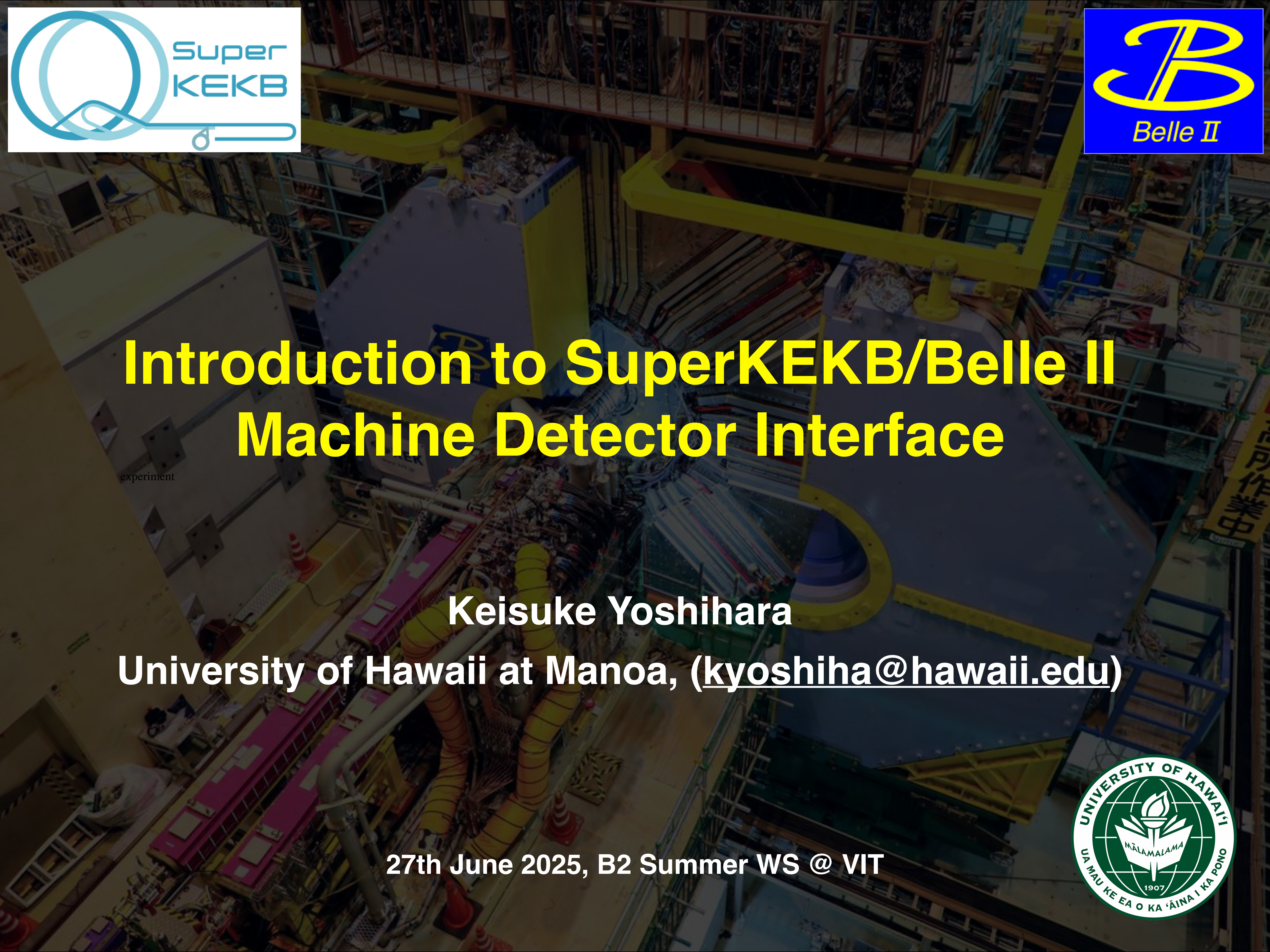

Introduction to SuperKEKB/Belle II Machine Detector Interface

experiment

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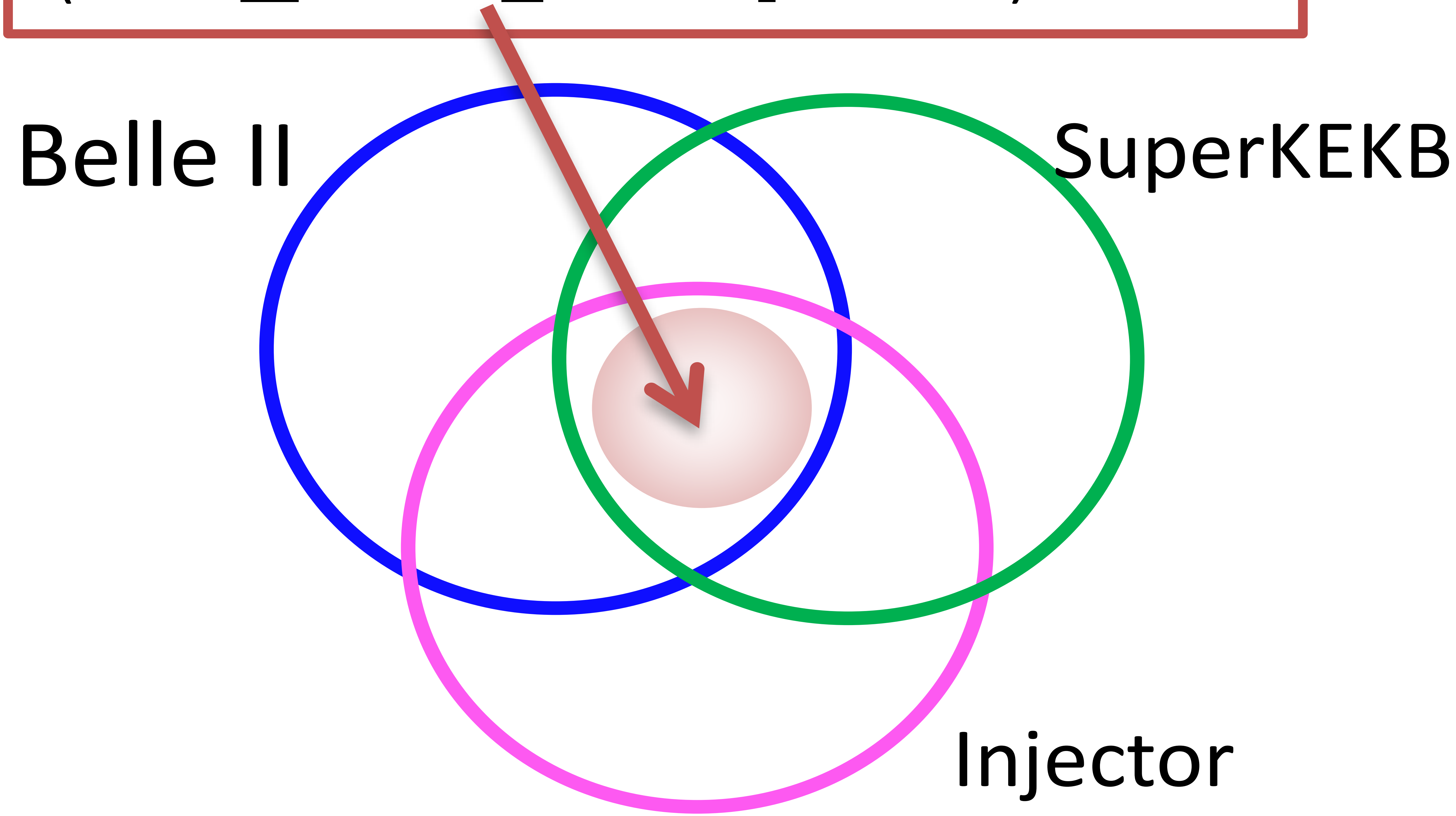
27th June 2025, B2 Summer WS @ VIT

