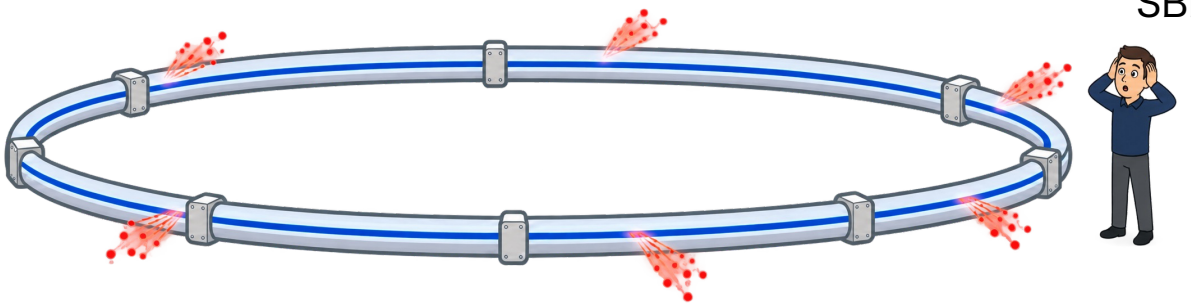


Sudden Beam Loss

Kenta Uno (KEK IPNS)
on behalf of SBL TF team

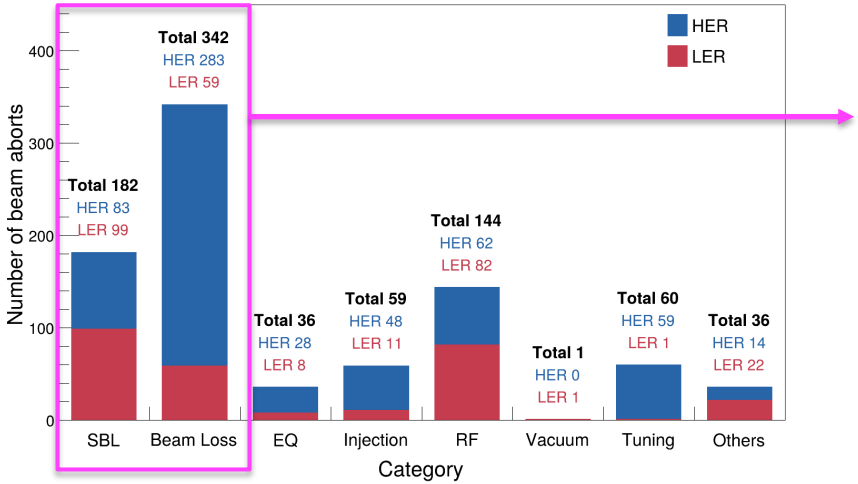
Accelerator Review Committee
October 27, 2026

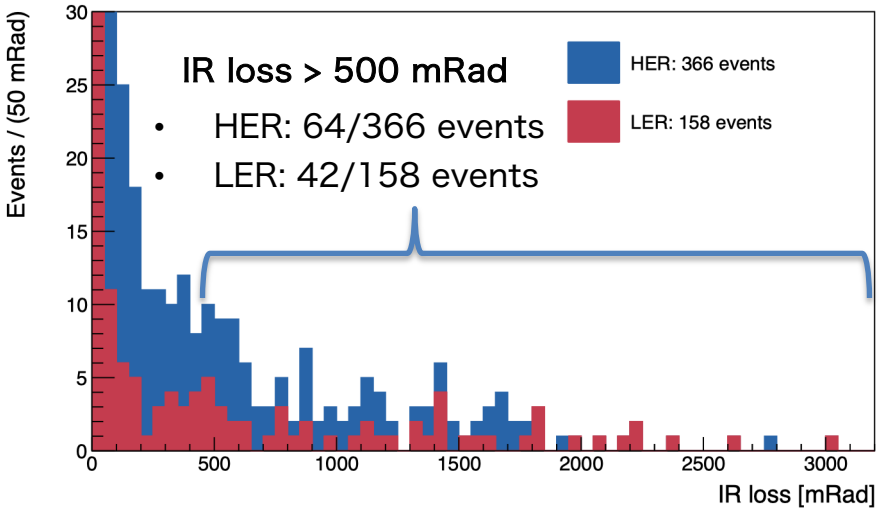
Introduction

Beam-loss-induced aborts are a major obstacle to stable operation

- Higher beam currents can lead to larger losses around the Interaction region (IR)
  - Long downtime due to QCS quenches and risk of damages to the Belle II detector

2026ab (Jan.26 – Jun.30)





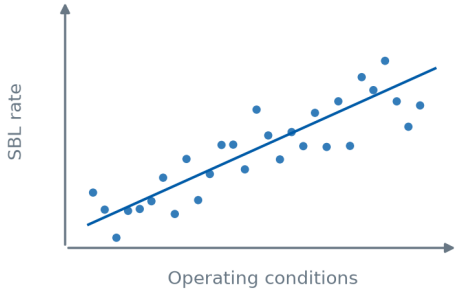
Major objectives of SBL TF:

- Identify and eliminate SBL sources
- Develop reasonable hypotheses based on past data
  - Then, propose operation conditions to reduce SBLs and studies to identify its causes.
- Mitigate IR loss to prevent QCS quenches even when SBL occurs
  - E.g. search for precursor signals, improve the abort system to abort the beam earlier

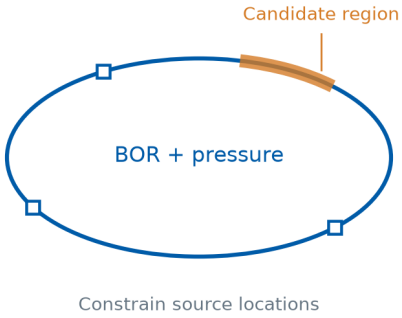
Approach to understanding SBLs

We have pursued these complementary approaches

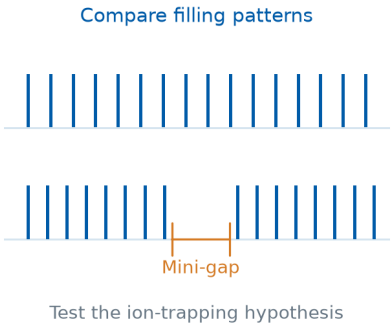
- **Explore correlations with operation conditions**
  - Statistical analysis of conditioning, machine states, and other variables
  - Anomaly detection.
- **Locate possible sources using beam diagnostics**
  - BOR phase analysis, pressure bursts, signals from clearing electrode
- **Test hypotheses during beam operation**
  - Bunch-current dependence and possible ion-trapping effects



Correlations



Localization

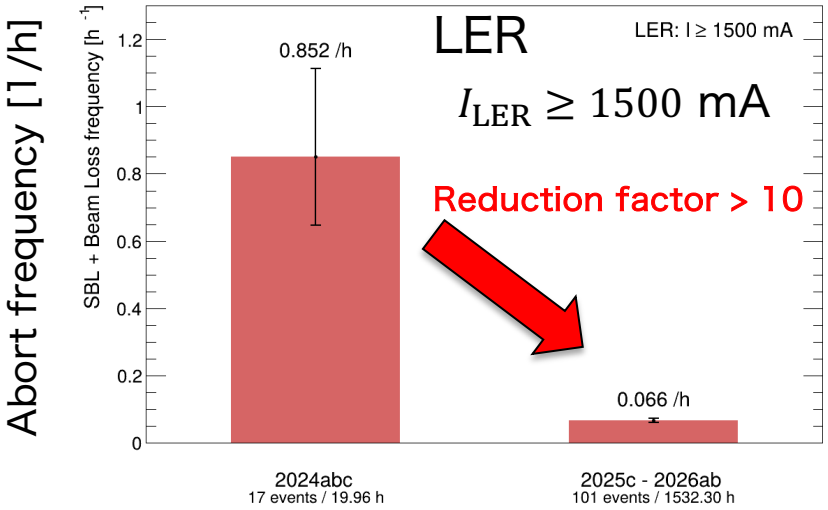


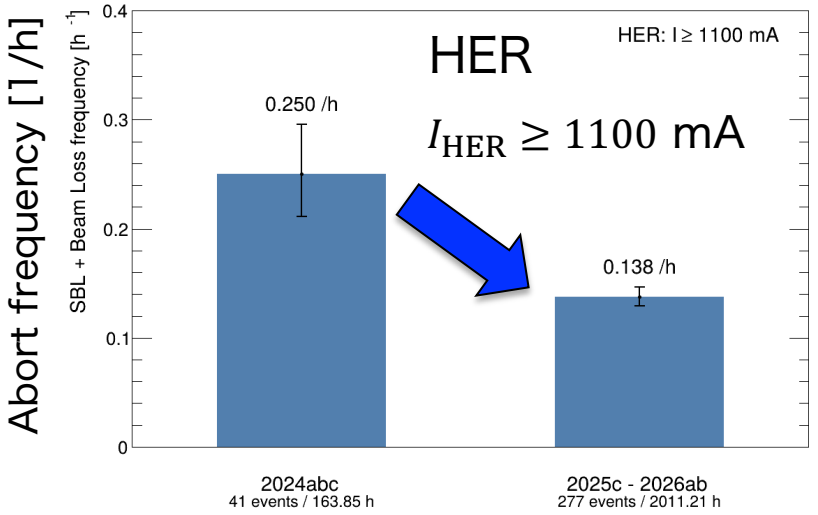
Beam studies

We present our current understanding of SBLs and our strategy for the next run based on these studies

