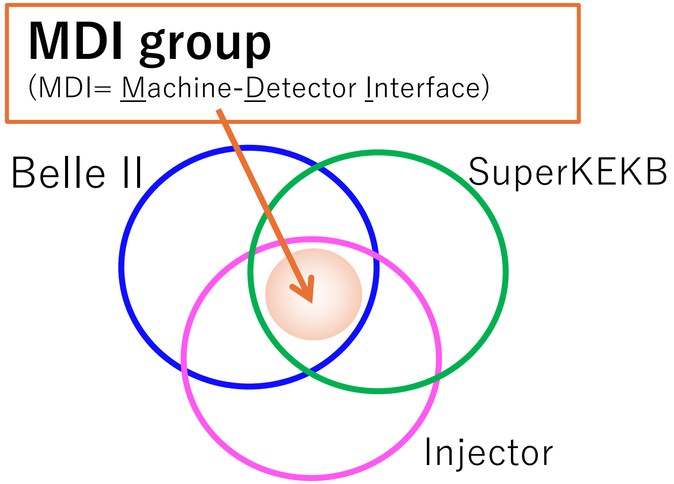
MDI group status



25th KEKB Accelerator Review

2025.1.15

Hiro Nakayama (KEK)

Our ultimate goal:

More integrated luminosity

Key Objectives

- Higher instantaneous luminosity
- Increase effective beam time

Major strategies

- Squeeze beam size at IP
- Increase beam currents
- Reduce downtime due to troubles
- Minimize DAQ deadtime (injection veto)

Challenges

- Short beam life due to narrow dynamic/physical aperture at small beta*y optics
- Beam blowup at higher beam currents
- Poor **injection efficiency** due to instability of injection beam charge and quality (emittance blowup in BT)
- Non-optimal **collimator settings** due to poor injection quality, TMC instability (beam size blow up), and head surface damage caused by severe beam loss
- **Beam background** impact on sensor lifetime and data quality for physics analysis
- Beam current limit due to RF power
- **Sudden Beam Loss** (SBL) events causing QCS quenches and severe collimator/sensor damage
- **Long injection BG duration** and large DAQ deadtime
- and so on…

topics covered by MDI activities

MDI group structure

MDI group
Leader: Hiro Nakayama

MDI group includes not only Belle II collaborators but also several experts from SuperKEKB vacuum, monitor, control, commissioning, injection, RF groups, as well as from LINAC group.

Beam background subgroup
Leader: Andrii Natochii
(10 staff, 7 postdoc, 7 students)

- **BKG simulation**
  - simulate storage and injection background
  - Find optimal collimator settings
- **BKG machine studies**
  - validate BKG simulation based on machine study data
  - understand and improve injection BG duration which causes DAQ deadtime
- etc..

Beam loss monitor subgroup
Leader: TakShun Lau
(8 staff, 3 postdoc, 7 students)

- **Sudden beam loss (SBL)**
  - beam loss monitors with fast readout
  - acoustic sensors
  - post-mortem abort timing analysis
  - BOR timing analysis
- **Faster abort delivery**
  - NLC CLAWS as a new abort source
  - Abort delivery using laser transmission in air
- etc..

new!

Machine learning activities (*)

- **ML application to accelerator parameter tuning**
- **Big data analysis using machine PV data**

(4 staff, 1 postdoc, 2 students)

There also exist other MDI-related topics which are directly reported to MDI meetings, such as **beam injection, collimator R&D, diamond abort system, etc…**

Smaller beam BKG | Longer beam life | Larger beam currents | Better injection performance

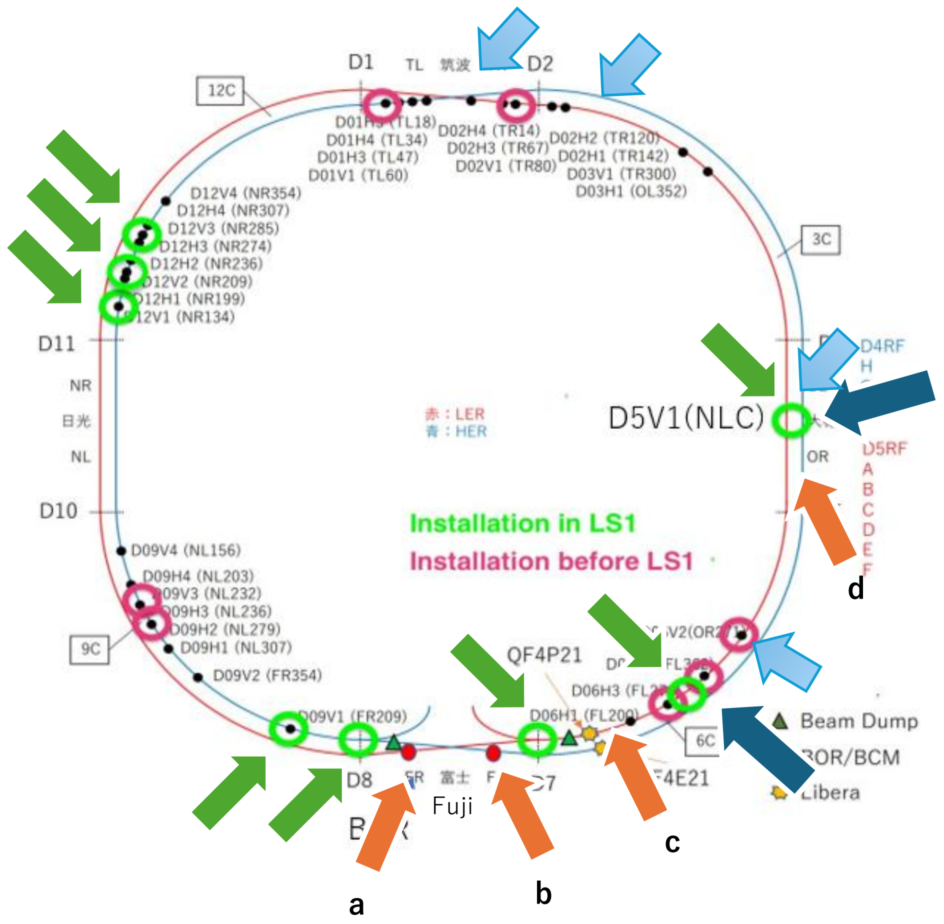
→ **Higher luminosity**

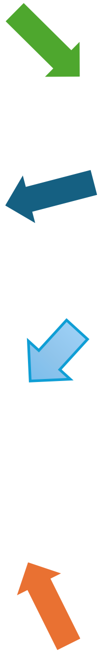
(*) B2/SKB/LINAC management has agreed to promote our further collaborations on "machine-learning application to accelerator tuning". Kickoff seminars are held to recruit (remote) Belle II collaborators and activities are started.

MDI-related major achievements during 2024 runs

1. **Faster beam abort**
   - Additional abort sensors (CLAWS) installed to LER D6, D5
   - Shorter abort delivery path to the LER abort kicker
2. **SBL analysis utilizing BORs(Bunch Orbit Recorders) data**
   - Multiple BORs enable timing/phase analysis of SBL origin
3. **Relaxed Belle II diamond abort threshold during injections**
   - Smoother operation startup and reduced injection-aborts
4. **Collimator operations**
   - LER NLC (Non-Linear Collimator) put into action
   - D02V1 orbit drift alarm implemented
5. **Machine learning application to SuperKEKB operation**
   - Automized injection parameter tuning based on Bayesian optimization
6. **Beam background machine studies**
   - Dedicated single-beam BKG machine studies in Apr. and Oct.
   - Detailed injection BKG simulation now available, dedicated machine studies for comparison

SBL sensors added for 2024 runs




New loss monitors
(at NLC, D6H4, HER masks, injection points)

New CLAWS scintillators at D5V1, D6V1

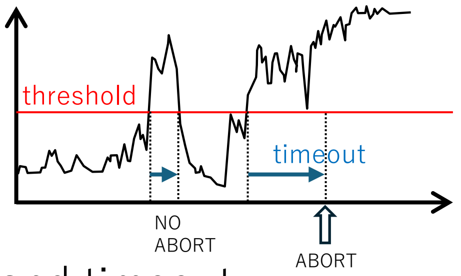
Acoustic sensors
(at D6V2,D2V1,D5V1, and QCS beam pipes)

