Mitigation plans
for Beam background and SBLs

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ARC-BPAC joint review

2025.12.18

Topics to be covered in this talk

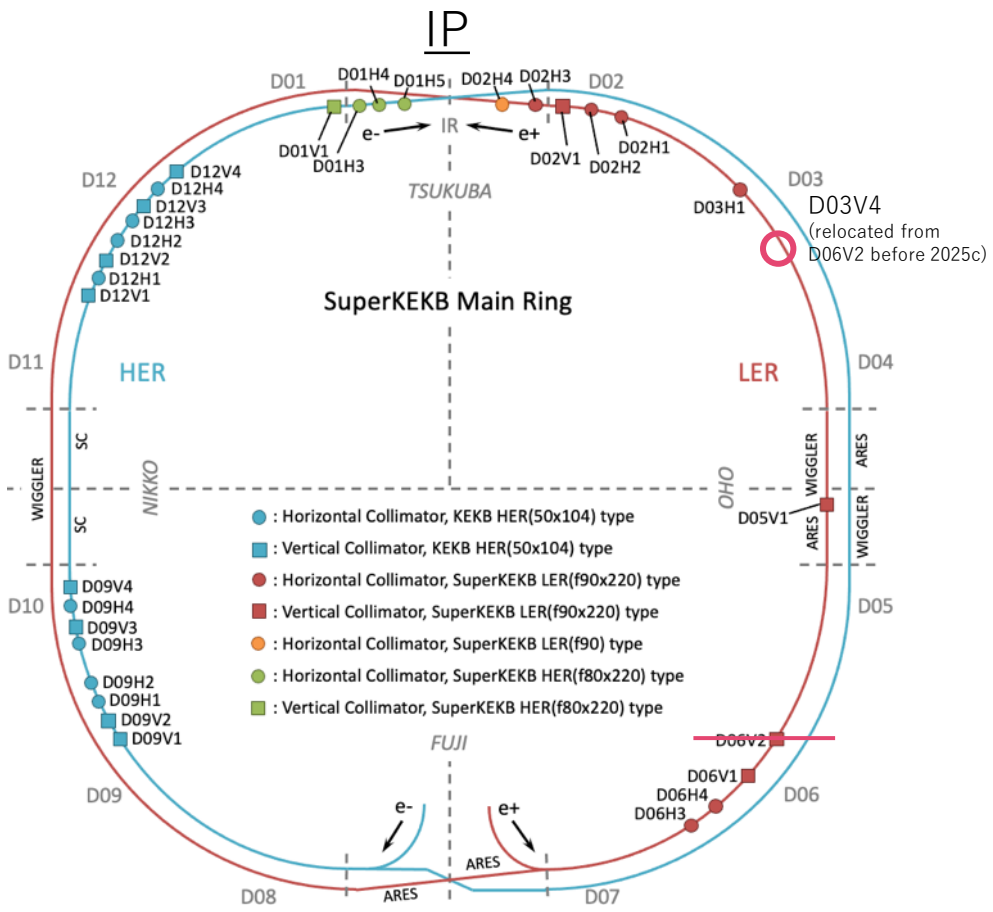
Requested topics by the Spokesperson

- Mitigation plan for beam backgrounds and SBLs (Hiro)
  - Collimators
  - Faster beam abort
  - PXD HV fast shutdown

  - Belle II HV emergency shutdown interlock for machine failure

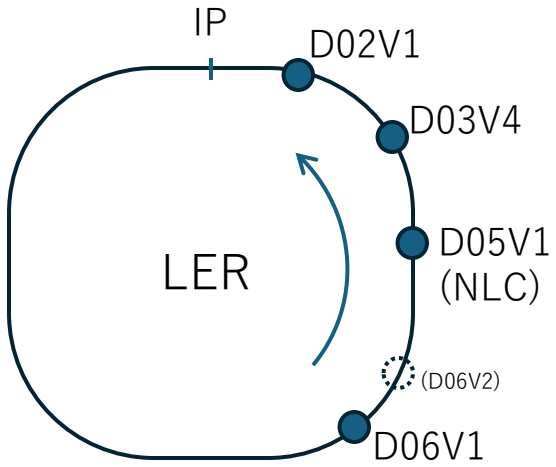
1) Collimators

Quick recap: SuperKEKB collimator system



- Collimators are installed along the main ring to **suppress storage/injection beam BG** and protect Belle II
- Tighter collimators are preferred for BG suppression
  - Except for the tip-scattering from (damaged) collimators near IP
- However, too tight collimators may limit the maximum beam current and luminosity
  - due to poorer injection efficiency, shorter beam lifetime, beam-size blowup due to TMC instability
- Therefore, an optimal tradeoff must be found for each run, **mainly depending on the injection conditions**.
- Collimators also play an important role to mitigate SBL impact on Belle II (and the QCS)
  - Upstream collimators, not the ones near the IP such as LER D02V1 or HER D01V1, should be set as the narrowest

