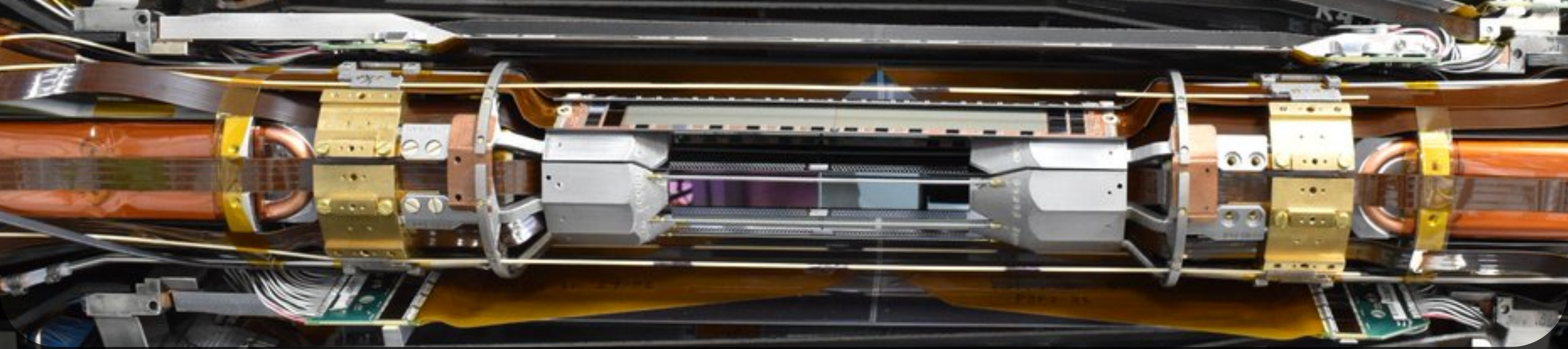


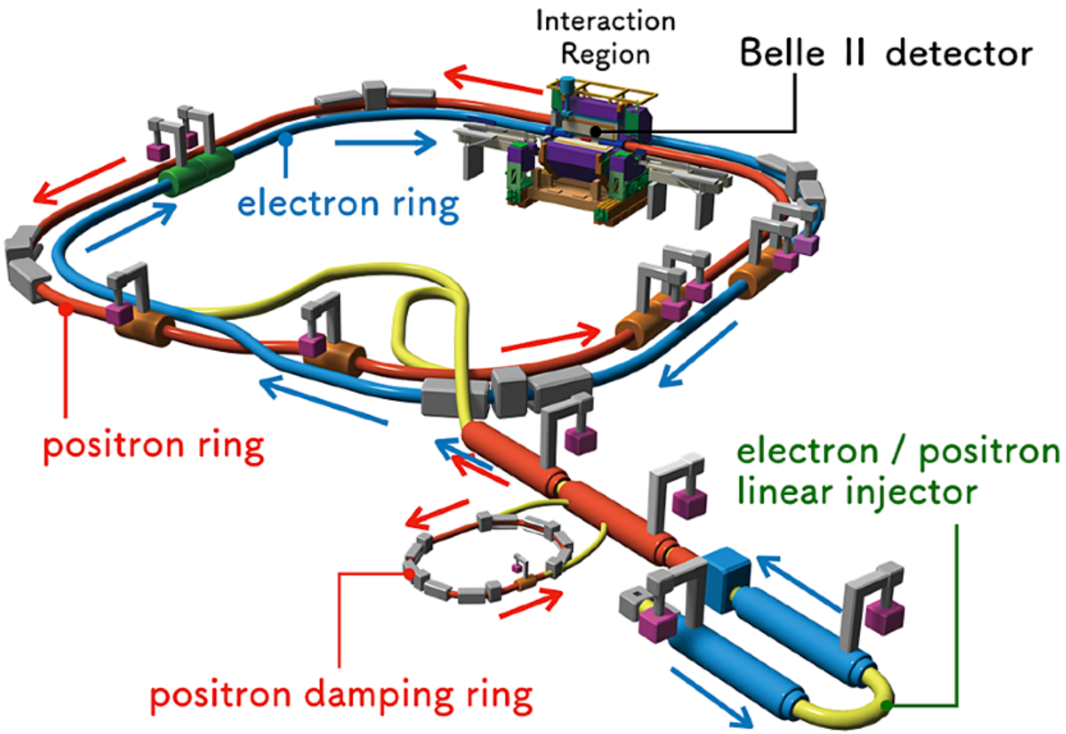
Belle II Pixel Vertex Detector

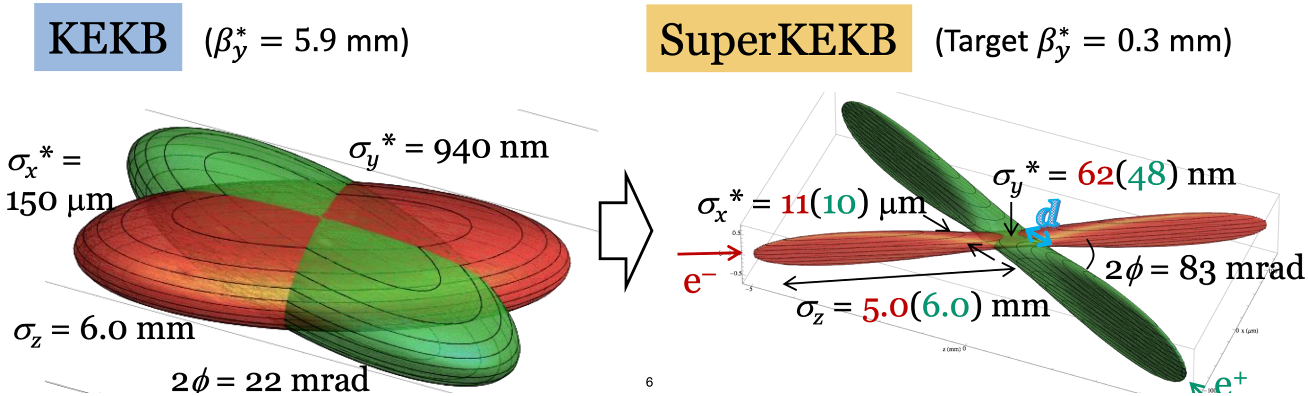
HLL Review, Ringberg, December 15th, 2022

Carsten Niebuhr, DESY

SuperKEKB and Belle II

- SuperKEKB
  - energy-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 $6 \times 10^{35}\ cm^{-2}s^{-1}$
    ongoing long shutdown 1 (LS1) since July 2022
    ~1.5 year for accelerator and detector improvements





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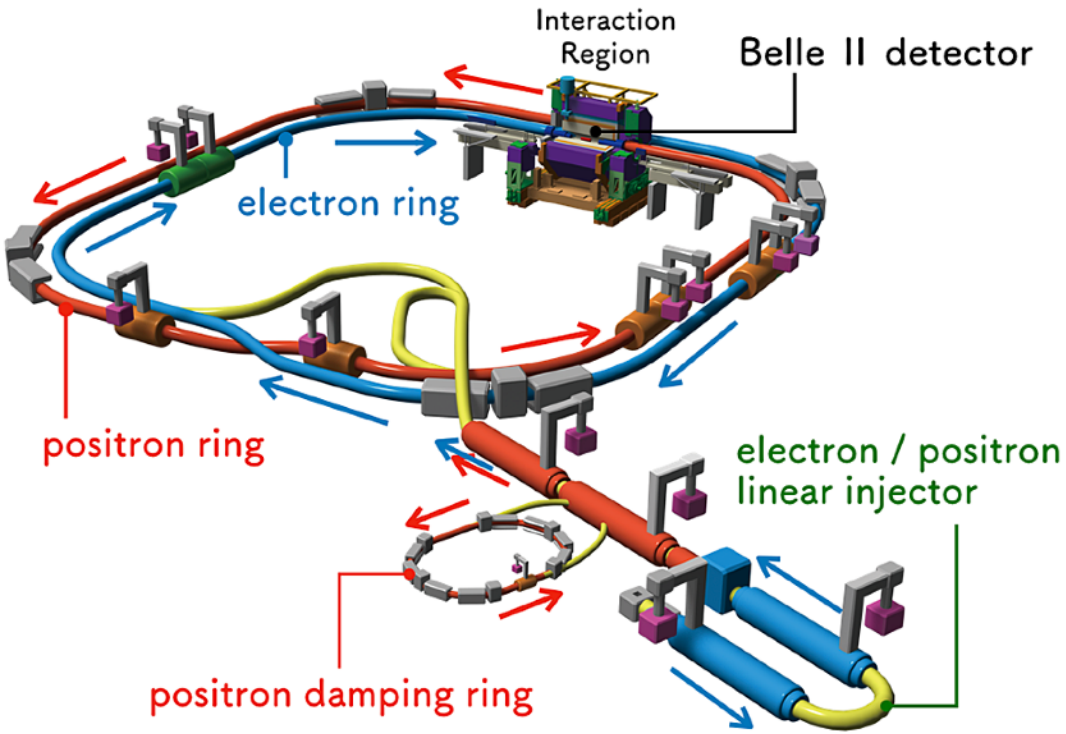
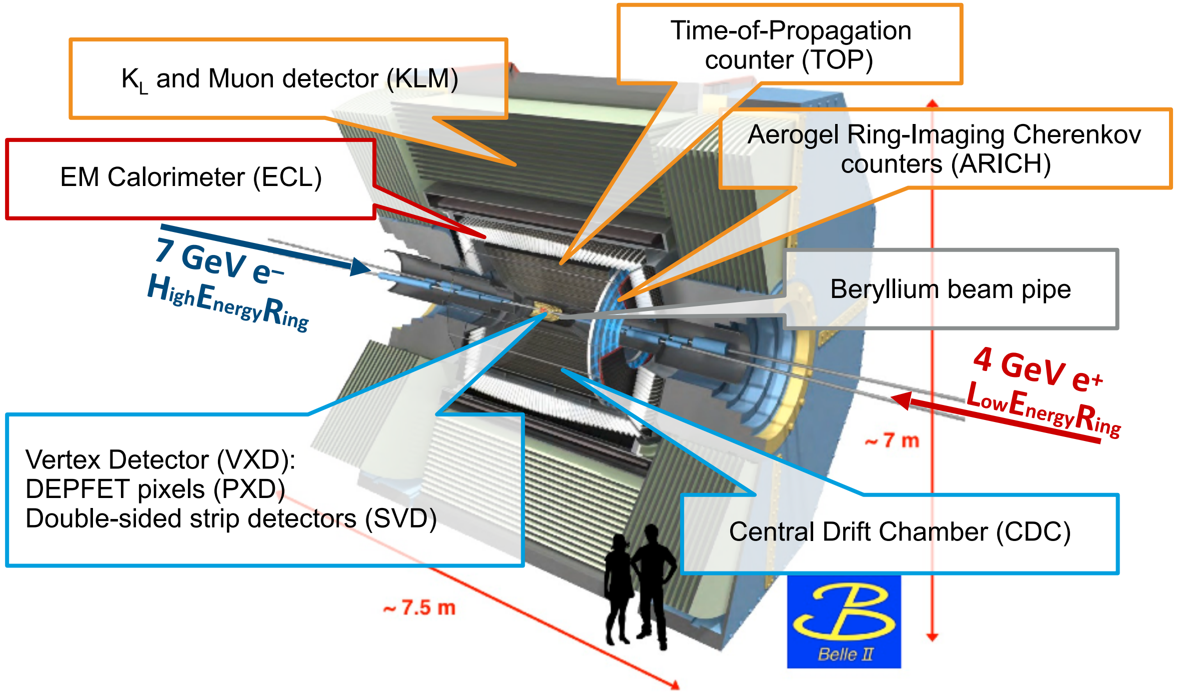


- Belle II
  - upgraded detectors
  - upgraded trigger rate: up to 30 kHz
  - L_{int} = 427.8 fb-1 recorded until summer 2022
    - physics data-taking with full setup since March 2019
    - target $L_{int} = 50\ ab^{-1}$ within the next decade (~50x Belle)
    - rich physics program: B, τ, , DM, searches for new physics, ...



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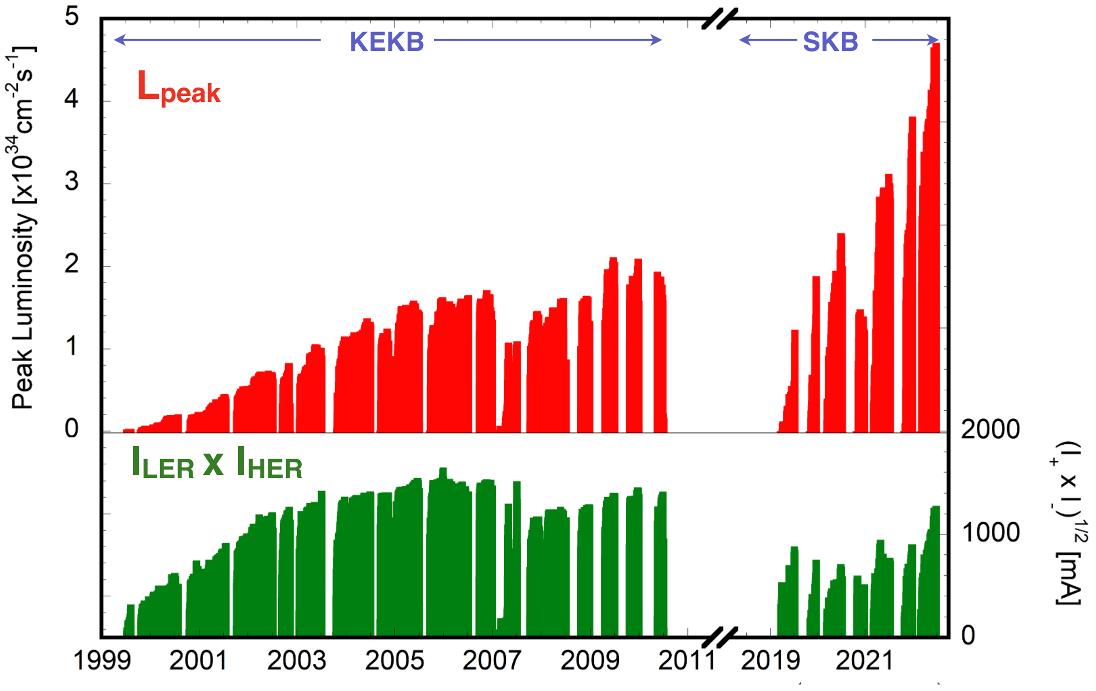
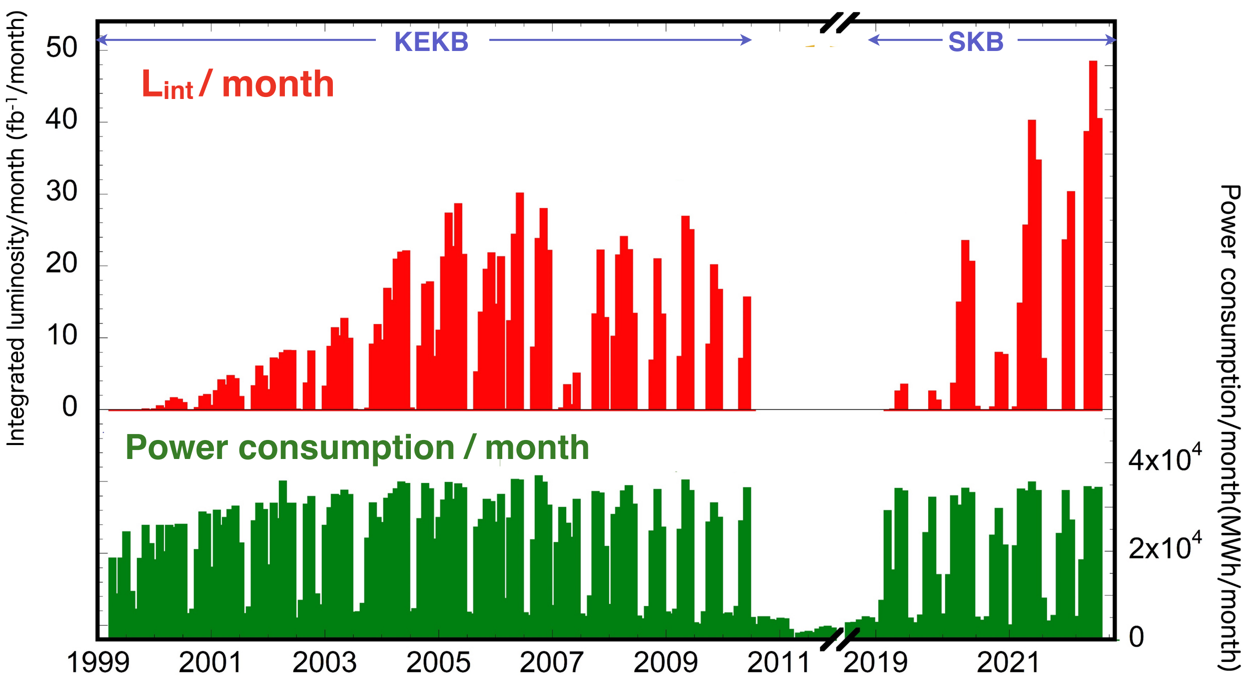
Comparison KEKB versus SuperKEKB and Projection





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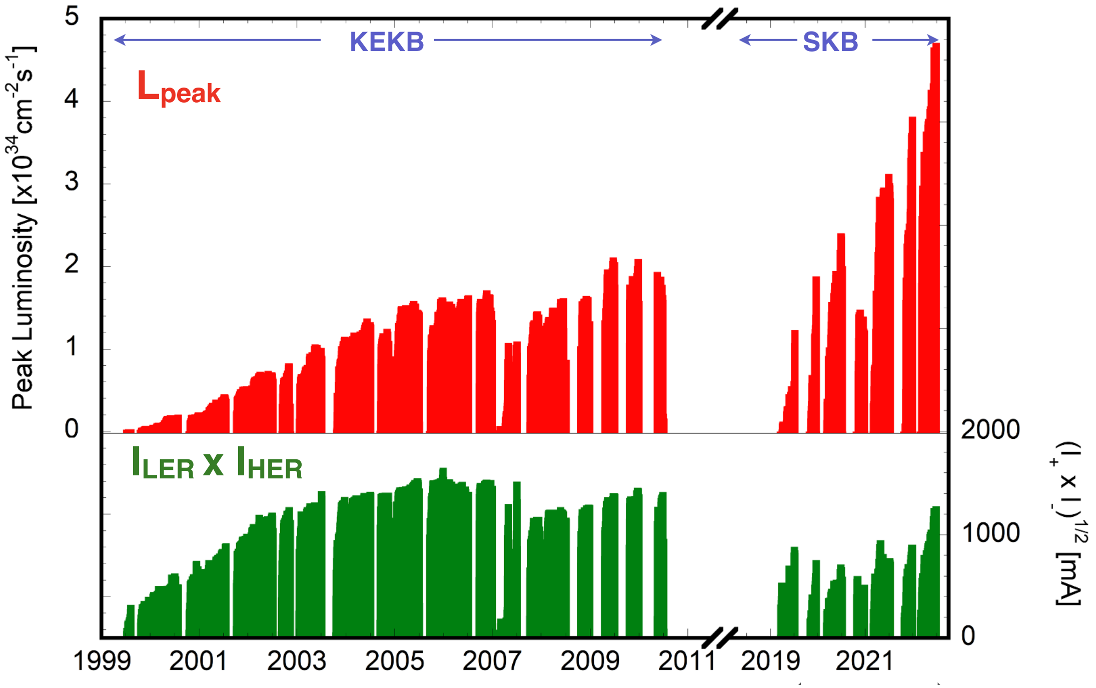
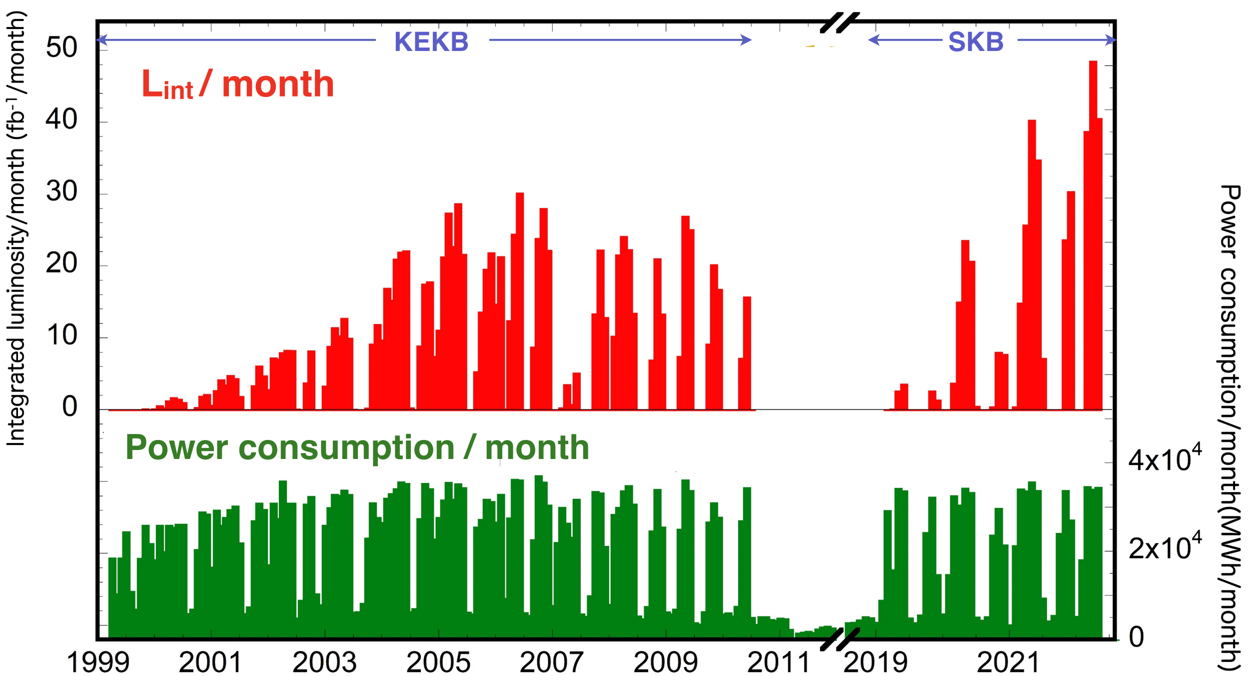
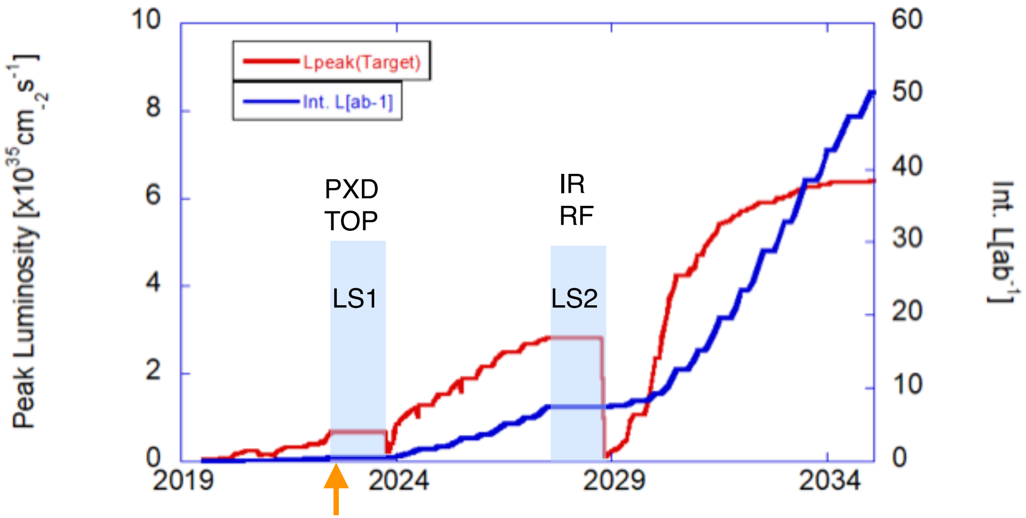




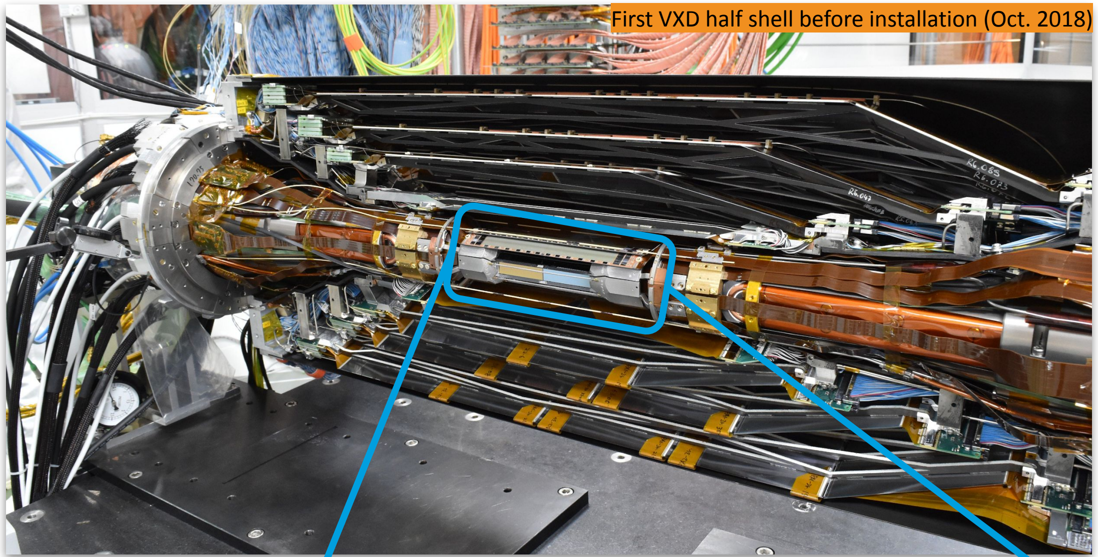


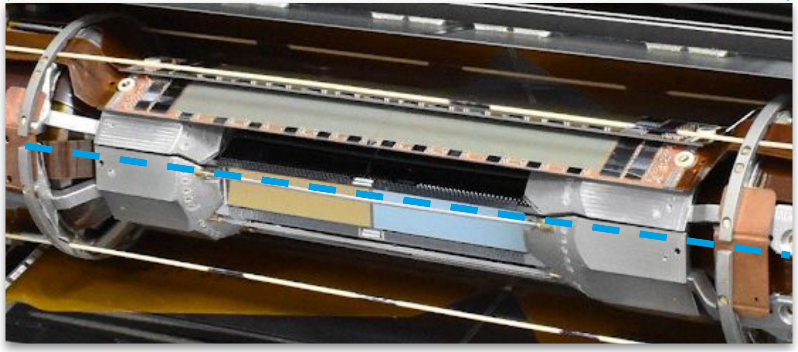
we are here …

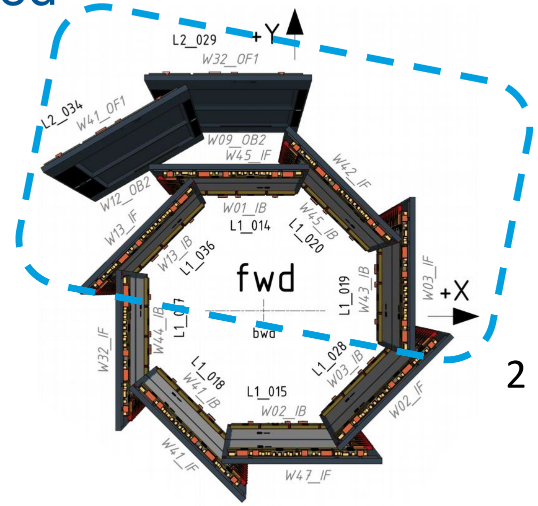
- Still a long way to go
- Next SuperKEKB milestone
  - achieve $1 \times 10^{35} cm^{-2} s^{-1}$

Belle II Vertex Detector

- Silicon Vertex Detector (SVD)
  - recent JINST publication
    [The Design, Construction, Operation and Performance of the Belle II Silicon Vertex Detector]
  - 4 layers of 2-sided silicon strips
  - r ≤ 140 mm
  - 0.34 x 10^6 channels
- 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, size 50x(55-85) μm^2
  - material budget: ~ 0.21 % X_0 / layer
- Acceptance
  - 17° < Θ < 150°
  - $p_T \gtrsim$ 40 MeV/c







