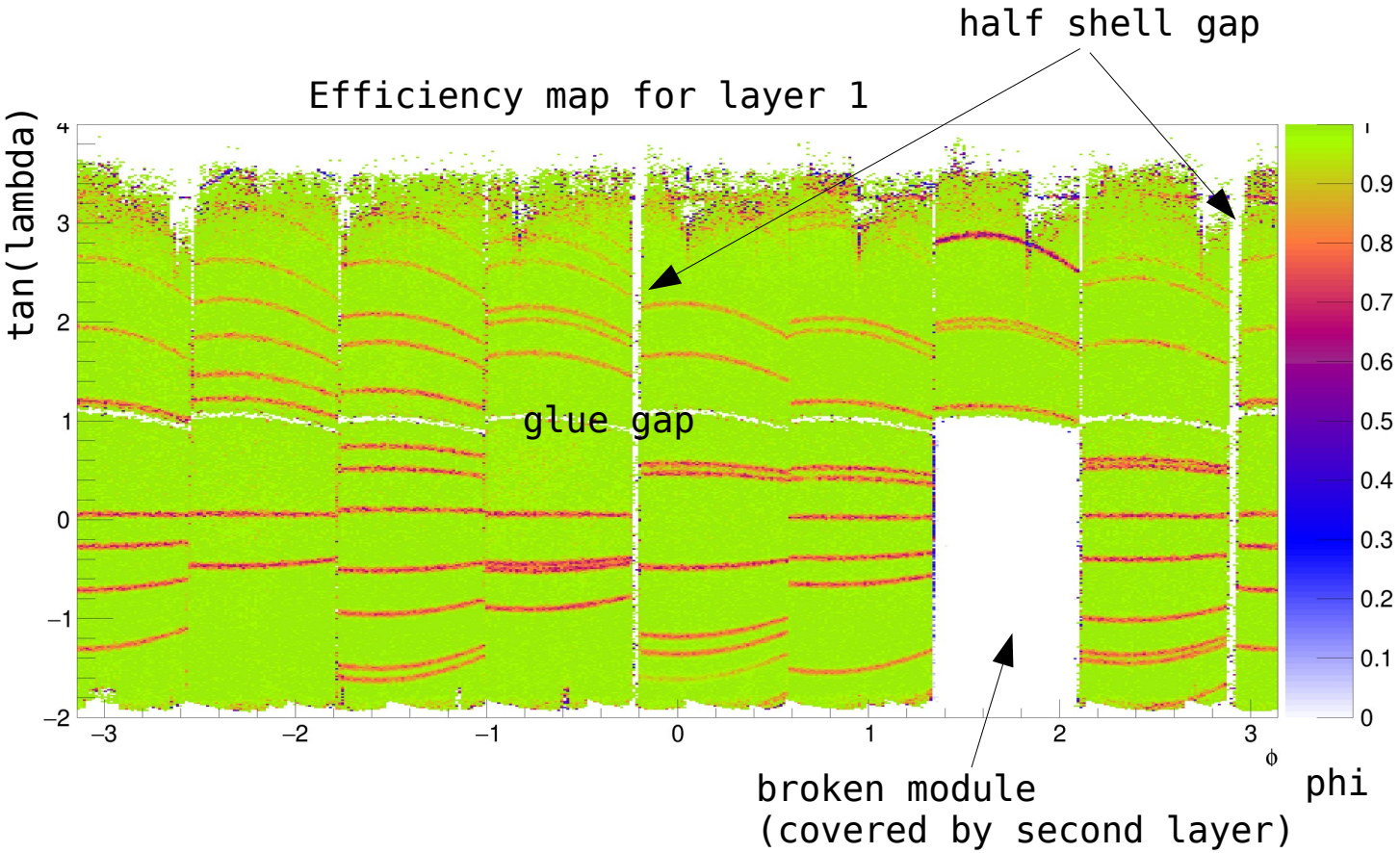
- Sensor reached current limit on HV
  - Set voltage not reached → drop in efficiency & cluster charge
  - Unexpected, reason unclear
  - Not a problem (currents are still low), but power supplies were limiting
  - Modified PSU for higher limit (>2mA) this summer
- Further studies planned this week

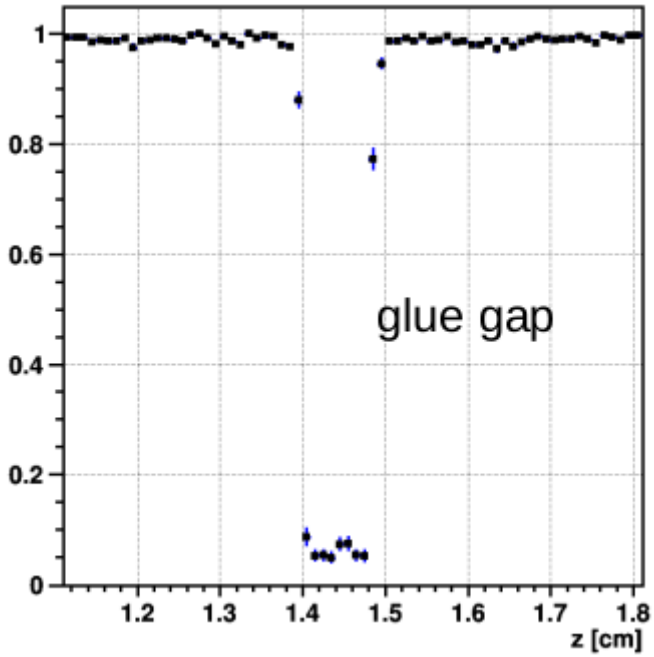
Hit Efficiency

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

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

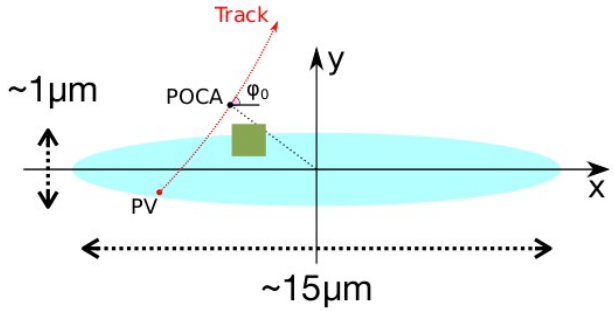
- Dead gates (4 rows each) degrade overall hit efficiency by 2 .5% (good regions > 99 % hit efficiency)

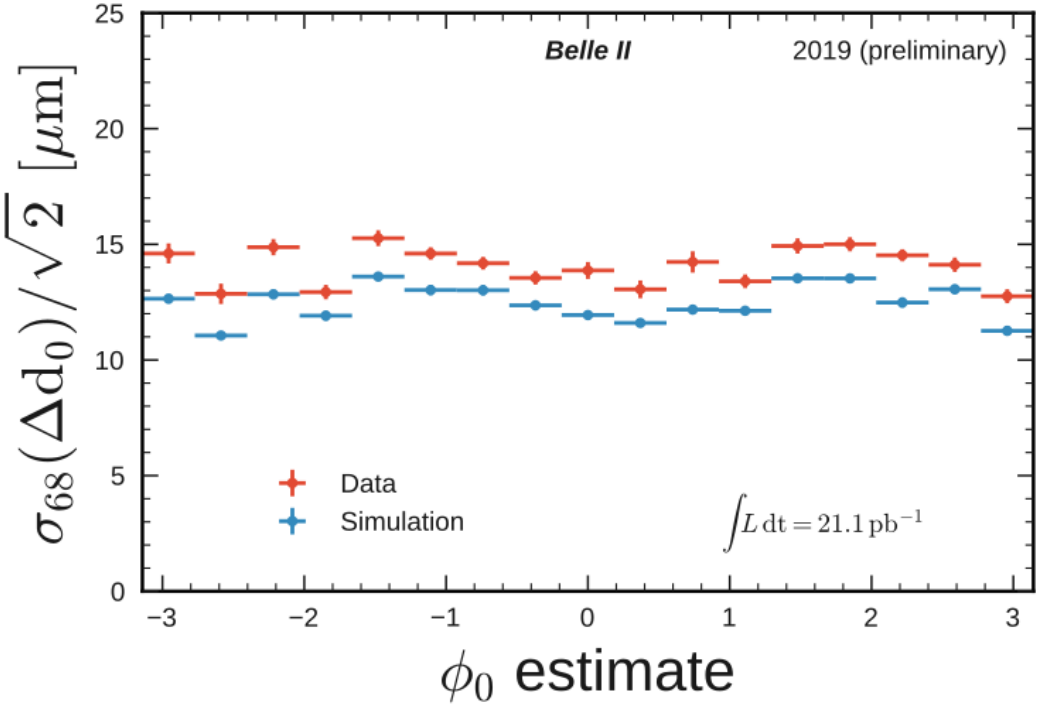


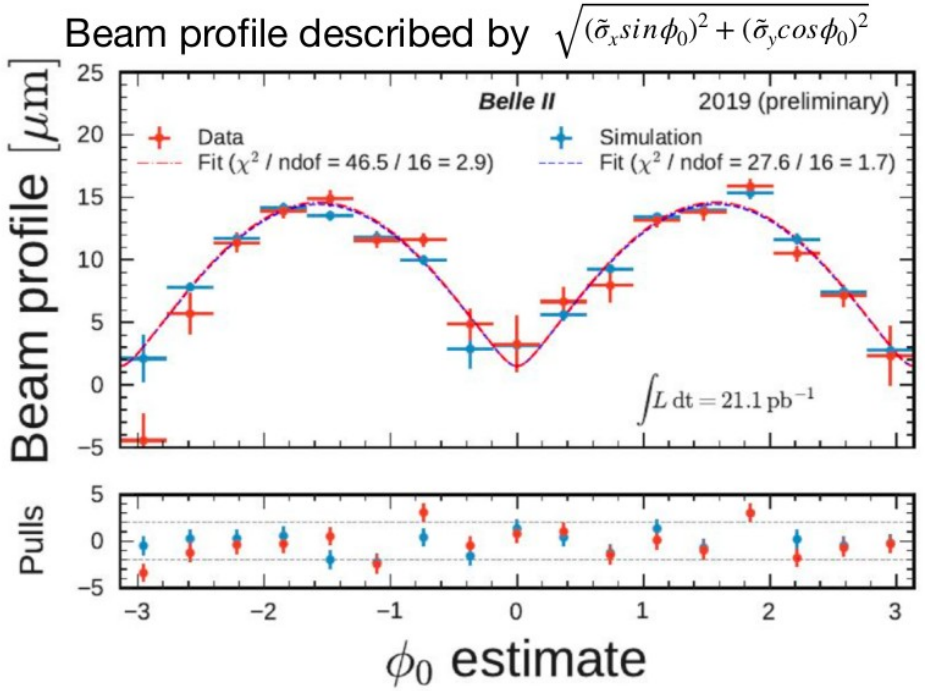


Vertex Resolution

- Measuring the point of closest approach from particles from the interaction point in x, y in di-muon events
  - Exploit small and flat transverse beam spot size in SuperKEKB
- Vertex resolution with PXD is close to MC expectations
  - d_0 resolution of 14.1 µm (data), MC 12.5 µm







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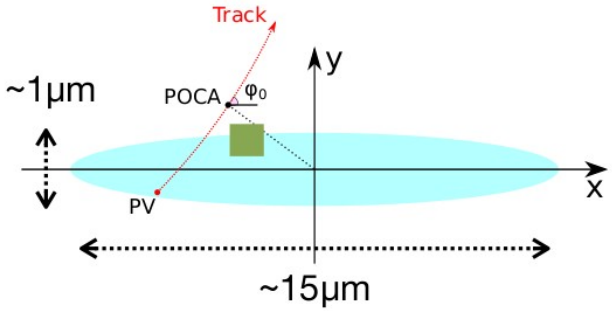
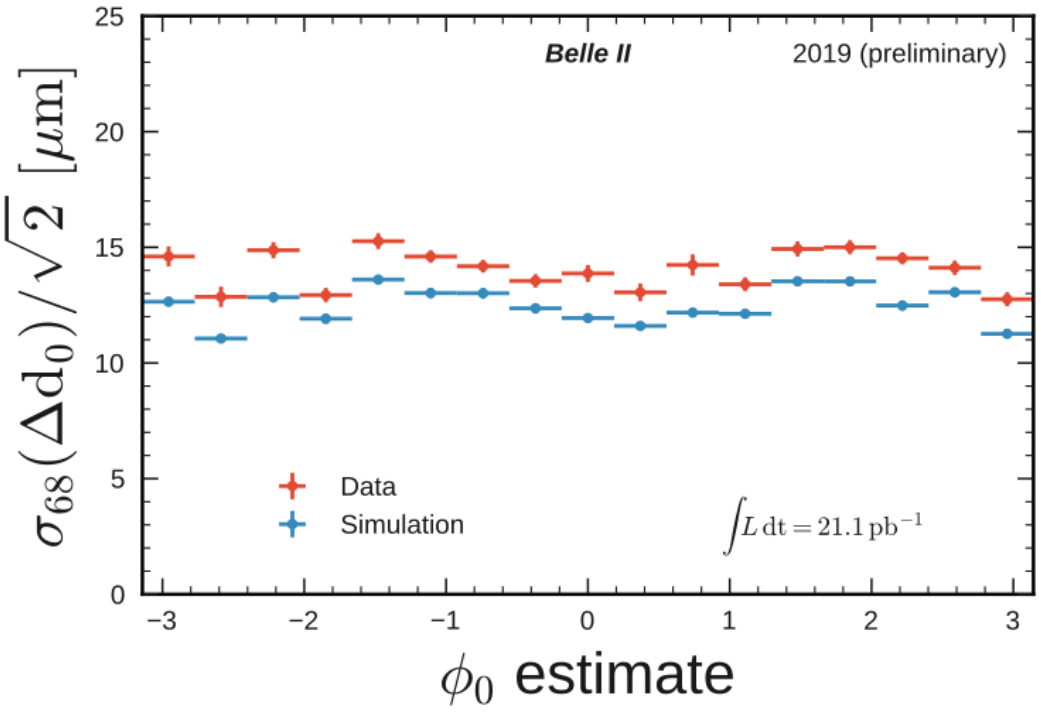
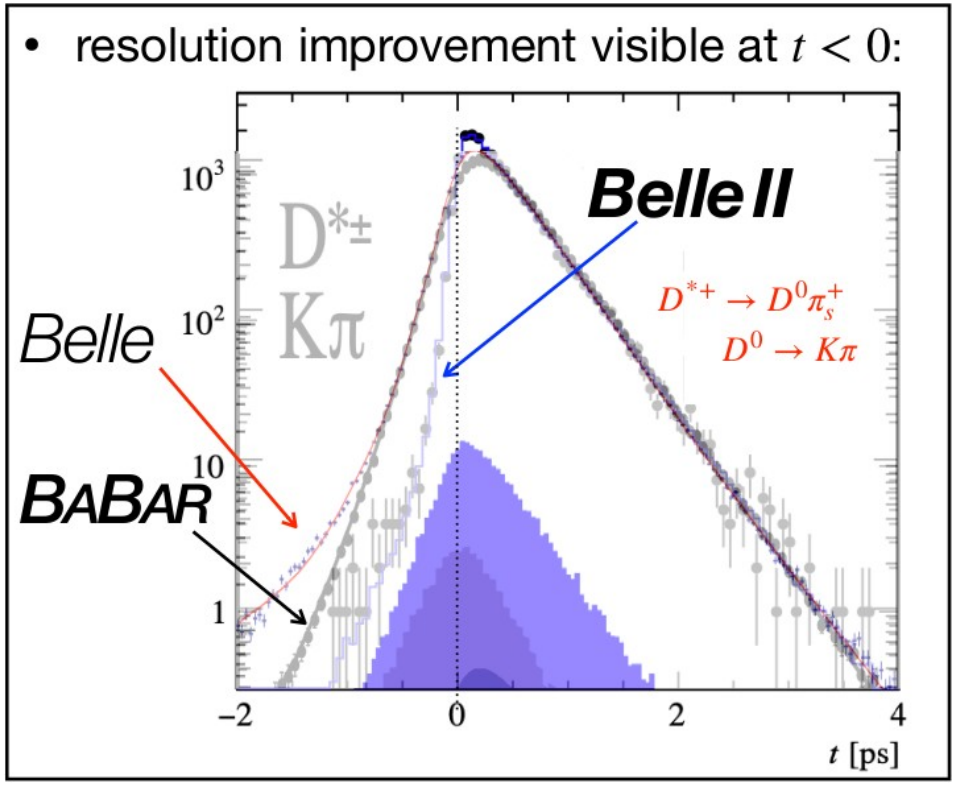
- Vertex resolution → Physics: life time measurement