1) Collimators
Mitigation of BG/SBL



Already implemented:

- **LER D05V1** (NLC, Non-Linear Collimator)
  - With the reinforced OHO radiation shield, D05V1 in 2025c can be further tightened
- LER D06V2 relocated to **D03V4** (closer to the IP, with a better phase)
  - Provides better protection for the important D2V1 collimator and Belle II.
  - Especially effective for BG/SBL originating around D5–D4 section (downstream of D6V2).

Further mitigation plans

- Use **D05V1 as the primary (narrowest) collimator** instead of D06V1
  - Especially important when we move to smaller beta*y, with much severer TMCI constraint
  - Tighter D05V1 may allow D06V1 widening while keeping the same storage BG level
  - However, in 2025c, D06V1 remains narrow due to severe injection BG
    - D05V1 less effective for injection BG
  - **Need to improve LER injection quality:** for example, additional fast kicker installed before 2025c significantly improved the quality of the LER 2nd bunch injection.

1) Collimator
2025c findings

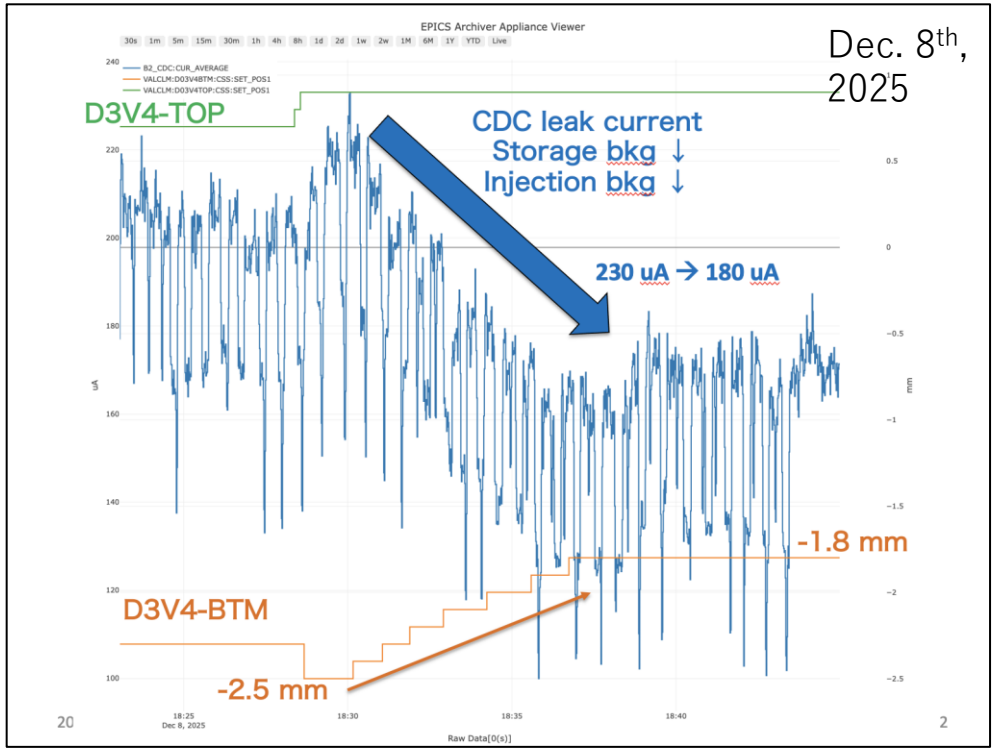
- <u>OHO radiation level improved</u>

<u>2024c</u>
LER~1200mA,
d~2.5mm (Ta head): ~100% of hourly limit
Cannot close D5V1 further

<u>2025c</u>
LER~1200mA,
d~2mm (Ta head): ~few % of hourly limit
d~2mm (Ti head): ~20 % of hourly limit