MDI group

(MDI= Machine-Detector Interface)



Outline

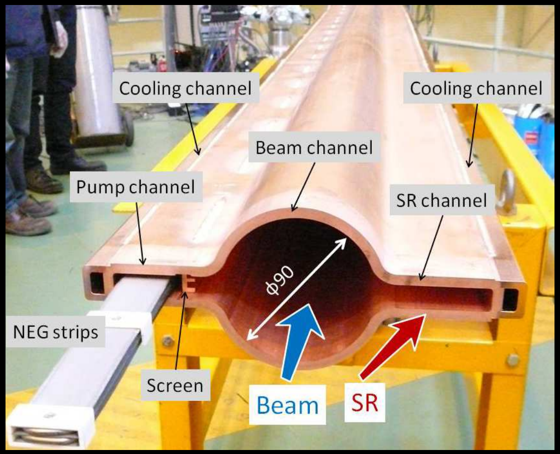
- Introduction
- Beam Background
- Beam Instability
  - SBL
  - Beam Diagnostics
  - Advanced Abort System
- Beam Injection

Introduction

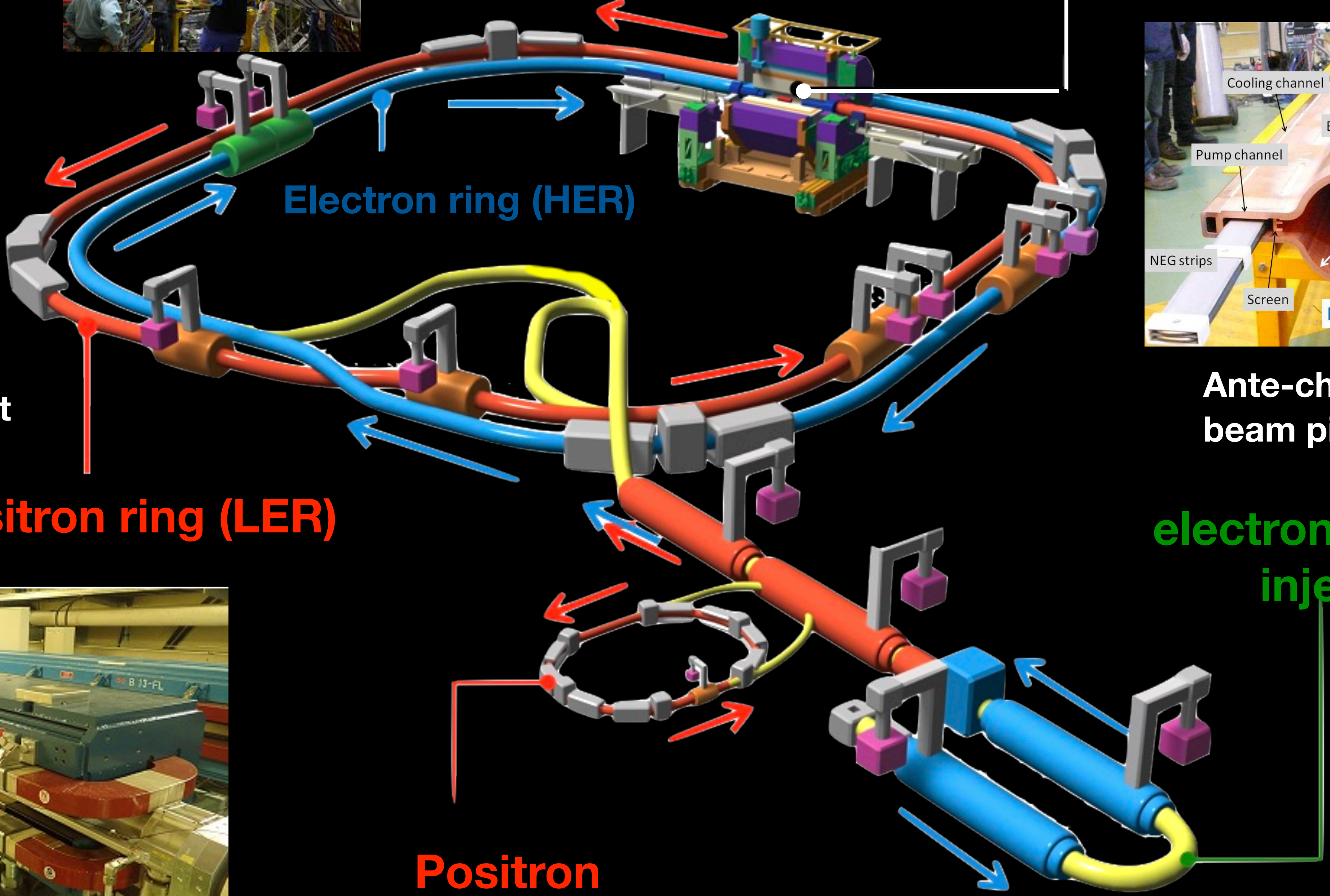
SuperKEKB

QCS magnets

RF reinforcement

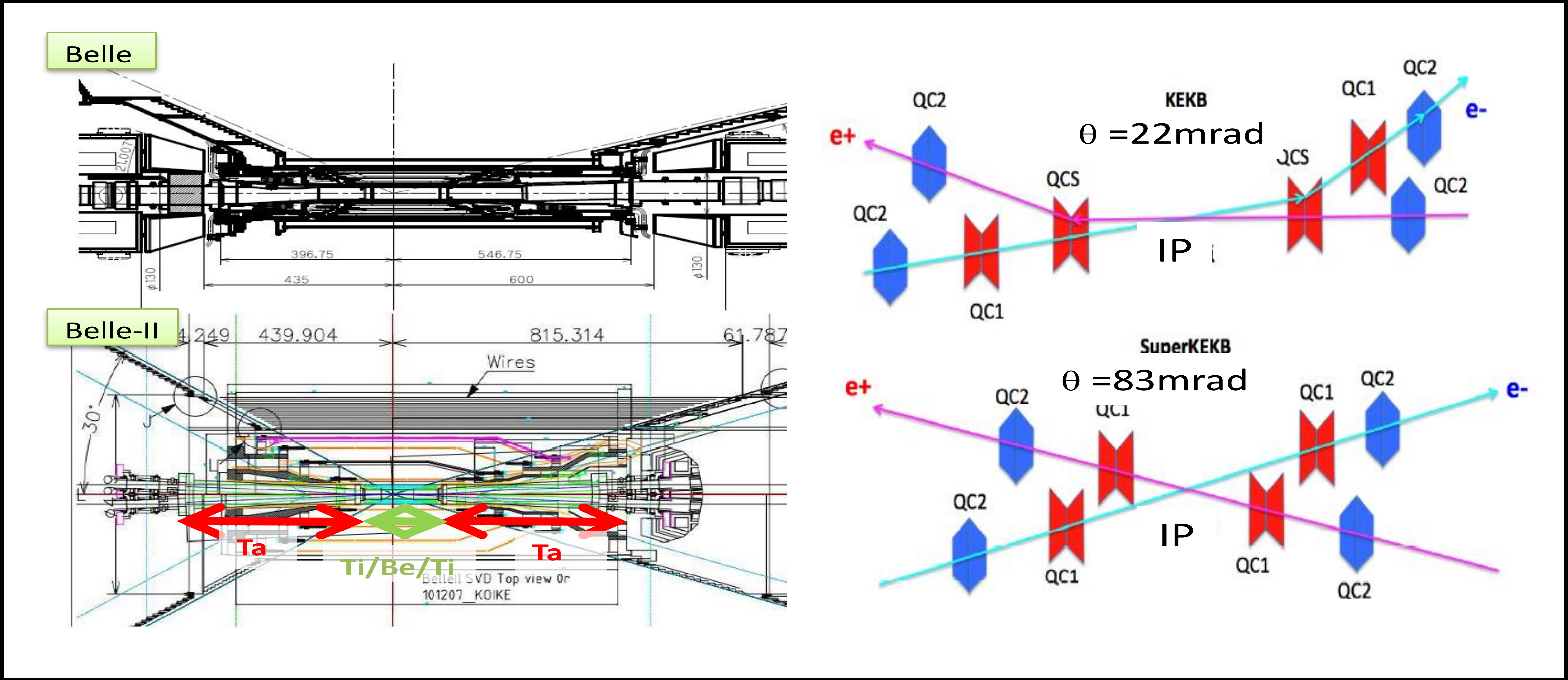


Ante-chamber beam pipe



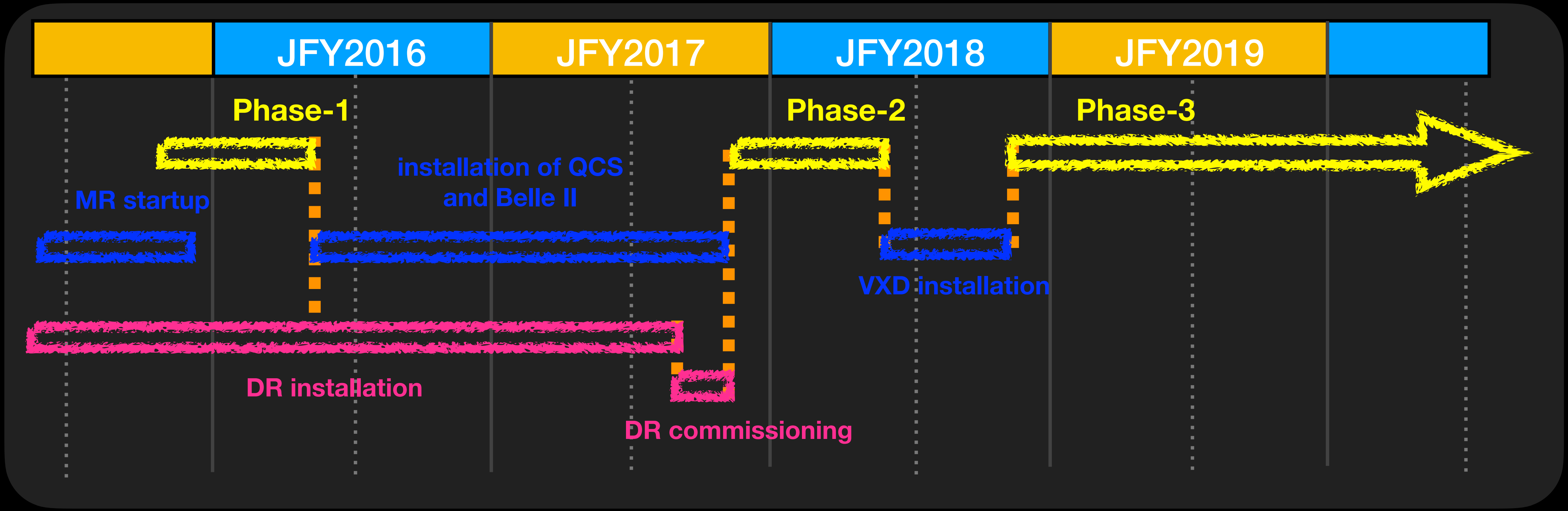