2 half shells

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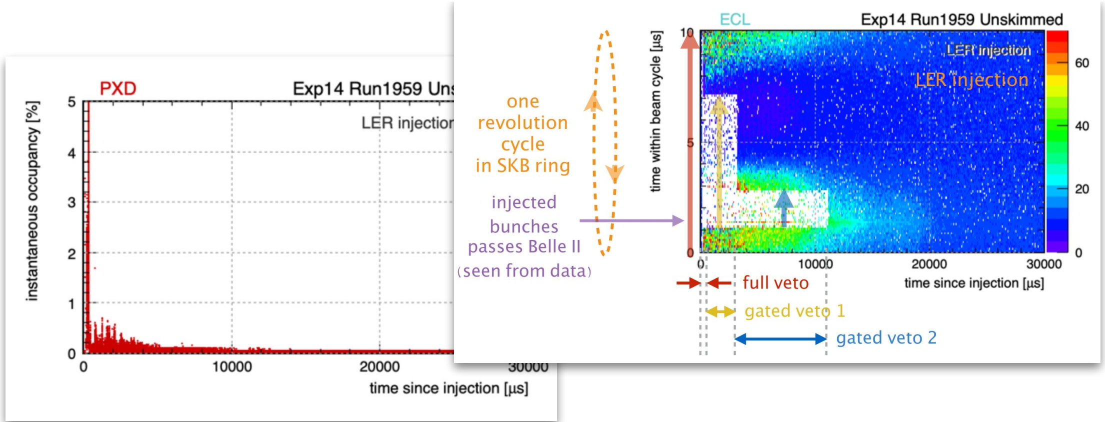
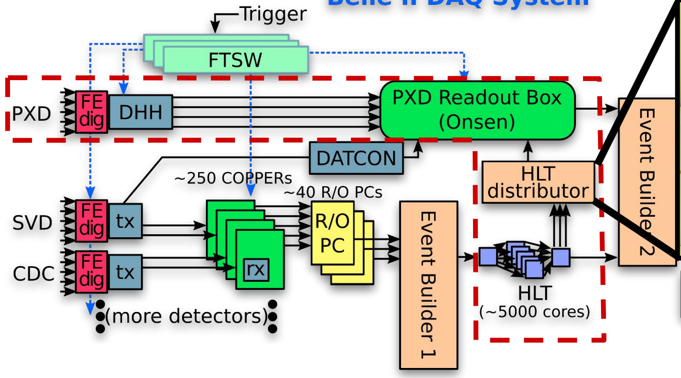
Tracking at SuperKEKB

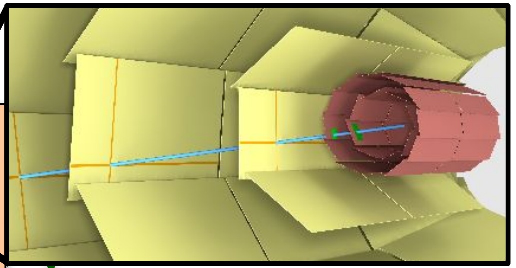
- Challenges
  - backgrounds increase with instantaneous luminosity
    - Synchrotron, Touschek intra-bunch scattering, beam gas, QED (2-photon, rad. Bhabha)
    - ▸ beam lifetime only few minutes (Touschek)
      ⇒ continuous "top up" injection (for 2400 bunches)

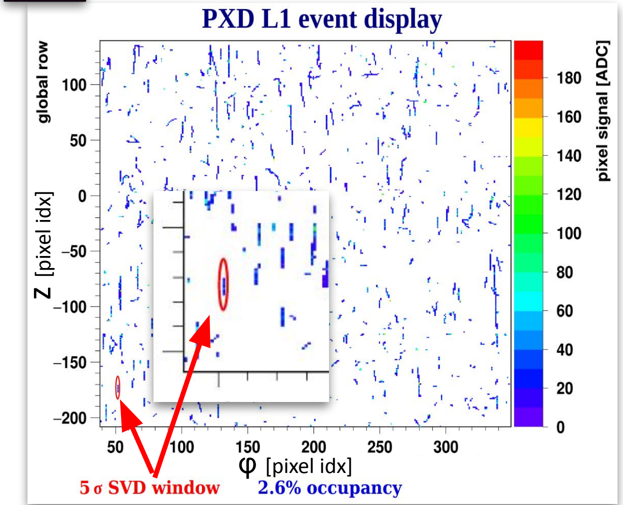
      @2x25 Hz ⇒ $\mathcal{O}$(4 ms) damping time with particle losses
  - challenge for detector/tracking overall
    - ▸ particular challenges for PXD later
  - smaller Lorentz boost
    - ▸ critical for time dependent measurements
    - ▸ compensate with better vertex resolution
- Track reconstruction and PXD role
  - (**H**igh **L**evel **T**rigger) track finding seeded in CDC (p_T > 100 MeV) or else SVD
  - PXD hits used in offline track fit → improved vertex resolution
  - too large PXD data volume at design lumi: need 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



Belle II DAQ System



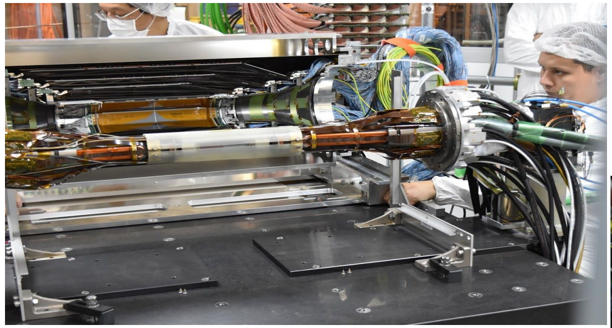


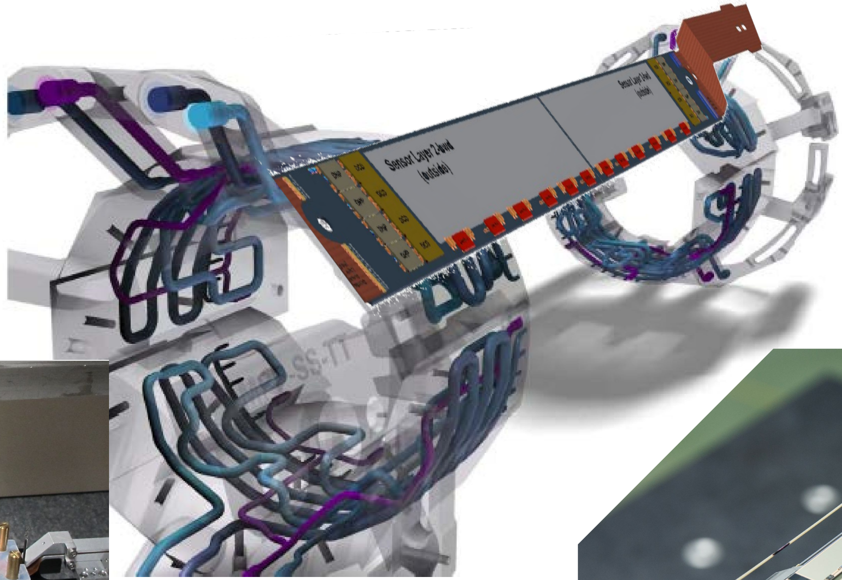


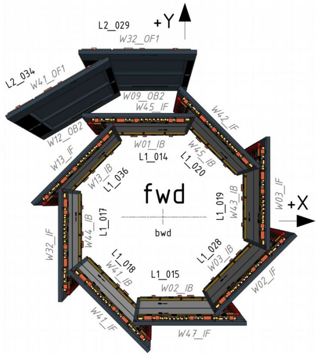
PXD in Belle II

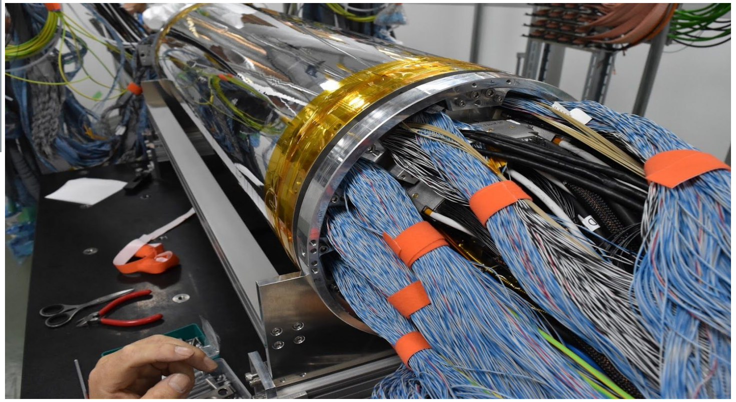
- PXD assembly
  - 2 PXD modules glued together (“ladder”)
  - 2 half shells mounted on Support and Cooling Blocks (SCBs)
    - SCBs provide cooling via 2-phase CO_2 and forced N_2 flow

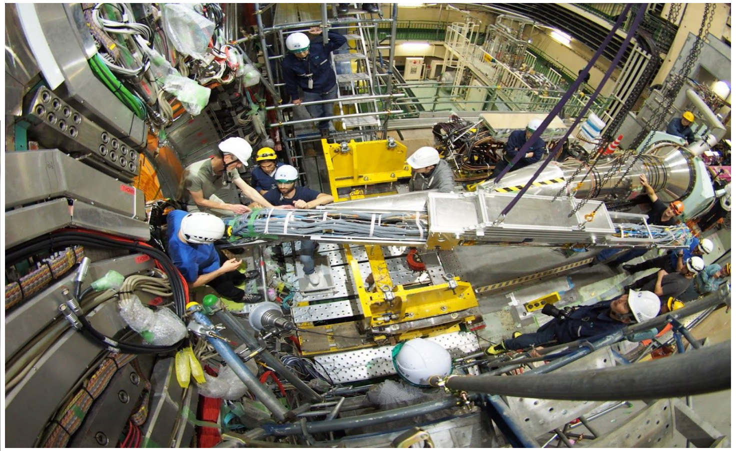
- Installation 2018 at KEK
  - PXD + BP + SVD marriage
  - VXD installation in Belle II

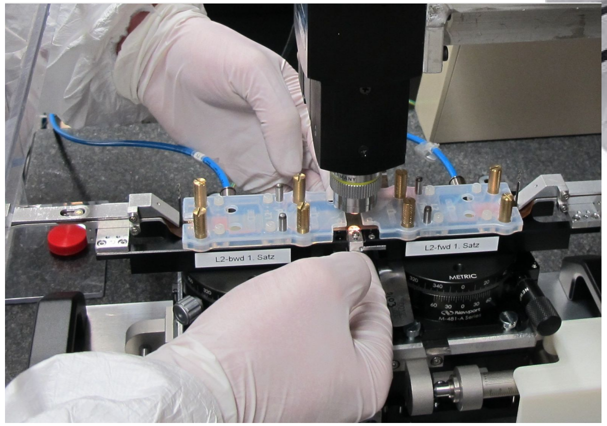


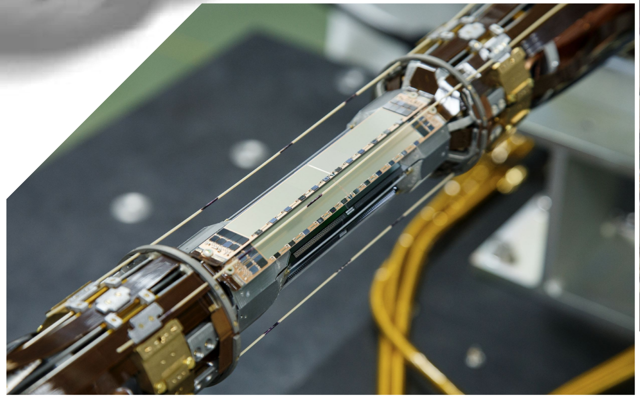






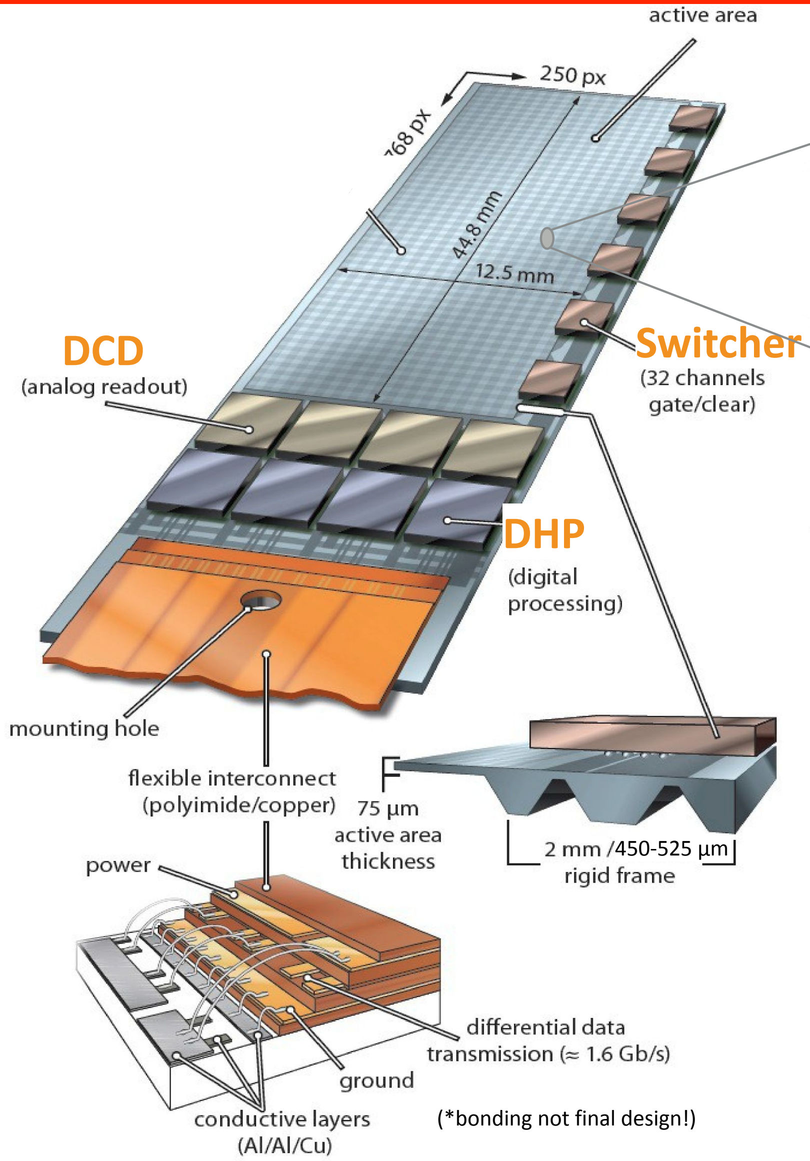


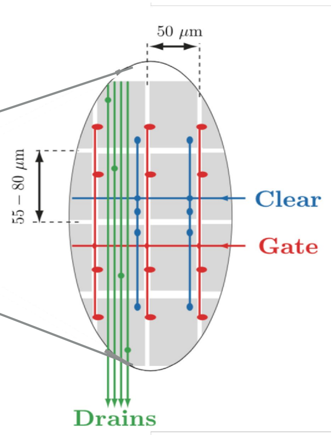


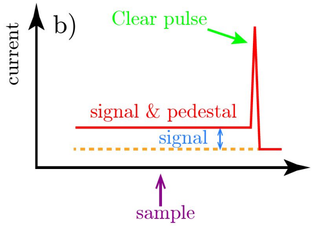


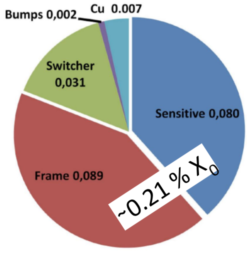
PXD Sensor Design

- Layout
  - matrix: 250x768 pixels, pixel size 50x(55-85) μm^2
  - ASICs (custom designed)
    - Switchers → DEPFET control
    - DCD → 256 channel ADC: 8 bit source current 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
  - single point sampling → median drain current pedestals stored on DHP for zero suppression
  - rolling shutter read-out → low power consumption
    50 kHz → 20 µs integration time (2x beam revolution cycle)
    dead-time free except for 100 ns read-clear cycle
  - design: 1% occupancy (layer 1, dominated by 2-photon QED)
    3% occupancy limit (DHP, DAQ, tracking)
  - power dissipated mainly in ASICs at end of stave ~ 10W/module





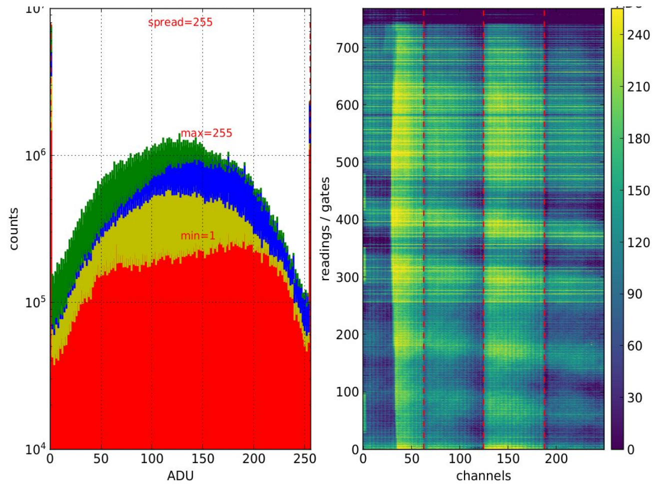




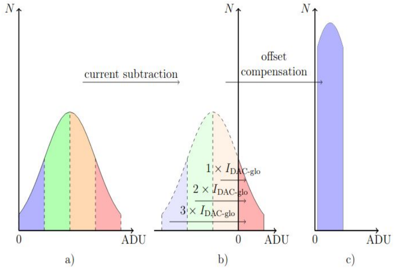
PXD Module Calibration

- 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

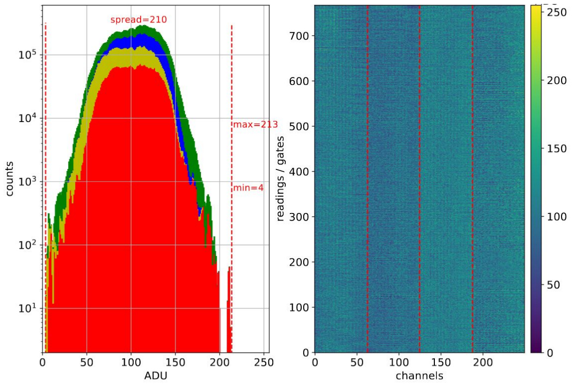
pedestal currents uncalibrated sensor



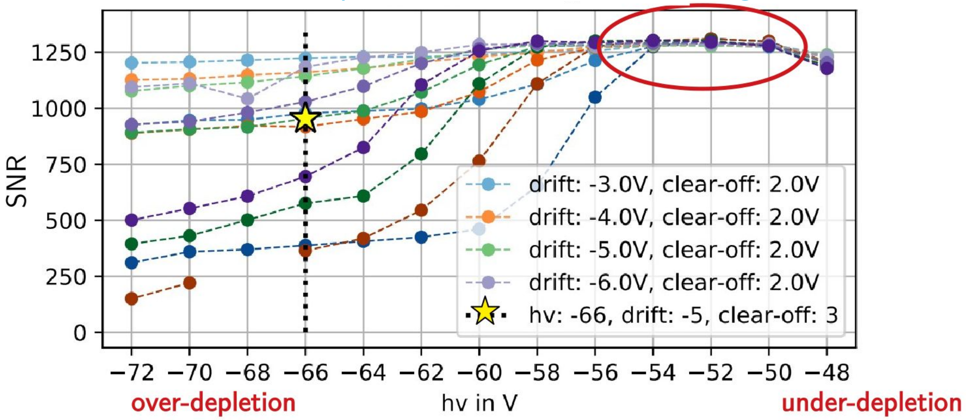
pedestal compression:
2 bit offset current per pixel



pedestals calibrated sensor



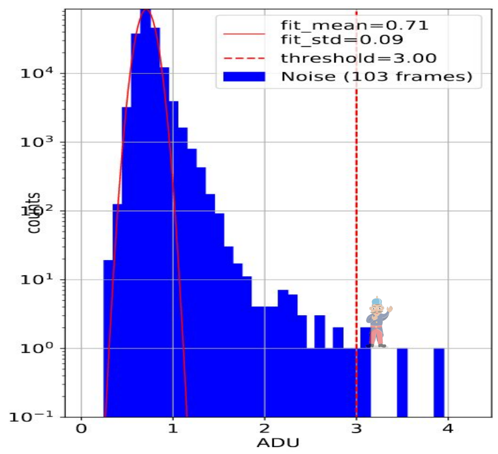
module SNR dependence on sensor biasing



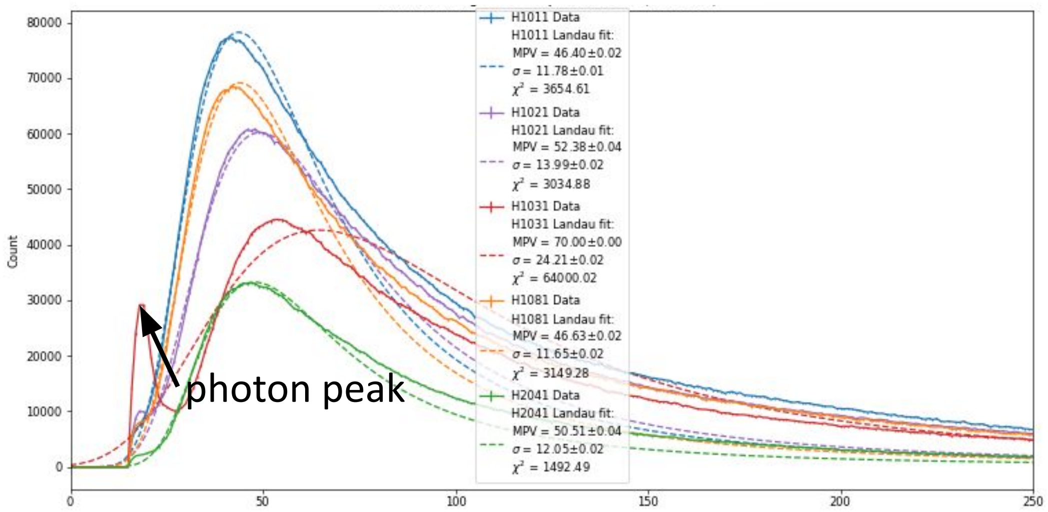
PXD Performance: Signal and Noise

- Noise performance $\mathcal{O}$(1 ADU) (~ 200 e⁻)
  - at a SNR of ~ 30 - 50
- Homogeneous noise and signal response across module matrix
  - stable throughout 2019 → 2022
  - however, recently see slight increase in noise with DCD irradiation

pedestal noise

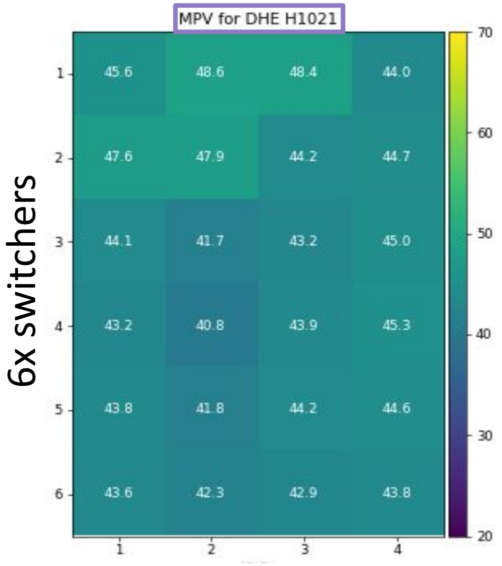


cluster charge distribution



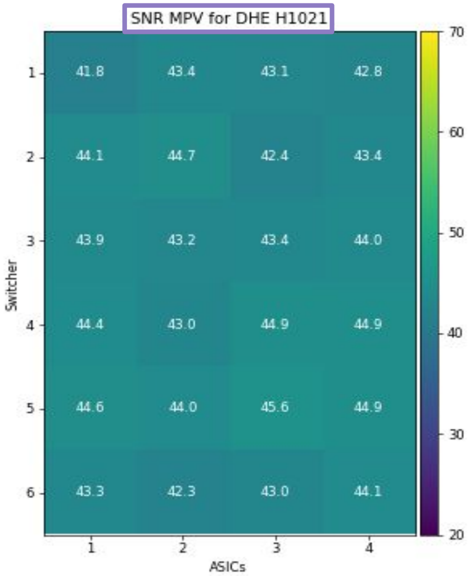
multi pixel cluster ADU

cluster charge MPV



4x DCD/DHPs

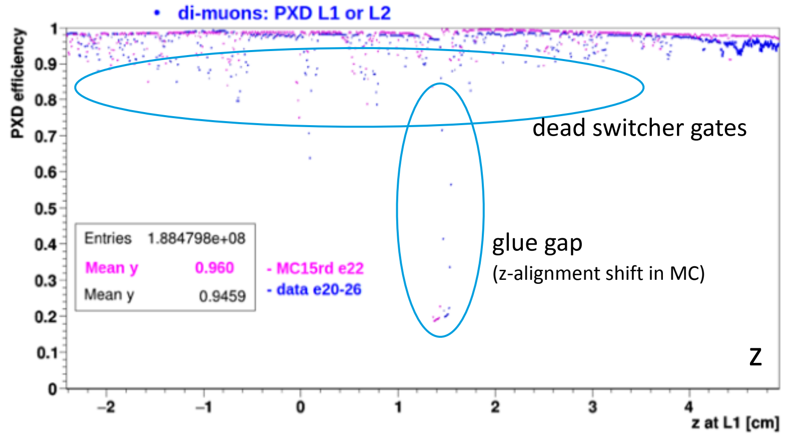
SNR MPV

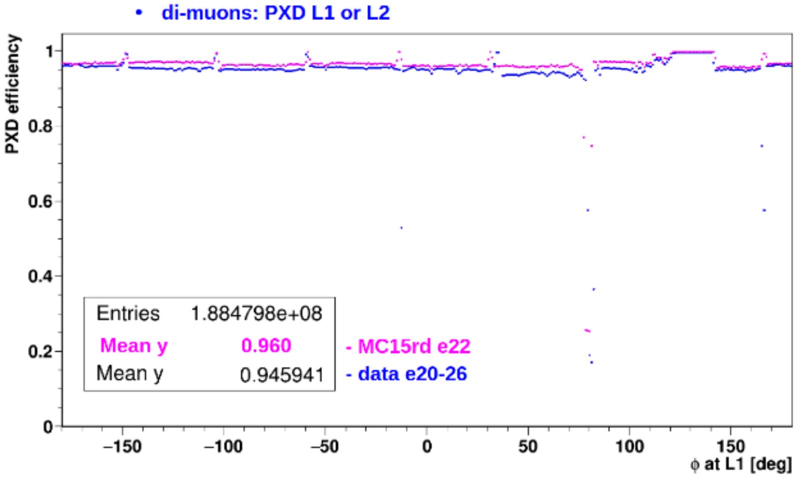


exp. 14, run 2129

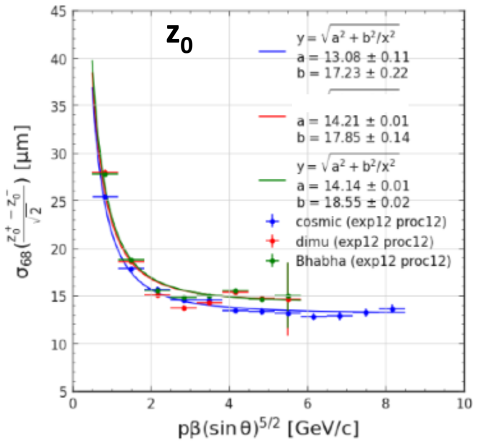
PXD Performance: Efficiency and Resolution

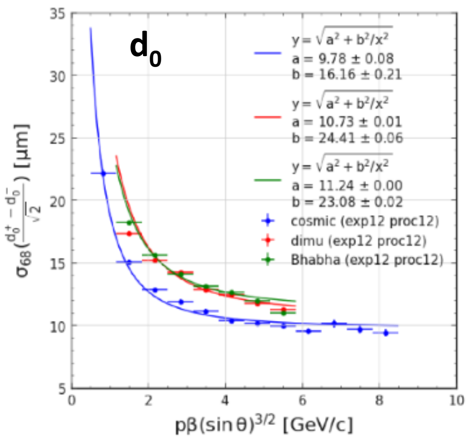
- Efficiency of ~96% to find hit in L1 or L2
  - ~99% single hit efficiency in fiducial regions
- PXD simulation captures most features already quite well
  - continued efforts to further improve

