

Sudden Beam Loss

Kenta Uno (KEK IPNS)

on behalf of SBL TF team

Accelerator Review Committee

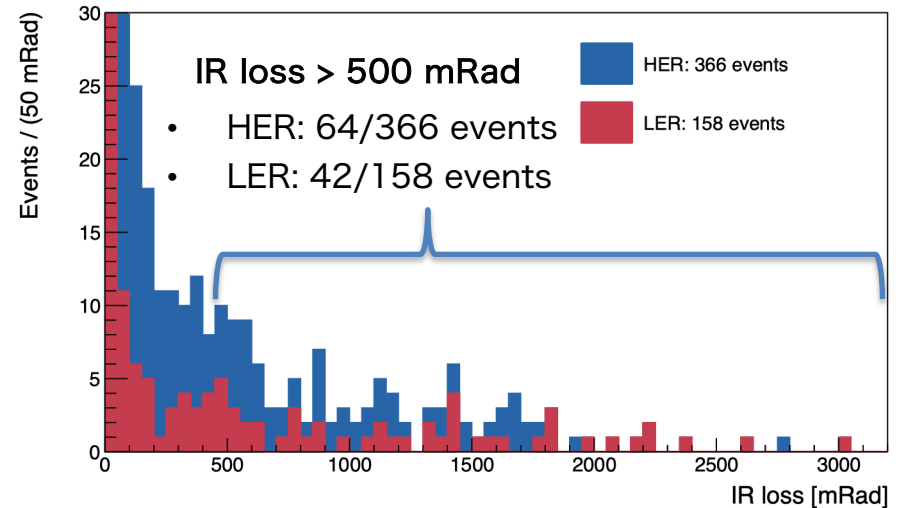
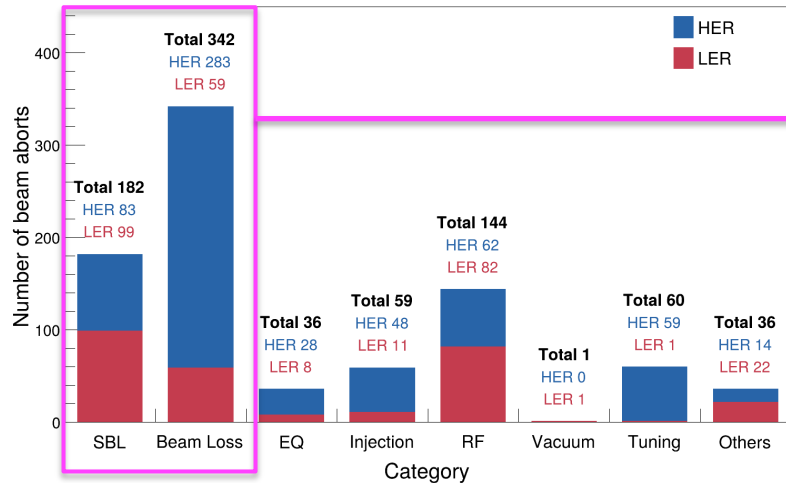
October 27, 2026

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)



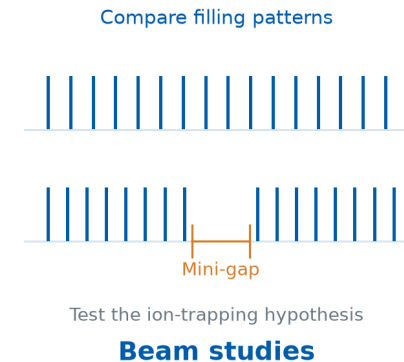
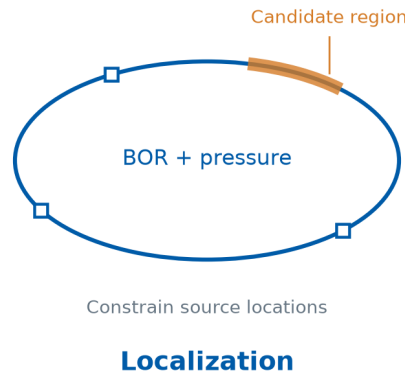
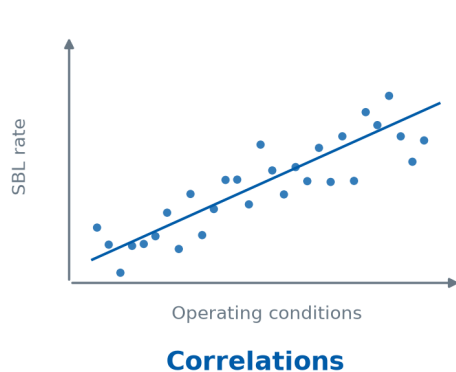
Major objectives of SBL TF:

- 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

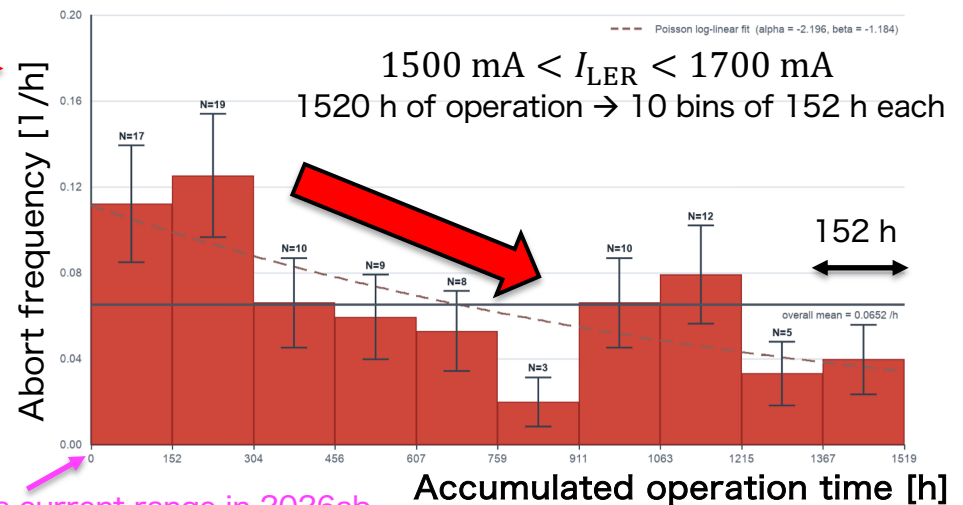
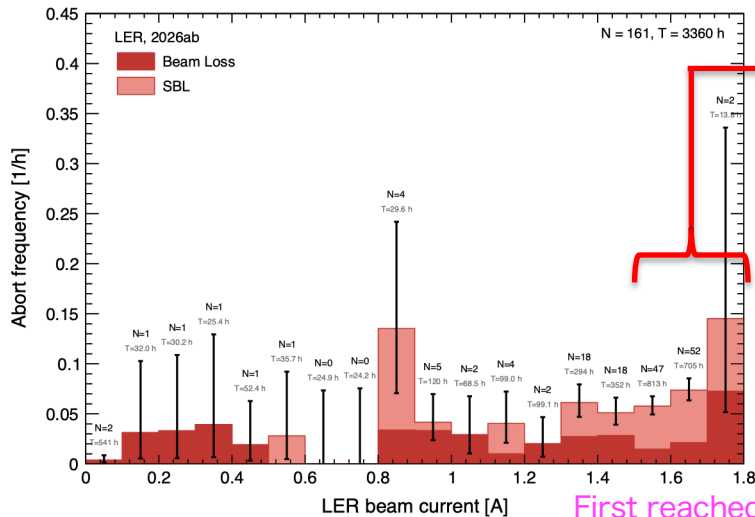
- Explore correlations with operation conditions
 - Statistical analysis of conditioning, machine states, and other variables
 - Anomaly detection.
- Locate possible sources using beam diagnostics
 - BOR phase analysis, pressure bursts, signals from clearing electrode
- Test hypotheses during beam operation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



