Mitigation plans
for Beam background and SBLs

Hiro Nakayama (KEK)
ARC-BPAC joint review

2025.12.18

Topics to be covered in this talk

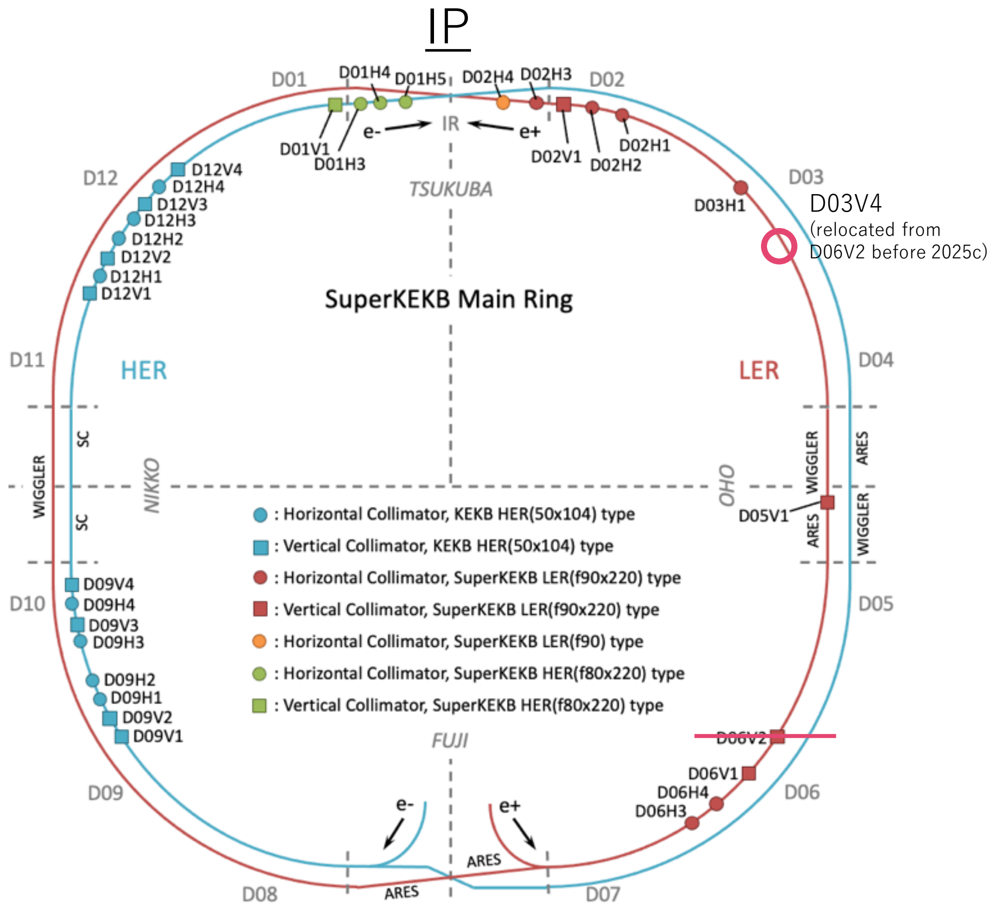
Requested topics by the Spokesperson

- 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

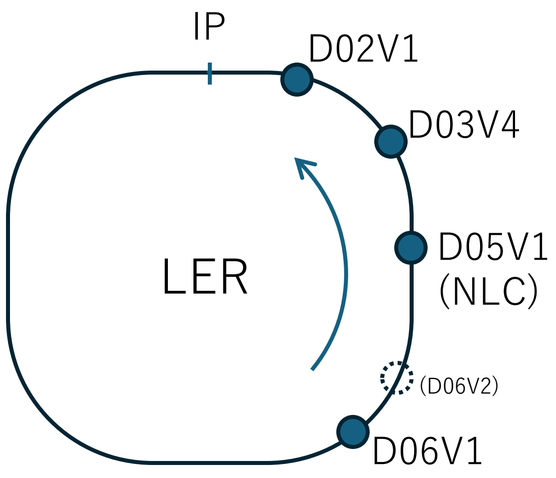
Quick recap: SuperKEKB collimator system



- 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 beam BG and SBL



<u>Already implemented:</u>

- **LER D05V1** (NLC, Non-Linear Collimator)
  - A vertical collimator with sextupole magnets placed upstream/downstream
  - Sextupoles create non-linear optics to amplify vertical deviation at the NLC
  - Allows efficient BG suppression with moderate aperture (less worry for TMCI)
  - Less effective for injection BG reduction → in 2025c, both NLC and D6V1 are tight
- **LER D03V4** (relocated from D06V2)
  - D03V4 is closer to IP, and has a better betatron phase
  - Provides better protection for the important D2V1 collimator and Belle II, especially against BG/SBL originating around D5–D4 section (downstream of original location at D6V2)