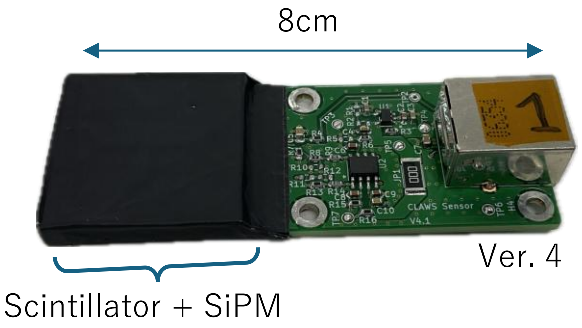
New BOR (Bunch Oscillation Recorders)
(based on iGp12,RFSoC)

a (D8, Fuji upstream), **b** (D7, Fuji downstream)
c (D6, before D6 masks) or **d** (D5, before D05V1)

1. Faster beam abort

Faster beam abort

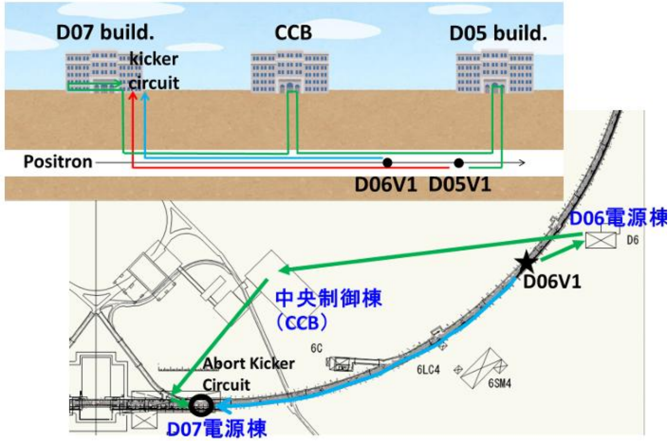




CLAWS scintillator

- Triggers beam aborts based on threshold and timeout
- Capable of detecting early-stage beam loss in SBL events
- Operating at IR since Run 1
- In 2024, also installed to LER D5V1, D6V1, aiming for detecting beam loss at upstream positions and deliver beam abort faster

Direct connection



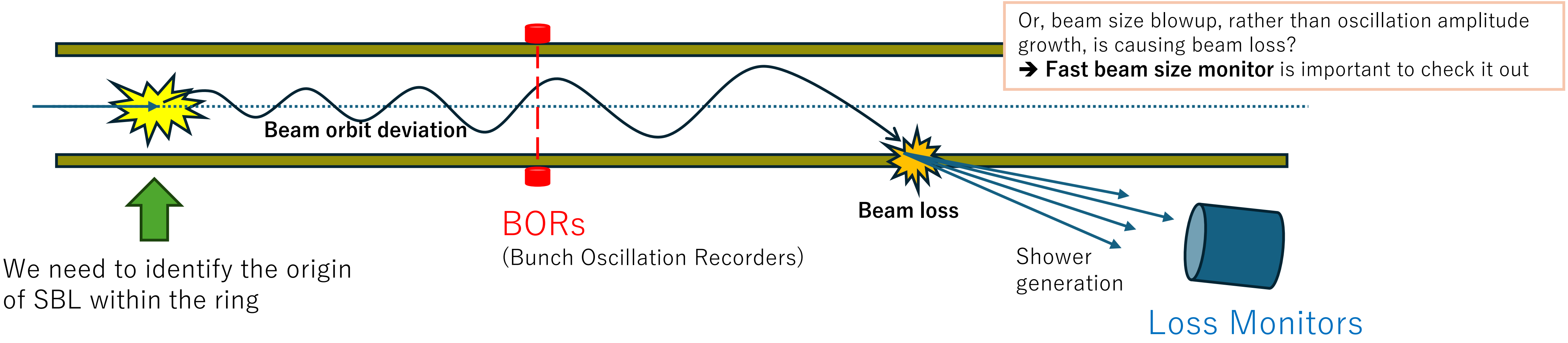
Direct connection to the abort kicker

- Abort requests are collected at the KEKB control building and then sent to the abort kicker (green arrows)
- **A direct connection** (light-blue arrows) from D6/D5 sensors to the abort kicker is added, utilizing a shorter cable path
- Its effectiveness was confirmed during the early 2024c runs.
- Activated for operation since Nov.28

Thanks to those efforts, we can gain 1~2 abort gaps (=5~10us) in Nov-Dec SBL events with earliest beam loss at D6V1 or D5V1.

2. SBL analysis using BOR data

Sensors to find the origin of SBL events

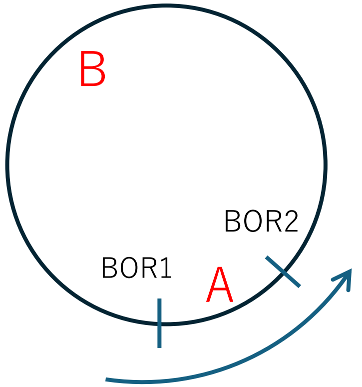


- **Loss Monitors**
  - Equipped with fast readout and provide chronological order of beam loss along the ring
  - Many LMs have been installed before LS1
- **BORs**
  - Can observe earlier stage of beam orbit deviation, prior to the beam loss
  - Multiple LER BORs are installed from 2024, making timing/phase analysis possible
  - This provides new and unique insights into understanding the origin of SBL
- Fast beam size monitors are also important to detect possible beam size blowup just before the abort

What can we know from BOR data?

Timing→ Location

- BORs reveals **the ring section which includes the location of SBL origin.** With three BORs installed, we can divide the ring into 3 potential sections.

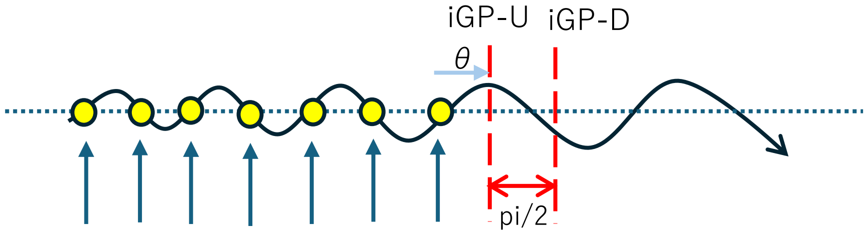


If BOR2 saw oscillation in the first turn but BOR1 didn't, the location of SBL origin should be included in the ring section A, not B.

Caveat:
BOR could overlook the oscillation if the amplitude is too small due to its betatron phase and/or poor S/N

Betatron phase

- Comparing the size of deviation of BORs (iGp12 sensors) at Fuji upstream and downstream, with 90 degree phase difference, **the betatron phase of the location of SBL origin** can be estimated
  - 1 revolution = ~45 rotations of phase
    = ~90 candidate locations



Candidate locations for SBL origin
(the phase should be 0 or pi)

$X_U = R \sin\theta$
$X_D = R \sin(\theta + pi/2) = R \cos(\theta)$
$\theta = ArcTan2(X_U, X_D)$

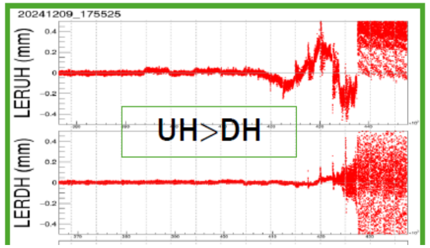
Pressure burst locations and BOR data

- Most of LER SBL events in 2024 are accompanied with the **pressure burst at D04/D10 sections**.
- **Statistical correlation analysis** and **knocker studies** suggests that D04/D10 sections are responsible for 2024 SBL events.
  - Pressure gauge readout is not fast enough to distinguish whether pressure bursts occurred before or after the beam loss.

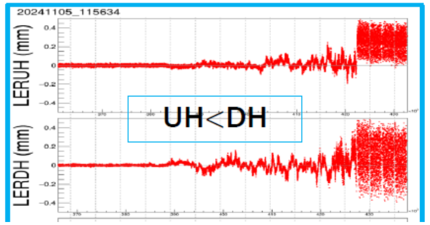
- **BOR phase analysis can provide additional information on SBL origin, as explained in previous page**
- By comparing amplitude of multiple BORs in major SBL events causing QCS quenches, estimated betatron phase of the oscillation origin seems to be consistent with phase of the pressure burst location.

