MAX-PLANCK-INSTITUT
FÜR PHYSIK

Operational Experience of the Belle II Pixel Detector

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MPI for Physics, Munich, Germany

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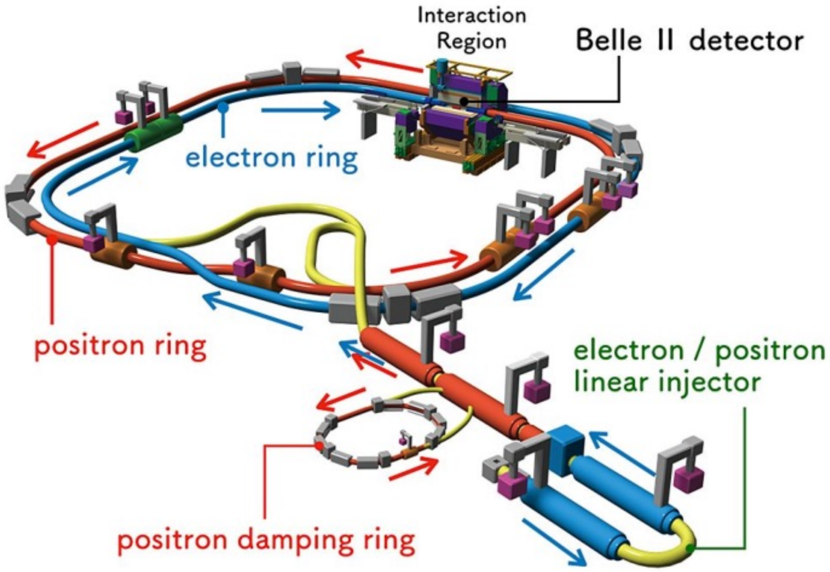
SuperKEKB & Belle II

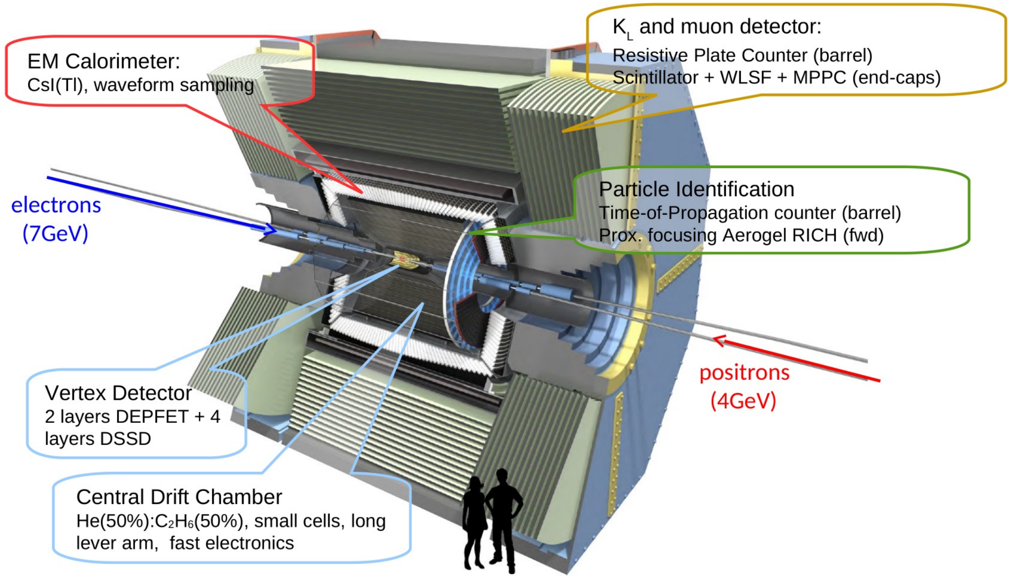
SuperKEKB

- Upgrade of existing KEKB accelerator.
- B factory: $E_{cm} = M_{\Upsilon(4S)} \approx 10.58$ GeV.
- Target luminosity: 6×10^{35} cm^{-2} s^{-1}
  - Nano-beam technology and increased current.
  - Challenge: higher background.
- World record: 3.12×10^{34} cm^{-2} s^{-1} @ June 2021.

Belle II

- Upgrade of Belle detector.
- Target: 50 ab^{-1} by 2030.
- Totally ~213 fb^{-1} of data until July 2021.
- Maximum trigger rate: 30 kHz.

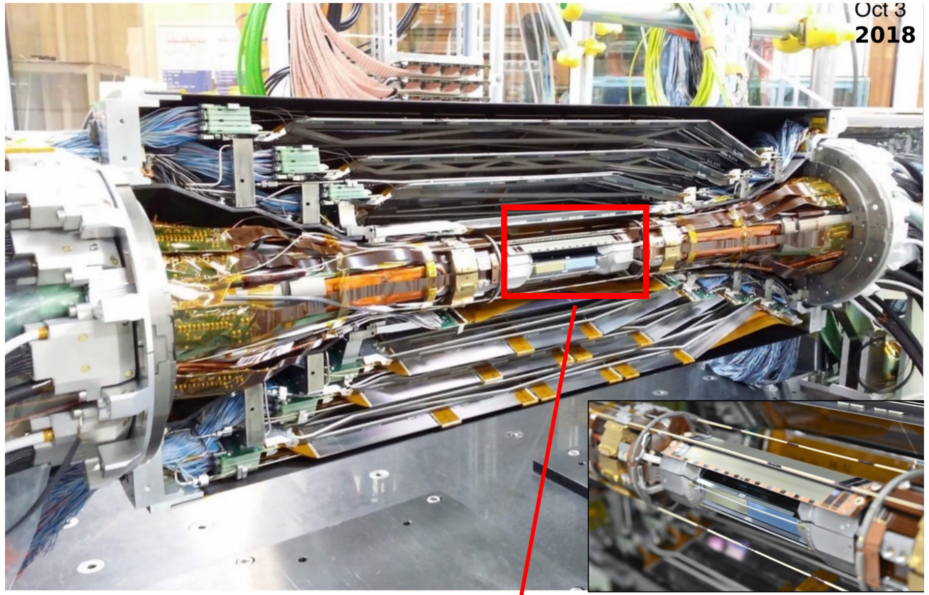


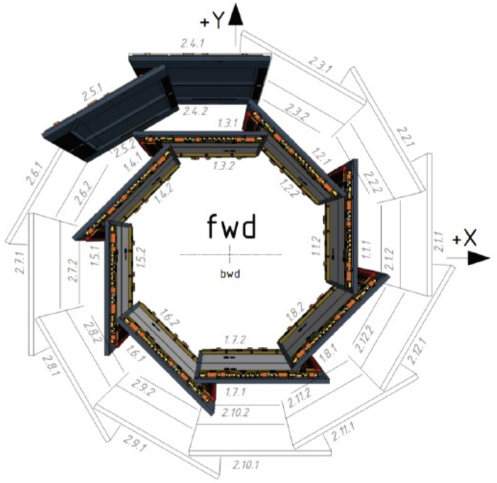


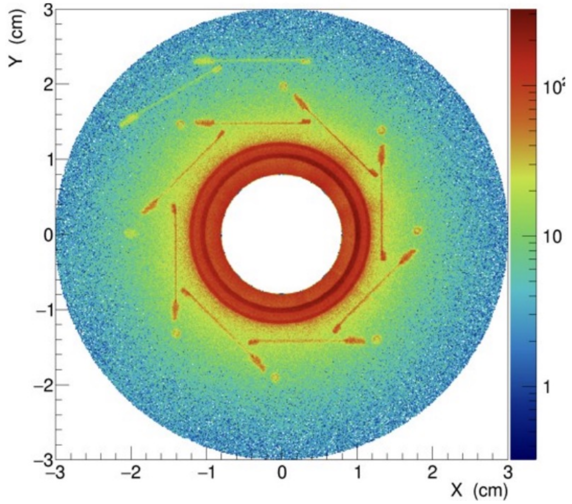
Vertex Detector on Belle II

- Silicon Vertex Detector (SVD): [see Yuma Uematsu's talk about SVD]
  - 4 layers of 2-sided silicon strips.
  - R ≦ 140mm.
- Pixel Vertex Detector (PXD):
  - 2 layers of DEPFET sensors.
  - 8 inner ladders at radius 14 mm.
  - 12 outer ladders at radius 22 mm (only 2 ladders installed).
  - ~7.7 x 10^6 pixels.
  - ~0.21% X_0 / layer material budget.

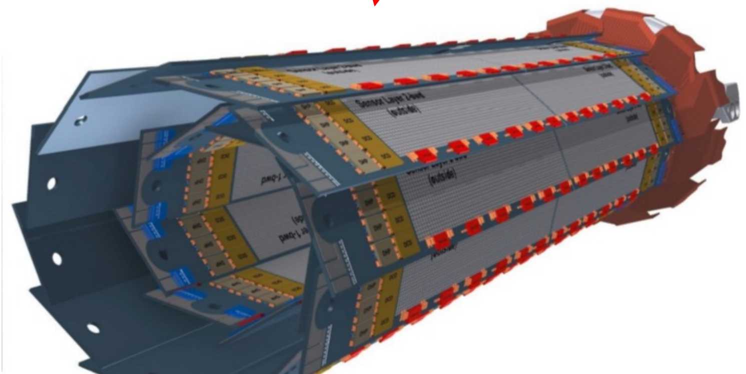
VXD half shell







Scatter plot from data

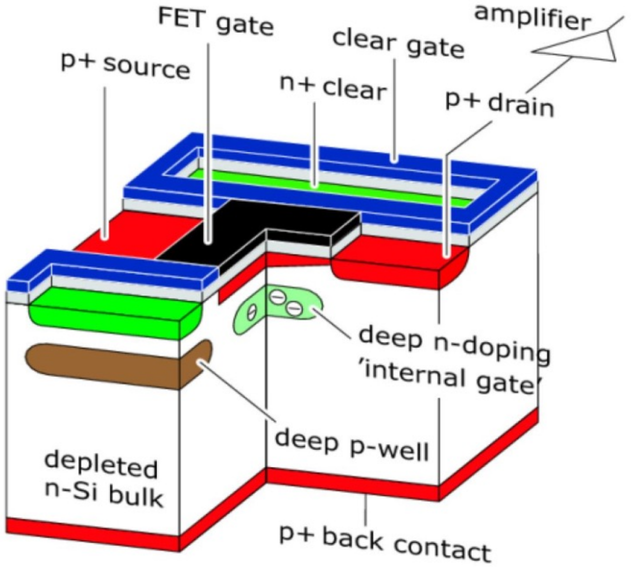


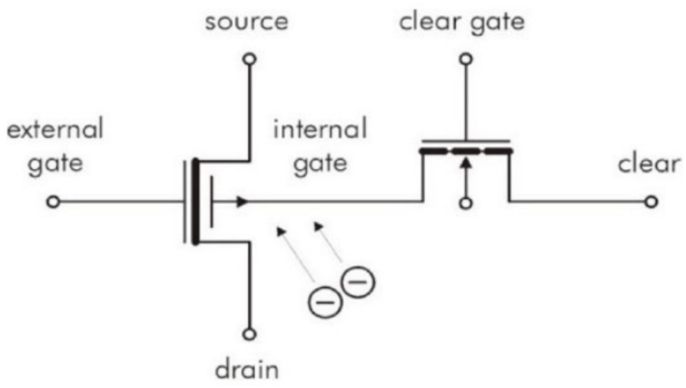
PXD

PXD Working Principle: DEPFET

- Depleted P-channel Field Effect Transistor (DEPFET) on top of fully depleted silicon bulk:
  - Fast charge collection (~ns).
  - Low power consumption.
  - High signal-to-noise ratio.
  - Thin sensors (75 um in active region).
- Working principle:
  - Collecting charges in the “internal gate”.
  - Drain current modulated by collected charges.
  - Gate must be cleared after readout.
  - Internal amplification:

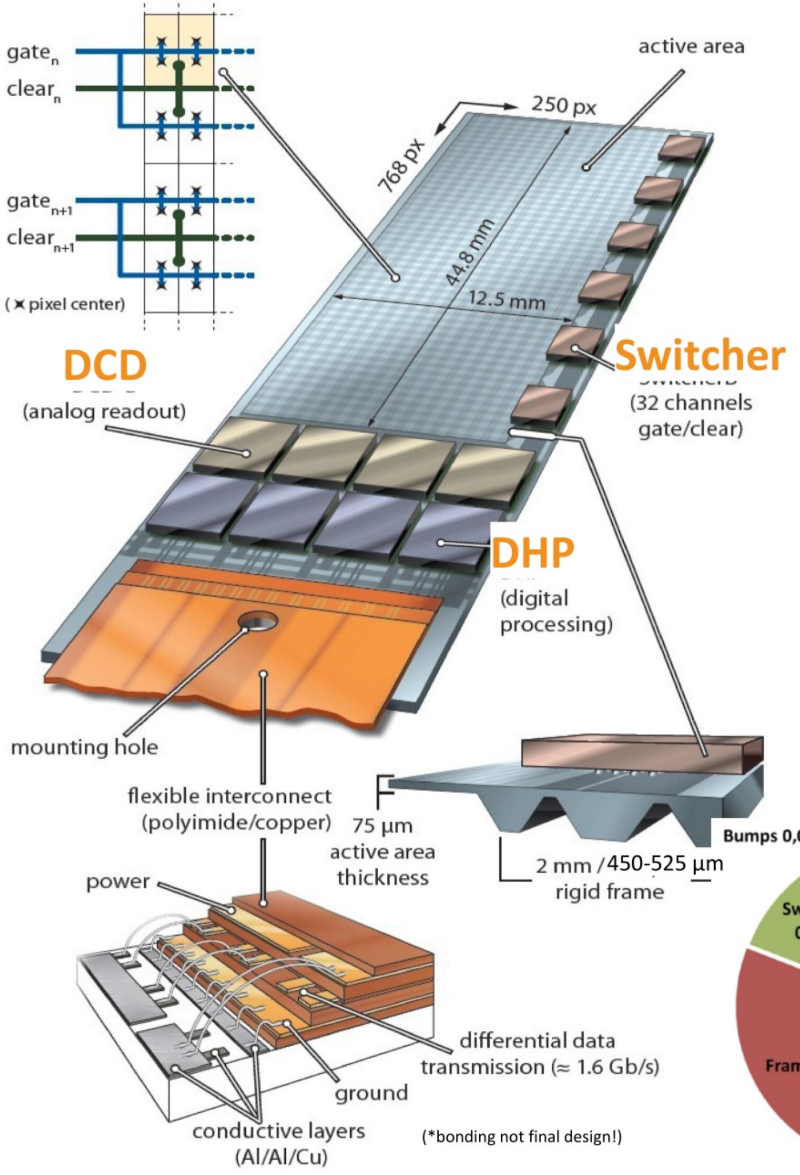
$$g_q = \frac{\partial I}{\partial q} \approx 500 \frac{pA}{e^-}$$

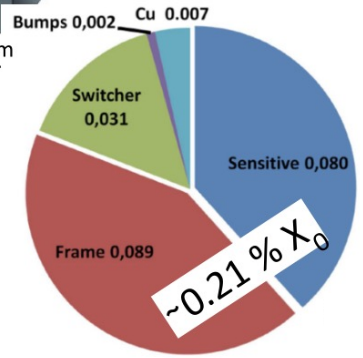




PXD Sensor / Module

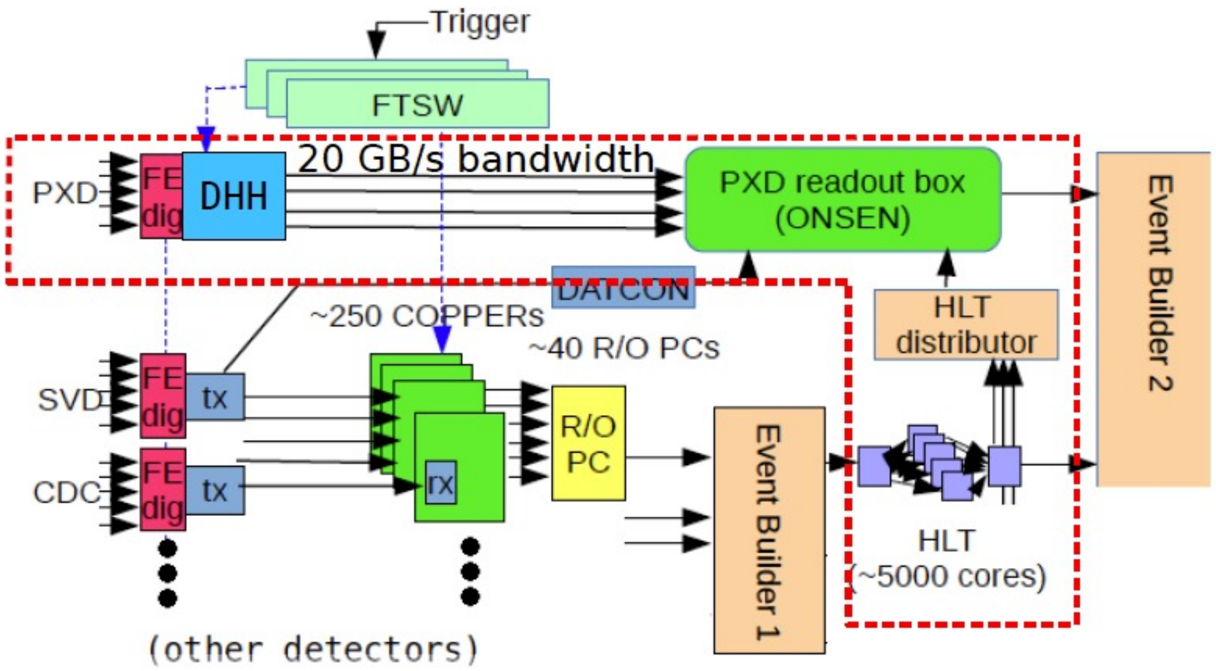
- Sensor:
  - Self-supporting 75 um thin DEPFET active area.
  - Pixel size: 50x(55-85) um^2.
  - 250 x 768 pixels per sensor.
  - 40 sensors in total.
- Module:
  - DEPFET sensor with ASICs.
  - 6 switchers: row control, 4 rows per channel.
  - 4 DCD: 256 channel 8-bit ADC.
  - 4 DHP: data processing, trigger and timing.
  - 40 modules in total.
- Ladder:
  - Two modules glued to one ladder.
  - 20 ladders in total.
- Design: 1% occupancy (layer 1), 3% occupancy limit (DHP, DAQ, tracking).
- Cooling:
  - 2-phase CO_2 cooling for ASICs at the end of stave.
  - N_2 gas for sensor and switchers.
- Radiation hard sensor and ASICs up to expected lifetime, measured up to 266 kGy during irradiation campaign.



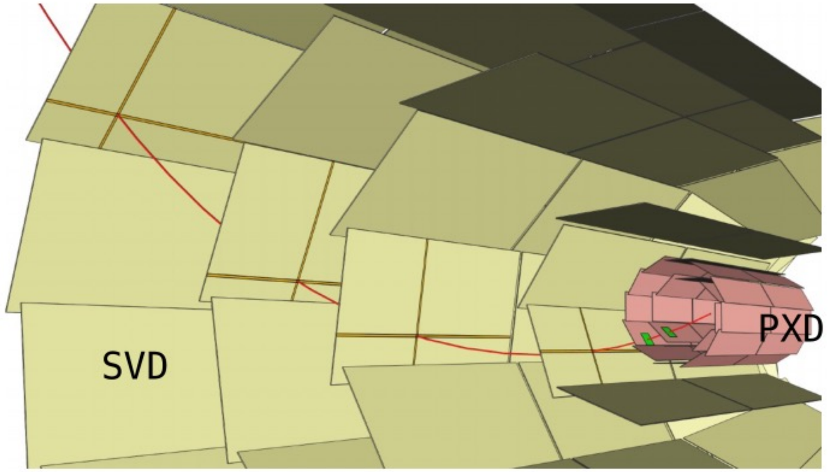


PXD DAQ

- PXD readout:
  - Rolling shutter readout mode.
  - Read 4-rows of pixels (1 switcher channel) at a time (~100ns).
  - Full integration time ~20 us.
- PXD has significant larger unfiltered raw data rate than other Belle II detectors:
  - Separate readout path.
  - Need to remove data that not belonging to tracks.
  - On High Level Trigger (HLT), Region of Interest (ROI) is calculated from track information.
    - 1/10 reduction rate.
  - Send ROIs back to PXD readout and select pixels within ROIs.
- Online selection has been tested but not turned on yet.