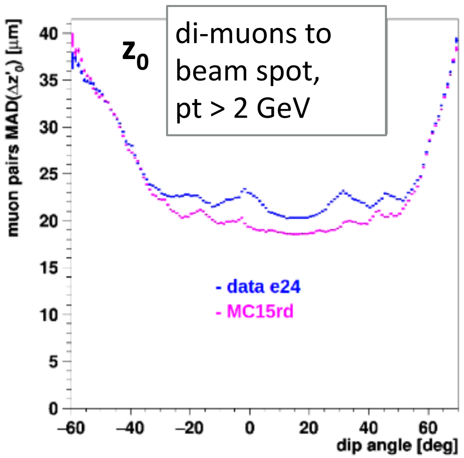


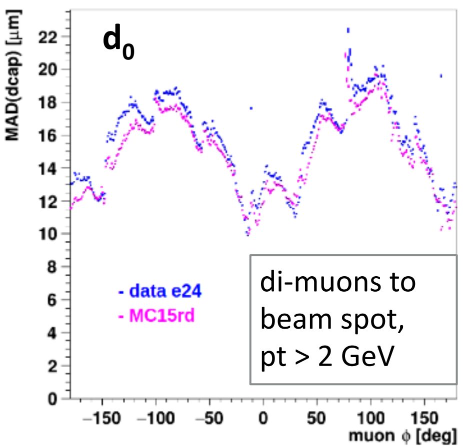


- Impact parameter resolution
  - 1.5 - 2x better than Belle
  - worse description in MC compared to efficiency
    - uncertainties somewhat too optimistic



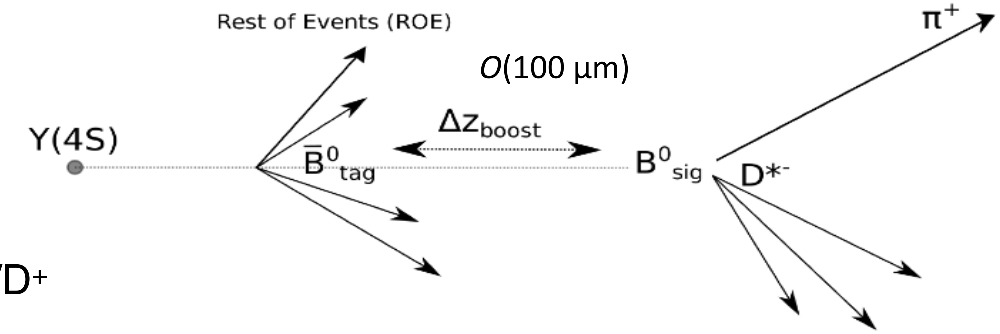


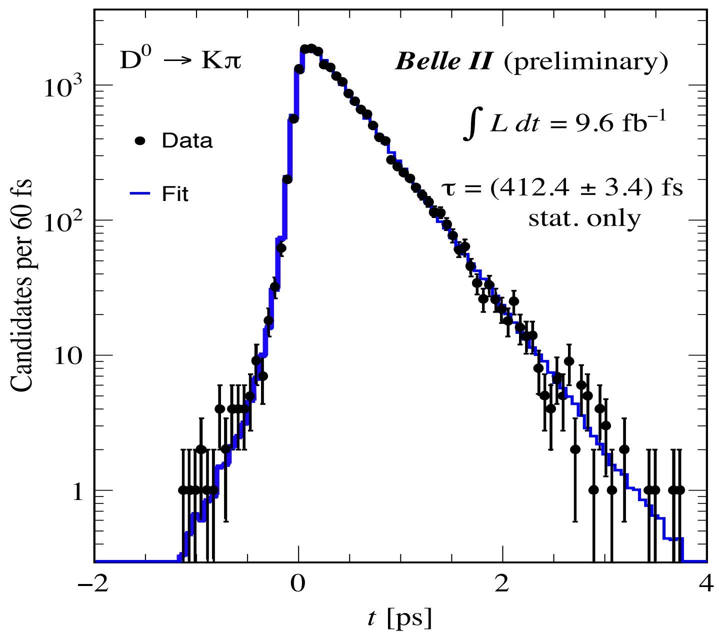




VXD Physics Performance

- Precise measurements of decay vertices crucial for time dependent measurements
  - Belle II proper time resolution ~2x better than Belle
  - thanks to PXD precision and smaller beam pipe diameter
- Belle II published world-leading lifetime measurements on charmed mesons: D^0/D^+





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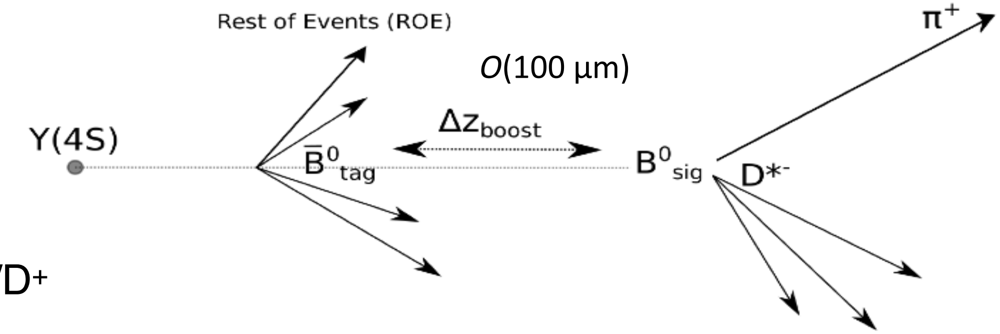
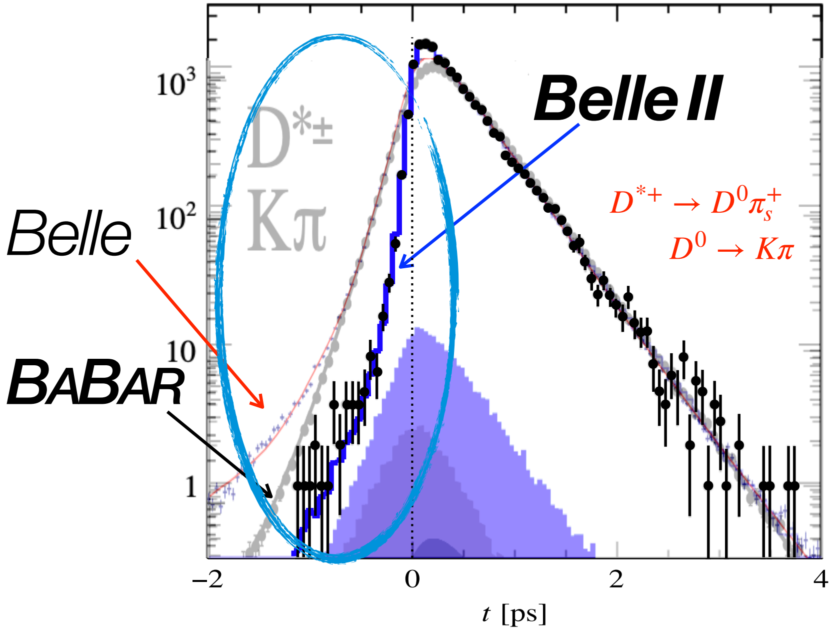
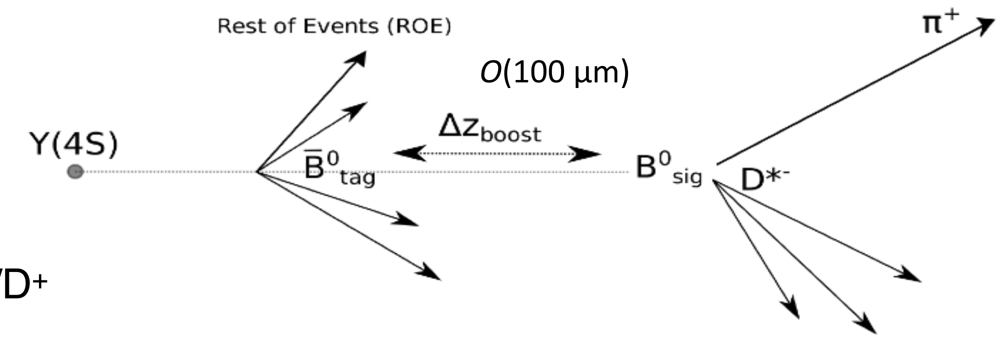




Factor 2 improved t-resolution at Belle II compared to Belle and BaBar

VXD Physics Performance

- Precise measurements of decay vertices crucial for time dependent measurements
  - Belle II proper time resolution ~2x better than Belle
  - thanks to PXD precision and smaller beam pipe diameter
- Belle II published world-leading lifetime measurements on charmed mesons: D^0/D^+
- **New**: lifetime measurements of charmed baryons: Λ_c and Ω^0_c
  - further measurements, eg on time-dependent CP violation in the pipeline



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

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

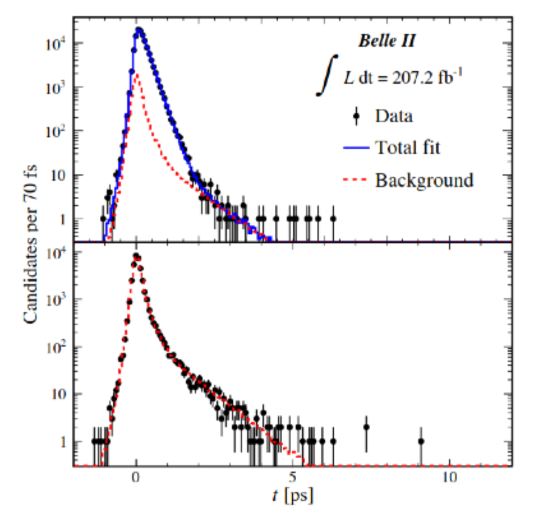


Figure 2: Decay-time distribution of $\Lambda_c^+ \to pK^-\pi^+$ events in the signal region (top) and sidebands (bottom) with fit projections overlaid.

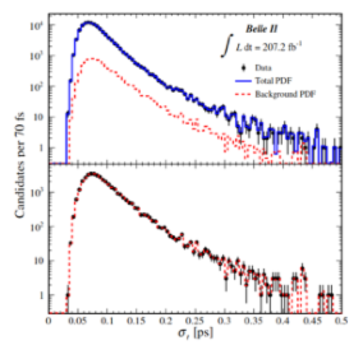


Figure 3: Decay-time uncertainty distribution of $\Lambda_c^+ \to pK^-\pi^+$ events in the signal region (top) and sidebands (bottom). The σ_t PDF used in the fit is shown by the solid blue histogram and the background σ_t PDF is shown by the dashed red histogram.

- Confirming LHCb results of 3σ tension with pre-LHC world average

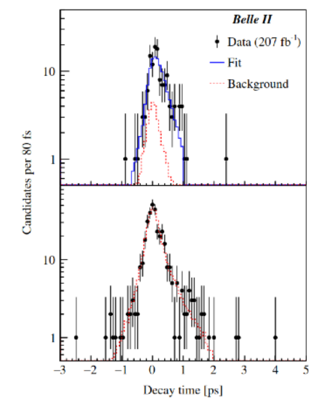


Figure 2: Decay-time distributions for $\Omega_c^0 \to \Omega^-\pi^+$ candidates populating (top) the signal region and (bottom) the sideband with fit projections overlaid.

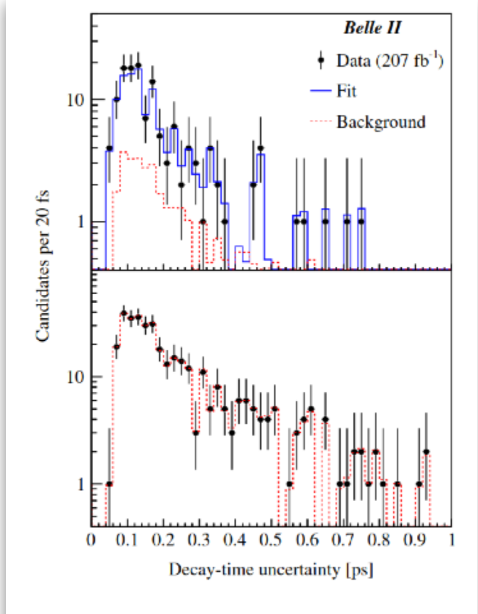


Figure 3: Decay-time-uncertainty distributions for $\Omega_c^0 \to \Omega^-\pi^+$ candidates populating (top) the signal region and (bottom) the sideband with fit projections overlaid.

Ω_c: arXiv:2208.08573 → Physical Review D Letters

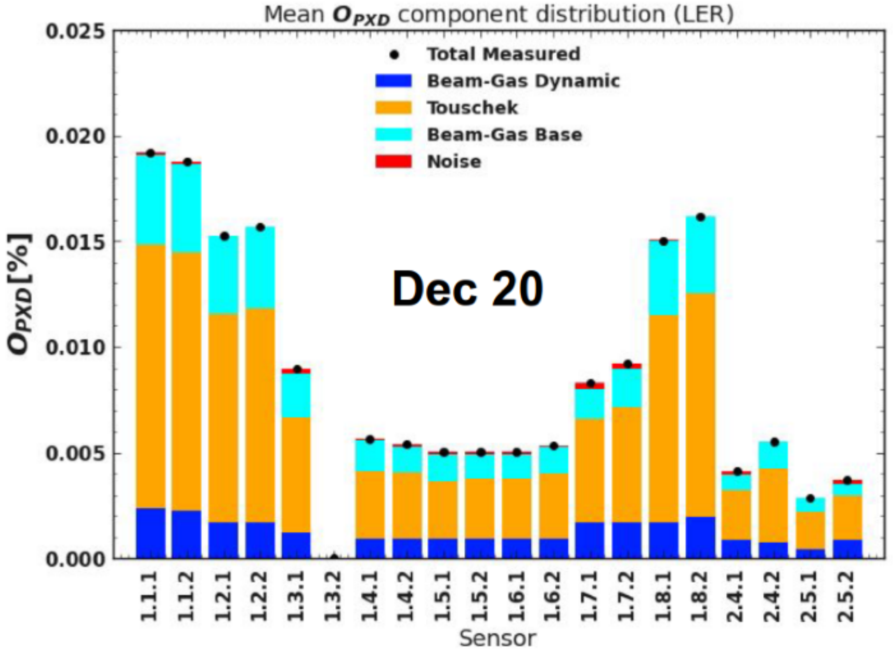
Λ_c: arXiv:2206.15227 → Physical Review Letters

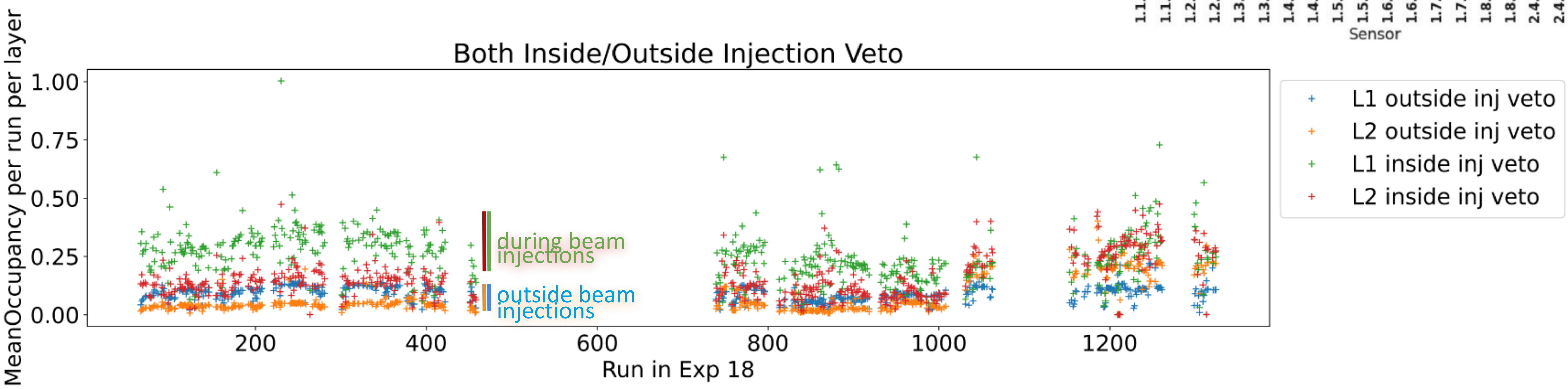
D^0/D^+: Phys. Rev. Lett. 127, 211801 (2021)

Background in PXD

- Impact of background
  - dominates occupancy (in particular during injections)
    → 1% / 3% limits not yet reached (on average)
  - still fake hits can deteriorate resolution (purity)
  - contributes to irradiation → ageing (slow irradiation) or even damages (fast irradiation)

Without injection background

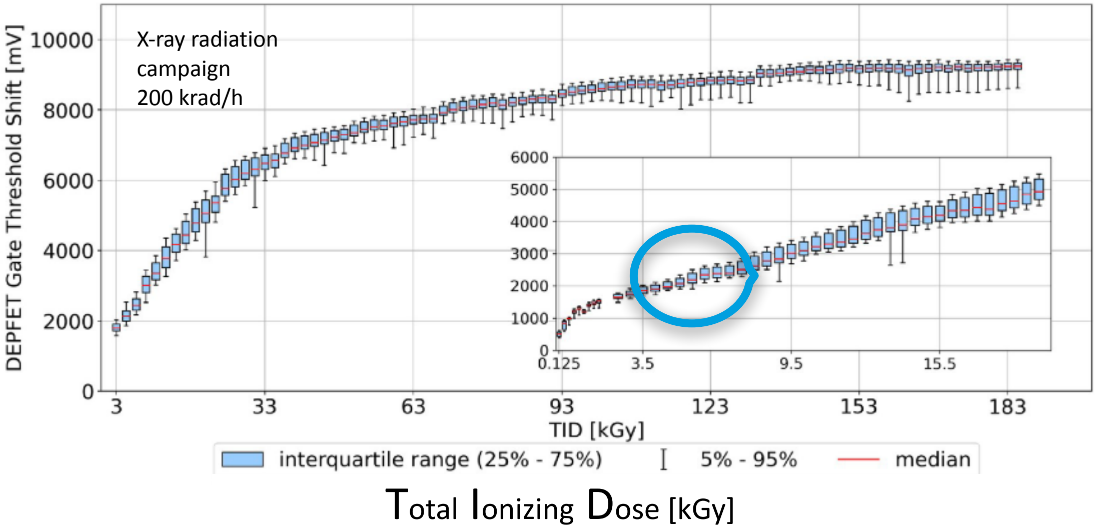




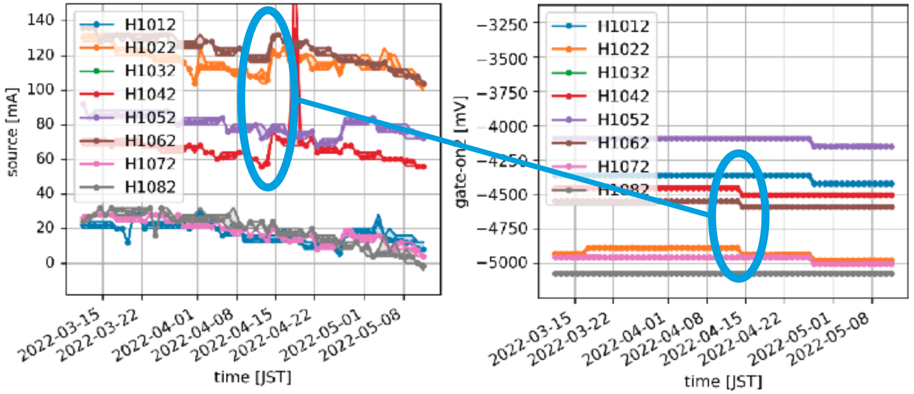
Radiation Effects

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

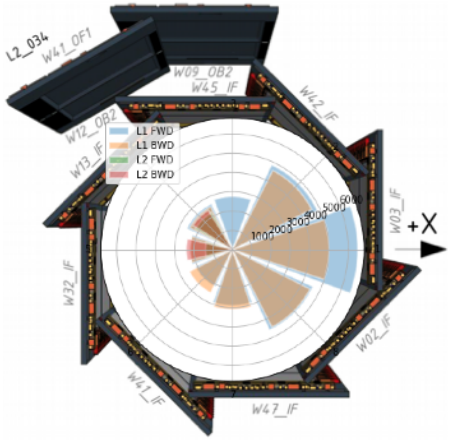
$$\mathrm{MPV} \sim g_q \sim \sqrt{I_{\mathrm{D}}} \sim (U_{\mathrm{Gate}} - U_{\mathrm{Threshold}})$$

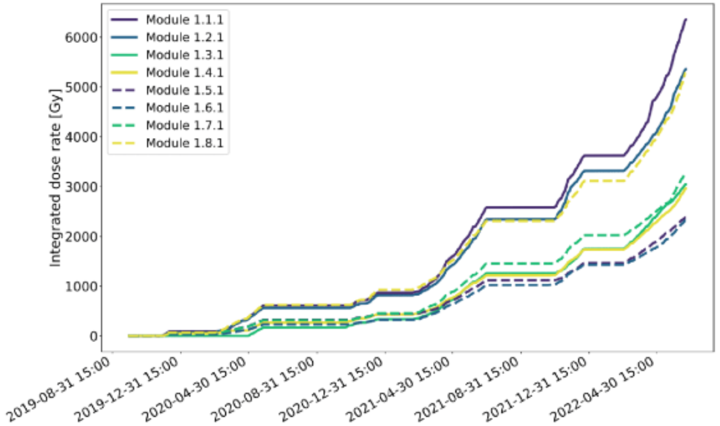


  - compensated by regular adjustment of gate voltage

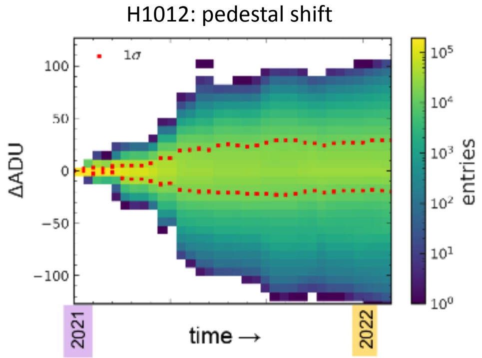


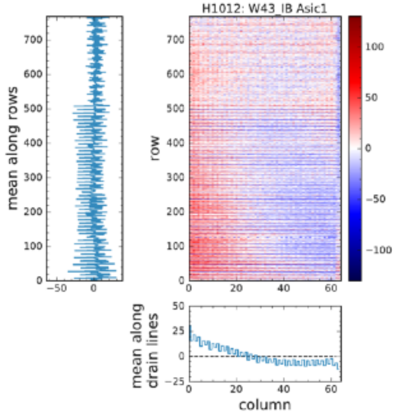
- PXD total dose measurement: 2019 - 2022: ~ 3-6 kGy
  - estimated from module occupancies
  - scaled to diamond sensor dose measurements to account for times without PXD data-taking (eg filling the machine with HV off)

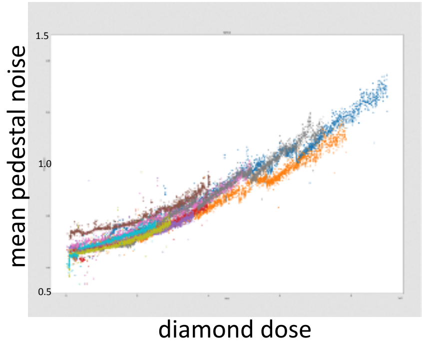




- Pedestal ageing
  - pedestal ageing and pedestal noise increase
  - inhomogeneous across matrix → potential challenge for pedestal compression with consequences for module performance







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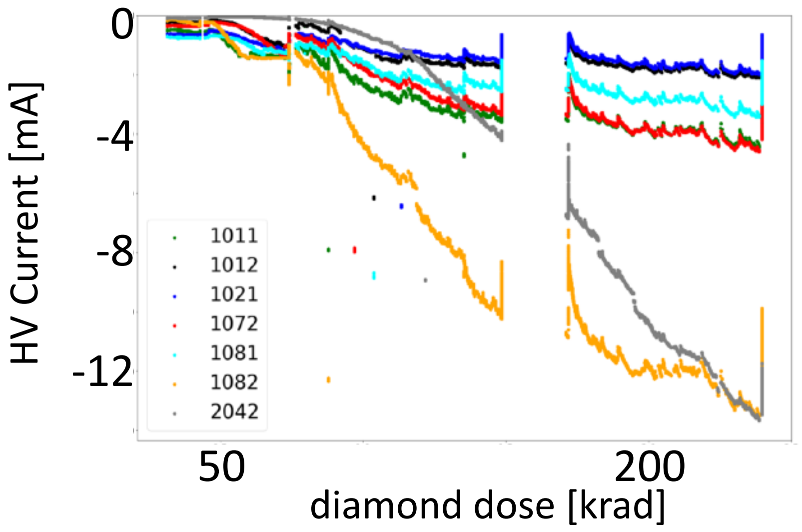
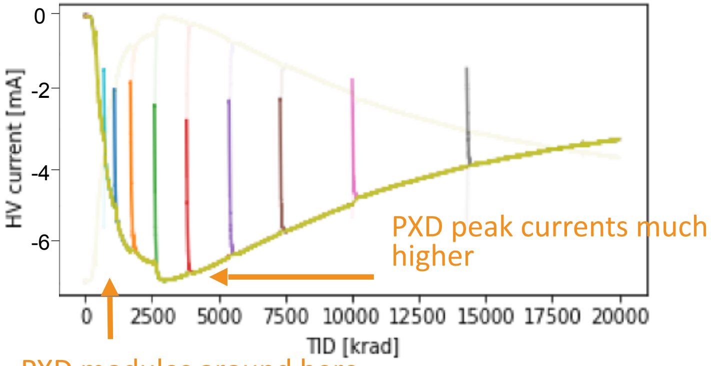
Increasing Backside (HV) Currents

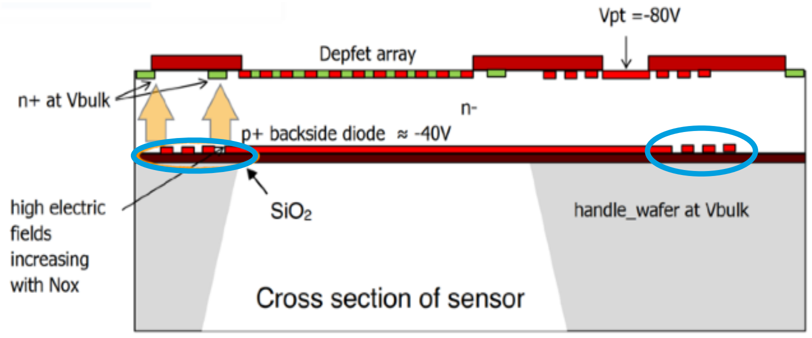
- Observe unexpected increase in HV currents of some modules
  - in guard ring area → not affecting active pixel matrix
  - so far no performance impact → but power supply patch needed
  - some annealing during beam off/HV on and beam on/HV off times



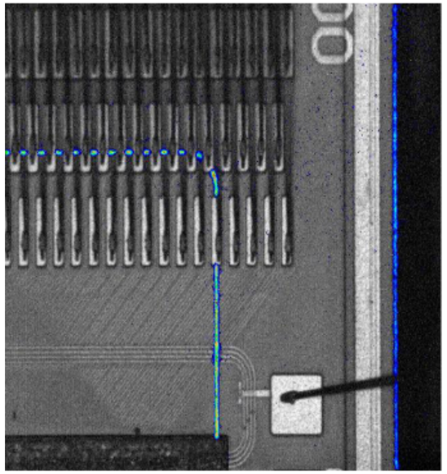


- x-ray lab campaigns
  - expect currents to saturate at certain dose
  - not observed in PXD yet