2026ab situation

Cleaning beam pipes works well → Significant reduction of beam abort rates





Operation time at $I > 1.5$ A

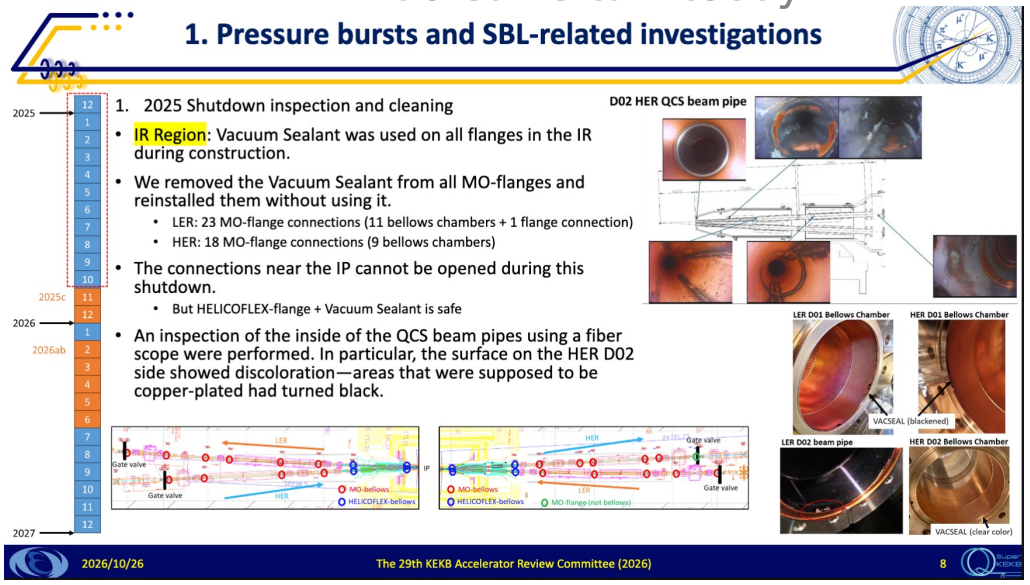
- 20 h → 1532 h

2024 2025-2026

Enabled stable operation at higher beam current ☺

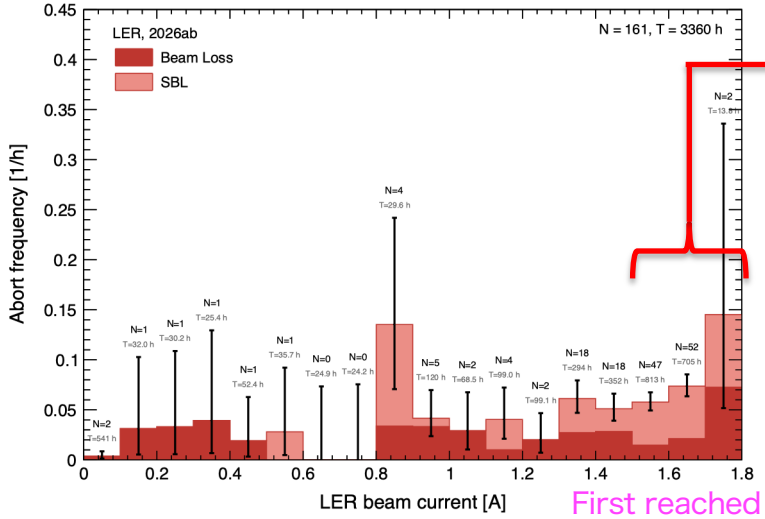
Focused on investigating the remaining abort events in detail

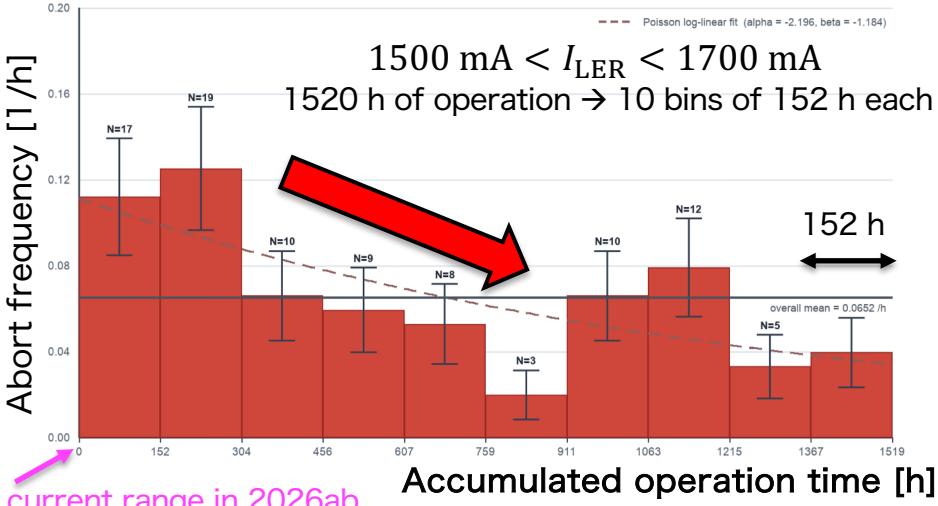
Yao-san's talk today



Conditioning effect on SBL rates

Conditioning: lower abort rates with longer operation at similar beam currents.





First reached this current range in 2026ab

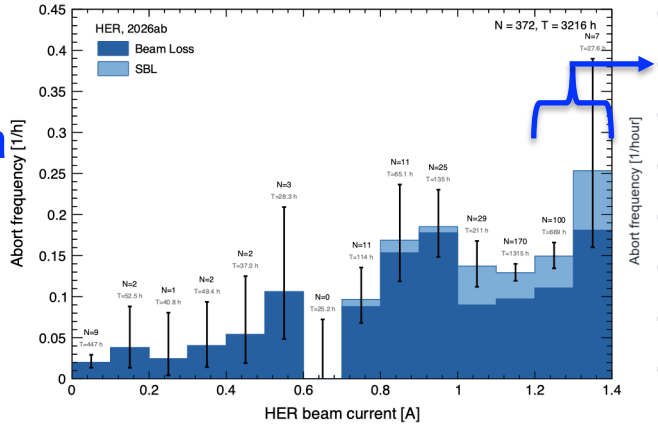
Fit the data with the exponential model: $r(t) = \exp(\alpha + \beta t)$ → $\beta = -1.2 \pm 0.36$

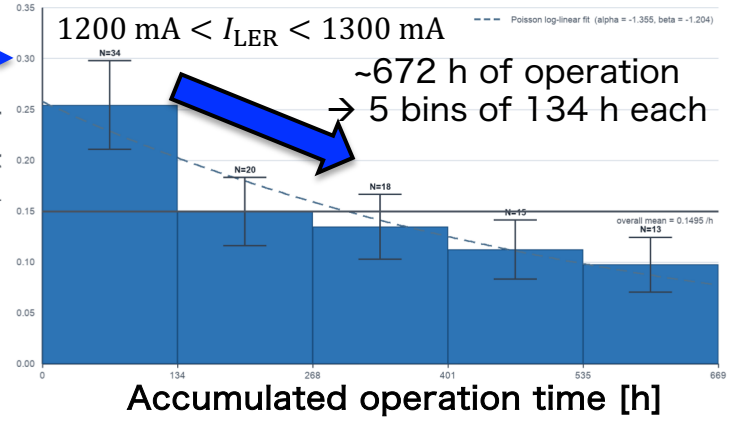
The null hypothesis $\beta = 0$ is rejected

- The same trend is observed with different binning and beam-current ranges

Also fit the HER data

→ $\beta = 0$ is also rejected





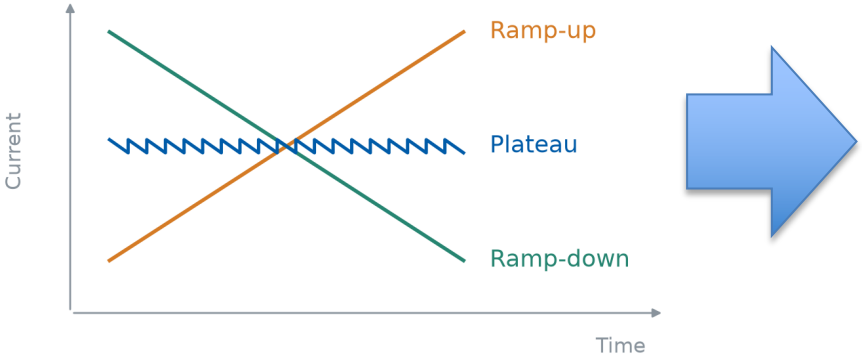
Conditioning effect is observed in both LER and HER