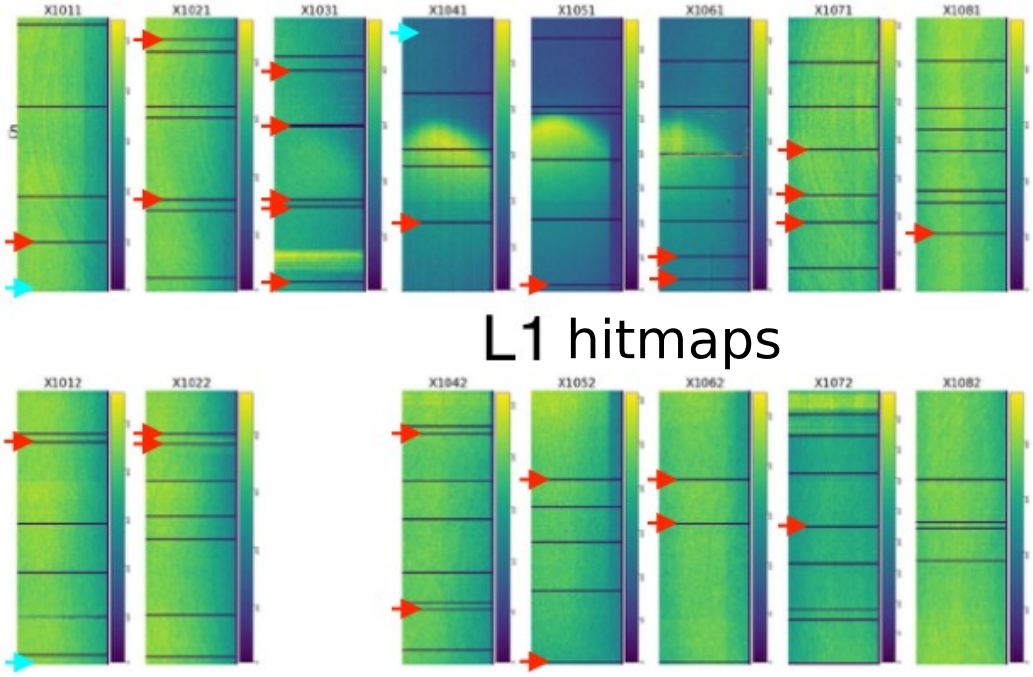




Beam Incidents Affecting PXD

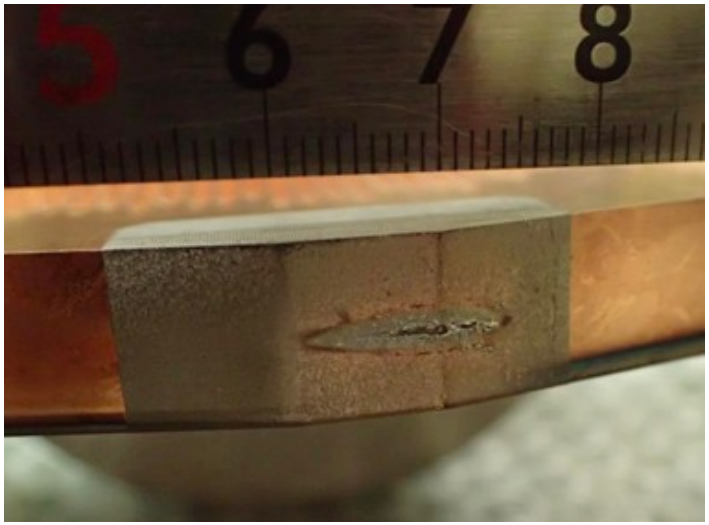
- Several incidents in 2019 and 2020:
  - QCS power supply failure
  - Instable beam due to beam dust particles (?), collimator damaged
  - Mis-operation of fast orbit feedback system
  - Beam abort not issued by diamond sensor
- Large <u>instant</u> radiation burst before beam was dumped (estimate: 300 rad in <40µs)
- Permanent damage in PXD: “dead” gates
  - Dangerous for QCS and other detectors, too

QCS:
Superconducting quadrupole coils close to interaction point



L1 hitmaps

Damaged collimator head

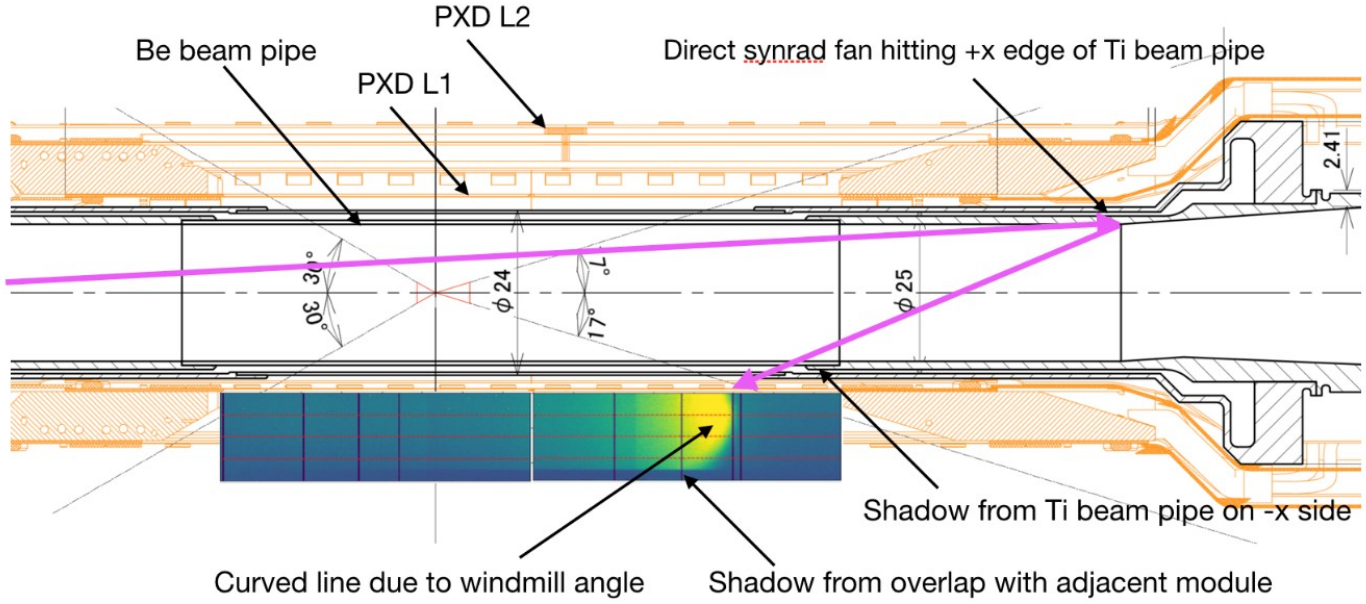


Mitigations

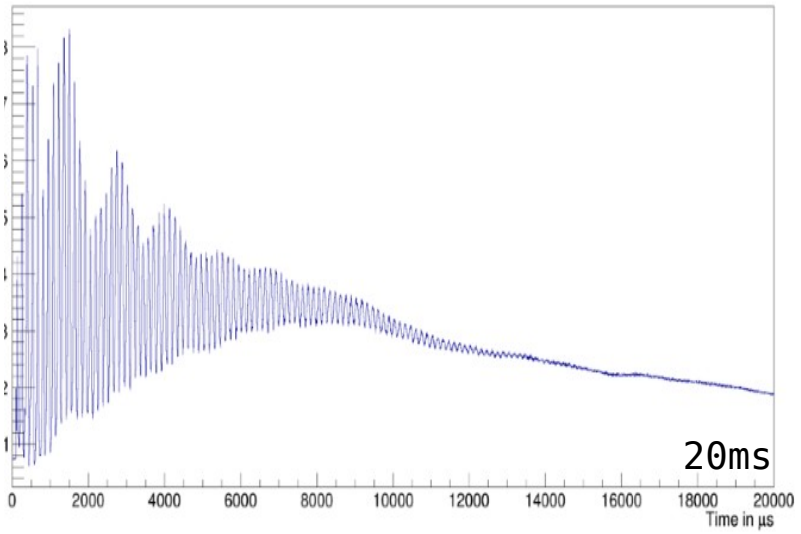
- Assumption & Studies
  - Single Event Effect (SEE) in Switcher ASIC?
  - → Several dedicated irradiation test for ASICs and sensor with e- beam at MAMI (next one scheduled end of this week)
    - Study tolerance to radiation burst
    - Can switching off prevent damage to the modules?
- The present emergency shutdown did not protect the sensors
  - → Upgrade the power supplies with a much faster system is ongoing O(100ms→100us)
  - Connected the PXD power supplies directly to the beam loss/diamond sensors
- From accelerator side
  - Understand and prevent this kind of uncontrolled beam losses
  - Faster beam abort and beam loss detection
  - Improve beam collimators

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!
  - May result in inhomogeneous irradiation of sensor
  - Stemming from injection, clear time structure
- Observation of photon components from other sources
- New beampipe (in preparation for 2022)
  - Switch from betatron to synchrotron injection (to be tested)

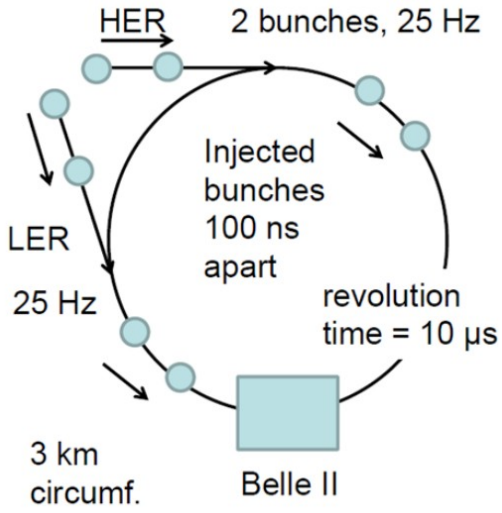


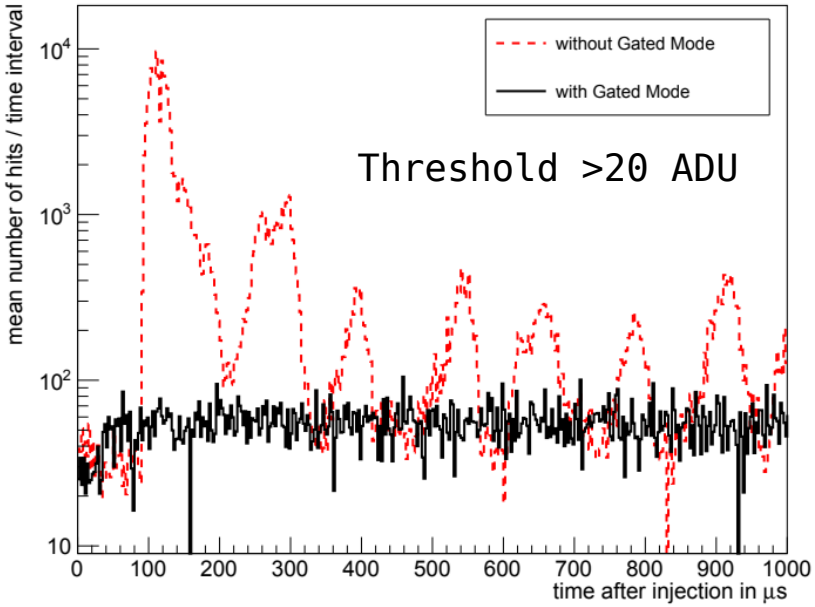
Time evolution of SR after injection



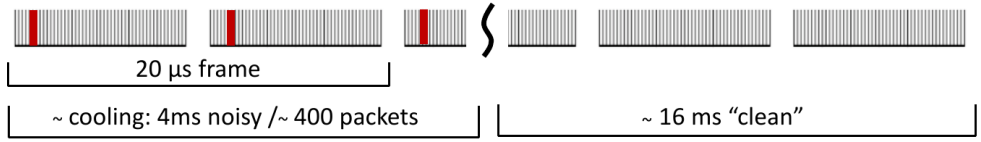
Gated Mode

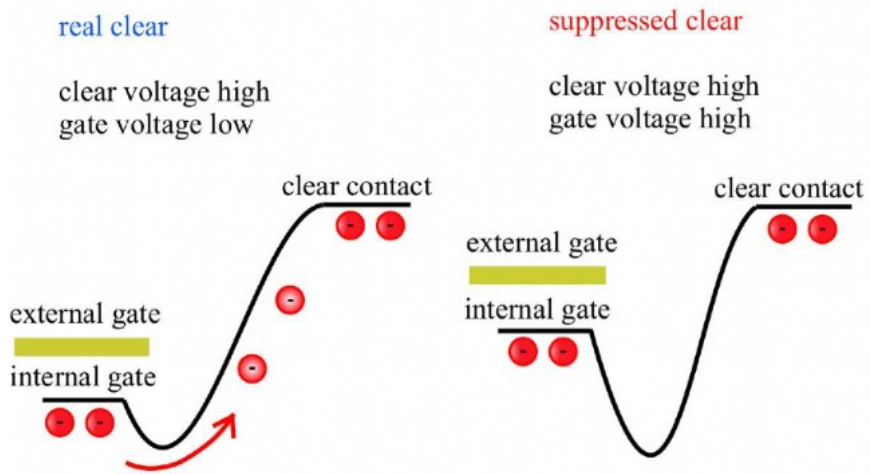
- SuperKEKB is using top up injection
- PXD can be “blinded” to suppress the noise from a freshly injected bunch
- Gating: change the voltages (potentials) such, that no new charge is collected while preserving the already stored charge.
- Gating two times per readout cycle
- Concept proved to work, but not ready for use in physics runs
  - Not needed now as overall occupancy is still low