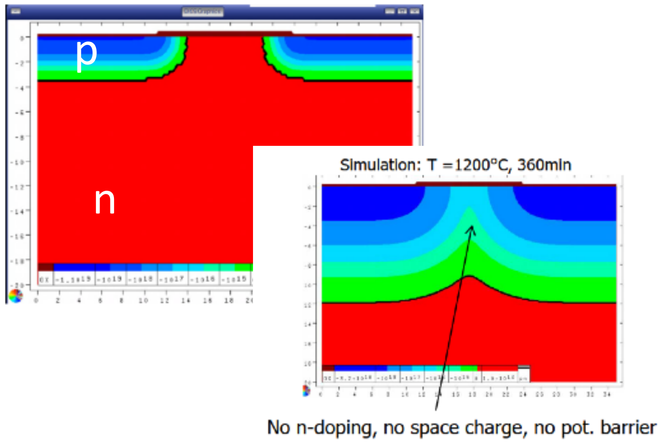
- Interpretation (Rainer)
  - unexpected shorts in thinly spaced guard ring structures
  - oxide charge increases with irradiation → higher breakthrough currents
  - from higher than expected lateral diffusion in (hot) SOI process
  - previously unnoticed due to wrong backside doping profile measurements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



emission microscope image visualizing avalanche breakdown at guard rings

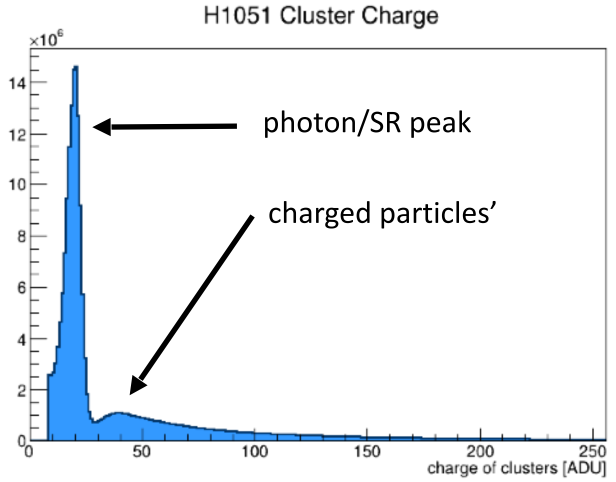


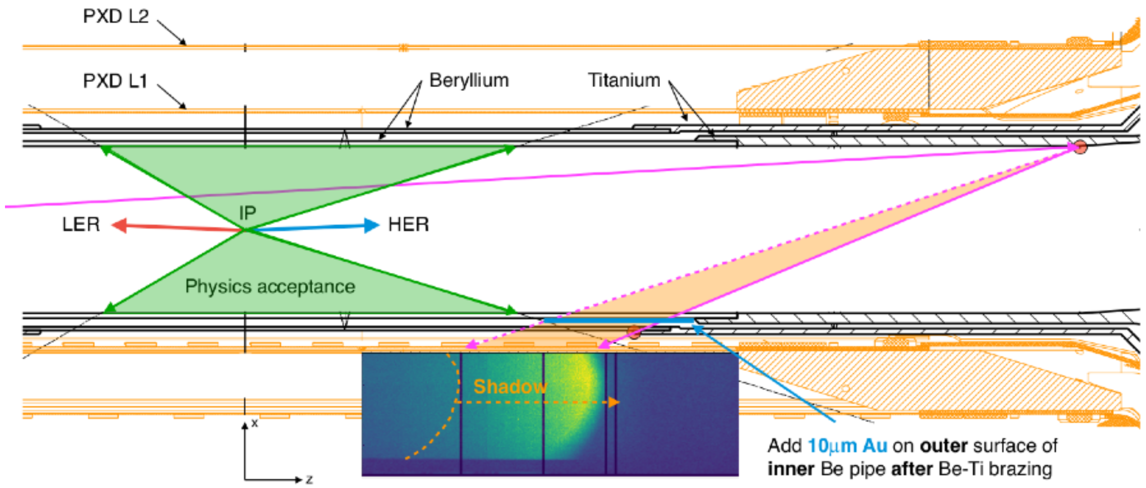
simulated diode guard ring structure before and after diffusion



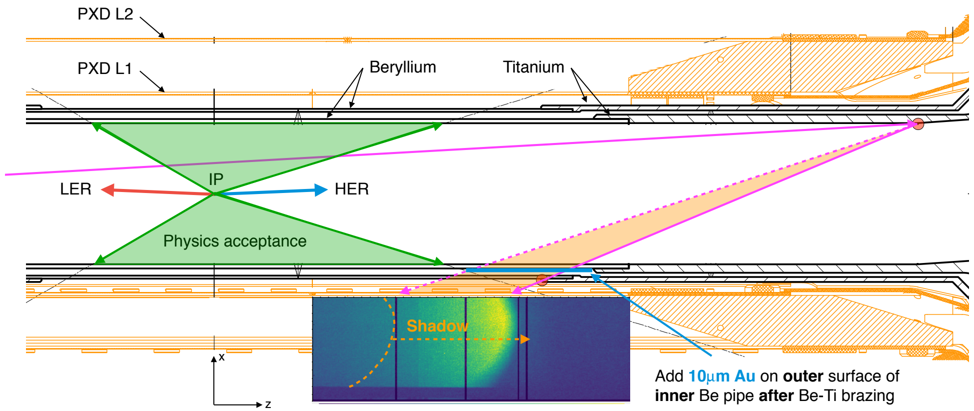
Synchrotron Radiation Background

- Interaction region designed to avoid direct SR photons hitting central Be beam pipe
  - but significant SR background observed in several -x modules
  - dominated by low energy, single pixel clusters (<10 keV)
  - mainly during HER injections (→ large betatron oscillations during cool down)
  - 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
  - sensitivity of PXD provides valuable feedback to accelerator
    - small modification of HER beam orbit
  - new modified beam pipe w/ new geometry and additional gold plating to be installed with PXD 2022 update

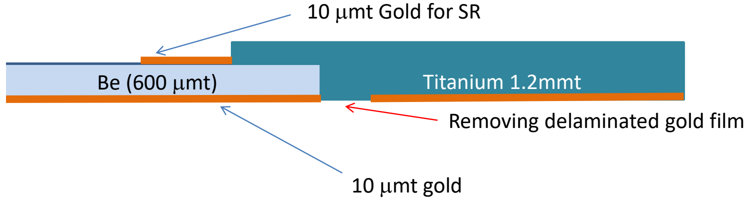




Status of Beampipe Production (KEK)



Gold film partially peeled IP pipe (inner cylinder)

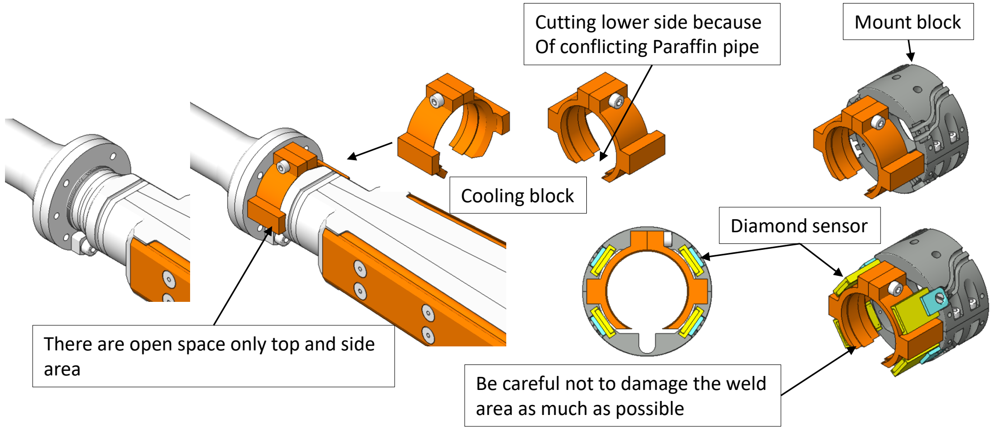


Current schedule

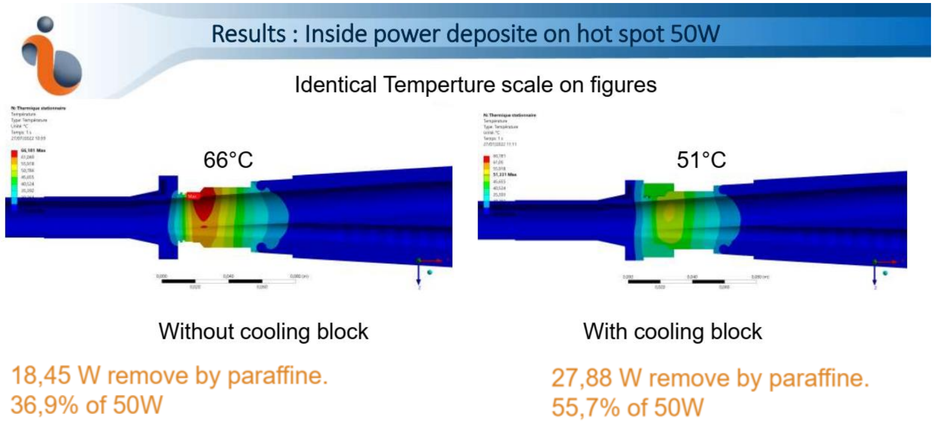
	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
IP part production										
Spare cylinder plating										
Inner+outer cylinder connection										
IP part +crock part										
Beam pipe + HM shields integration										

- Production delayed due to gold delamination issue
- Beam pipe should be ready for diamond mounting in January/February

Mitigation of hot spot issue



Thermal FEM simulation

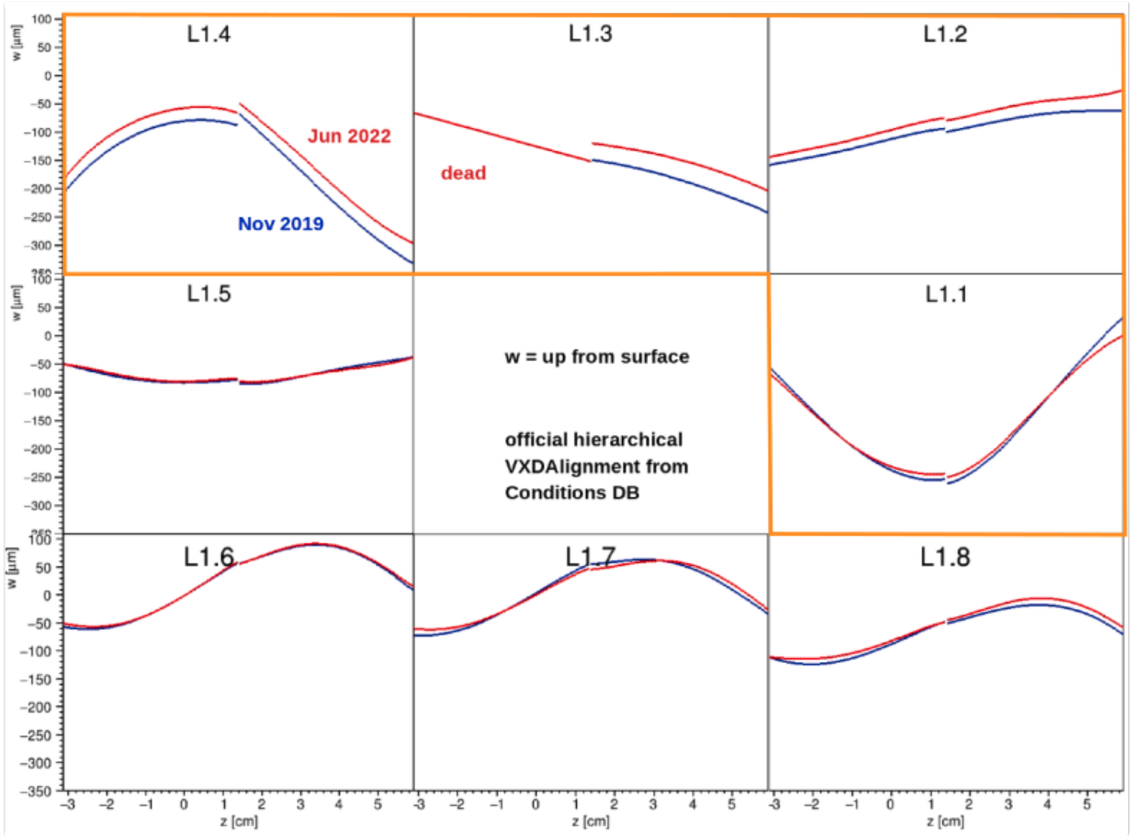


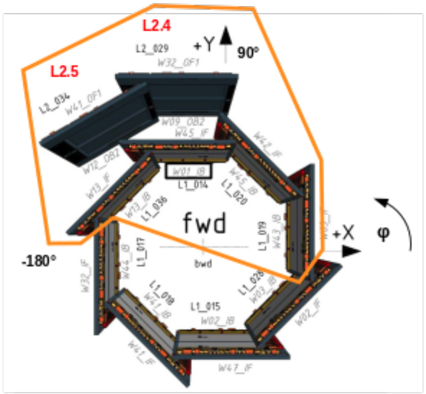
Cooling block => 15°C lower

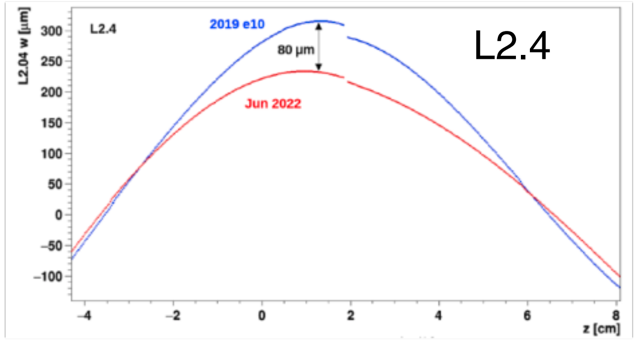
New cooling block
Will be mounted on the LS1 pipe

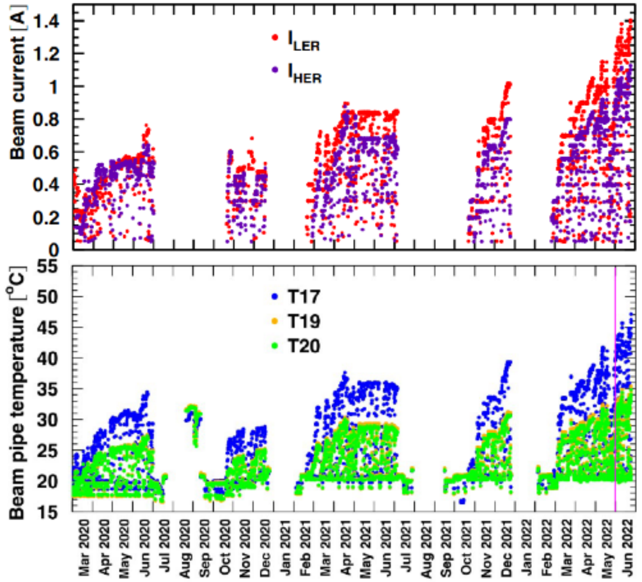
Surprise in 2022: Alignment

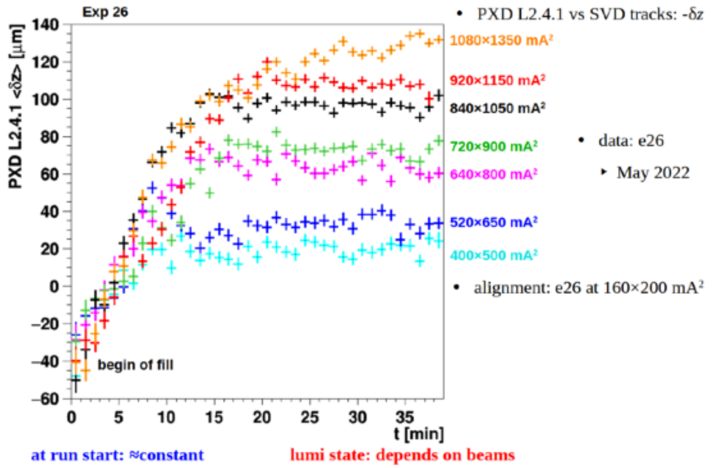
- In general quite stable alignment parameters over 3.5 years of operation
  - significant but stable ladder deformations
  - observe global z-shifts of detector eg with earthquakes
  - observe bowing (L2 in particular) with increasing beam currents
- Caused by warming up / thermal expansion of beampipe due to increasing beam currents
  - result in stress on PXD not fully compensated by PXD gliding mechanics





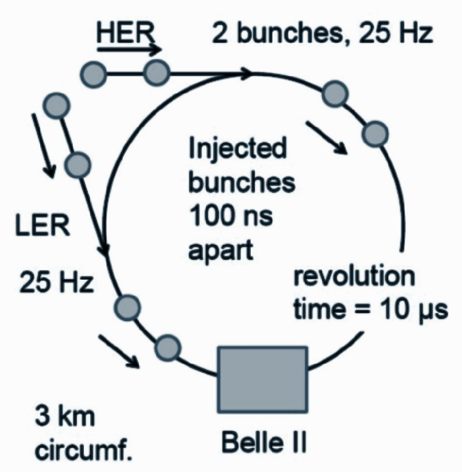






Operational Challenges

- SuperKEKB is operated in top-up mode: continuous injection up to 2x25 Hz
  - at design luminosity, Touschek effects limit beam lifetime to few mins
  - injected bunches produce high background rates, damping takes a few ms
  - mitigation trigger veto: full veto (all Belle II 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)



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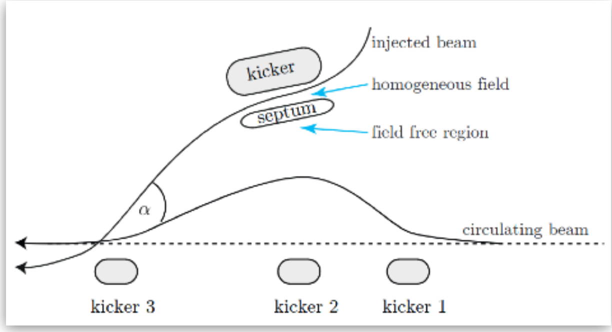
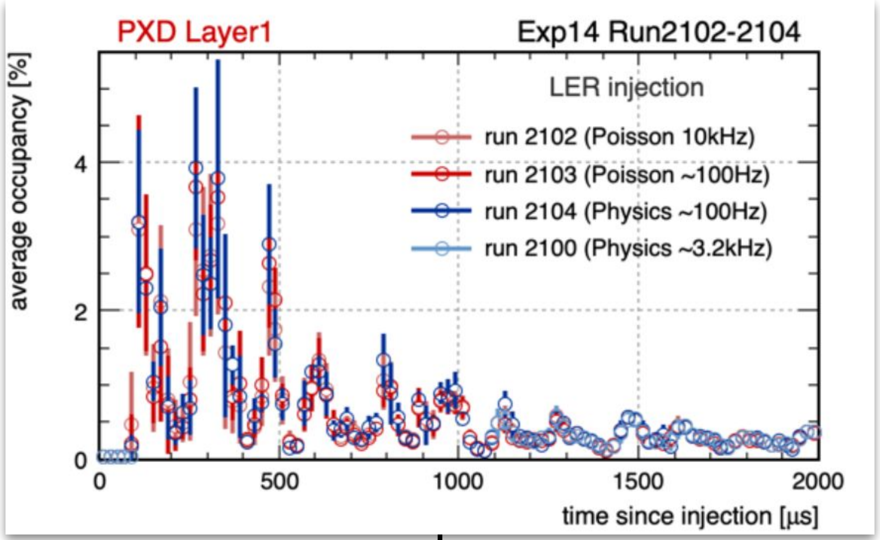


PXD Occupancy: vetoless runs during injection



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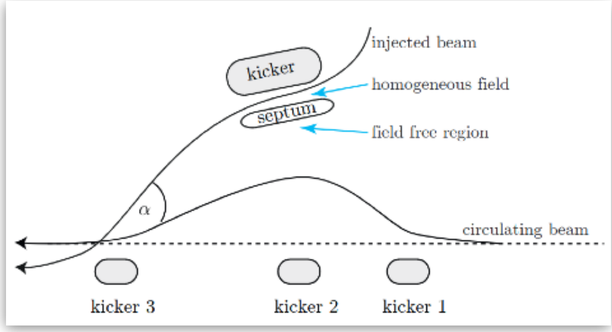
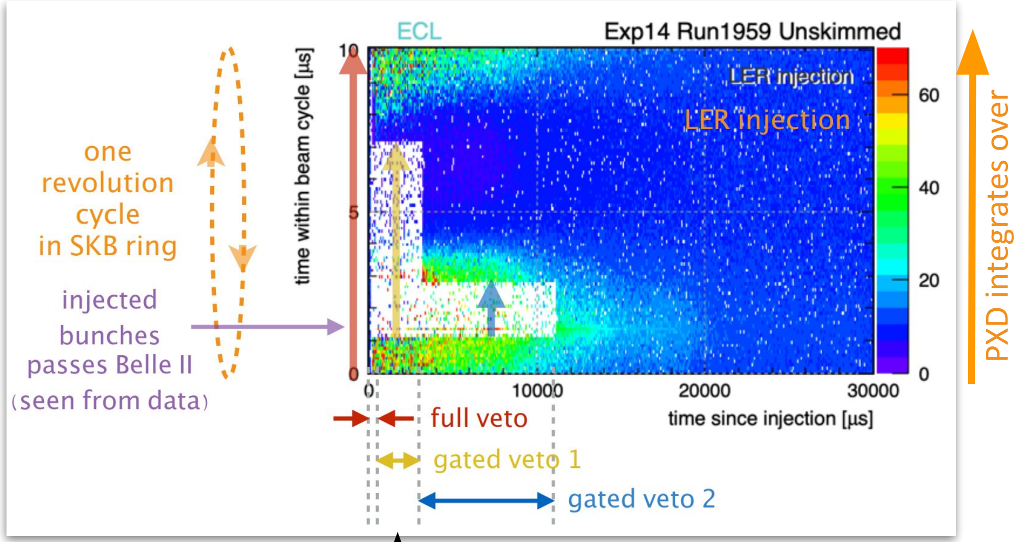


Injection trigger vetoes: (on ECL occupancy)



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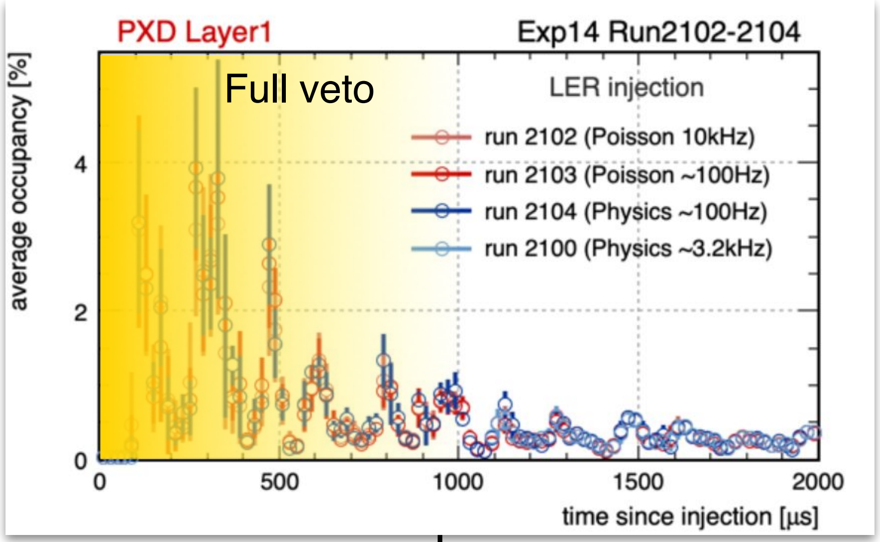
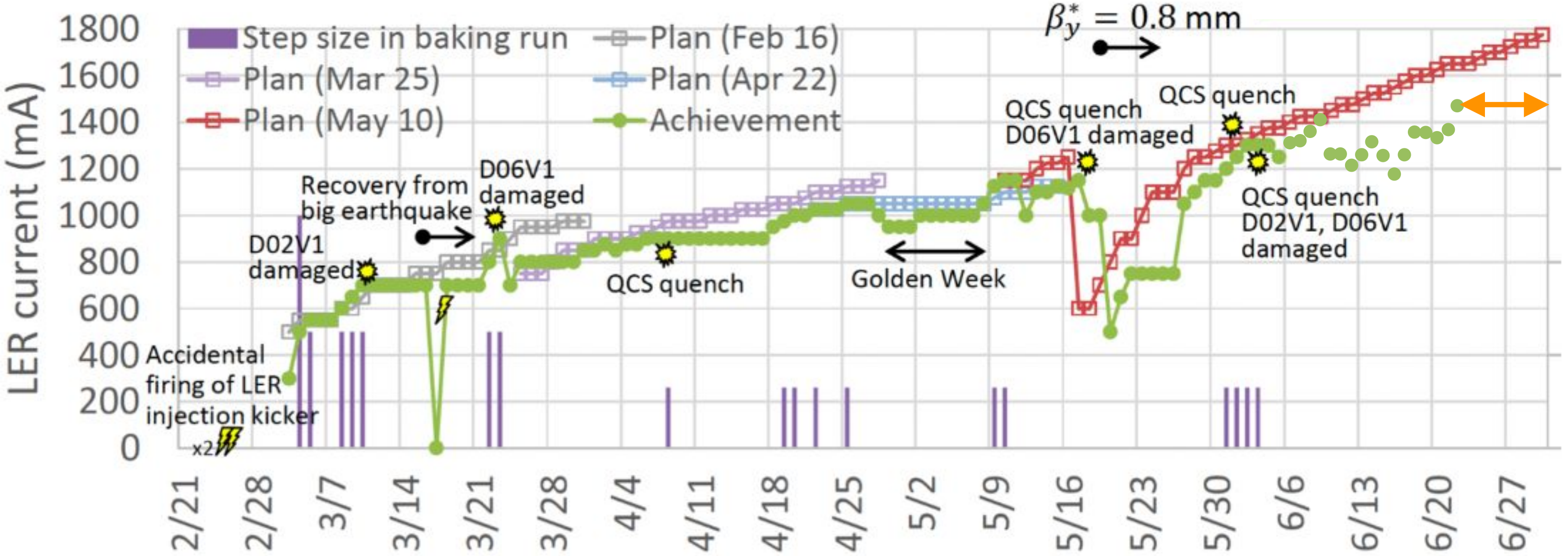
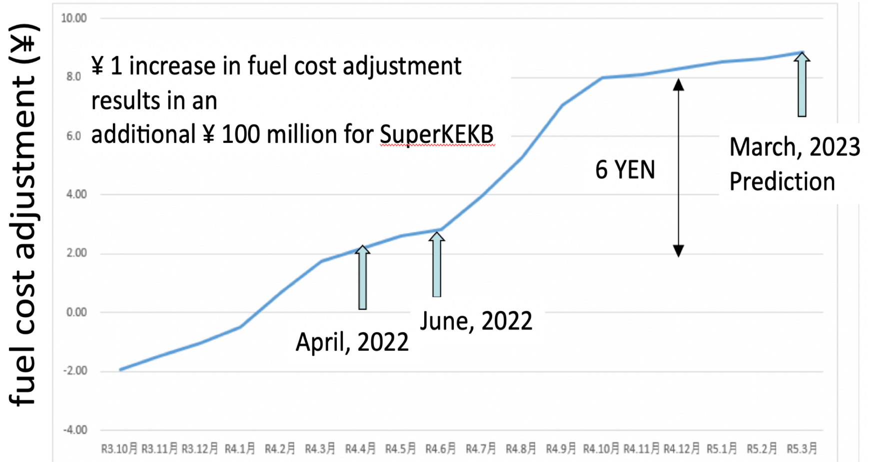


Challenges in SuperKEKB Operation in 2022

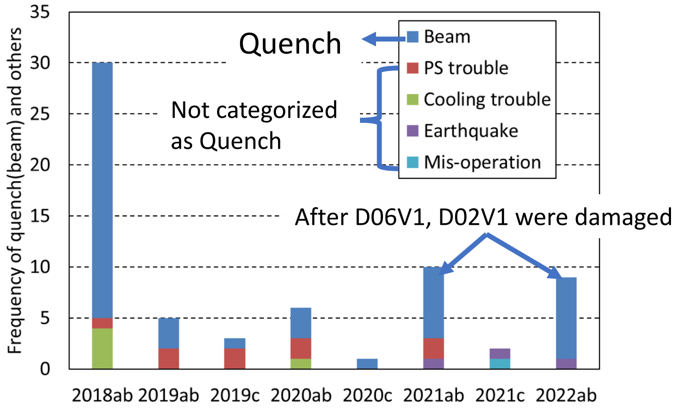
Moving target: slower than planned ramp-up of beam currents