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

Conditioning effect on SBL rates

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



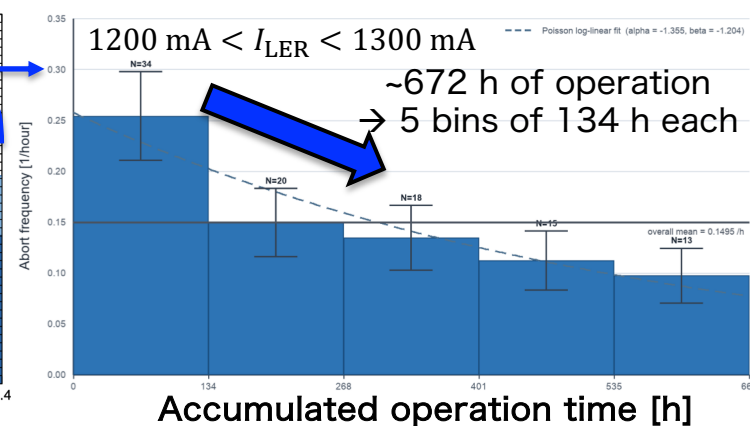
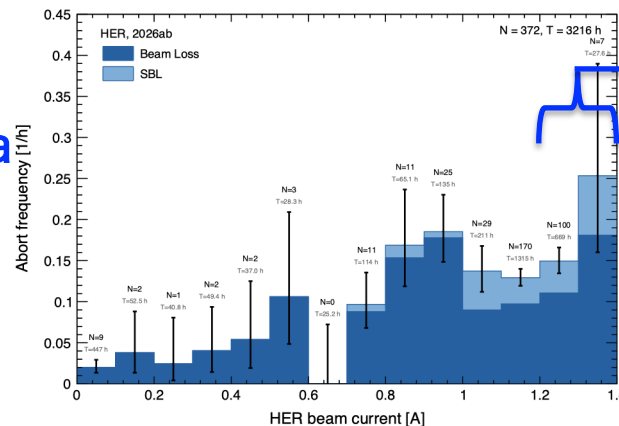
Fit the data with the exponential model: $r(t) = \exp(\alpha + \beta t) \rightarrow \beta = -1.2 \pm 0.36$

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



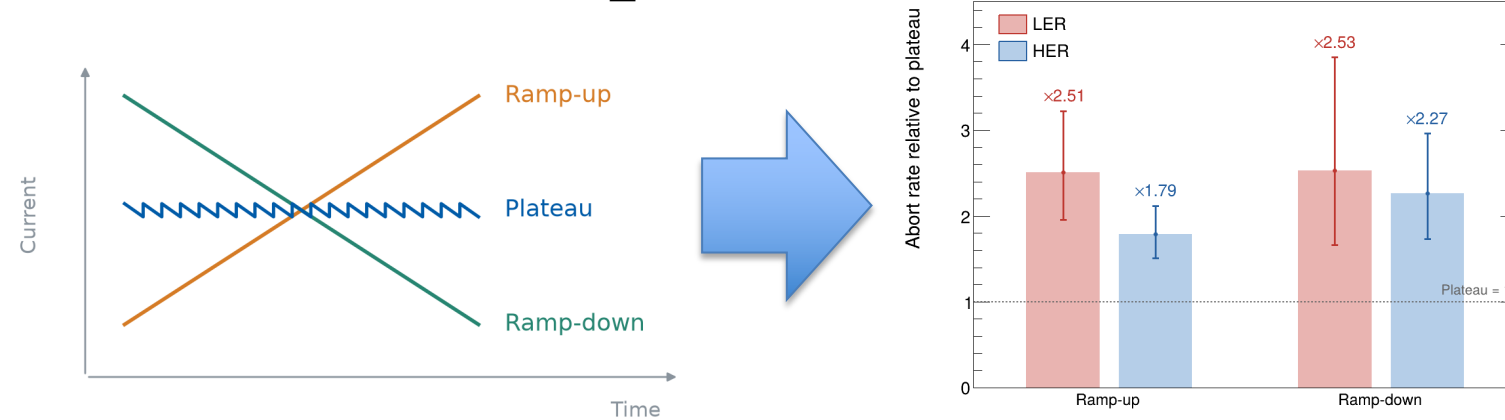
Conditioning effect is observed in both LER and HER