1) Collimator

2025c findings

- <u>Improved radiation level in the OHO hall (where NLC is located)</u>

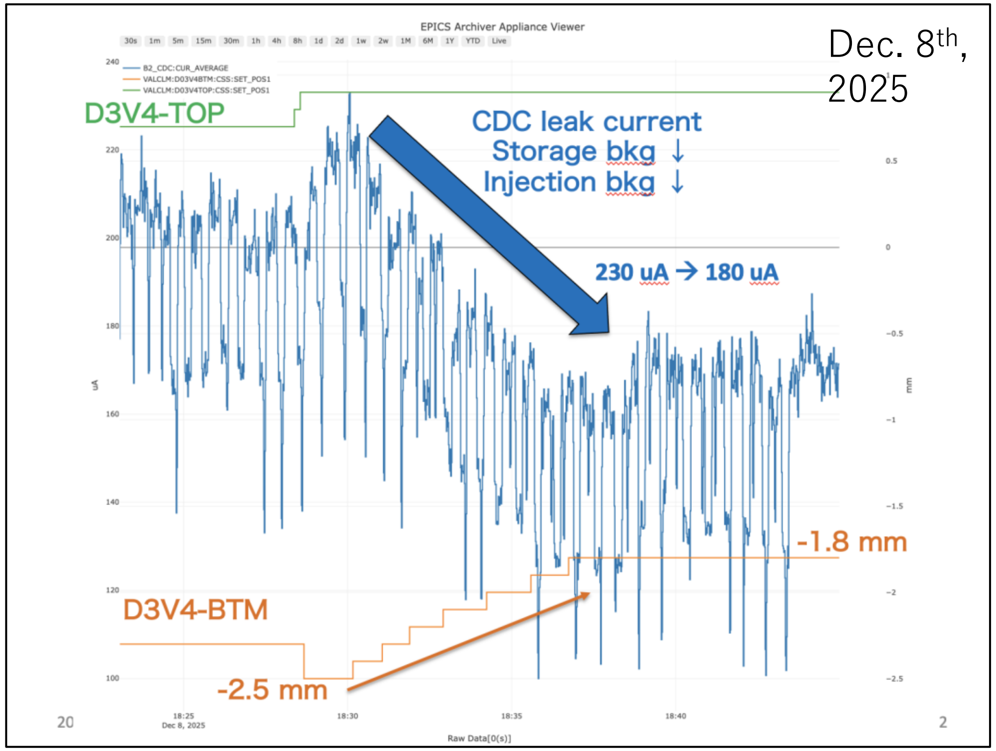
<u>2024c</u> (LER~1200mA)
d~2.5mm (Ta head): **~100%** of hourly limit
Cannot close D5V1 further

Reinforcement of
OHO radiation shield

<u>2025c</u> (LER~1200mA)
d~2mm (Ta head): **~ 5%** of hourly limit
d~2mm (Ti head): **~20%** of hourly limit

We can fully utilize D5V1 in 2025c (!)

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



Both storage/injection BG decreased when D3V4BTM was closed

1) Collimator
BG mitigation strategy with collimators

Towards larger beam currents and higher luminosity

- Beam BG scales roughly with I^2, which might limit the beam current
  - Max beam current could also be limited by poor injection performance, short lifetime, etc.
- Vacuum scrubbing will gradually reduce beam-gas BG
- In addition, **tightening collimators can reduce Beam-Gas/Touschek BG**

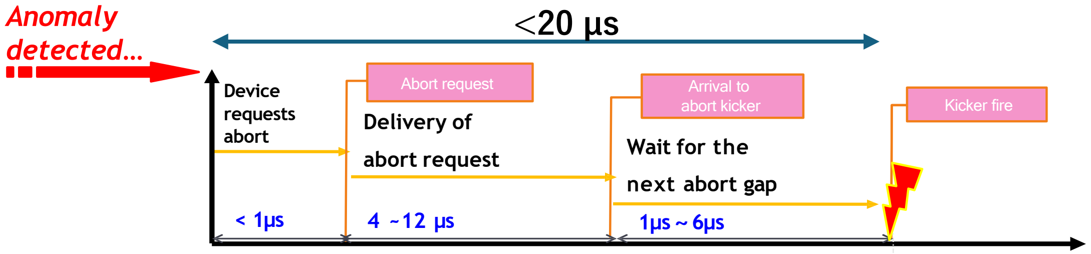
  (Lumi-BG does not depend on collimators)

Limitations when tightening collimators

- **Possible degradation of injection efficiency** which limits max beam current
  → **If injection quality is excellent**, this degradation would be acceptable
- **Possible enhance of TMC instability** which limits max bunch current
  → NLC can suppress beam BG with less TMCI. However, NLC is less effective for suppressing injection BG and other collimator needs to be kept tight.
  → **If injection quality is excellent**, we can open other collimators and achieve TMCI mitigation with moderate injection BG