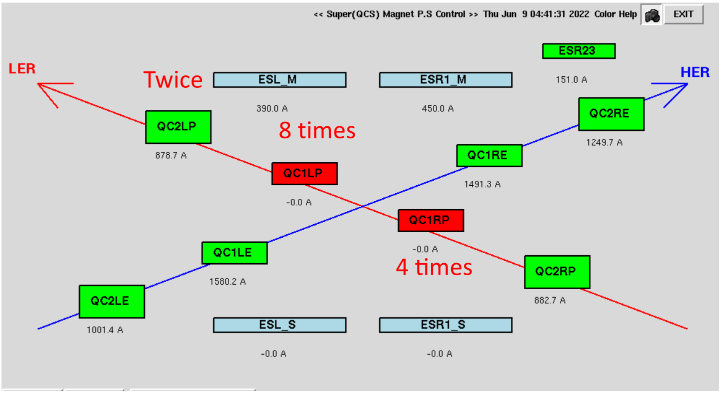


Increasing electricity costs: premature run-end

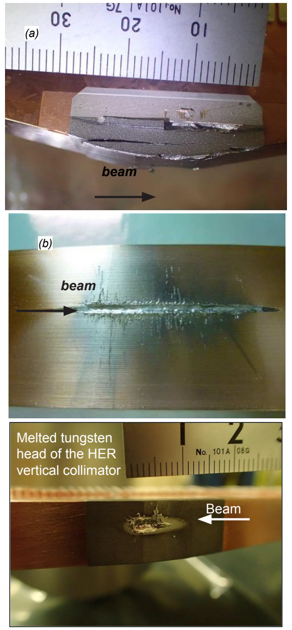


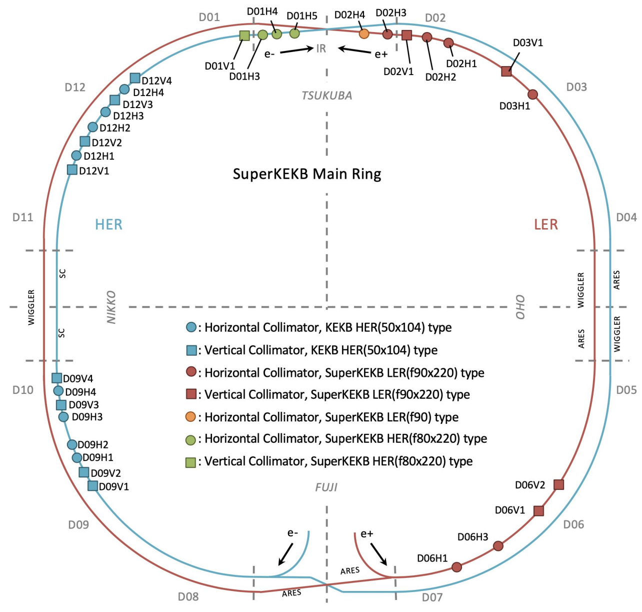
QCS quenches





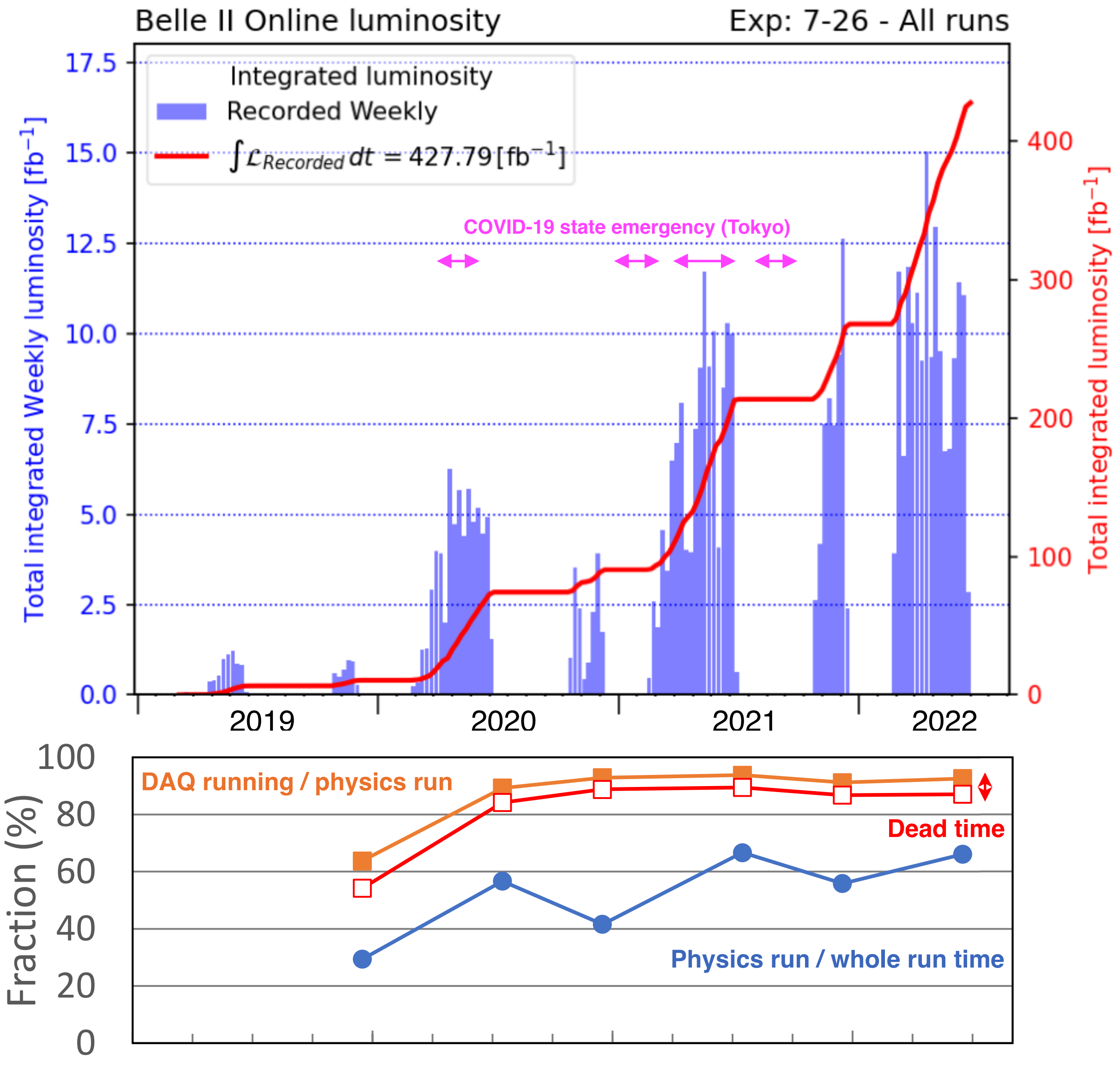
Damaged collimators

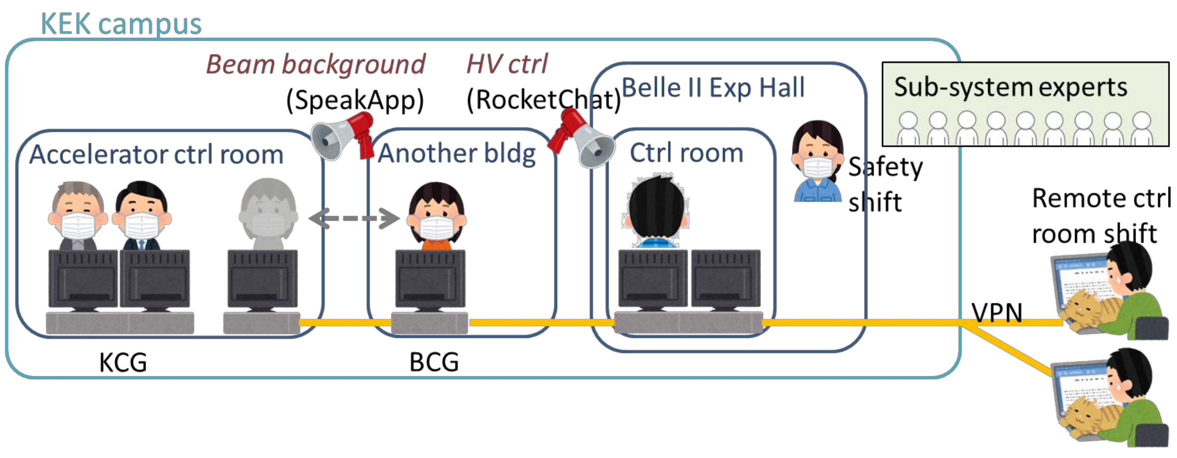




Overview Belle II Operation

K. Matsuoka





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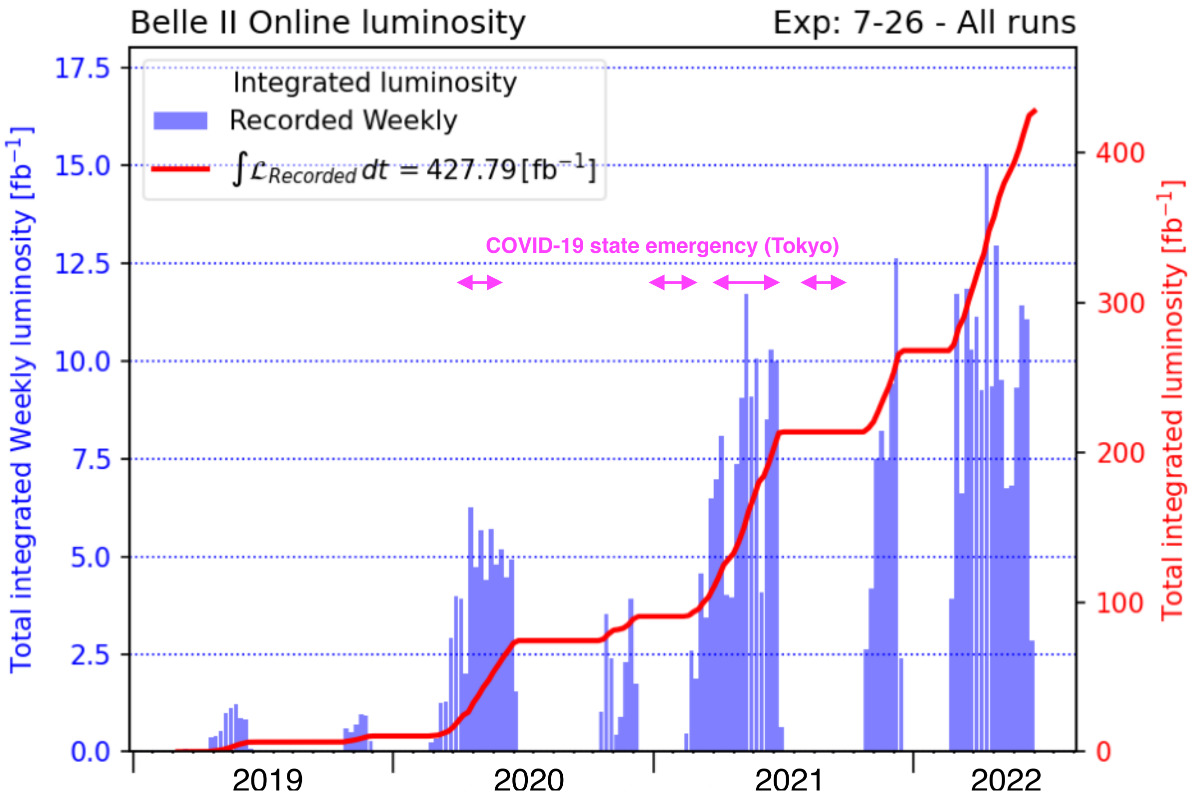

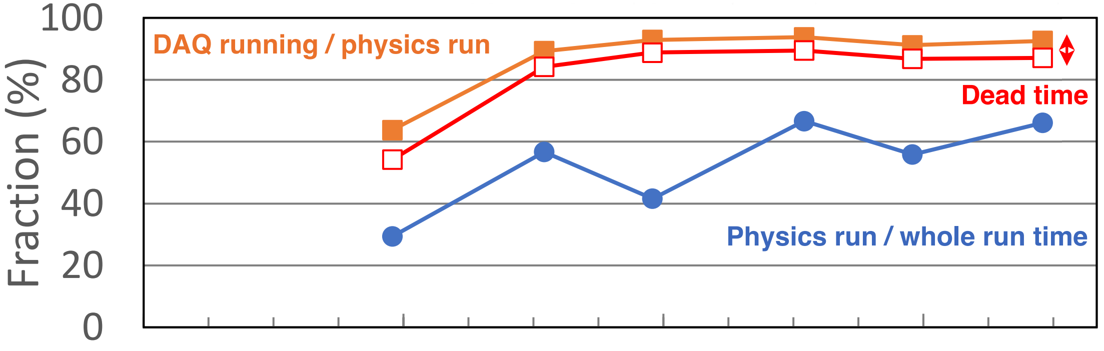

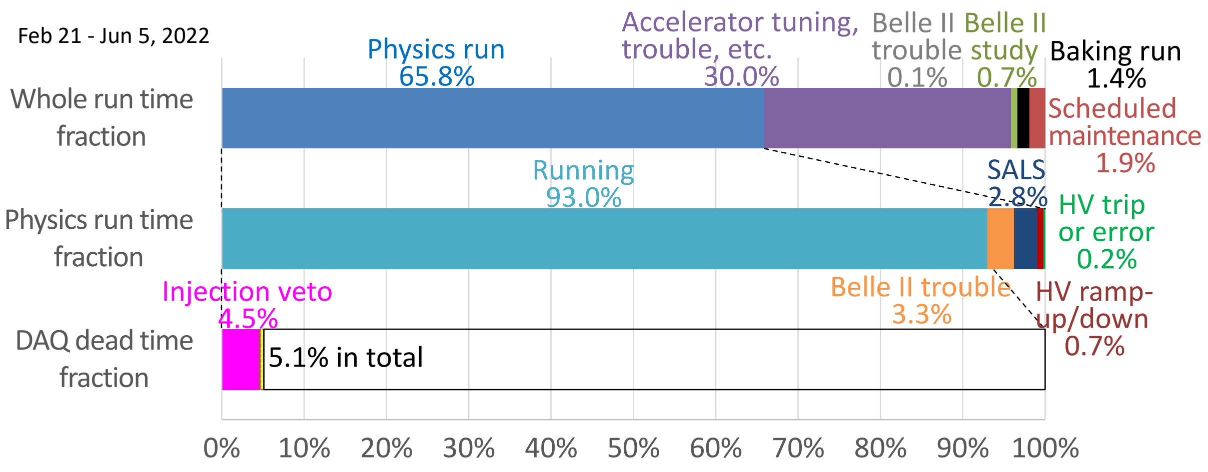

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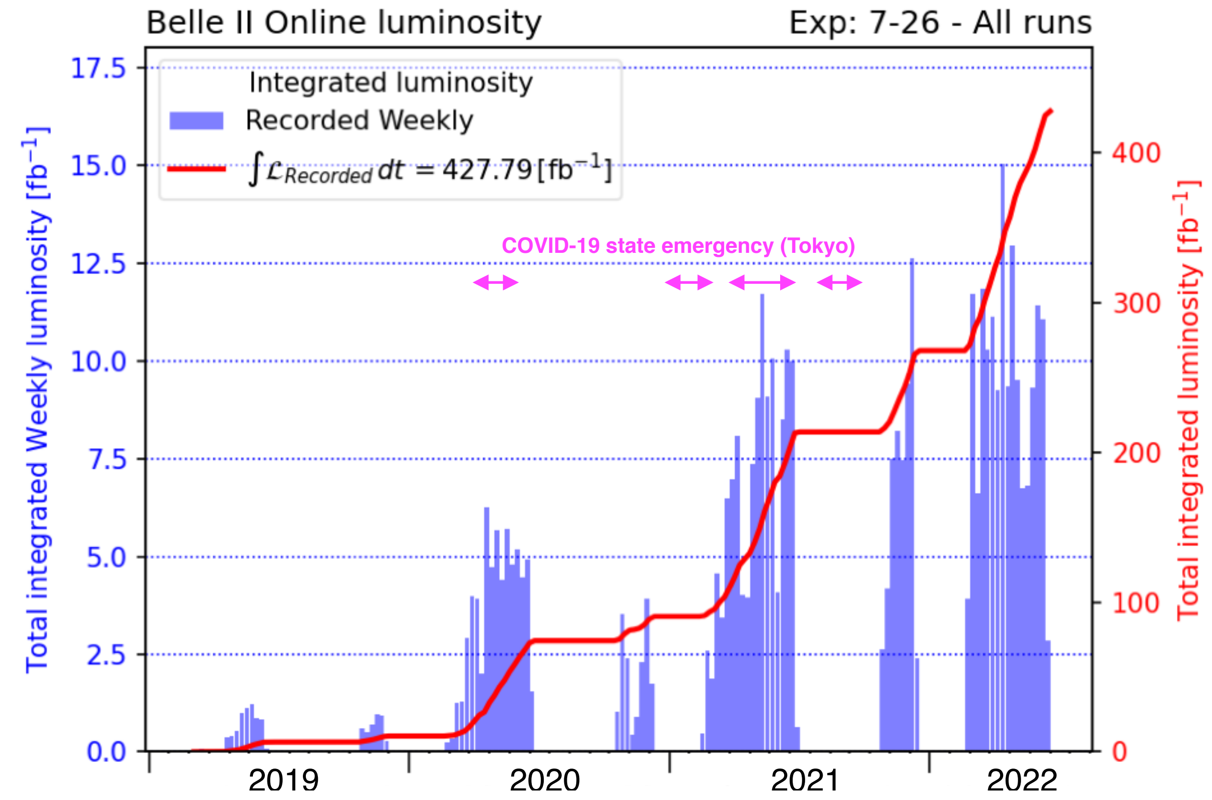

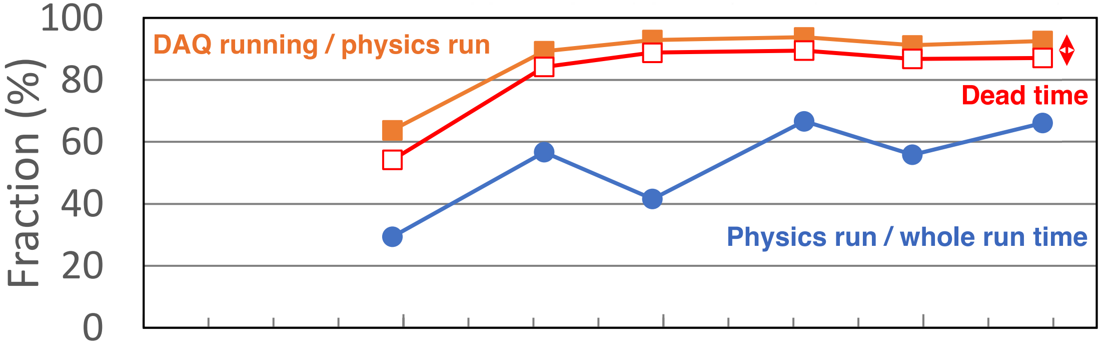

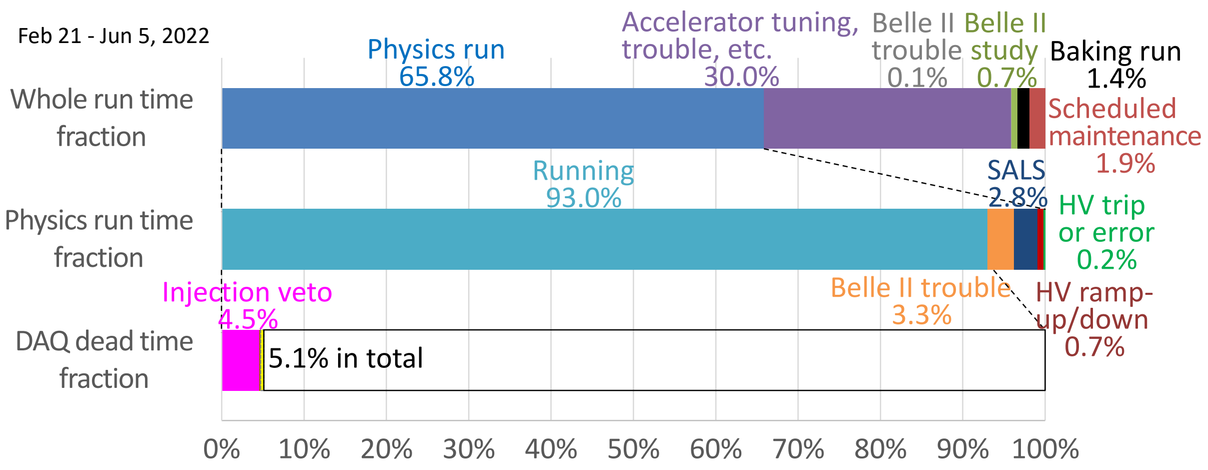

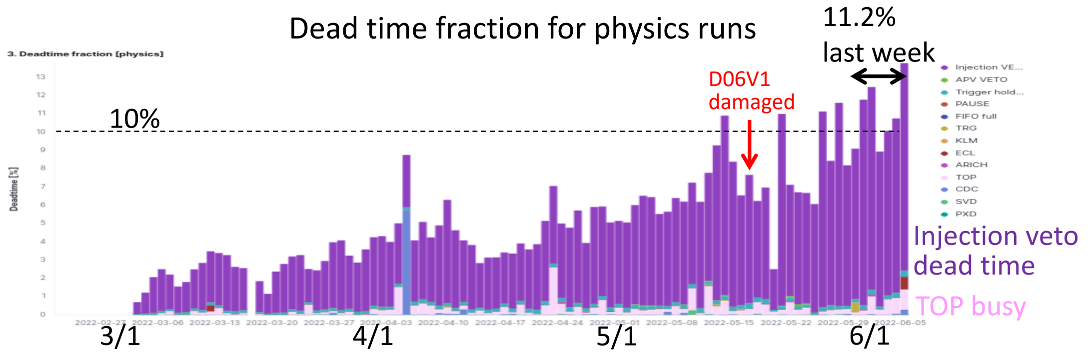

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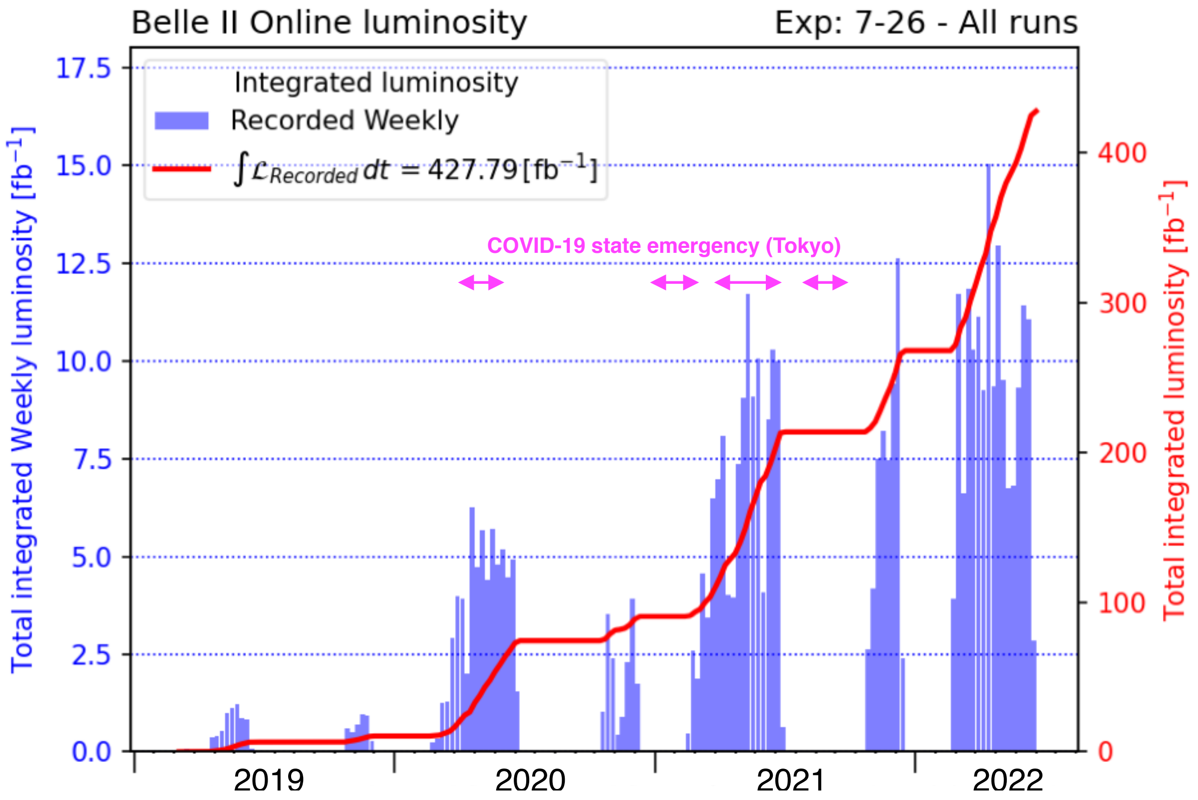
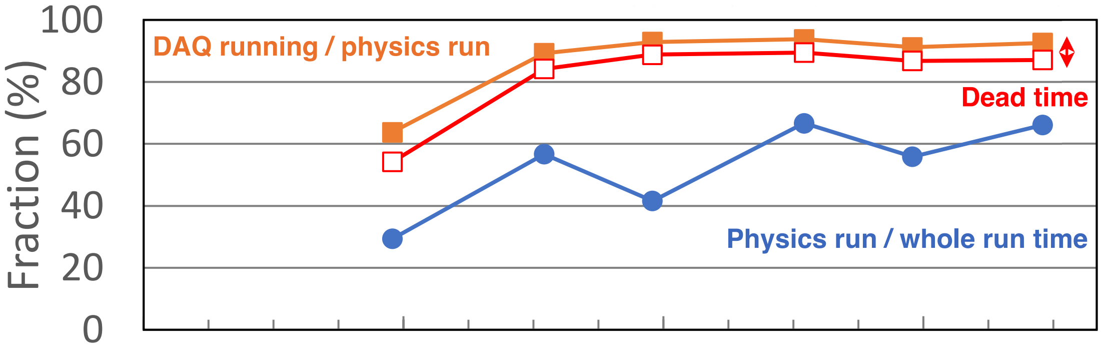
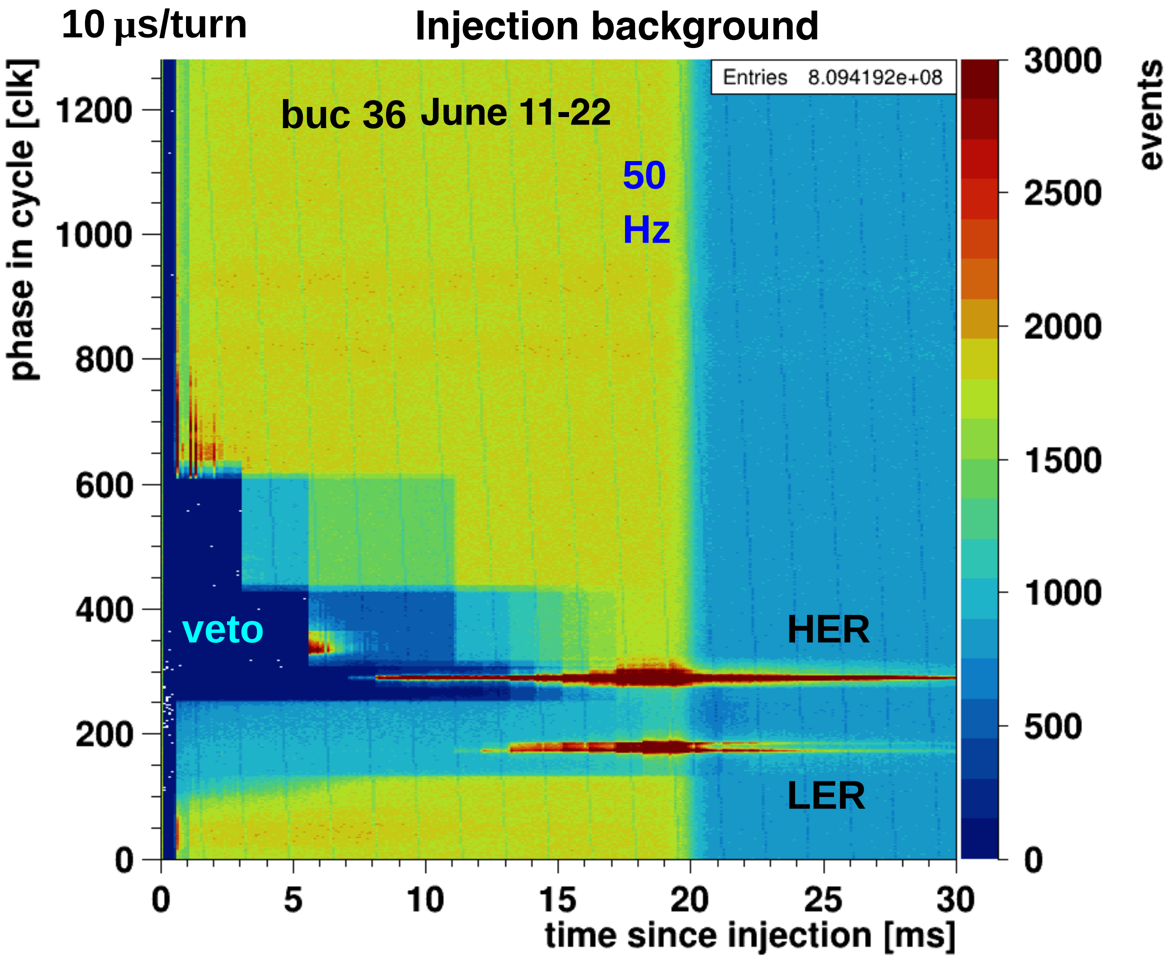






- Improved operation due to increased automatization, simplification, visualization
- However, reaching goal of 90% data taking efficiency will be hard to achieve at high injection background

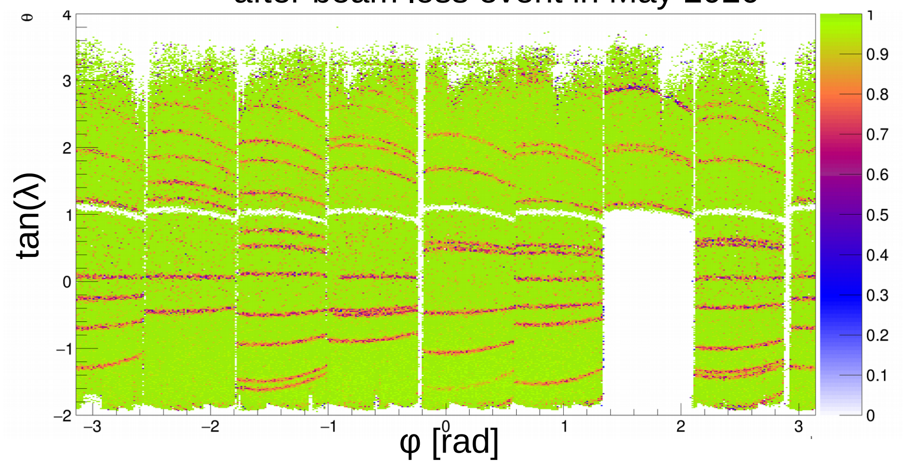
Summary of Background Situation in 2022ab

- Beam background in 2022ab: below the Belle II detector limit
  - TOP PMT rates dominated by LER single-beam BG and luminosity BG
  - Belle II did not limit the maximum beam currents for operation
- Injection BG duration got worse at higher beam currents
  - Need wider injection veto window → large DAQ deadtime: ~10%
  - Also affected recorded data: some degradation seen in CDC performance outside trigger veto
- **Major issue: Sudden Beam Loss events (SBLs)**
  - Frequency of QCS quenches x8, with severe collimator damage
  - Become more likely at higher (bunch) current? → limit the max beam currents for operation
- Investigation on SBL issue made good progress
  - Timing analysis using fast beam loss monitors shows initial beam loss location
  - International task force launched: fruitful discussion inviting experts from other collaborations
  - Several hypotheses are on the table, but conclusion not reached yet (homework for runs after LS1)
- Another major issue: stability of injection performance
  - Difficult to keep good condition for a long time → limit the max beam currents for operation
    - Many improvement works planned during LS1 (inj. efficiency, emittance, inj. kicker, etc...)

