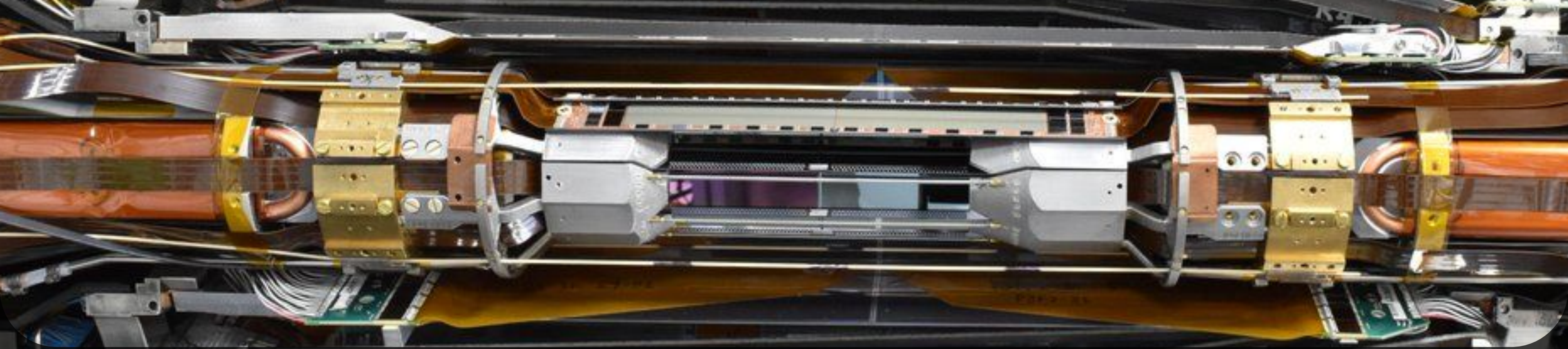

Operational Experience and Performance of the Belle II Pixel Detector

CEPC 2022, October 24th

Arthur Bolz, DESY

For the Belle II PXD Collaboration

DESY.

JENNIFER 2

EU grant n.822070

DEPFET

Active Pixel Detector

Belle II

DESY.

Outline

Introduction

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- PXD Detector

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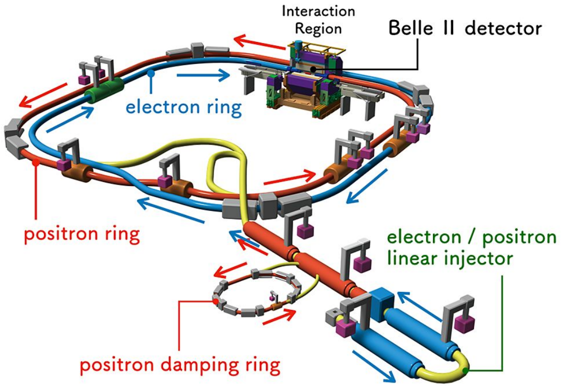
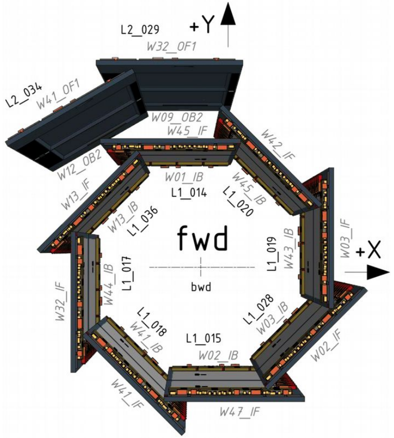
- VXD Performance
- Operational Challenges: backgrounds, beam-losses, irradiation and aging

PXD2 2022 Upgrade

- Future of PXD

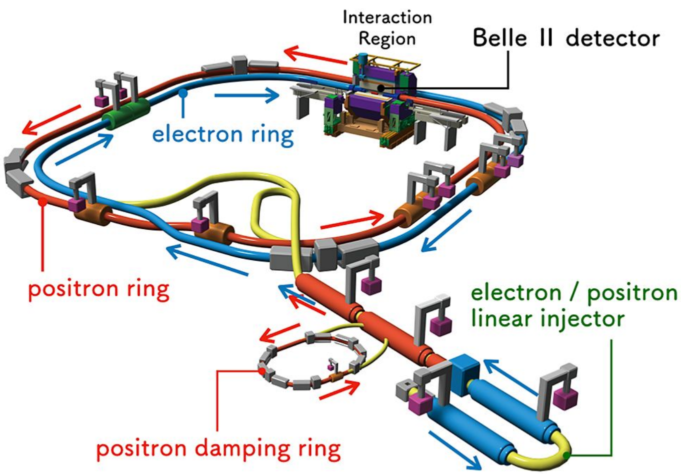




Setting the Scene

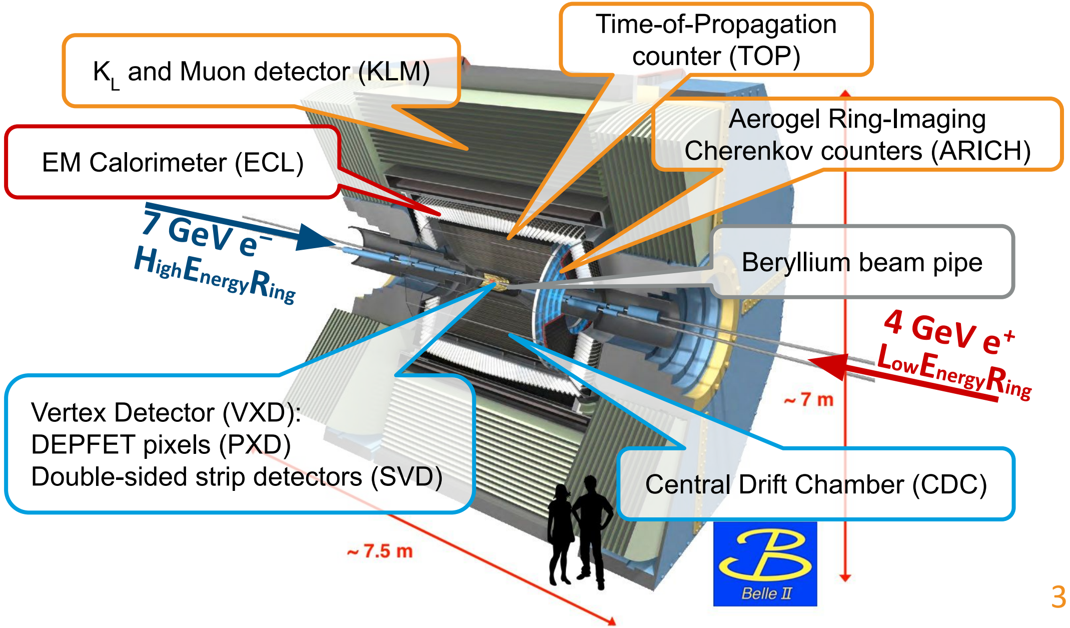
Super KEKB

- asymmetric e^+e^- collider
- $E_{cm} = M_{\Upsilon(4S)} \approx 10.58$ GeV ⇒ "B factory"
- $L_{peak} = 4.7 \times 10^{34}$ cm^{-2}s^{-1} (June 2022)
  - "nano-beam" scheme and increased currents
  - goal 6×10^{35} cm^{-2}s^{-1}
- ongoing long shutdown 1 since July 2022:
  - ~1.5 year for accelerator and detector improvements



Belle II

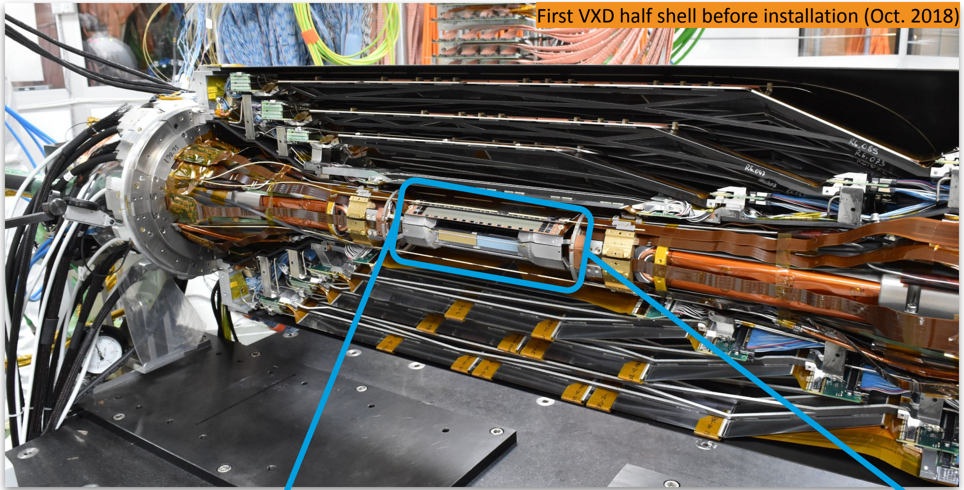
- L_{int} 427.8 fb^{-1} recorded until summer 2022
  - physics data-taking w/ full setup since March 2019
  - target L_{int}: 50 ab^{-1} within ~203Xs (~50x Belle)
- upgraded trigger rate: up to 30 kHz
- upgraded detectors
- rich physics program: B-, τ-, searches for new physics, …

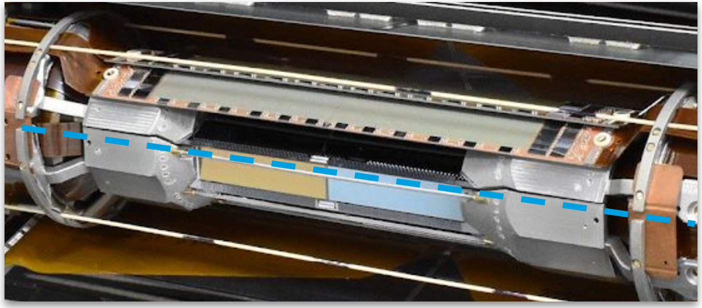


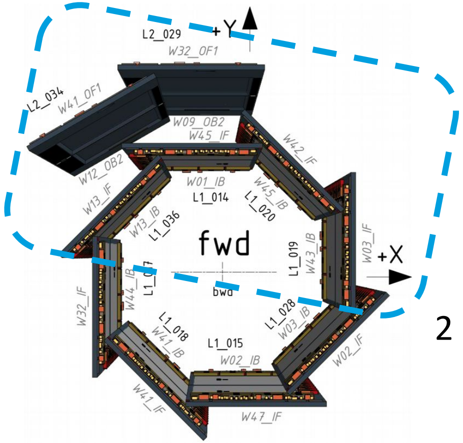
Setting the Scene

Belle II Vertex Detector (VXD)

- **Silicon Vertex Detector (SVD)**
  - 4 layers of 2-sided silicon strips
  - r ≲ 140 mm
- **Pixel Vertex Detector (PXD)**
  - 2 layers at radii 14 mm and 22 mm
  - 8 inner + 12 outer module-pairs (“ladders”)
    - ⇒ only 8 (inner) + 2 (outer) ladders installed
  - ~7.7 x 10^6 pixels
  - ~0.21 % X_0 / layer material budget
- **acceptance**
  - 17° < Θ < 150°
  - p_T ≳ 40 MeV





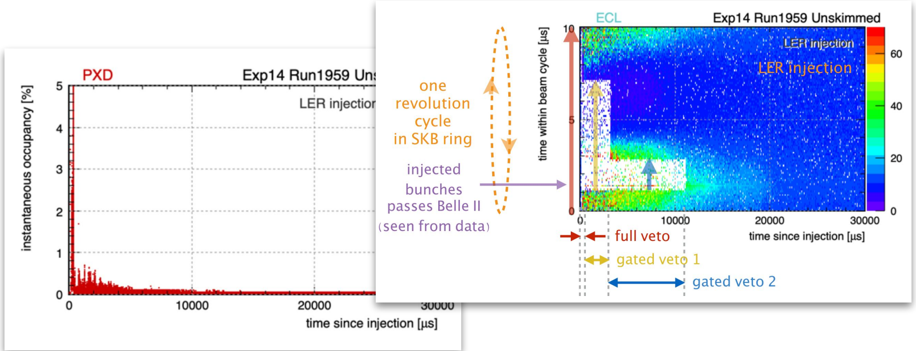


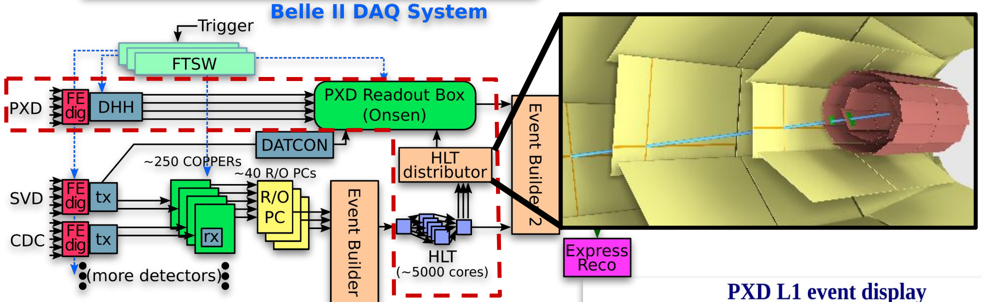
2 half shells

Tracking at SuperKEKB

Challenges

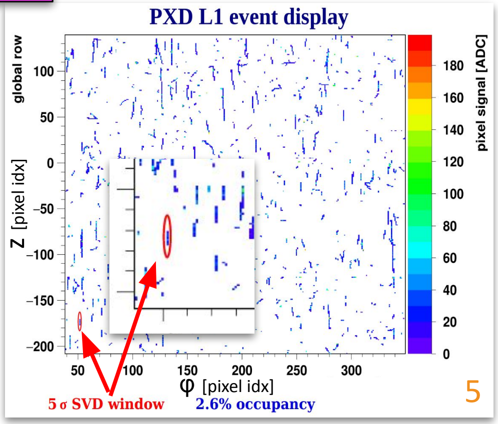
- **increased backgrounds** with instantaneous lumi
  - beam lifetime only few minutes
    ⇒ continuous “top up” injection (for 2400 bunches)
    (50 Hz @ 4 ms cooldown ⇒ 4 ms damping time with particle losses)
  - “Synchrotron”, “Touschek intra-bunch scattering”, “Bhabha”, “2 photon”...
  - challenge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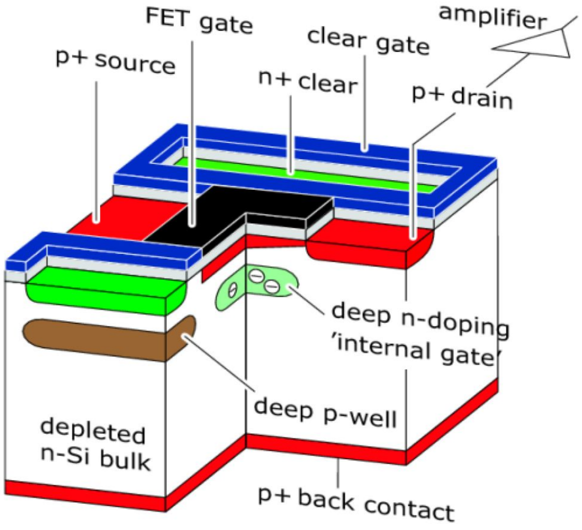
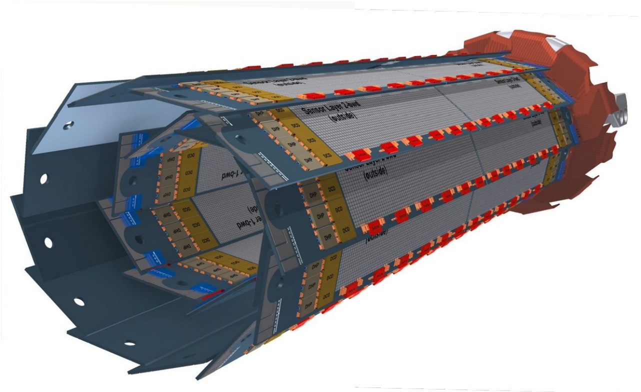
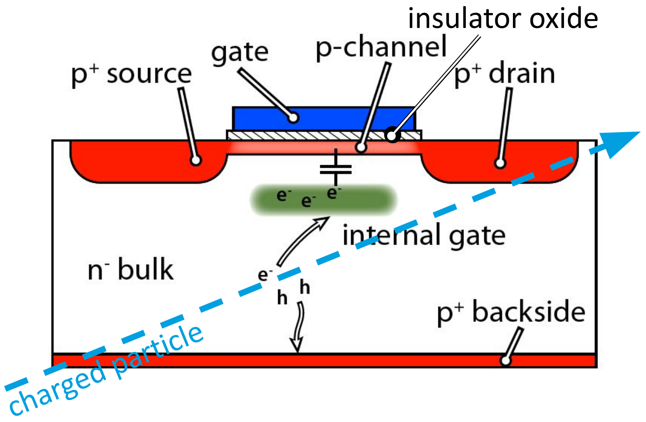