SuperKEKB bunch pattern





Summary

- Belle II first particle physics experiment to use a DEPFET pixel vertex detector
  - Challenging operating conditions close to the IP
- Good performance demonstrated
  - Vertex resolution close to MC expectations
- Suffering from damages due to to instantaneous radiation bursts

Outlook

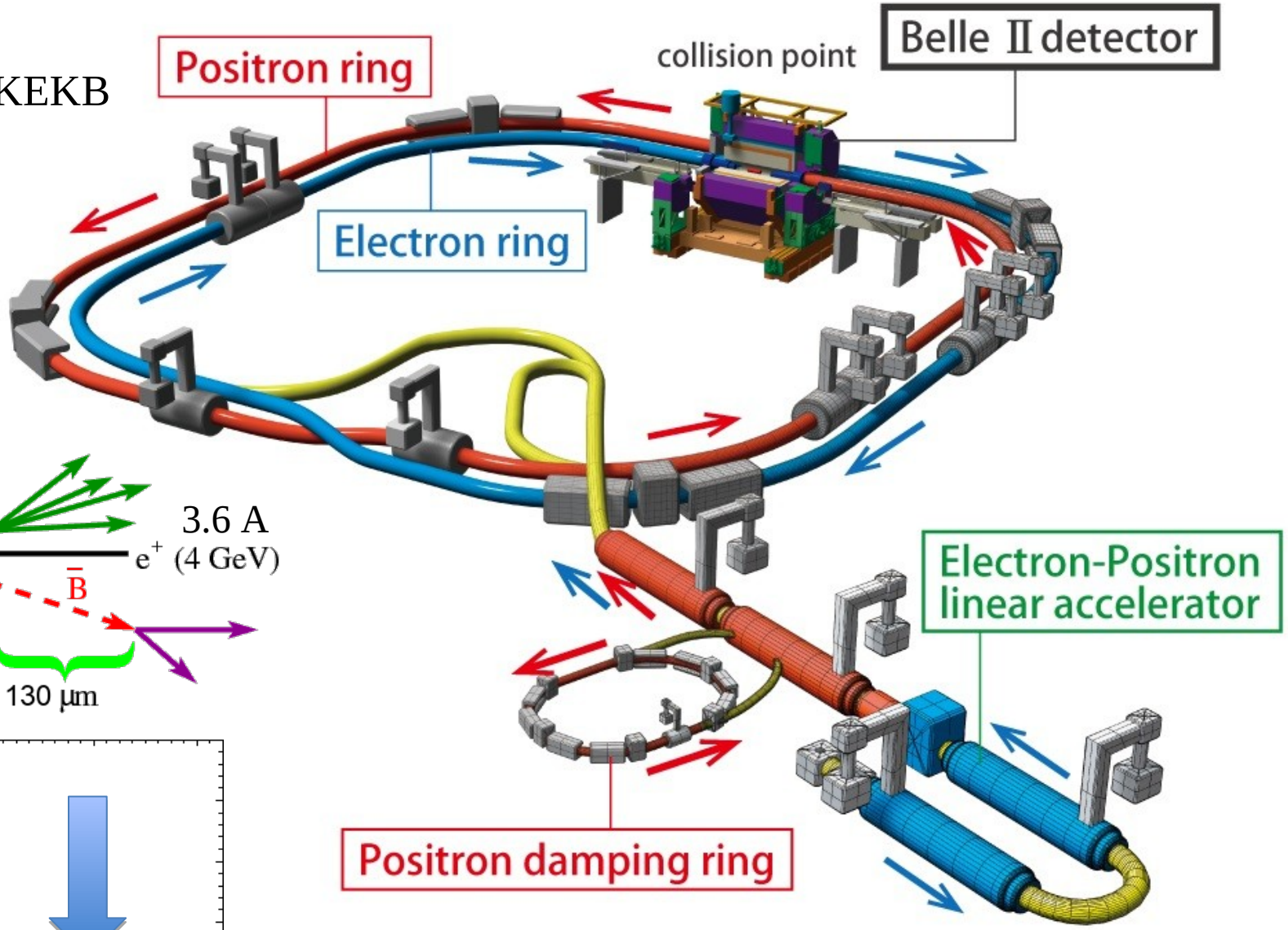
- Understand and prevent damage by “beam incidents”
- Production, assembly and testing of new modules is ongoing
  - Replace current PXD with all full detector setup in 2022

Backup

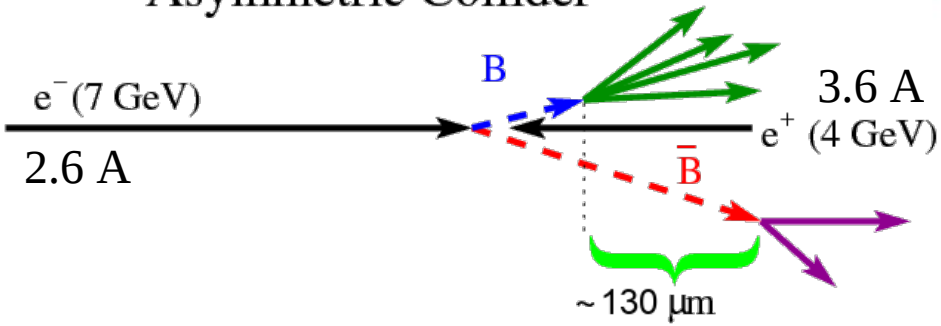
COVID-19

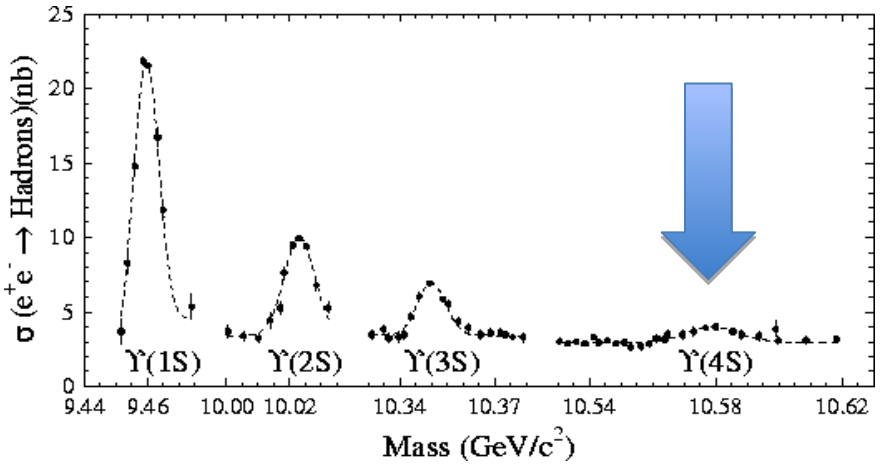
- SuperKEKB and Belle II continued to run until scheduled summer break
  - Operation will restart in October
- Impact
  - No external collaborators (international and nation) allowed on campus from March on
  - Distancing of shifters (Control Room, sub-detectors)
  - → Remote shifts introduced even for control room shifts
- PXD was already prepared for remote operation from the beginning!
  - Minimal impact on operations
  - But problematic for maintenance work over summer

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



Asymmetric Collider

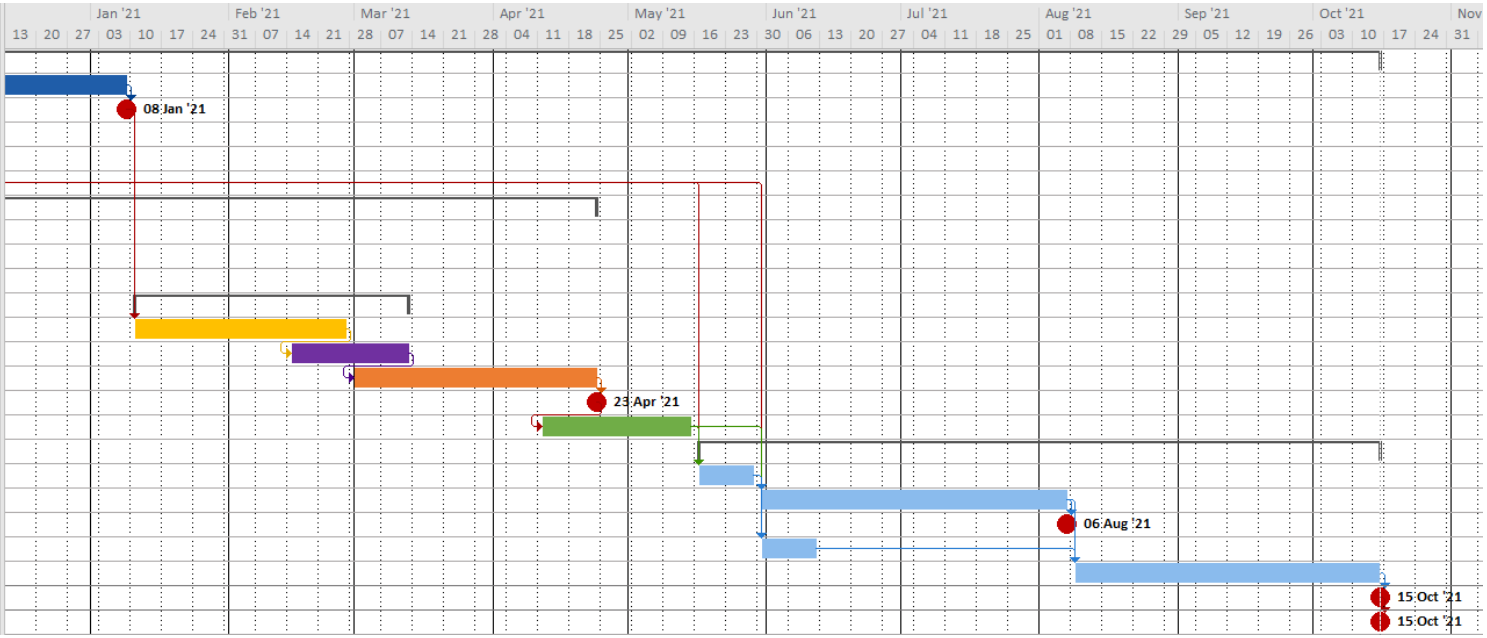




$$L = \frac{N_+ N_- f}{4\pi\sigma_x^* \sigma_y^*} R_L$$

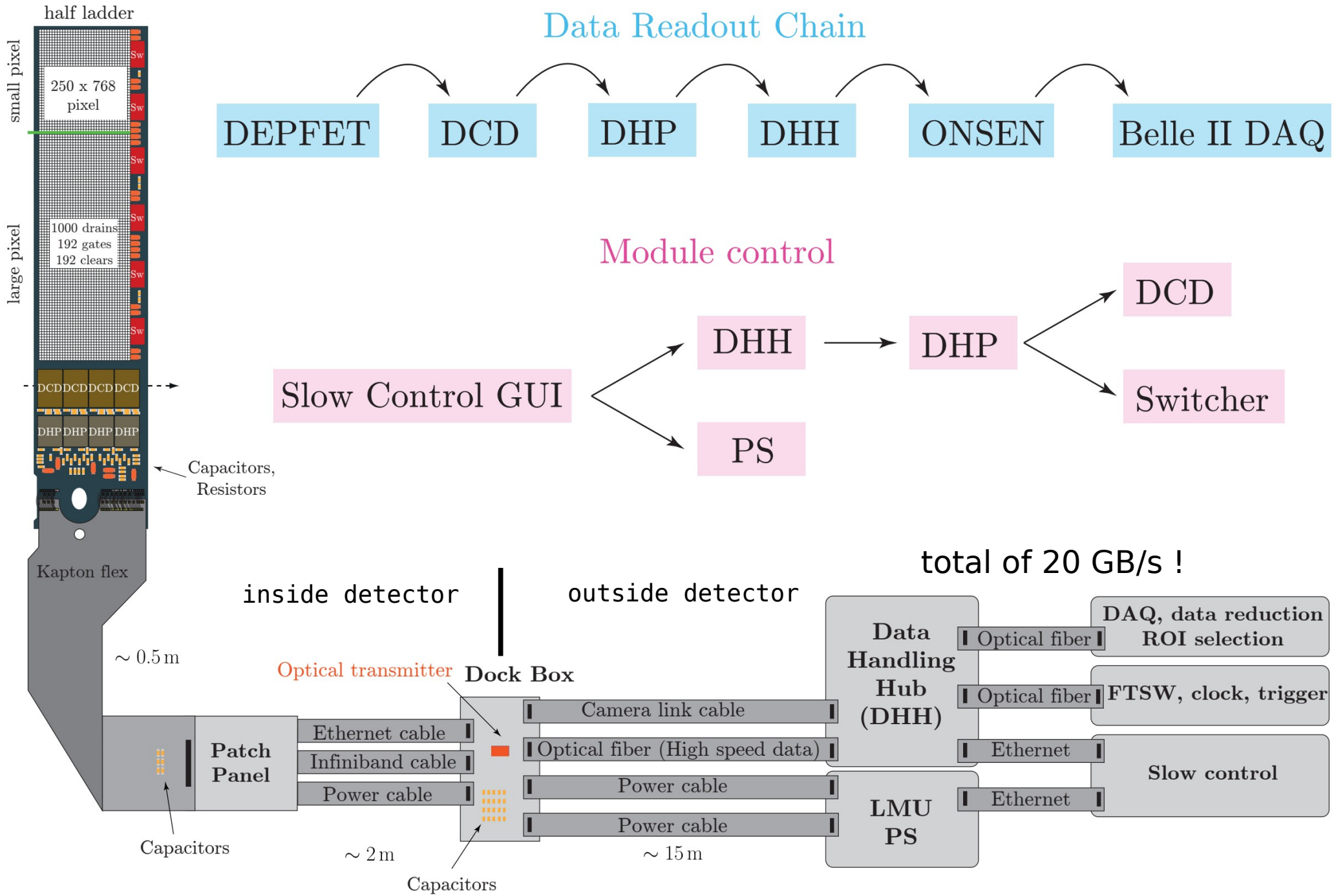
PXD Schedule – Conservative Scenario

	Task Name	Start	Finish	Duration
1	**PXD2**	**Mon 03/02/20**	**Fri 15/10/21**	**445 dys**
2	PXD9-21: 12 wafers Phase 2-3	**Mon 04/05/20**	Fri 08/01/21	9 mons
3	**sensors from PXD9-21a**	Fri 08/01/21	Fri 08/01/21	0 dys
4	**L2 module assembly**	**Mon 20/04/20**	**Fri 12/06/20**	**40 dys**
5	assemble all available L2 Ladders	Mon 20/04/20	Fri 12/06/20	8 wks
6	**first batch L2 ladders available**	Fri 12/06/20	Fri 12/06/20	0 dys
7	**L1 Module assembly**	**Mon 03/02/20**	**Fri 23/04/21**	**320 dys**
8	batch PXD21-1 (2 L1 pairs) ready	Mon 03/02/20	Mon 03/02/20	0 dys
9	Phase 2 modules (1 L1 pair) ready	Mon 03/02/20	Mon 03/02/20	0 dys
10	2 L1 ladders ready	Mon 03/02/20	Mon 03/02/20	0 dys
11	**batch PXD21-3a (7 pairs)**	**Mon 11/01/21**	**Fri 12/03/21**	**45 dys**
12	FC, SMD, possibly rework	Mon 11/01/21	Fri 26/02/21	7 wks
13	Kapton attachment	Mon 15/02/21	Fri 12/03/21	4 wks
14	module char.: BN/DESY/HLL/MPP	Mon 01/03/21	Fri 23/04/21	8 wks
15	**All Modules done**	Fri 23/04/21	Fri 23/04/21	0 dys
16	assemble 7 remaining L1 ladders	Mon 12/04/21	Fri 14/05/21	5 wks
17	**Half Shell Assembly**	**Mon 17/05/21**	**Fri 15/10/21**	**110 dys**
18	HS1	Mon 17/05/21	Fri 28/05/21	2 wks
19	HS1 Test at DESY	Mon 31/05/21	Fri 06/08/21	10 wks
20	**Half Shell 1 ready**	Fri 06/08/21	Fri 06/08/21	0 dys
21	HS2	Mon 31/05/21	Fri 11/06/21	2 wks
22	HS2 test at DESY	Mon 09/08/21	Fri 15/10/21	10 wks
23	**Half Shell 2 ready**	Fri 15/10/21	Fri 15/10/21	0 dys
24	**Ship Half Shells to KEK**	Fri 15/10/21	Fri 15/10/21	0 dys