- BOR can give additional observation which supports our assumption that D04/D10 sections are responsible for 2024 LER SBLs.
- BOR might also give insights on SBLs without pressure bursts

#6 2024-12-09 17:55:25
Burst at D04_L02



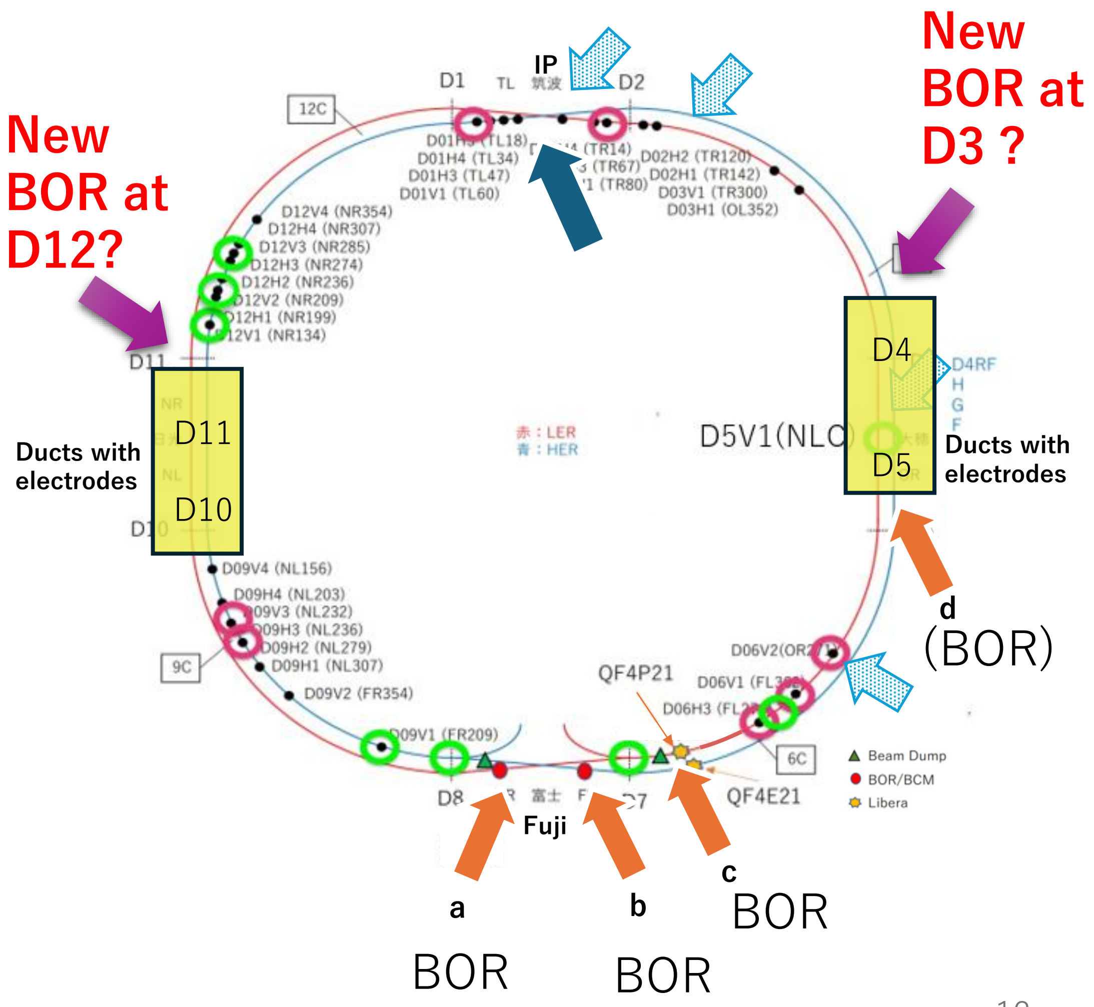
#4 2024-11-05 11:56:33
Burst at D10_L02



Size of oscillation amplitude at upstream and downstream BORs (UH/DH) depends on the pressure burst location

Candidate location for new BORs

- **To improve our understandings on SBLs, we plan to install more BORs**
- **Where should we install new BORs?**
  - To understand SBLs accompanied with D4/D10 pressure bursts, BORs should be installed both upstream and downstream of the suspected section (D4-D5 and D10-D11, shown as yellow box).
  - **Candidate location: LER D12 and D3 sections**
- Other requirements:
  - nu_y should be matched with existing BORs
  - beta_x should be not too small (so as beta_y)
  - BPM cable length not too long for goof S/N
  - Less impact on closed orbit feedback by using BPM for RFSoC
- After discussion with SKB experts, we have selected **MQW6NRP**(D12) and **MQW8OLP**(D3)
- Once LER SBLs are fully understood, some BORs can be moved to HER



3. Relaxed Belle II diamond abort threshold during injections

Belle II diamond threshold

- Belle II diamond sensors installed at IP protect the VXD sensors
- Unlike most of SKB abort systems which are disabled during injections, Belle II diamond abort threshold, tuned for collisions, could not be increased during injections
- As a result, many diamond-only aborts were correlated with injections
- Frequent diamond injection aborts, particularly during beam startup, disrupted smooth operation.

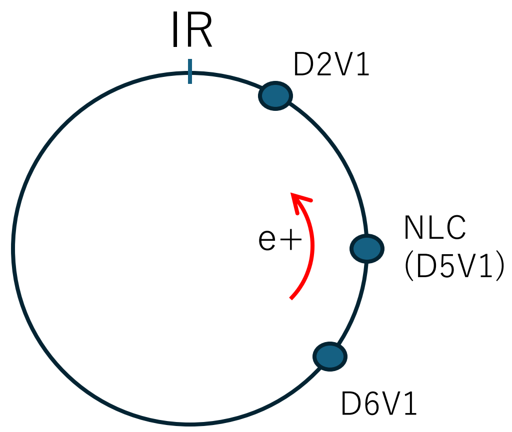
- **New firmware update of the diamond readout system was developed to allow relaxed threshold during injection**
- **The new firmware successfully suppressed harmless injection aborts during 2024c**

4. Collimator operation

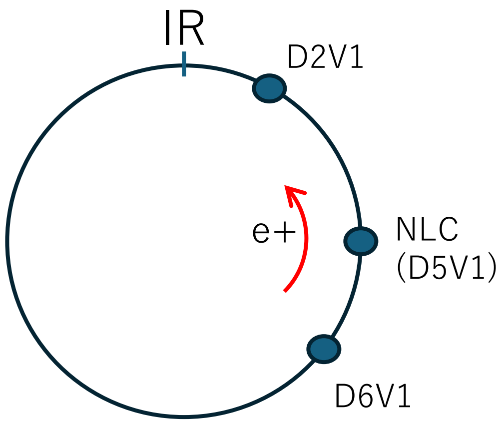
- Collimator operation are handled by the Belle II collimator expert team
- Frequent collimator optimizations were necessary to address injection condition change, new optics setting, etc…

Non-linear collimator (NLC) put into action

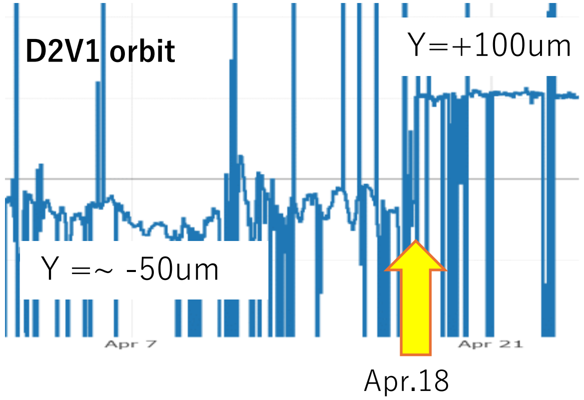
- NLC(D5V1) is designed to reduce beam background **with a wider aperture and less impedance than D6V1,** enabling further increases in bunch current without triggering TMCI instability
- In 2024ab, NLC was installed but cannot be utilized extensively due to elevated radiation levels in the OHO experimental hall where it is located.
- In 2024c, we attempted to use the NLC more aggressively after increasing the maximum permitted radiation levels in the OHO hall by reclassifying its radiation safety area category.
- However, we still reached the limit of hourly radiation dose, due to **unexpectedly large injection losses at NLC**
  - we set smaller beta_x at SNAP to reduce injection loss
- Therefore, **NLC aperture were still wider or comparable with D6V1 in late 2024c**.