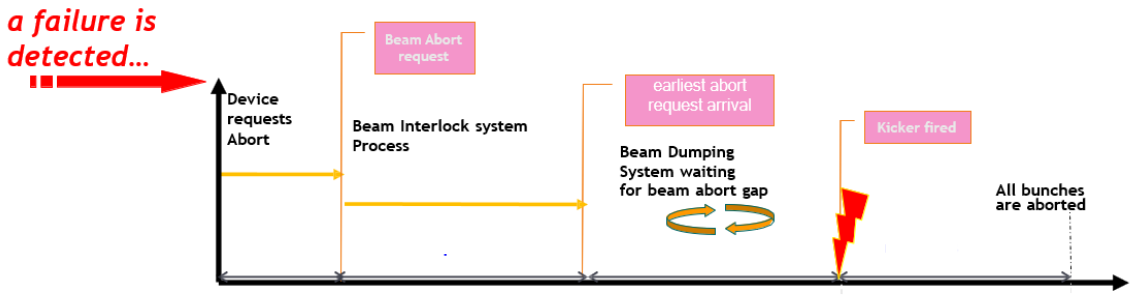
Radiation level in OHO experimental hall much improved thanks to reinforced shields

- <u>BG mitigation by D03V4 tuning</u>



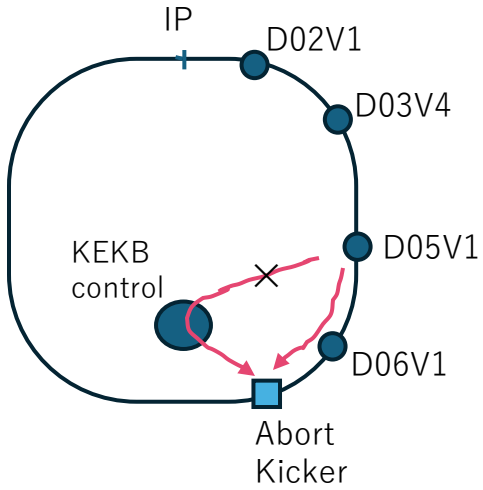
Both storage/injection BG decreased when D3V4BTM was closed

2) Faster beam abort

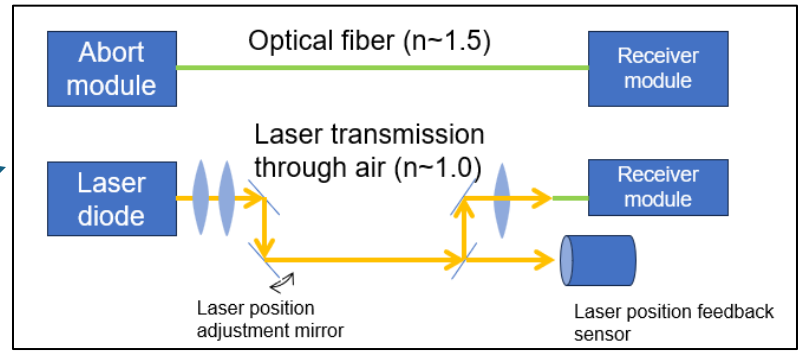


- To mitigate damage from SBL events, where beam loss develops within a few turns, the beam must be aborted as quickly as possible after detecting the loss.
- Countermeasures to speed up beam abort is critical.
- **Already implemented:**
  - **The second abort gap** for shorter kicker waiting time (from 0-10us to 0-5us).
  - **Fast-response loss monitors** installed for triggering aborts
    - VXD diamond data sampling: 10us -> 2.5us
    - CLAWS scintillators with very fast response, etc.
  - **Direct abort trigger delivery path in LER**, from the loss monitor to directly the abort kicker (not going through SKB control)
  - Abort trigger issued by D6V1/D5V1 CLAWS (near the abort kicker)
    - 5~10us gain if the first trigger is issued by D6V1/D5V1