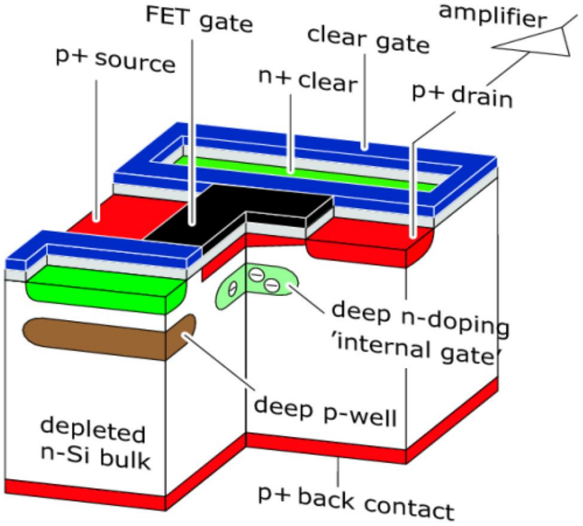
PXD Working Principle

DEPFET pixels: depleted p-channel field effect transistors



principle:

- Field Effect Transistor (FET) on top of fully depleted silicon bulk
  - ***gate*** voltage regulates ***source*** → ***drain*** current
- ***internal gate***: deep n-implant below FET gate
  - collects free electrons to modulate drain current
- periodic active clearing of internal gate
  - via ***clear implant*** (n+) and “punch through” mechanism



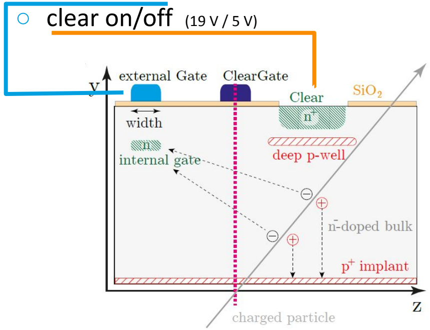
characteristics:

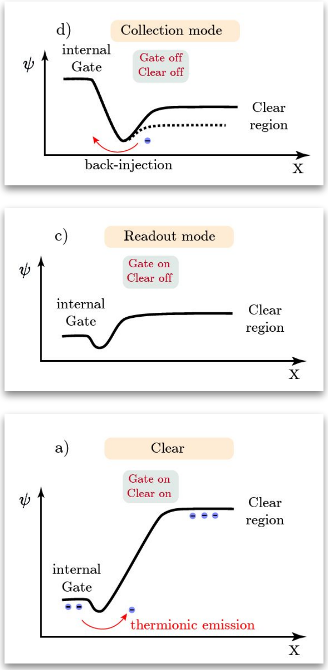
+ fast charge collection (O(ns))
+ provide full analogue charge signal
+ internal amplification $g_q = \frac{\partial I}{\partial q} \approx 500 \frac{pA}{e^-}$
+ high signal-to-noise ratio
+ low power consumption
+ thin sensors (75 µm in active region: DEPFET matrix)
- non-destructive signal readout

PXD Working Principle

DEPFET operation

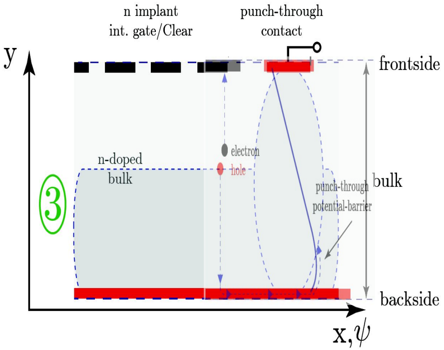
- pixel state changed by regular change of *gate* and *clear* voltages
  - gate on/off (-2.5 V / 3 V vs Source)
  - clear on/off (19 V / 5 V)

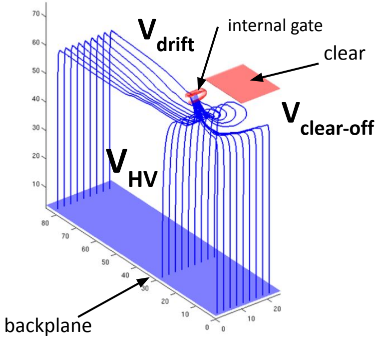




- **charge collection** *gate off, clear off*:
  - charges drift to internal gate
  - no drain current
- **readout** *gate on, clear off*:
  - new charges drift to clear
  - stable drain current can be read out
- **clear** *gate on, clear on*:
  - charges drift from internal gate to clear

Sensor biasing





- **bulk depletion**
  - negative backside HV via frontside punch-through contact (~-70 V)
- **field shaping**
  - *deep p-well* prevents free e⁻ drift to clear
  - *clear gate* potential barrier between internal gate and clear
  - *drift voltage* to guide free e⁻ to internal gate
  - ...
- ***bulk*** **(n^+, V+) and *guard* (p^+, V-)**
  - structures around whole matrix to keep external charge carriers out

> ➢ **PXD modules operated with 24 different voltages** (including ASICs)

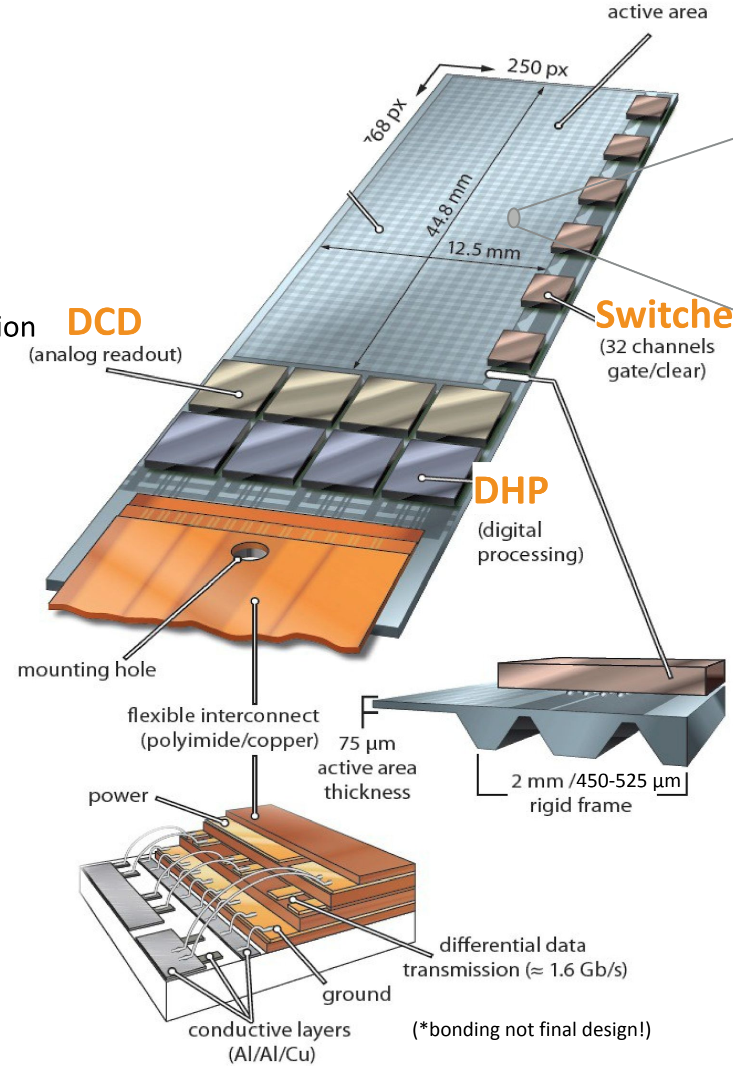
PXD Sensors

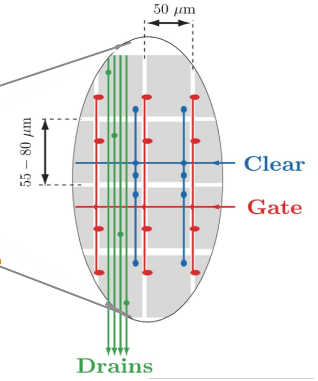
Layout

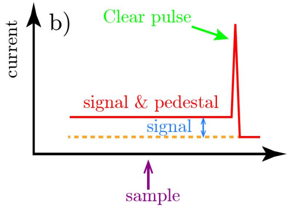
- matrix
  - 250x768 pixels, pixel size 50x(55-85) μm^2
- ASICs (custom designed)
  - *Switchers* → DEPFET control
  - *DCD* → 256 channel ADC: 8bit source currents digitization
  - *DHP* → data processing: pedestal correction, zero suppression, …
- all silicon design
  - mechanically self supporting modules
  - thinned to 75 µm (active region)
  - small total material budget ~0.21 X_0

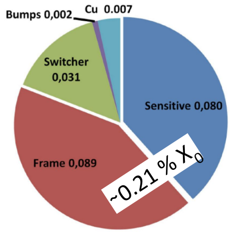
Operation

- rolling shutter read-out → low power
  50 kHz → 20 µs integration time (2x beam revo. cycle)
  dead-time free except for 100 ns read-clear cycle
- design: 1% occupancy (layer 1)
  3 % occupancy limit (DHP, DAQ, tracking)
- single point sampling → median drain current
  pedestals stored on DHP for zero suppressio
- power dissipated mainly in ASICS at end of stave
  ~ 10W/module







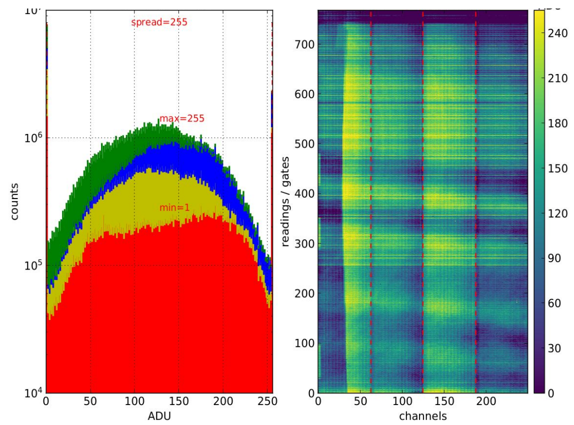


PXD Modules

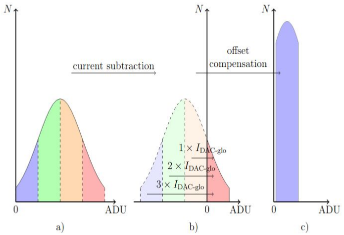
Calibration

- sensors characterized before installation
  - continuous optimization of working points needed during operation
- DCD calibration
  - optimize on linearity, ADC errors, noise, …
- biasing optimization
  - optimize on signal to noise, …
- pedestal optimization on DCD
  - pedestal compression via switchable input currents per pixel
  - noise reduction via *Analog Common Mode Correction*

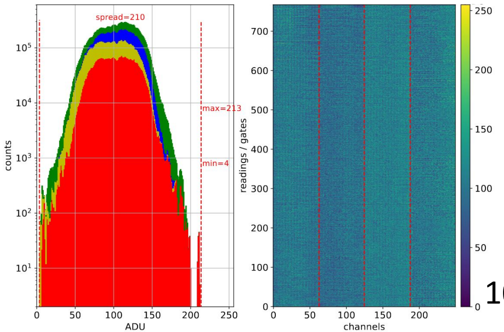
pedestal currents uncalibrated sensor



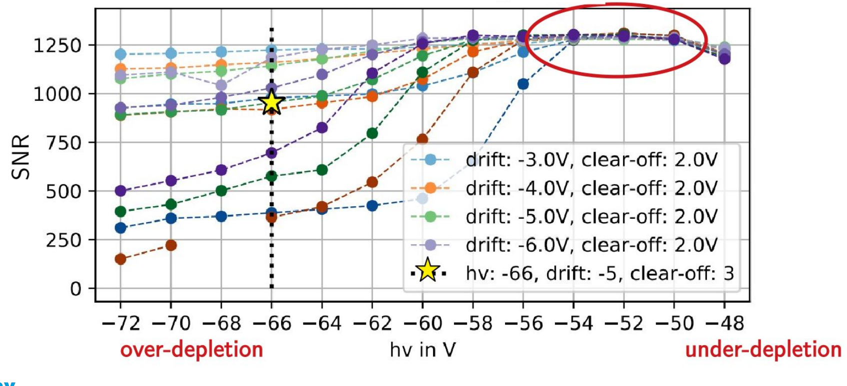
pedestal compression:
2 bit offset current per pixel



pedestals calibrated sensor



module SNR dependence on sensor biasing



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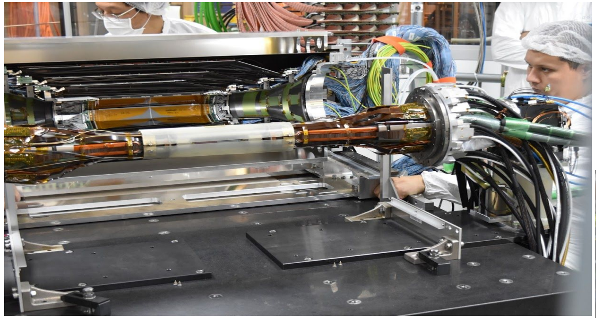
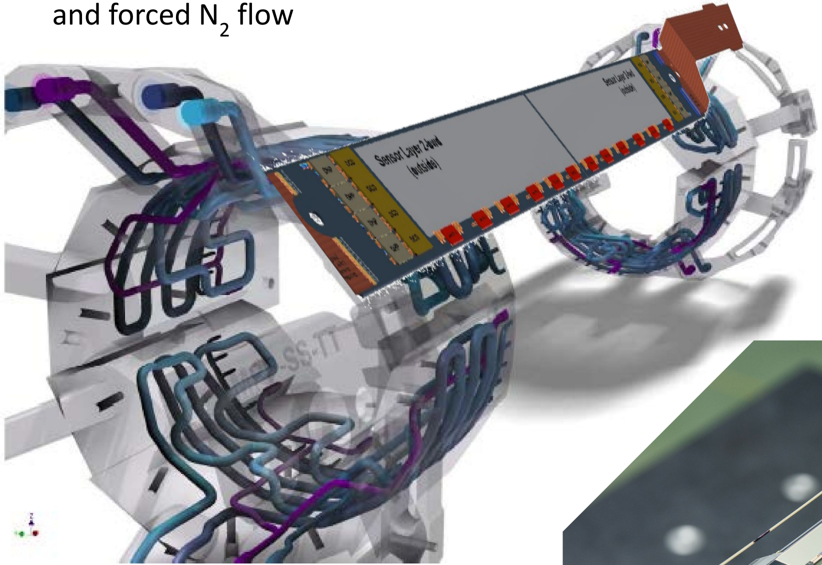
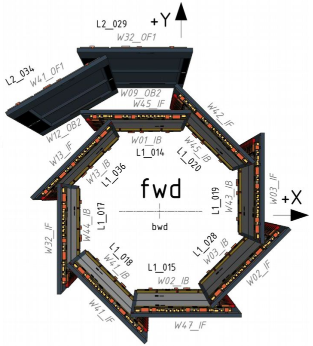
PXD in Belle II

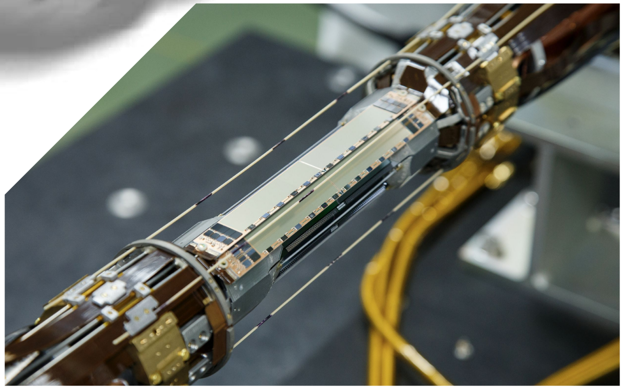
PXD assembly

- 2 PXD modules glued together (“ladder”)
- 2 half shells mounted on Support and Cooling Blocks (SCBs)
- provide cooling via 2-phase CO_2 and forced N_2 flow