dipole magnets newly installed in LER (~4 m)

Beam Pipe Design

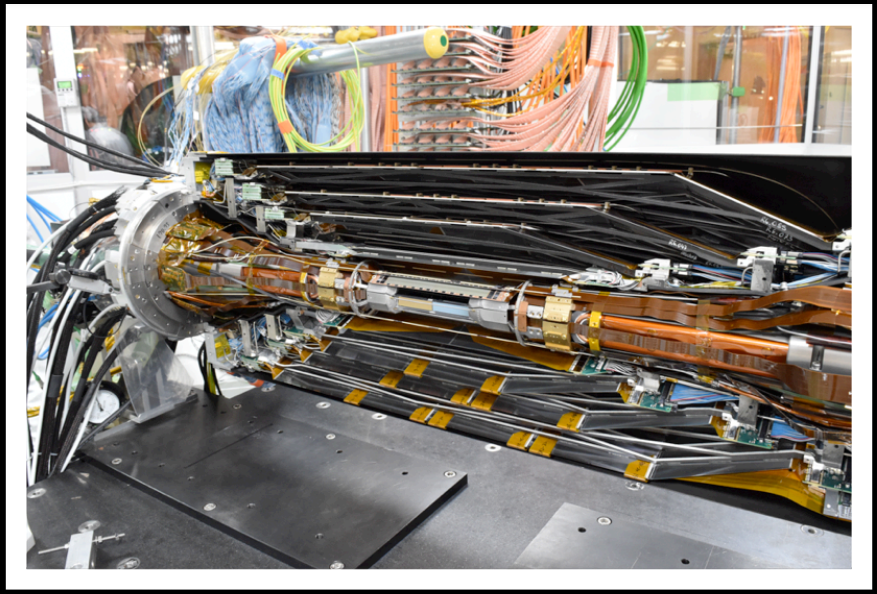


- Smaller pipe radius (15 →10mm) and wider beam crossing angle.
- Pipe crotch starts closer to IP.
- Innermost layer (PXD) added inside the detector.
- Final focusing quadrupoles installed separately for each ring, enabling a more flexible optics design.
- No bending magnets near the IP for lower emittance, reduced background.