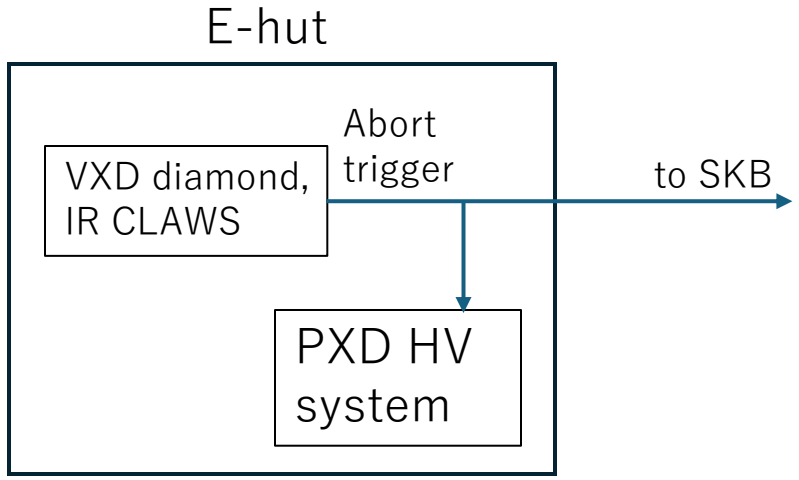
  → Thanks to all these improvements, LER beam can now be aborted within ~**20us.**



- **Further mitigation plans**
  - Abort trigger issued by more LER D03V4 CLAWS
  - Direct abort delivery path to the abort kicker also in HER
    - Already prepared before 2025c, to be enabled soon
  - Longer-term R&D: laser-based abort trigger delivery in air
    - Feasibility test ongoing in the MR tunnel



3) PXD HV fast shutdown



- The abort trigger from the VXD diamond is also sent directly to the PXD HV system, allowing to start PXD HV shutdown earlier than the beam abort.
- Is there any **“precursor signal of SBLs”** that could provide an even faster trigger for PXD HV shutdown?
  - Such signal might also be used to trigger beam aborts, but the allowable false-trigger rate would need to be much lower.

- Potential candidates for SBL precursor signals

  A: Beam-pipe clearing electrode signals

  Abnormal current or voltage patterns might precede SBL

  B: Beam orbit fluctuation (BORs)

  Orbit fluctuations could indicate start of an instability that eventually evolves into SBL

  C: Beam size blow-up (fast monitor)

  A rapid increase in beam size might occur just before the abort in SBL

- Note: all candidates are **still under preliminary investigation** and **not yet ready for practical use** (especially for B and C)

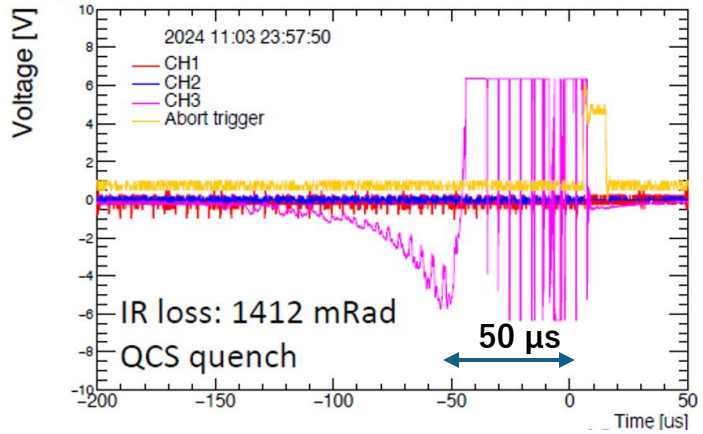
3) PXD HV fast shutdown
A: Clearing electrode signal

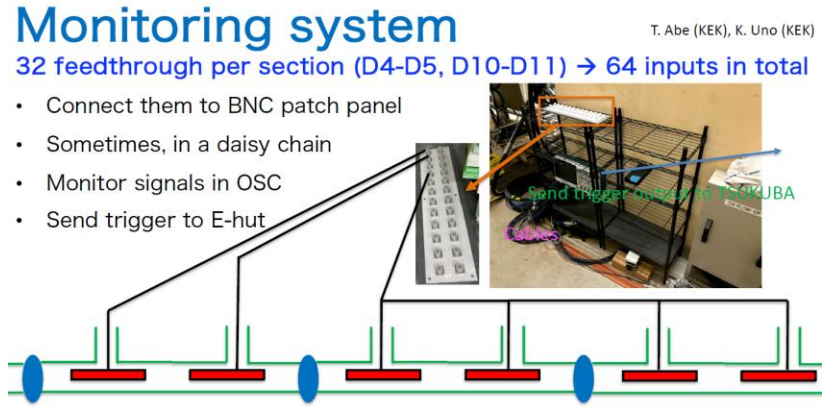
- In some SBL events during the 2024c run, abnormal signal appeared **O(10 μs) earlier** than the abort trigger, at the clearing electrode of D10 beam pipe where pressure burst was observed.
- Prior to the 2025c, 32 clearing electrodes around LER D04 and D10 were connected to oscilloscopes