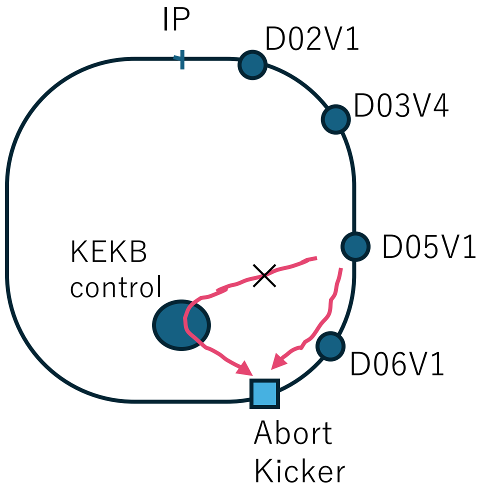
Conclusion:
Collimators can reduce single-beam BGs but it requires good/stable injection quality.

2) Faster beam abort

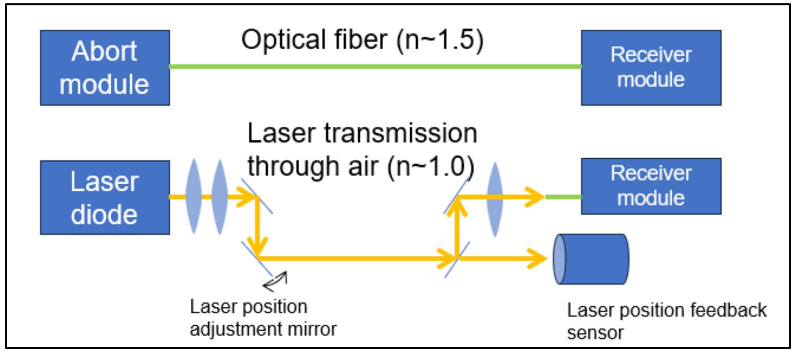


- To mitigate damage from SBL events, where beam loss develops within a few turns, the beam must be aborted as quickly as possible after detecting the loss.
- Countermeasures to speed up beam abort is critical.
- **<u>Already implemented:</u>**
  - **The second abort gap** for shorter kicker waiting 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 CLAWS at LER D5V1/D6V1** (near the abort kicker)
    - 5~10us gain if the first trigger is issued by D6V1/D5V1

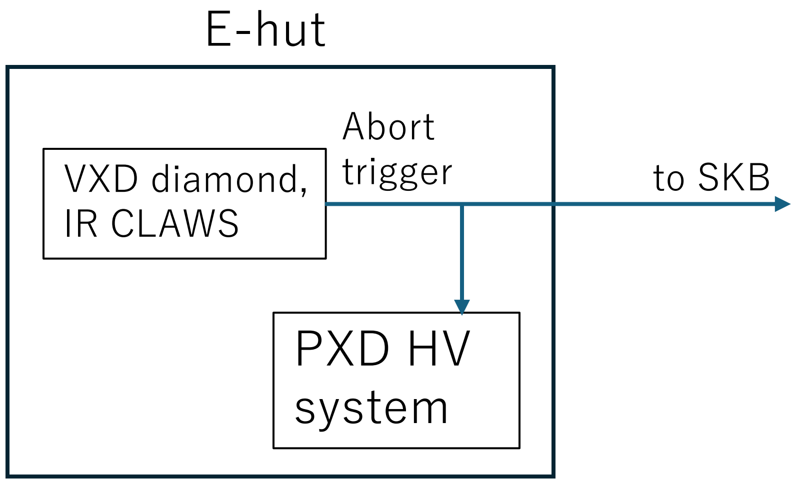
  → Thanks to all these improvements, LER beam can now be aborted within ~**20us.**



- **<u>Further mitigation plans</u>**
  - Abort trigger issued by more LER CLAWS (D3V4)
  - Direct abort trigger delivery path to **HER** abort kicker
    - 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

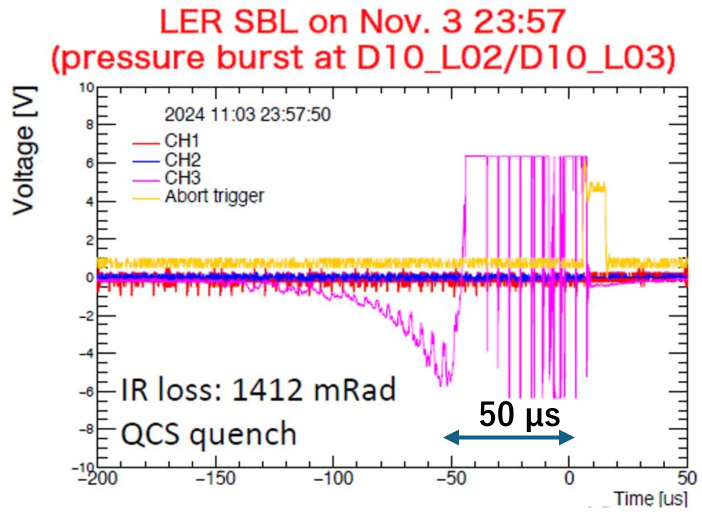
  C: Beam size blow-up（fast monitor)