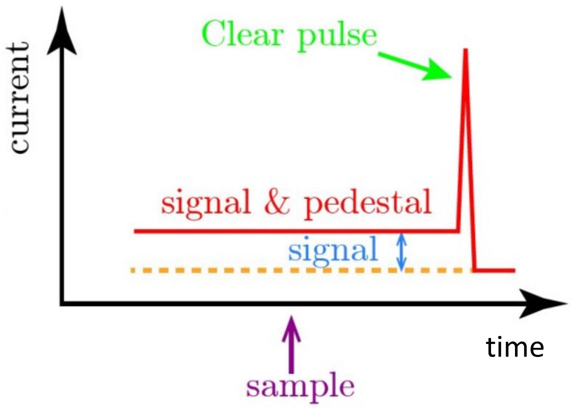


ROI extrapolation on HLT

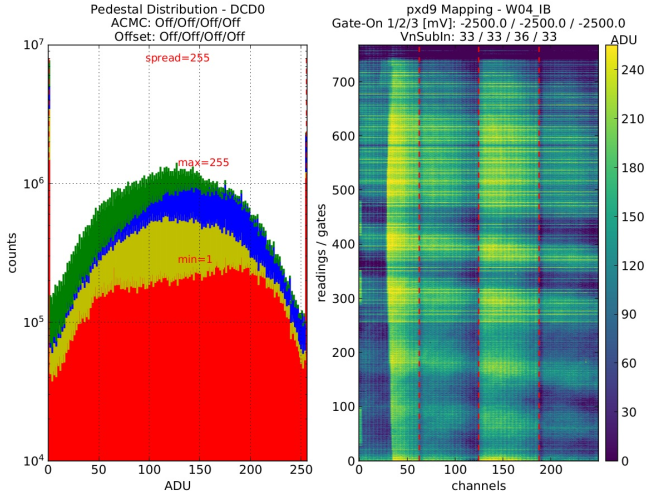


PXD Module Calibration

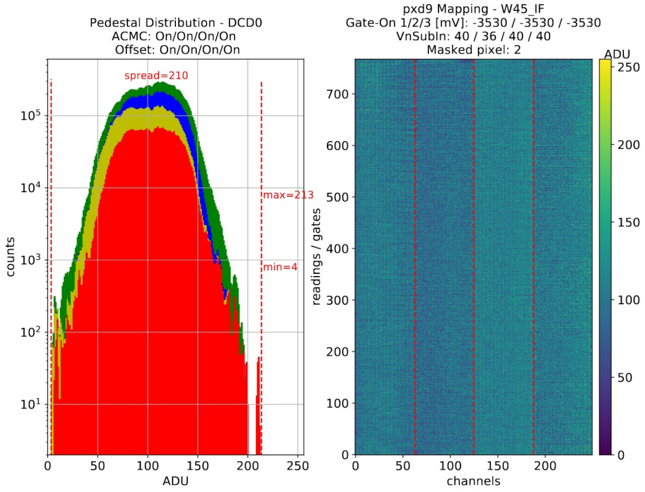
- Modules need characterization before installation.
  - Continuous optimization of working points during operation.
- Median drain current pedestals stored on DHP for zero suppression.
- Pedestal optimization on DCD:
  - Pedestal spreading compression via switchable offsets for input currents per pixel.
  - Noise reduction via Analog Common Mode Correction (ACMC).
  - Low noise < 1 ADU (~200 e$^-$).



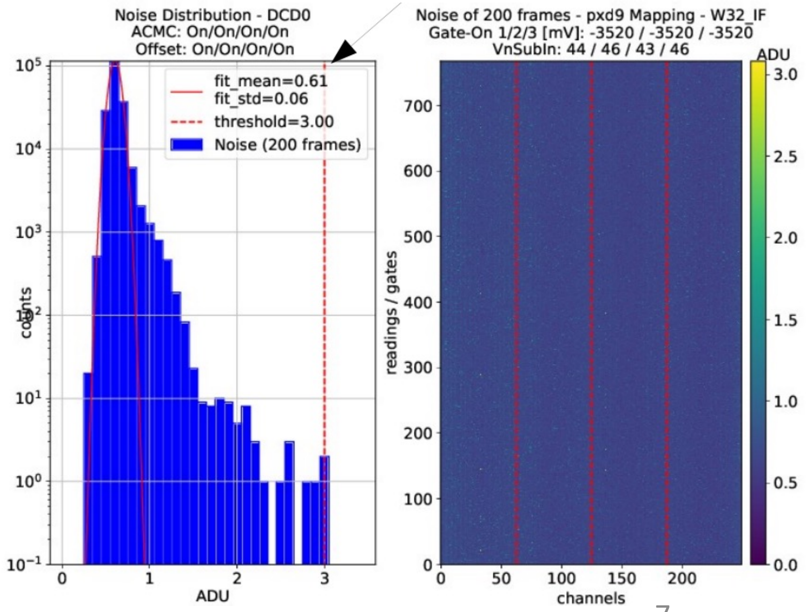
Uncalibrated Pedestals



Calibrated Pedestals

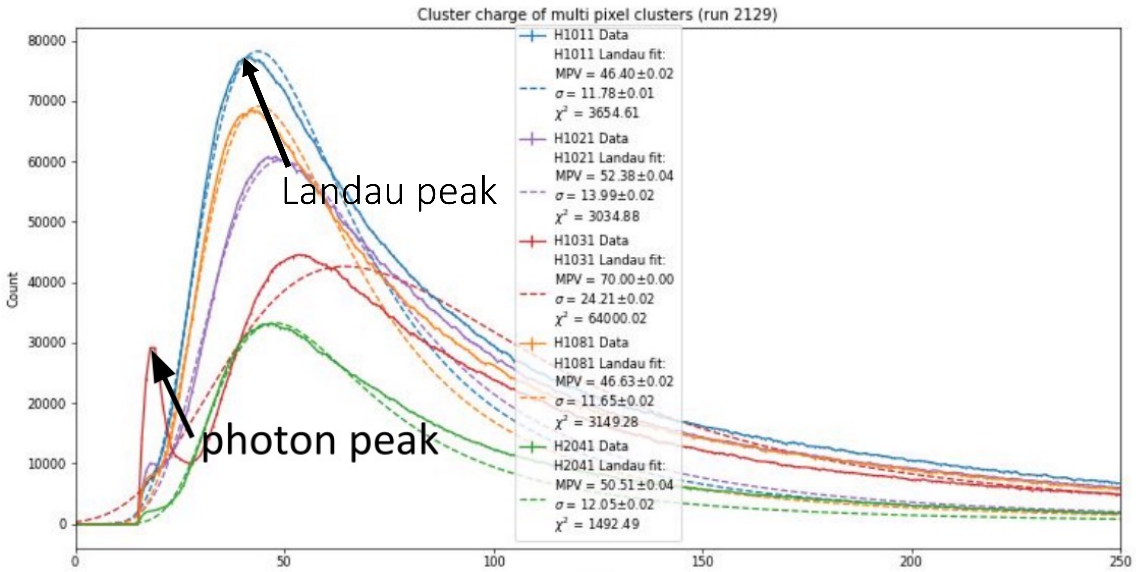


Noise of 0.61 ADU



PXD Performance: Signal and Noise

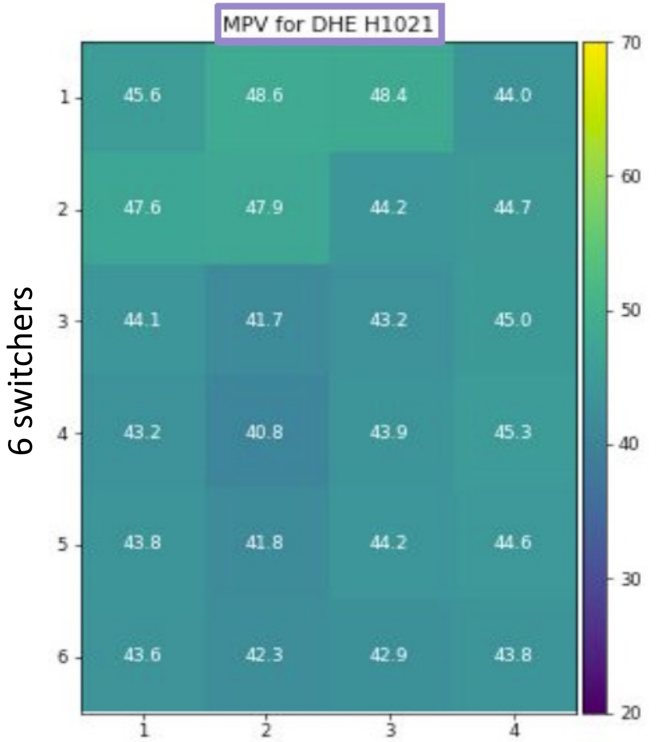
- Most Probable Values (MPV) of cluster charge and SNR uniform over 24 ASIC combinations within one module.
- Signal to Noise Ratio ~ 30 to 50.
- Homogeneous noise and signal response across module matrix.