LER D2V1 orbit alarm



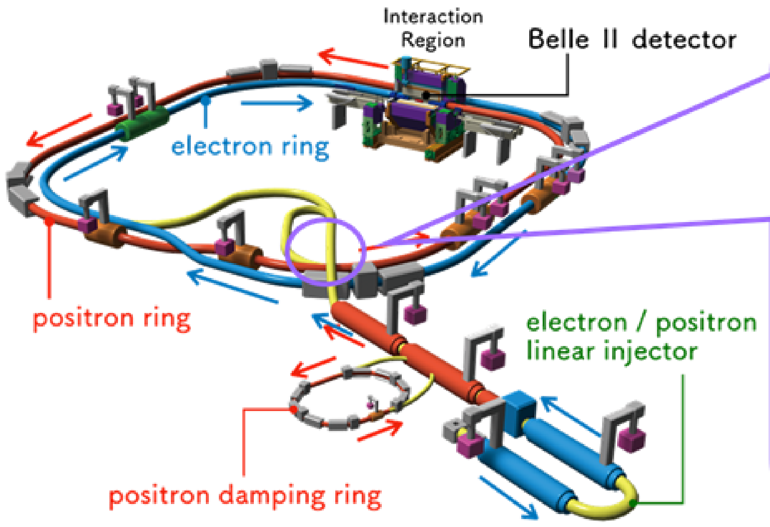
- Motivation
  - **The LER D2V1 collimator should be kept wider than D6V1 or D5V1** to prevent severe Belle II damage by secondary shower from D2V1 to IR
  - However, the LER vertical orbit position at D2V1 sometimes jumps by **O(100um),** which can unintentionally make D2V1 the narrowest.
    - Jumps after optics corrections, maintenance days, etc..
    - Typical D2V1 width is ~1mm, so O(100um) is not negligible at all.
  - **This resulted in several major QCS quenches in 2024 Apr.**

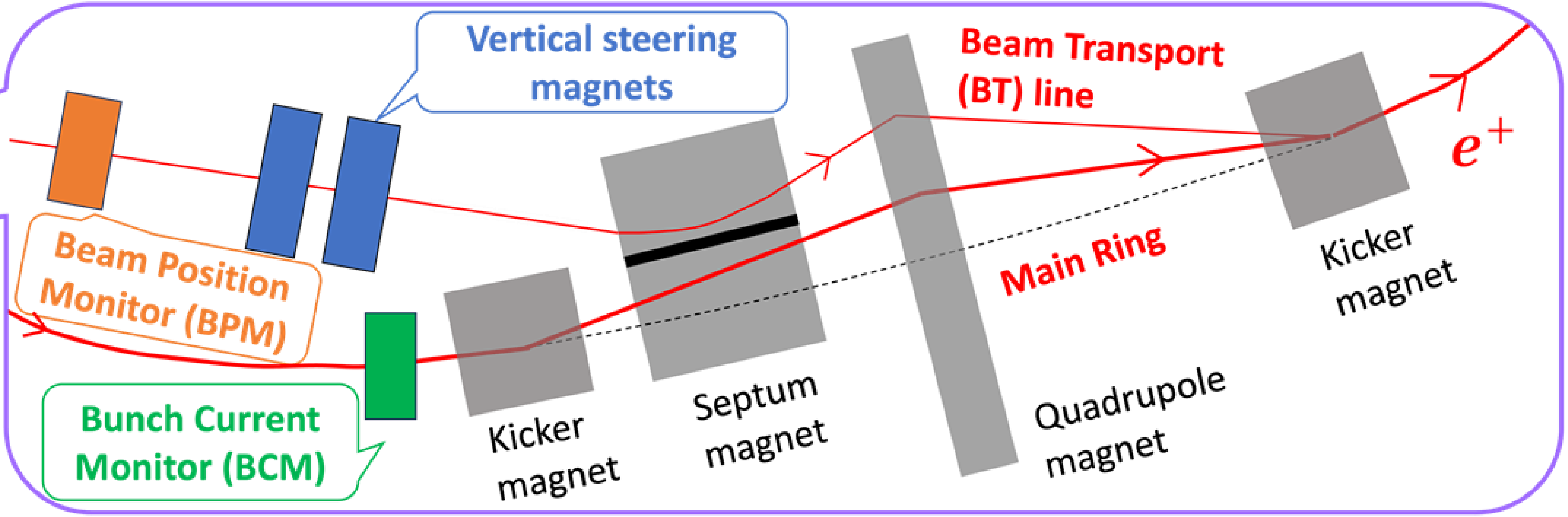


- To address this issue, an **alarm system** is implemented.
  - If orbit position at D2V1 changes drastically, SKB operators and Belle II collimator team are notified. If necessary, expert update the collimator setting accordingly.

5. ML-based beam injection tuning

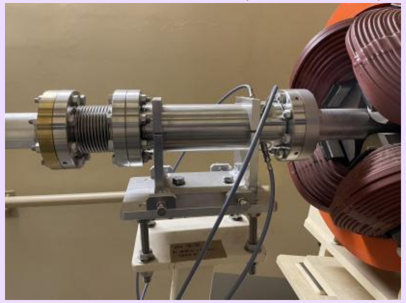
Injection tuning at SuperKEKB





Vertical steering magnets

Beam Position Monitor (BPM)



Bayesian optimization with the following parameters

- **Tuning parameters**

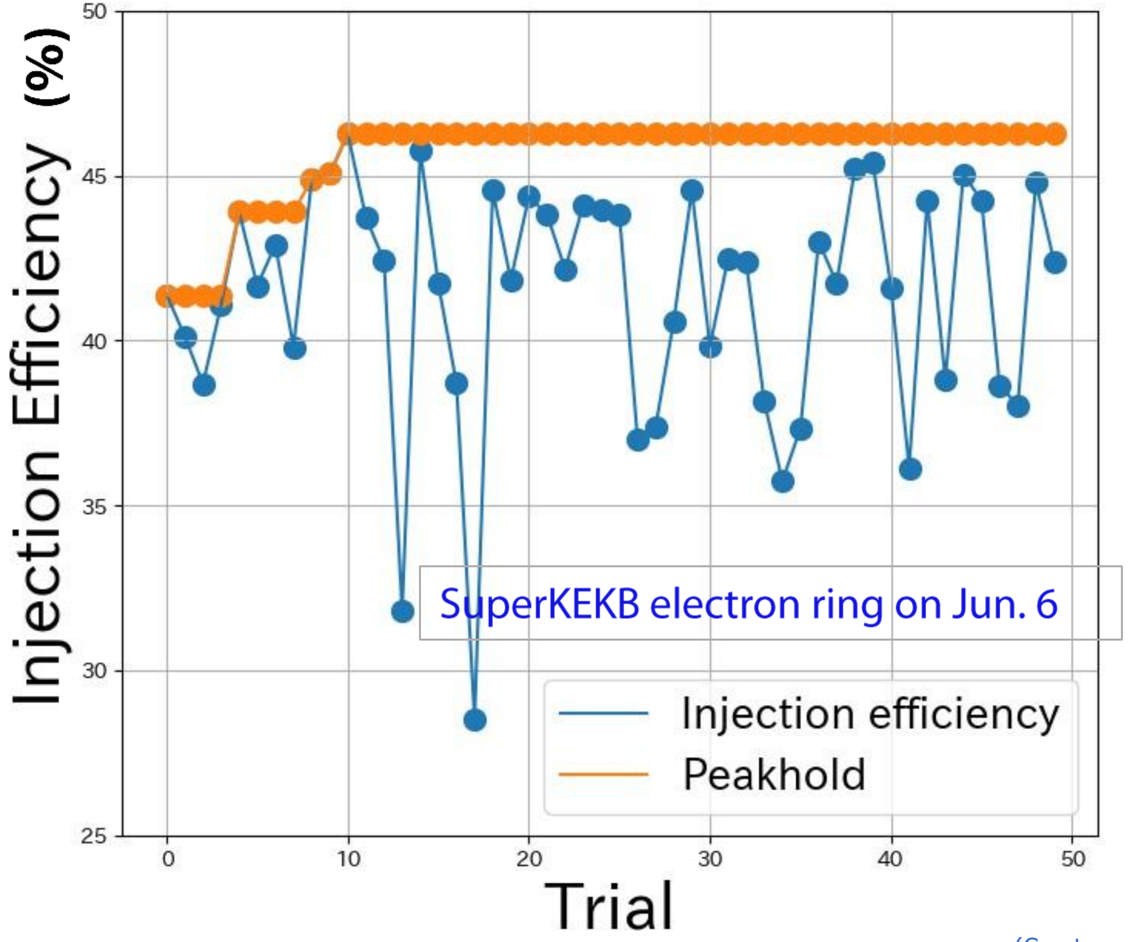
  Vertical steering magnets × **2** (We tune the kick angle [rad])