- In 2025c, **three LER SBL events occurred on Dec. 6,8,9, all with pressure burst at D11_L21**
- Unfortunately, D11_L21 was not monitored at that time → new oscilloscope already connected on Dec. 10
- ~~No SBL events occurred since then~~
  - ~~Abnormal signal was observed when small pressure burst occurred at D11_L21 (but didn't abort the beam)~~

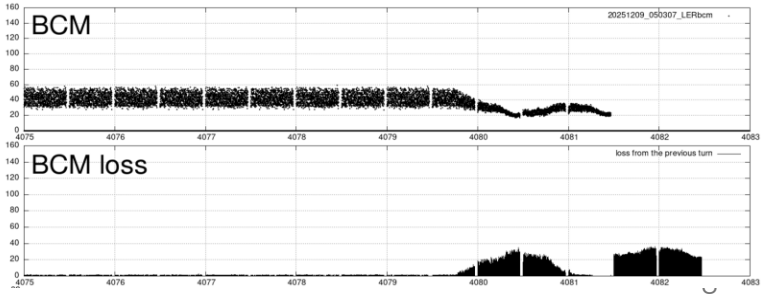
Another LER SBL on Dec. 15, with pressure burst at D11_L21. Was D11_L21 electrode signal seen?

LER SBL on Nov. 3 23:57
(pressure burst at D10_L02/D10_L03)