SBLs during beam-current change

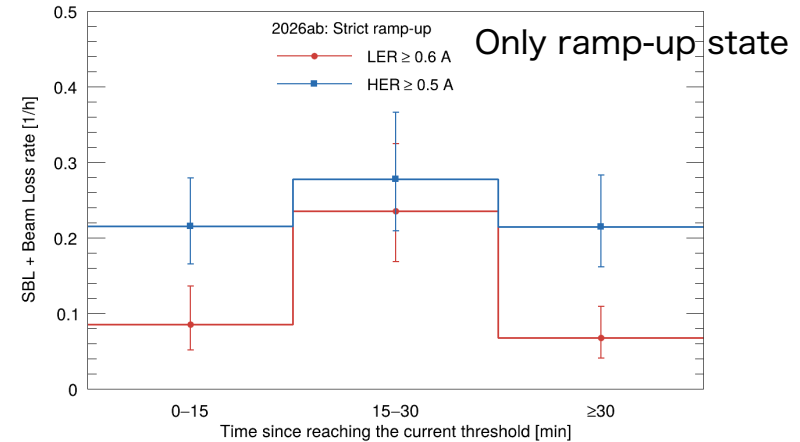
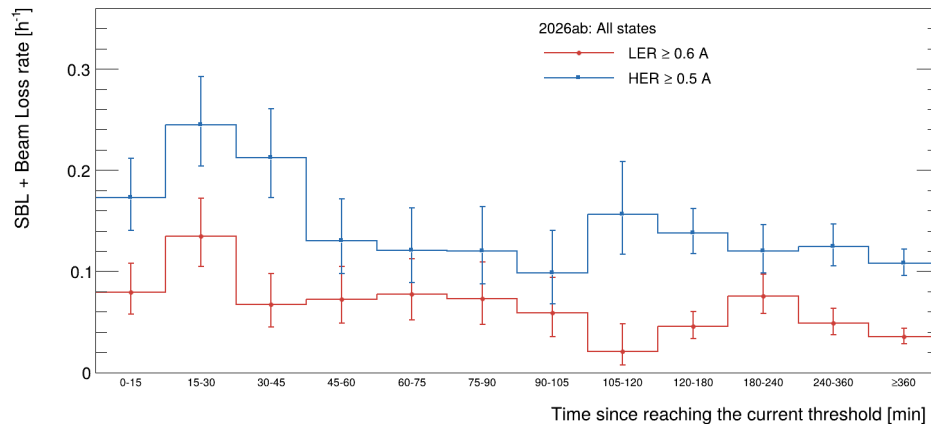
The frequency during beam current changes appears to be higher

- 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

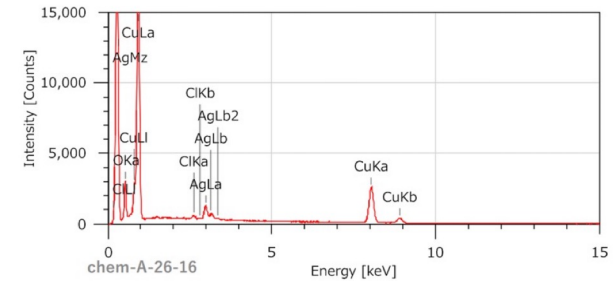
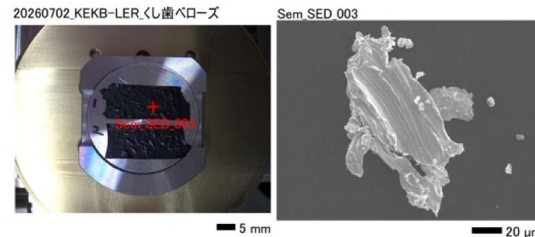
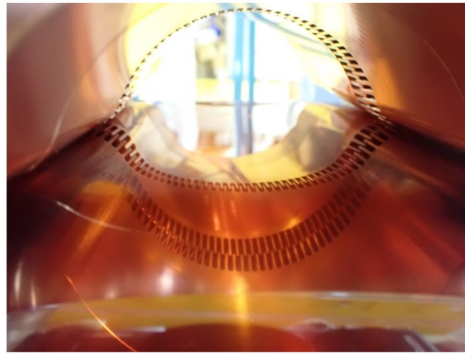
Hypothesis: thermal deformation $\rightarrow$ Dust?

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: dust from RF-finger rubbing falling through the comb gaps, and dust from rubbing between comb teeth



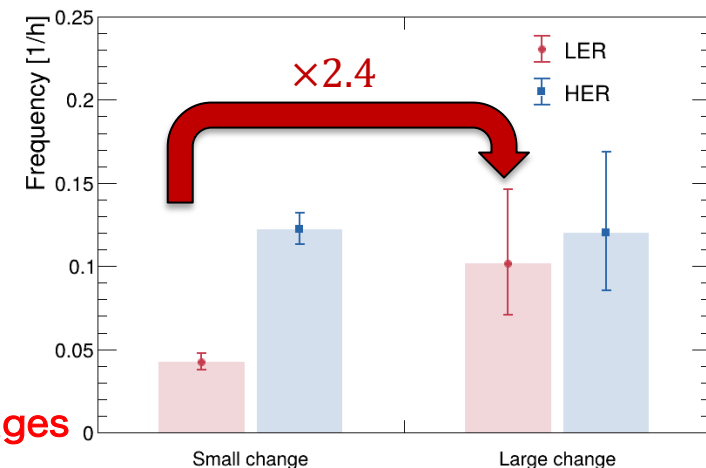
Could thermal deformation during beam operation also release dust?

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

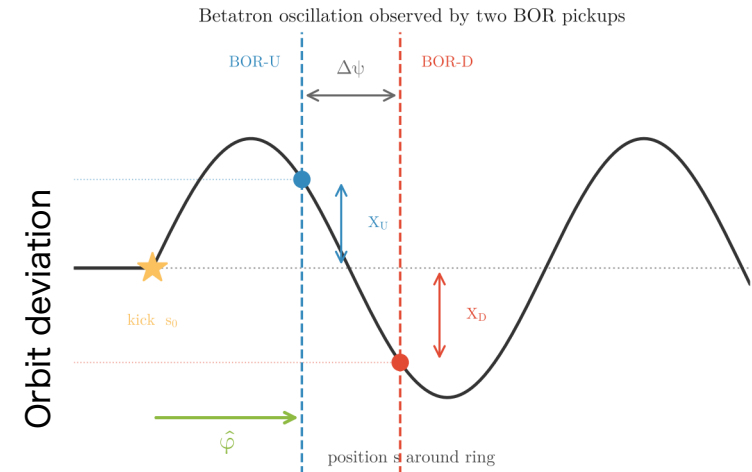
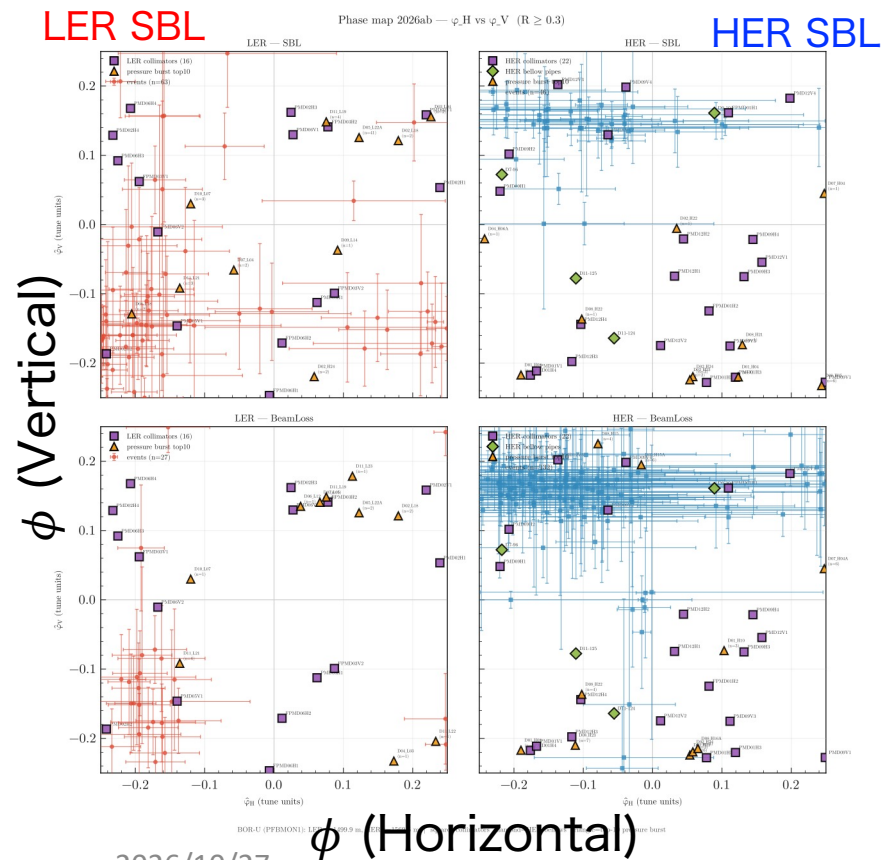
✂ Bunch-Oscillation-Recorder (BOR)