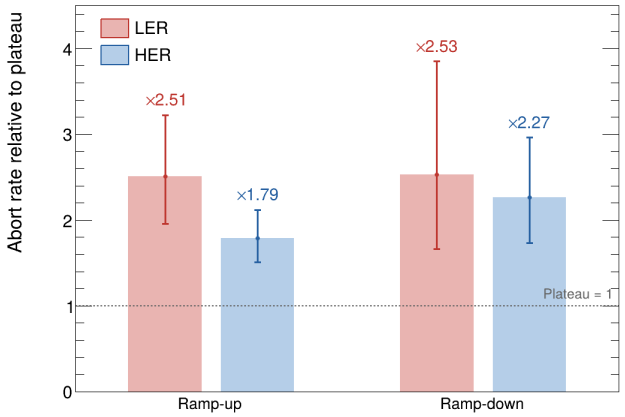
SBLs during beam-current change

The frequency during beam current changes appears to be higher

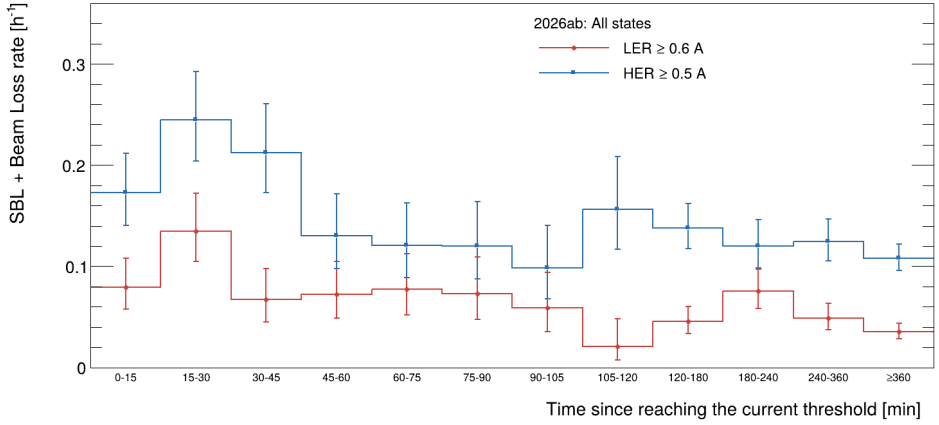
- Use 2026ab data with $I \geq 0.5$ A

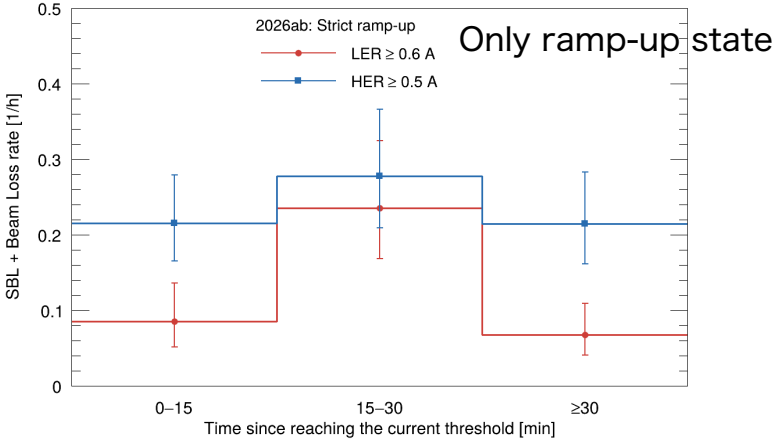
※ consider beam currents and conditioning effects





Higher frequency is especially observed early after abort recovery





Similar trends are also observed in the 2024 and 2025 data

Beam current/conditioning alone do not fully explain the frequency dependence

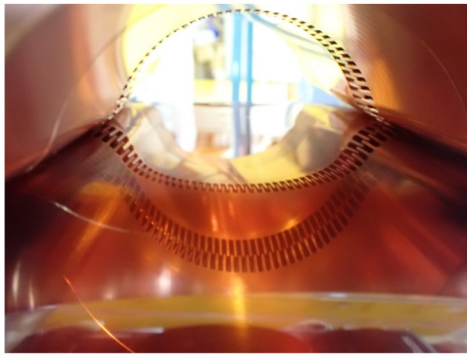
Hypothesis: thermal deformation → Dust?

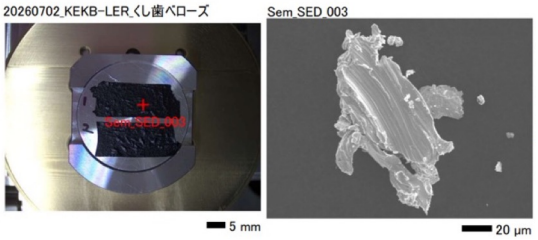
Hypothesis: thermal deformation

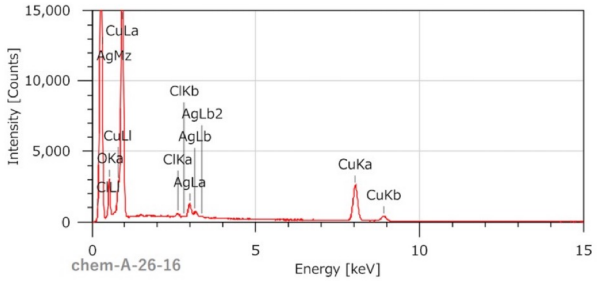
Thermal deformation could release dust that interacts with the beam

- Dust release was observed when bellows were manually expanded/compressed

Two mechanisms: rubbing at the RF fingers produces dust. The dust falls through the comb gaps. Rubbing b.t.w. the comb teeth also produces dust



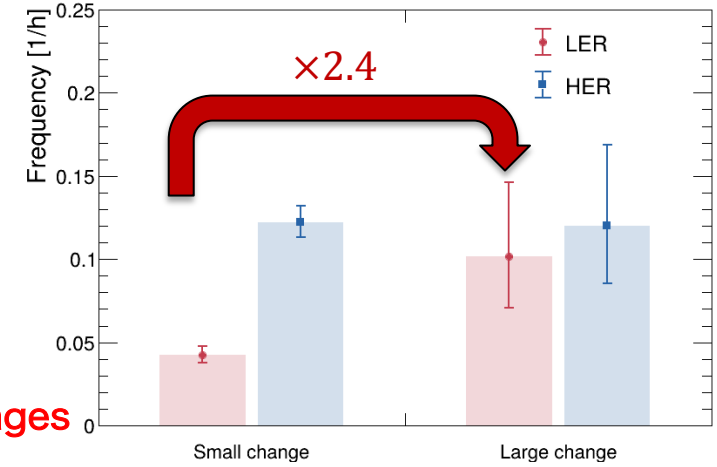




Could thermal deformation during beam operation also release dust?

Check a dependence on temperature changes

- Take 2026ab data under plateau condition
  - Compare rates with small/large temperature changes
- Use ~1100 temperature sensors for each ring
  - 10-min change in the ring-averaged temperature



LER: Tendency toward higher rates at large temperature changes

HER: No clear temperature dependence is observed

These observations are consistent with the thermal deformation hypothesis for LER

→ Temperature stability should be considered for the 2027ab run

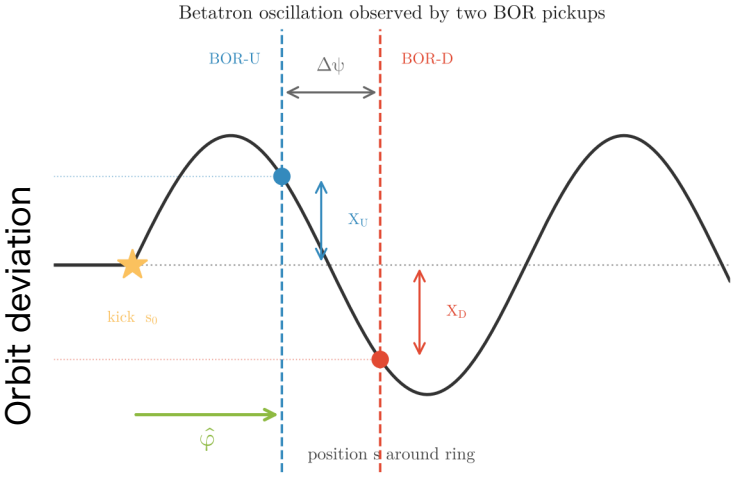
How to find the location; BOR

※ Bunch-Oscillation-Recorder (BOR)

BOR is useful to identify the kick source

- $X_U = A\sin\phi,\ X_D = A\sin(\phi + \Delta\psi)$

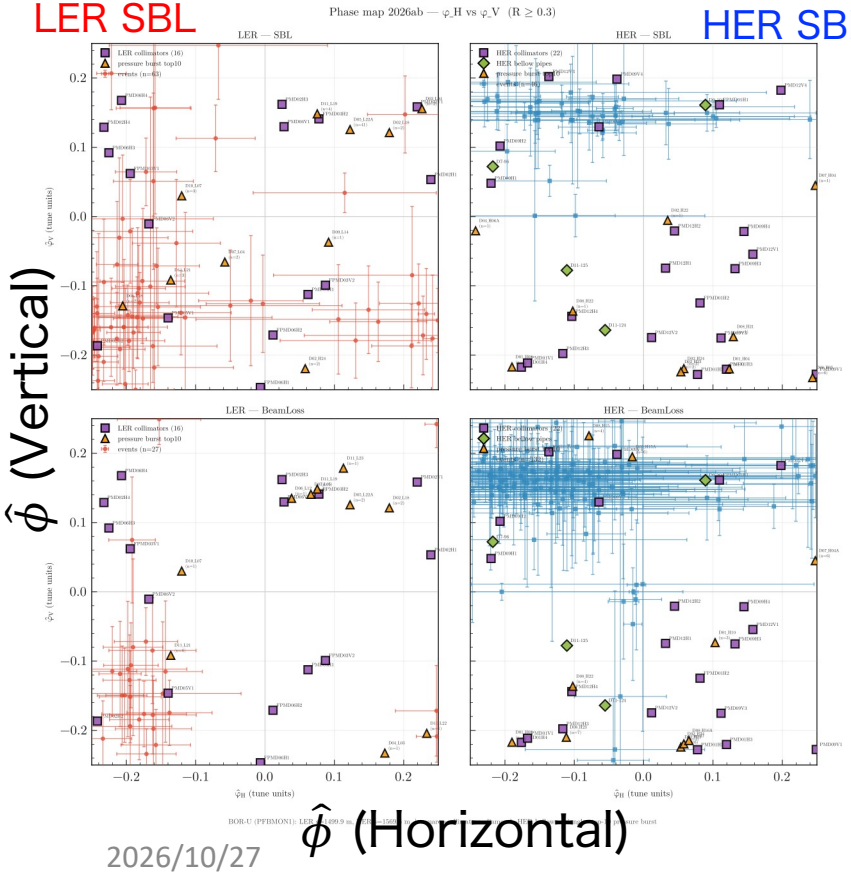
→ $\phi = \arctan2(X_U, X_D)/2\pi$ (if $\Delta\psi = 90°$)