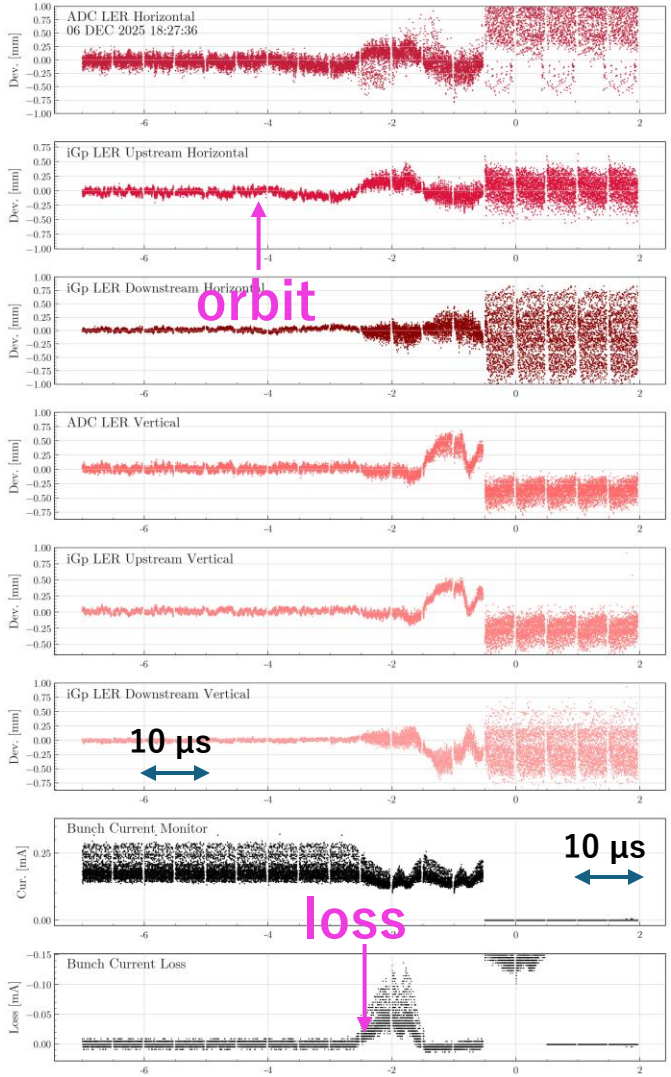


LER SBL on 2025-12-09 05:03

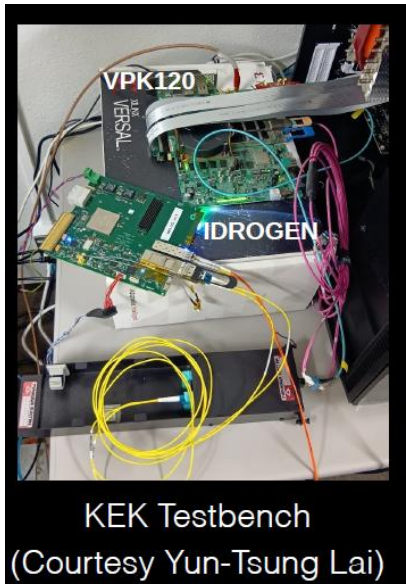


3) PXD HV fast shutdown

B: Beam orbit fluctuations

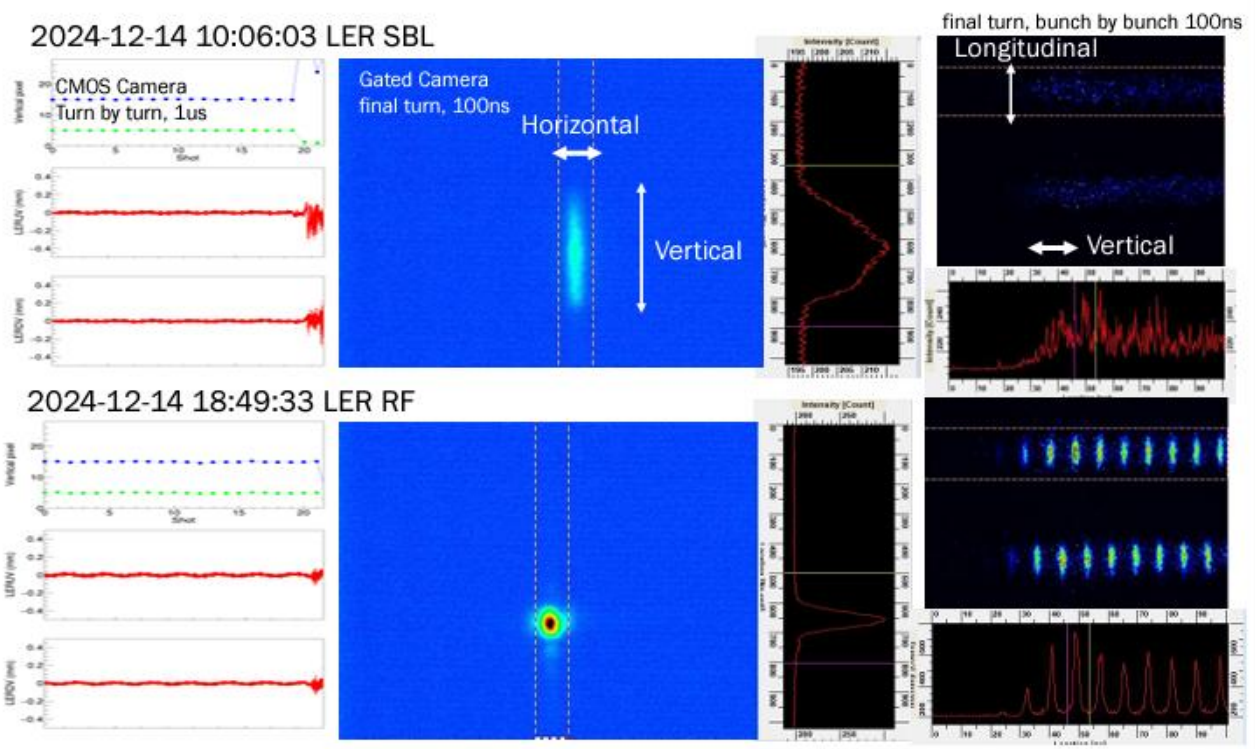


- In SBL events, **beam instability appears first and is followed by beam loss**, indicating potential for **earlier anomaly detection**.
- BOR systems (BOR, iGp12, RFSoC) provide **bunch-by-bunch orbit fluctuation measurements** before the abort
- However, precursor oscillations appear to be small, making them challenging to distinguish from normal beam fluctuations.
- **AI-based analysis combining multiple BOR waveforms** is therefore being explored.
  - An offline study using 2024 abort data has started.
  - See H. Haigh's talk at the recent MDI meeting: https://kds.kek.jp/event/57545/#3-bor-data-analysis-anomaly-fi
- **Hardware R&D ongoing for real-time triggering**
  - IDROGEN board can host White Rabbit slave, enabling precise time synchronization among distant modules
  - A Versal board (VPK120) can aggregate data from multiple IDROGENs and perform real-time ML-based data processing
  - See K. Yoshihara's talk at the recent CEF workshop: https://kds.kek.jp/event/57383/#8-superkekb-bor-readout-projec