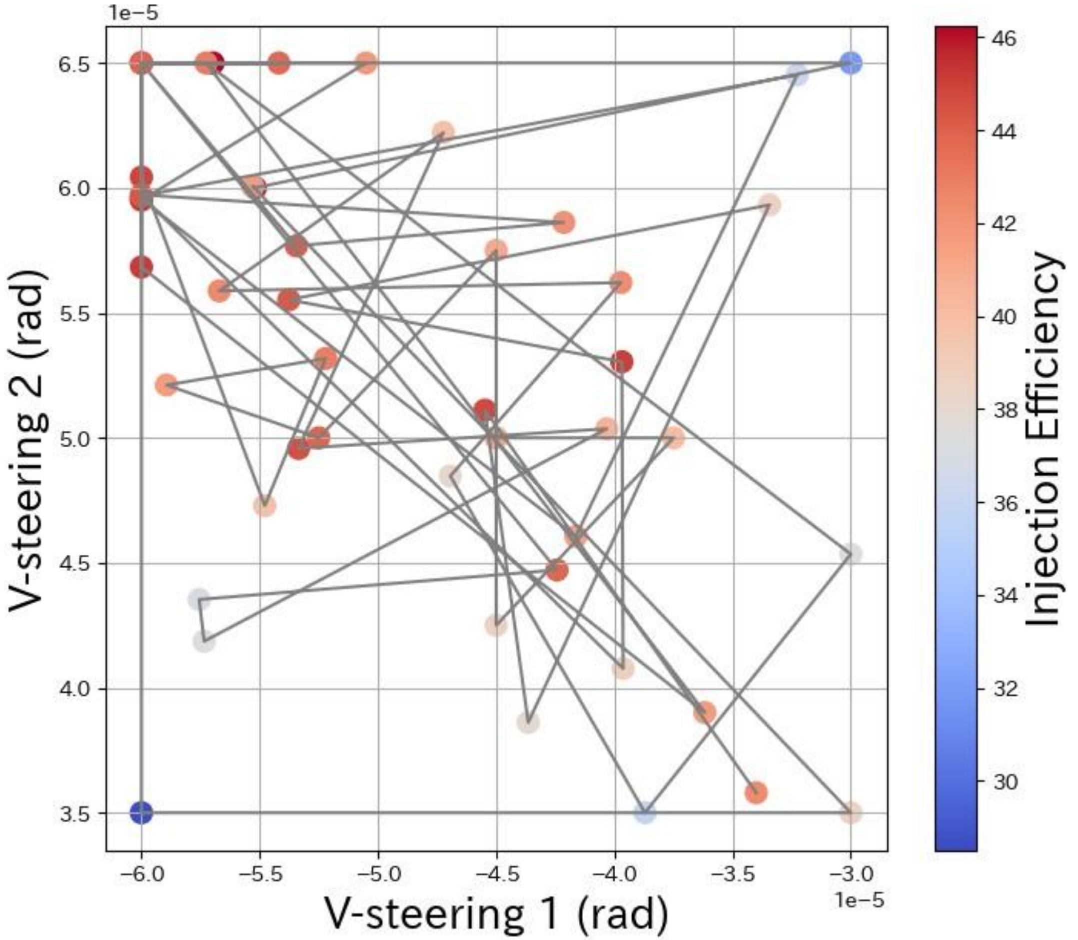
- **Evaluation parameter**

$$\text{Injection efficiency} = \frac{\text{Current increased in the ring.(measured by \textbf{BCM})}}{\text{Current entering the ring(measured by \textbf{BPM})}}$$

Beam injection to the SuperKEKB main ring (e⁻)

- An efficiency of 42% reaches 46% within 15 trials (~12 mins). No beam abort for 50 trials!
- Reasonable anti-correlation between the two steering magnets





(Courtesy of S. Kato)

ML-based injection tuning in 2024c

- ML-based tuning was tried 40 times in 2024c (LER:21, HER:19) in Nov. and Dec.
- The tuning successfully improved the injection efficiency by ~10% on some days.
    - not as good as this on other days, but at least the efficiency did not get worse
- No beam abort was issued during those tuning
    - demonstrated safe parameter scan

ML-based injection tuning has demonstrated its effectiveness during 2024c operation.
Advanced tuning using more injection parameters will be tried in 2025 runs.

Injection efficiency (ε) before and after the ML-based tuning

Δε

表 5.9: 入射調整ツール運用における日ごとの最適化結果

番号	測定日	リングの種類	最適化回数	調整前/後入射効率	入射効率向上量	備考
1	11 月 14 日	HER	3	59.4% / 70.2%	10.8%	
2	11 月 15 日	LER	2	86.3% / 90.8%	4.5%	1 バンチ目の入射効率
3	11 月 17 日	HER	2	20.7% / 26.8%	6.1%	LER の電流が減少中
4	12 月 05 日	LER	3	65.8% / 98.2%	32.4%	運用例 1 1 バンチ目の入射効率
5	12 月 06 日	LER	2	71.9% / 76.9%	5.0%	
6	12 月 07 日	HER	9	68.2% / 71.1%	2.9%	パラメータ比較スタディ
7	12 月 11 日	LER	3	61.7% / 64.4%	2.7%	
8	12 月 13 日	LER	5	77.5% / 82.0%	4.5%	再現性の確認スタディ
9	12 月 14 日	HER	5	58.4% / 68.5%	10.1%	パラメータ比較スタディ 再現性の確認スタディ
10	12 月 14 日	LER	2	69.0% / 77.8%	8.8%	
11	12 月 17 日	LER	1	59.8% / 69.1%	9.3%	
12	12 月 25 日	LER	3	54.5% / 68.4%	13.9%	運用例 2 パラメータ比較スタディ 片リング運転中

New initiative:
Machine-Learning application to accelerator operation

- There have been several ongoing efforts to utilize machine-leaning (ML) technique for accelerator operation
  - Beam injection tuning (Mitsuka, Kato, Natsui)
  - Anomaly detection (Matsuoka)
  - "BGNet" for real-time beam background decomposition (Yannik, Benjamin)
- **B2/SKB/LINAC management agreed to endorse our further collaborations on this field, in the MDI framework.**
- **A series of kickoff seminars** are being held to recruit more Belle II collaborators
  - ✓ Anomaly detection and correlation studies (Sep. 2): https://kds.kek.jp/event/52122/
  - ✓ Machine learning for SuperKEKB operation (Sep. 5): https://kds.kek.jp/event/52121/
  - **Meeting with ML experts from SKB/LINAC on Oct. 10th Thursday at 2pm:** https://kds.kek.jp/event/52503/
  - **BGNet introductory seminar** on Oct. 11th Friday at 3pm: https://kds.kek.jp/event/52538/
  - **BG simulation tutorial** on Oct. 11th Friday at 22:30JST : https://indico.belle2.org/event/13409/