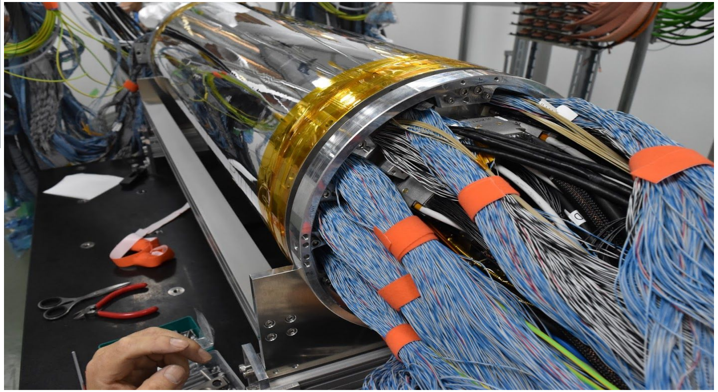


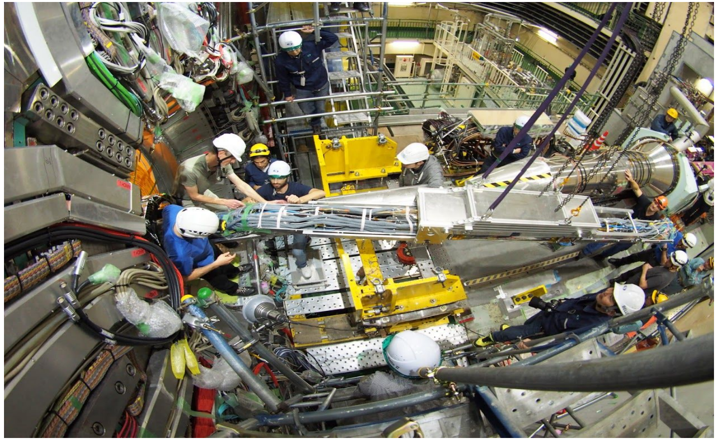




Installation 2018 at KEK

- PXD + BP + SVD marriage
- VXD installation in Belle II





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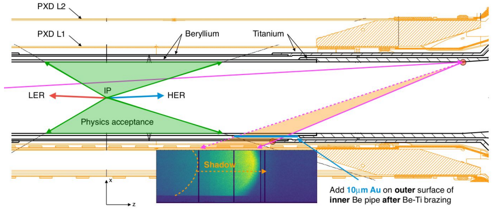
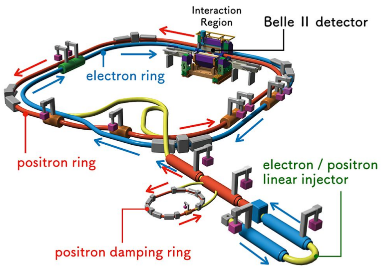
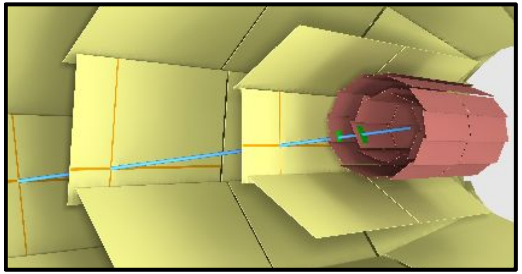
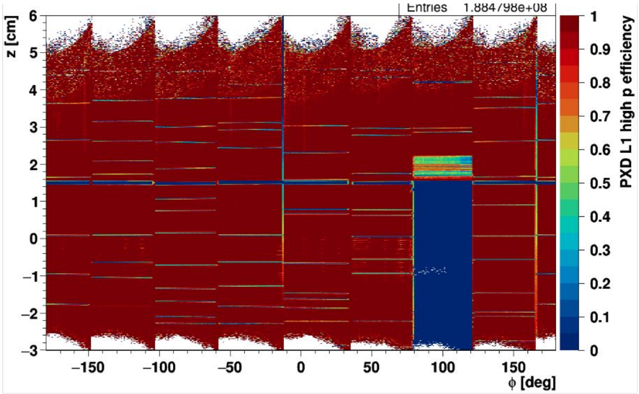






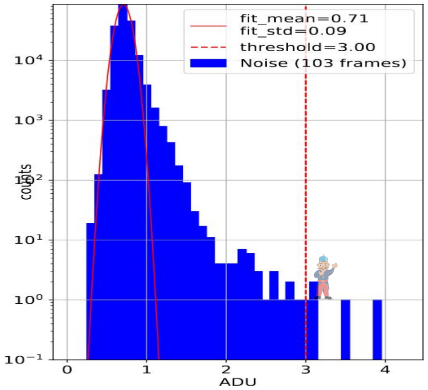


PXD Performance

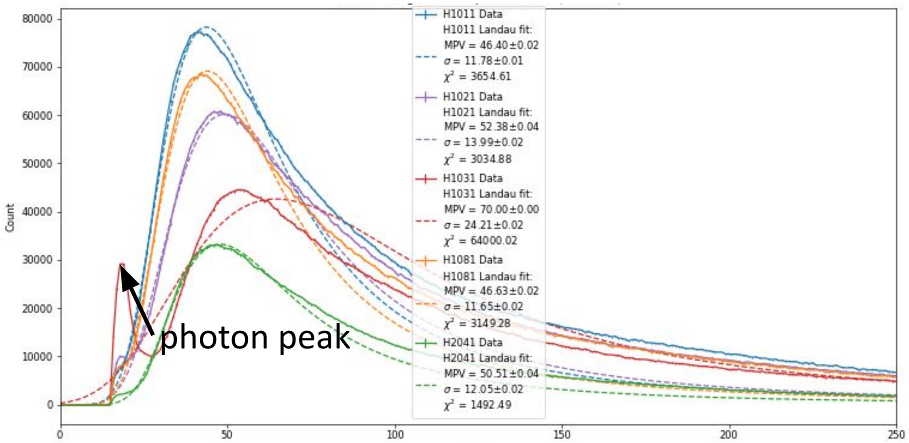
Signal and noise

- noise performance < 1 ADU (~200 e^-)
- at a SNR of ~30 - 50
- homogeneous noise and signal response across module matrix
- stable throughout 2019 ⟶ 2022
  - although see slight increase in noise with DCD irradiation

pedestal noise



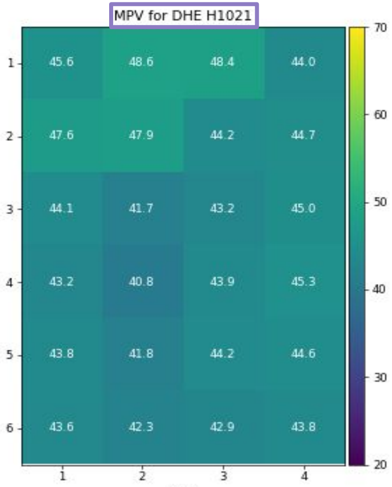
cluster charge distribution



multi pixel cluster ADU

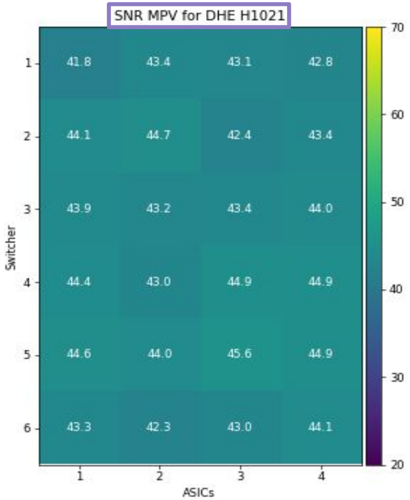
cluster charge MPV

6x switchers



4x DCD/DHPs

SNR MPV

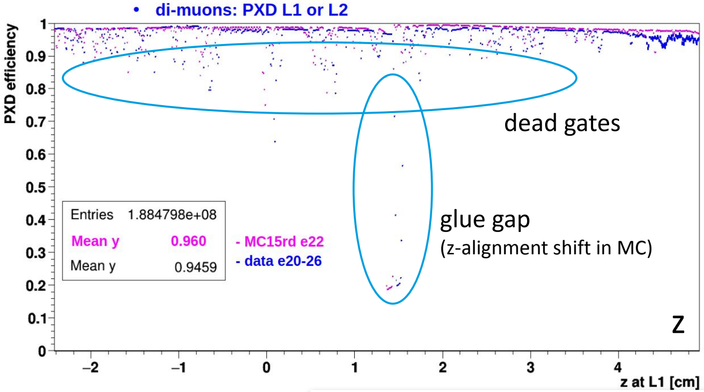


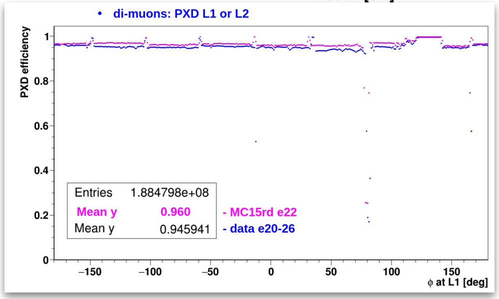
exp. 14, run 2129

PXD Performance

Efficiency

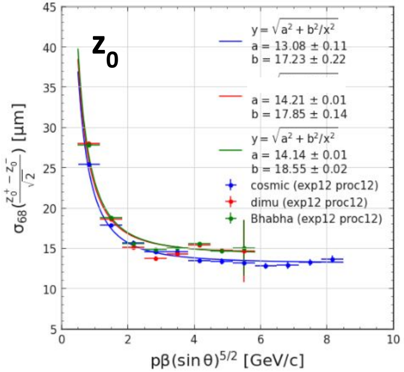
- ~96% hit in L1 or L2
  - ~99% single hit efficiency in fiducial regions
- PXD simulation captures lots of features already well
  - continued efforts to further improve
  - challenging also due to radiation damages (see later)

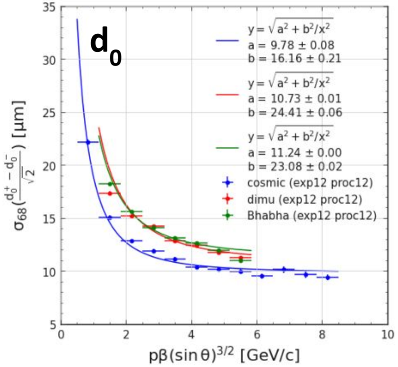


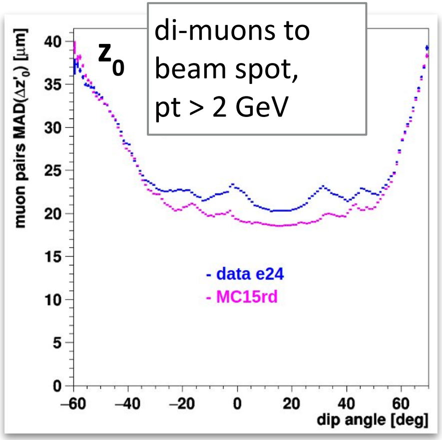


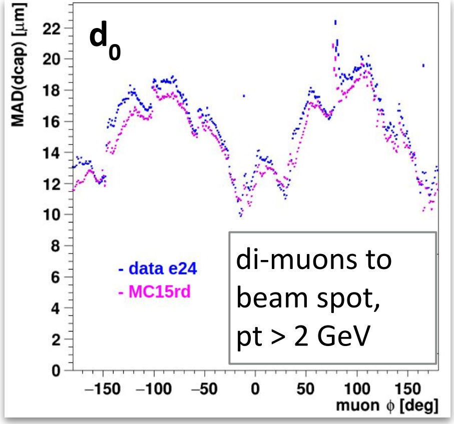
Impact parameter resolution

- 1.5 - 2x better than Belle
- worse description in MC compared to efficiency
  - too optimistic uncertainties assumed









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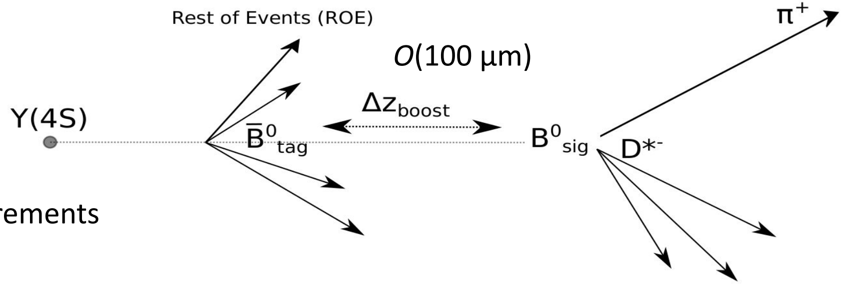
VXD Performance

World leading lifetime measurements



- precise measurements of decay vertices crucial for time dependent measurements
  - Belle II proper time resolution ~2x better than Belle
    (despite SuperKEKB operating at smaller Lorentz boost compared to KEKB/Belle)
  - largely thanks to PXD and smaller beam pipe diameter
- Belle II published world-leading lifetime measurements on charmed mesons: D^0/D^+, **New:** Λ_c, and Ω_c^0
  - further measurements, eg on time-dependent CP violation in the pipeline

1

$\tau(\Lambda_c)$: $203.20 \pm 0.89\,(\text{stat}) \pm 0.77\,(\text{syst})$ fs

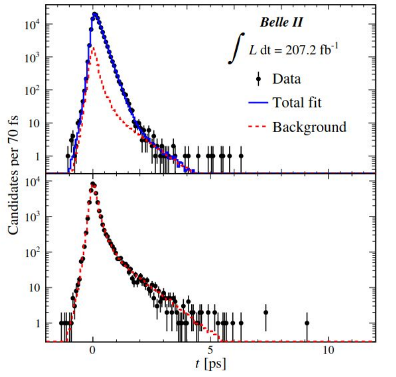


Figure 2: Decay-time distribution of $\Lambda_c^+ \to pK^-\pi^+$ events in the signal region (top) and sidebands (bottom) with fit projections overlaid.

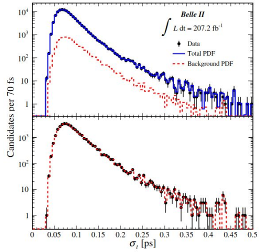


Figure 3: Decay-time uncertainty distribution of $\Lambda_c^+ \to pK^-\pi^+$ events in the signal region (top) and sidebands (bottom). The σ_t PDF used in the fit is shown by the solid blue histogram and the background σ_t PDF is shown by the dashed red histogram.

$\tau(\Omega_c^0) = 243 \pm 48\,(\text{stat}) \pm 11\,(\text{syst})$ fs

- confirming LHCb result in 3σ tension with pre-LHC world average

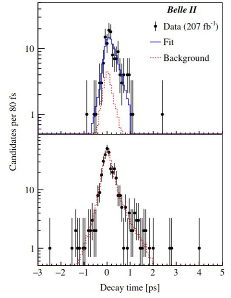


Figure 2: Decay-time distributions for $\Omega_c^0 \to \Omega^-\pi^+$ candidates populating (top) the signal region and (bottom) the sideband with fit projections overlaid.

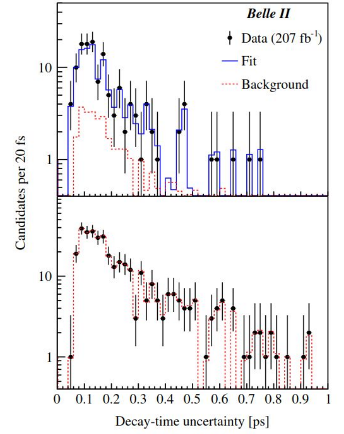


Figure 3: Decay-time-uncertainty distributions for $\Omega_c^0 \to \Omega^-\pi^+$ candidates populating (top) the signal region and (bottom) the sideband with fit projections overlaid.