Computed horizontal/vertical phases with 2026ab

LER SBL

HER SBL



The phase appear to cluster in specific region

- This could indicate common source locations

Same phase ⇏ Same location

→ Need to narrow down the candidate

Analysis is ongoing…

we will inspect some beam pipes based on this result

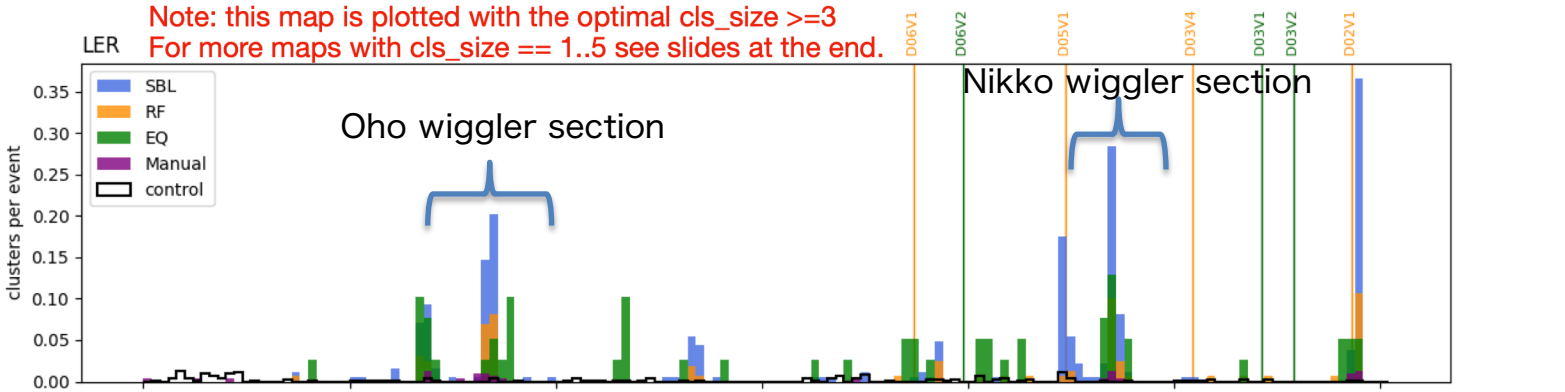
Pressure anomalies

D. Meleshko

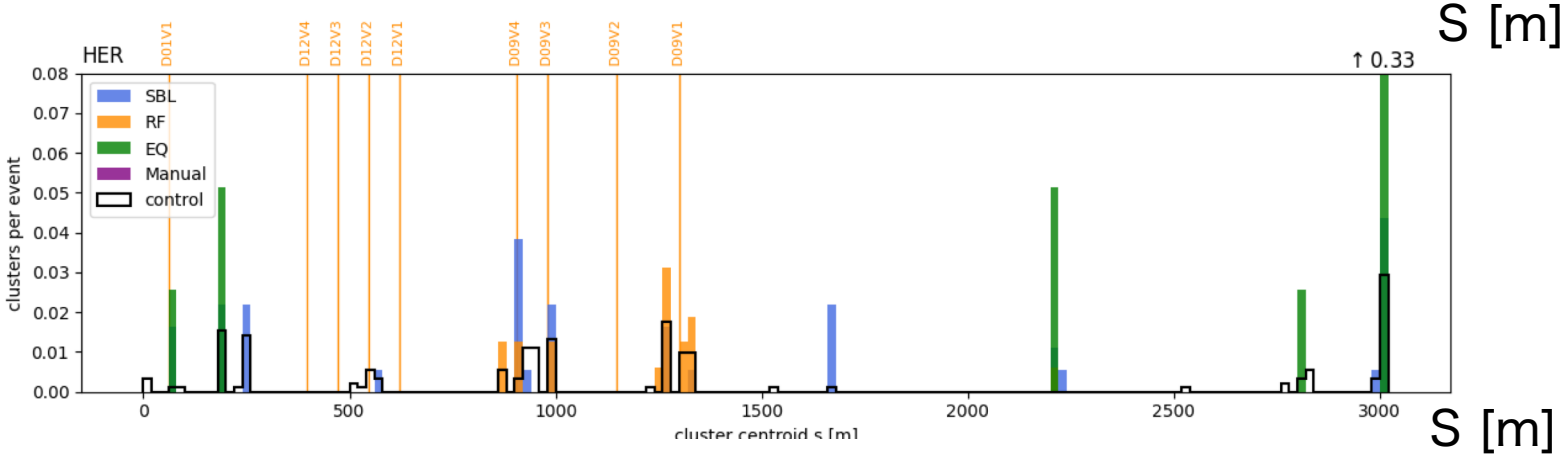
Tried to identify the location by checking pressure anomalies

- Identify pressure rises within ±10s of each event, using the preceding 5-15 min

LER



HER



Pressure anomalies are observed near bellows chambers in the wigger sections

- Correlations with BOR phase analysis are under investigation
- Some of these chambers will be replaced with water-cooled versions before 2027ab

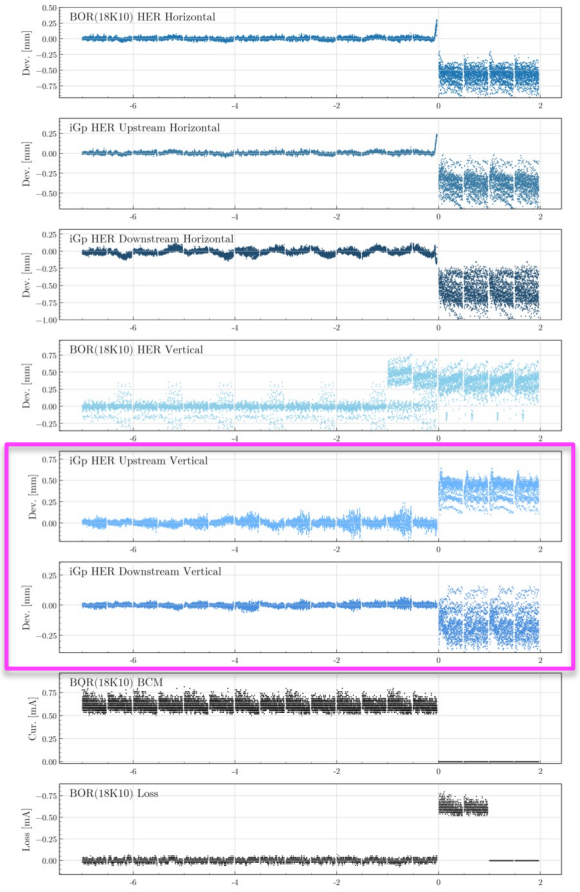
For other reasons. See Yao-san's talk

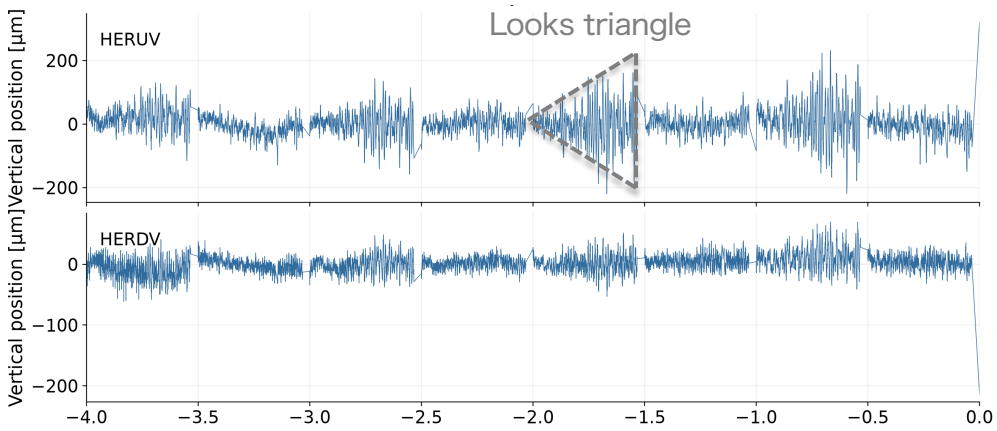
Other indication: HER oscillation

Found the interesting oscillation at HER SBL/Beam Loss event

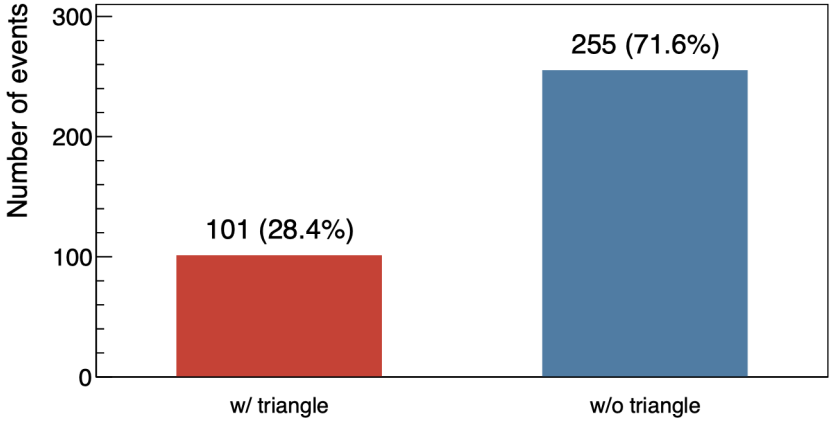
- The oscillation amplitude grows the train tail and decreases after the gap