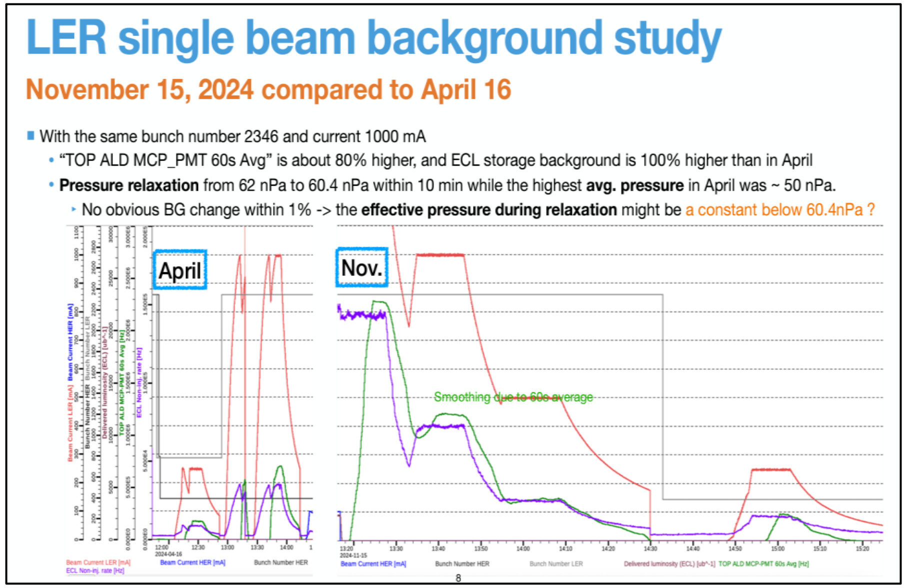
More Belle II collaborators (incl. remote people) get involved in this new effort

6. Beam Background machine studies

Single-beam + Luminosity BKG studies

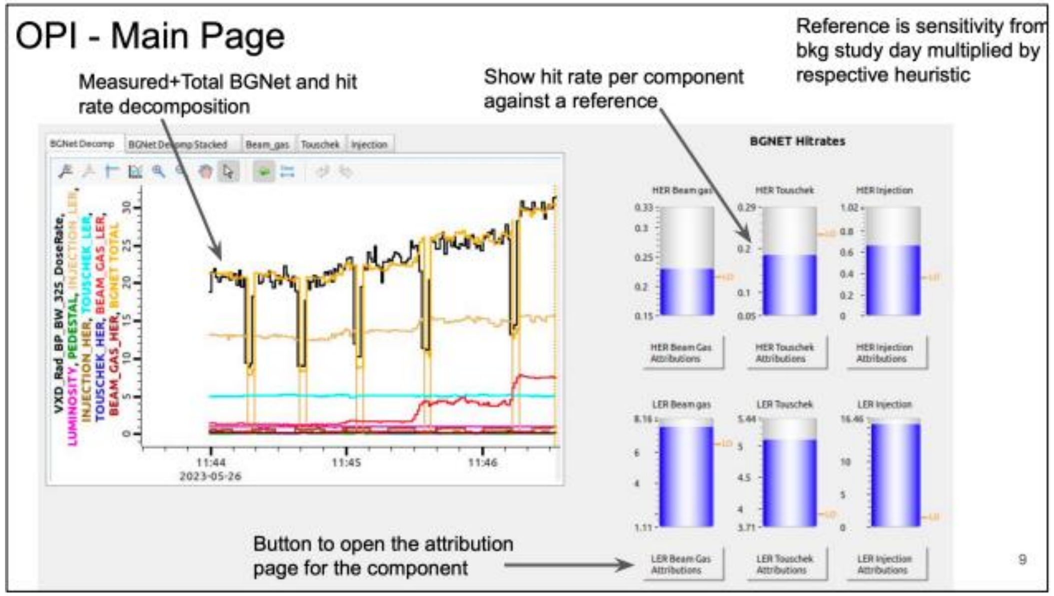
- **Higher Belle II beam background rates** seen in 2024c
  - Under the same machine parameters, storage and injection BKG observed in Belle II (CDC, iTOP, and ECL) are approximately twice as high as those measured during 2024b.
  - For example, at the end of November, LER backgrounds were the dominant component, accounting for about 70% of the total storage BG rates, with a Coulomb-to-Touschek ratio of approximately 50:50.

- Part of the background increase is due to vacuum work during summer shutdown (leading to higher pressure and hence beam-gas backgrounds), but the entire increase needs further study.
- A designated background study was carried out on Nov. 2024
  - Separately measure Touschek/Beam-gas BKG components by varying number of bunches and beam currents
  - To be compared with the similar study in Apr. 2024

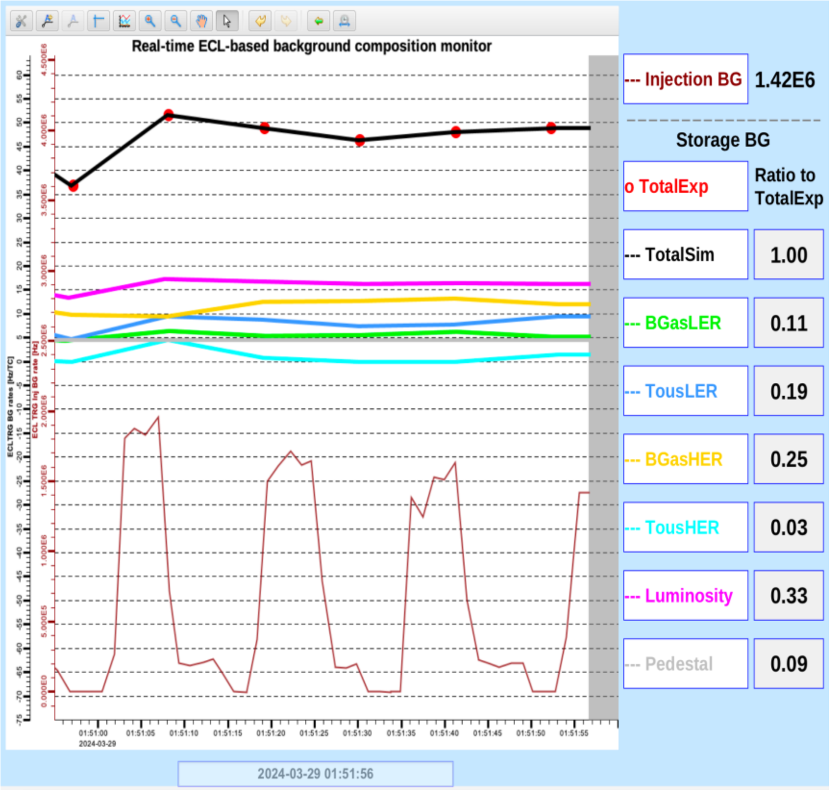


Real-time BKG component monitors

- “BGNet”: neural-network training using hundred of EPICS PVs



- ECLTRG: MC-template fitting using hit distribution in ECL trigger cells

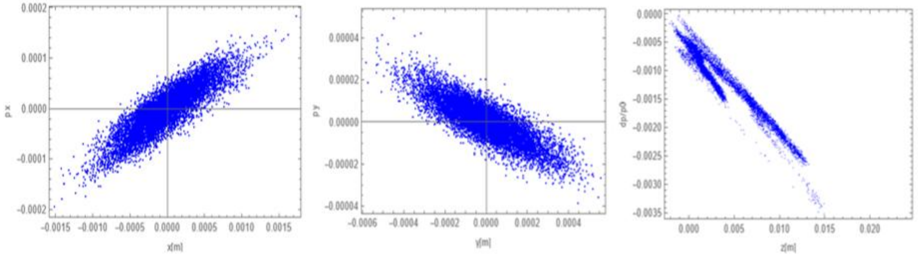


- Provides Touschek/Beam-gas/Luminosity BG ratio even during usual physics runs
- Powerful tools for machine/collimator tuning

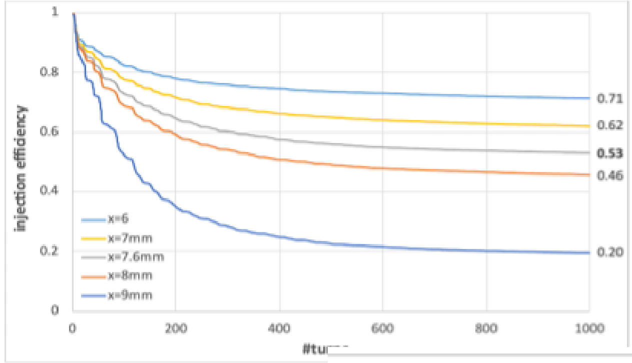
Injection BKG simulation

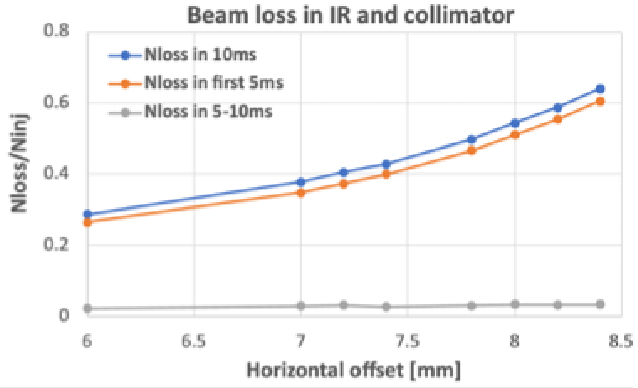
- **HER injection simulation** (by Meng Li)
  - Initial condition
    - simulated distribution at BT end with emittance adjustments
  - Main ring tracking simulation
    - See injection efficiency, beam loss rates at IR/collimators up to 1000 turns (=10ms)
    - Scan over various simulation parameters
- **Main findings**
  - Injection errors (offset, angle, emittance of injected beam, X-Y coupling) mainly affect **injection efficiency**
  - Beam-beam effect strength, cancel coil error and crab waist have a large effect on **injection BKG duration.**
  - **IR loss rate** can be suppressed by minor collimator adjustment, especially by D1V1
- **Dedicated machine studies** to confirm those findings were conducted at the end of 2024c run. Analysis is ongoing.