BOR is useful to identify the kick source

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

$\Rightarrow \phi = \arctan2(X_U, X_D)/2\pi$ (if $\Delta\psi = 90^\circ$)

Computed horizontal/vertical phases with 2026ab



The phase appear to cluster in specific region

- This could indicate common source locations

Same phase $\nRightarrow$ Same location

$\rightarrow$ Need to narrow down the candidate

Analysis is ongoing...

we will inspect some beam pipes based on this result

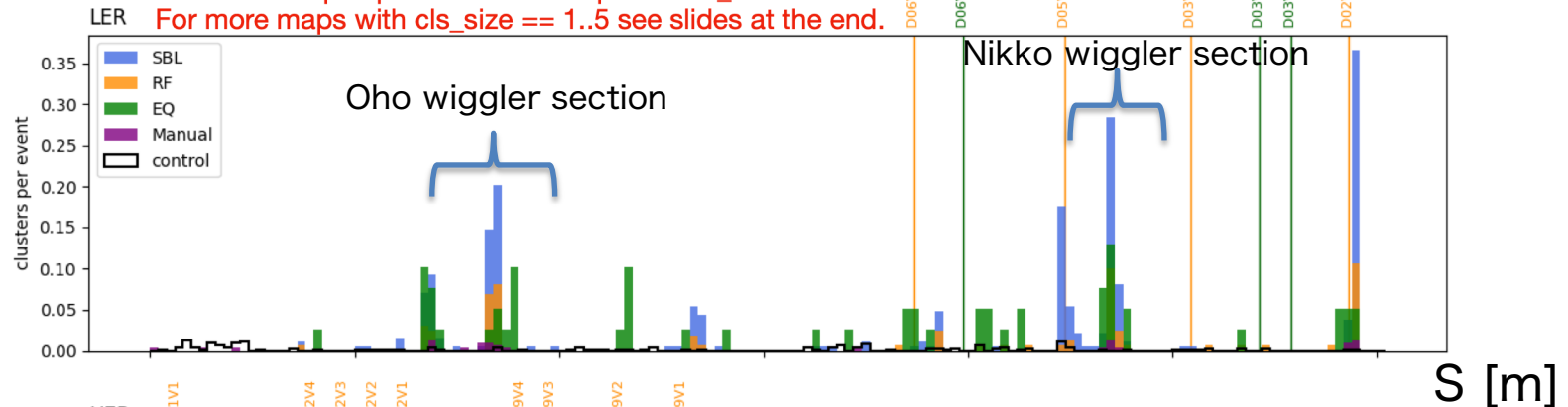
Pressure anomalies

Tried to identify the location by checking pressure anomalies

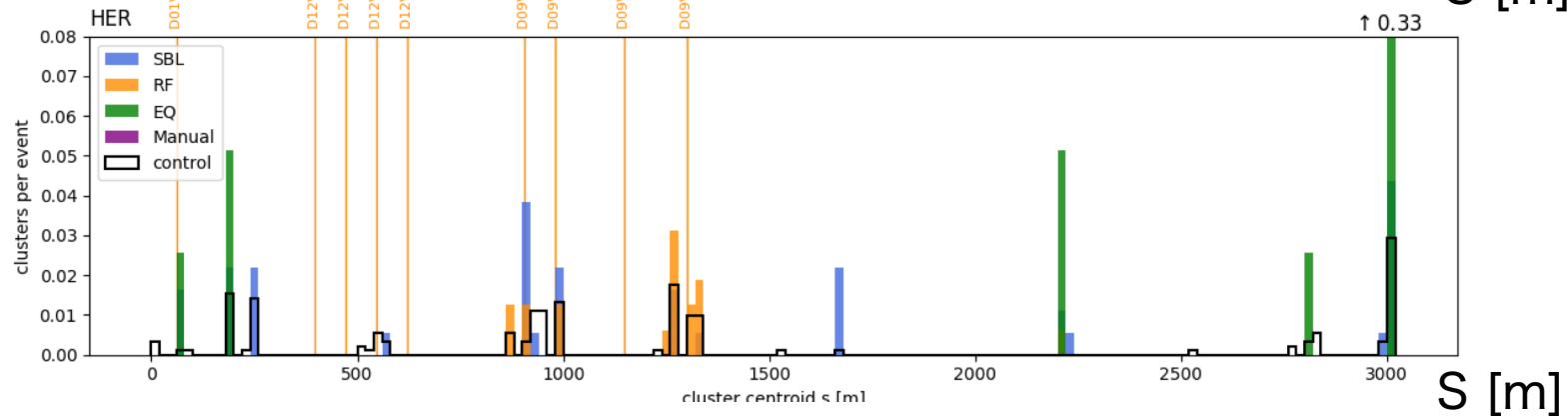
- Identify pressure rises within ± 10 s of each event, using the preceding 5-15 min

Note: this map is plotted with the optimal `cls_size` ≥ 3
For more maps with `cls_size` == 1..5 see slides at the end.