- After half shell assembly assume long (2x10 weeks) testing time before transport to KEK in mid October 2021
- Current base plan:
  - extract and dismount present VXD in January 2022
  - even under above conservative assumptions have ~ 3 months contingency for PXD completion
- If new beam pipe ready, aligned and tested early enough then mounting of PXD could already start in 2021

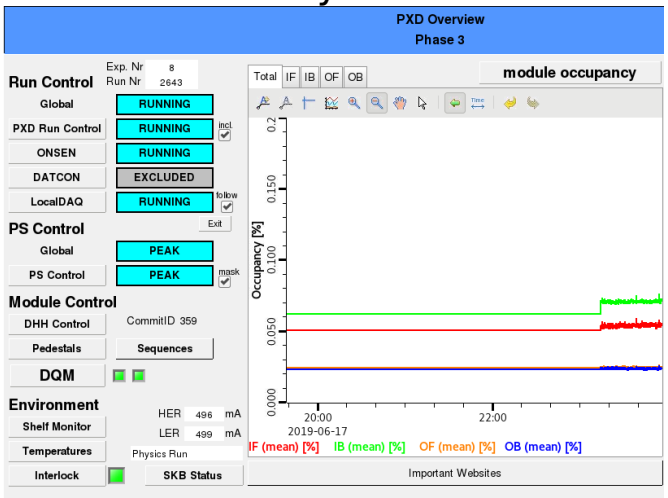
System Layout



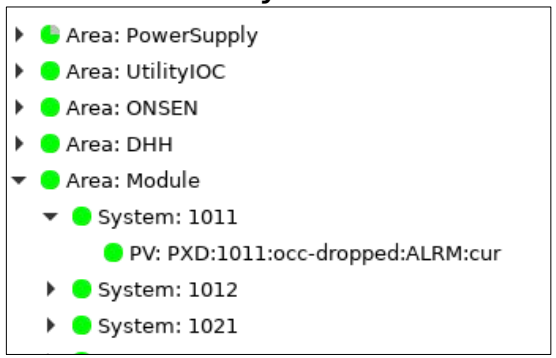
Slow Control and Monitoring

- 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

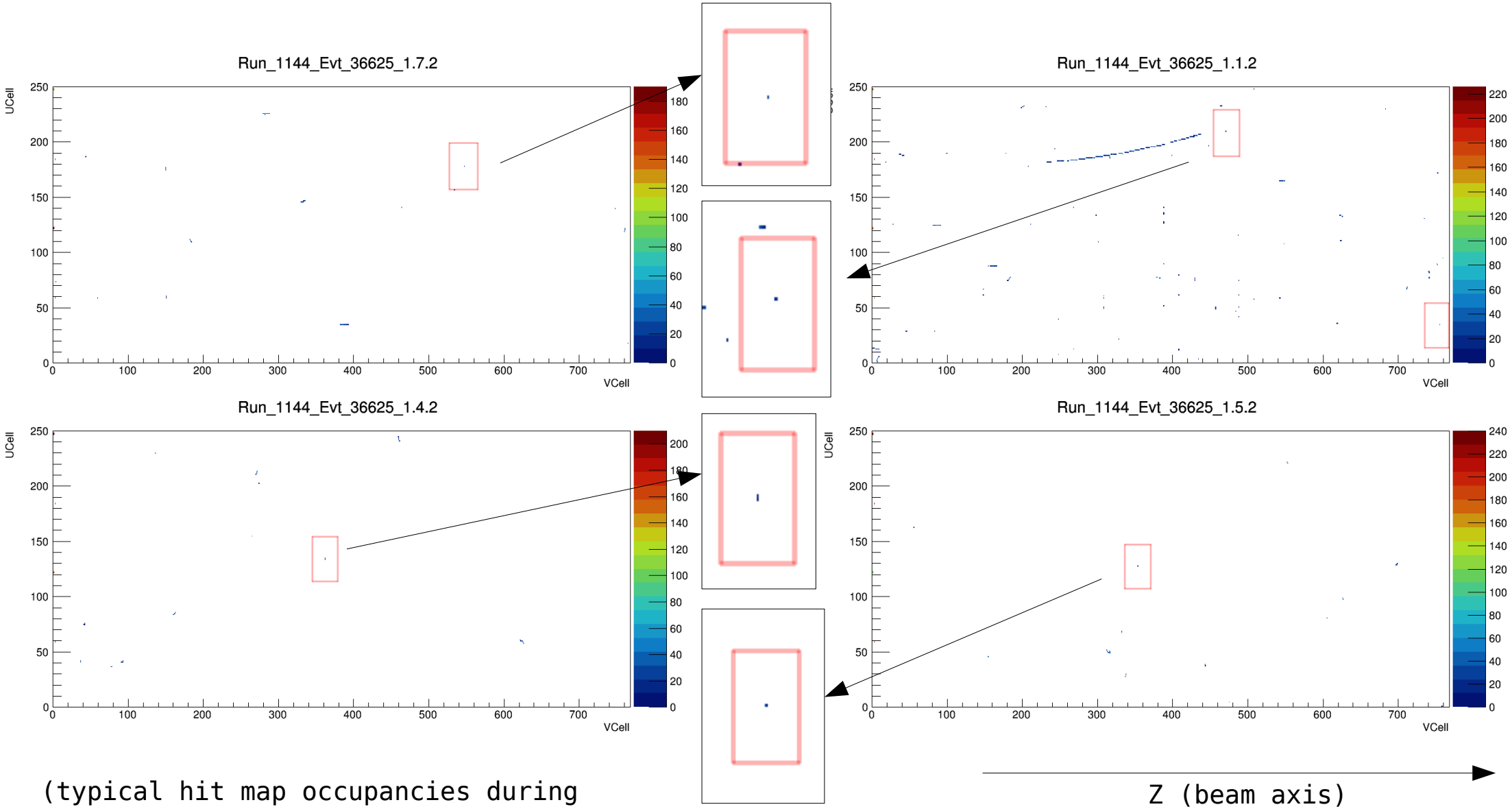


Alarm System Tree



Online ROI Selection

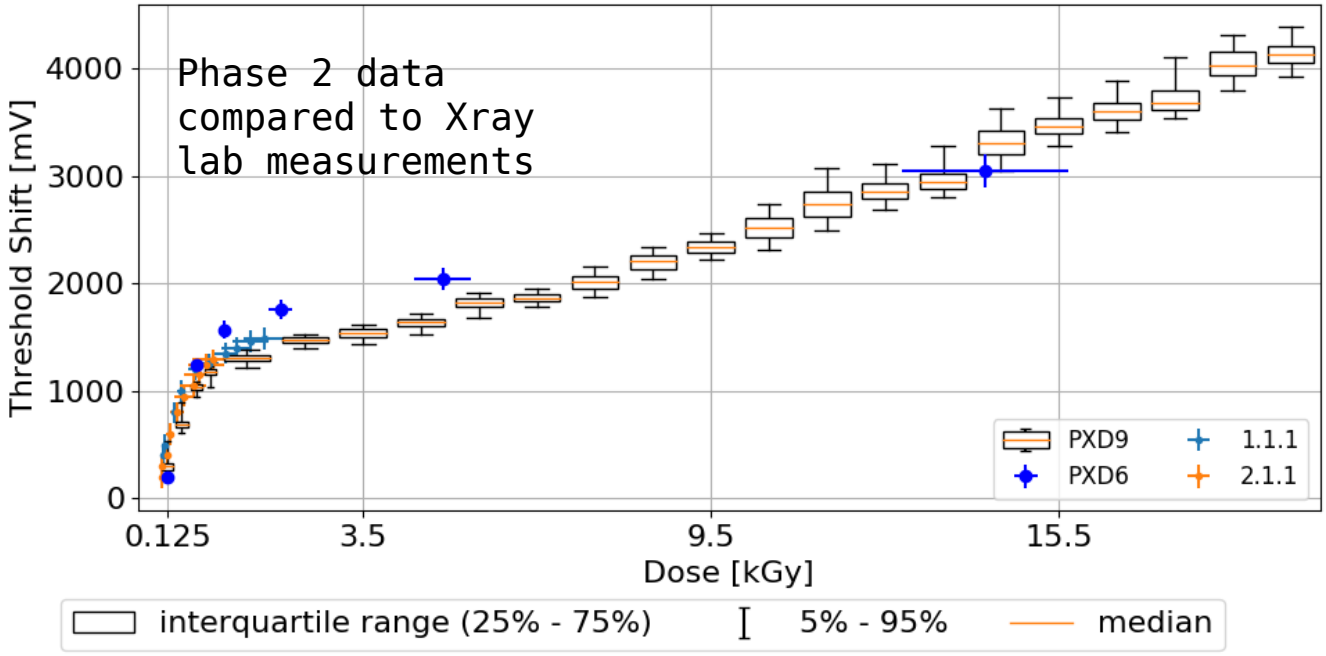
- Region Of Interest selection needs accurate ROI calculation on High Level Trigger
- Hit maps for different modules of same event: clusters fit to ROI computed on HLT

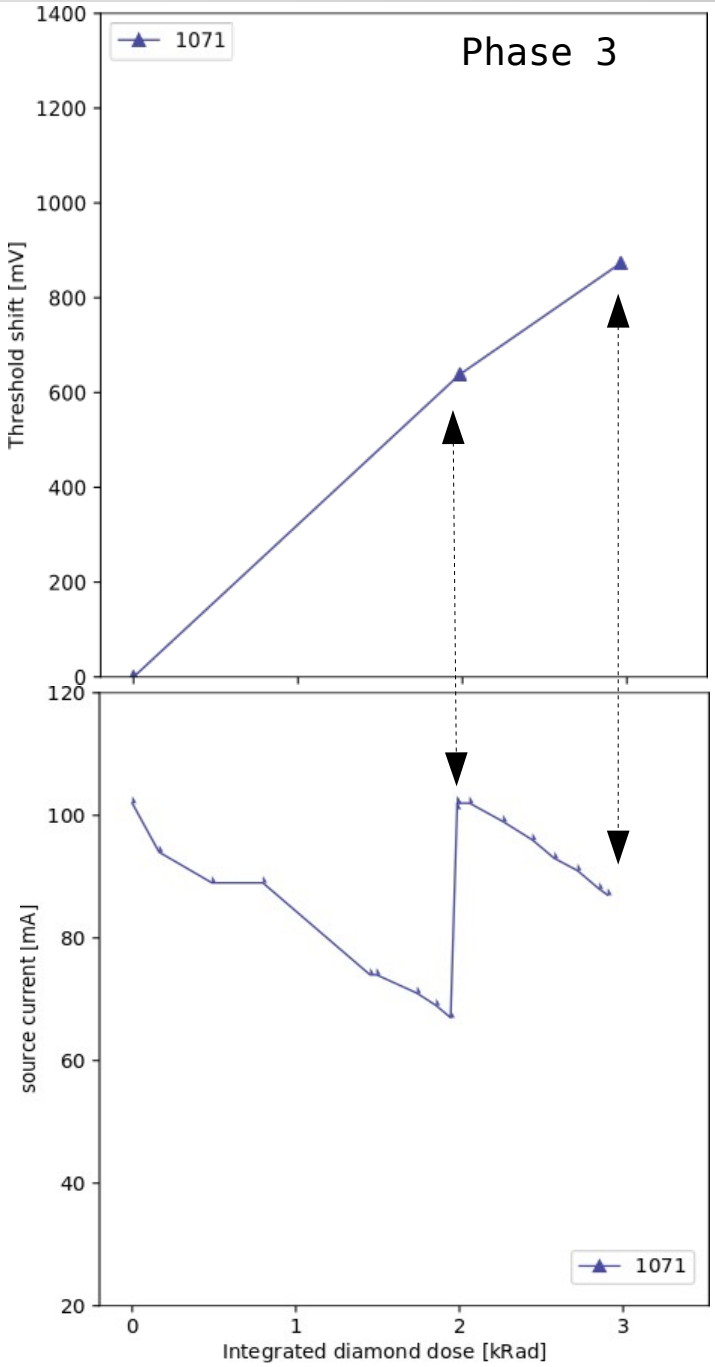


(typical hit map occupancies during spring 2019 run)

Compensation for Radiation Damage

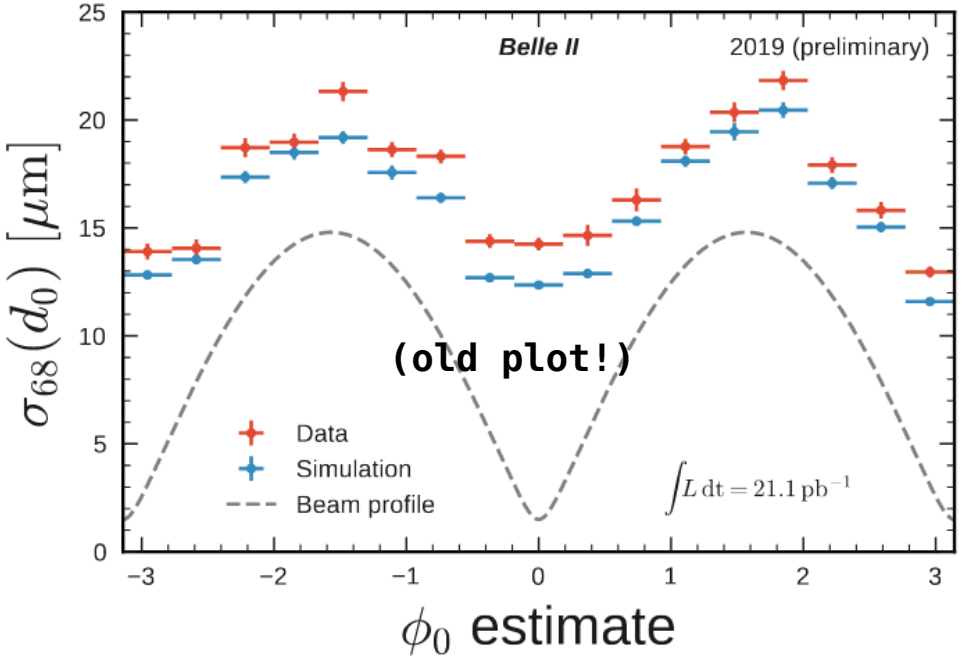
- MPV for cluster changes with irradiation
- Expected, must be corrected for by increasing voltages
- Voltages adjusted to have same source current (100 mA) again
- Radiation dose from diamond sensors → scaling needed