Initial beam distribution



➤ Injection horizontal offset





Plans for 2025 runs

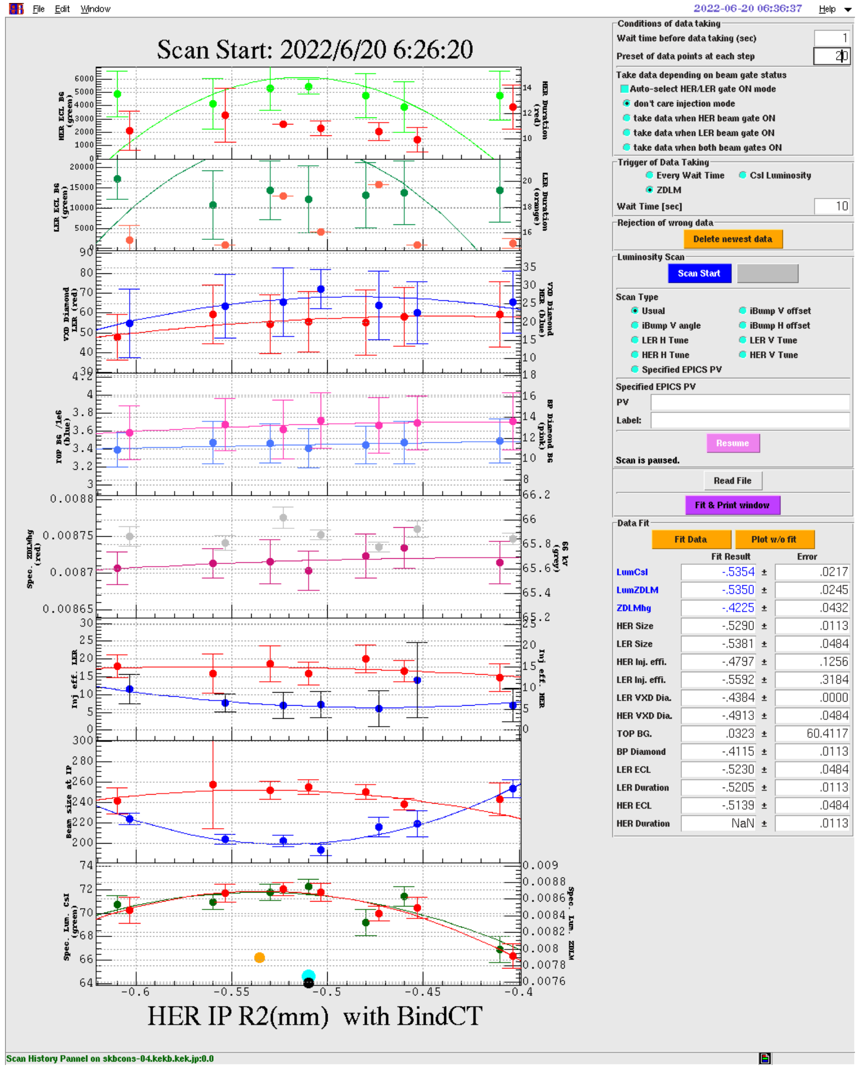
- Implement faster abort delivery in HER (loss monitors and direct path)
- Test laser transmission in air of abort request for even faster delivery

- Install new BORs for further understanding of SBL mechanism
- Automatic production of timing analysis plots using Loss Monitors and BOR data
- Upgrade the beam abort database (integrated with SBL verification database)
- Discuss the possibility of LER vertical collimator at D03 to mitigate the SBL loss at IR

- Enhance measurements of the beam properties by the Belle II detector like the collision energy, beam spot profile, boost vector, etc.

- Investigate the possibility to apply ML-based injection tuning algorithm to other machine tunings such as IP knob tuning, collimator tuning, etc… (see following slides)

Future prospect: IP coupling tuning



Normal coordinate | Physical coordinate

$$\begin{pmatrix} X \\ p_X \\ Y \\ p_Y \end{pmatrix} + \begin{pmatrix} \eta_X \\ \eta'_X \\ \eta_Y \\ \eta'_Y \end{pmatrix} \delta = \begin{pmatrix} \mu & 0 & -R_4 & R_2 \\ 0 & \mu & R_3 & -R_1 \\ R_1 & R_2 & \mu & 0 \\ R_3 & R_4 & 0 & \mu \end{pmatrix} \begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix}$$

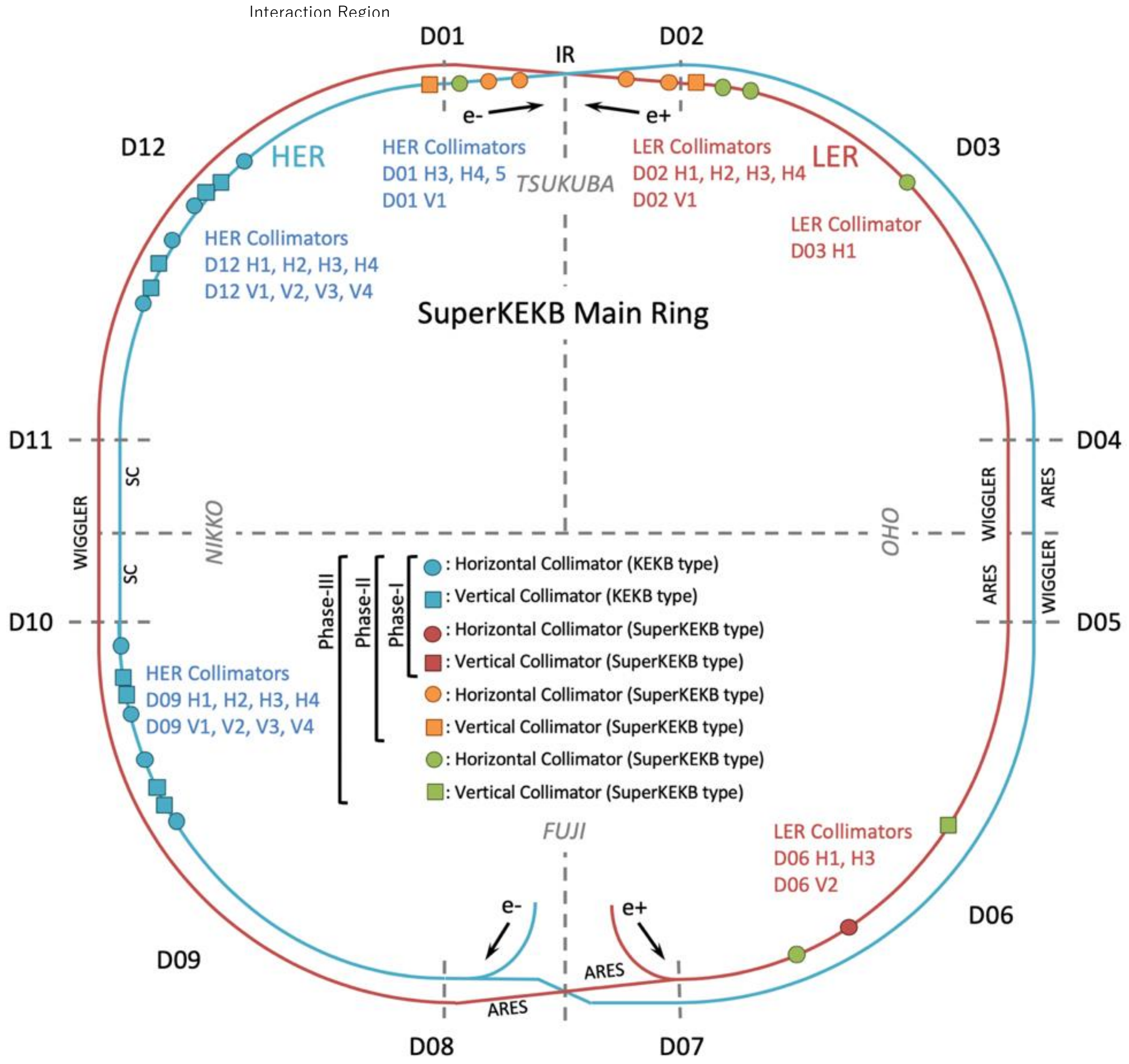
Number of parameters
= (R1-4 + η)
x (w/o + w/ chromatic)
x (LER + HER)
= 5 x 2 x 2
= 20