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

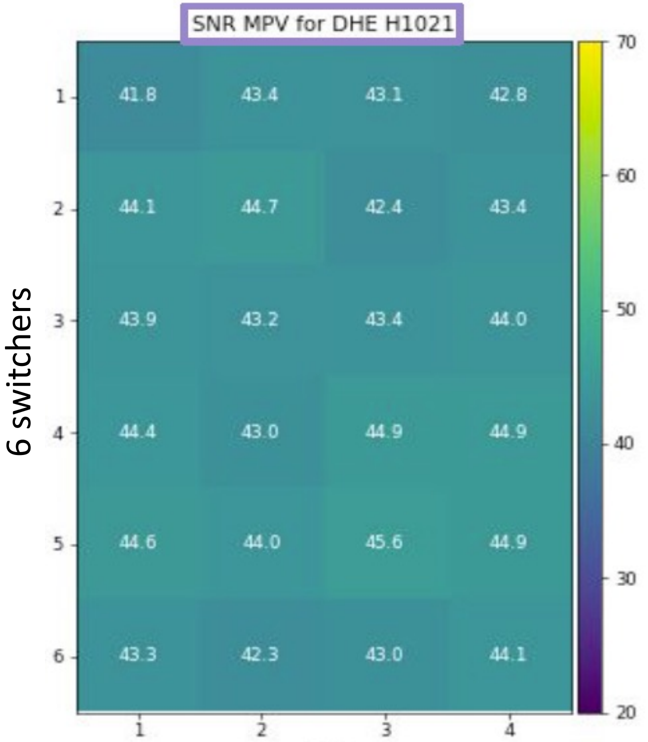
Sensitive to radiation damage

Cluster Charge MPV



4 DCDs

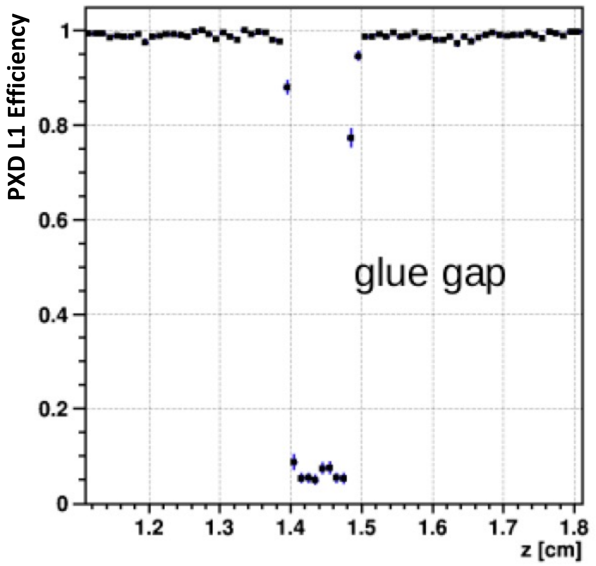
SNR MPV



4 DCDs

PXD Performance: Hit Efficiency

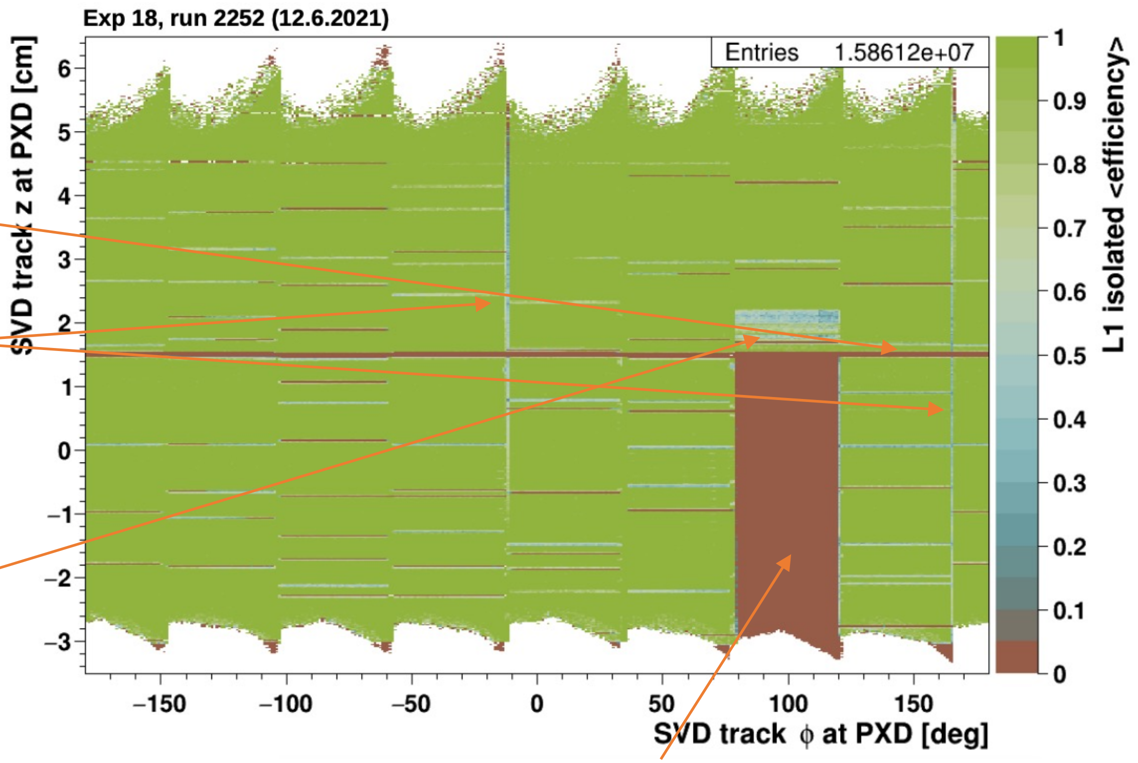
- Defined by hits found close to track intercepting points in modules.
- Influenced by tracking quality and alignment.
- Take only tracks with good tracking and p_T > 1 GeV/c.
- Bad switcher channels (4 rows each) degrade overall hit efficiency by ~3% (good regions ~ 98% hit efficiency).
- Noisy switcher from May 10th beam loss.
- Module 1032 was broken.
    - Covered by layer 2 module.



Glue gaps

Half shell gap

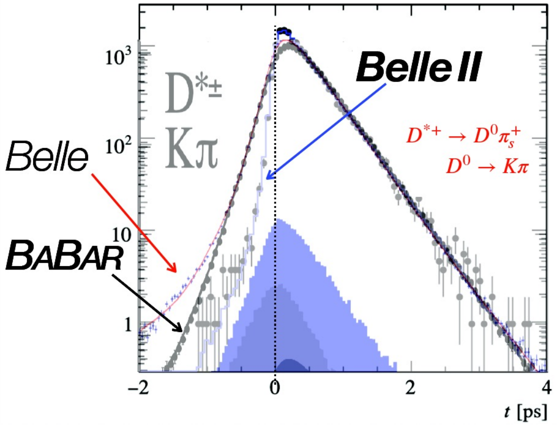
Noisy switcher from May 10th beam loss incident



Broken module

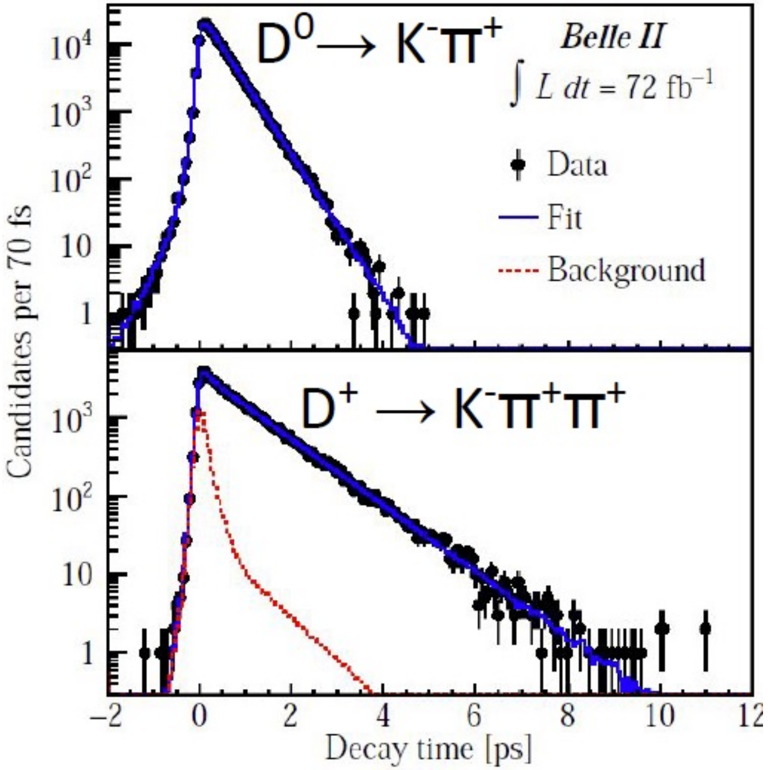
PXD Performance: Resolution and Lifetime

- Vertex resolution with PXD is close to MC expectations.
  - d_0 resolution of 14.1 um (data), 12.5 um (MC).
- D lifetime measurement:
  - 4th Belle II physics paper, submitted to PRL, arXiv: 2108.03126.
  - Belle II proper time resolution ~2x better than Belle.
  - Precision better than all previous measurements and comparable with world average.
  - Vertex detectors played key role in this measurement.



$\tau(D^0)$ = 410.5 ± 1.1 (stat) ± 0.8 (syst) fs
$\tau(D^+)$ = 1030.4 ± 4.7 (stat) ± 3.1 (syst) fs

World Average
(410.1 ± 1.5) fs
(1040 ± 7) fs



PXD Operation

- In general, PXD operation is stable for 2020/2021.
  - There are still several challenges for operation.
- Due to COVID-19, limited local PXD manpower in KEK.
  - Most of the PXD expert shifts are done in remote.
- Various automations to reduce the load of the shifters.
- New people are on boarding to the PXD group, for operation and R&D, even on the hardware side.

PXD Operation: Beam Loss Events

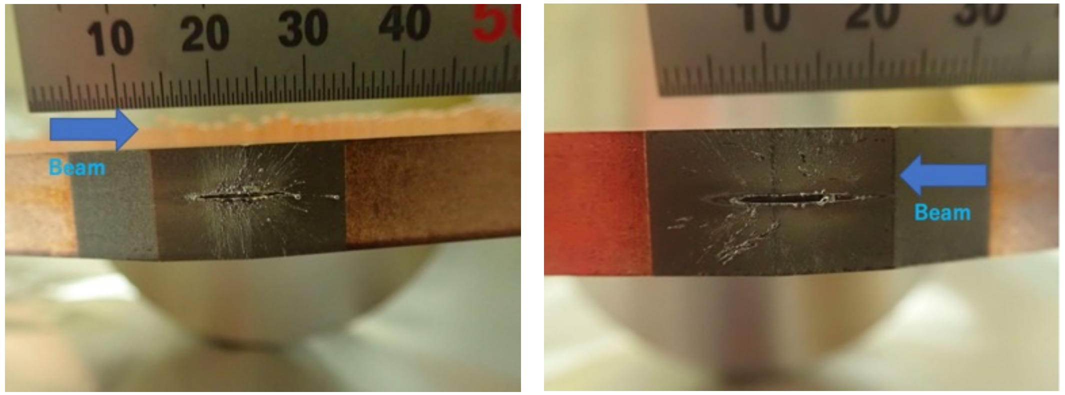
Beam loss event on May 10th ,2021:

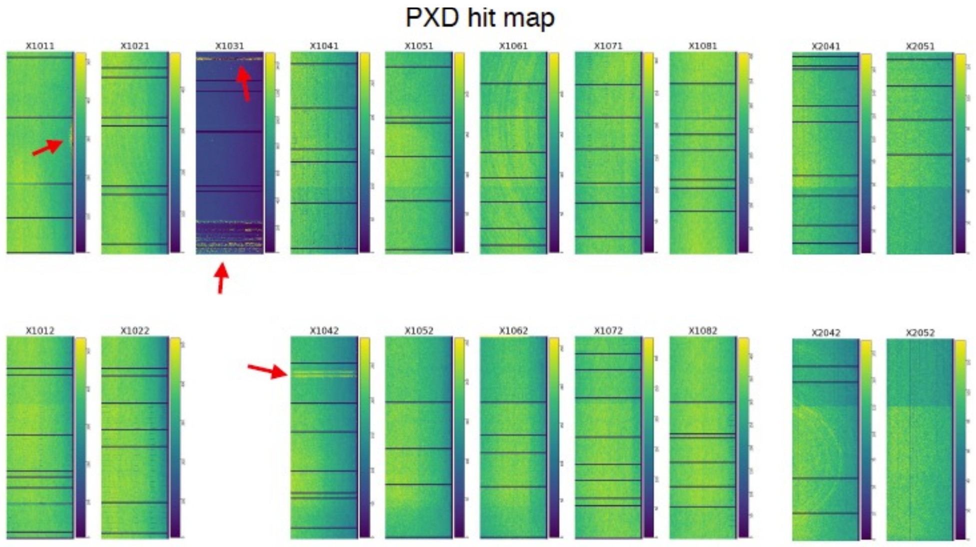
- Not the first of such incidents, but the most serious one for the damage of a single module.
- Partial damage of PXD, diamond sensor readout and collimator.
- The reason is not fully clear.
- Not always detected early enough to safely dump beams before damage happens.
- Impact on PXD:
  - Large instant radiation dose.
  - Permanent damage: new dead switcher channels (unexpected behavior).

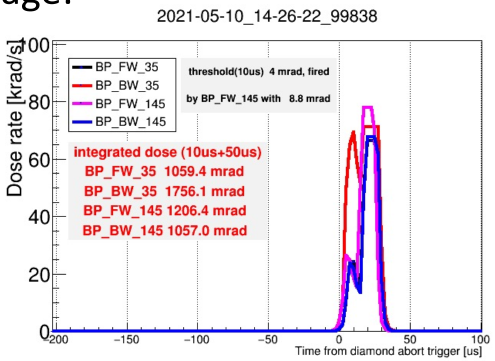
R&D to understand the mechanism of switcher damage:

- Radiation test at MAMI @ Mainz.
- Damage effect reproduced during tests.
- Discussion to continue tests at MAMI.

Damaged collimator jaws

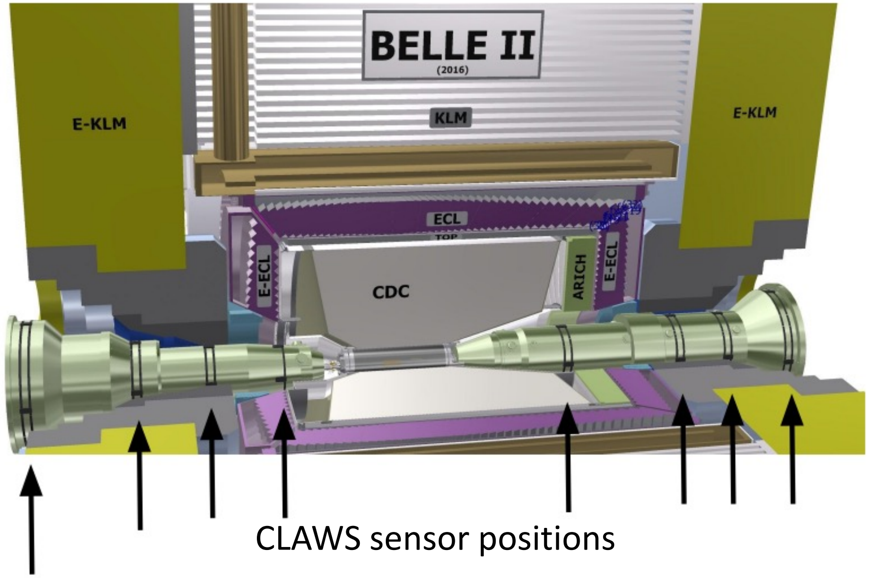


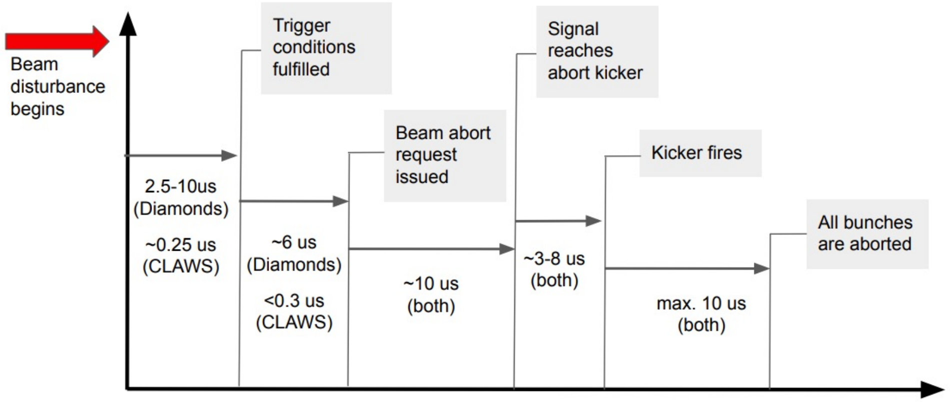




PXD Operation: Mitigation for Beam Loss Events

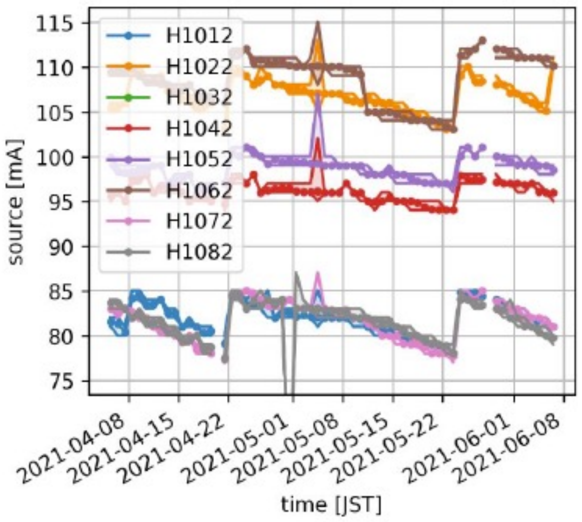
- Several systems to detect beam disturbance and issue beam abort signal:
  - Diamond sensors on the beam pipe.
  - Beam loss monitors along the rings.
  - Others.
- Early detection of beam abort with CLAWS:
  - **S**c**i**ntillator **L**ight **a**nd **W**aveform **S**ensors.
  - Close to interaction point.
  - Faster to detect and issue beam abort signal.
  - Speed up abort process time by ~10us (about one revolution of the beam).
  - Turned on for beam abort since end of May 2021.
- Reduce beam dump time on accelerator side.
- PXD emergency power off:
  - O(100ms) → O(100us).
  - Tests still ongoing.
  - Could also harm on its own.



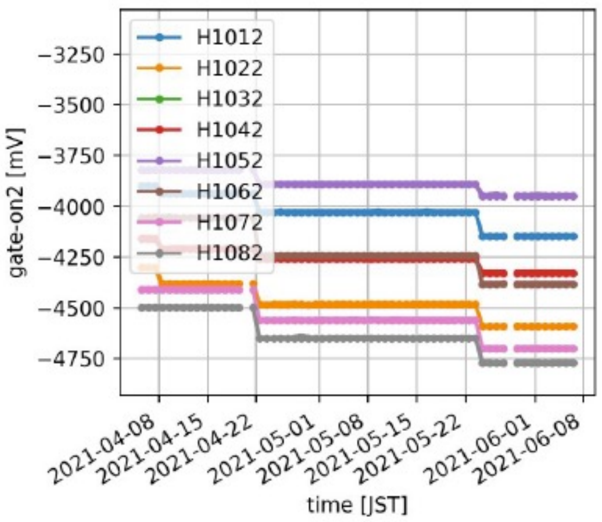


PXD Operation: Radiation Effect (Threshold Shift)

- X-ray radiation campaign @ 266 kGy:
  - Oxide damage causes shift of MOSFET threshold voltages.
  - Threshold voltage shift can be compensated by adjustment of gate voltage.
- Integrated dose in PXD:
  - Rough estimate < 20 kGy until end of 2020.
  - More precise measurements for 2021 in progress.