LER



HER



Pressure anomalies are observed near bellows chambers in the wiggler sections

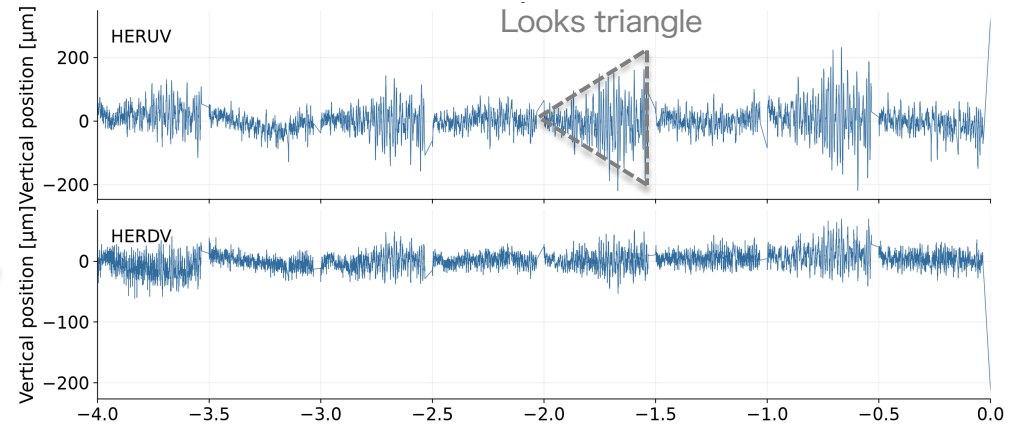
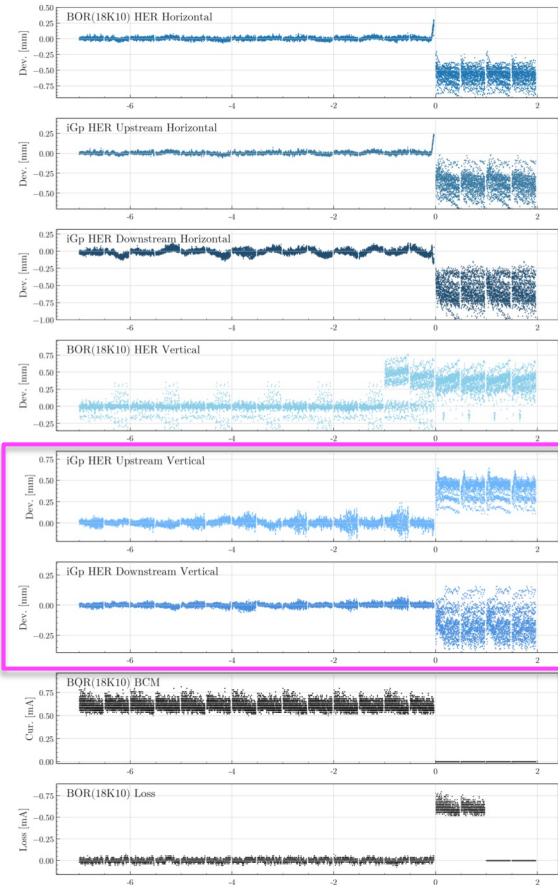
- Correlations with BOR phase analysis are under investigation
- Some of these chambers will be replaced with water-cooled versions before 2027ab

Other indication: HER oscillation

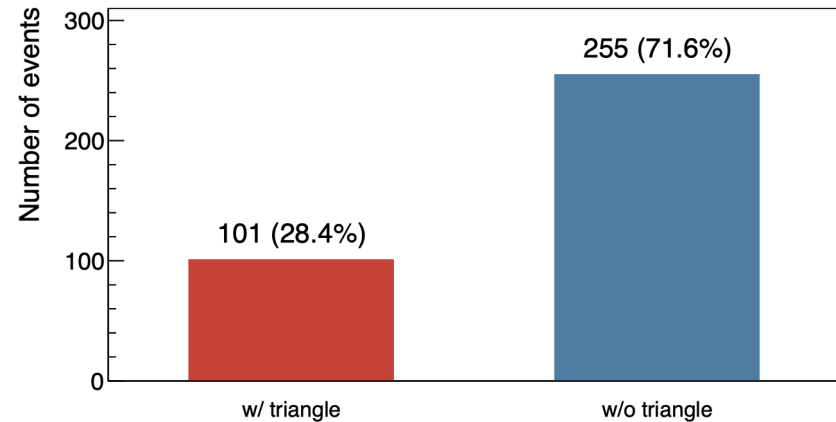
Found the interesting oscillation at HER SBL/Beam Loss event