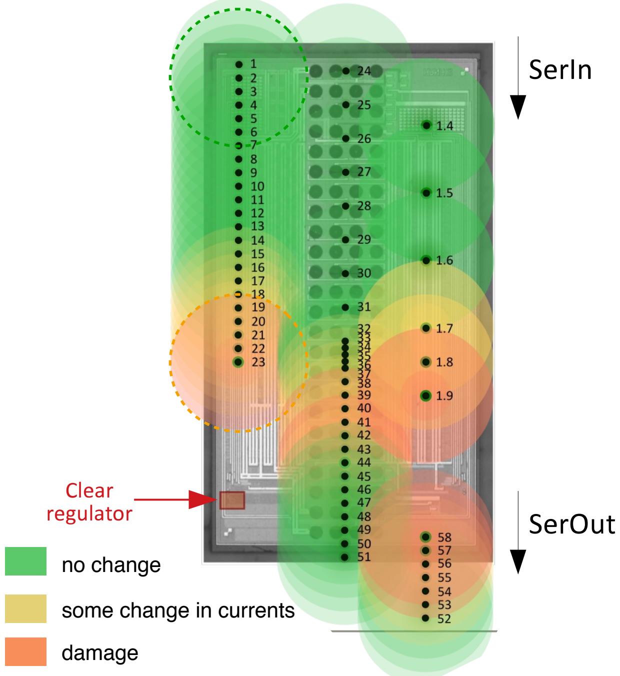
Impact of Sudden Beam Losses on PXD

- Several major beam losses starting in 2019 led to QCS quenches and damaged collimators and PXD
  - typical dose rate ~300rad in ~40µs
  - causing unstable / inefficient switcher gates
  - present overall loss in efficiency ~2.5 %
  - exact failure mechanism not yet fully understood
- Effects well reproduced in MAMI beam tests
  - simulate duration and dose rate of beam splash
  - scan switcher area with pencil beam
  - sensitive area coincides with location of regulators
- Mitigation
  - reduce time between loss detection and beam abort
  - reduce time to power-down modules from ~100ms to ~100µs
    - several improvements already implemented
    - final step (safe „short cut“ of module) still to be finalised/tested

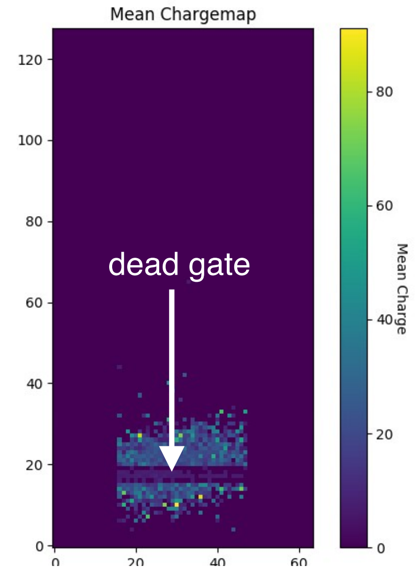
L1 efficiency map
after beam loss event in May 2020



Switcher footprint



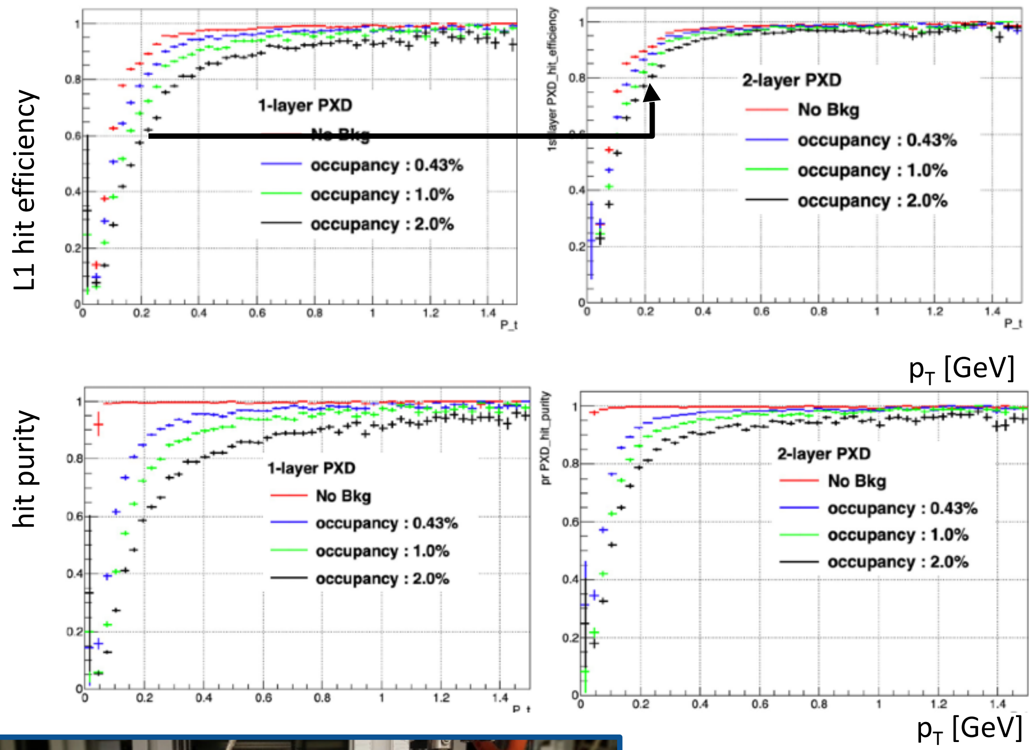
Hybrid 5 mini-matrix

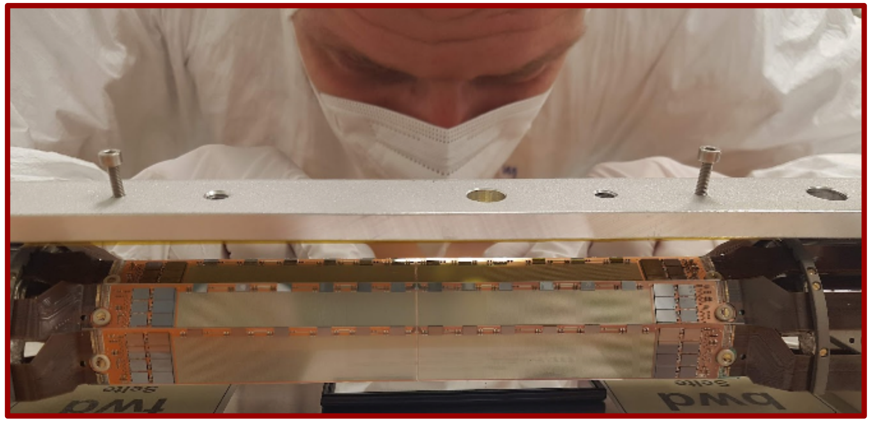


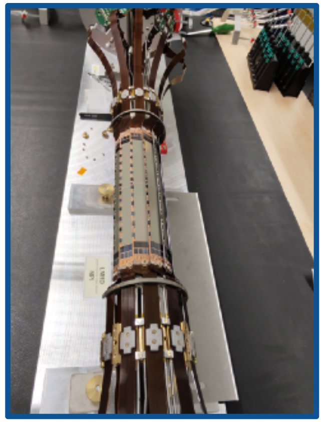
Preparing for PXD2

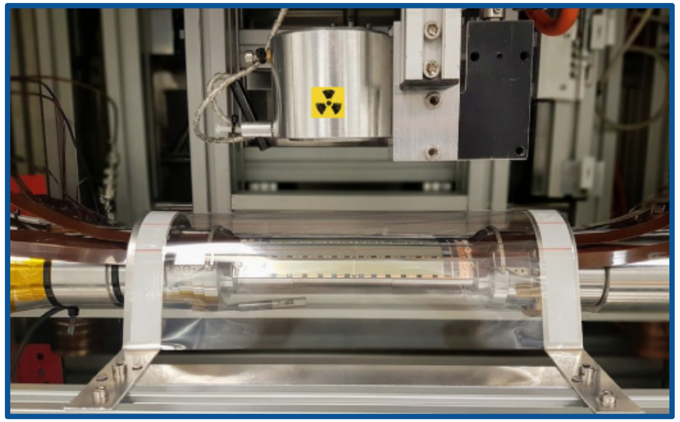
- PXD1 is incomplete
  - only 10/20 ladders (8/8 inner, ½ broken, 2/12 outer) installed
    - not enough good modules available pre-2018 (ladder glueing issue)
  - very good vertexing performance so far
    - but not guaranteed for higher future lumi ⇒ higher backgrounds
  - suffered significant damage due to uncontrolled beam losses
- Ongoing efforts to install 2nd, complete PXD2
  - same technology but improved manufacturing processes + more 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 ongoing long shutdown (LS1):

MC study of 1 layer versus 2 layer performance



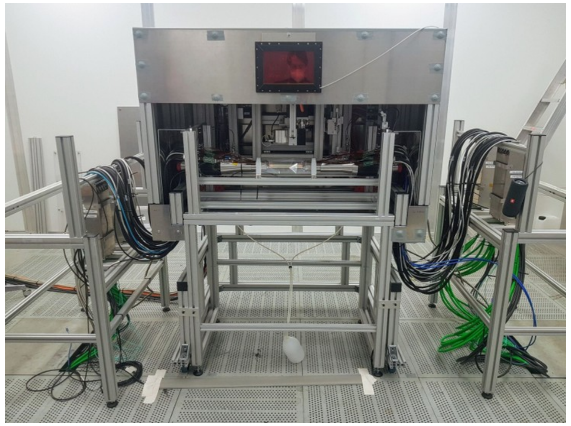


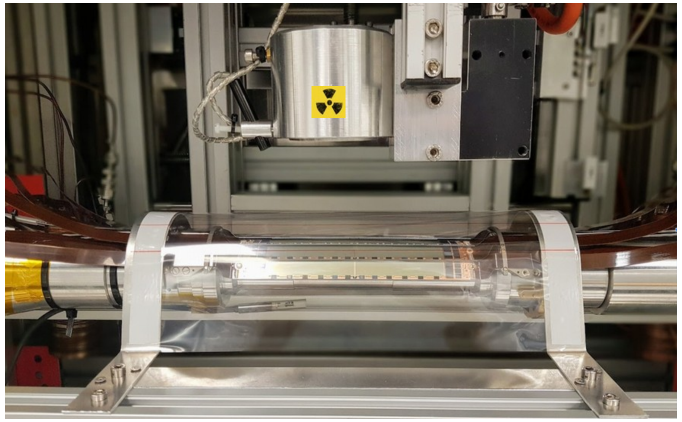


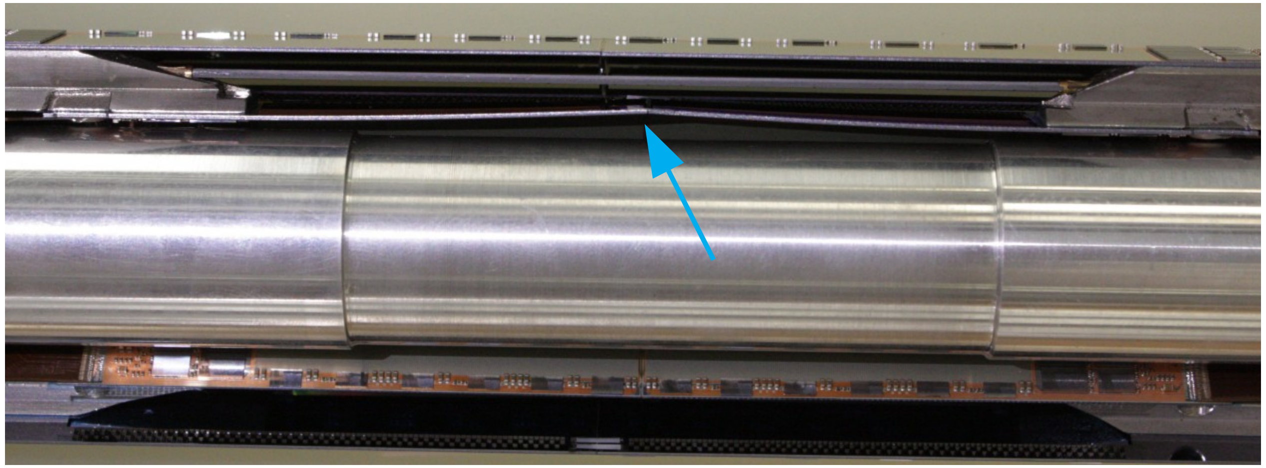


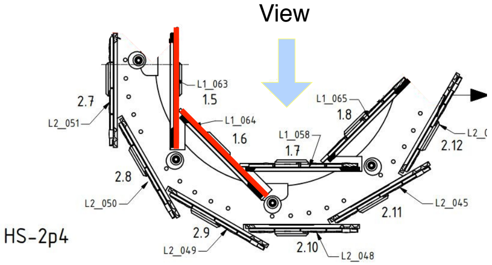
Status of PXD2 Half-Shells

- Both PXD2 half-shells assembled and safely transported from MPP to DESY in spring/summer
- Commissioning of first half-shell faced several technical difficulties mostly related to CO_2 cooling system
- When removing the commissioned half-shell from setup found two bent L1 ladders
- Major issue as two basic assumptions of the PXD mechanical design seem to be violated
  - functionality of gliding mechanisms (SCB & ladder) to compensate for thermal effects
  - durability of adhesive joint between modules
- Mitigation indispensable, in particular in view of more demanding operating conditions after LS1
  - PXD power dissipation will double
  - twice higher beam currents will lead to increased beam heating of beam pipe
- Commissioning suspended until solution found









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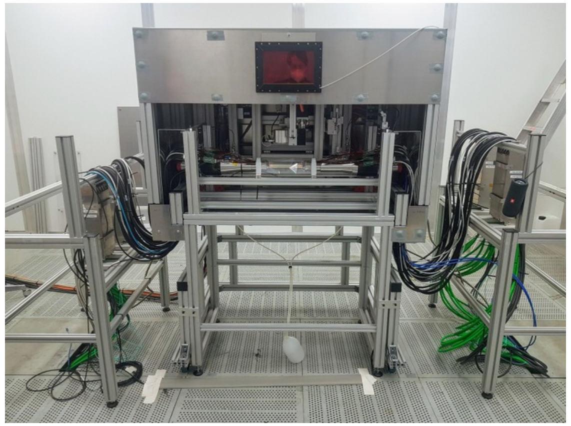
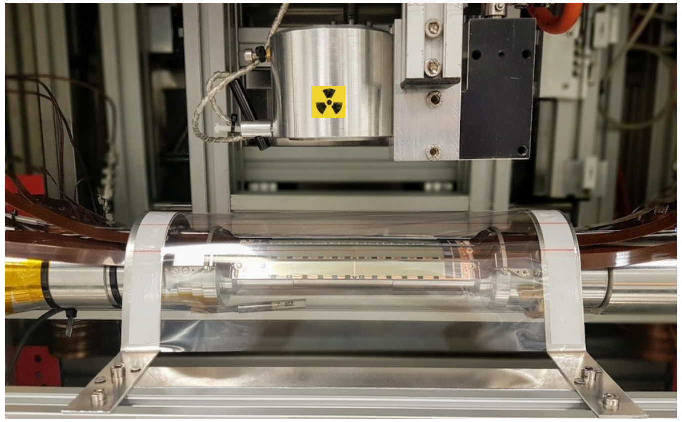
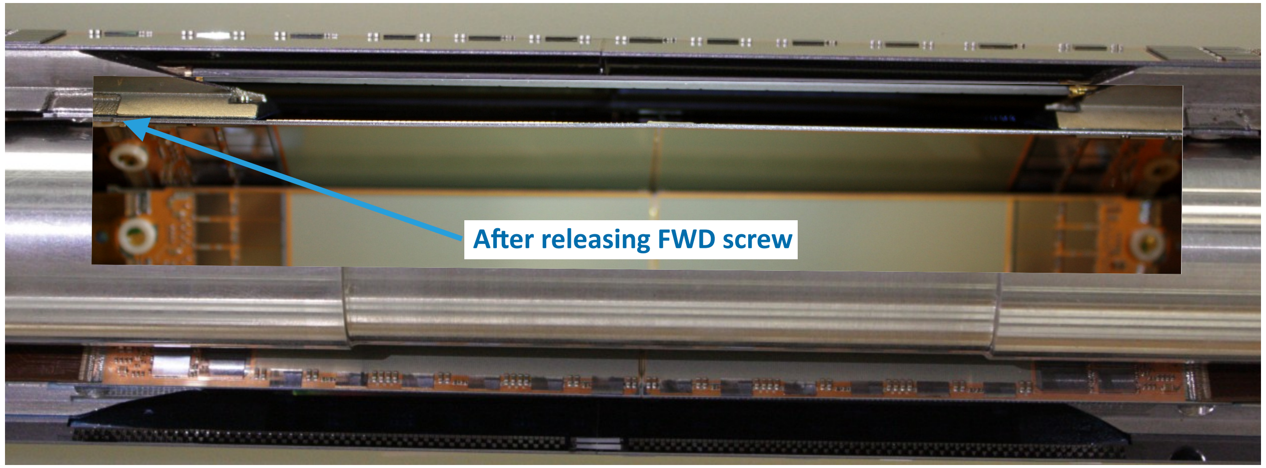
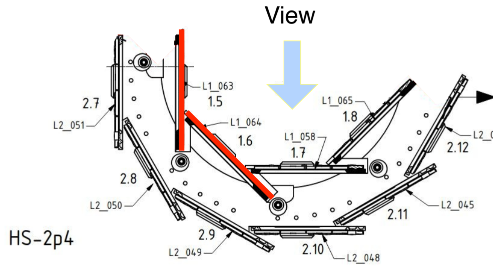
Status of PXD2 Half-Shells

- Both PXD2 half-shells assembled and safely transported from MPP to DESY in spring/summer
- Commissioning of first half-shell faced several technical difficulties mostly related to CO_2 cooling system
- When removing the commissioned half-shell from setup found two bent L1 ladders
- Major issue as two basic assumptions of the PXD mechanical design seem to be violated
  - functionality of gliding mechanisms (SCB & ladder) to compensate for thermal effects
  - durability of adhesive joint between modules
- Mitigation indispensable, in particular in view of more demanding operating conditions after LS1
  - PXD power dissipation will double
  - twice higher beam currents will lead to increased beam heating of beam pipe
- Commissioning suspended until solution found







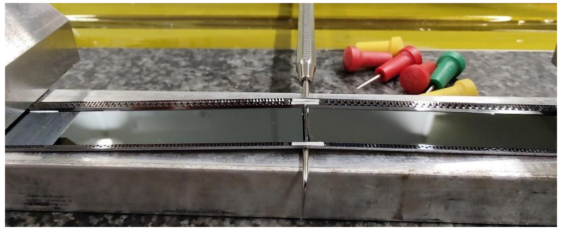


Summary of Current Understanding

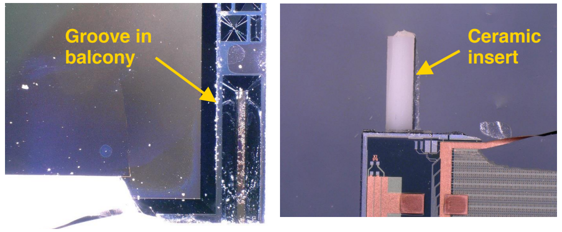
- Broken L1 ladders during commissioning of HS2p4 appear to be the result of a combination of several factors
  1. Adhesive joint can open under permanent mechanical stress and at **elevated temperatures** (> 40°C)
     - such temperatures may well have been reached in the setup in August
  2. **Too high torque** will prevent ladder from gliding under compression (likely in PXD1 too)
     - explore minimum torque which simultaneously meets mechanical and thermal requirements
  3. SCB gliding with respect to beampipe did not work as expected in DESY setup
     - possible cause could be maximum **asymmetric operation** of the half-shell due to lack of power supplies, which led to SCB tilting
  4. As a result of MARCO problems, the operating conditions in August most likely resulted in **thermal expansion and deformation of the dummy beampipe**, which has significantly contributed to the issue

  - Such conditions have to be avoided both in the DESY setup and in Belle II
- Additional studies have been performed to confirm this picture and to derive more quantitative guidelines on what needs to be changed for PXD2

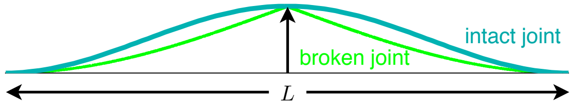
Mechanical stress test



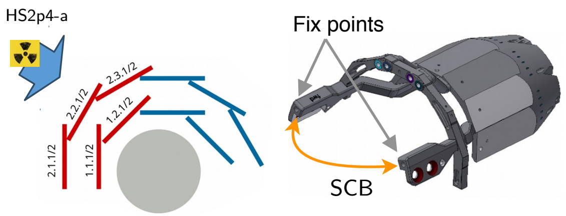
Broken adhesive joint with glue remnants



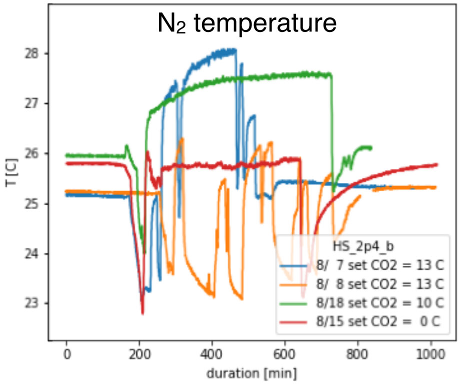
Result of non-functional ladder gliding



Asymmetric powering

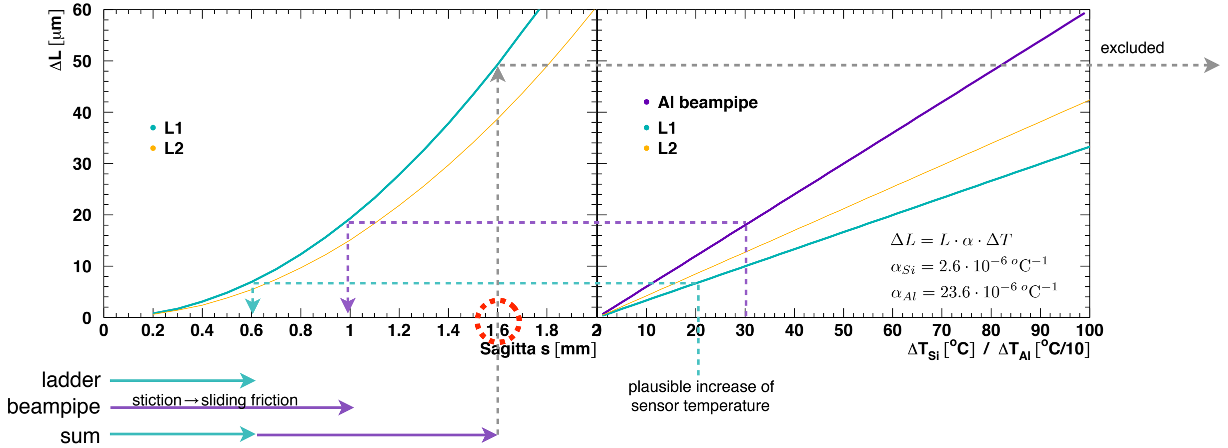


Non-standard operating conditions

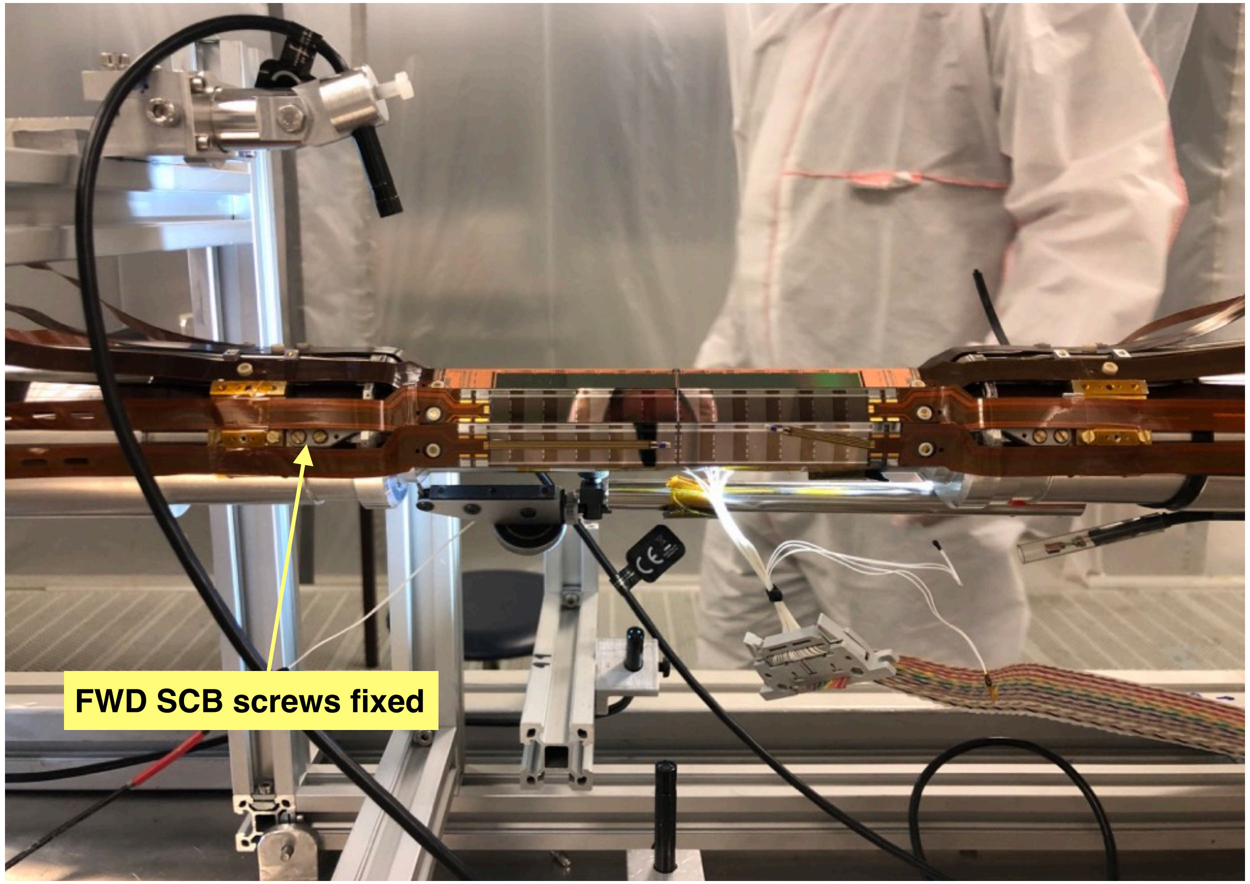


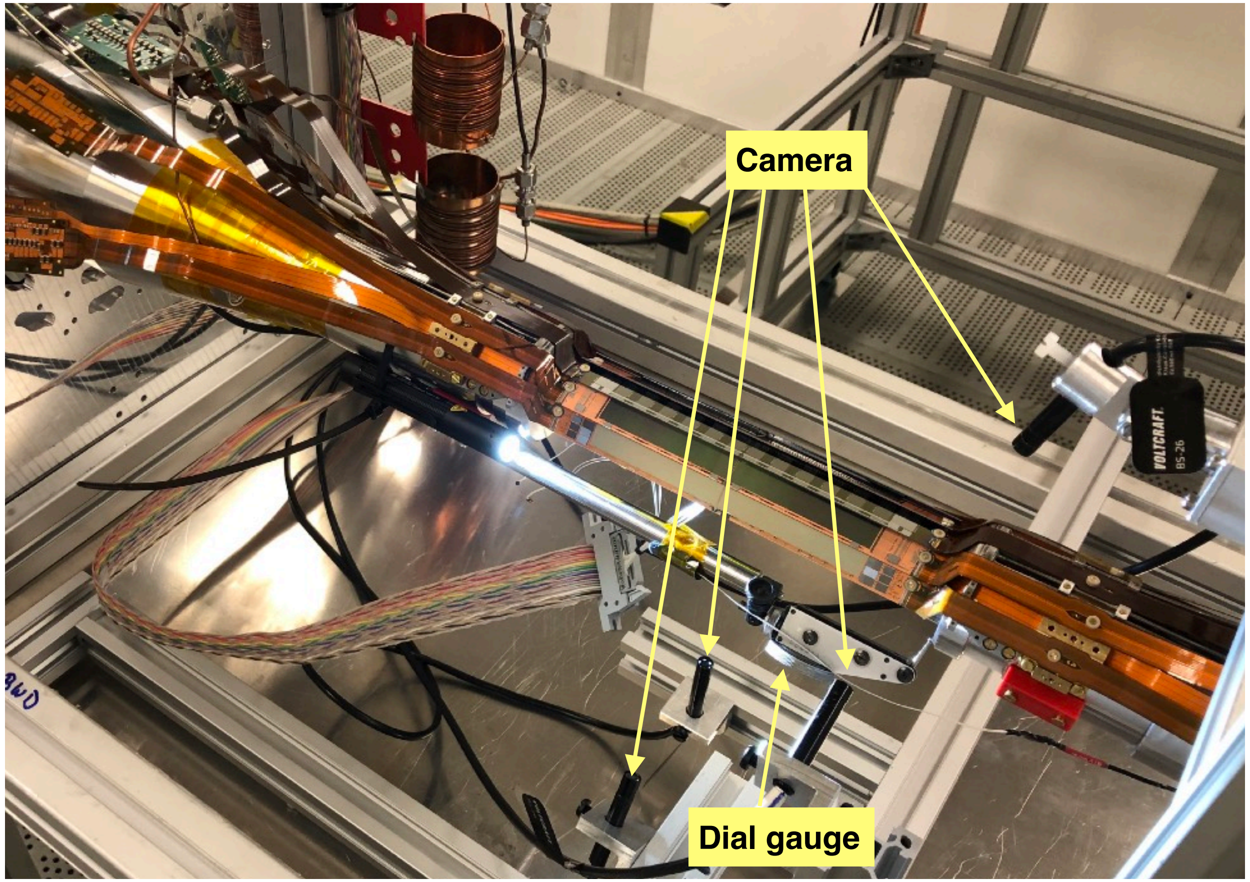
$\Delta T \sim$ 2-3°C for $T_{CO2} \geq 10$°C