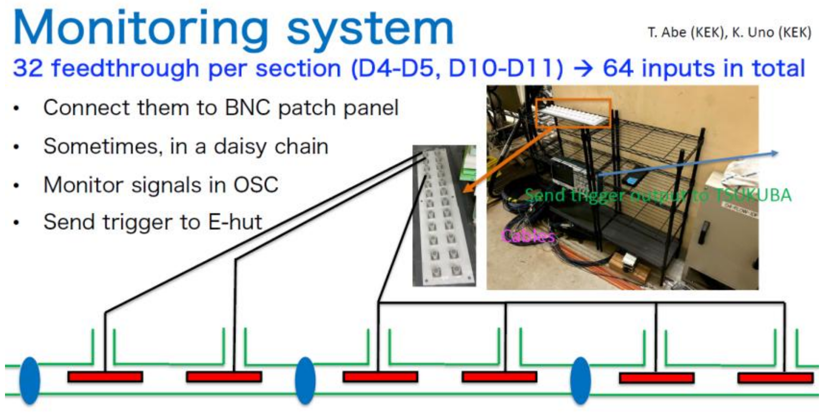
  A rapid increase in beam size might occur just before the abort in SBL

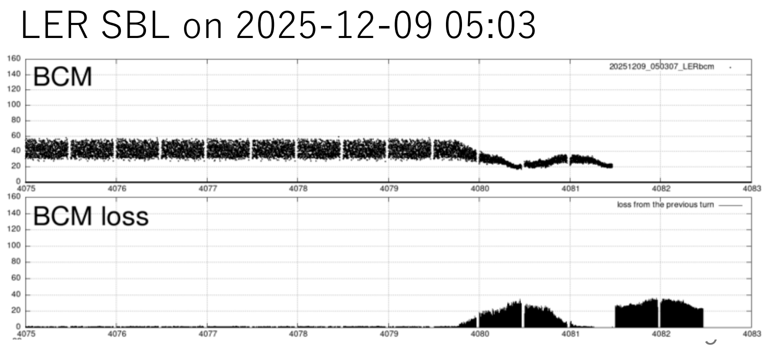
- Note: all candidates are **still under preliminary investigation** and **not yet ready for practical use** (especially for B and C)

3) PXD HV fast shutdown
A: Clearing electrode signal

- In some SBL events during the 2024c run, abnormal signal appeared <u>**O(10 μs) earlier**</u> than 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, but the electrode was not monitored at that time. We added an oscilloscope to the electrode on Dec. 10.
- On Dec. 15th, SBL occurred again with pressure burst at D11_L21, but no abnormal signal was observed at the electrode. We keep monitoring.