6/16 12:29 HER Beam Loss





About 30% of HER SBL/BL events show the oscillation pattern

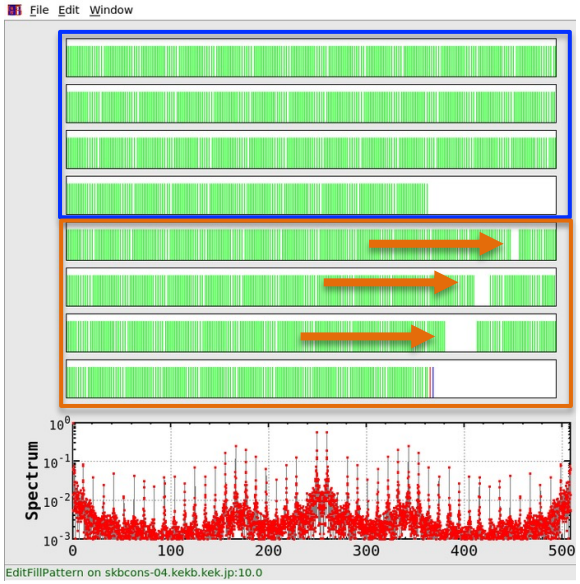


Ion trapping is a possible cause

→ Investigating whether mini-gaps can suppress these oscillations

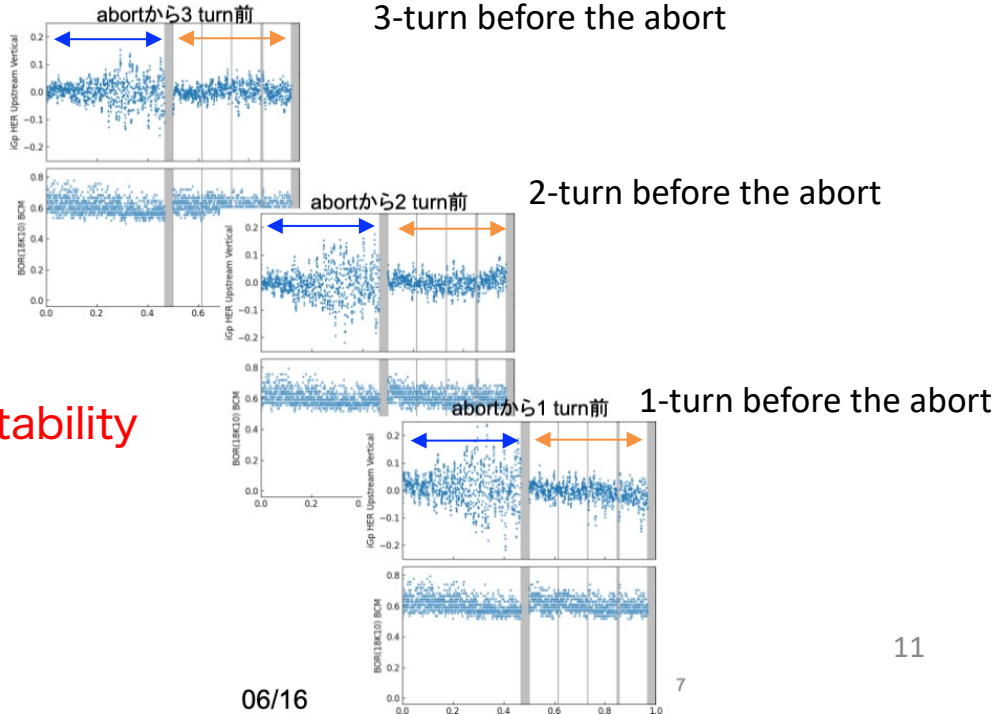
SBL: study during physics run

We tested different bunch-fill patterns during physics runs



- First train: same configuration
- Second train: added mini-gap
  - 10 buckets
  - 20 buckets
  - 40 buckets

e.g. June 16. HER abort event



Mini-gap may help suppress the instability

More investigation is ongoing

Strategy for 2027ab operation

Vacuum scrubbing for 2027ab

Both LER and HER show a clear conditioning effect

- Utilize vacuum scrubbing with detuned optics to reduce the SBL/Beam Loss rate

→ Developed a semi-empirical model to estimate how much time is needed

- Rate ∝ beam currents ⊗ conditioning terms ⊗ machine state

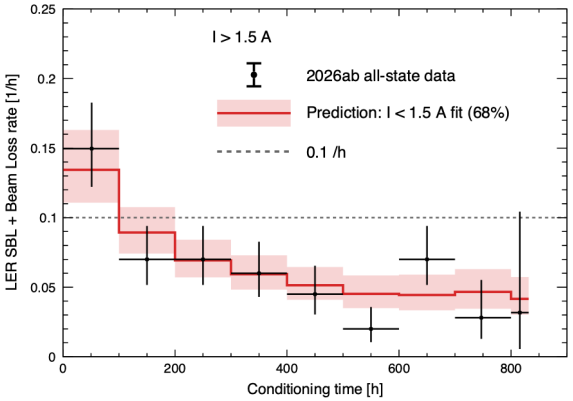
$$r(I,H,s) = f_0\, exp\left[k\left(\frac{I-\alpha[\mathrm{A}]}{0.1\ [\mathrm{A}]}\right)\right] \times \left[1 + E exp\left[-\frac{H}{\tau}\right]\right] \times C(s)$$

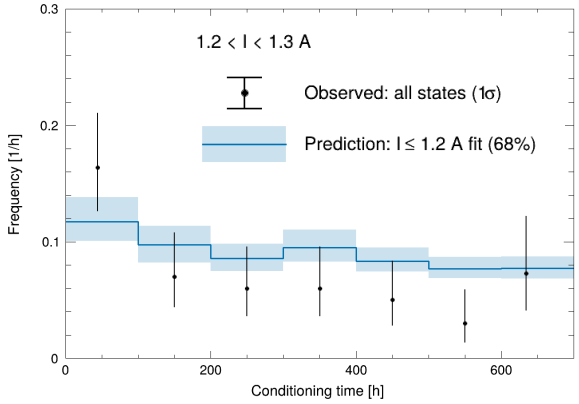
※ selected from several candidate models based on likelihood and agreement b.t.w predictions and observations

f_0: Event rate after sufficient conditioning at $I = \alpha$ A plateau [1/h]
α: baseline beam currents, $\alpha = 1.5$ A for LER, 1.2 A for HER
k: Current dependence; +100 mA → rate×e^k
H: accumulated operating time within the same 100 mA current bin
E: Excess rate without conditioning → rate×(1+E)
τ: conditioning time const [h]
s: machine state; plateau, ramp-up, falling
$C(s)$: State-dependent rate factor

Prediction checks beyond the fitted data

- Test predictions for later periods and higher beam currents using data excluded from the fit



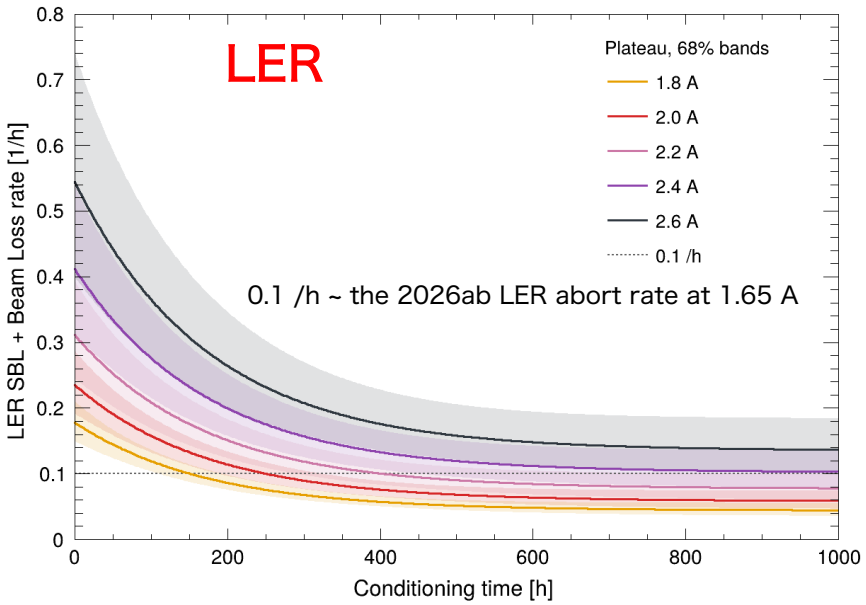


The model reasonably reproduces the conditioning trend for both rings

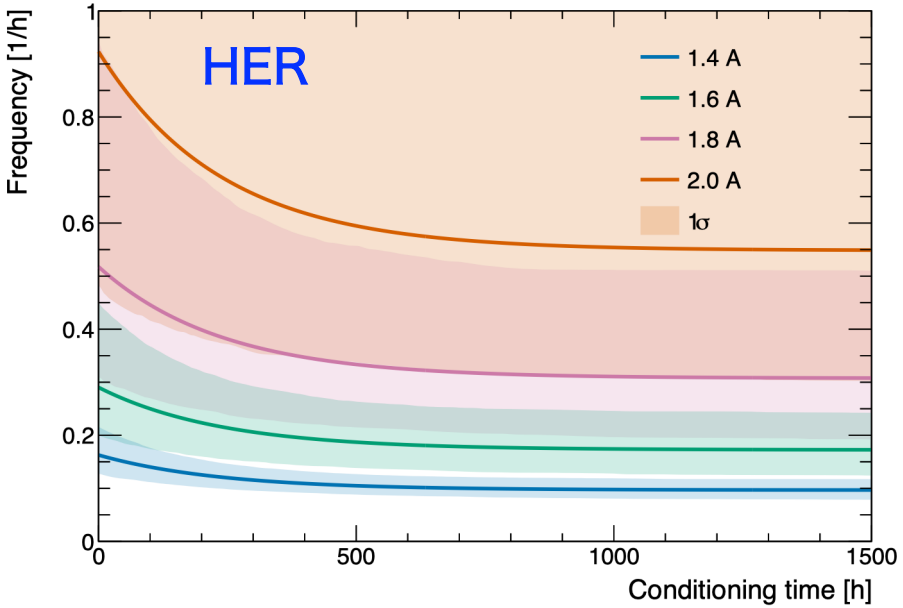
→ Used to estimate scrubbing time at higher beam currents

Prediction at higher beam currents

Conditioning time const $\tau = 173^{+48}_{-38}$ h



Conditioning time const $\tau = 239^{+118}_{-83}$ h



Results motivate 150-250 h of high-current vacuum scrubbing

- Balancing hardware constraints and physics running time, we propose:
  - Reach at least 2.0 A (LER) and 1.6 A (HER) early in the run.
  - Secure 100-150 h of vacuum scrubbing, targeting 150 h.