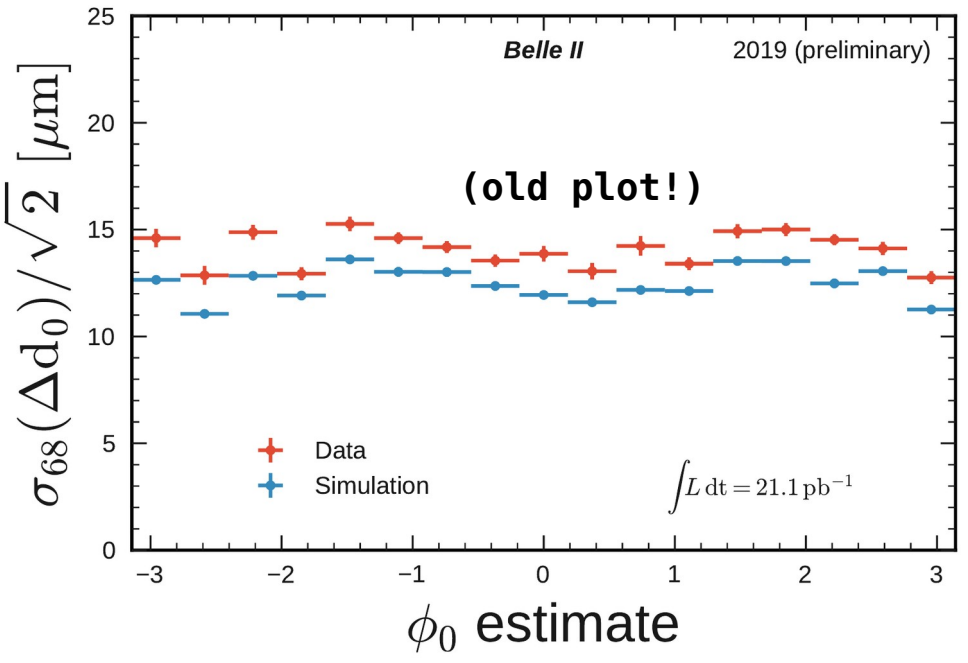




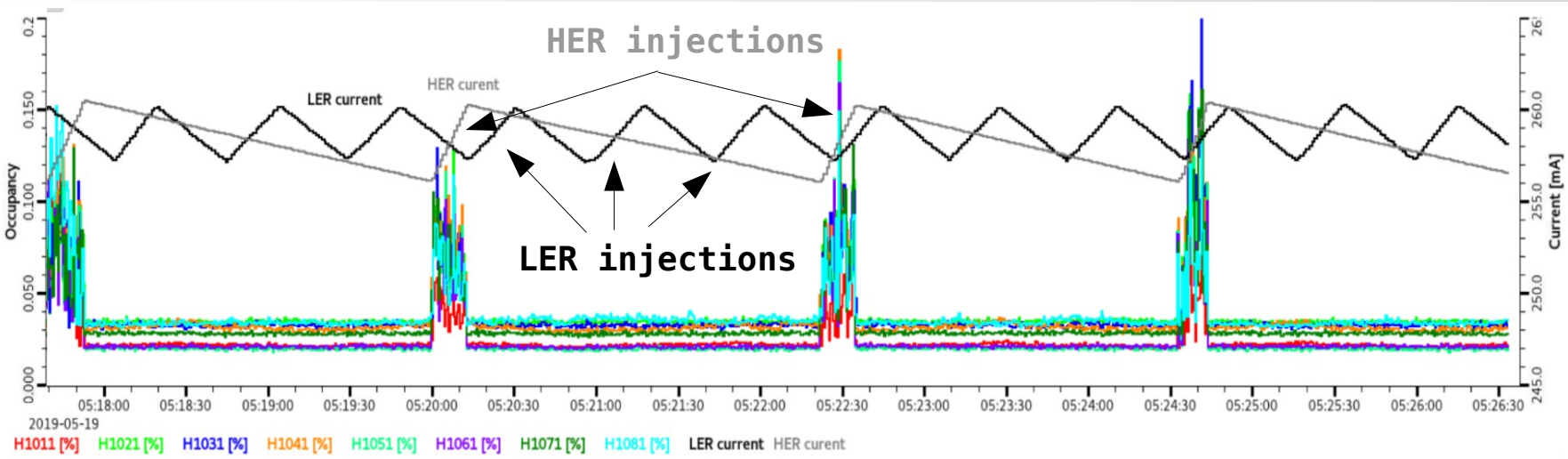
Vertex Resolution

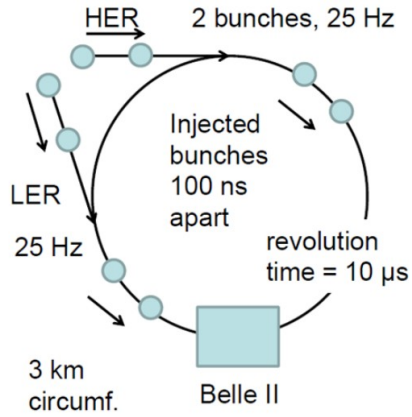
- Measuring the point of closest approach from particles from the interaction point in x, y in di-muon events
- Vertex resolution with PXD is close to MC expectations
  - d_0 resolution of 14.5 µm achieved



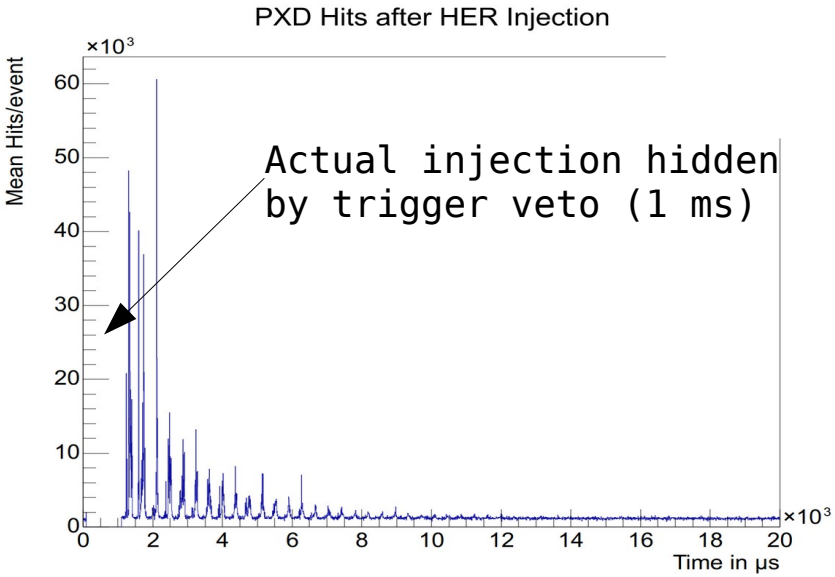


Continuous Injection Backgrounds



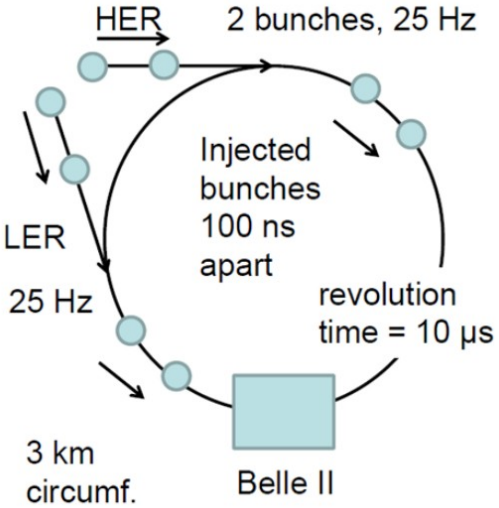


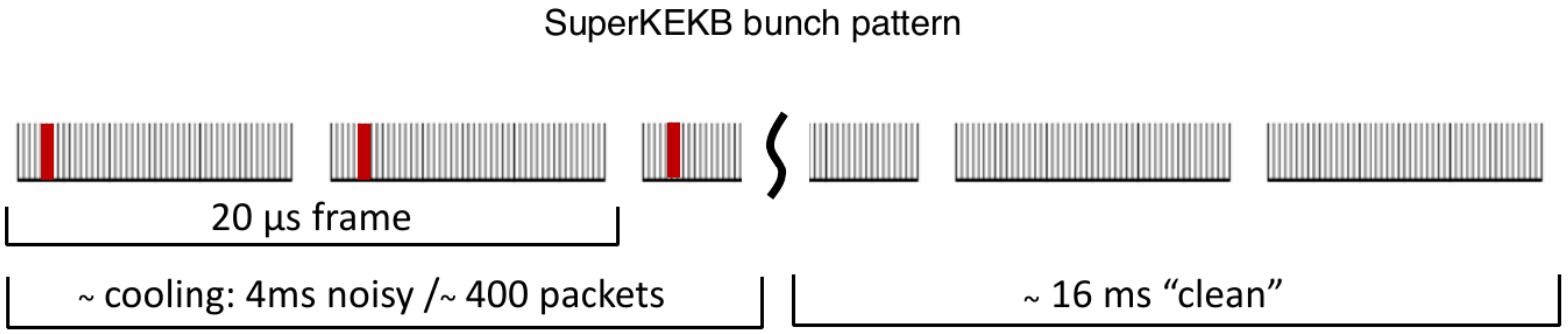
- Increased luminosity by continuous (top-up) injection, max 50 Hz
- Large background during HER injection (noisy bunch) → can lead to readout problems
- Belle II Trigger Veto (=no readout)
  - Full veto during injection (1-2 ms) and then for ~10 ms each time the bunch passes by (~2 µs)
- For PXD: Possible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



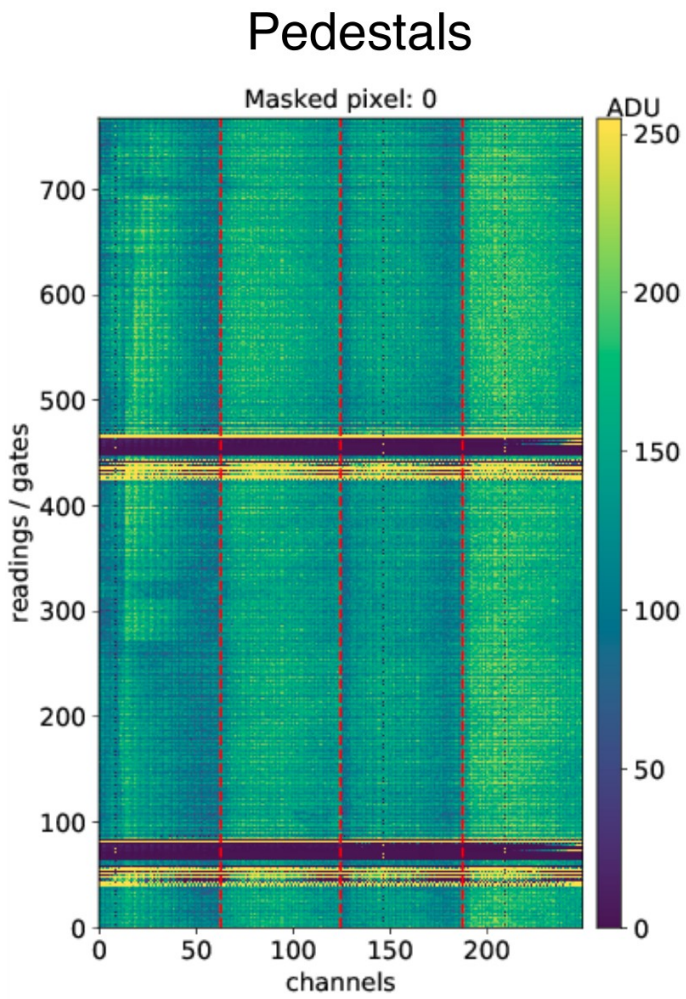
Rolling shutter! Integrated over 20 µs.

Gated Mode



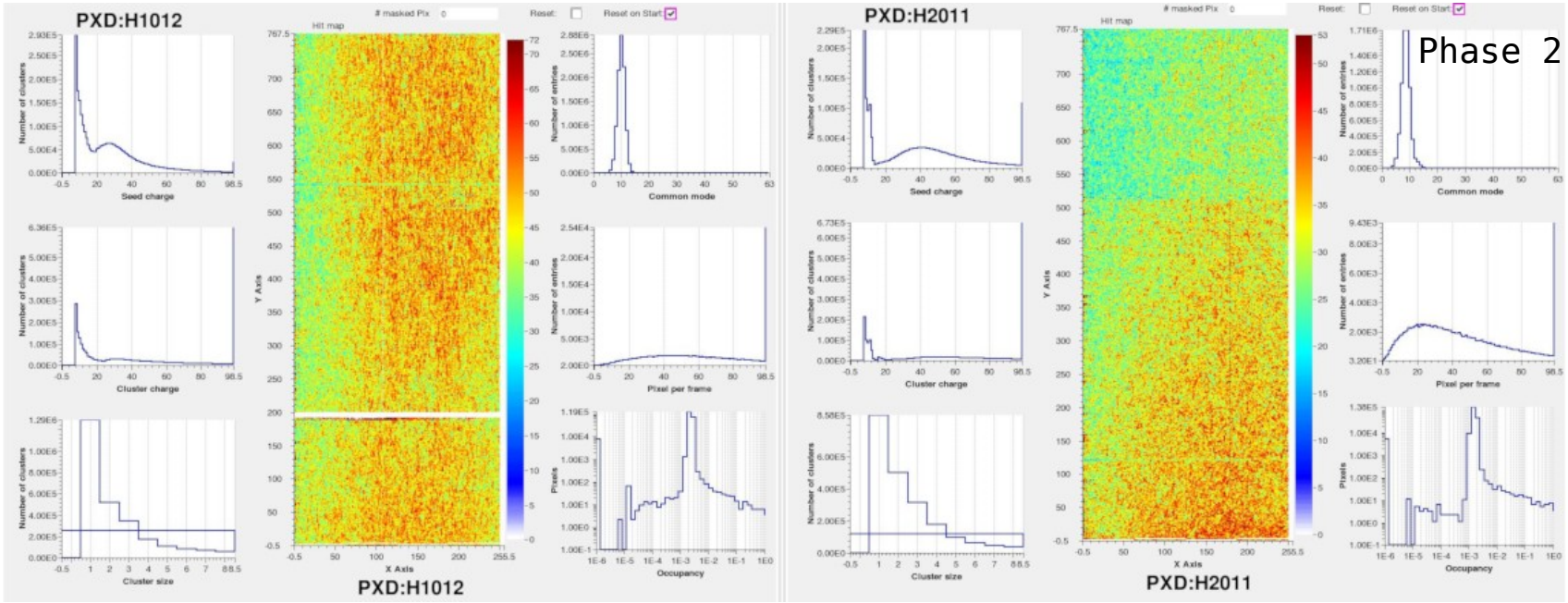


- Gating: change the voltages (potentials) such, that no new charge is collected while preserving the already stored charge.
- Gating two times per readout cycle
- Read out continuous during gating, but the data is unusable (and rejected at the frontends)
- → fraction of the detector area is lost
- Large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