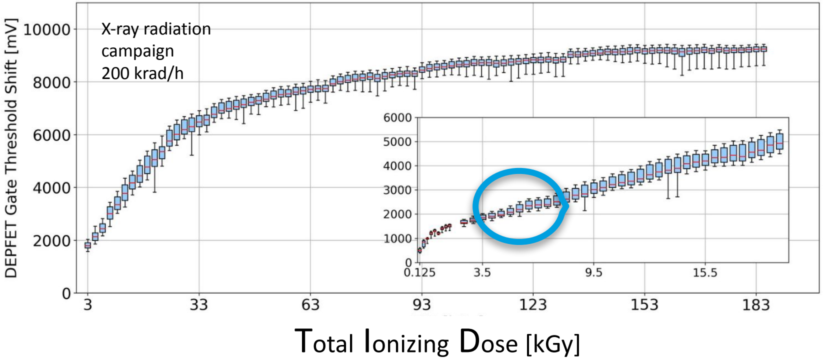
Ω_c: arXiv:2208.08573 → Physical Review D Letters
Λ_c: arXiv:2206.15227 → Physical Review Letters
D^0/D^+: Phys. Rev. Lett. 127, 211801 (2021)

Operational Challenges

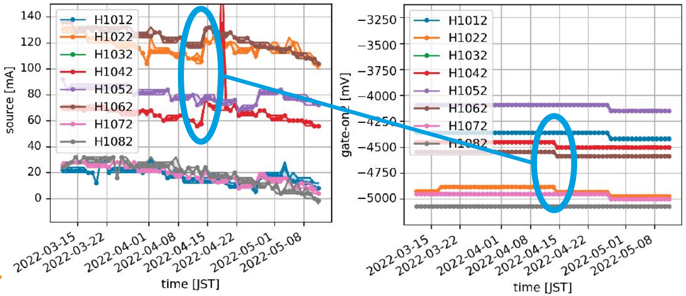
Radiation effects: threshold shift

- radiation damages oxide layer
  - causes shift of MOSFET threshold voltage

$$\mathrm{MPV} \sim g_q \sim \sqrt{I_\mathrm{D}} \sim (U_\mathrm{Gate} - U_\mathrm{Threshold})$$

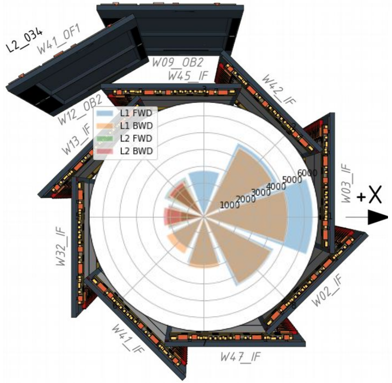


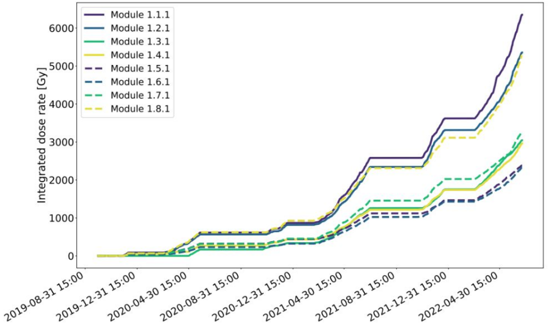
- compensated by regular adjustment of gate voltage



PXD total dose measurement: 2019 - 2022: ~ 3-6 kGy

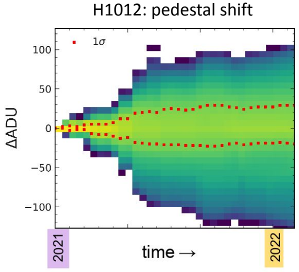
- 2019 - 2022: TID ~3-6 kGy depending on module
- estimated from module occupancies
- scaled to diamond sensor dose measurements to account for times without PXD data-taking

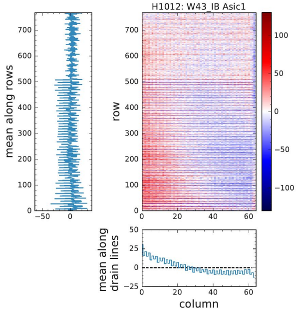


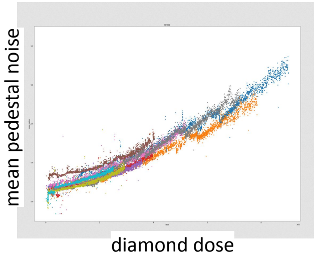


Pedestal aging

- pedestal aging and pedestal noise increase
- inhomogeneous across matrix → potential challenge for pedestal compression with consequences for module performance



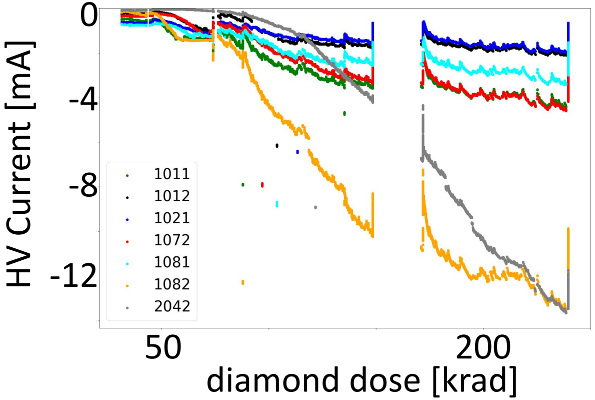


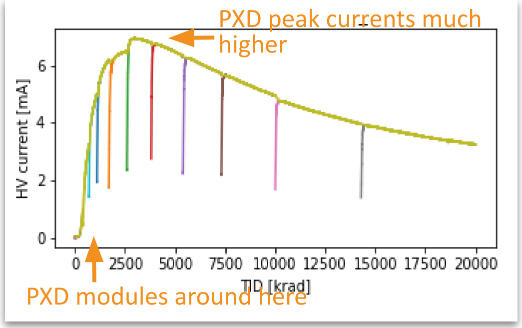


Operational Challenges

Radiation effects: increasing hv currents

- observe unexpected increase in HV currents of some modules
  - in guard ring area → not affecting active pixel matrix
  - so far no performance impact → but power supply patch needed
- some annealing during *beam off/HV on* and *beam on/HV off* times

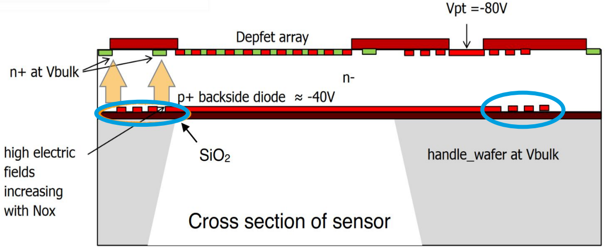




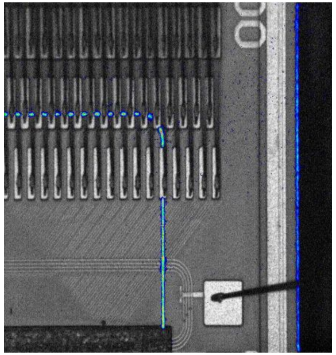
- x-ray lab campaigns: expect currents saturate at certain dose
- not observed in PXD yet

interpretation

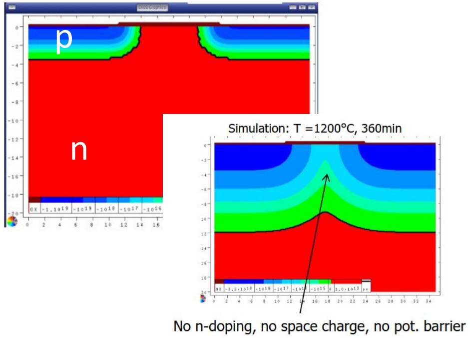
- unexpected shorts in thinly spaced guard ring structures
- oxide charge increases with irradiation → higher breakthrough currents
- from higher than expected lateral diffusion in (hot) SOI process
  - previously unnoticed due to wrong backside doping profile measurements (via SIMS)
- further studies with dedicated test structures ongoing



emission microscope image visualizing avalanche breakdown at guard rings



simulated diode guard ring structure before and after diffusion

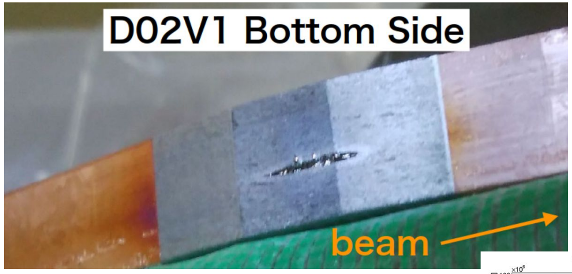


Operational Challenges

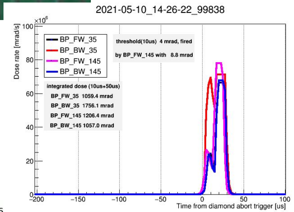
Beam loss events

- reasons not fully clear
  - unstable beams due to dust particle collisions?
  - glitches of accelerator components?
- major issue of accelerator, eg preventing lumi ramp-up
- not always detected early enough to safely dump beams
  - min. 40 µs delay from error to beam dump
  - collimator damage, QCS (superconducting final focussing magnets) quenches, …,

LER collimator damage on Nov 15 '20

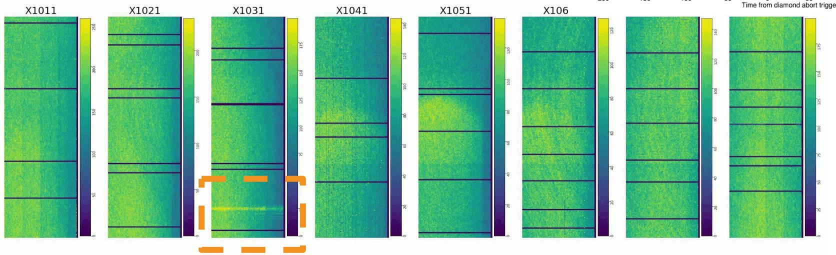


DCU Dose

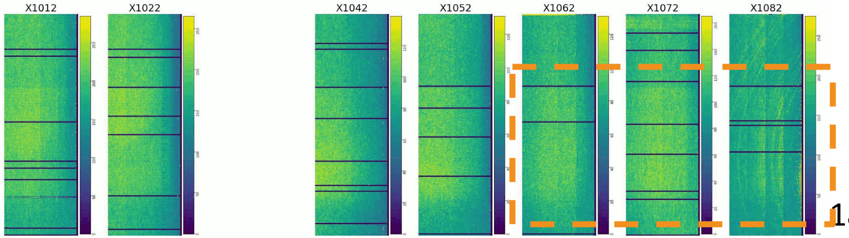


impact on PXD:

- large instant radiation dose before beam could be dumped
  (~40 µs splash, total dose unknown)
- permanent damage: dead switcher gates
- exact failure mechanism still under study
  - radiation studies: problem localized in the switcher at clear & gate regulators
- mitigation procedures
  - SuperKEKB + Belle II: earlier detection and faster beam dump
  - PXD: faster emergency power off
  - (updated switcher design)



layer one occupancy before/after beam loss in May '21



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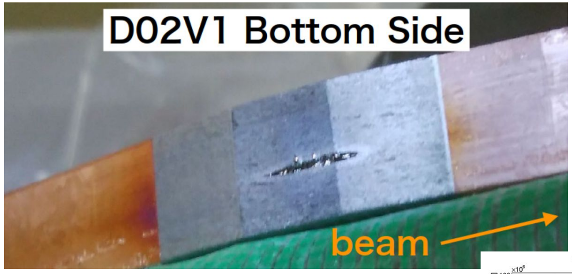
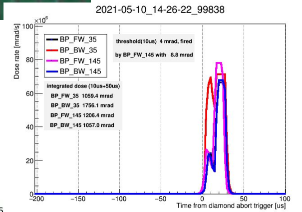


DCU Dose



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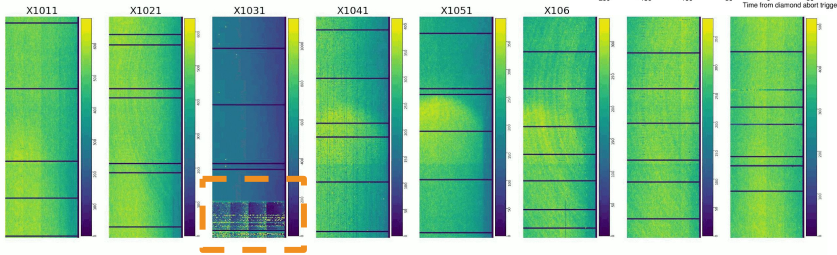

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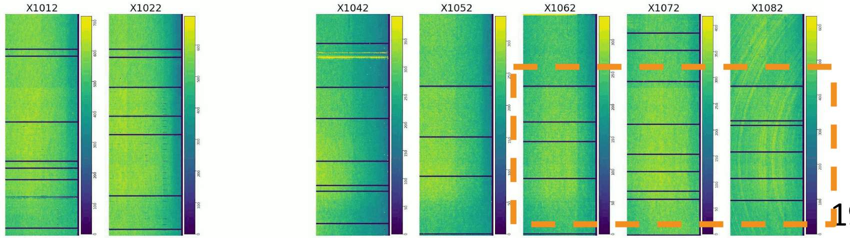
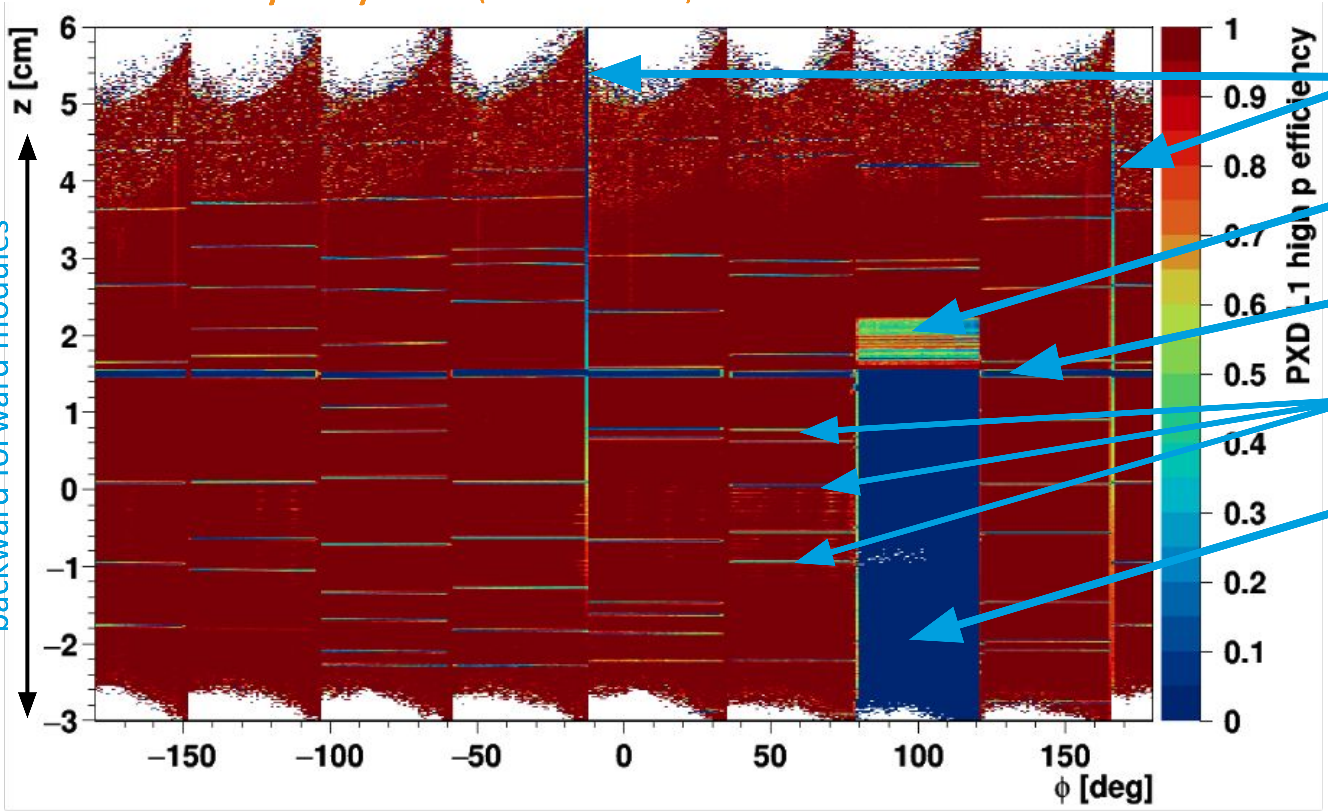


PXD Performance

Pixel hit efficiency in layer one (di-muons e20-e26)

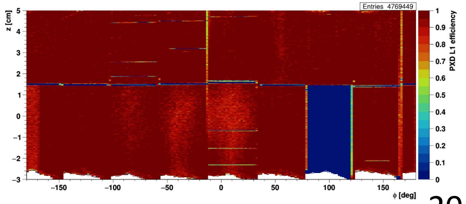
backward forward modules



8 ladders

- half shell gaps
  (problems during installation)
- noisy switcher from May 10th 2021 beam loss incident
- glue gap (~0.8 mm) covered by layer 2
- dead gates (4 rows) ~2.5 % global efficiency loss
- installed broken module covered by layer 2

2019 state:



Outline

Introduction

- SuperKEKB, Belle II, and the Belle II Vertex Detector

The Pixel Vertex Detector (PXD)

- Working Principles
- PXD Modules and Calibration
- PXD Detector

PXD Operation in Belle II

- PXD Performance
- VXD Performance
- Operational Challenges: backgrounds, beam-losses, irradiation and aging

PXD2 2022 Upgrade

- Future of PXD

PXD 2022

Building a 2nd PXD

PXD1 was incomplete

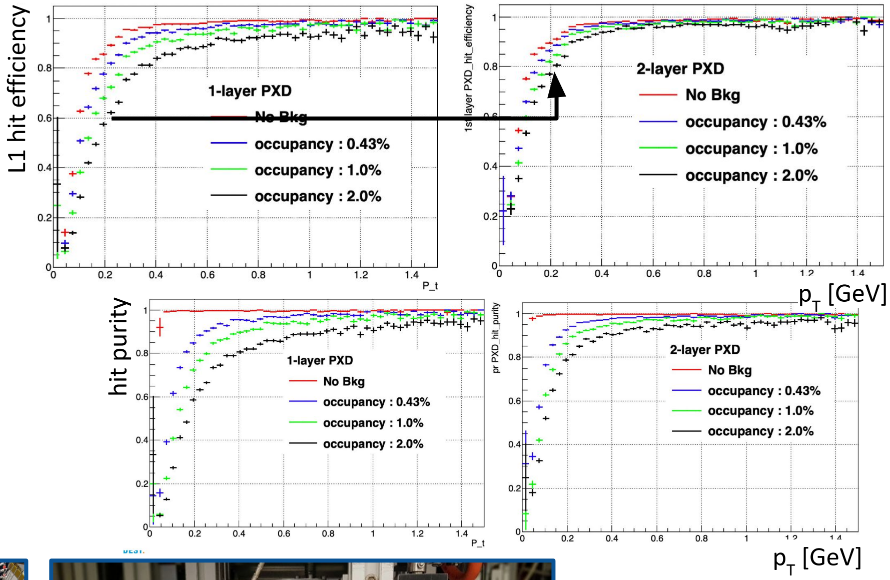
- only 10/20 ladders (8/8 inner, ½ broken, 2/12 outer) installed
  - not enough good modules available pre-2018
- good vertexing performance so far
  - but not guaranteed for higher future lumi ⇒ higher backgrounds
- suffered significant damage due to uncontrolled beam losses

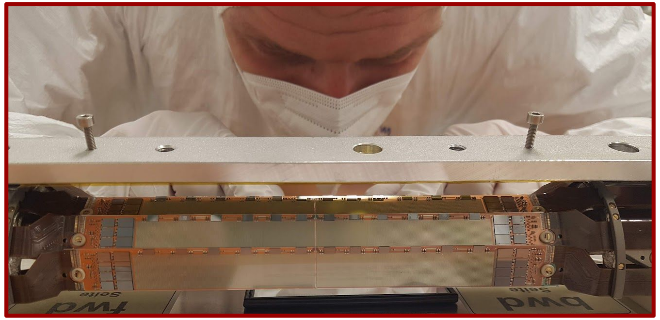
ongoing efforts to install 2nd, complete PXD2

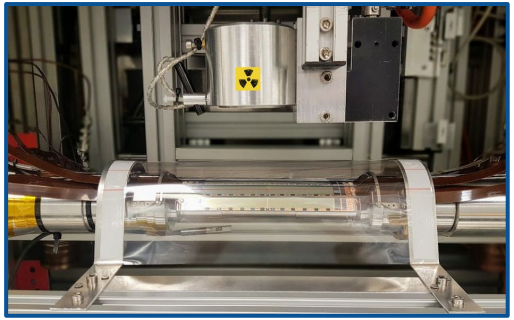
- same technology but improved manufacturing processes + time
- module production & assembly of both half shells completed
  - pre-commissioning at DESY ongoing
  - slowed down due to issues with pxd mechanics (gliding mechanism)
- PXD2 to be installed during current long shutdown 1:
  - 6/2022 ⟶ ~ fall/winter 2023

1 layer vs 2 layer PXD performance

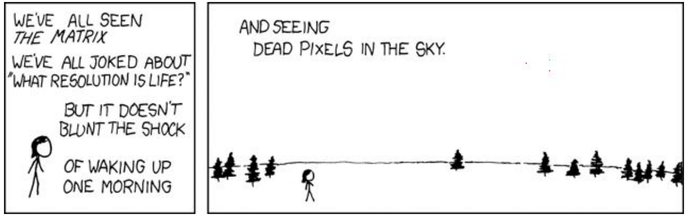
- L1 performance (efficiency, purity) will deteriorate with increasing occupancy
- can be (partially) recovered by second layer







Conclusion

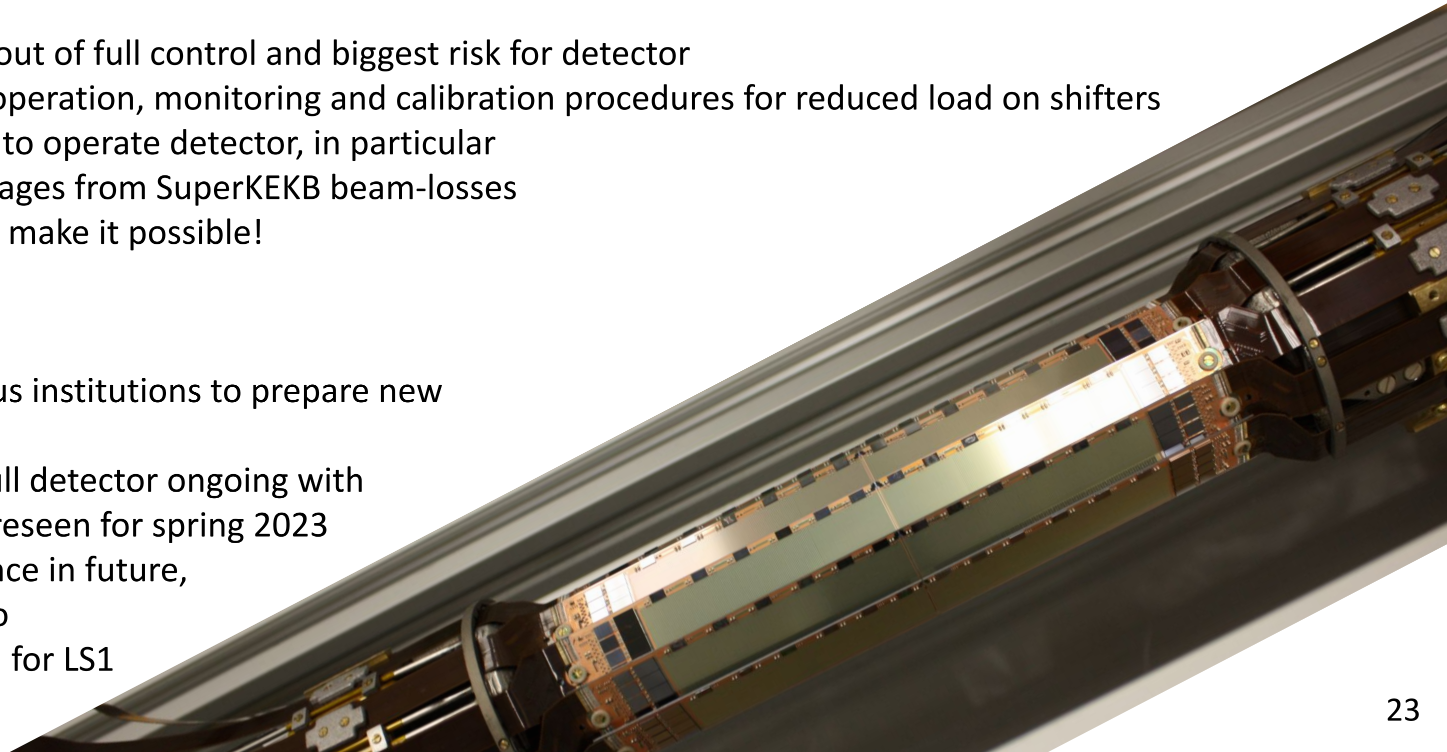


PXD status

- very good performance of PXD and stable operation throughout 2019-2022
- setbacks from beam loss events with high instantaneous dose rate
  - damages to detector
  - so far have remained out of full control and biggest risk for detector
- improved / automated operation, monitoring and calibration procedures for reduced load on shifters
- still lot of effort needed to operate detector, in particular
  - in face of further damages from SuperKEKB beam-losses
- big thanks to those who make it possible!

PXD future

- great efforts from various institutions to prepare new and complete PXD
- pre-commissioning of full detector ongoing with installation in Belle II foreseen for spring 2023
- to retain PXD performance in future, rely on improvements to SuperKEKB also planned for LS1

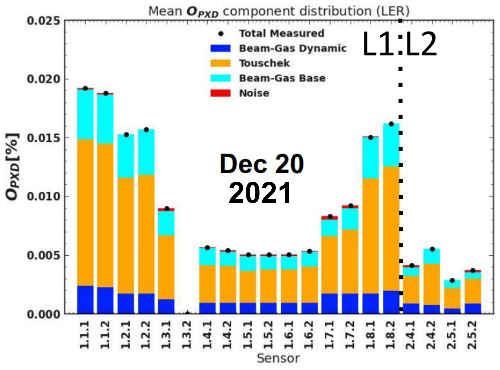


Backup

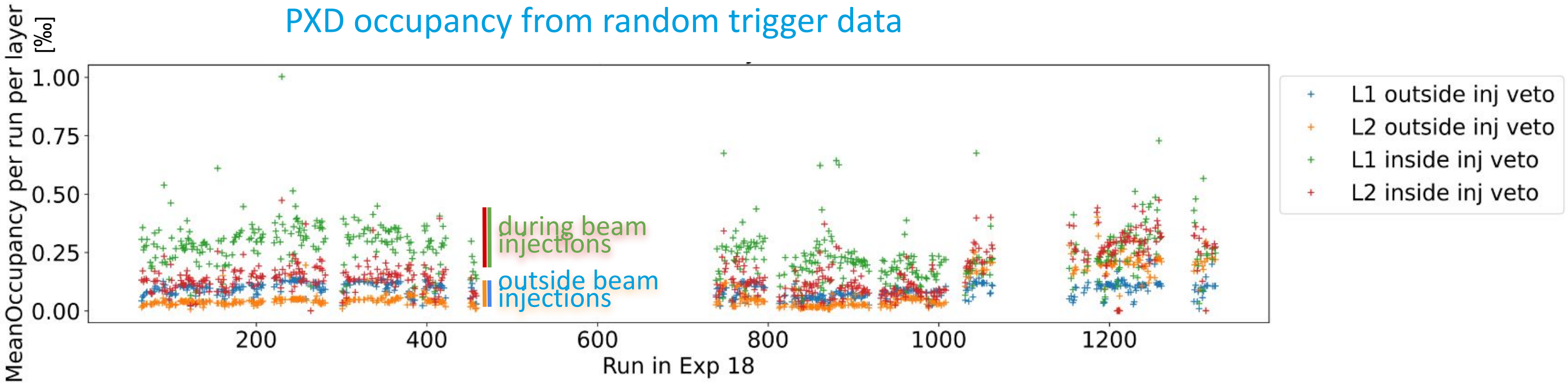
Operational Challenges

Backgrounds

- what is background?
  - synchrotron radiation,
  - lost electrons or whole beams inducing secondary particles with pipe or restgas
  - ...
- why important?
  - can deteriorate performance (fake hits)
  - contributes to/dominates occupancy (in particular during injections) ⟶ 1%/3% limits not hit yet (on avg)
  - contributes to irradiation ⟶ aging (slow irradiation) or even damages (fast irradiation)



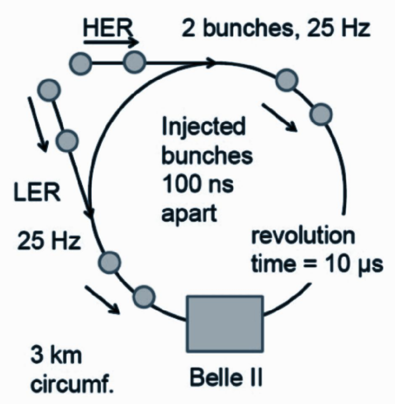
PXD occupancy from random trigger data



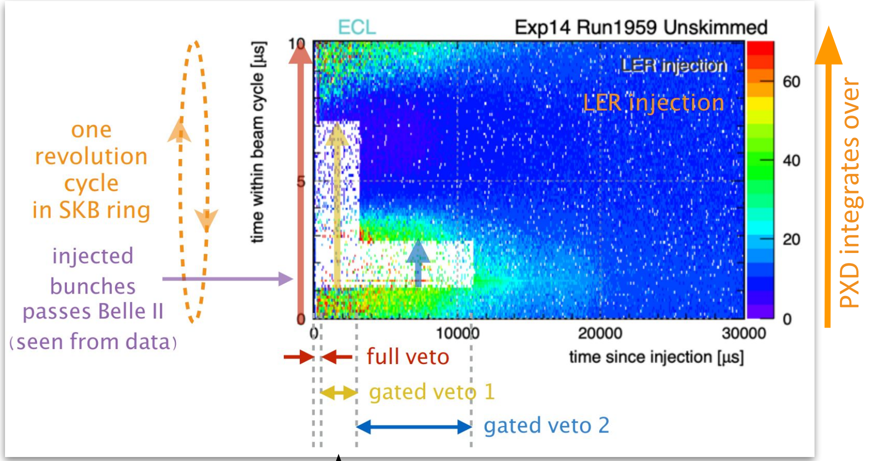
Operational Challenges

Backgrounds: injection

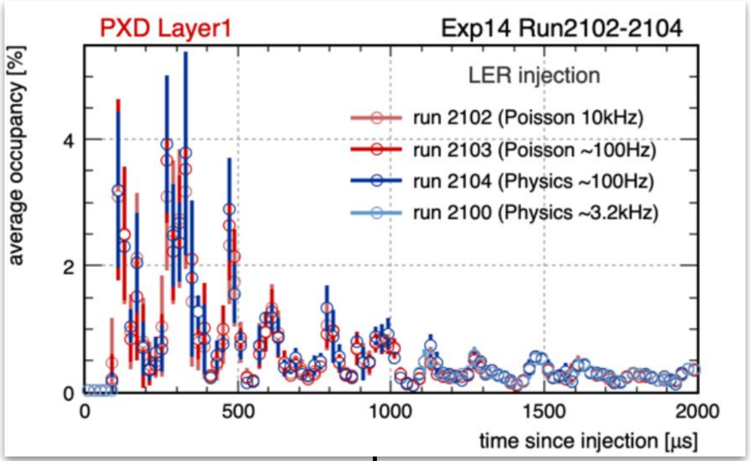
- SuperKEKB is operated in top-up mode: continuous injection up to 50 Hz
  - at design luminosity, Touschek effects limit beam lifetime to few mins
  - injected bunches produce high background rates, damping takes few ms
  - mitigation: full veto (all BII detectors) + gated veto (all but PXD)
- PXD cannot halt data collection (default operation):
  - 20 μs integration time vs 10 μs beam revolution time
  - injection spikes can saturate DAQ → not yet critical (partial data loss at sub-permille level)



Injection trigger vetoes: (on ECL occupancy)



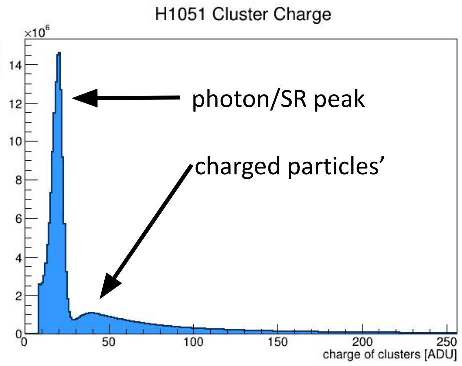
PXD Occupancy: vetoless runs during injection