- 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

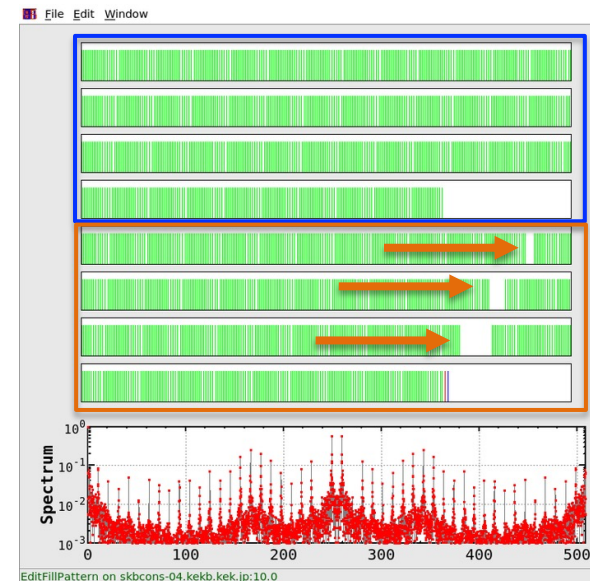


Ion trapping is a possible cause

→ Investigating whether mini-gaps can suppress these oscillations

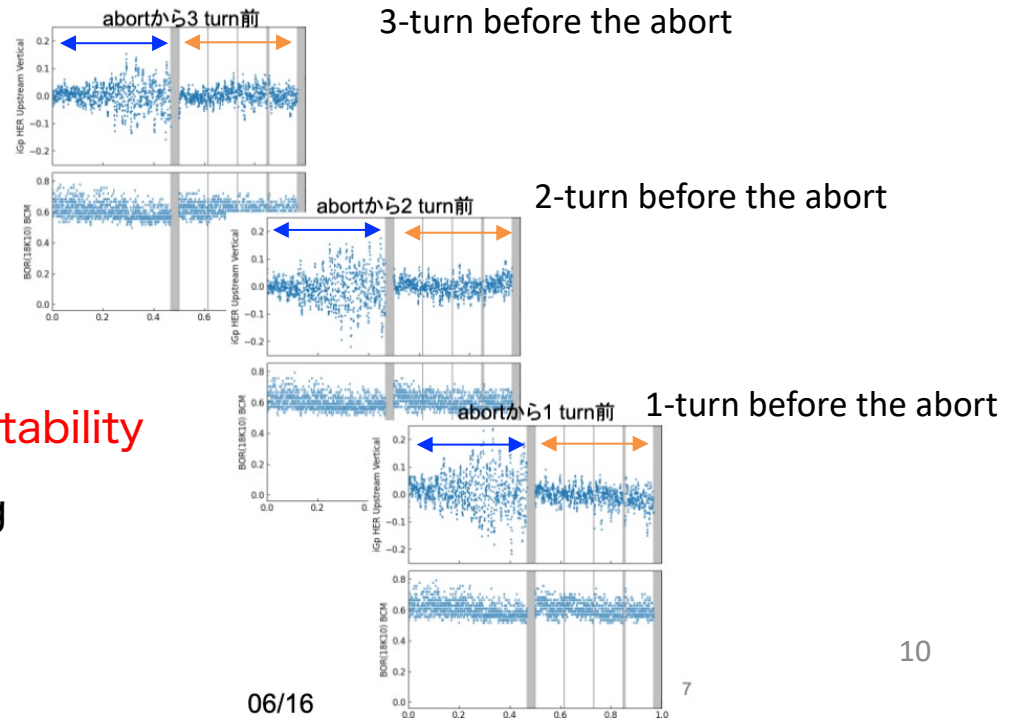
SBL: study during physics run

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 $\propto$ beam currents $\otimes$ conditioning terms $\otimes$ machine state

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

※ 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 $\rightarrow$ rate $\times e^k$

H : accumulated operating time within the same 100 mA current bin

E : Excess rate without conditioning $\rightarrow$ rate $\times (1+E)$

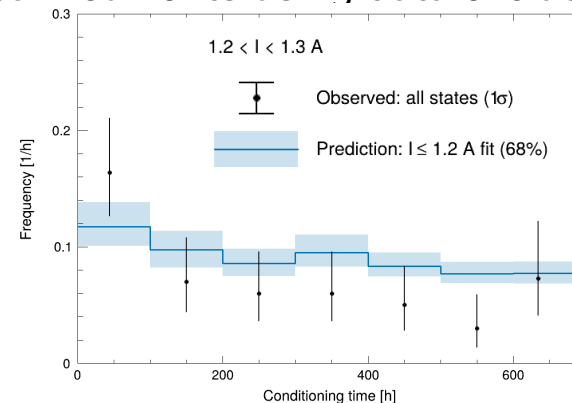
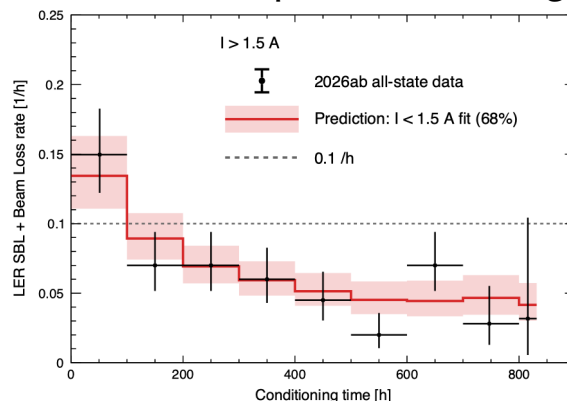
τ : conditioning time const [h]

s : machine state; plateau, ramp-up, falling

$C(s)$: State-dependent rate factor

Prediction checks beyond the fitted data

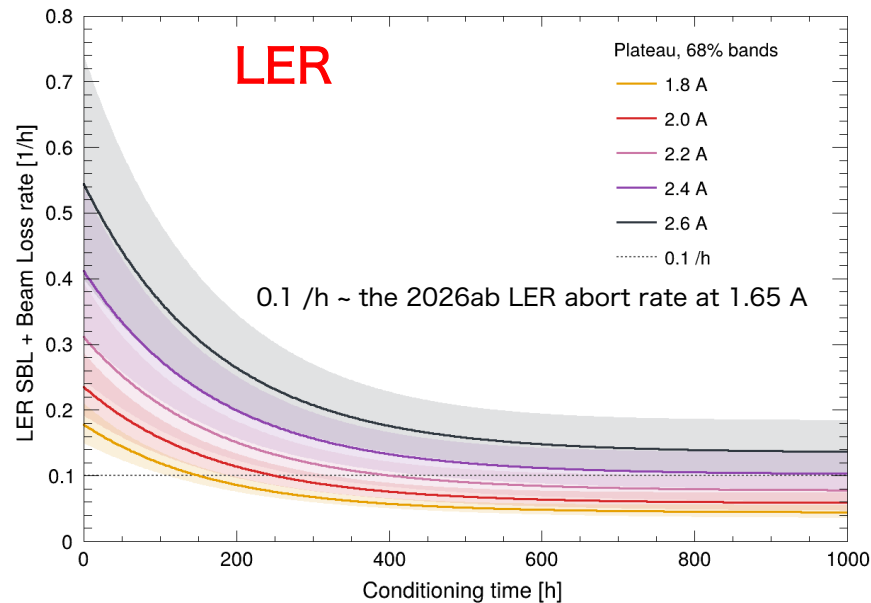
- Test predictions for later periods and higher beam currents using data excluded from the fit



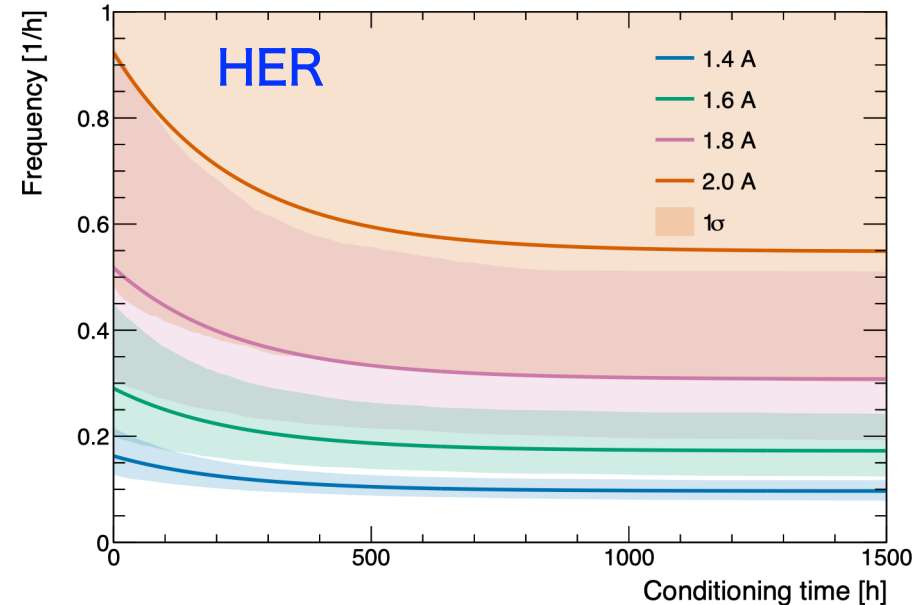
The model reasonably reproduces the conditioning trend for both rings