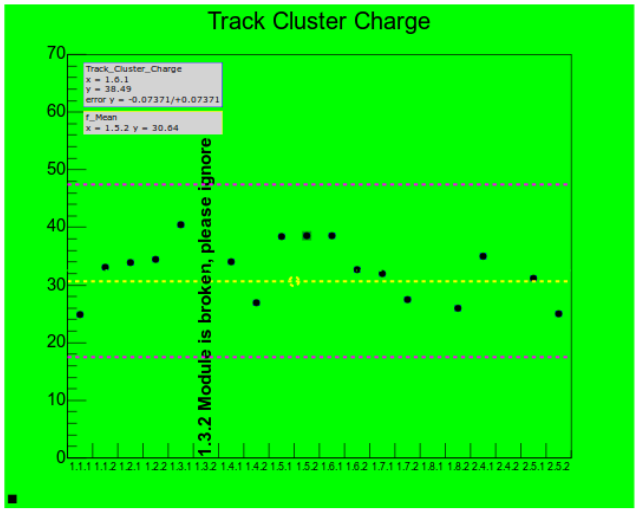


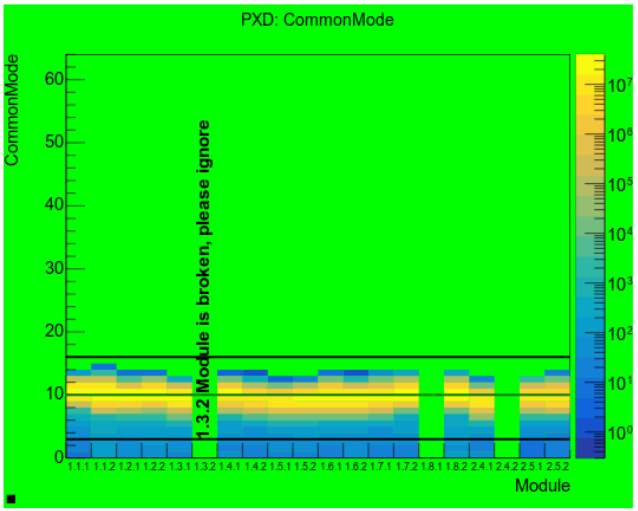
Online Monitoring

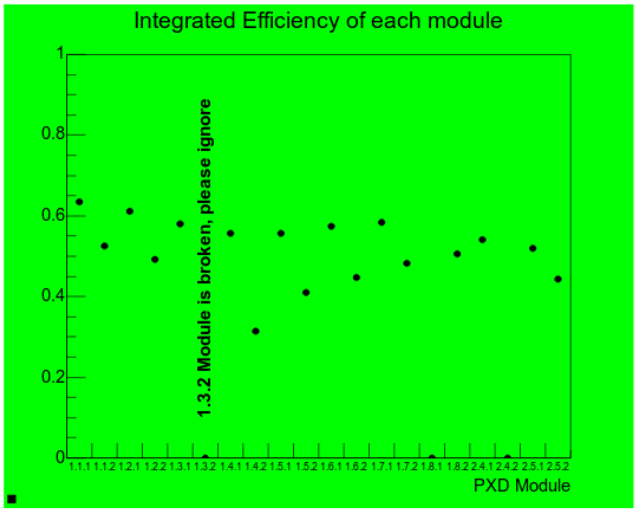
- Histograms from local DAQ



- Histograms from express reconstruction for online monitoring performance

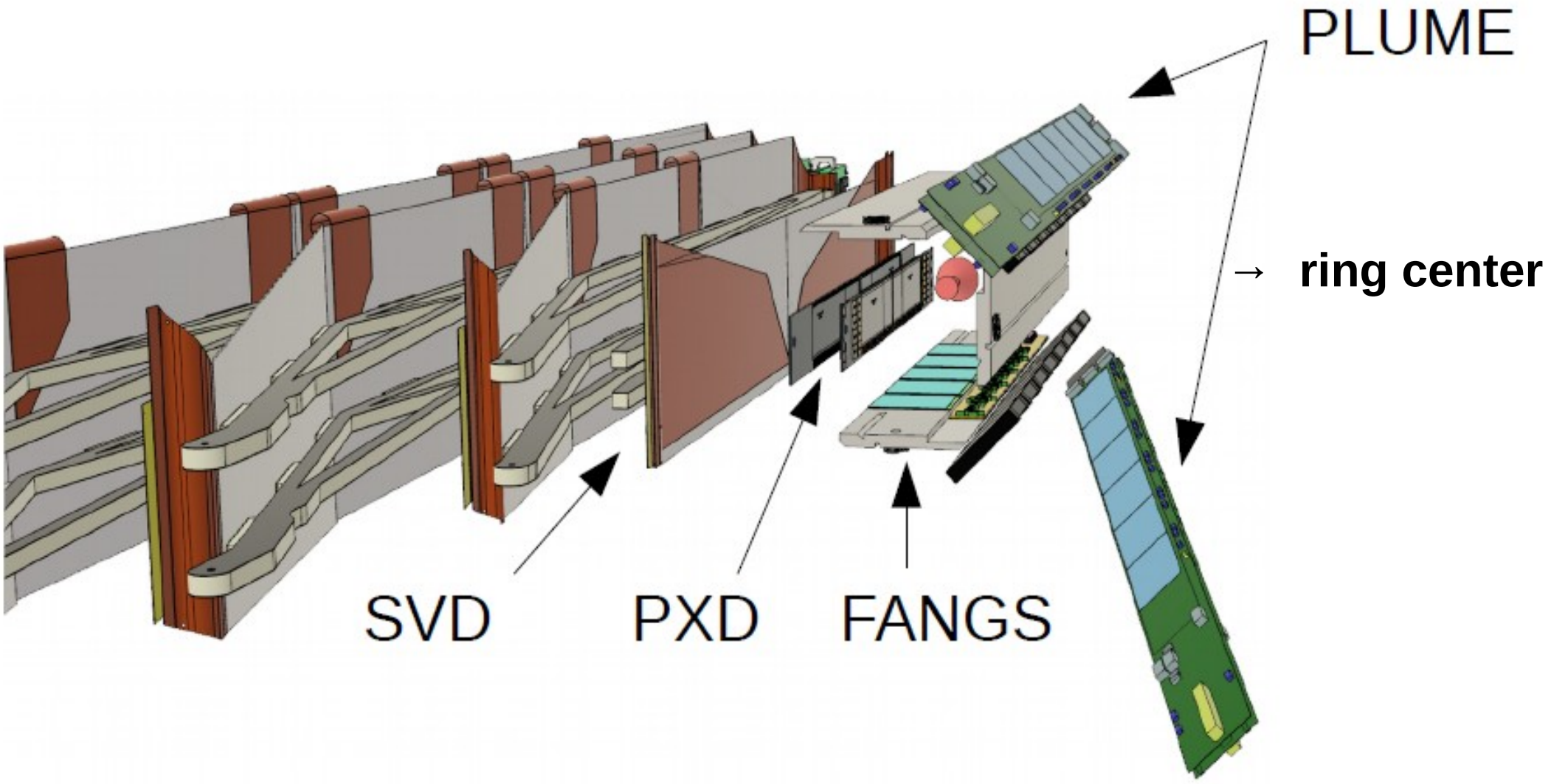






VXD Installation

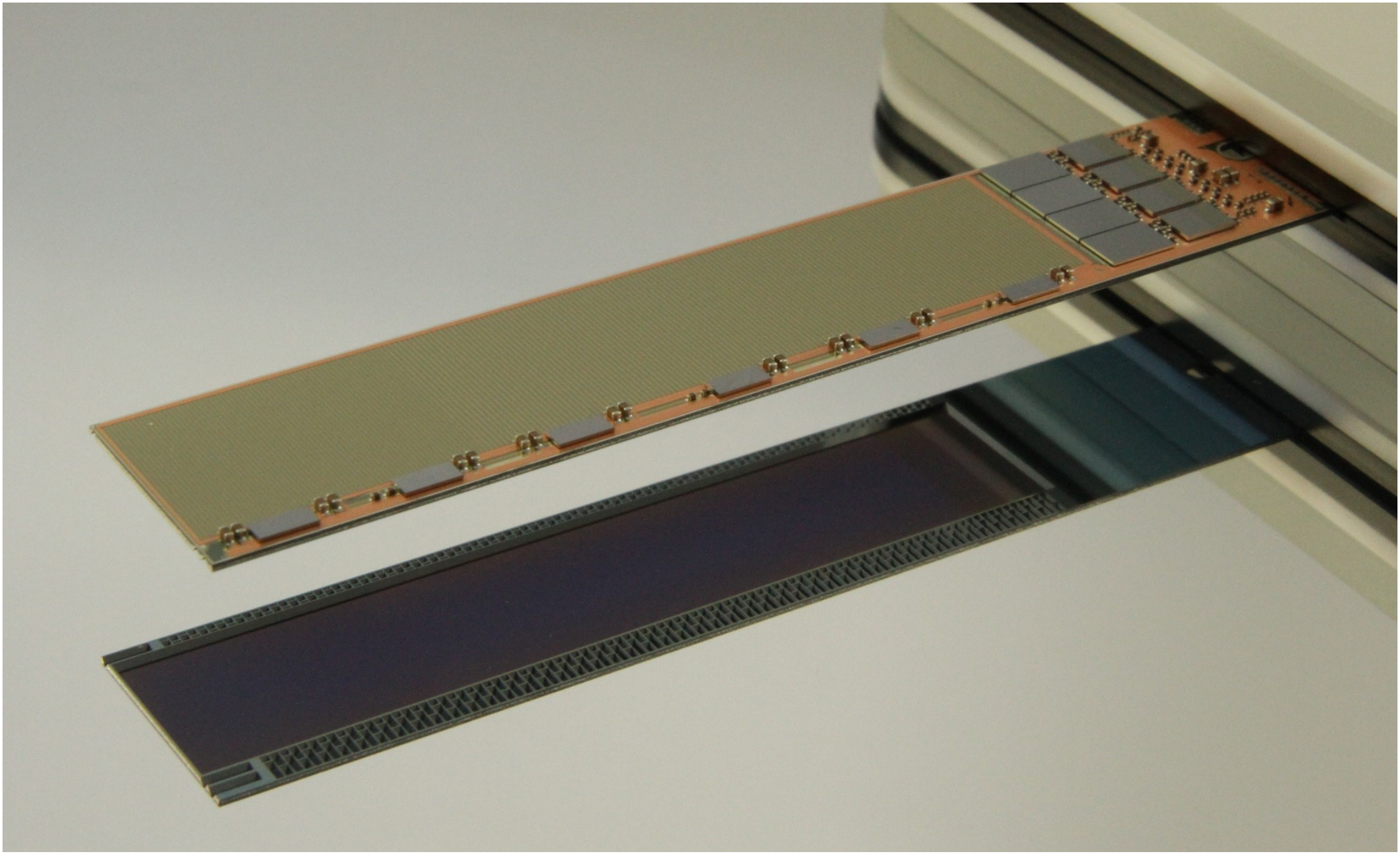
Phase 2 VXD and BEAST II



Background in Pixel detector

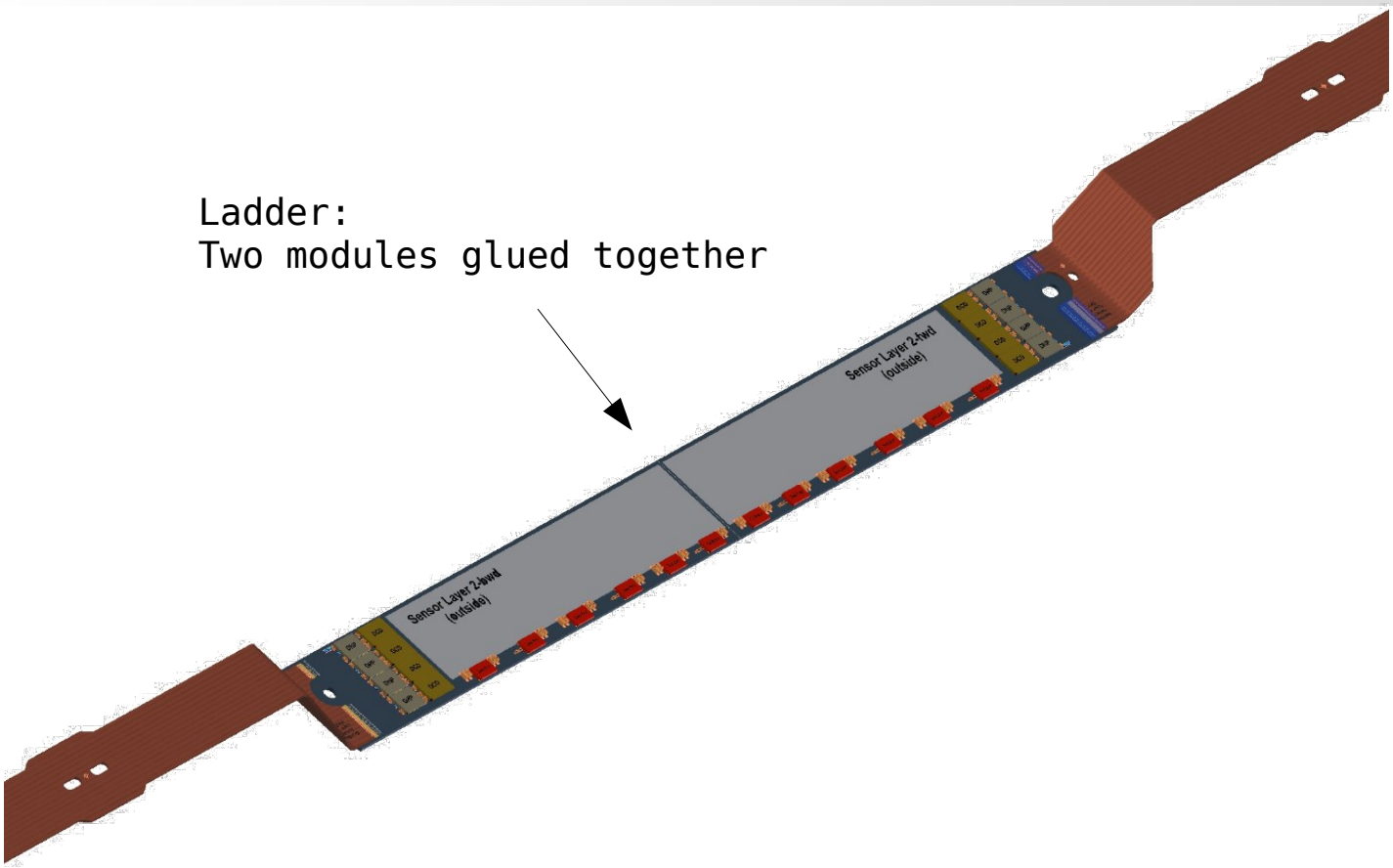
- Occupancy of PXD dominated by background
  - physics <1% occupancy
- Beam related background by
  - Synchrotron radiation
  - Beam - gas reactions
  - Touschek effect – intra-beam scattering because of high particle density
- Interaction background
  - Radiative QED, two photon processes
- Can be studied 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