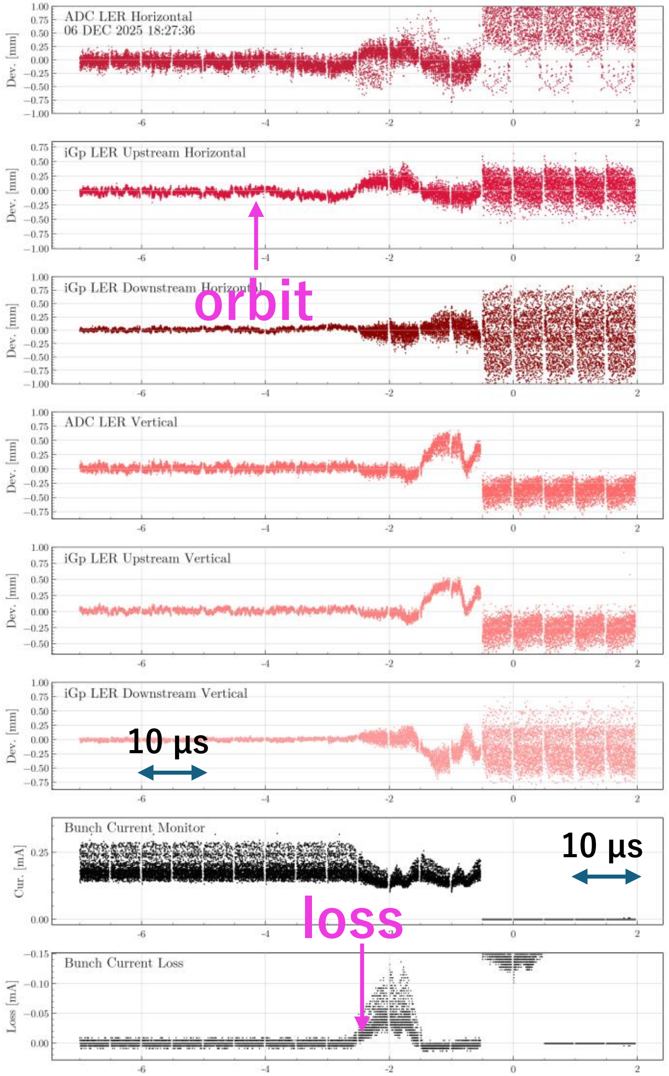




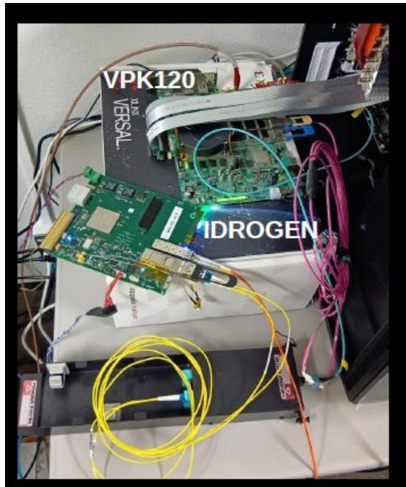


3) PXD HV fast shutdown

B: Beam orbit fluctuations

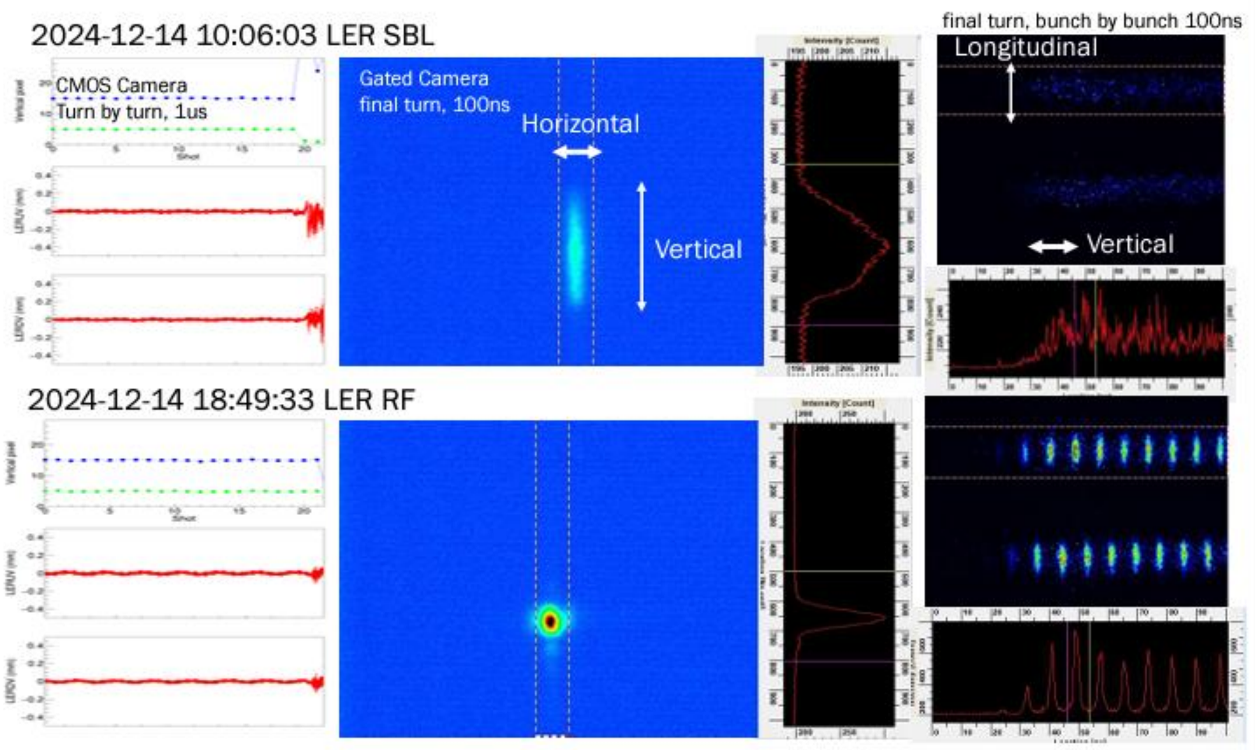


- In SBL events, **beam instability appears first and is followed by beam loss**, indicating potential for **earlier anomaly detection**.
- BOR systems (BOR, iGp12, RFSoC) provide **bunch-by-bunch orbit fluctuation measurements** before the abort
- However, precursor oscillations appear to be small, 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)