→ If the model is valid, SBL rates during physics runs should be substantially reduced

Discussion with hardware group is ongoing

to assess the risks of rapidly increasing beam currents

Mitigation of beam losses

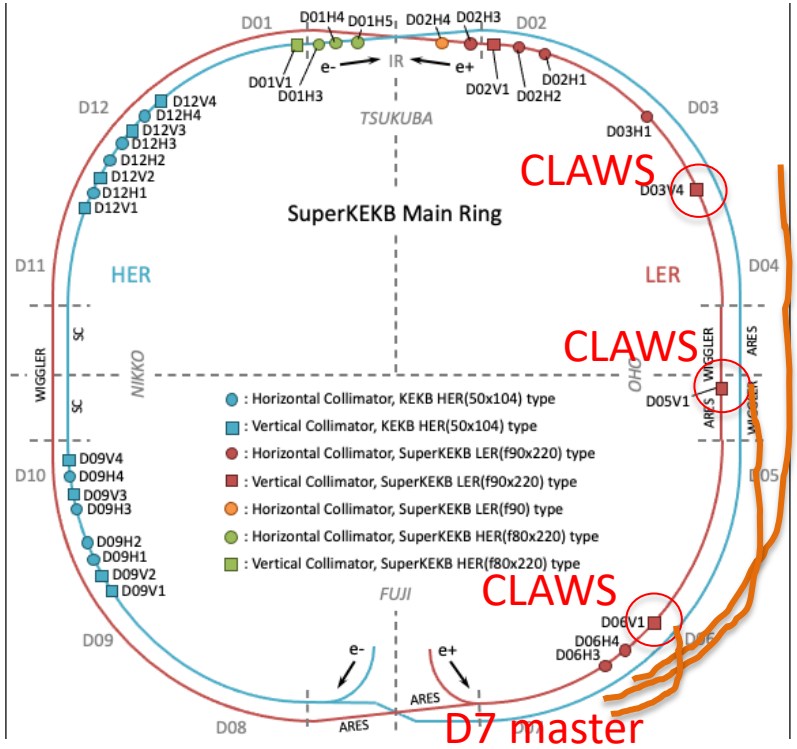
Earlier SBL detection and beam abort can mitigate IR losses

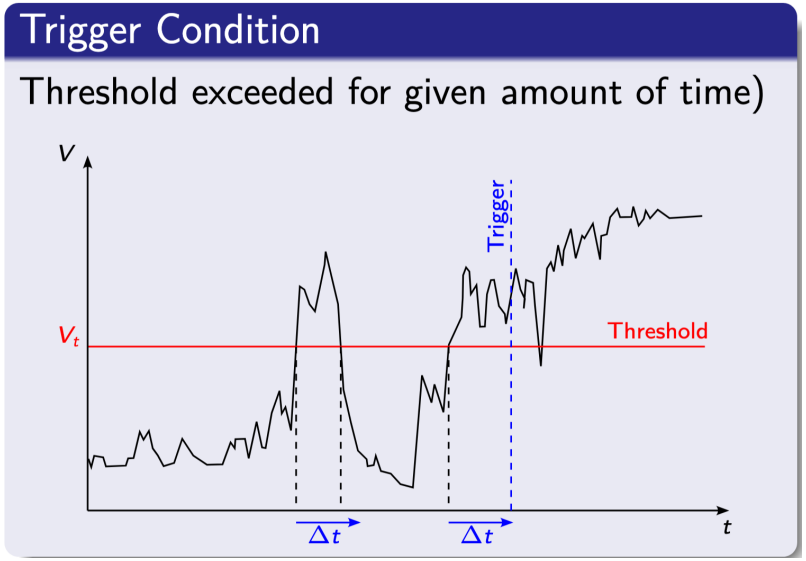
- BOR- and beam-size-based anomaly detection are being developed as longer term approaches

→ A more immediate approach is trigger earlier using beam-loss signals

Many beam-loss monitors are distributed around the ring

- E.g. CLAWS sensors (scintillator + SiPM) near collimators use TOT criteria to trigger an abort

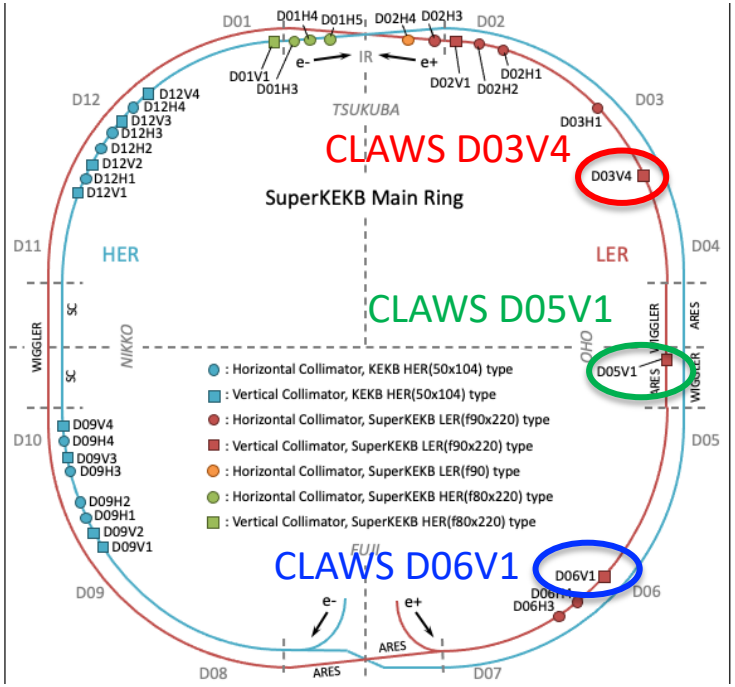


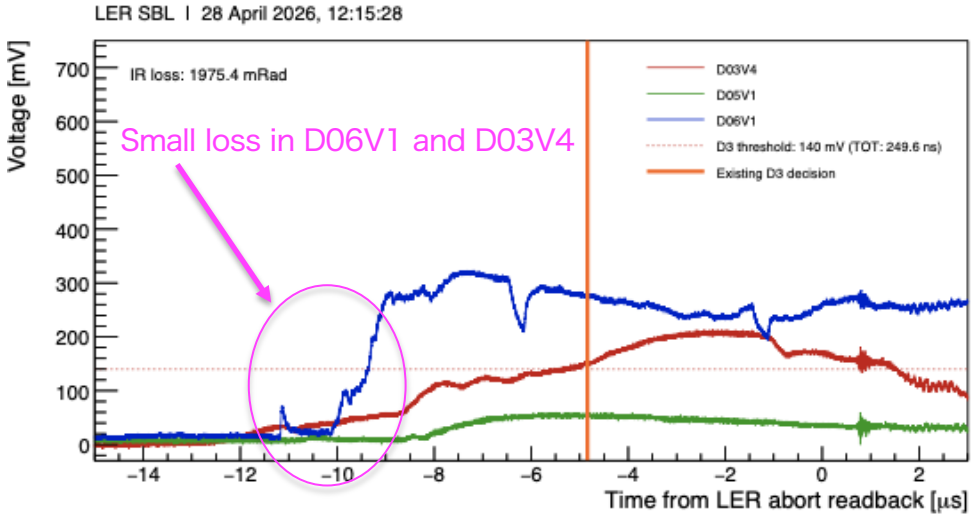


→ With a single CLAWS signal, earlier detection is limited by the need to avoid fake aborts

Advanced abort system

Idea: make abort decisions using information from multiple sensors



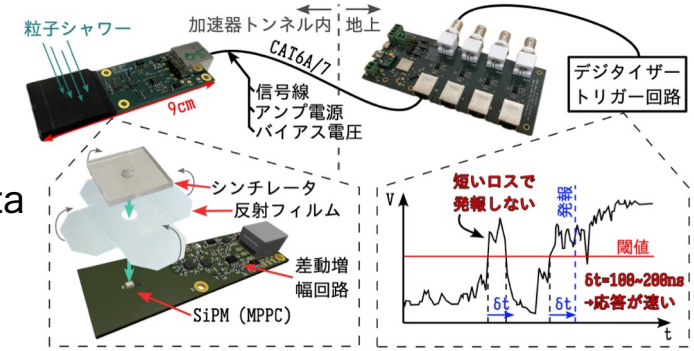


Can we use a coincidence b.t.w the two signals ?