Operational Challenges

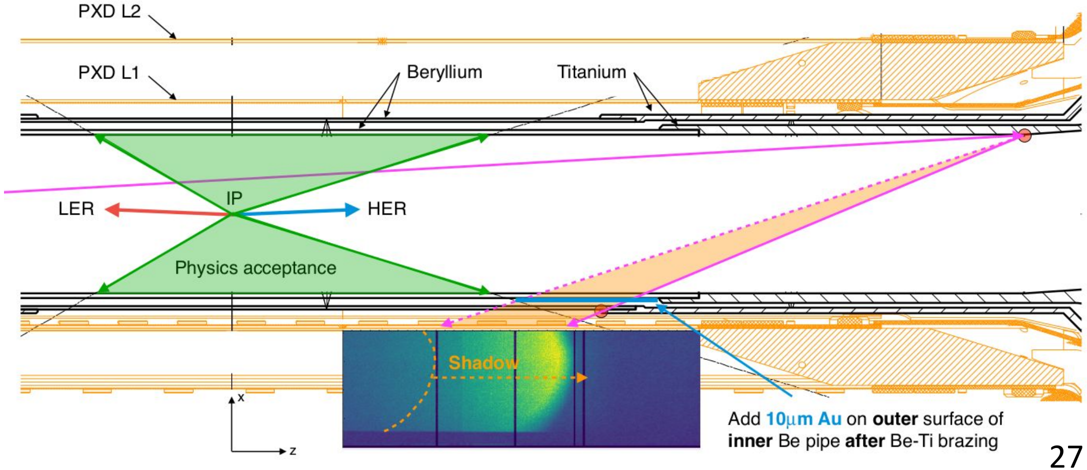
Synchrotron radiation

- interaction region designed to avoid direct SR photons hitting central Be beam pipe
- still: large SR background observed in several -x modules after change of optics
  - dominated by low energy, single pixel clusters (<10 keV)
  - appear during HER injections (→ large betatron oscillations during cooldown)
  - origin: back-scattering photons from SR fan hitting +x edge of Ti beam pipe
- results in high localized hit density
  - inhomogeneous module irradiation
  - deterioration of clustering and tracking



mitigation

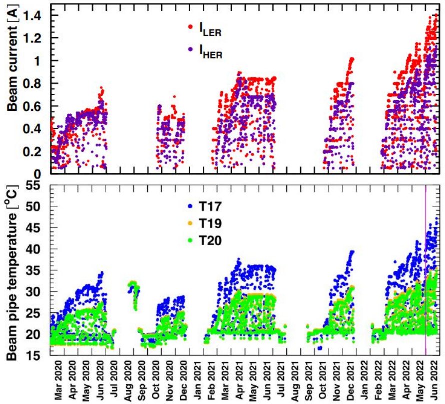
- small modification of HER beam orbit
  - sensitivity of PXD provides valuable feedback to accelerator
- new modified beam pipe w/ new geometry and additional gold plating to be installed with PXD 2022 update

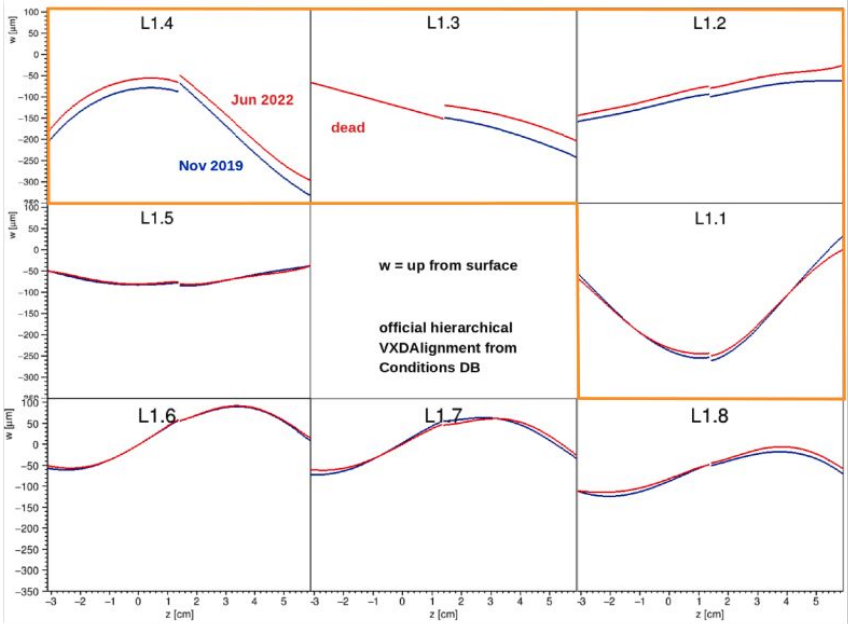


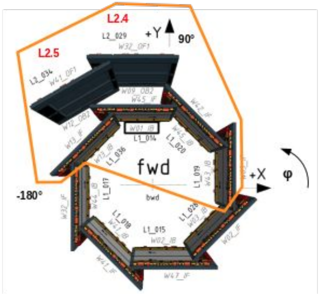
Operational Challenges

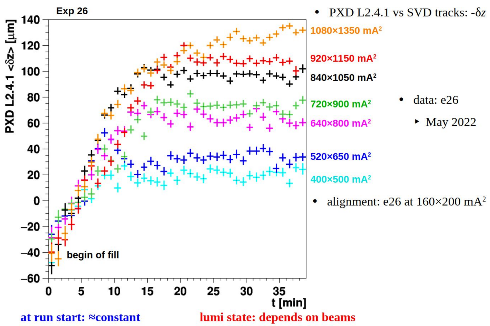
Alignment

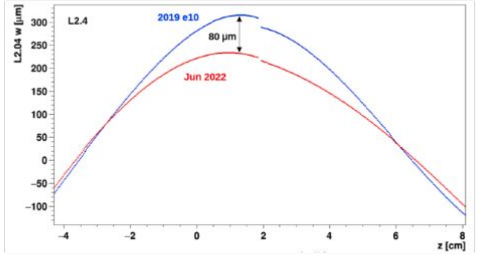
- overall stable alignment
- small and stable PXD ladder deformations
- observe global z-shifts of detector eg with earthquakes
- observe z-movement (L2 in particular) with increasing beam currents
  - result in warming up of beampipe and thermal expansion
  - result in stress on PXD not fully compensated by PXD mechanics







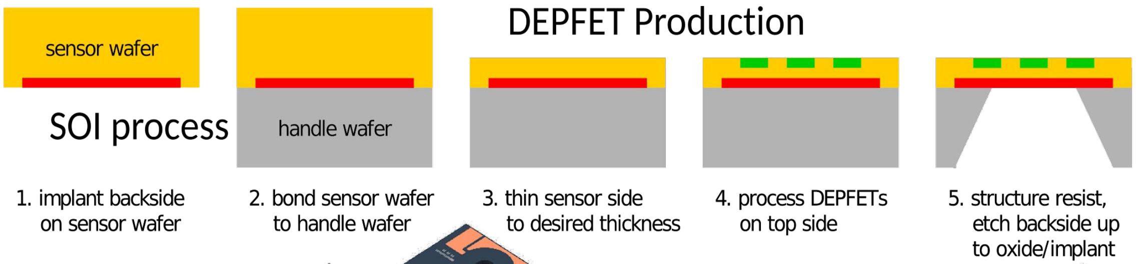


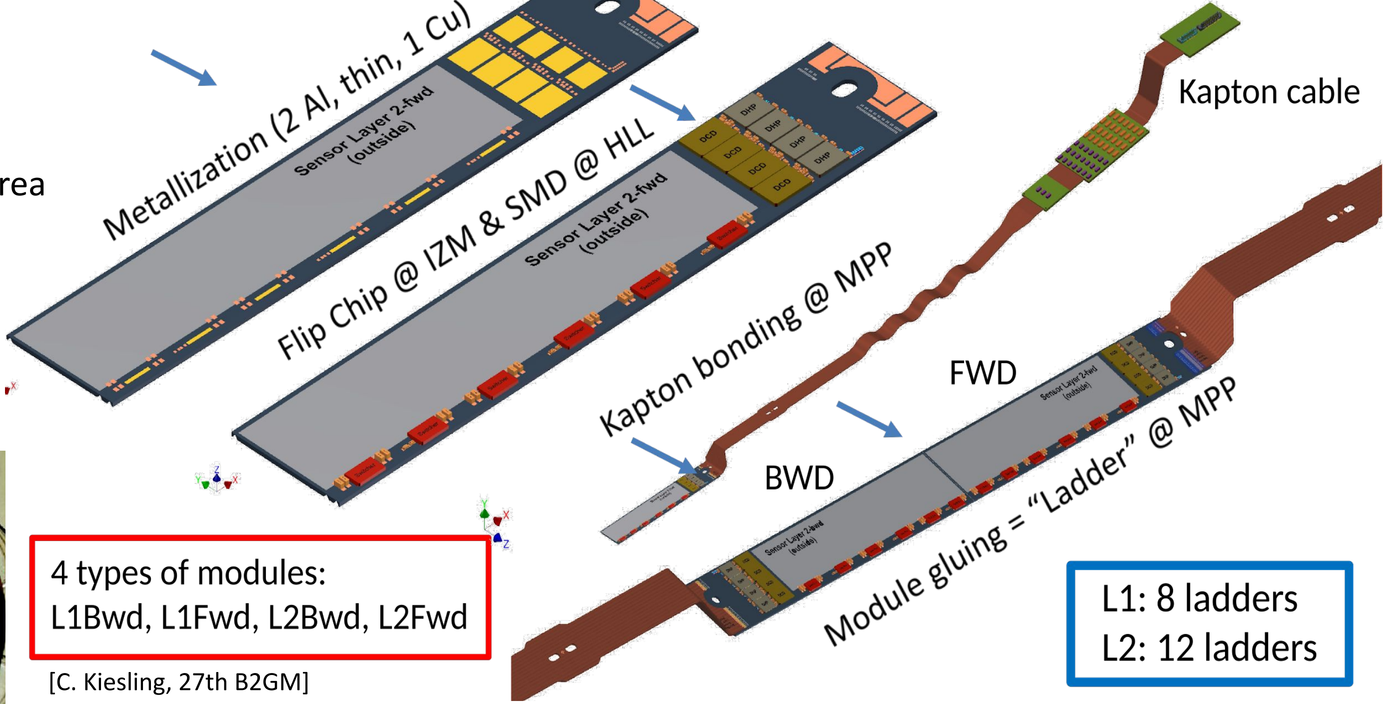


PXD Modules

Production

- 250 x 768 pixels per module
- pixel pitch varies in z-direction
  50 x 55 - 85 µm^2
  - best resolution in Belle II forward direction (at 45° incident angle)
- thinned to 75 µm in sensitive area
- mechanically self-supporting
  - thicker end of stave and (perforated) frame
  - host readout and control ASICS

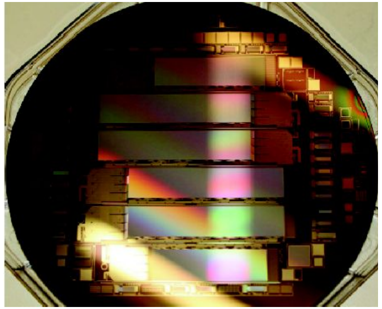




4 types of modules:
L1Bwd, L1Fwd, L2Bwd, L2Fwd

[C. Kiesling, 27th B2GM]

L1: 8 ladders
L2: 12 ladders

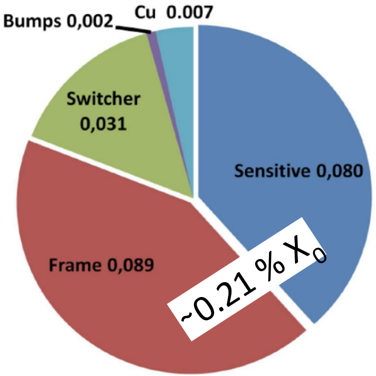


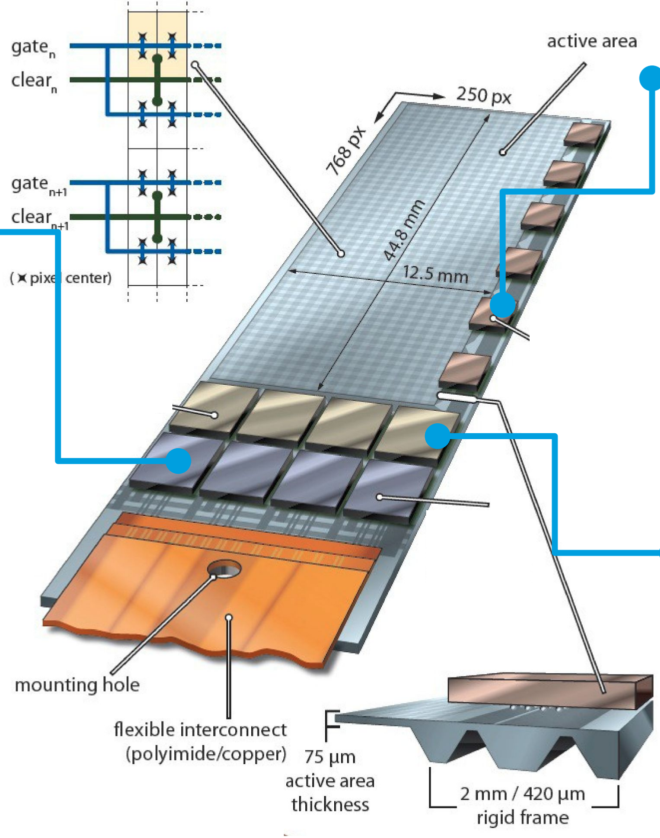
PXD Modules

ASICS

4 x DHP: Data Handling Processor

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





6 x Switcher: Row Control

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

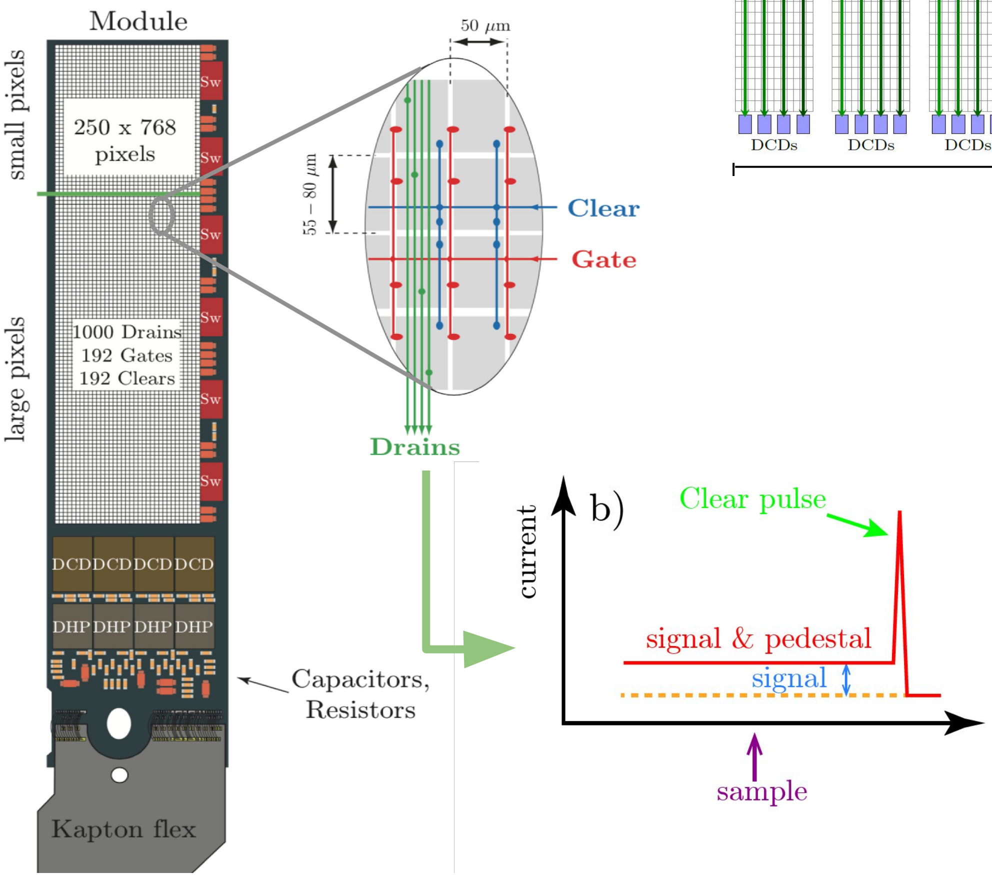
4 x DCD: Drain Current Digitizer

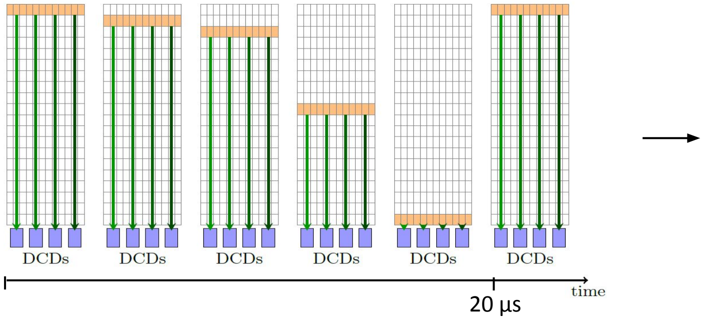
- **pipeline 8-bit ADC per channel**
- 256 input channels
- 92 ns sampling time
- UMC 180 nm
- rad. hard proved (10 Mrad)