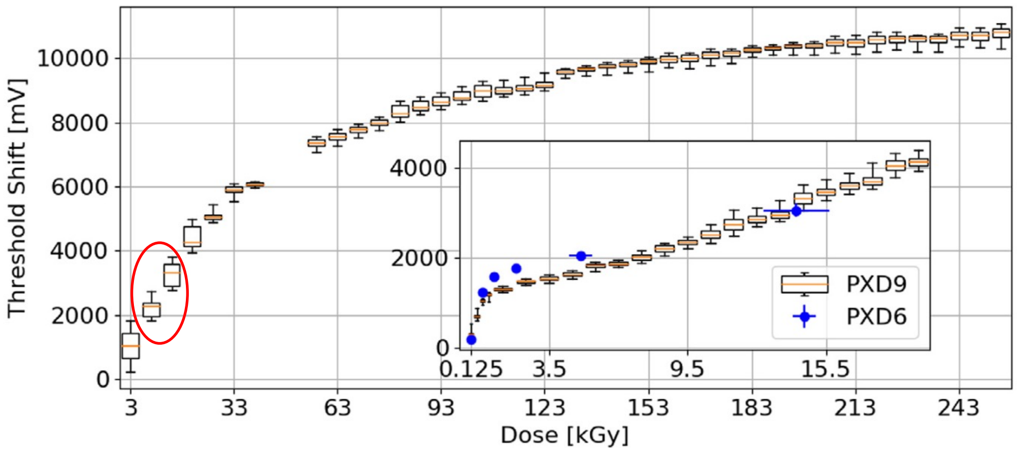


Source Current



Gate Voltage

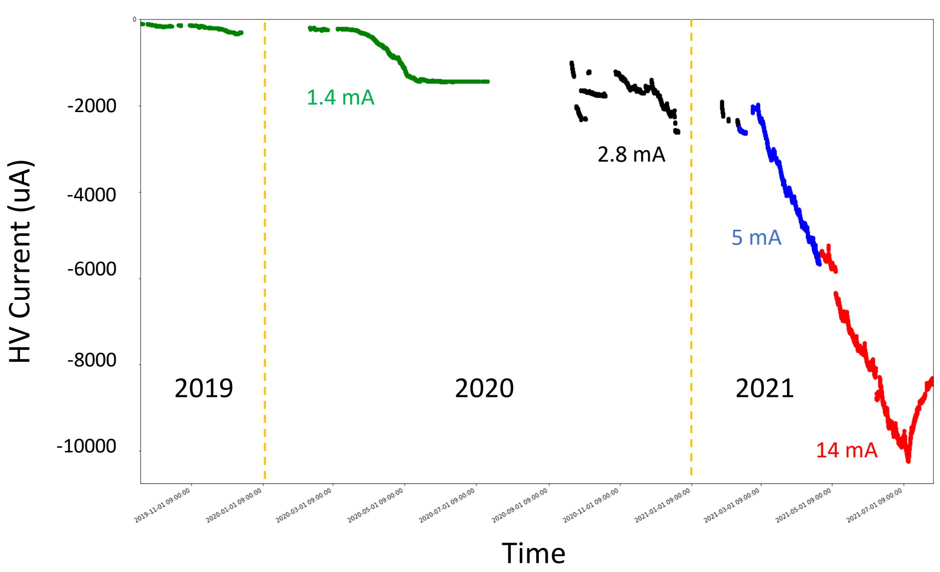
https://doi.org/10.1016/j.nima.2020.163522

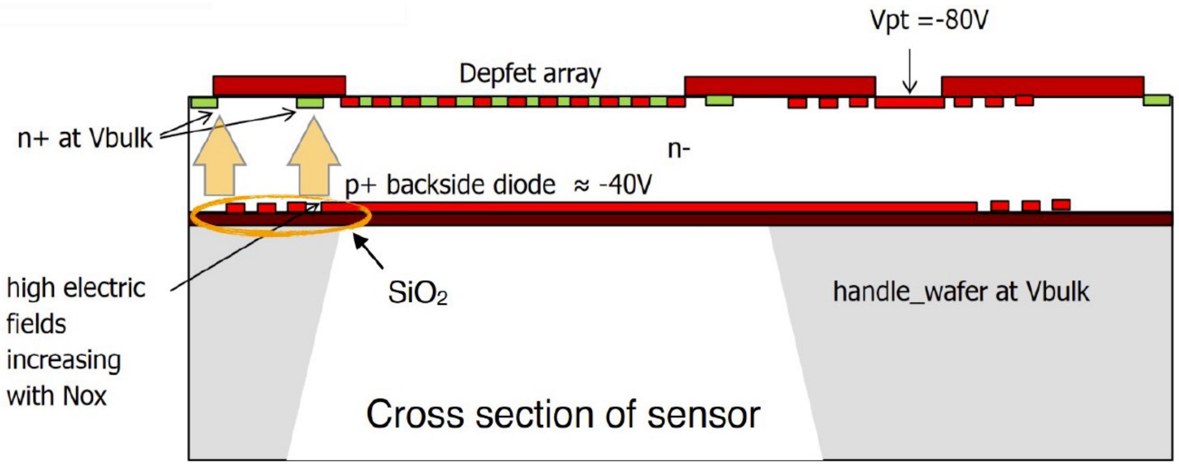


PXD Operation: Radiation Effect (HV Current)

- HV is the depletion voltage of the DEPFET sensor.
- Increased HV currents of some modules:
  - Some of them reached power supply limits.
  - Can’t reach set voltage: worse SNR and efficiency.
- Recovery observed during (beam off / HV on) and (beam on / HV off) times.
- X-ray irradiation campaign to investigate the effect:
  - Reproduced the increasing HV current w/ irradiation and annealing effect w/o irradiation.
  - Saturation of HV current at certain dose of radiation.
- Mitigation by modifying PS units to higher HV current limits.
  - HV current limit: 1.4 mA → 2.8 mA → 5 mA → 14 mA
  - Part of the PS units modified in parallel to the data taking.
  - Remaining units have been modified to 14mA HV current limit during summer shutdown.
- Interpretation: charge-up effect at handle wafer bond oxide and avalanches at bulk.

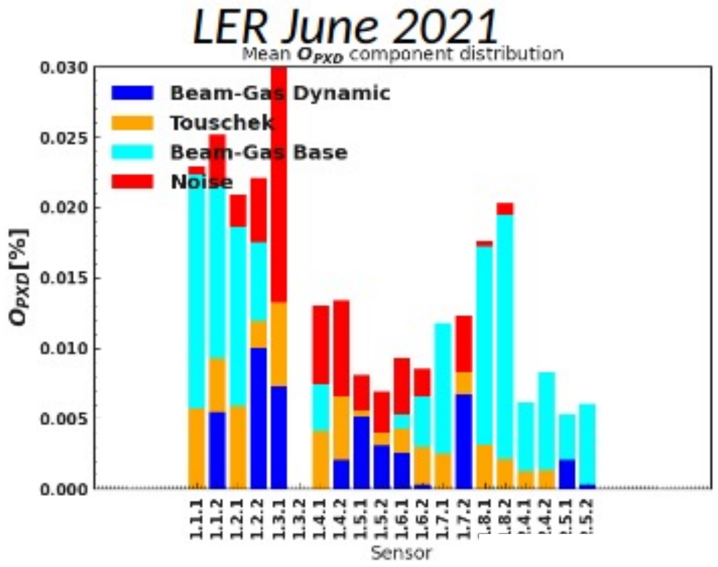
Module 1082

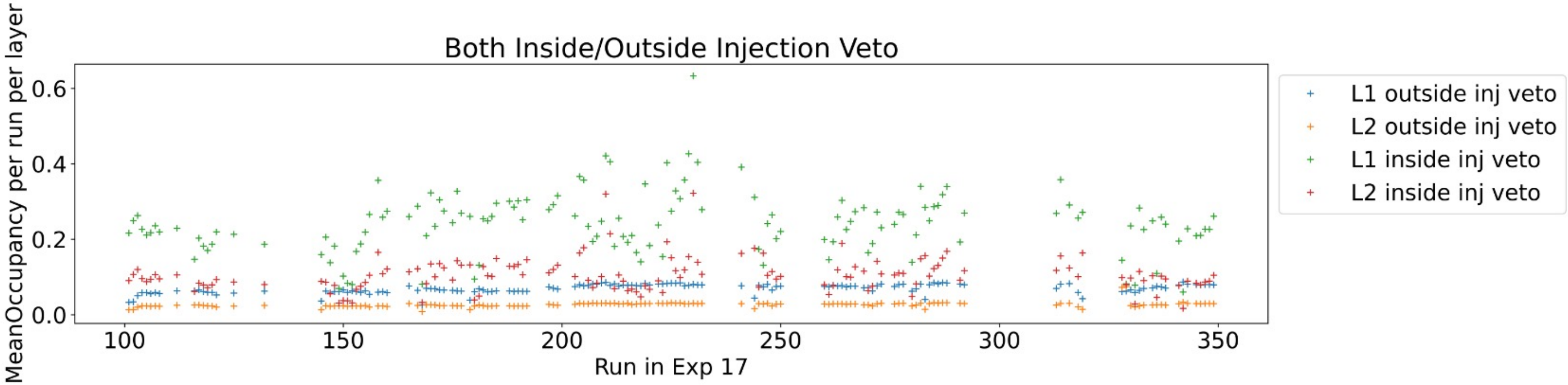




PXD Operation: Backgrounds

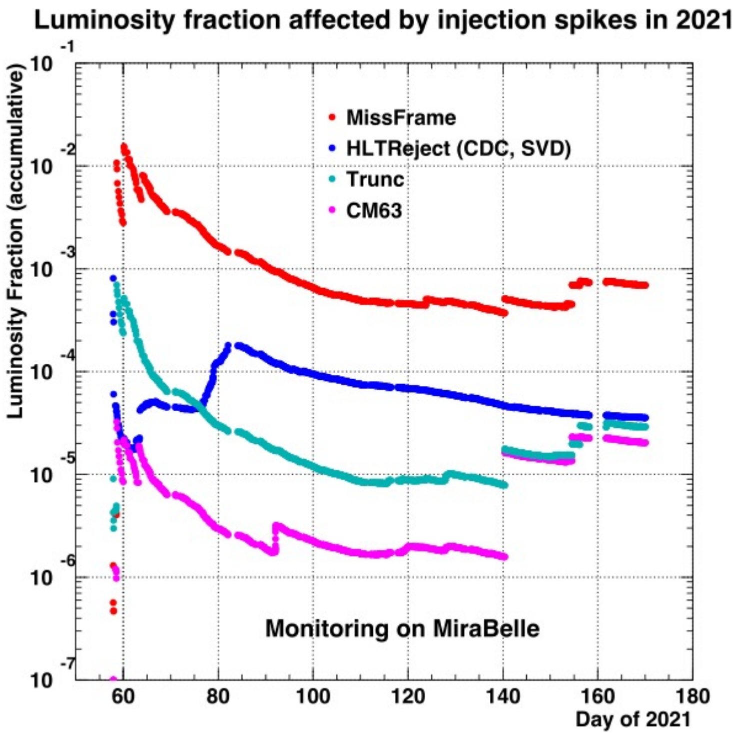
- Single-beam backgrounds:
  - Touschek scattering: scattering of particles within a bunch.
  - Beam-gas scattering: Coulomb scattering and Bremsstrahlung (scattering off gas molecules).
  - Injection background: continuous injection of charge into beam bunch.
  - Synchrotron radiation.
- Luminosity backgrounds:
  - Two-photon background.
- Background effects:
  - Deteriorate performance (fake hits).
  - Contributes to occupancy (especially during injection).
    - Maximum occupancy 3%: at which the ASICs can't handle the high data rate.
  - Irradiation to sensors: aging or damages.