Aiming at automatic adjustment by combining

- **Communication with SAD optics server**
- **Bayesian optimization**
- **Dimensionality reduction algorithms**
- **Compatible with a low background.**

- Down-hill simplex method was (partially?) applied in the KEKB era.
- Under investigation on feasibility of ML-based tuning.

Future prospect: Collimator optimization



- Collimators in the SuperKEKB Main Ring are essential for suppressing beam background.
- Optimization is complex, with 31 collimators (= ~60 parameters!) to fine-tune.
- Key considerations include not only beam loss rate within Belle II, but also beam lifetime, injection efficiency, and transverse impedance.
- Currently, optimization relies on (limited number of) collimator experts

- ML application for this challenging task could be a game-changer

We are currently facing issues with the reproducibility of collimator head position measurements and plan to install additional position sensors to strengthen the control system. Once we achieve reliable measurements, we will be able to apply ML effectively.

Summary

- The MDI group facilitates various opportunities for collaboration among Belle II, SuperKEKB, and LINAC teams.
- During 2024 run, understanding of SBL events had significantly improved and several countermeasures were implemented.
- New initiative such as machine-learning application to machine operation look promising

backup

Faster Abort delivery

Summary

We have speeded up the abort response at LER
- by installing new CLAWS
- by configuring the new D07 abort master

There are six abort-request events with new D07 abort master.
- 11/28 19:05, gain: 5.929us
- 11/28 19:40, gain: 13.839us
- 11/29 02:04, gain: 10.589us
- 12/03 06:11, gain: 13.539us
- 12/04 11:22, gain: 4.829us
- 12/04 12:47, gain: 6.129us

Note, this number ignore the abort master delay for synchronizing the output timing with the abort gap.

HER upgrade will be followed in the next year.

iGp12 plots for 2024c QCS quench events

#14 2024-12-24 14:40:56 D04_L03

少し前に跳ね

#13 2024-12-23 09:23:12 D04_L07, (D06_L06/D6H4)

#12 2024-12-21 21:28:05 D04_L08

少し前に跳ね

#11 2024-12-19 09:50:27 D04_L03, (D11_L20)

#10 2024-12-17 09:33:35 D04_L03

#9 2024-12-15 20:21:34 D04_L02, D02_L18(D2V1)

#8 2024-12-14 19:56:32 D10_L08, D11_L21, D05_L22A(NLC

#7 2024-12-11 08:43:27 D04_L03

#6 2024-12-09 17:55:25 D04_L02

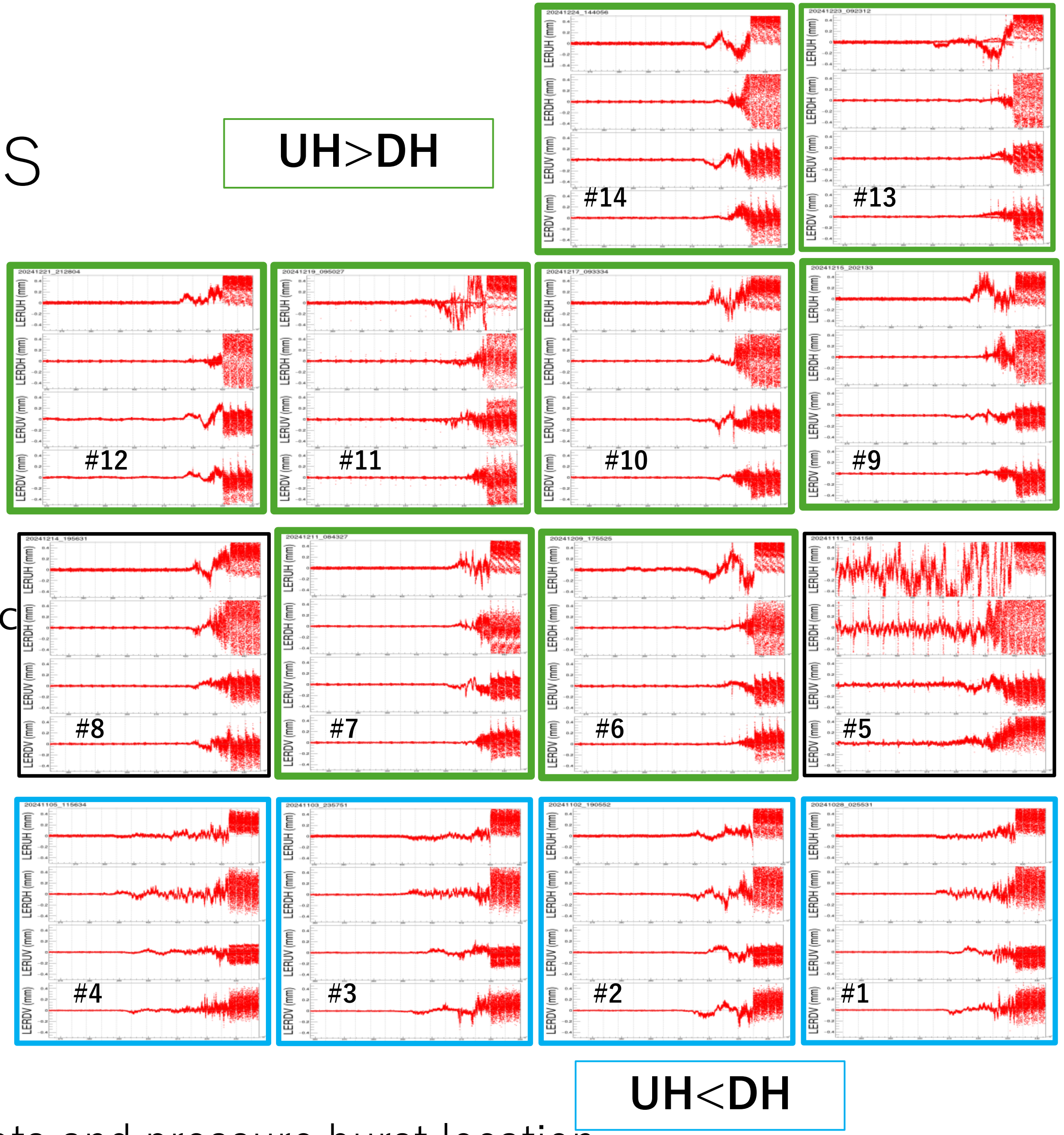
#5 2024-11-11 12:41:57 D10_L07,D10_L08

#4 2024-11-05 11:56:33 D10_L02

#3 2024-11-03 23:57:50 D10_L02

#2 2024-11-02 19:05:51 D10_L02

#1 2024-10-28 02:55:28 D10_L02



Similar dependency in LERUH/DH plots and pressure burst location

2-2 injection gate for 2024c start

- SKB injection gate is an external input
  - As a start, I cabled it from the same NIM module used for CLAWS, same delay and same width [-16 μs;400 μs]
  - New programmable gate generator module allowing for separate gates will be provided and installed by SKB
  - The injection-gate leading-edge and the signals from injected bunches reaching the IR should be aligned at the DCU inputs; the DCU internal delays of diamond signal and injection veto have been measured and are well known (it has a dependence on shape and size of diamond signal)