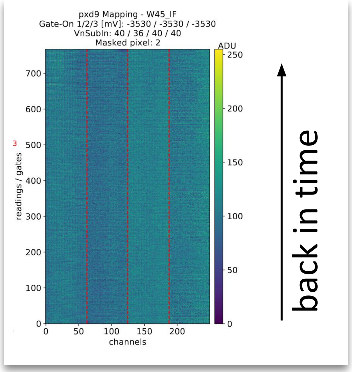
⇒ all 3 custom PXD designs

PXD Modules

Readout scheme







rolling shutter mode:

- signals read gate by gate
- read-clear cycle in ~100 ns
  - full integration time 20 µs (1 "frame")
  - twice SuperKEKB revolution time

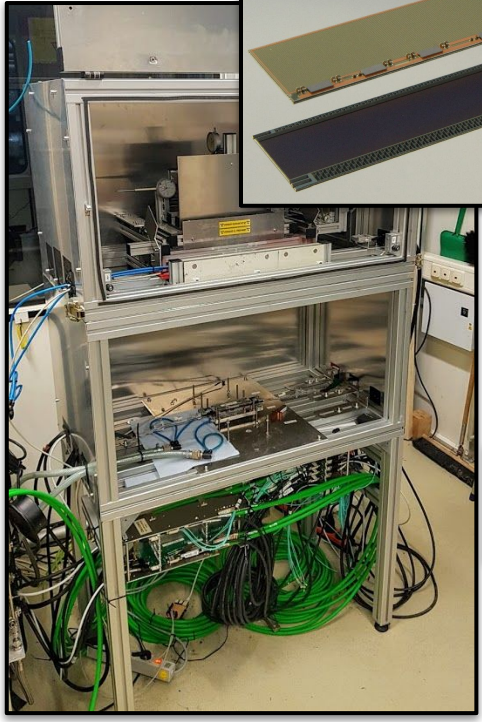
sampling:

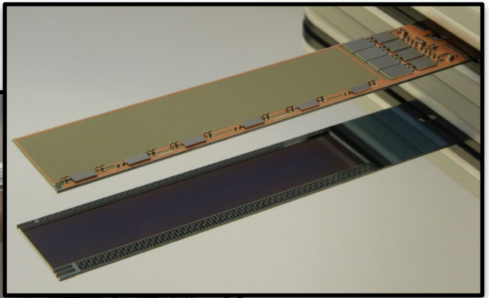
- drain currents measured once
- pedestal correction on DHP
- zero suppression:
  - only signals above threshold send out

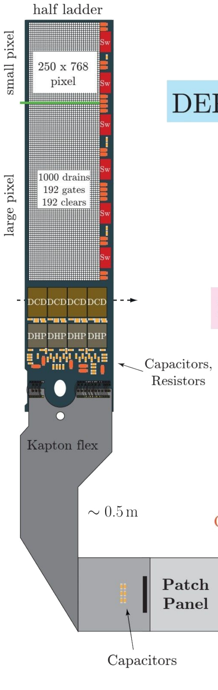
PXD Module Operation

Readout and control

(pictures: testsetup at DESY)







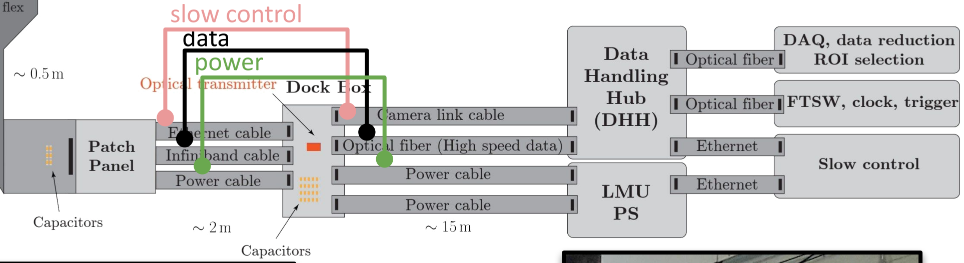
Data Readout Chain

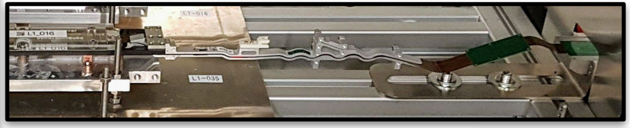
DEPFET → DCD → DHP → DHH → ONSEN → Belle II DAQ

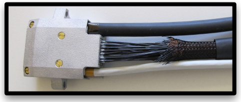
Module control

Slow Control GUI → DHH → DHP → DCD, Switcher

Slow Control GUI → PS



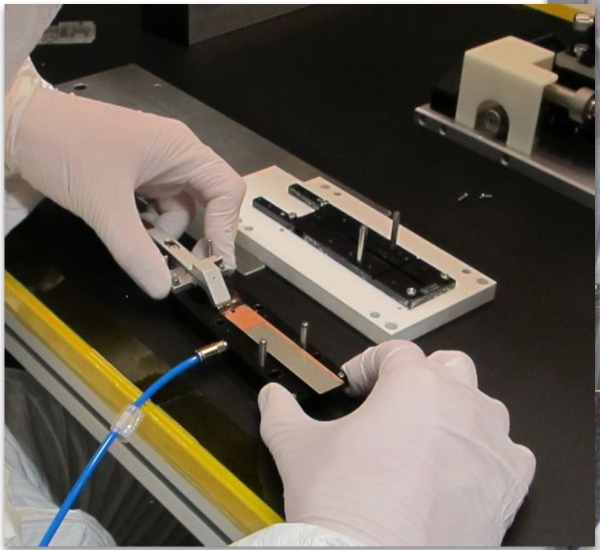


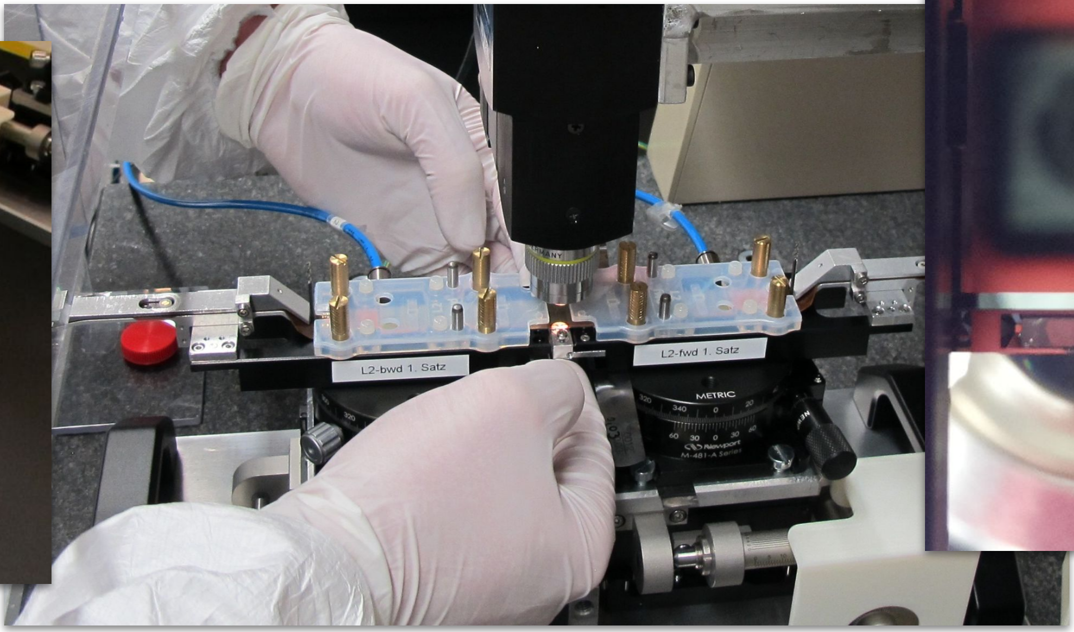


Module Production

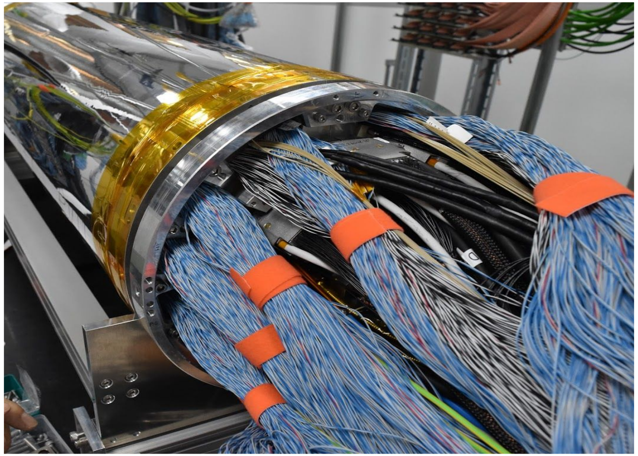
Ladder gluing

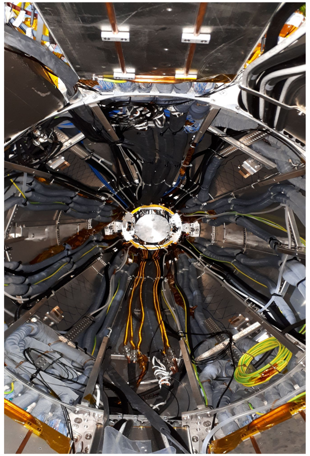
- special jig for module handling, glue dispersion, alignment under microscope
- ceramic stiffening rods on backside
- critical step in PXD1 production
  - revised procedure for PXD 2022 avoids touching matrix side of sensors

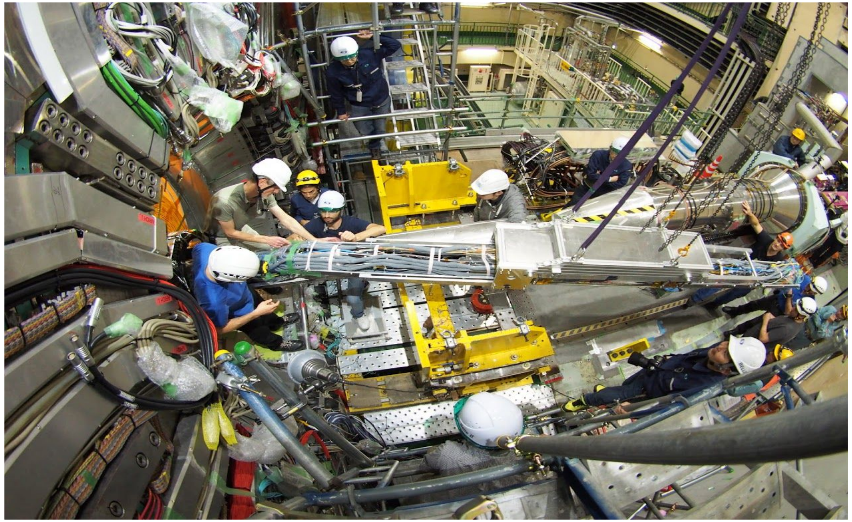


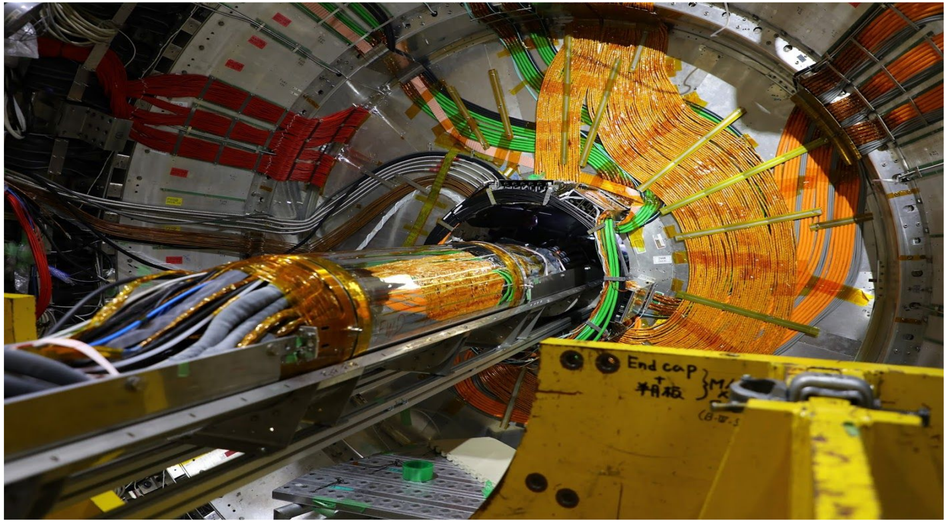


VXD Installation 2018





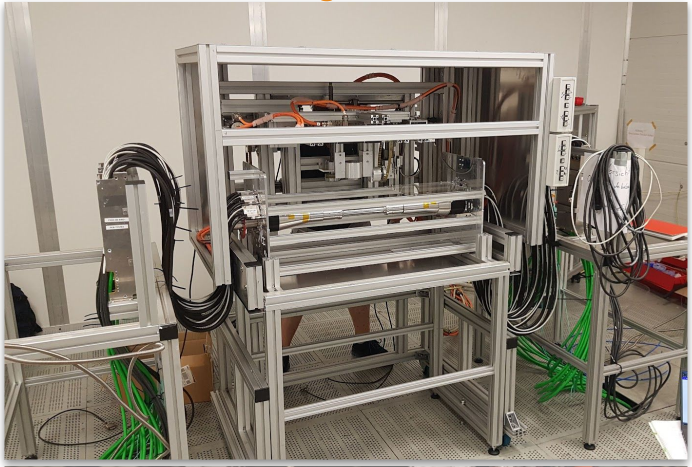


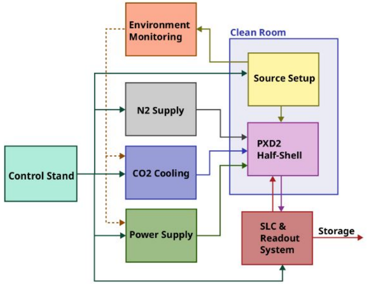


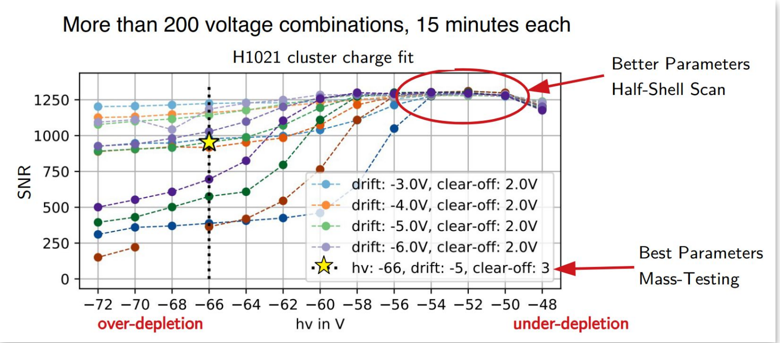
PXD 2022

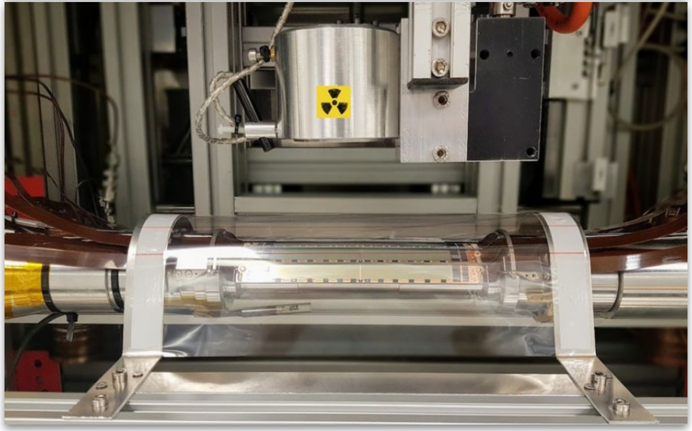
Pre-Commissioning at DESY

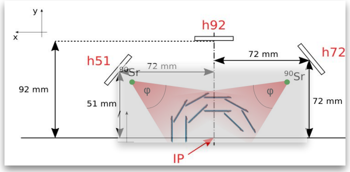
- perform full electrical tests to ensure no damage occurred during ladder mounting
- perform measurements with 90 Sr source to optimize working point
- before installation in Belle II this is only possible in the DESY setup