KEK Testbench
(Courtesy Yun-Tsung Lai)

3) PXD HV fast shutdown
C: Beam size blowup



From Ikeda-san's report at SKB review
https://www-kekb.kek.jp/MAC/2025/

- In the 2024c run, **some SBL events showed a larger beam size prior to the abort**
  - CMOS, gated, and streak cameras recorded the beam size just before the abort, with integration times of 0.1–1 μs (corresponding to 1–10% of a turn).
  - The magnitude of orbit fluctuations during the integration window is insufficient to explain the observed size increase, suggesting that a genuine **beam size blow-up occurs prior to the abort**

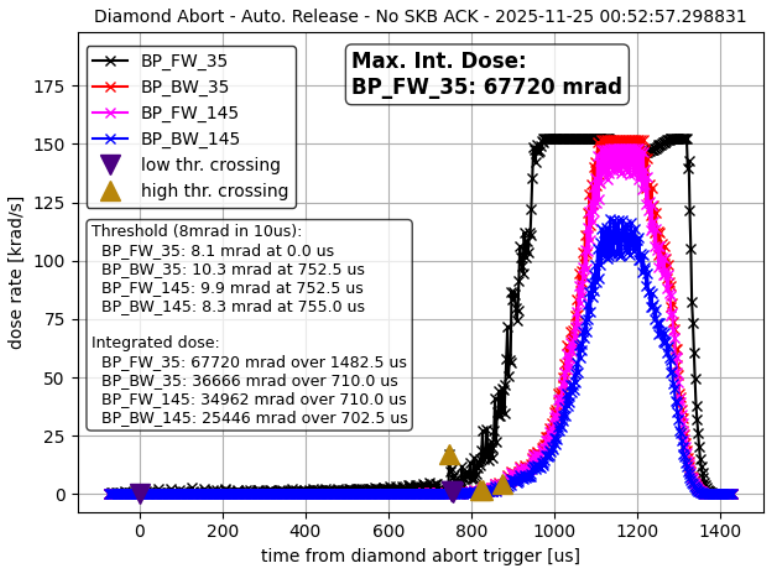
- **Development of a silicon-based ultrafast X-ray beam size monitor is in progress**
  - See Riku Nomaru's recent conference paper presented at IBIC 2025: https://meow.elettra.eu/90/pdf/TUPCO31.pdf

Beam size was measured also for 2025c LER SBL events. Data analysis is now ongoing.

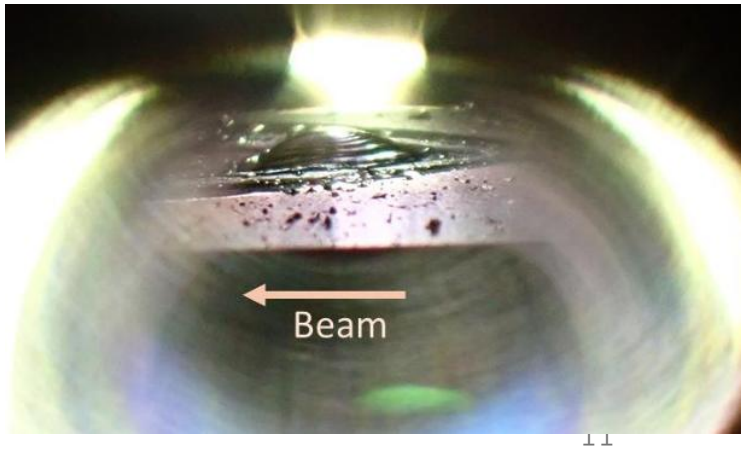
4) Belle II HV emergency shutdown in case of machine failure

- 2025-11-25 00:52, HER abort kicker system entered a failure mode and immediately issued an abort request
- However, since the kicker itself was in failure, the beam was not extracted
- This activated the SuperKEKB emergency interlock, forcing the weak-bending magnets to turn off
- The stored beam was then lost in an uncontrolled manner, causing severe **HER D01V1 collimator damage, largest-ever dose in the VXD diamonds**, and the QCS-L quench
- Since the incident, beam operation has had to be **stopped every few days to refill the QCS He tank**, indicating a possible degradation of the QCS-L cooling performance.