Machine and Detector Commissioning

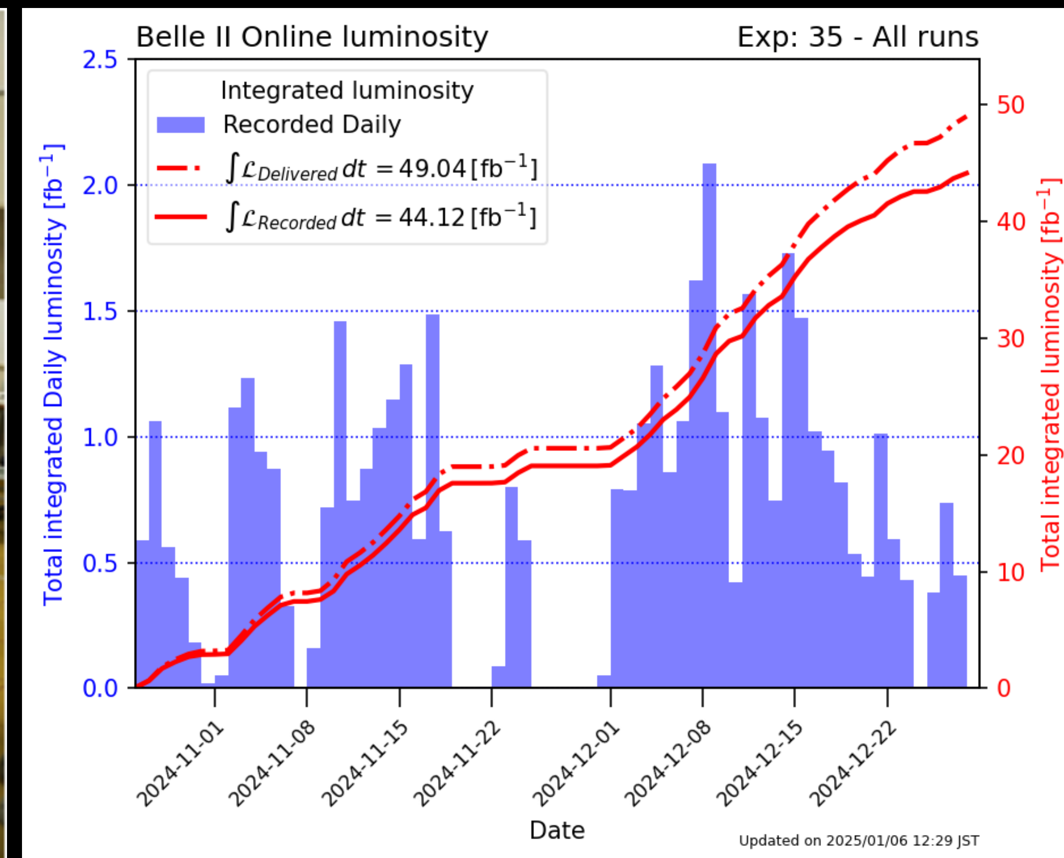


- **Phase-1: Startup of the machine:**
  - commissioning without collisions
  - low emittance beam tuning
  - vacuum scrubbing
- **Phase-2: Commissioning w/o VXD**
  - β* squeezing at IP
  - DR commissioning
  - collision tuning
- **Phase-3: Commissioning w/ full Belle II detector**
  - collision tuning
  - collimator tuning and background study
  - continuous injection



VXD detector

SuperKEKB Operation in the Fall 2024 Run



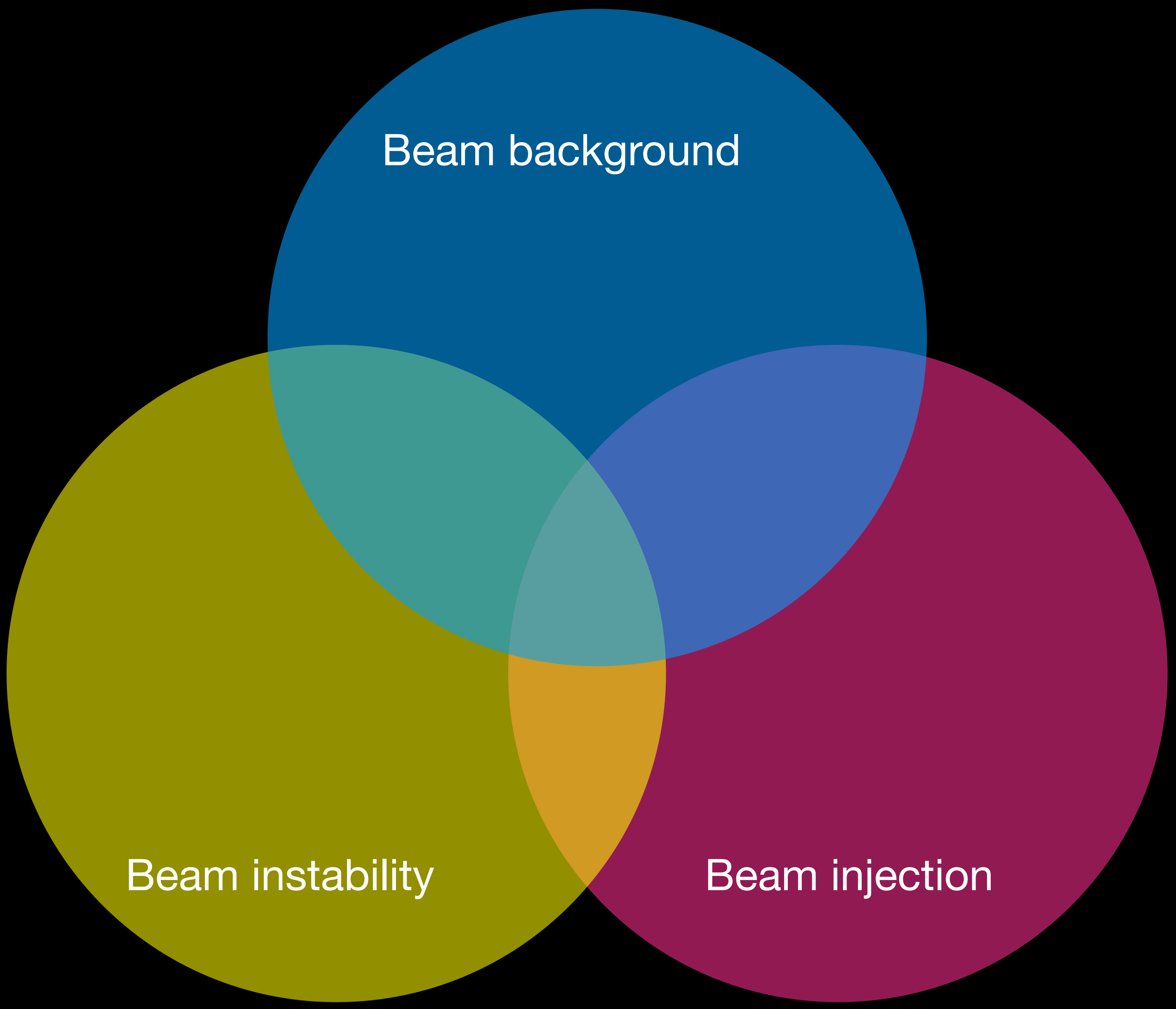
SuperKEKB luminosity is steadily increasing:

- **5.1 x 10^{34} $cm^{-2}s^{-1}$** achieved (World Record).
- LER/HER: 1632/1259 mA, specific lumi: 5.32 x 10^{31} $cm^{-2}s^{-1}mA^{-2}$

However, our target luminosity is 6 x 10^{35} $cm^{-2}s^{-1}$, which is an order of magnitude higher than the current achievement.