Sagitta vs length change   Temperature vs expansion

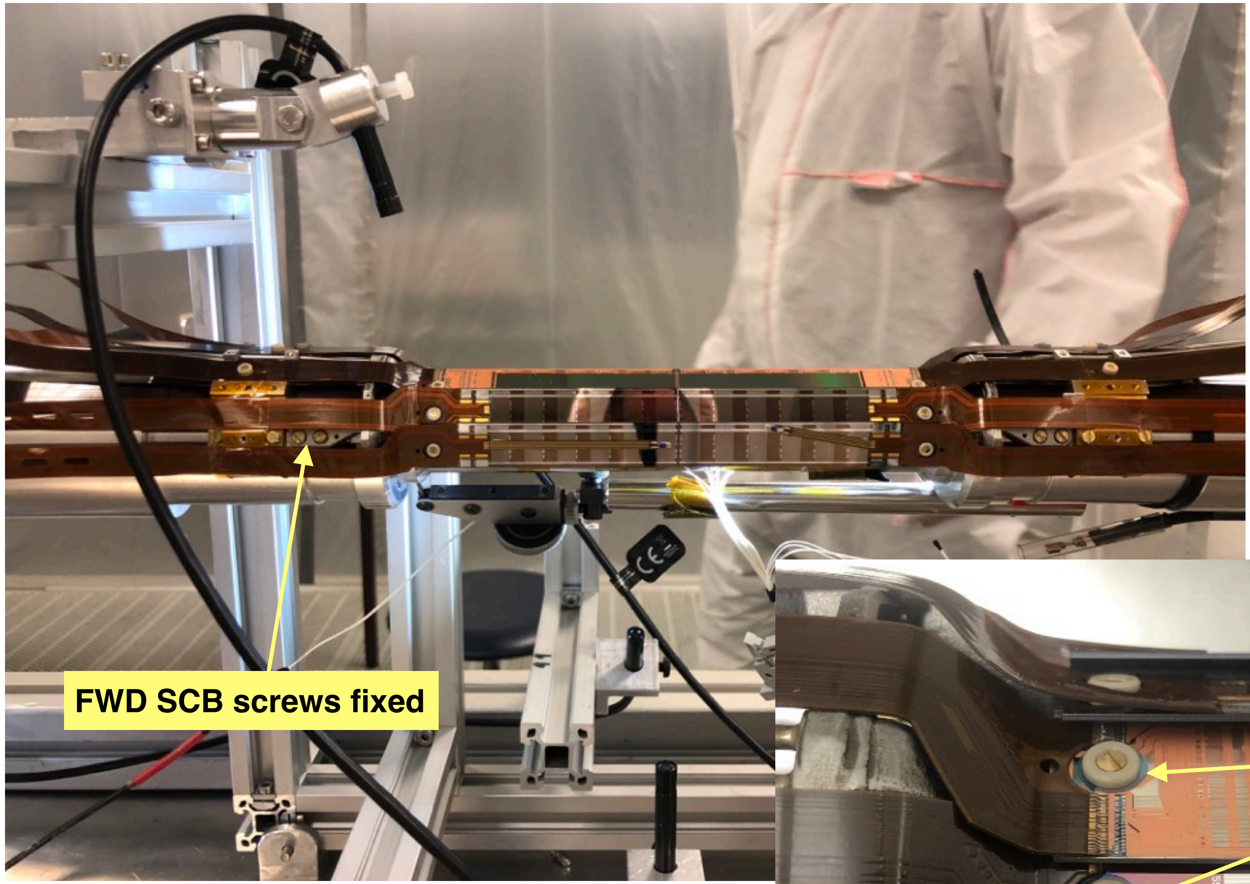


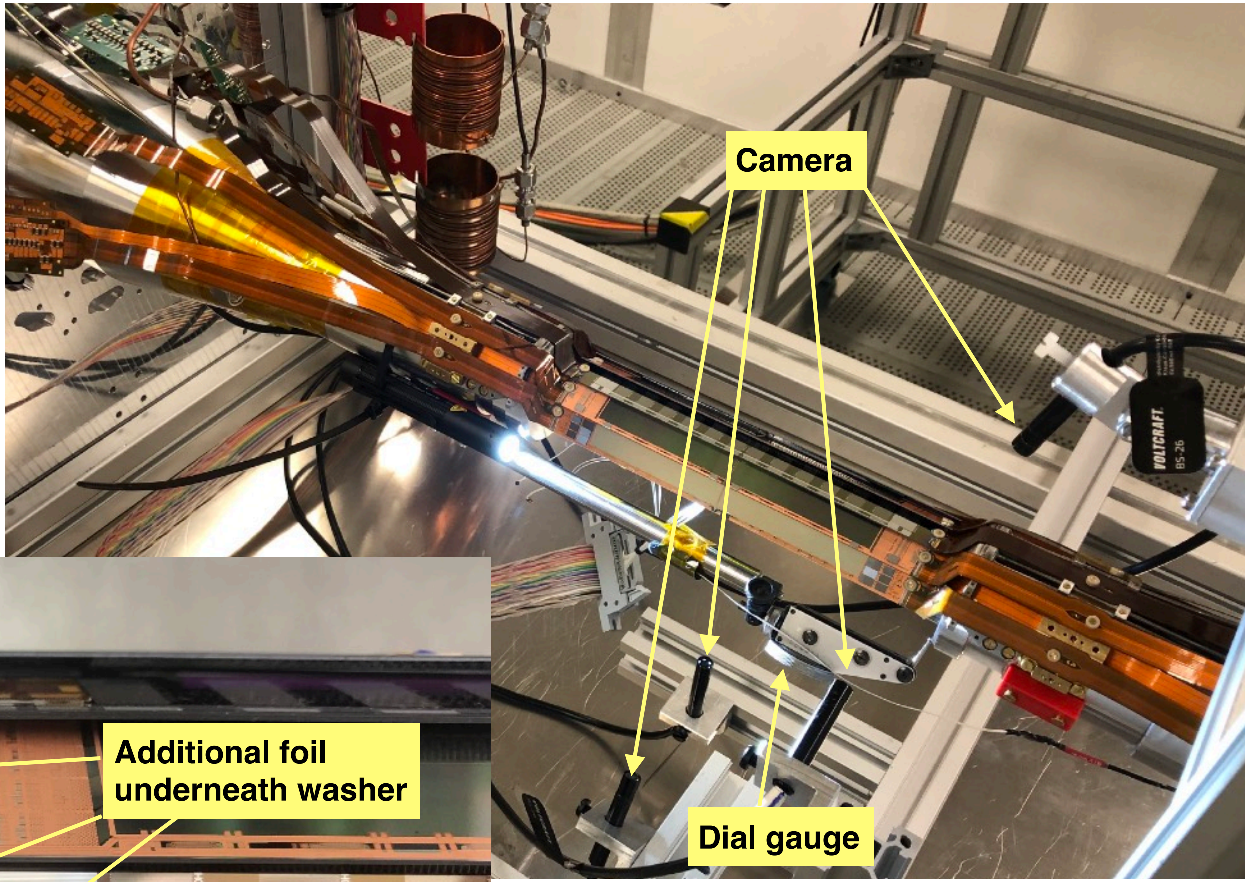
Ladder Gliding Test

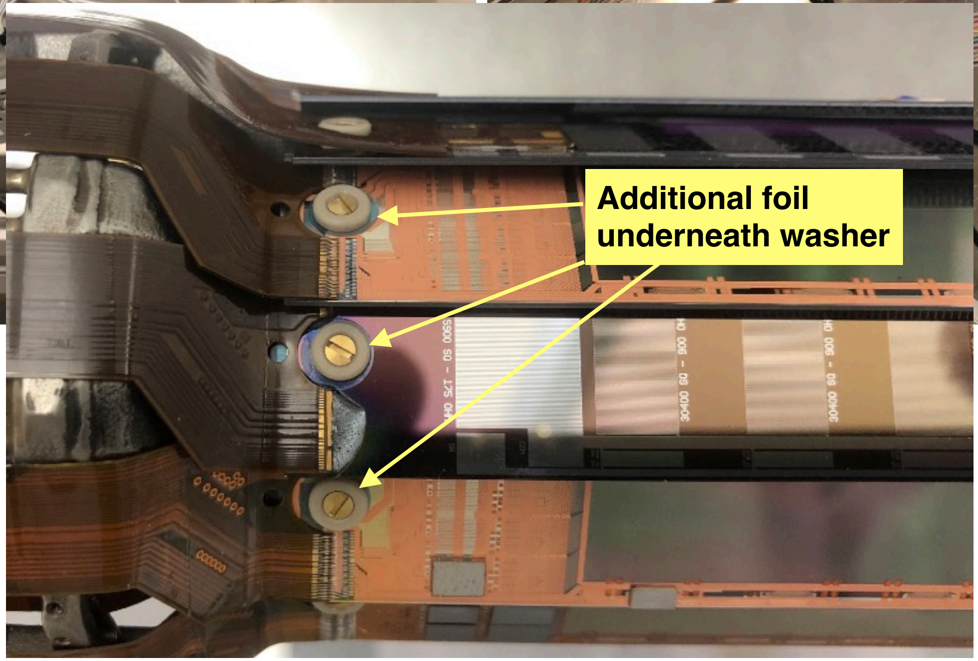




Ladder Gliding Test



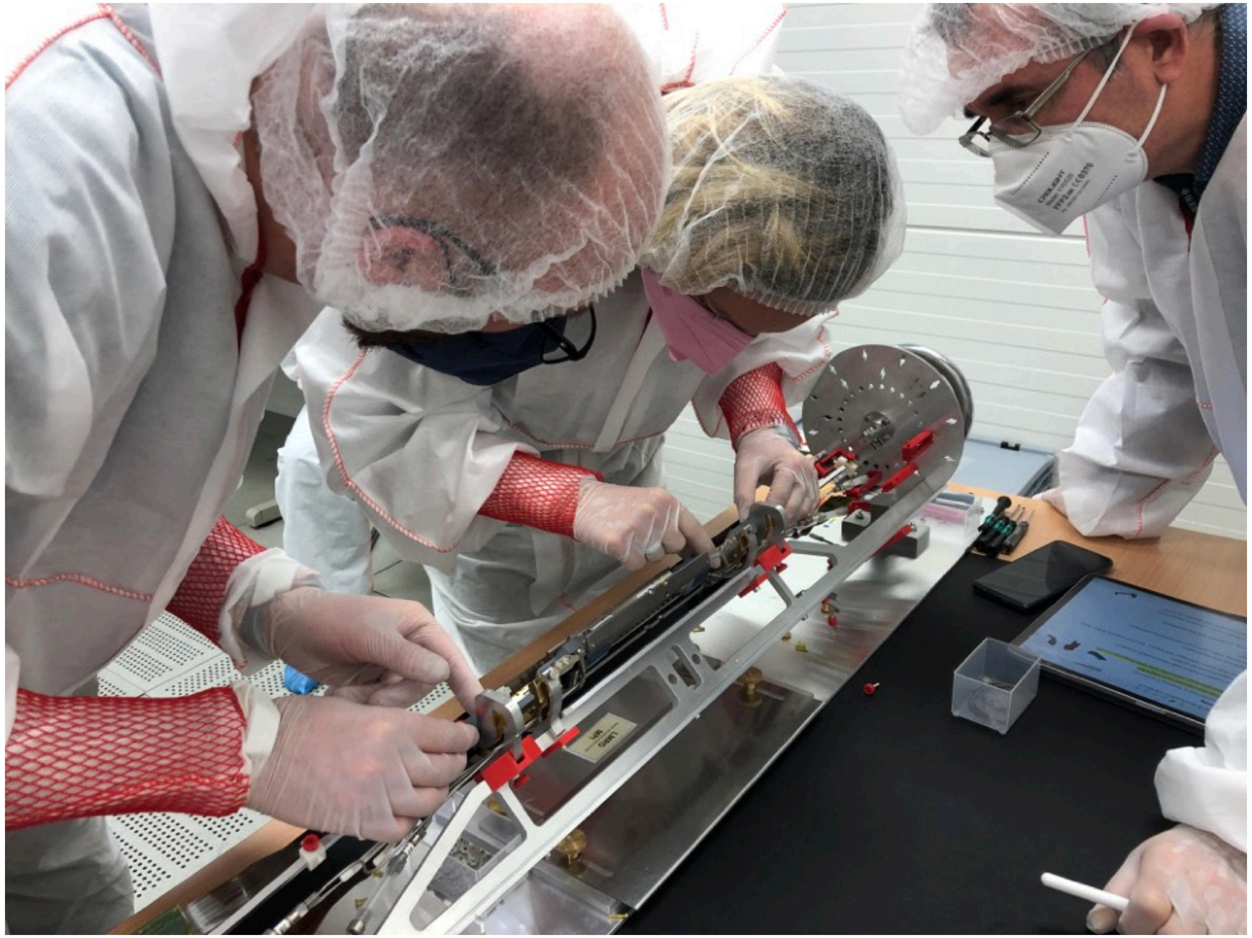




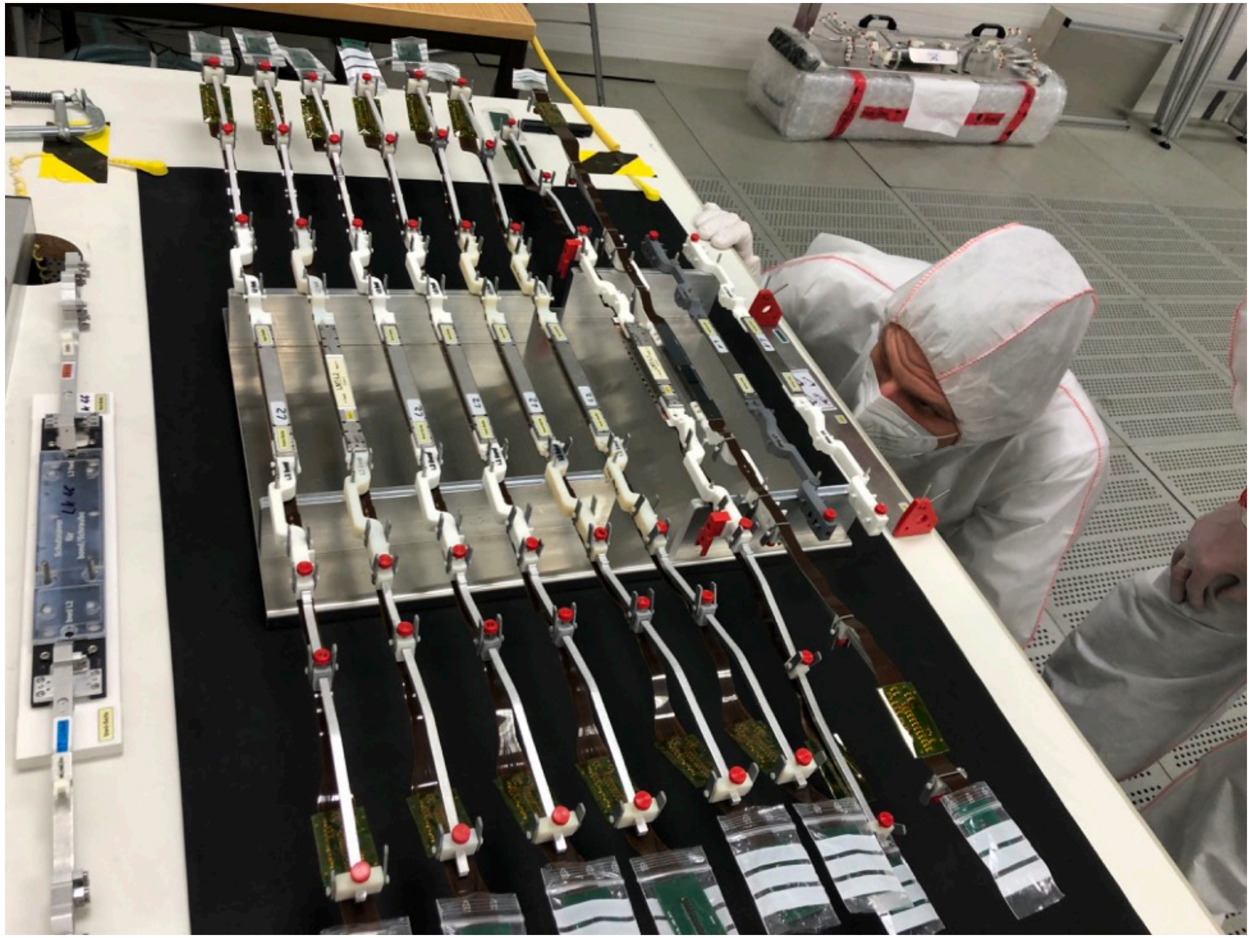
Dis- and Re-Assembly of broken Half-Shell

Operators: Enrico and Carina

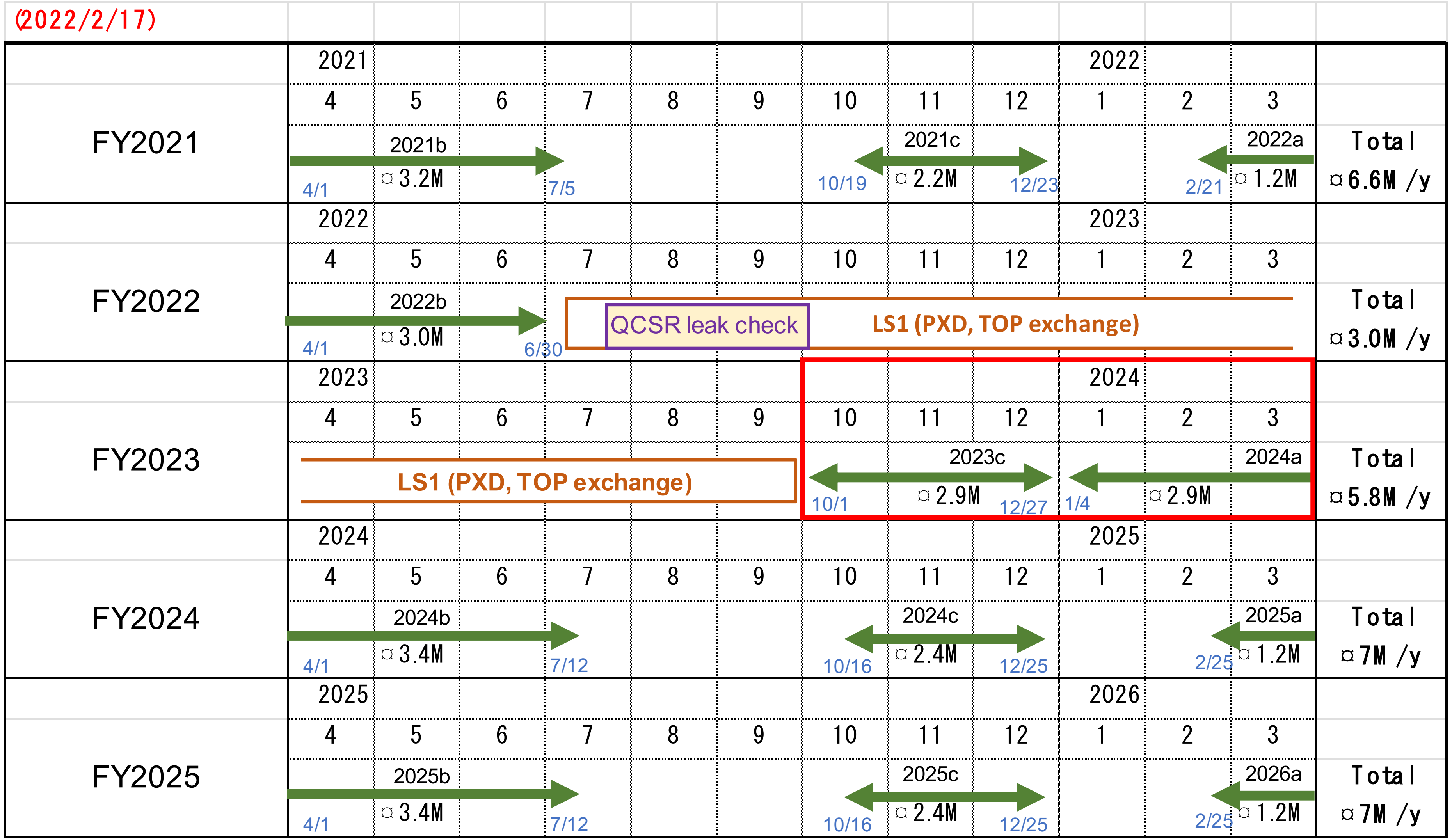
Checklist and protocol: Hans-Günther



Inspection of dismantled ladders during interim storage



SuperKEKB Mid-Term Run Plan



Under discussion

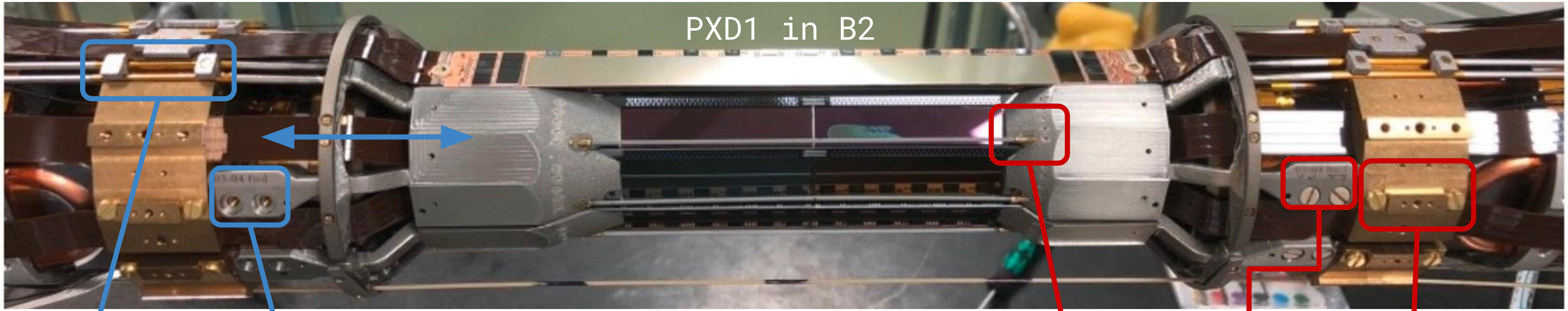
Conclusion

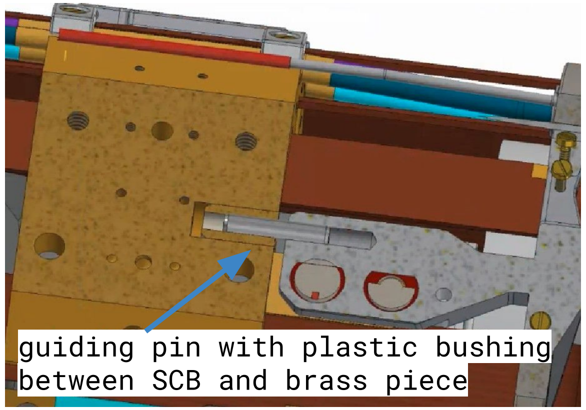
- PXD status
  - very good performance of PXD1 and stable operation throughout 2019-2022
  - setbacks from beam loss events with high instantaneous dose rate
    - damages to detector
    - so far have remained out of full control and biggest risk for detector
  - improved / automated operation, monitoring 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

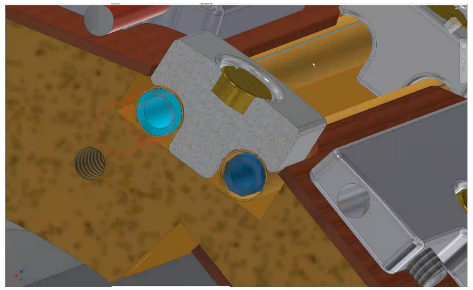
- PXD future
  - great efforts from various institutions to prepare new and complete PXD2
  - pre-commissioning of full detector ongoing
  - unexpected mechanical problems required in-depth investigations
    - PXD2 completion now on critical path for LS1
    - making all efforts to minimize the overall delay
  - to retain PXD performance in future, rely on improvements to SuperKEKB also planned for LS1

Backup

SCB Gliding Mechanism







- sagitta of bent L1a as well as all L2 modules being straight hints at multiple cumulative failures, any issue w/ SCB gliding not sufficient (aka also need issue w/ foil, ladder screw torque, HS operation mode, glue, …)
- details not understood yet → studies at MPP and DESY