Prediction at higher beam currents

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



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

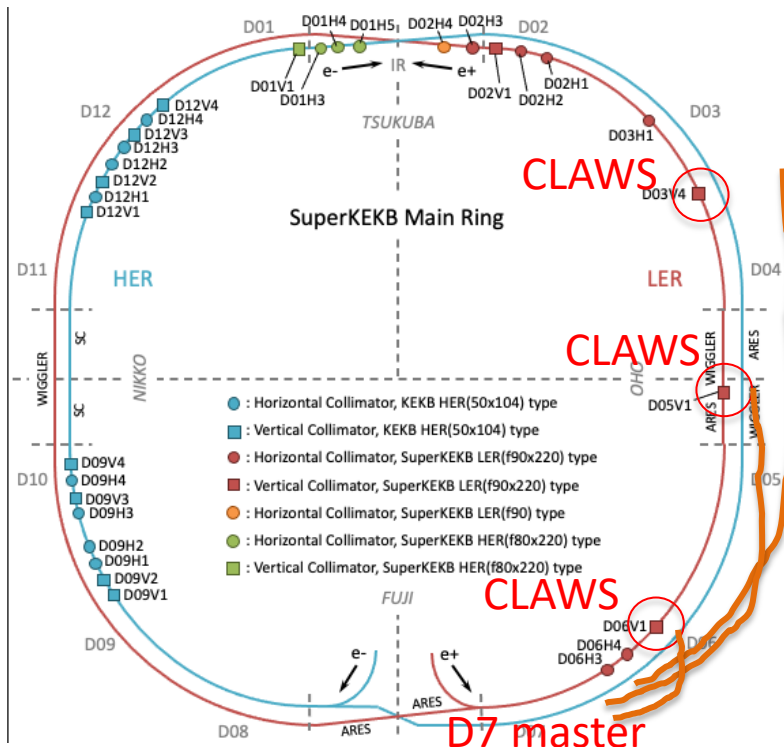
Mitigation of beam losses

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

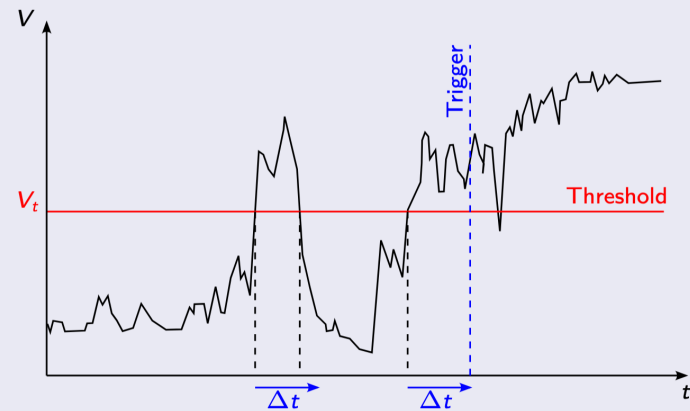
Many beam-loss monitors are distributed around the ring

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



Trigger Condition

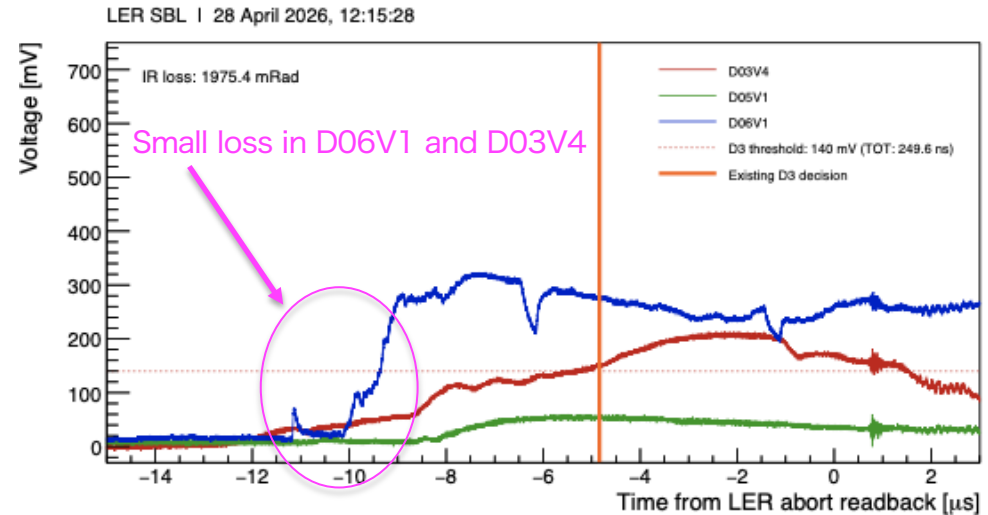
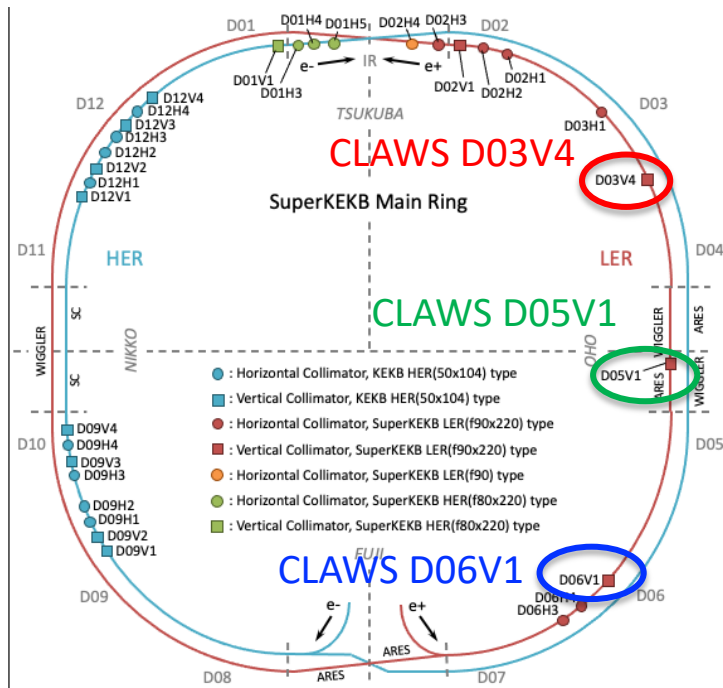
Threshold exceeded for given amount of time)