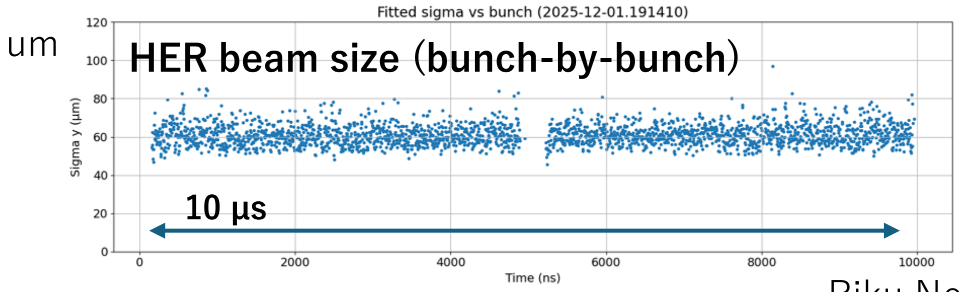
3) PXD HV fast shutdown
C: Beam size blowup



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**

- **Ongoing R&D of a silicon-based X-ray beam size monitor**



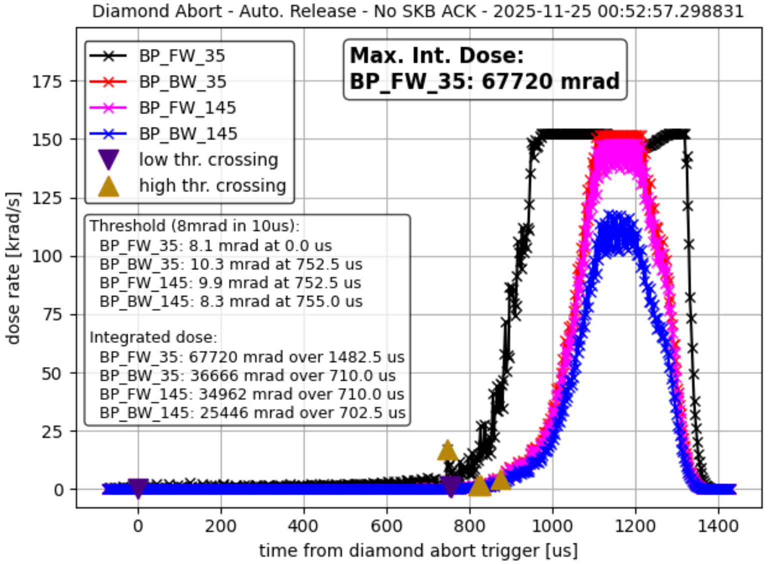
Riku Nomaru

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

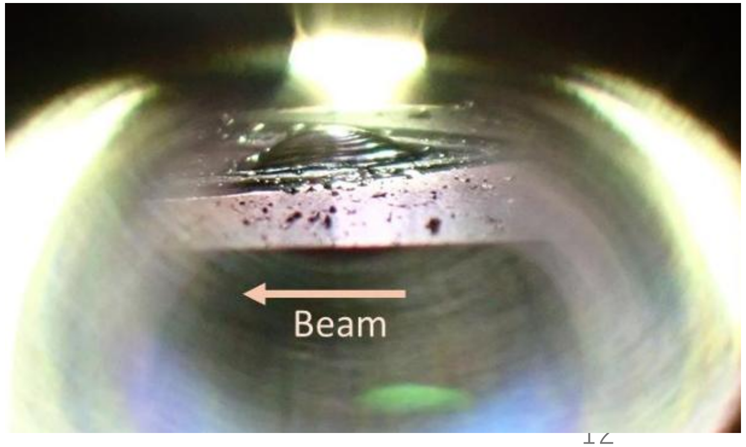
4) Belle II HV emergency shutdown in case of machine failure