Challenges Towards High Luminosity

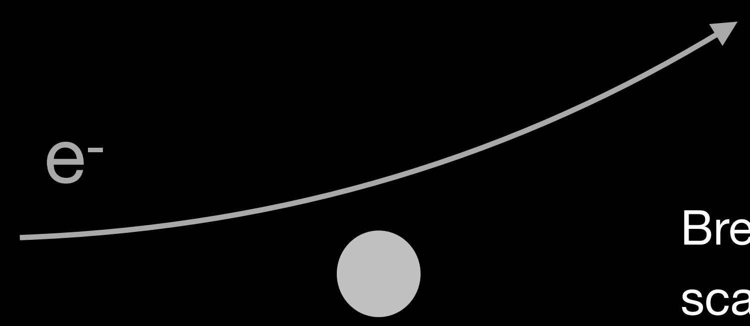
- **Beam Background**
    - Additional shields for mitigation
- **Beam Instability**
    - Sudden Beam Loss
    - Beam blow-up due to beam-beam interaction
- **Beam Injection**
    - Powerful injection to maintain the beam current



Beam Background

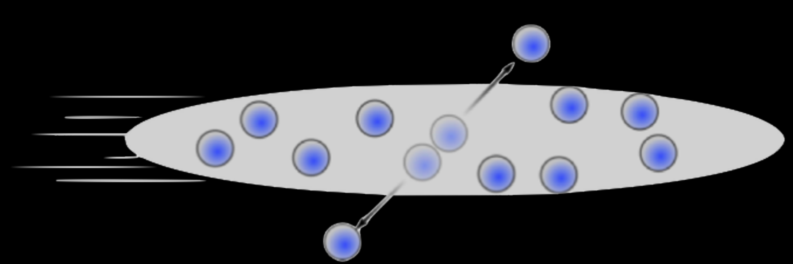
Beam Background

Beam gas



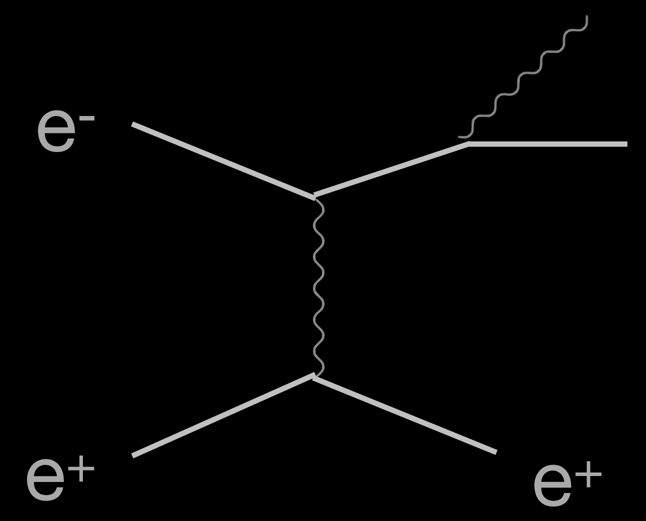
Bremsstrahlung or Coulomb scattering with a gas atom in the beam pipe

Touschek effect



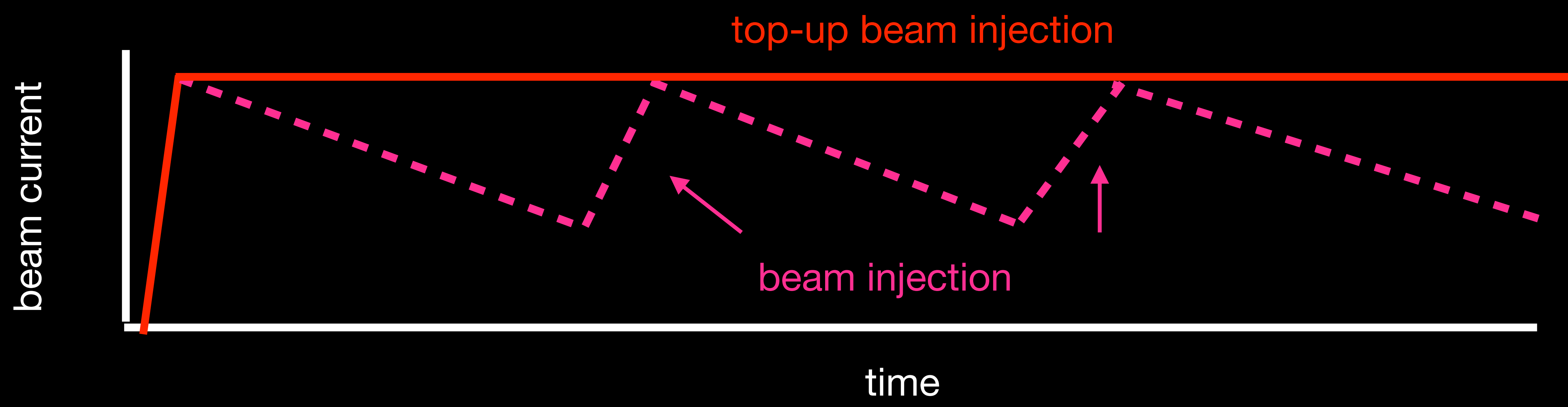
Coulomb scattering between particles within a beam bunch