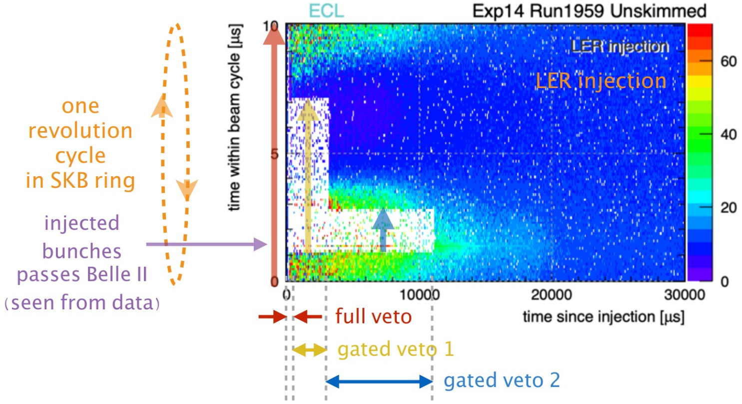


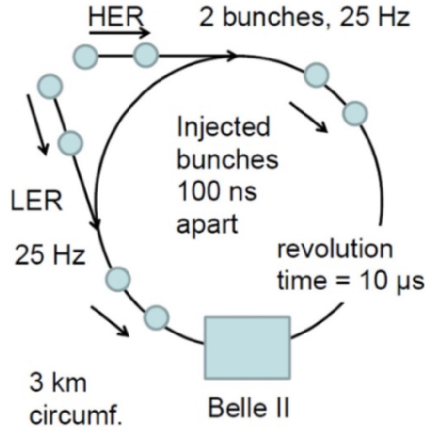


PXD Operation: Injection Backgrounds

- Continuous injection in SuperKEKB:
  - Top-up injection rate up to 50 Hz.
  - At design luminosity, beam lifetime is ~few minutes.
  - Injected bunches produce high backgrounds. Damping takes a few ms.
  - Use trigger veto to avoid noise:
    - full veto for all Belle II detectors.
    - gated veto for all except PXD due to long integration time (20 us).
- Elevated PXD occupancy after full veto for a few us:
  - Injection spikes can saturate PXD readout and cause partial data loss.
  - In 2021, the ratio of partial data loss is far from being critical (in sub-per mille level).
  - In the future, to reduce data loss, gated mode can be used to blind PXD when injected bunches passing by.

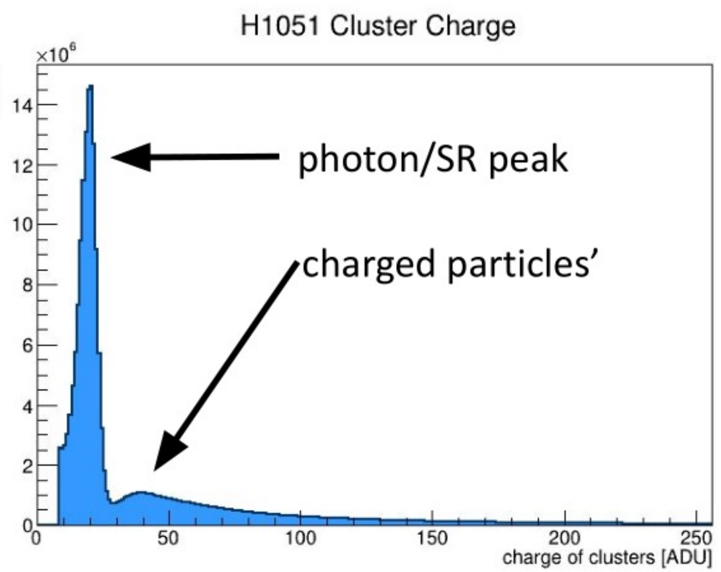


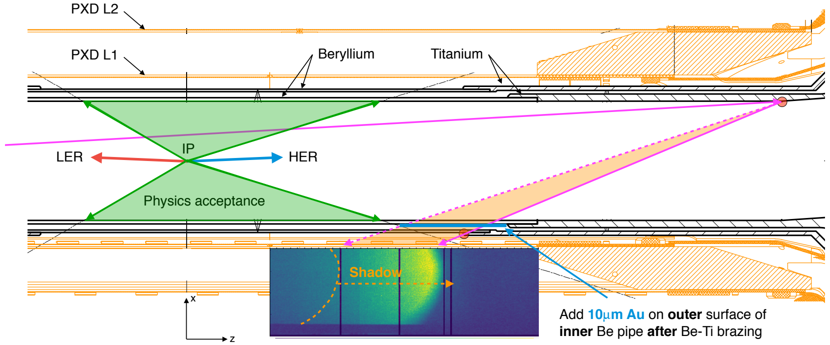




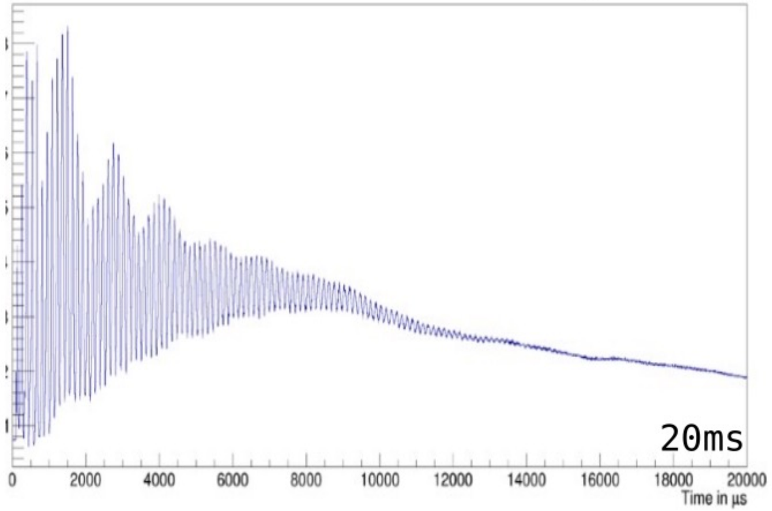
PXD Operation: SR Background

- IR region is designed to avoid direct SR photons hitting central beam pipe
- Observed large SR background:
  - Happened in –x modules after change of optics.
  - Dominated by secondary photons
  - Appear during HER injections with clear time structure
  - Origin: back-scattering photons from SR fan hitting +x edge of Ti beam pipe
- Effects on PXD:
  - Highly localized hit density
  - Inhomogeneous module irradiation
  - Deterioration of clustering and tracking
- Mitigation:
  - Small modification of HER beam orbit
  - New beam pipe with additional gold plating to be installed with PXD 2022 update.

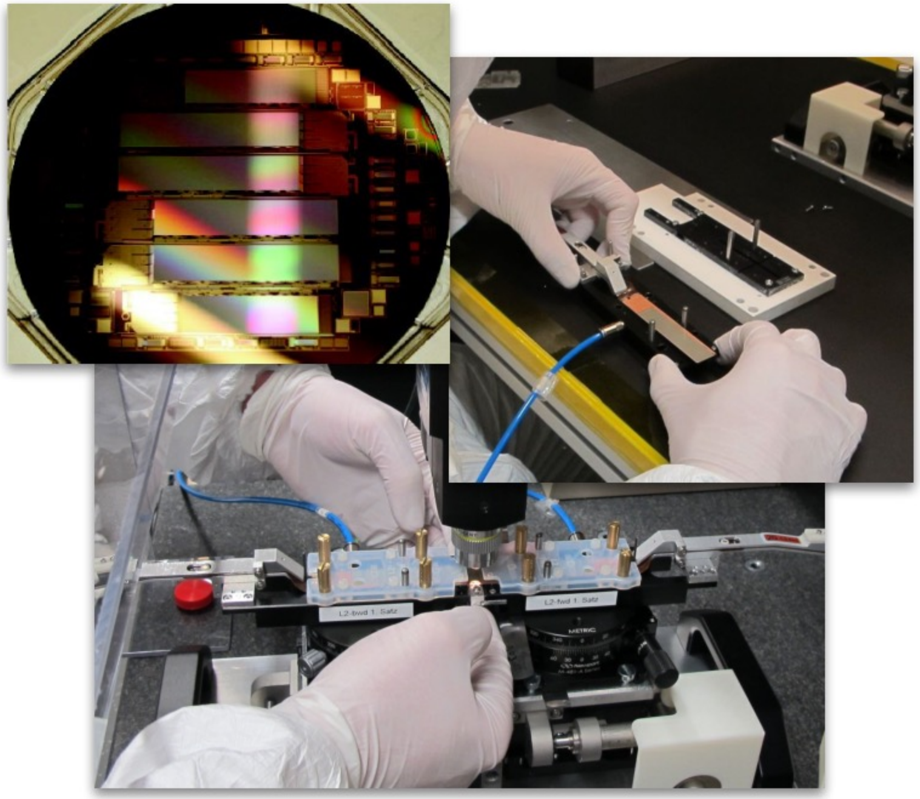




Time evolution of SR after injection



PXD2022

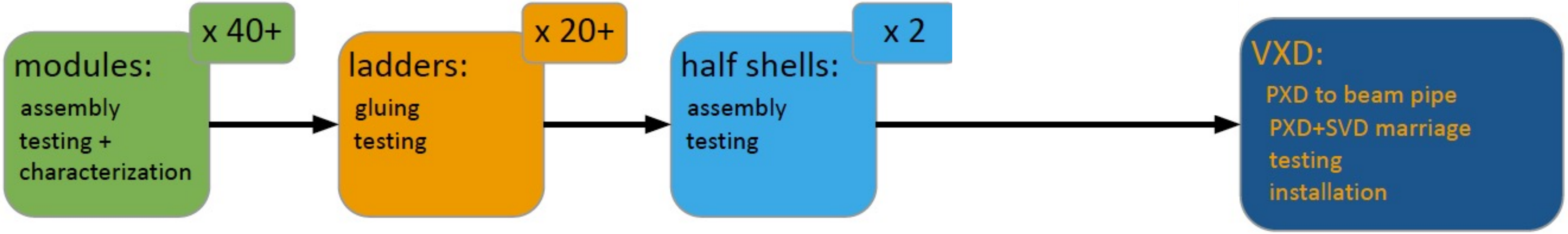


PXD remains incomplete:

- Only 10/20 ladders installed:
  - Layer 1 is full with 8 ladders.
  - Layer 2 only has 2 ladders out of 12.
- Good vertexing performance so far, but not guaranteed for higher luminosity.

Ongoing efforts to build complete PXD:

- Same technology but improved manufacturing process.
- Module production & HS assembly & testing ongoing.
- PXD2 to be installed during next long shutdown 2022.