- 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

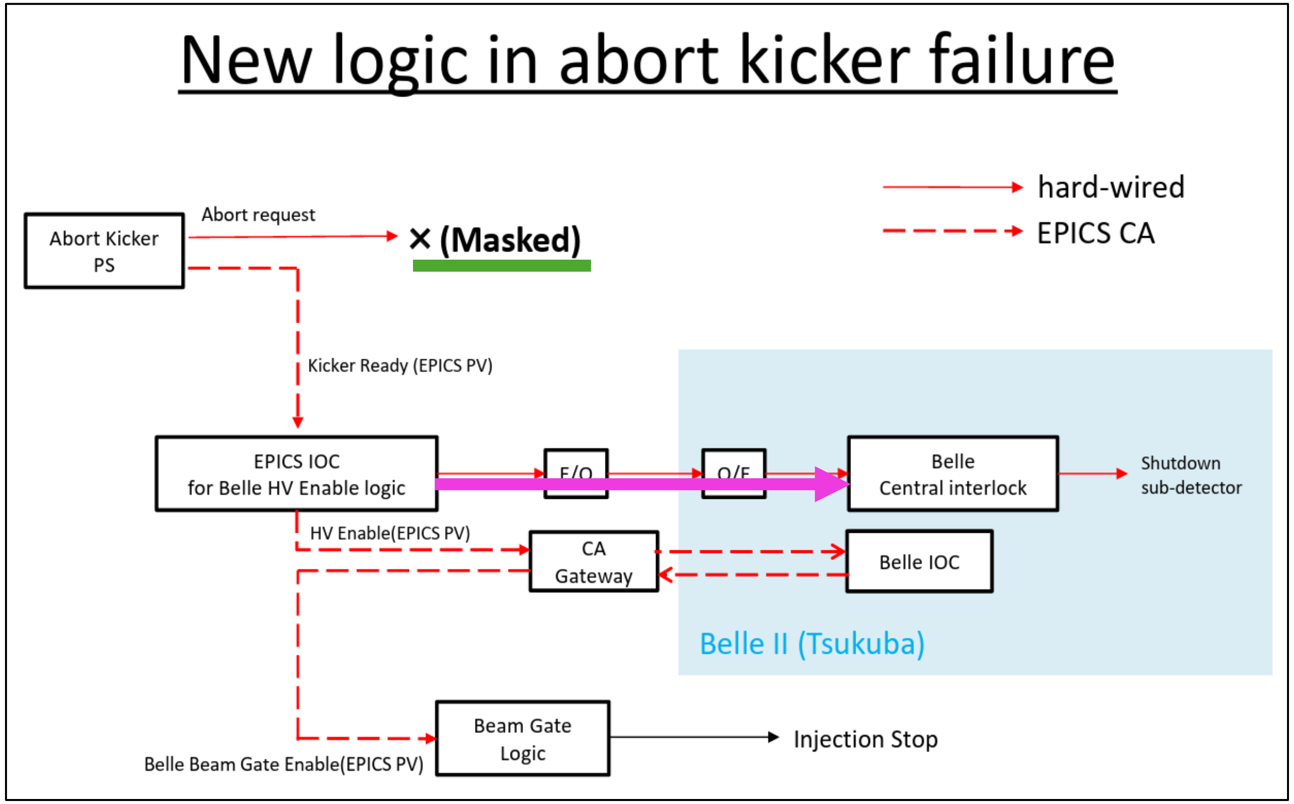


HER D01V1 BTM jaw heavily damaged



To be replaced after 2025c

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



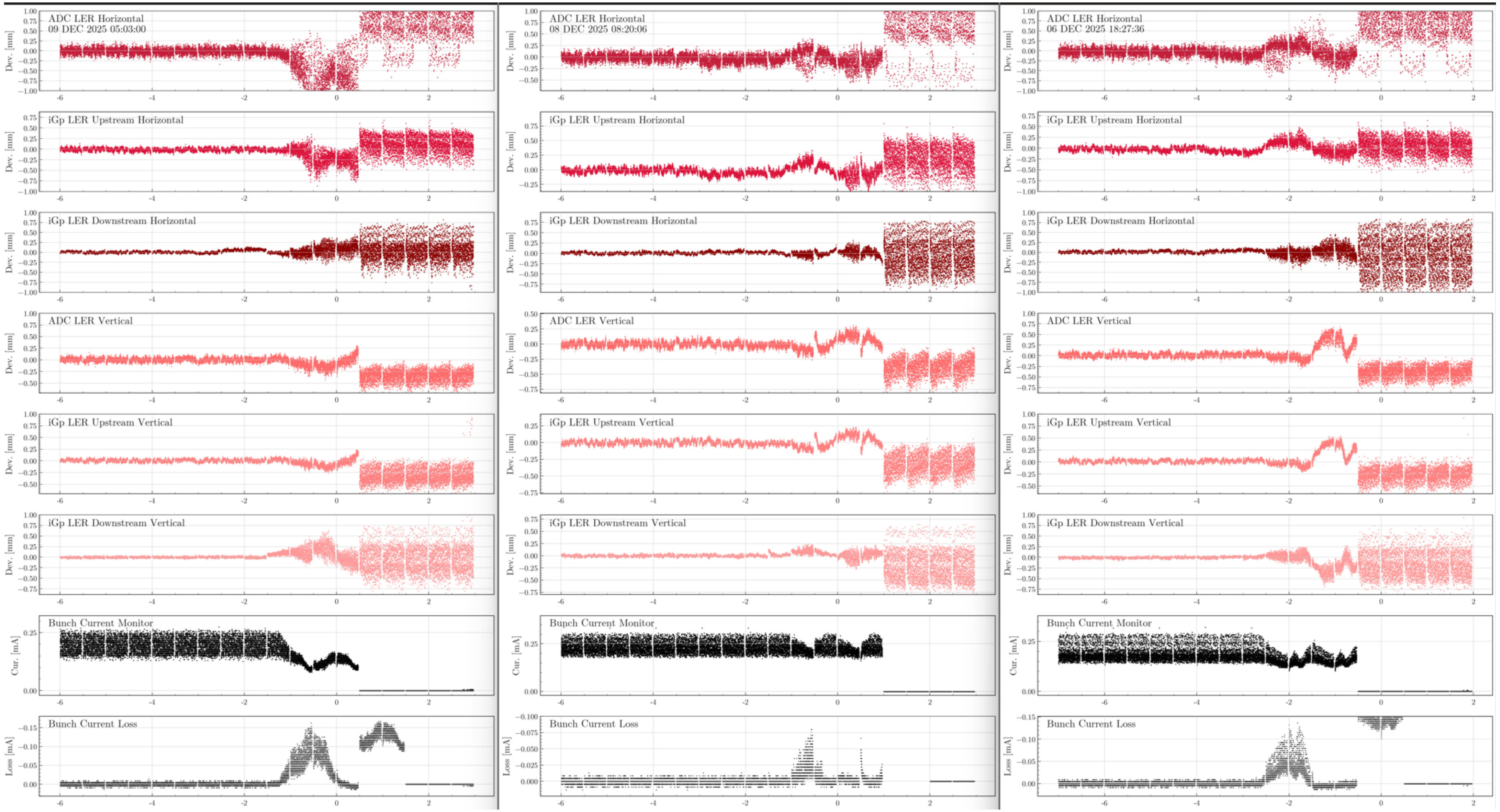
- In the event of an abort kicker failure, **immediate beam abort request is no longer issued**
- Instead, the failure now triggers a **newly installed hard-wired signal** directly connected to the **Belle II central interlock**, then **Belle II HV starts shutdown** to reduce risk of sensor damage
- 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