Radiative Bhabha Process



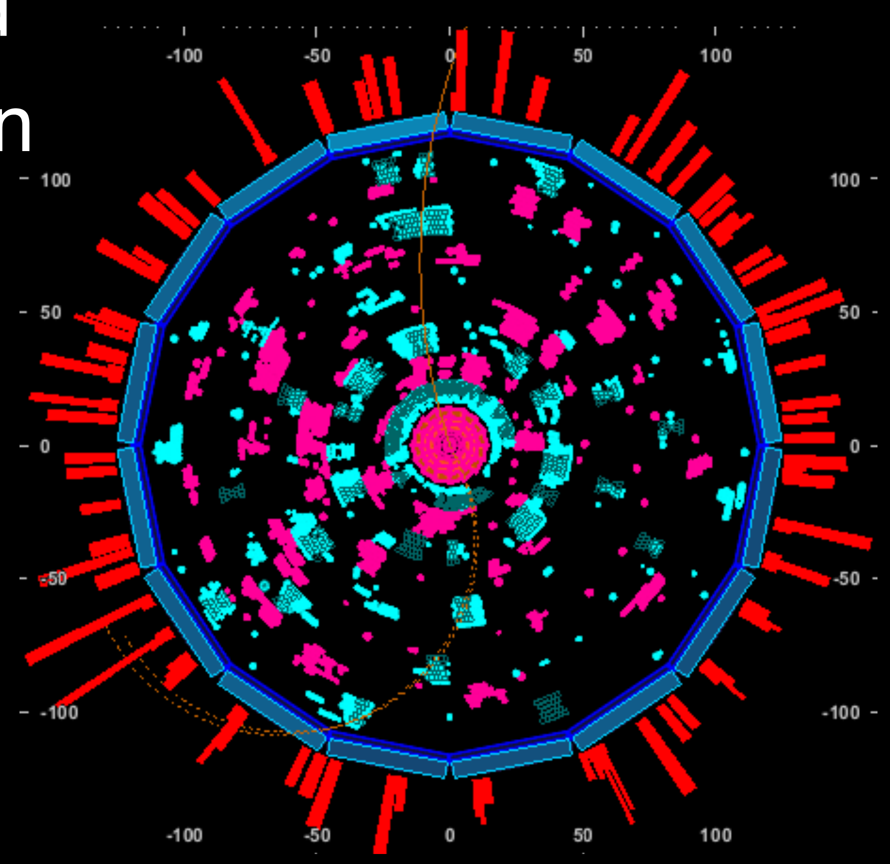
Beam particles deviated from the nominal orbit will eventually be lost by hitting beam pipe or collimator generating electromagnetic showers.

Injection Background

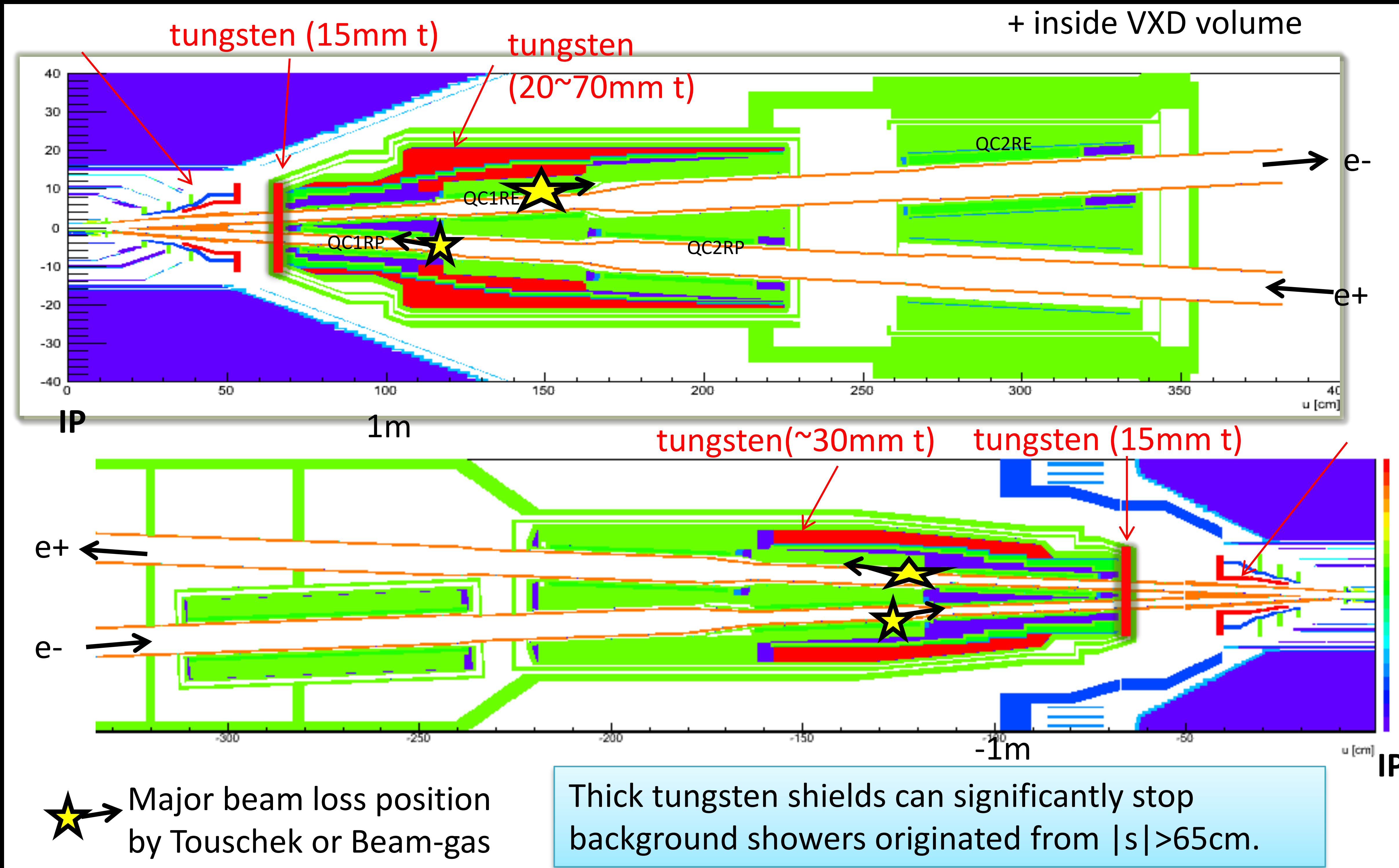


- **Top-up beam injection scheme** is applied during the data-taking. The beam oscillation remains for some time (~10 ms), making large injection background.

- Injection veto is applied to minimize the injection background. If the veto length is not sufficient, a trigger burst may occur.