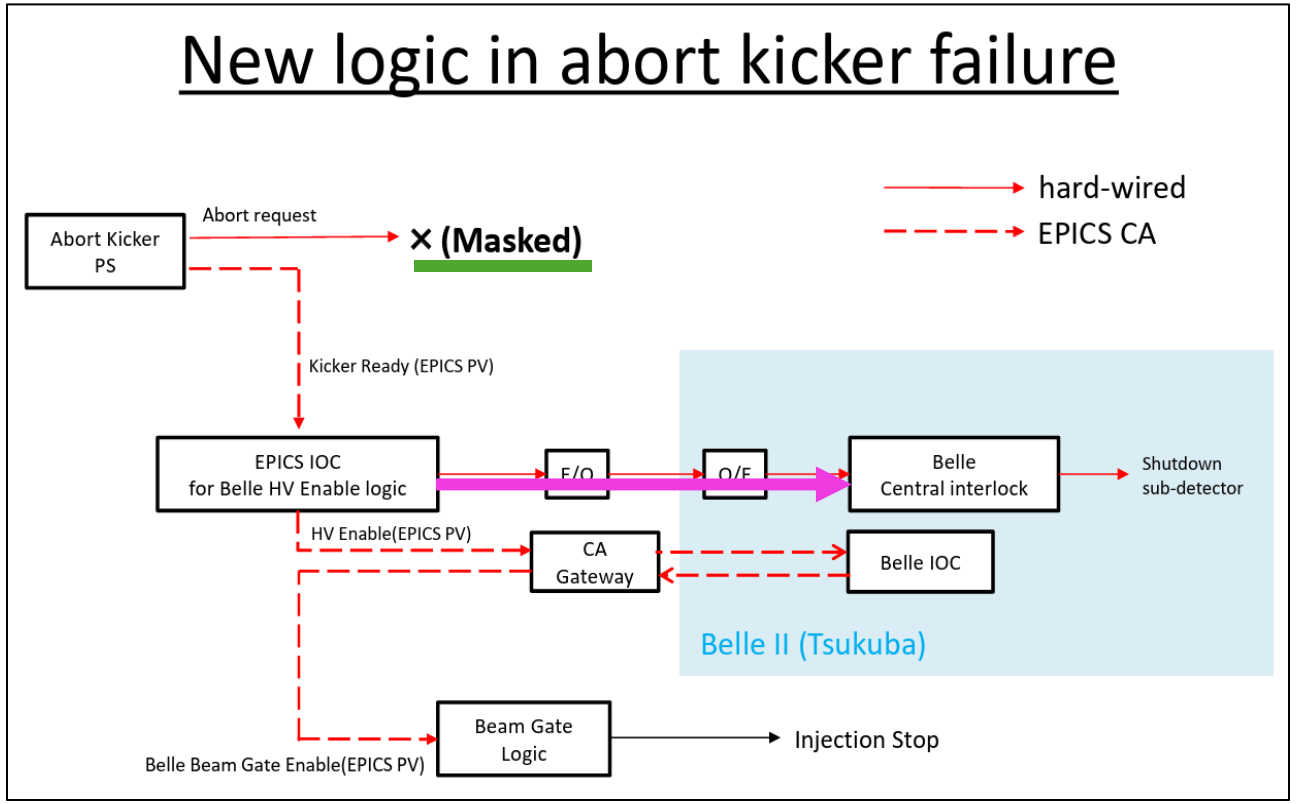
VXD diamond



D01V1 BTM jaw heavily damaged



4) Belle II HV emergency shutdown in case of machine failure



- In the event of an abort kicker failure, **immediate beam abort request is no longer issued**
- Instead, the failure now triggers a **newly installed hard-wired signal** directly connected to the **Belle II central interlock**, then **Belle II HV starts shutdown** to reduce risk of sensor damage
- The stored beam should be then disposed of **using a safer method**, which is currently under consideration by SKB experts (not yet implemented)
  - if beam abort request is issued by other source, it triggers SKB emergency interlock

Summary

- Further mitigation of beam BG by collimators requires better injection quality
- Further mitigation of SBL damage is under investigation:
  - Faster abort request delivery
  - Possible candidates for SBL “precursor” events
- Emergency Belle II HV shutdown interlock is implemented after the abort kicker failure incident on Nov. 25th

LER SBL in 2025c