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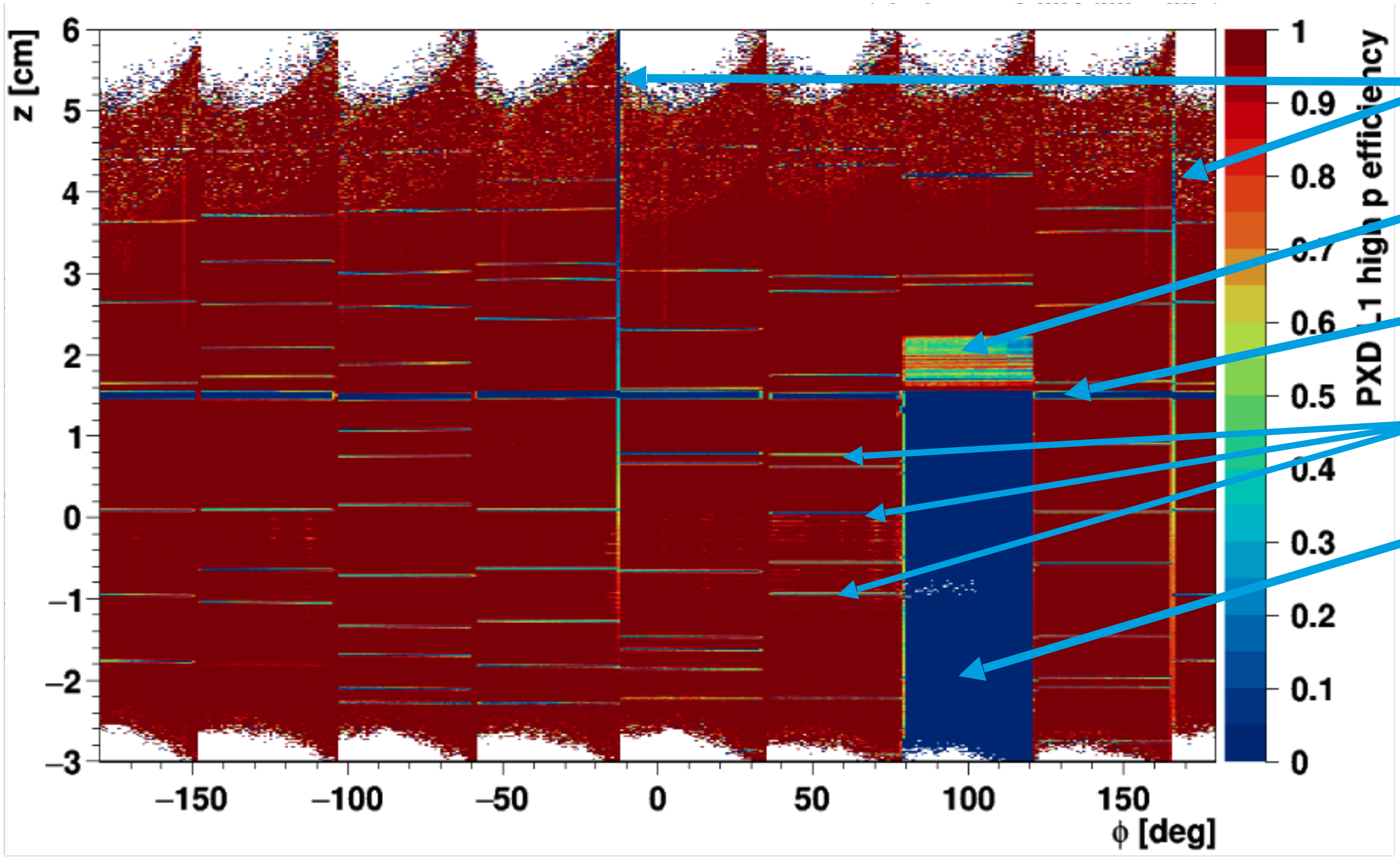
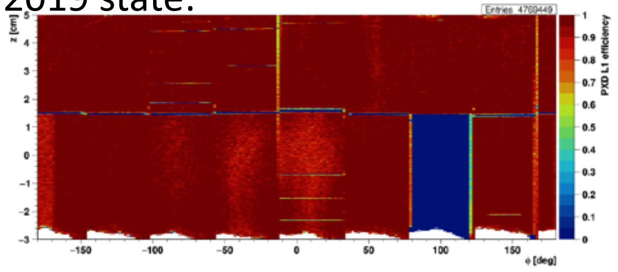
PXD L1 Efficiency Map



- 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:

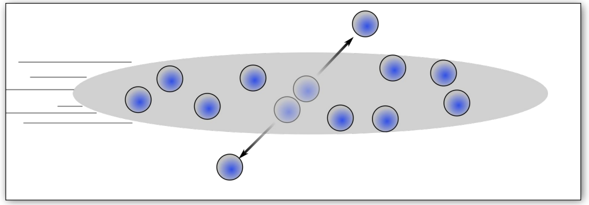


8 ladders

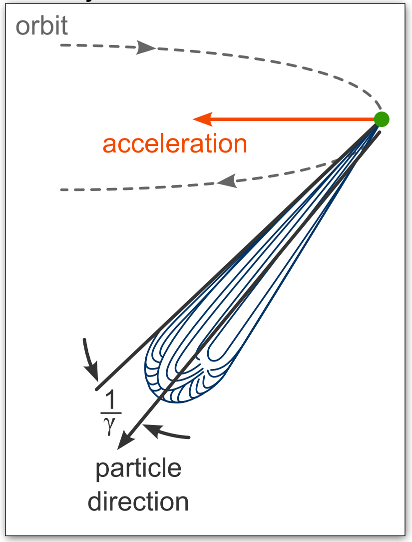
Main Background Sources at SuperKEKB

- Single beam (LER and HER)
  - Touschek: single scattering within same bunch → particles get lost when they drop out of momentum acceptance of the machine
    - rate $\propto I_{\pm}^2 / (n_b \sigma_x \sigma_y \sigma_z E_{\pm}^3) \propto 1/\tau_{\text{beam}}$ ⇒ reduced energy asymmetry
    - nano beam ⇒ increased background
  - beam gas: rate $\propto I_{\pm}\, p\, Z_{eff}^2$ (approx. $\propto I_{\pm}^2$)
    - elastic Coulomb scattering
    - bremsstrahlung
  - synchrotron radiation: $P_\gamma \propto E_{\pm}^4 I_{\pm} \rho^{-1}$
  - injection background (2 x 25 Hz)
- Beam-beam (irreducible): rate $\propto L$
  - radiative Bhabha: $e^+e^- \to e^+e^- (\gamma)$
    - (a) emitted photon (neutrons), (b) spent e+/e-
  - 2-photon process: $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-e^+e^-$

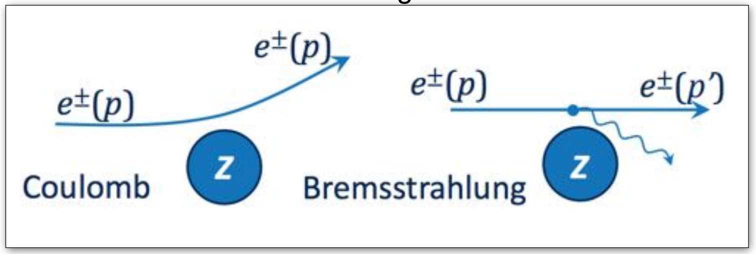
Touschek



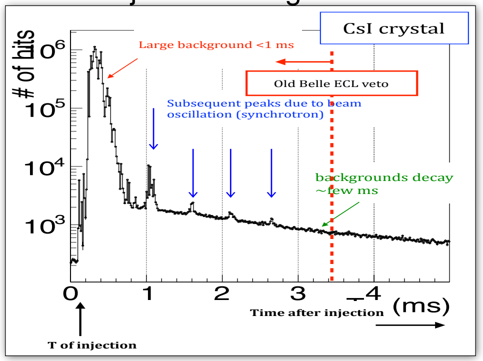
Synchrotron radiation



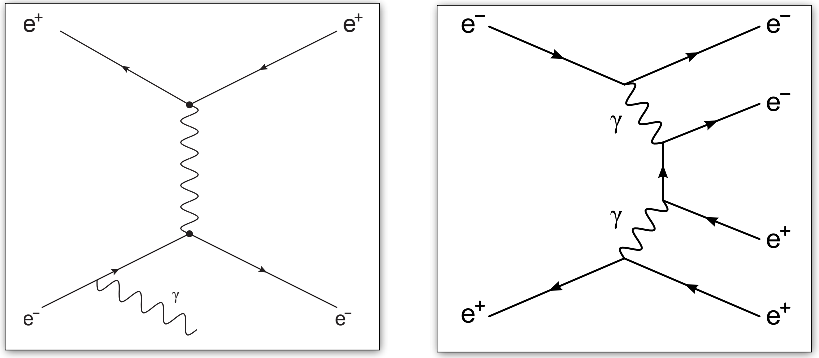
Beam gas



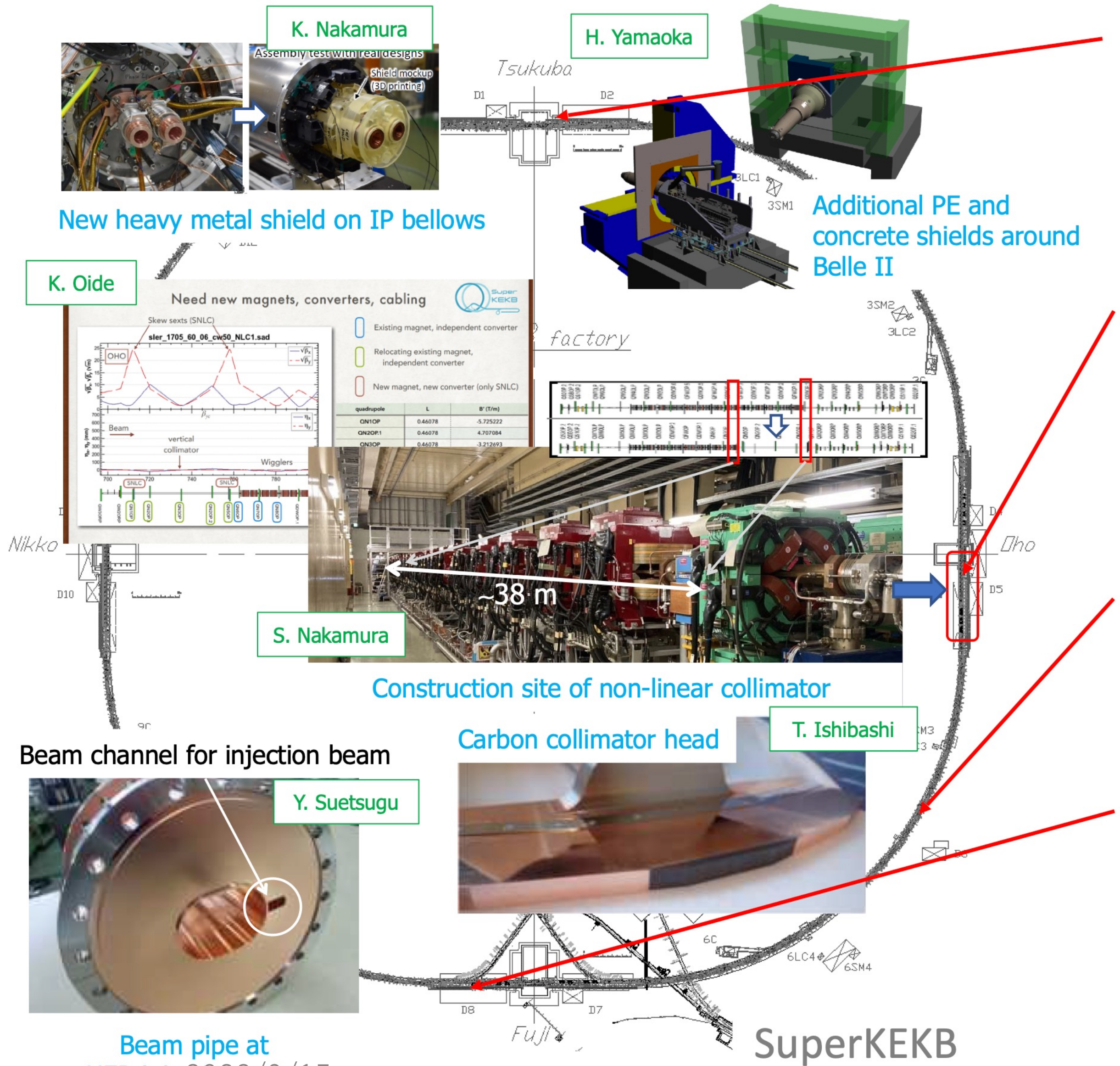
Injection background



Beam beam



SuperKEKB Activities during LS1

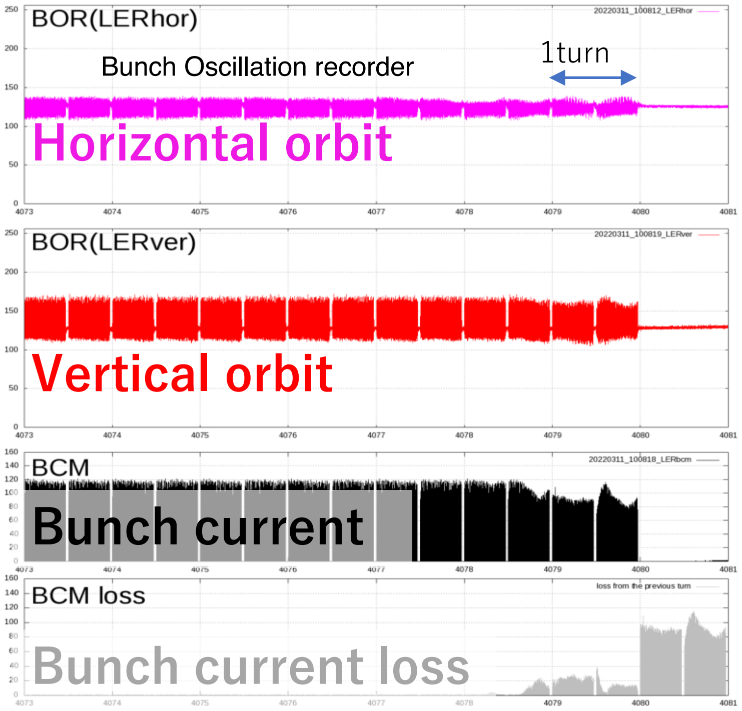


- IR radiation shield modification
  - For BG reduction
    - New heavy metal shields around IP bellows
    - Additional concrete & polyethylene shields around Belle II
    - Material change from W to SUS of QCS cryostat front plate
- Nonlinear collimator (LER)
  - For impedance and BG reduction
    - New collimation scheme less likely to cause TMCI
    - Removal of 50 wiggler magnets
    - Installation of 2 skew sextupole and 5 quadrupole magnets
    - Installation of new vertical collimator with wider aperture
- Robust collimator head (LER)
  - As countermeasure against kicker-pulser misfiring and resulting destruction of collimator
    - Replacement with carbon head of horizontal collimator D06H3
- New beam pipes with wider aperture at HER injection point
  - For improvement of injection efficiency
    - New beam pipes with wider aperture
    - New BPM for precise measurement of injected beam.

2022/9/15 4

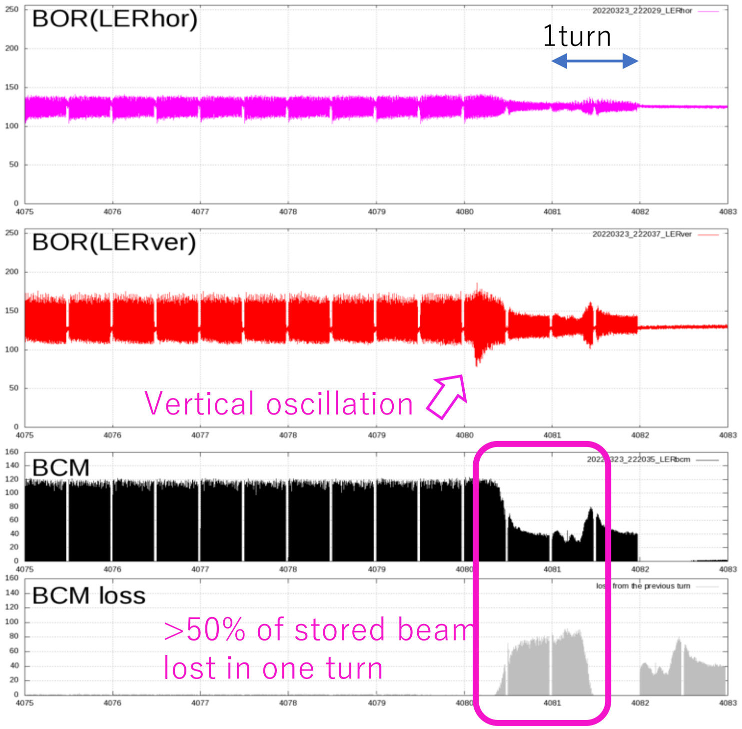
Major Threat: Sudden Beam Loss (SBL) Events

2022-03-11 10:08



- **QCS quench (#1 in 2022ab)**
- HUGE IR loss (544mRad)
- **Severe D2V1 damage**
  (pressure burst >10^{-5} Pa)

2022-03-23 22:20



- IR loss was small (12mRad)
- This is not QCS quench, but..
- **Severe D6V1 damage**
  (pressure burst >10^{-4} Pa !)

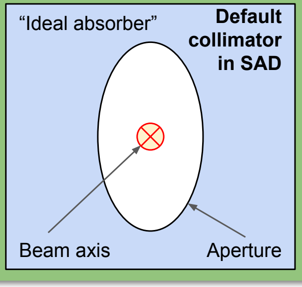
- Possible causes under study
  - too fast for usual beam instability
  - dipole oscillation
  - energy loss
  - beam size blowup
  - dust particles unlikely
    - can't explain vertical loss
  - fireballs
    - interesting idea, but so far no evidence of electric discharge around collimators
- Cause of sudden beam loss events not yet really understood

Background Understanding & Projections

Data/MC ~ 10^{-3}–10^{3} → **Data/MC ~ 10^{-1}–10^{1}** → **Data/MC ~ 1** [LER single beam ~3-4]

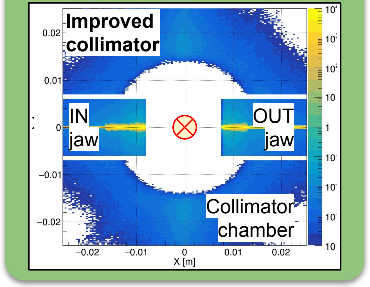
Phase 1 and Phase 2 experiences 2016-2018

IR beam pipe geometry improvement
+
Measured background decomposition methodology



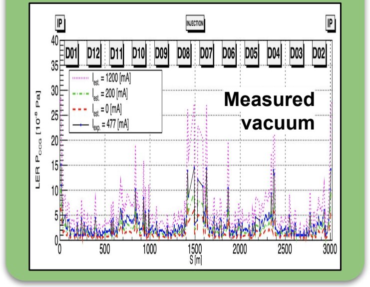
Early Phase 3 experiences 2019–2022

IR beam pipe geometry improvement
+
Realistic collimator profile
+
Particle interaction with collimator materials



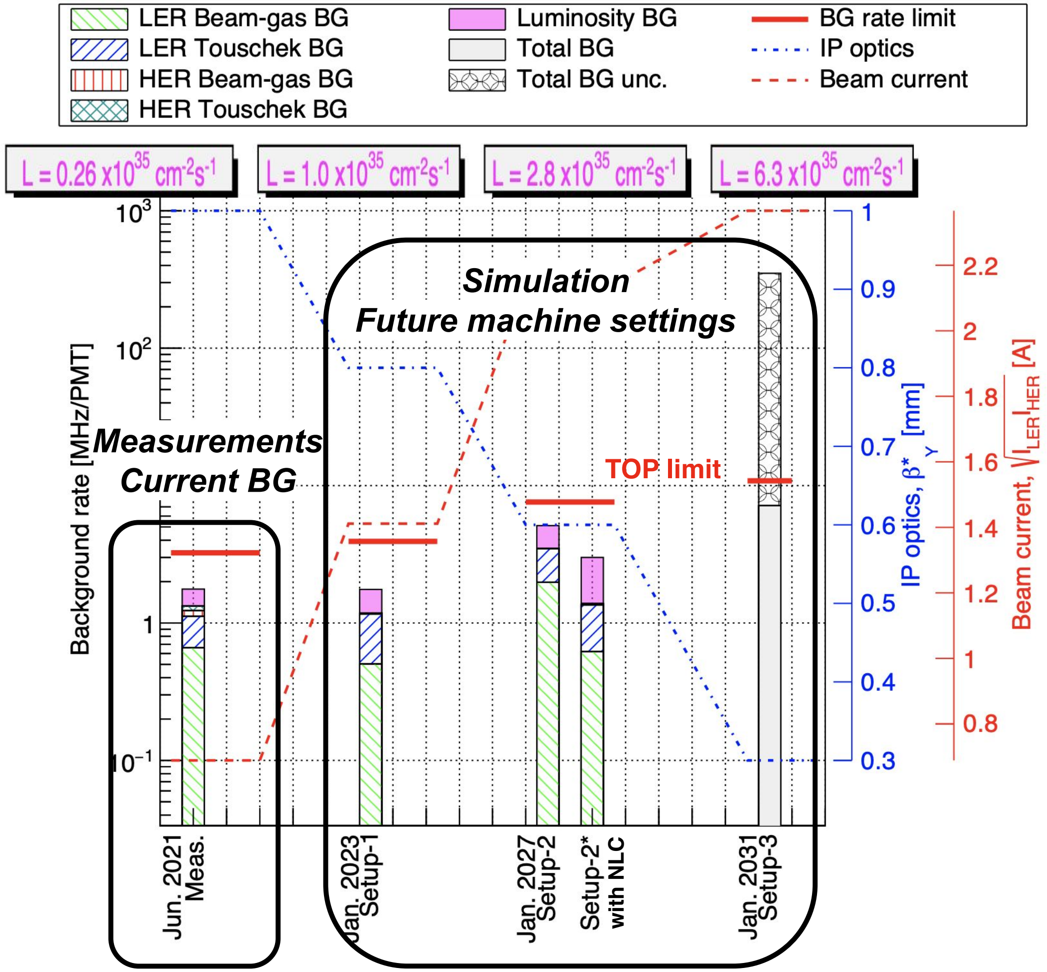
Early Phase 3 experiences 2019–2022

Measured beam pipe gas pressure
+
Accurate translation of beam losses from `SAD` to `Geant4`
+
Improved `Geant4` model



- Realistic background simulations indispensable to
  - study impact of beam optics parameters on Belle II backgrounds
  - develop new collimators
  - mitigate backgrounds through machine or detector adjustments and upgrades
- Significant improvement in understanding over the past years
  - thanks to dedicated background studies and huge simulation efforts
- Used to predict background evolution at future machine settings
  - backgrounds high but acceptable (CDC tbc) until the luminosity of about 2.8x10^{35} cm^{-2}s^{-1}
  - for the target luminosity of about 6.3x10^{35} cm^{-2}s^{-1} machine conditions are very uncertain ⇒ no reliable background prediction possible at the moment

Snowmass Whitepaper arXiv:2203.05731

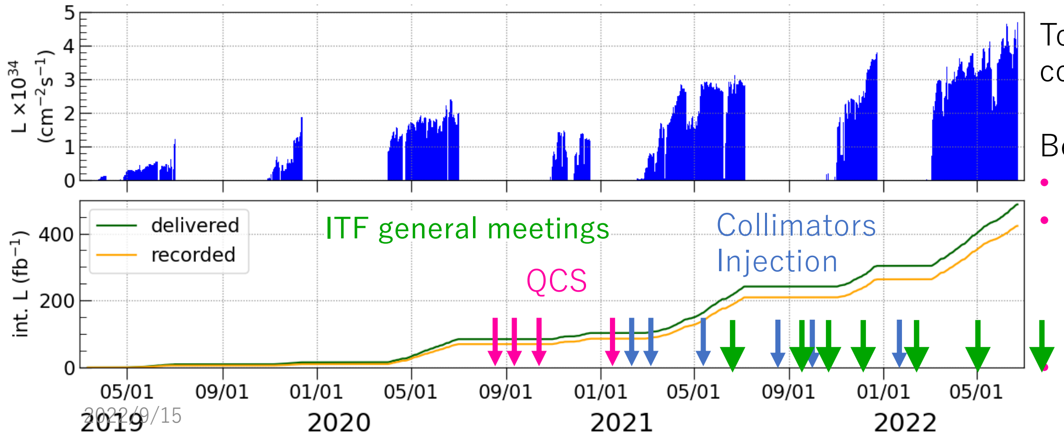


Measured and predicted Belle II backgrounds

SuperKEKB Long-Term Operation Plans

M. Masuzawa

SuperKEKB long-term operation plan meetings



Topics shifted from QCS(IR) to collimators/injection/BG

Because

- No great idea on IR/QCS
- Collimator/injection/BG issues seemed more immediate and critical problems to be solved during the machine operation. We needed to prepare (including which upgrade items to do) for LS1.

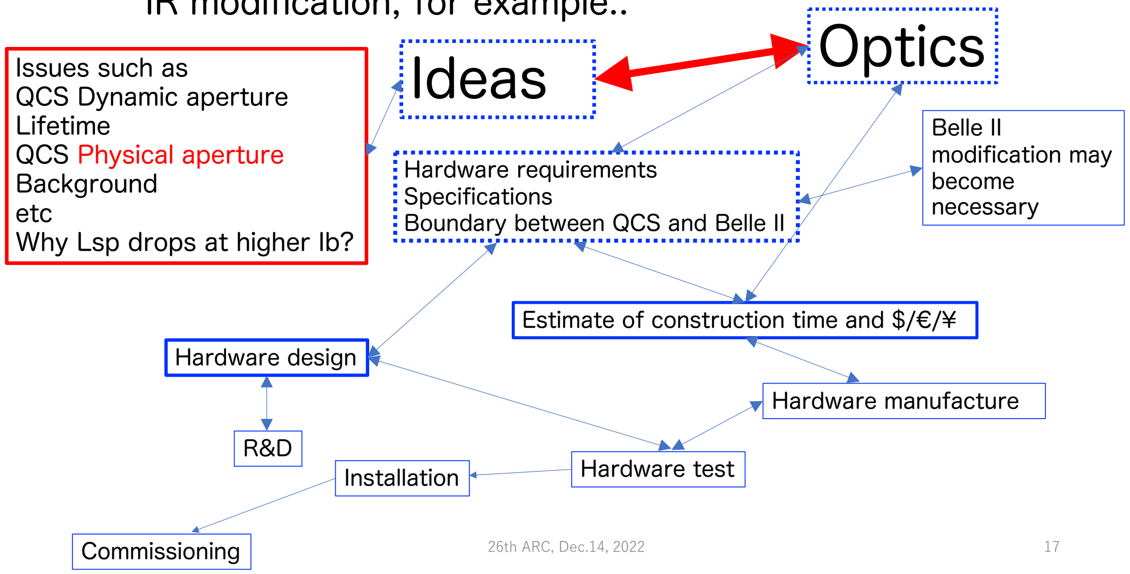
International Task Force (ITF)

Discussions lead by the following sub-groups

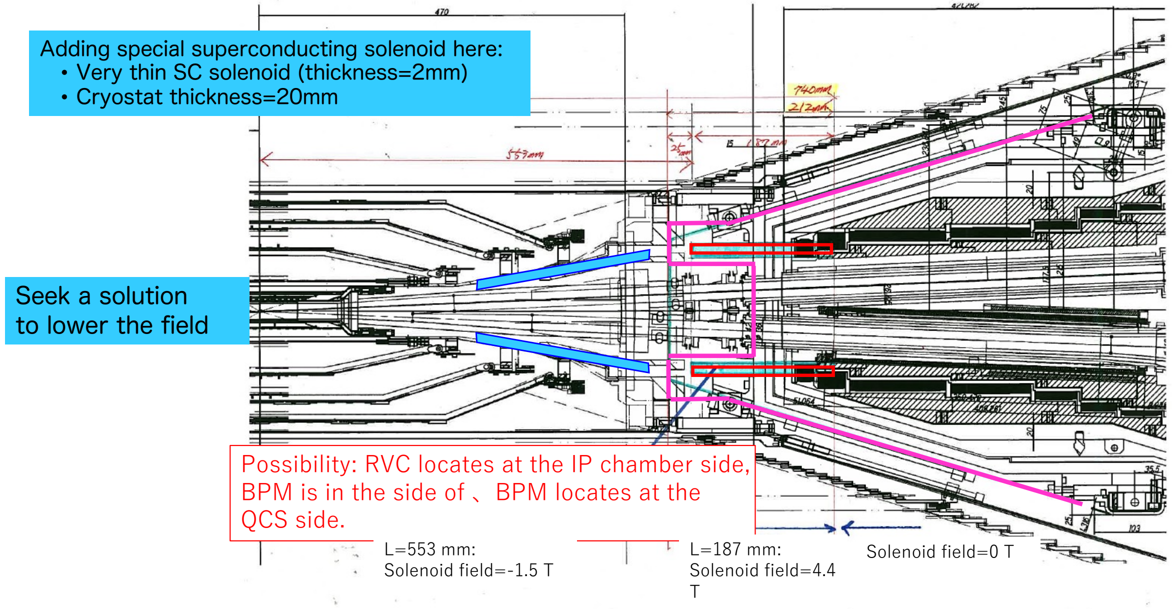
- Optics
- Beam-beam
- Sudden beam loss
- Linac
- TMCI

Many useful suggestions on improving the machine performance have been made through our activities.

Something needs to be done
IR modification, for example..



Toy study



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