→ Could suppress fake aborts compared with simply lowering a single-sensor threshold

Hardware setup is almost ready

~5 us earlier abort signals on average in both rings from past data
→ Further analysis is ongoing





1 Picoscope per 1 abort source

Board with Zynq



Algorithms using multiple signals is possible

Summary

Key findings

- Both rings show conditioning and machine-state dependence
- Temperature correlations in LER, BOR phases, and pressure anomalies provide clues to possible causes
- HER oscillation patterns motivate further mini-gap studies

Priorities for 2027ab

- Target ~150 h of high beam-current vacuum scrubbing (at least, 2 A/1.6 A)
- Inspect candidate locations and test mitigation measures
- Develop multi-sensor abort system: potential for ~5 us earlier abort signals

※ Longer-term R&D: real-time SBL precursor detection

- Synchronize multi-BOR readout for online anomaly detection
  - Offline BOR studies suggest ≥10 μs warning before beam loss for many SBLs
- Fast beam-size monitoring with FPGA-based processing
  - Beam-size blow-up is observed several to tens of μs before abort in some SBLs.

Backup

Phase reconstruction — method

- Baseline subtraction per bunch
  - No kicks: BOR stable at 0
  - Kicked bunches lead to $X_{U,D} \neq 0$
- Two BOR pickups at phase separation $\Delta\psi$
  - $X_U = A\sin\varphi, \quad X_D^{\mathrm{sc}} = A\sin(\varphi + \Delta\psi)$
  - Invert → source phase per bunch:

$$A_i \propto \sqrt{X_U^2 + (X_D^{\mathrm{sc}})^2}$$

$$\varphi = \frac{1}{2\pi}\arctan 2\left(X_U,\ \frac{X_D^{\mathrm{sc}} - X_U\cos\Delta\psi}{\sin\Delta\psi}\right)$$

- Circular mean over all selected bunches
  - Currently equal weighting, also tried A^2 weighting

LER: $\Delta\psi = 90° \Rightarrow \varphi = \arctan 2(X_U, X_D)/2\pi$
HER: $\Delta\psi_H = -38.7°\ \Delta\psi_V = -35.6°$

Phase estimator

$$\hat{\varphi} = \frac{1}{2\pi}\arg\left(\sum_i w_i\, e^{i2\pi\varphi_i}\right)$$

$w_i = A_i^2$ or $w_i = 1$

Coherence: $R = \dfrac{|\sum A_i^2\, e^{i2\pi\varphi_i}|}{\sum A_i^2}$

SEM: $\sigma_{\hat{\varphi}} = \sqrt{-2\ln R}/\sqrt{N_{\mathrm{eff}}}$

$R \approx 1$ single coherent source
$R \approx 0$ no coherent kick

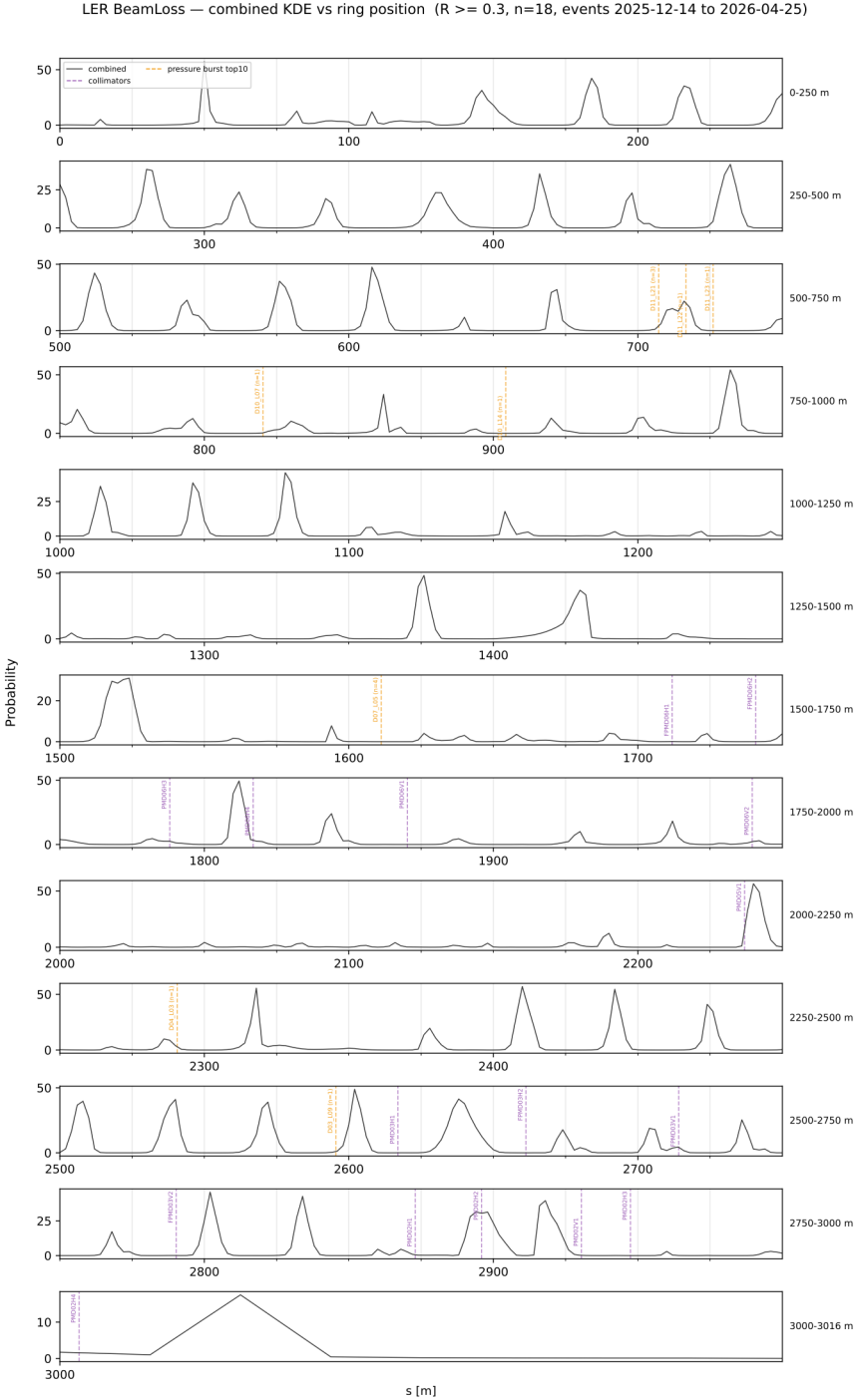
Uncertainty on $\hat{\varphi}$

Signal window: pre-abort samples only. Baseline selection: $t \in (-5, -0.5)$ turns for the main analysis. Samples with significant BCM loss are excluded by a lost-bunch mask.

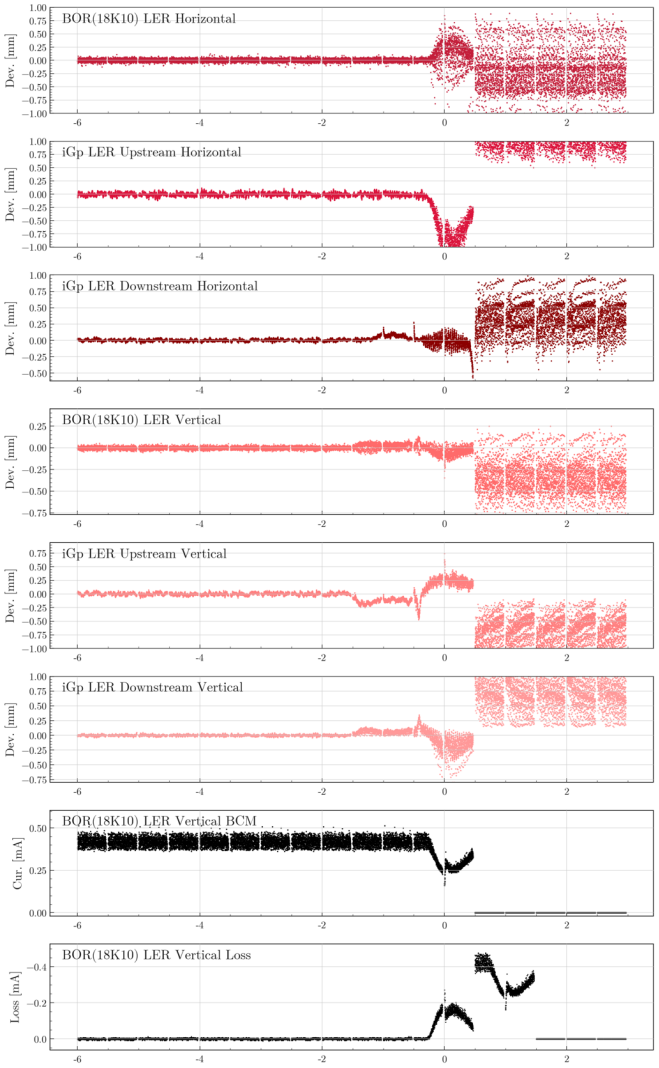
$$\sigma_{\hat{\varphi}}^{\mathrm{tot}} = \sqrt{\sigma_{\mathrm{stat}}^2 + \sigma_{\mathrm{slope}}^2 + \sigma_{\mathrm{amp}}^2 + \sigma_{\mathrm{noise}}^2 + \sigma_{\mathrm{mask}}^2 + \sigma_{\mathrm{turn}}^2}$$

Component	Method	Interpretation
σ_{stat}	Bootstrap resample bunches ($N = 100$)	finite-sample bunch scatter
σ_{slope}	Resample $X \to X(1+\epsilon)$ per sensor, $\epsilon \sim \mathcal{N}(0, \sigma_{\mathrm{cal}}/\lvert\mathrm{slope}\rvert)$	calibration uncertainty
σ_{amp}	$\mathrm{std}(\hat{\varphi})$ over 20 amplitude thresholds	sensitivity to bunch selection
σ_{noise}	Propagate sensor noise through phase formula	readout noise contribution
σ_{mask}	Recompute $\hat{\varphi}$ for several BCM-loss mask thresholds	sensitivity to BCM masking choice
σ_{turn}	turn-to-turn scatter of the phase mean	non-stationarity / evolving source