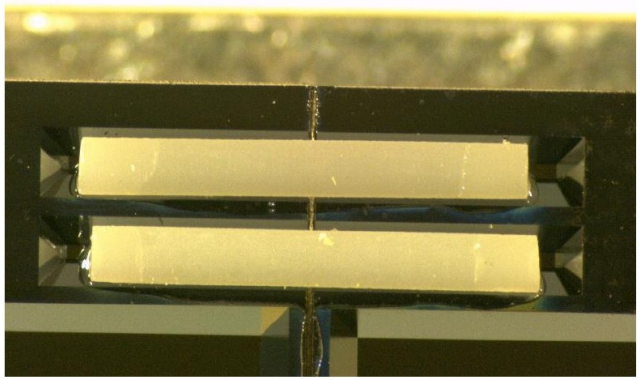


Ladder Gluing

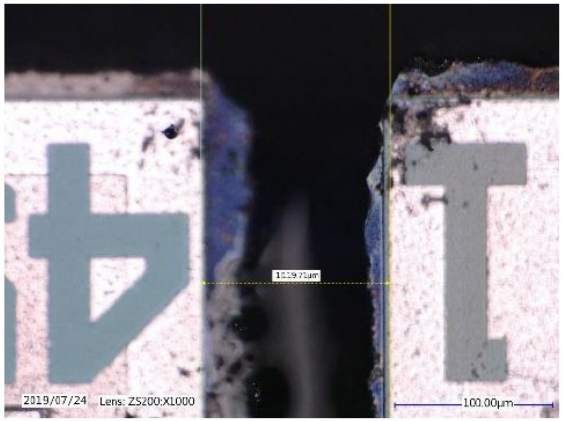
Ladder:
Two modules glued together



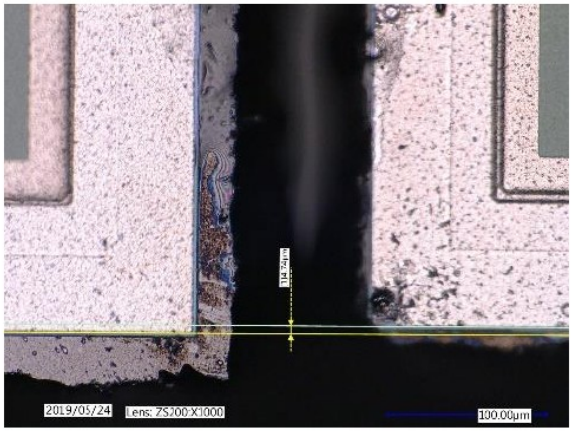
Stiffeners



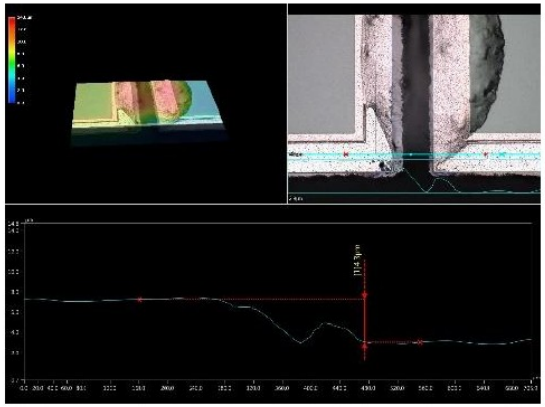
gap: glue gap between Al



dx: lateral displacement



dH: step between modules

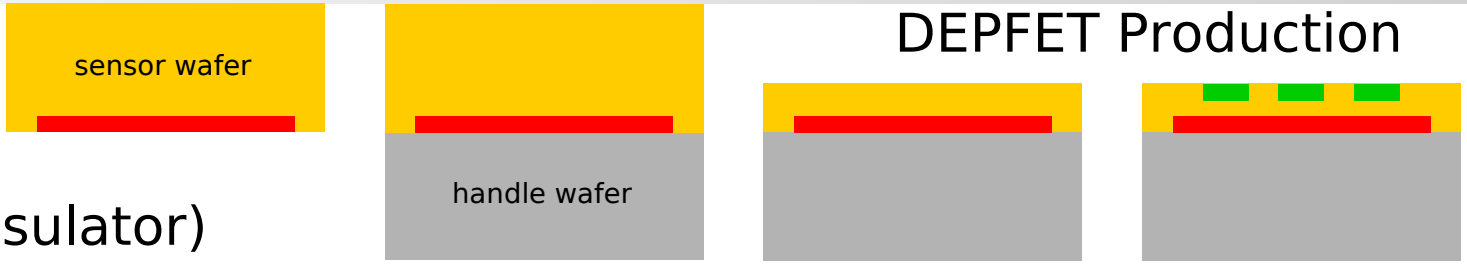


DEPFET Module Production

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)

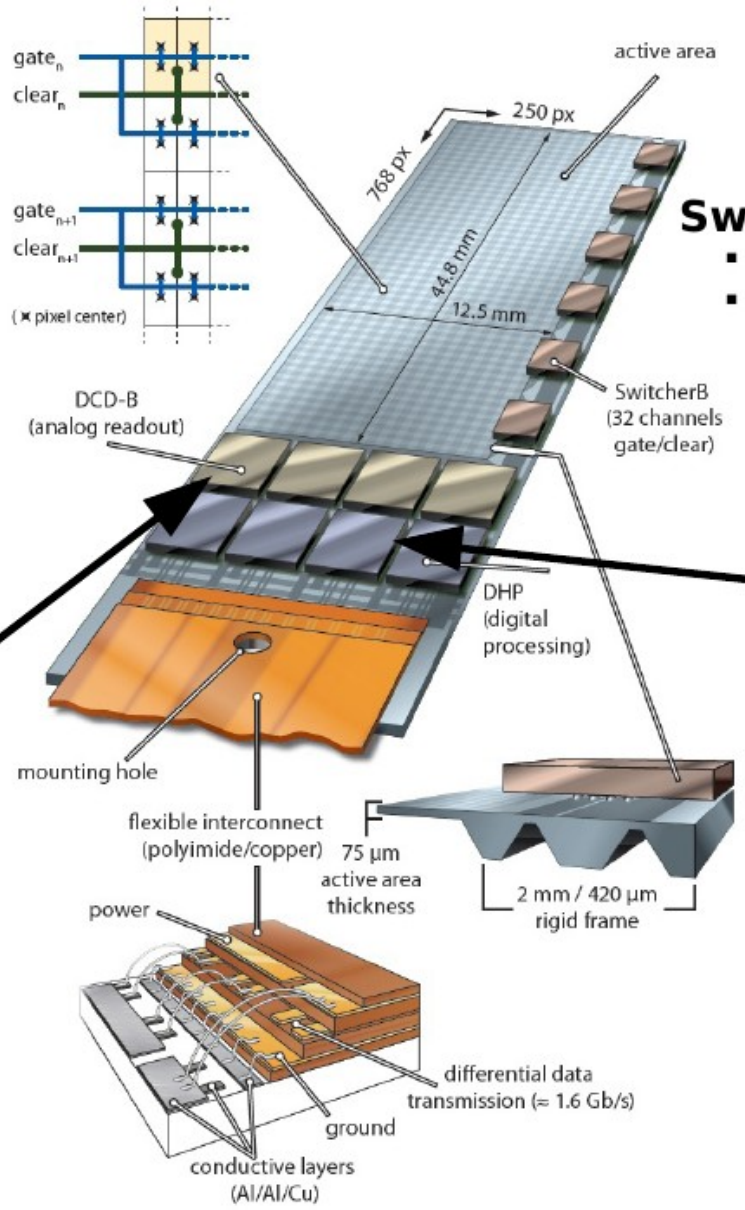
Flip Chip ASICs & mount SMD

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

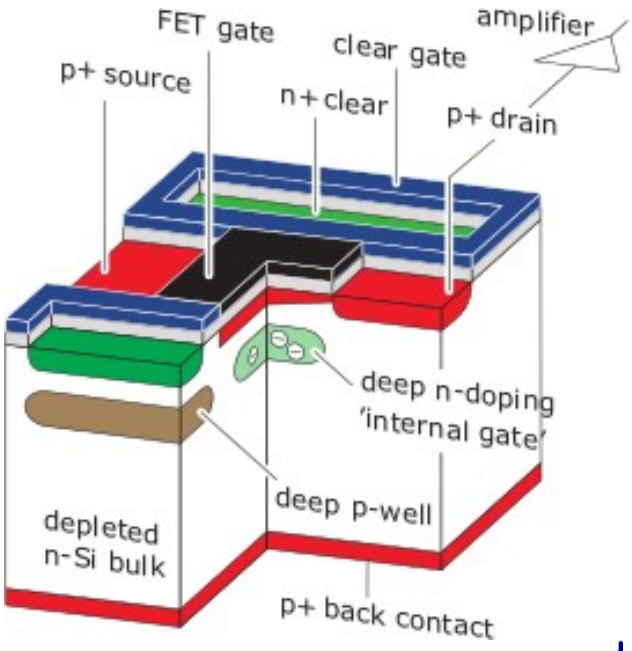
- Common mode and pedestal correction
- Data reduction (zero suppression)
- Timing and trigger control
- Rad. Hard proved (100 Mrad)

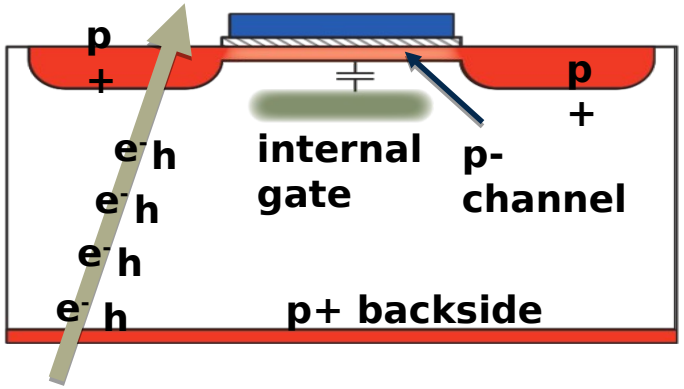
DCDB - Drain Current Digitizer

Amplification and digitization of DEPFET signals.

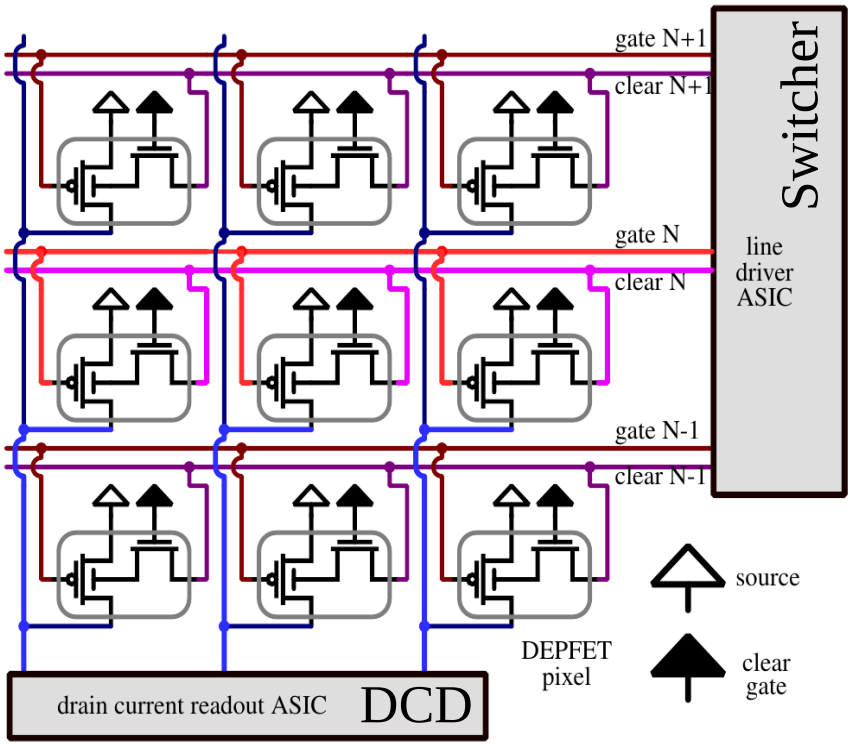
- 256 input channels
- 8-bit ADC per channel
- 92 ns sampling time
- Rad. hard proved (10 Mrad)