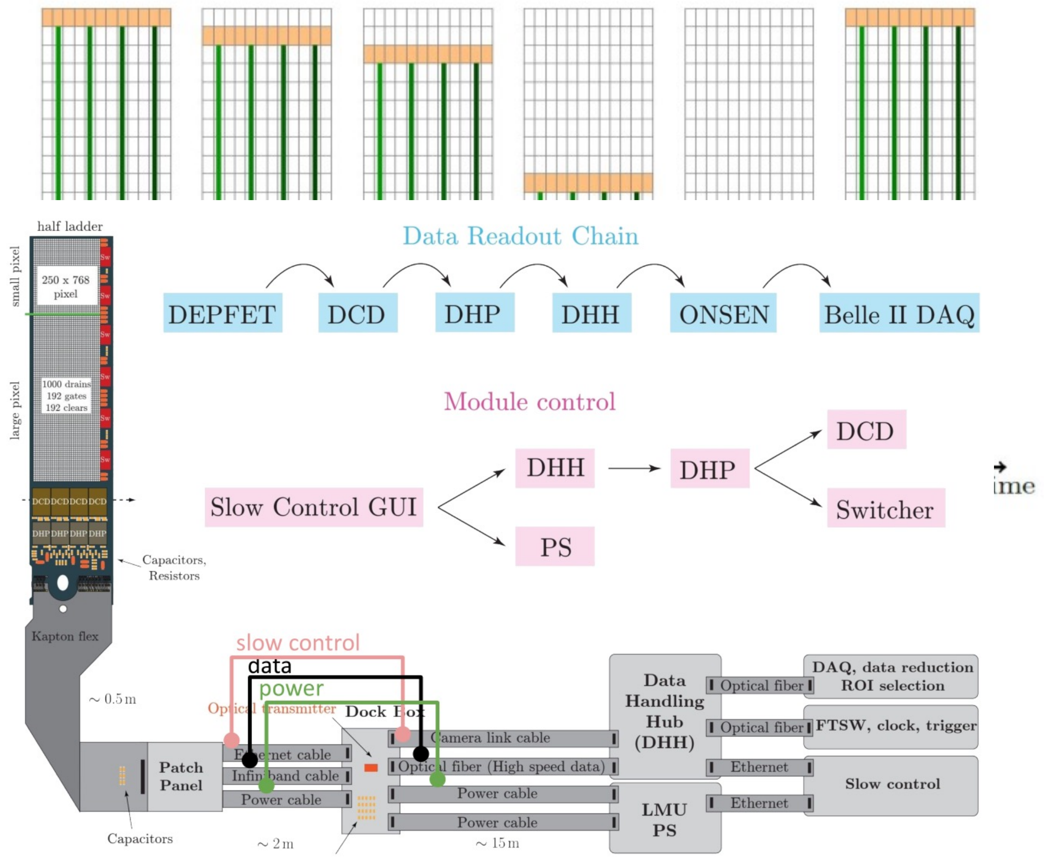
Summary

- PXD is working well since the start of Belle II data taking in 2019.
- The performance of PXD is excellent.
- Superior lifetime resolution compared to Belle/BaBar as demonstrated by the D lifetime measurement.
- There are damaged switcher channels due to beam loss events.
- Efforts have been made to automate the operation for reducing shifters' load.
- Full PXD detector:
  - Production, testing and assembly is ongoing.
  - Planned installation in 2022.

Backup

PXD Readout and Control

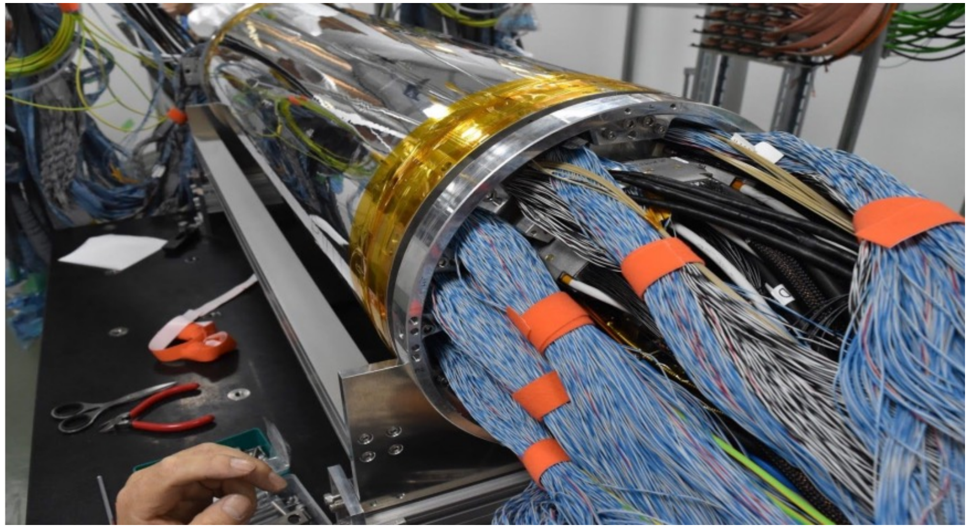
- Rolling shutter readout mode with low power consumption:
  - Signal read gate by gate.
  - Each gate consists of 4 rows.
  - Gate is cleared after reading.
  - Read-clear cycle for each gate is ~100ns.
    - Full integration time ~20 us (1 “frame”).
    - ~2x SuperKEKB revolution time (~10 us).
- Sampling by DCD: drain currents measured once.
- Pedestal correction and zero suppression on DHP.
- Event building and trigger handling on DHH.
- ROI selection on ONSEN.
- Filtered data transferred to Belle II DAQ for further processing and storage.

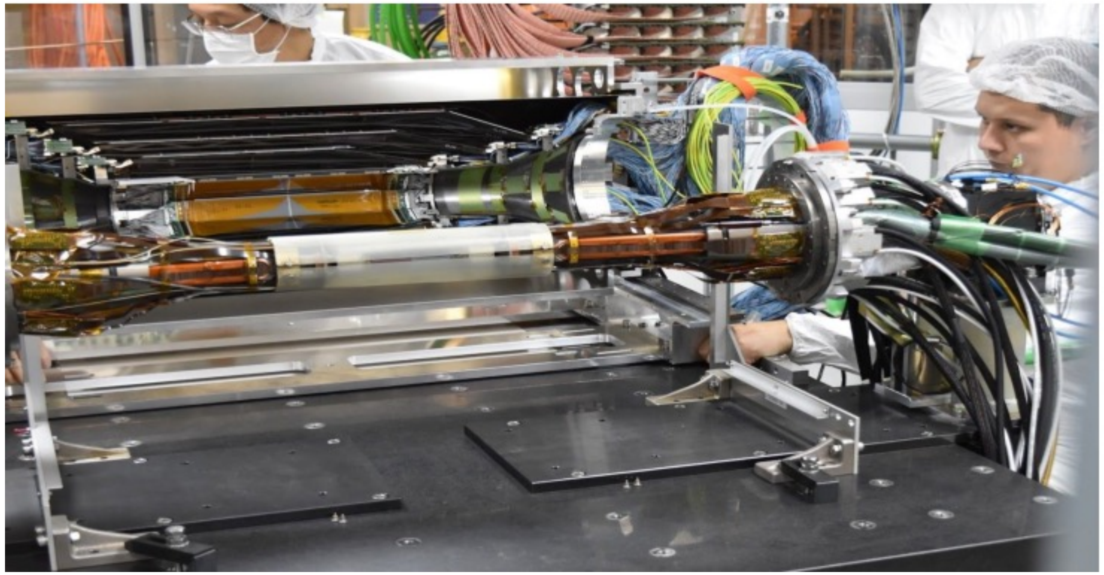


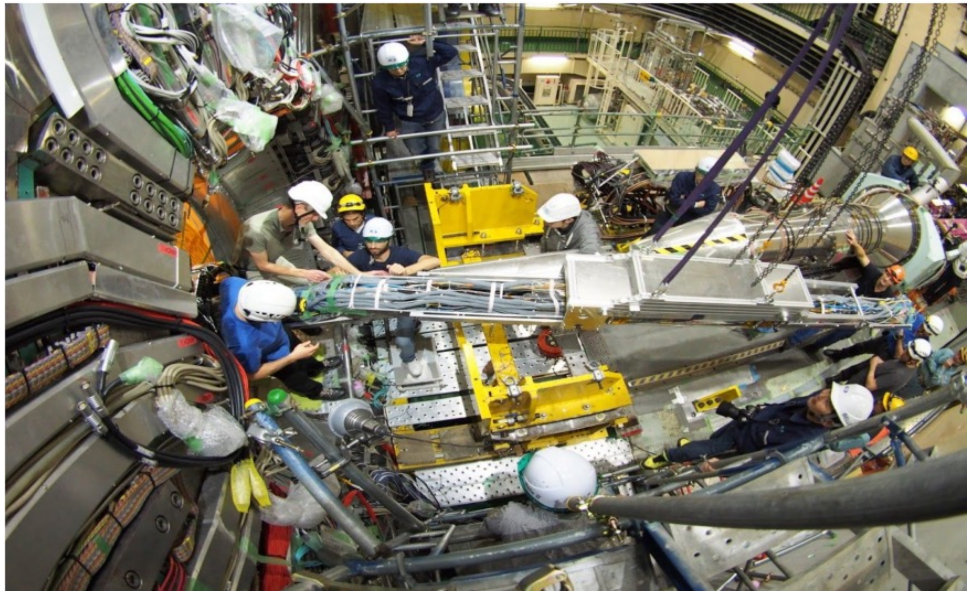
PXD Assembly & Installation in 2018

PXD assembly at KEK:
- Assemble mechanical ladder frame SCB.
- Provide cooling via 2-phase CO_2 and forced N_2 flow.

Installation to Belle II in late 2018:
- SVD + PXD + BP marriage.
- VXD installation into Belle II.







PXD Operation: Gated Mode

- Gated mode can blind PXD modules when noisy bunches pass.
    - To protect PXD from the noises from the injected bunches.
    - The voltages applied on the DEPFET sensors are changed.
    - Newly created charges are not collected.
    - Charges at internal gate are preserved.
    - Gate twice per readout frame.
- Challenges:
    - Switching into gated mode results in pedestals fluctuations, produce noise on their own.
    - Synchronization with injections.
    - Optimizing module parameter for GM.
- Currently not ready for regular gated mode operation.