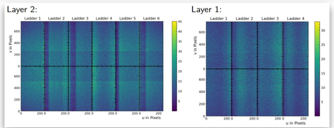


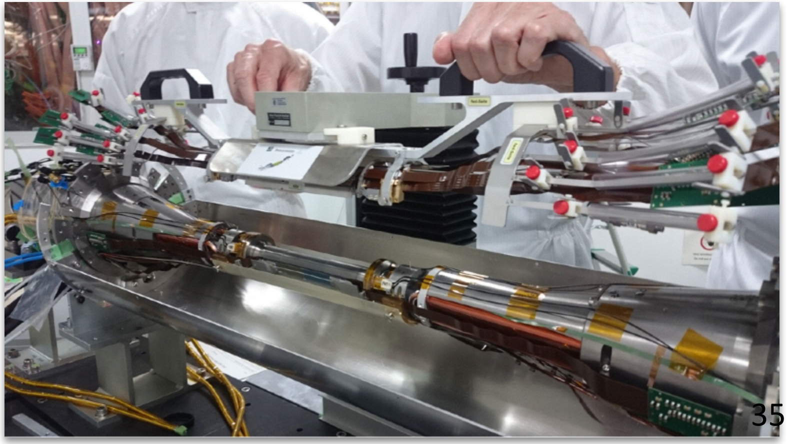








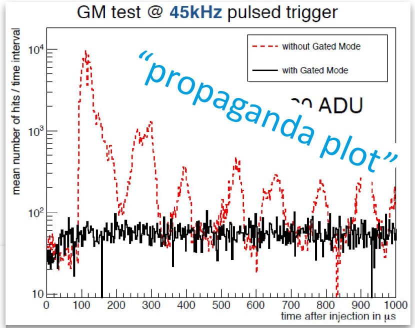


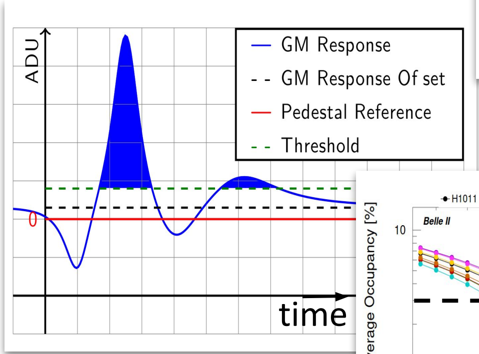


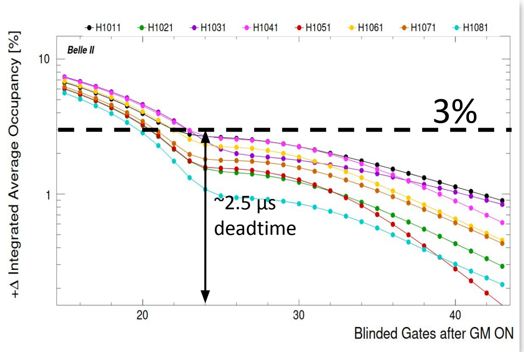
Operational Challenges

Gated mode

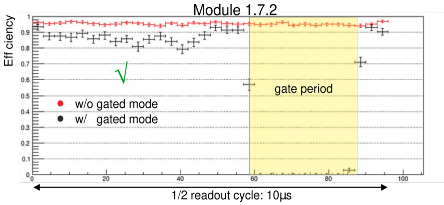
- "gated mode" can blind PXD modules when noisy bunches pass
  - newly created charges are not collected
  - charges at internal gate are preserved
- challenges:
  - switching into gated mode results in pedestal fluctuations
    - produce noise on their own
      $\longrightarrow$ still larger than injection noise
  - synchronization with injections
  - optimizing module parameters for GM

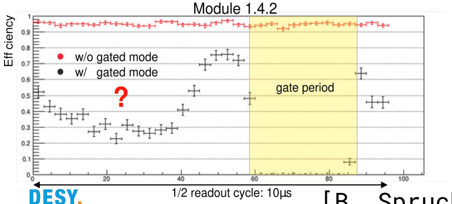






[R. Karl]



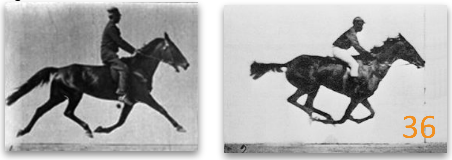


DESY. [B. Spruck]

real GM "efficiencies"

- 2021 dedicated runs for PXD GM studies
  - inconsistent module behaviour
  - GM not ready yet
    nor useful for current injection conditions
  - **cost-benefit too high compared to slightly increasing global trigger veto**

"gaited mode"



VXD Performance

Impact parameter and beam profile

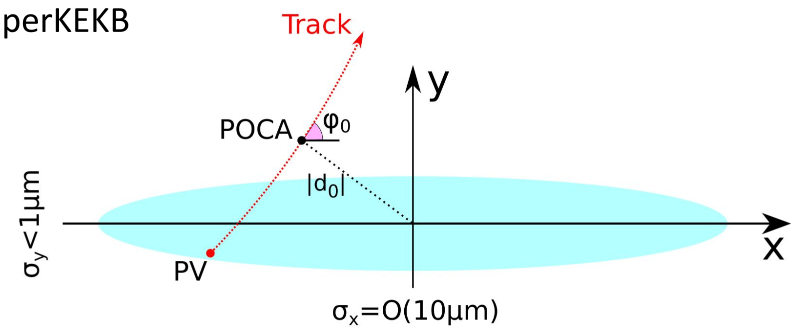
- resolution: 1.5 - 2 x better than Belle

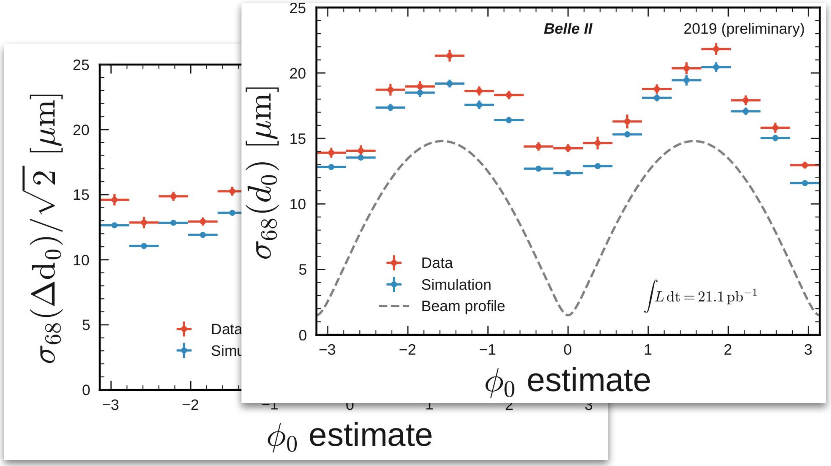
	Data	Simulation
$\hat{\sigma}(d_0)$ [μm]	$14.2 \pm 0.1\,(\text{stat}) \pm 0.1\,(\text{syst})$	$12.5 \pm 0.1\,(\text{stat})$
$\hat{\sigma}(z_0)$ [μm]	$16.1 \pm 0.1\,(\text{stat}) \pm 0.1\,(\text{syst})$	$13.9 \pm 0.1\,(\text{stat})$

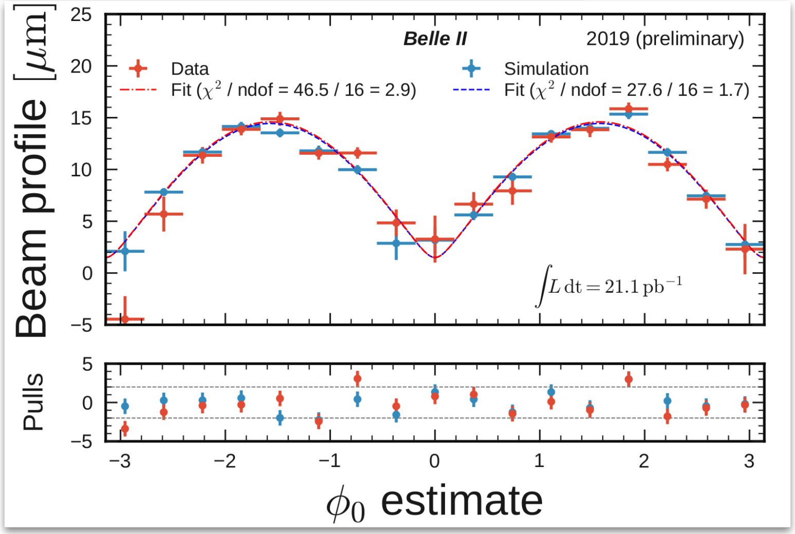
- beam profile:
  - study impact parameter d_0 and resolution in di-muon events
  - φ-dependence gives info about beam profile:

$$\sigma^2_{d0} = \sigma^2_{intr} + (\sigma_x \sin\varphi)^2 + (\sigma_y \cos\varphi)^2$$

  - unfold beam profile → consistent with expectations from SuperKEKB





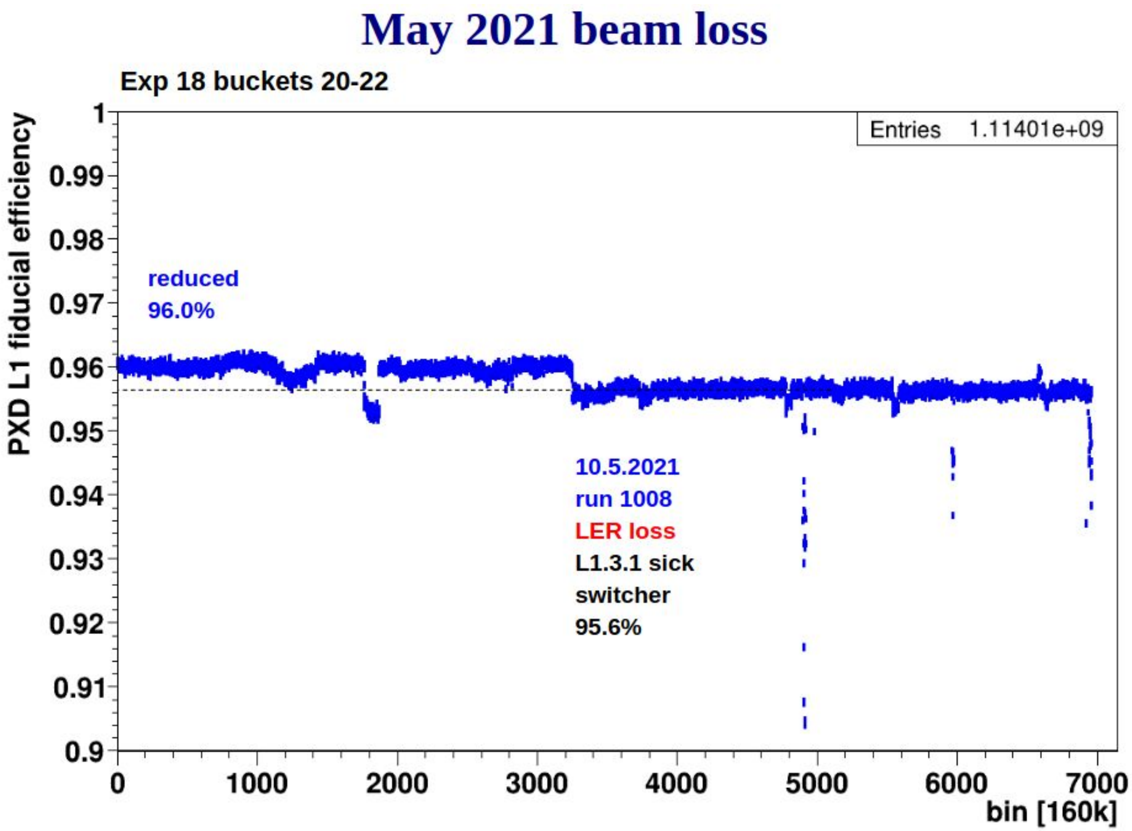


  - more involved methods study d_{01} and d_{02} correlations in 2-track events

[BELLE2-NOTE-PL-2019-011], [BELLE2-PUB-TE-2020-001]

Operational Challenges

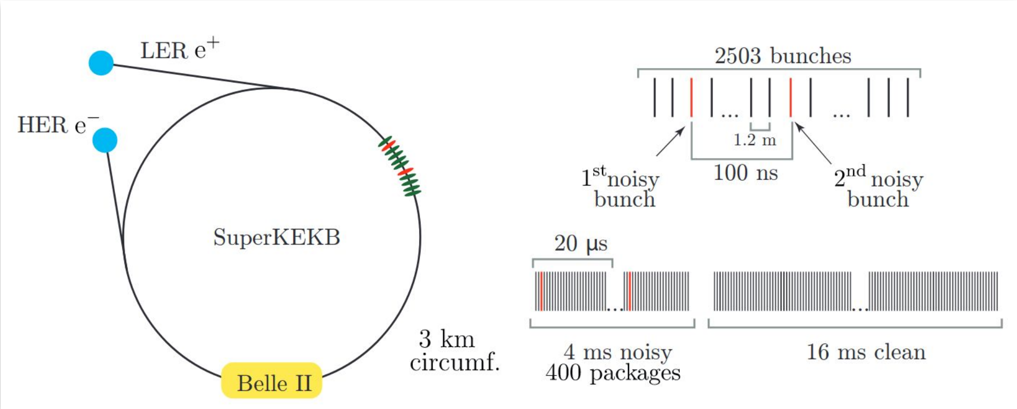
Beam loss impact on global L1 efficiency

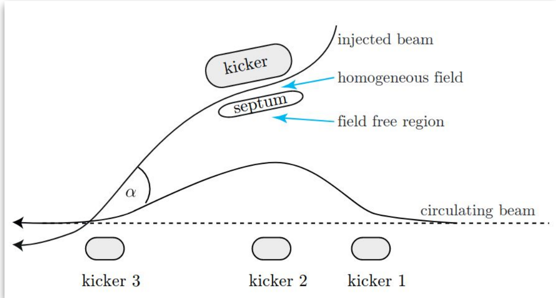


SuperKEKB

Design parameters and injection scheme

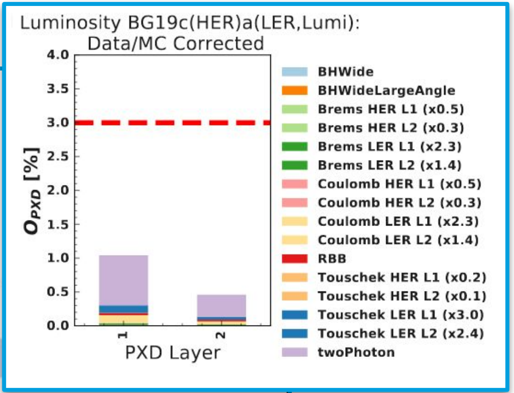
	LER	HER	
Energy	4.0	7.0	GeV
Current	3.6	2.6	A
Number of bunches	2500		
Bunch Current	1.44	1.04	mA
Circumference	3016		m
Emittance ε_x	3.2(1.9)	4.6(4.4)	nm
Emittance ε_y	8.64(2.8)	12.9(1.5)	pm
Coupling	0.27	0.28	
Beta function β_x	32	25	mm
Beta function β_y	0.27	0.30	mm
Crossing angle $(2\Theta_c)$	83		mrad
Beam-beam parameter ξ_x	0.0028	0.0012	
Beam-beam parameter ξ_y	0.0881	0.0807	
Luminosity $\mathcal{L}$	8×10^{35}		$cm^{-2}\ s^{-1}$





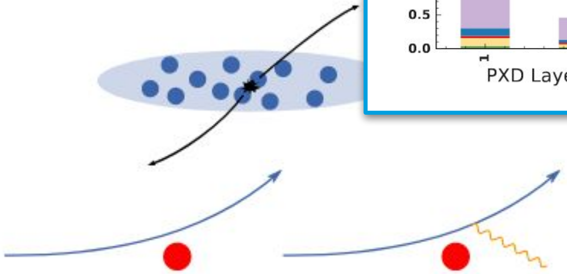
→ beam lifetime limited by (unavoidable) Touchek effect to few minutes
→ 50 Hz injection
→ 10 µs revolution time
→ 4 ms cooldown
⇒ 20% noisy *dead-time* w/o detector readout
⇒ PXD: cannot (simply) *stop* charge collection

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** $\propto N_{gas\ molecules} \times N_{particles} \rightarrow \mathbf{P} \times \mathbf{I} \times \mathbf{Z_{eff}^2}$

▷ **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!

HLT and Track Finding