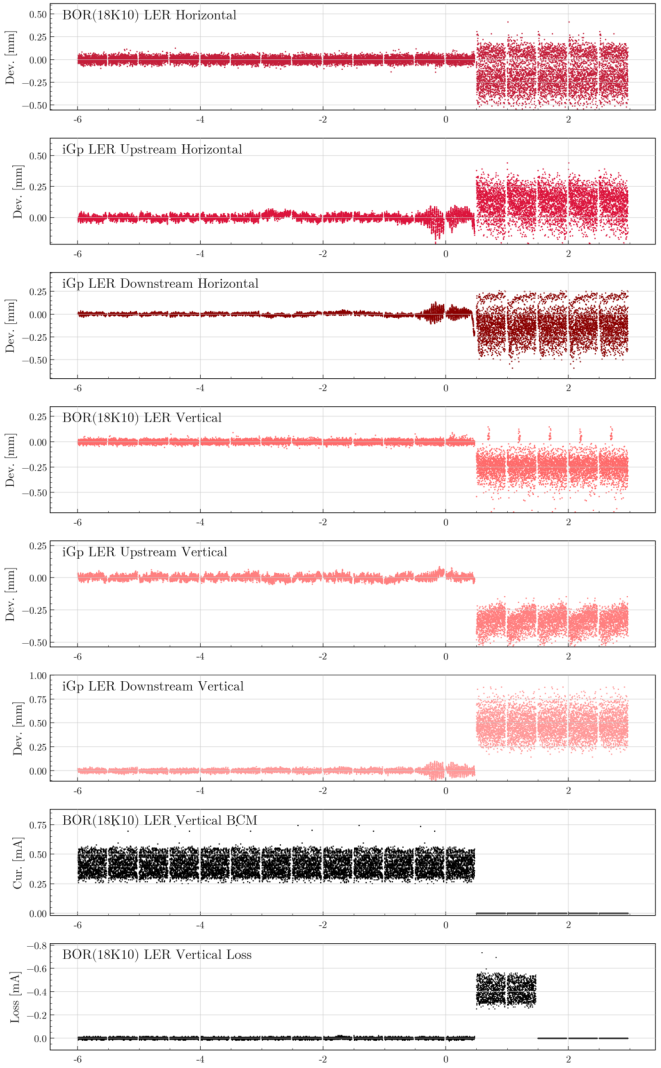
LER Beam Loss



SBL vs Beam Loss



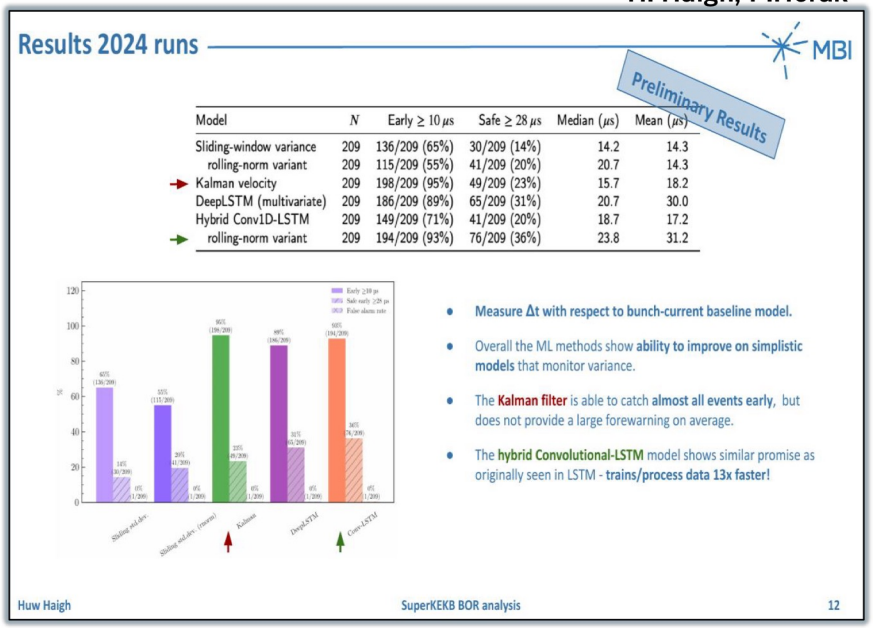
Bunch current Loss Monitor



Bunch current Loss Monitor

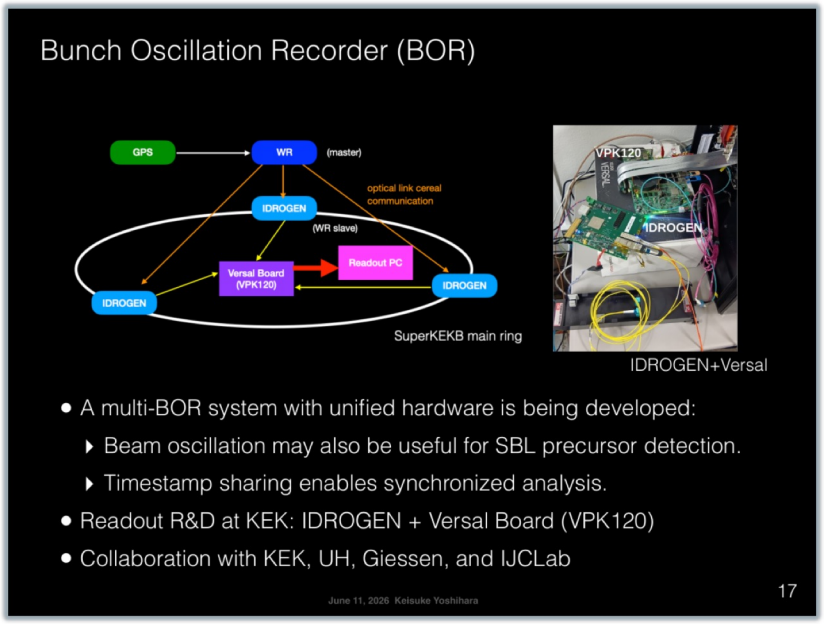
c) BOR waveforms

H. Haigh, P.Horak



- Offline analysis on 209 SBLs in 2024
- Various anomaly-detection methods are compared
- 71–90% can be flagged ≥10 μs before loss, depending on the method. Up to 36% have a ≥28 μs warning margin in the preliminary study.

Y. Yoshihara



- Install multiple BORs and synchronizeed readout to conduct online analysis for anomaly triggering
- Hardware R&D for IDROGEN modules and Versal Board is currently ongoing

Riku Nomaru, Bela Urbschat, Cody Driver, Gaku Mitsuka,
Matt Andrew, Keisuke Yoshihara

Fast Beam Size monitor (SiXRM)

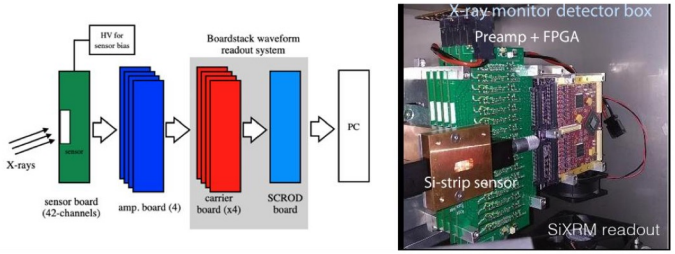
Yoshihara's report at the MDI parallel session SiXRM paper draft

Motivation

- **Bunch-by-bunch beam size measurement is critical for understanding SBL mechanism.**
- In some SBL events, beam-size blow-up appears to start much earlier than beam oscillation seen in BOR.
- Fast beam size measurement could be a candidate of SBL precursor signal required for turning PXD back on.

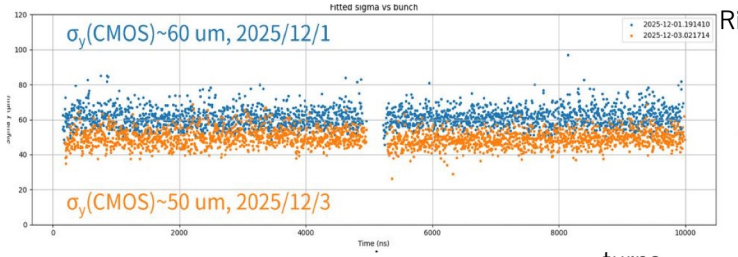
Current SiXRM setup and its readout

Yoshihara



SiXRM employs Belle II TOP boardstack to enable bunch-by-bunch measurement

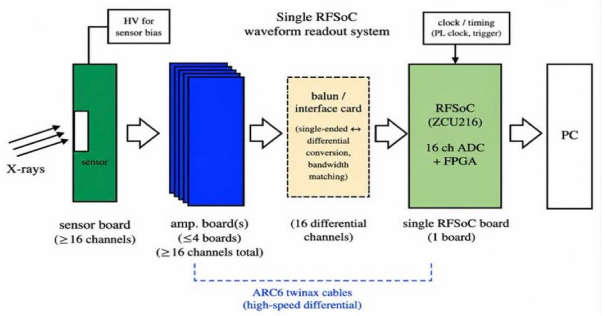
Successful bunch-by-bunch beam size measurement



Riku Nomaru

Consistent with turn-by-turn measurement by CMOS sensor

RFSoC-based readout and NN-based beam-size estimation on FPGA are getting ready



Yoshihara