→ 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

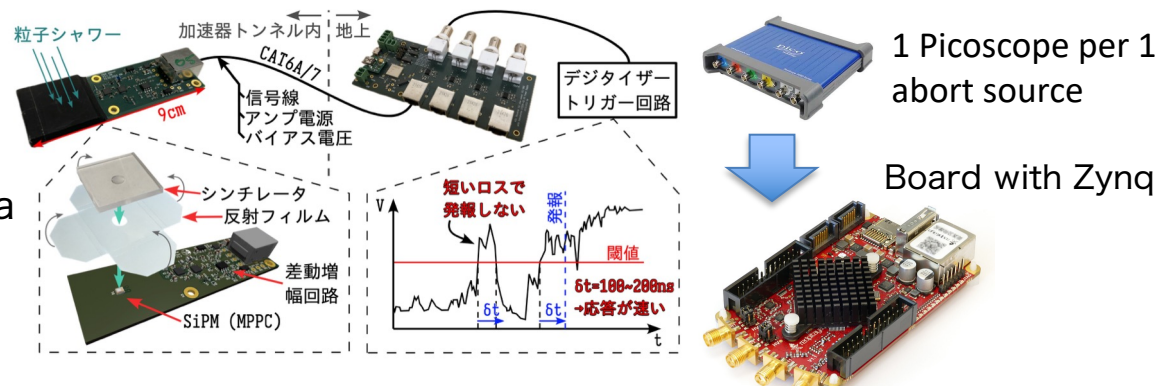


Can we use a coincidence b.t.w the two signals ?

→ 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



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 $\geq 10 \mu s$ 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

c) BOR waveforms

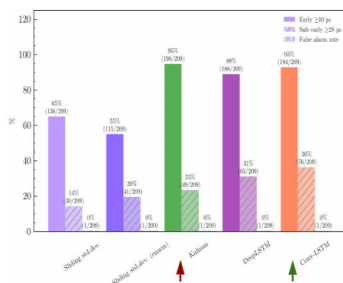
H. Haigh, P. Horak

Results 2024 runs



Preliminary Results

Model	N	Early $\geq 10 \mu\text{s}$	Safe $\geq 28 \mu\text{s}$	Median (μs)	Mean (μs)
Sliding-window variance	209	136/209 (65%)	30/209 (14%)	14.2	14.3
rolling-norm variant	209	115/209 (55%)	41/209 (20%)	20.7	14.3
→ Kalman velocity	209	198/209 (95%)	49/209 (23%)	15.7	18.2
DeepLSTM (multivariate)	209	186/209 (89%)	65/209 (31%)	20.7	30.0
Hybrid Conv1D-LSTM	209	149/209 (71%)	41/209 (20%)	18.7	17.2
→ rolling-norm variant	209	194/209 (93%)	76/209 (36%)	23.8	31.2



- Measure Δt with respect to bunch-current baseline model.
- Overall the ML methods show **ability to improve on simplistic models** that monitor variance.
- The **Kalman filter** is able to catch **almost all events early**, but does not provide a large forewarning on average.
- The **hybrid Convolutional-LSTM** model shows similar promise as originally seen in LSTM - **trains/process data 13x faster!**

HuW Haigh

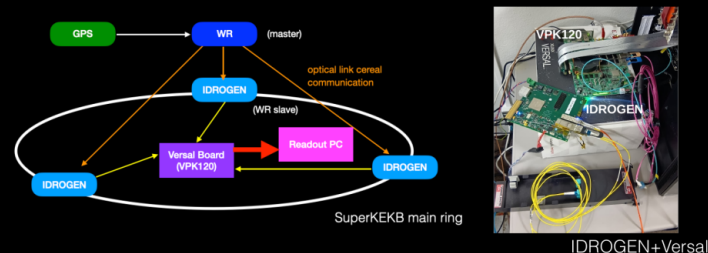
SuperKEKB BOR analysis

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- Offline analysis on 209 SBLs in 2024
- Various anomaly-detection methods are compared
- 71–90% can be flagged $\geq 10 \mu\text{s}$ before loss, depending on the method. Up to 36% have a $\geq 28 \mu\text{s}$ warning margin in the preliminary study.

Y. Yoshihara

Bunch Oscillation Recorder (BOR)



- A multi-BOR system with unified hardware is being developed:
 - ▶ Beam oscillation may also be useful for SBL precursor detection.
 - ▶ Timestamp sharing enables synchronized analysis.
- Readout R&D at KEK: IDROGEN + Versal Board (VPK120)
- Collaboration with KEK, UH, Giessen, and IJCLab

June 11, 2025 Keisaku Yoshihara

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

Fast Beam Size monitor (SiXRM)

[Yoshihara's report at the MDI parallel session](#)

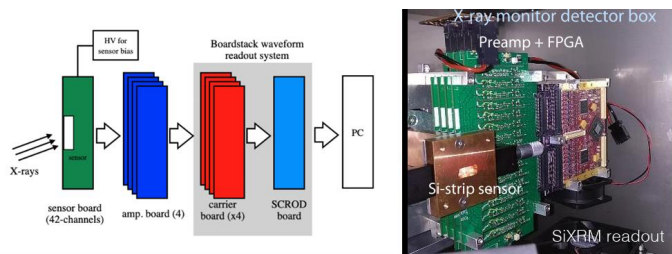
[SiXRM paper draft](#)

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.

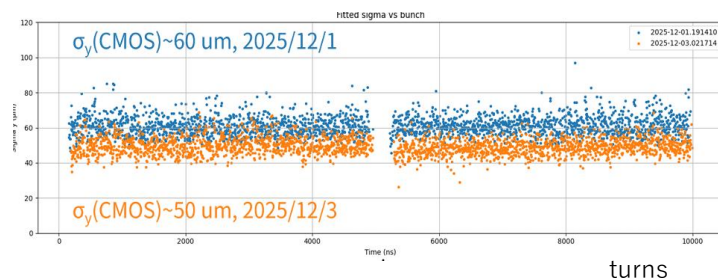
Current SiXRM setup and its readout

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