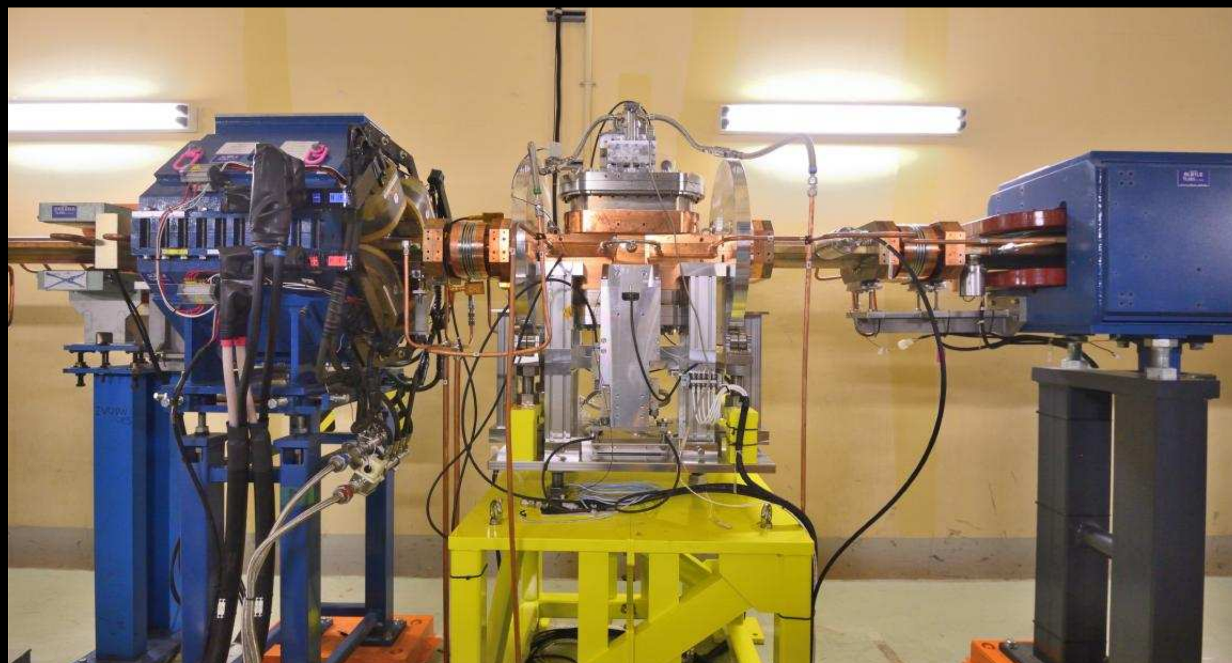
Tungsten Shields in QCS

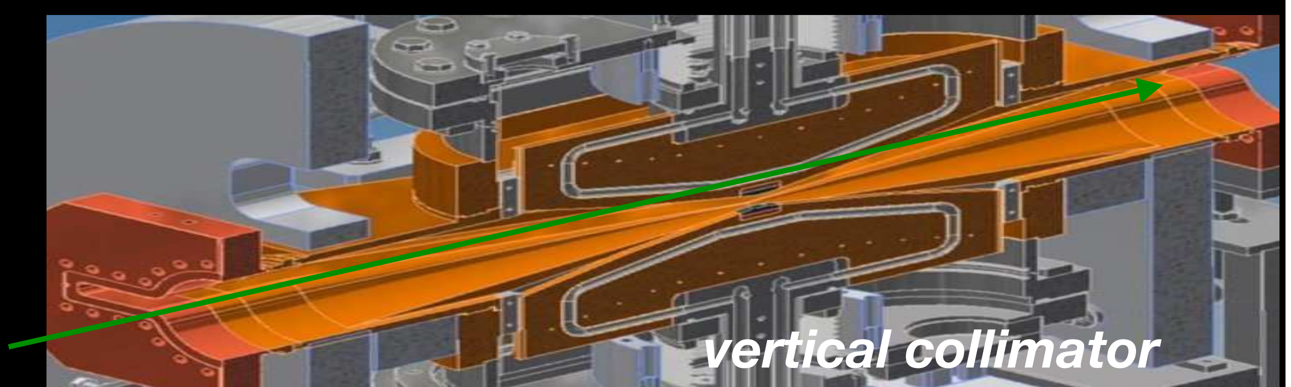


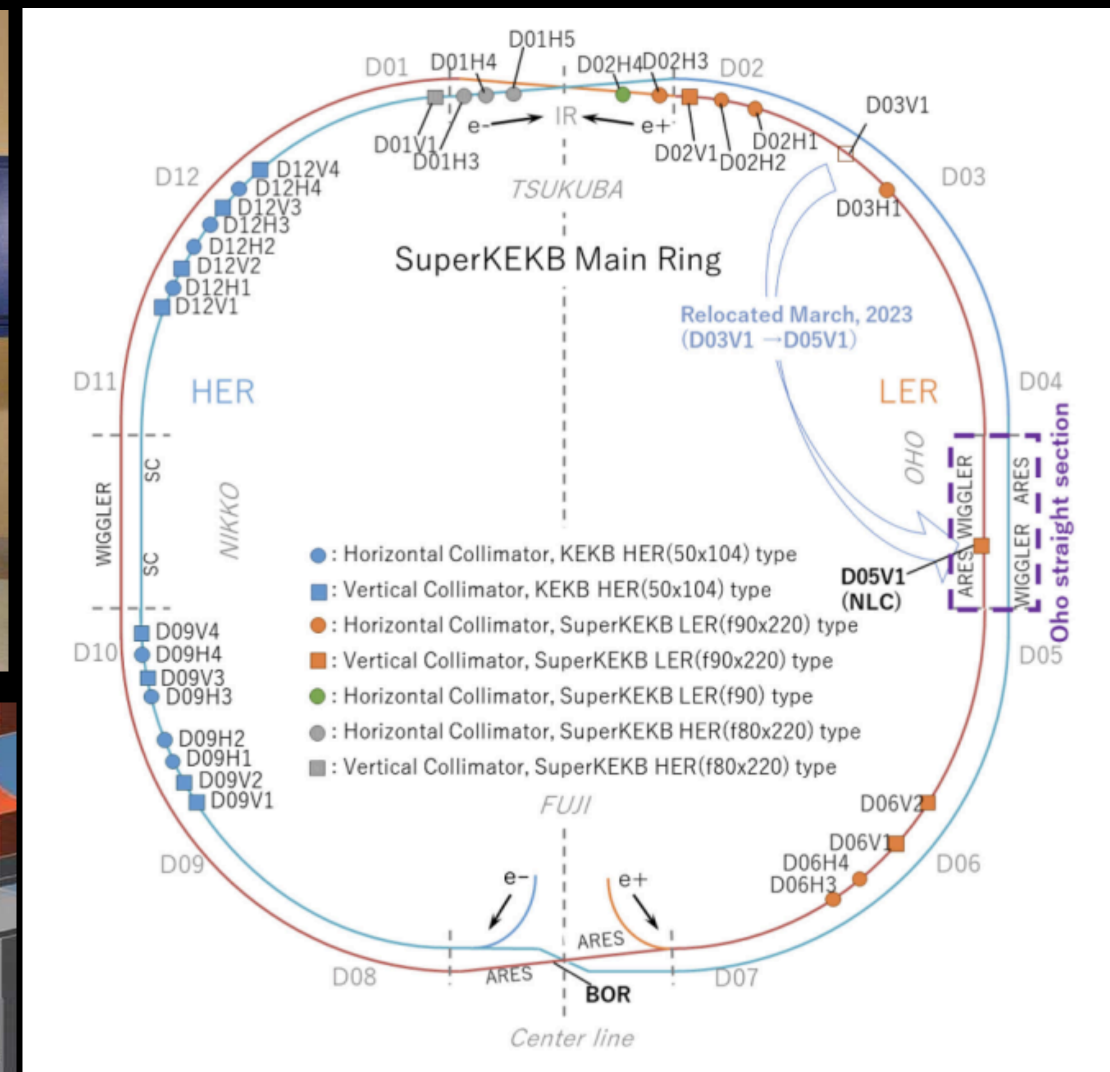
Thick tungsten shields can significantly stop background showers originated from |s|>65cm.