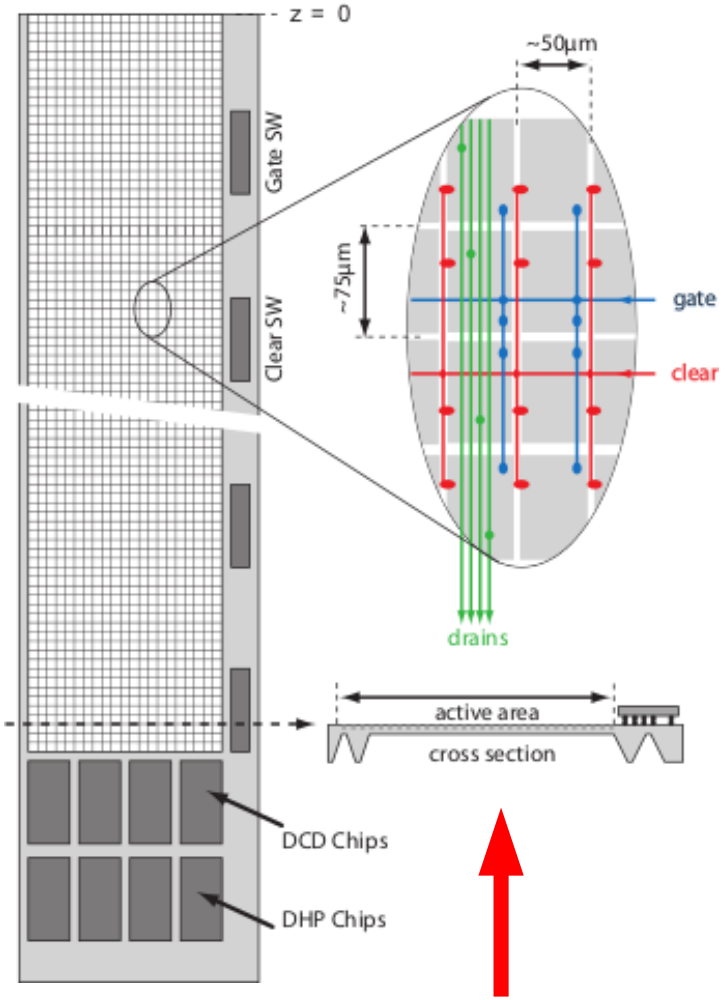
DEPFET Pixel sensor

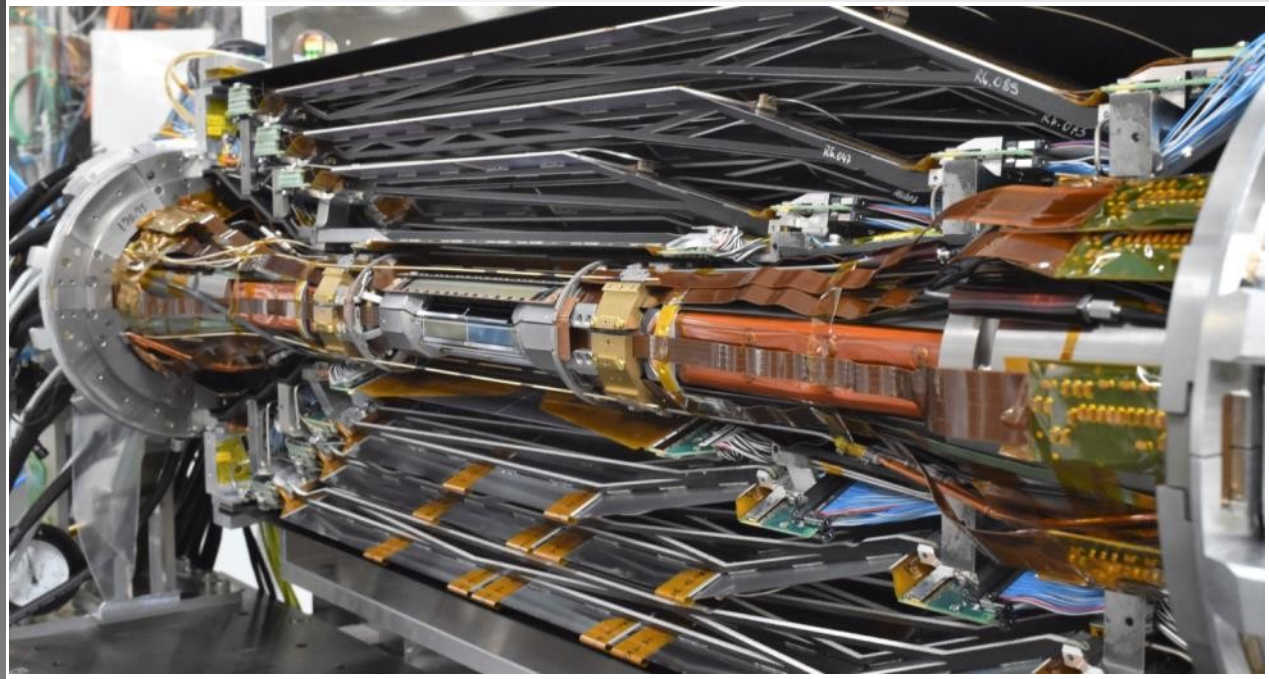


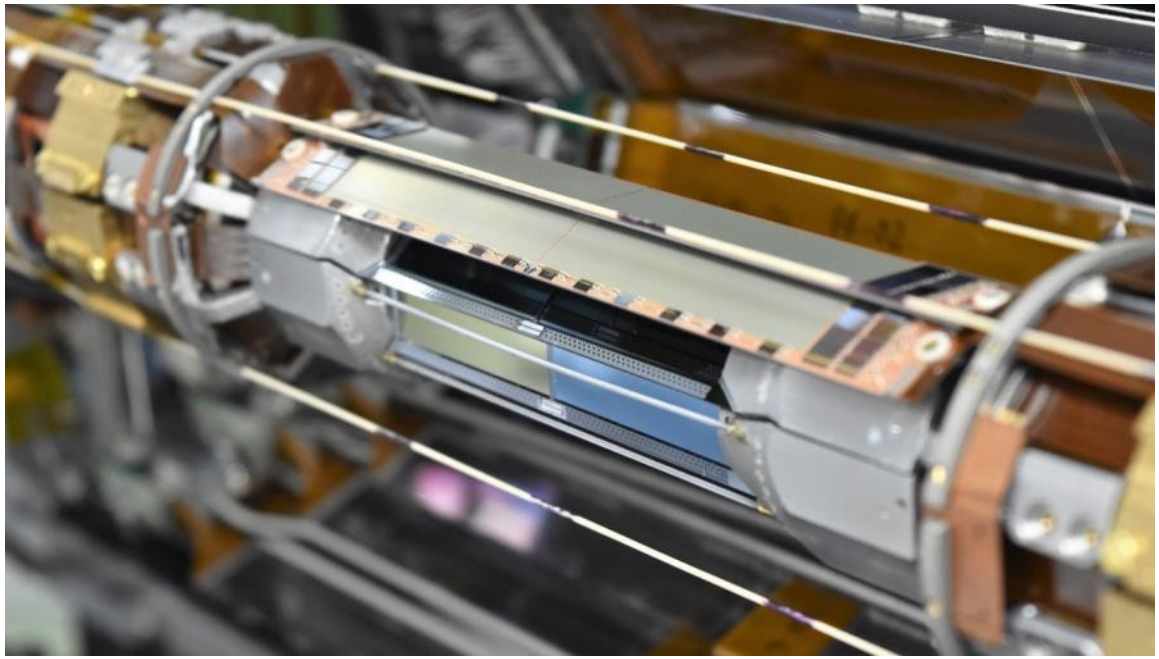


- Switcher (selected readout gates & clear)
- Drain Current Digitizer
- DHP – Digital processor
  - Zero suppression

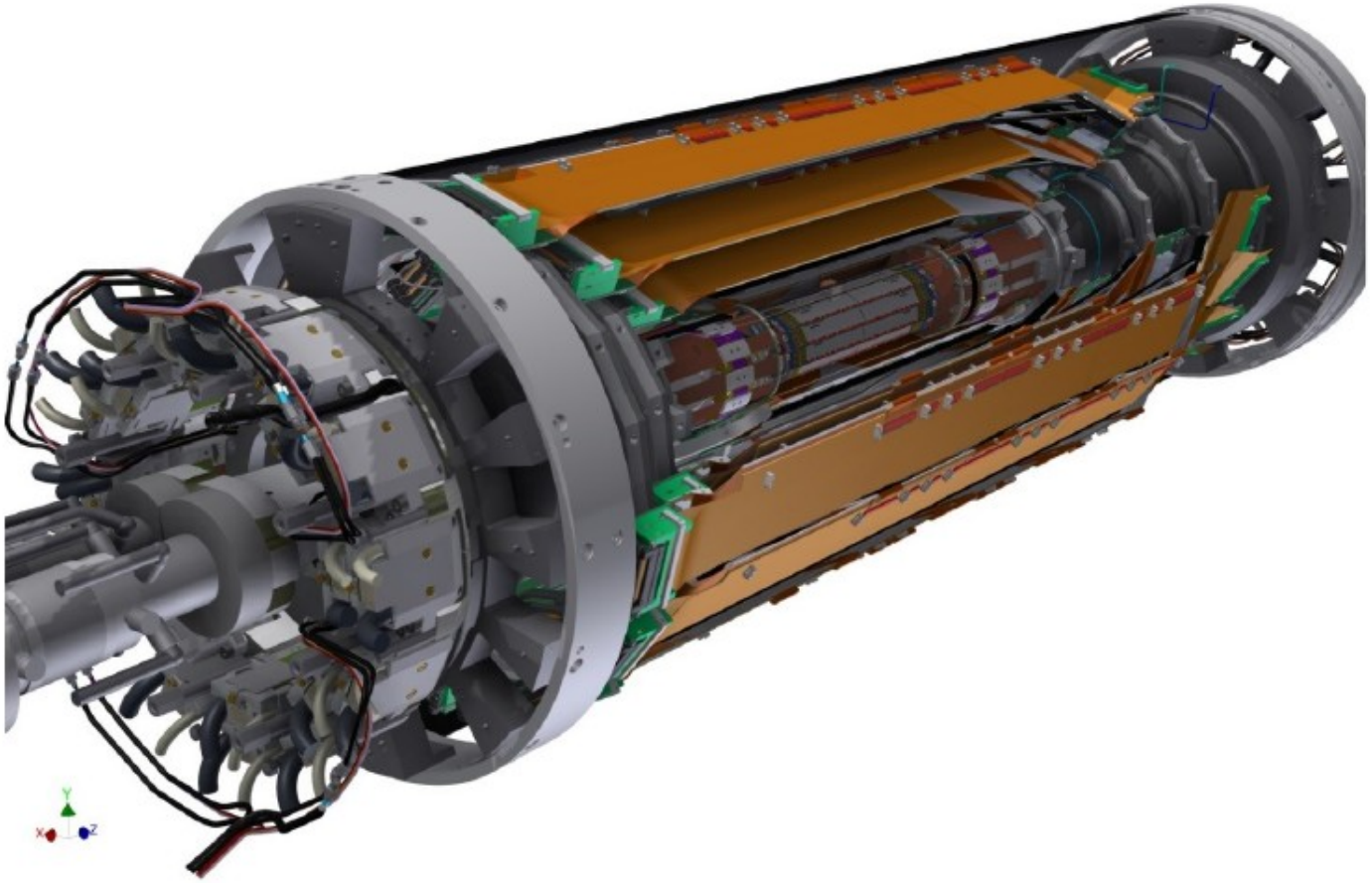


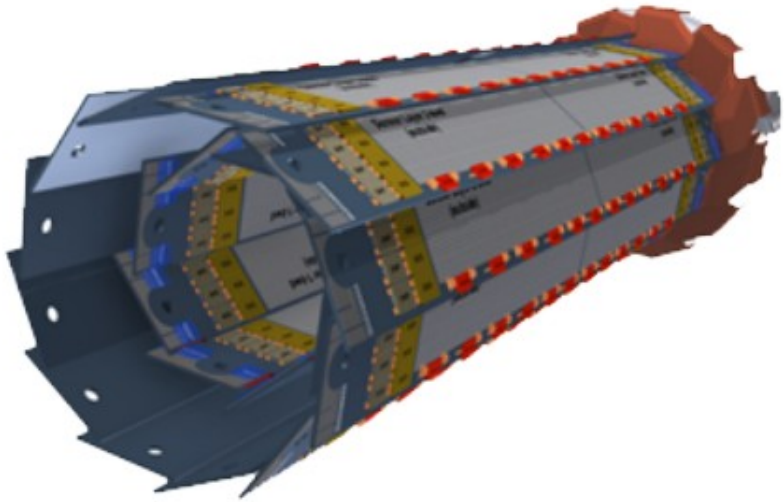






The Belle II vertex detector

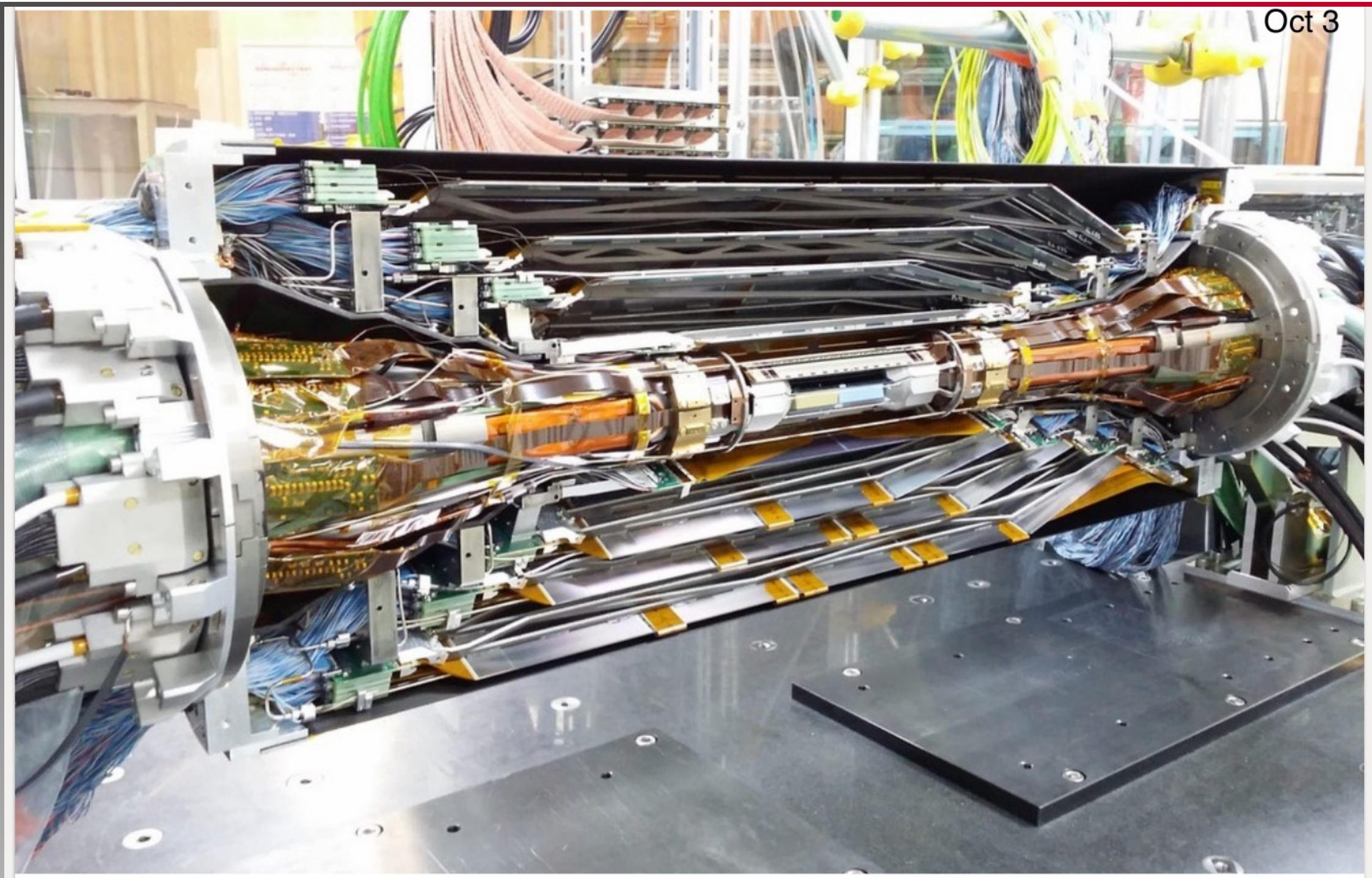




• **Pixel Detector (PXD)**
2 layers of DEPFET pixels
r = 1.4 cm, 2.2 cm
L = 12 cm
~ 0.027 m^2

• **Silicon Vertex Detector (SVD)**
4 layers of DSSD
r = 3.9 cm, 8.0 cm, 10.4 cm, 13.5 cm
L = 62 cm
~ 1 m^2

Vertex Detector (One Half Shell)



Waver