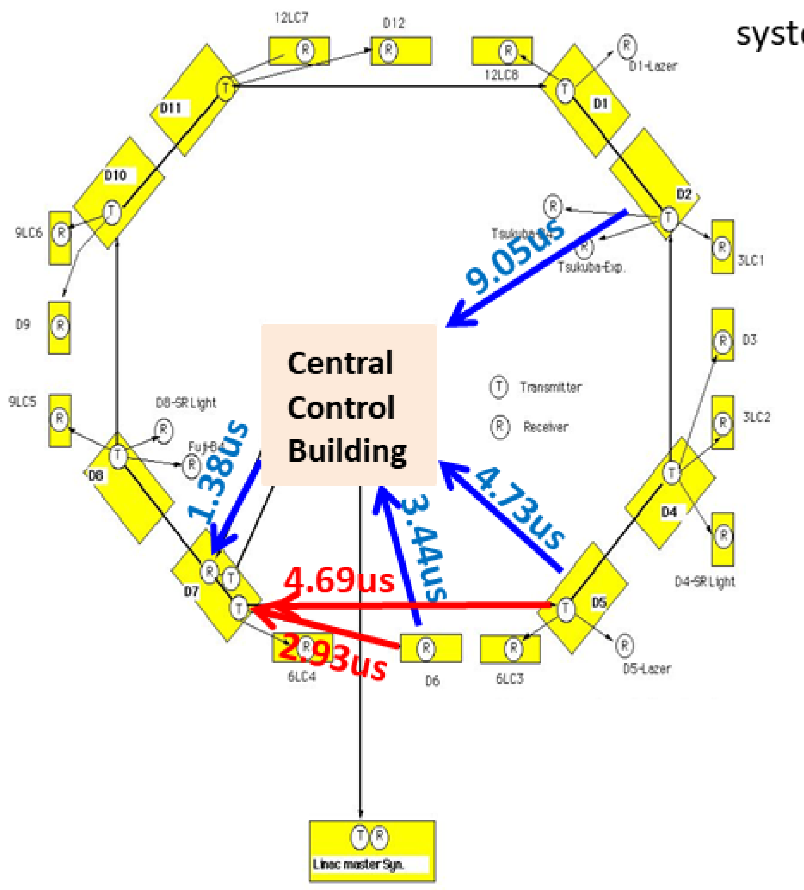
- Further mitigation of beam BG by collimators requires better injection quality
- Further mitigation of SBL damage is under investigation:
  - Faster abort request delivery
  - Possible candidates for SBL "precursor" events
- Emergency Belle II HV shutdown interlock is implemented after the abort kicker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

LER SBL in 2025c

2025.12.09 2025.12.08 2025.12.06



Abort signal transferring time



The fastest abort response in the current system is "**CLAWS@IP => D02 => CCB => D07**".

If we detect the beam loss and launch the abort request at D05 or D06, the following gain in signal transferring is expected.

	via CCB	Directly D07
D05	4.32 us	5.74 us
D06	5.61 us	7.5 us