credit: Hiro Nakayama

Collimator System







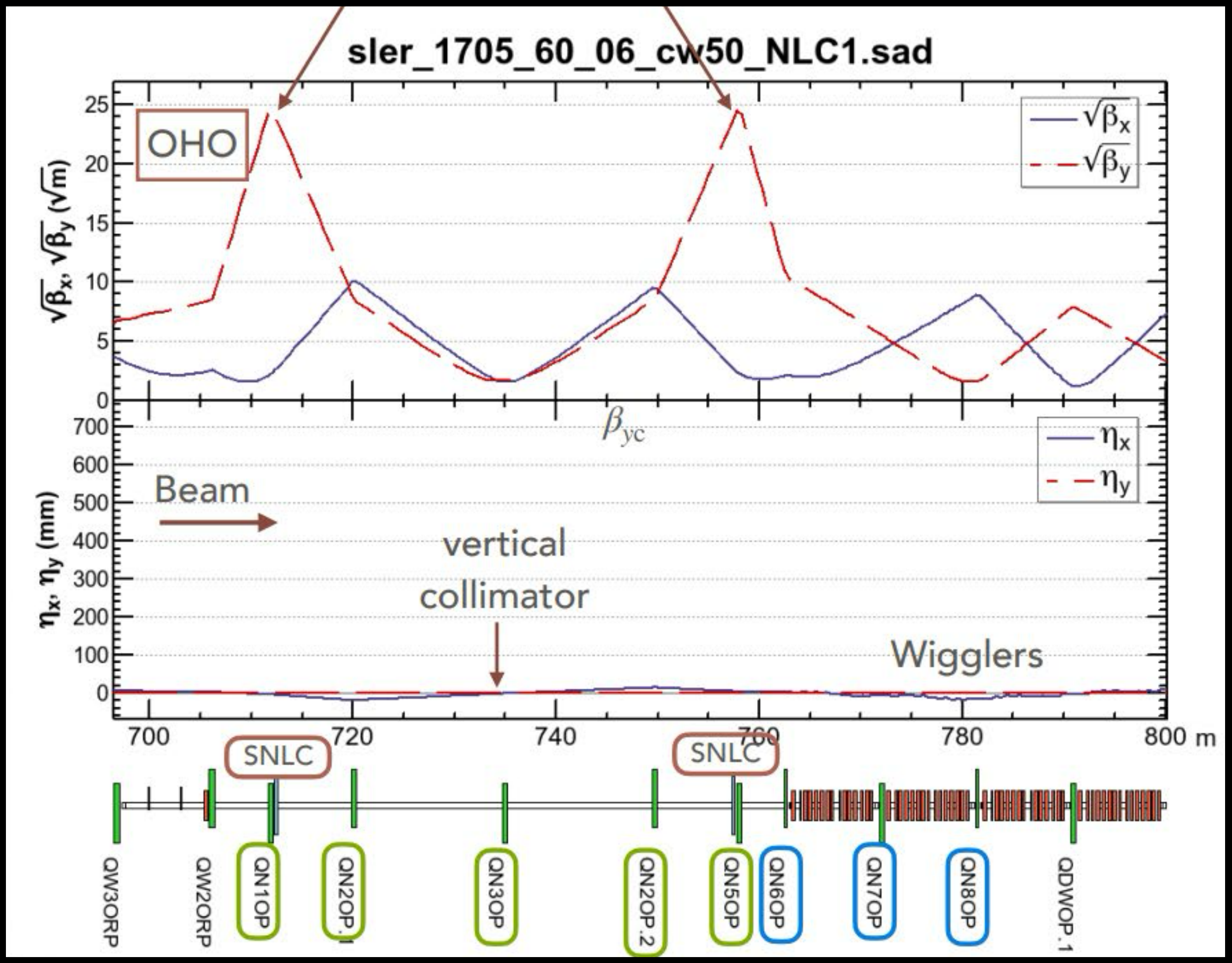
- Collimators are used to reduce the beam background.
- 32 collimators (20 for HER, 11 for LER) are installed along the ring.
- Shall we tighten the collimators for zero background?
  - TMCI (beam instability) may be casued as ring impedance increases, therefore no more increase in bunch current

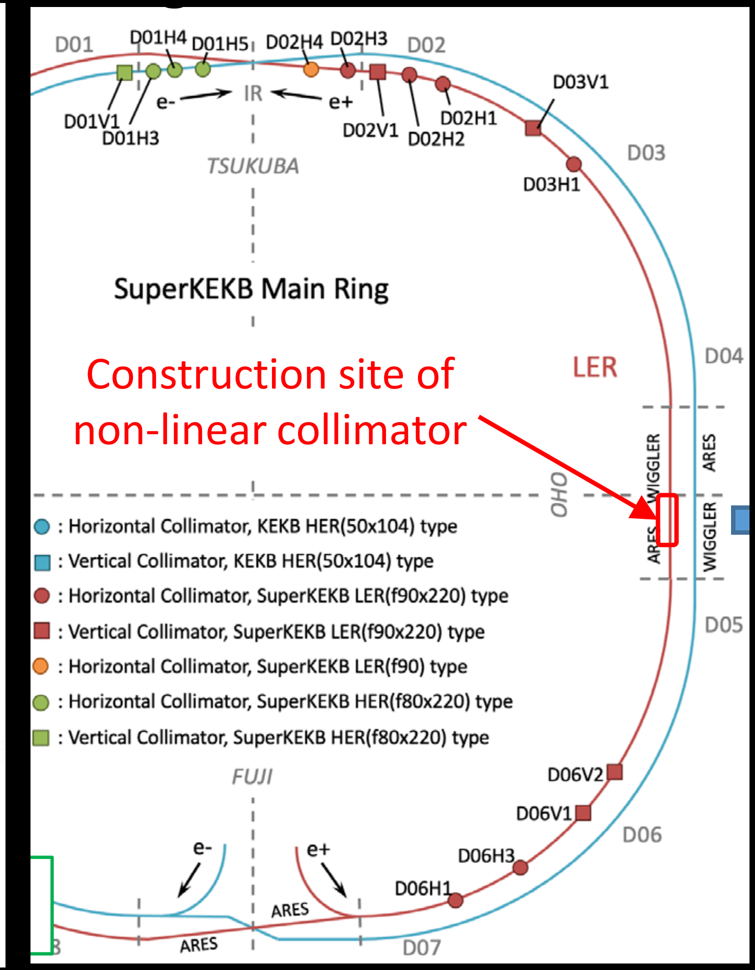
Non-linear Collimator

"Non linear collimator" is a vertical-type collimator located in-between two **skew-sextuple magnets**. The non-linear vertical kicks are utilized to enlarge theoretical displacement of particles at small β_y section.

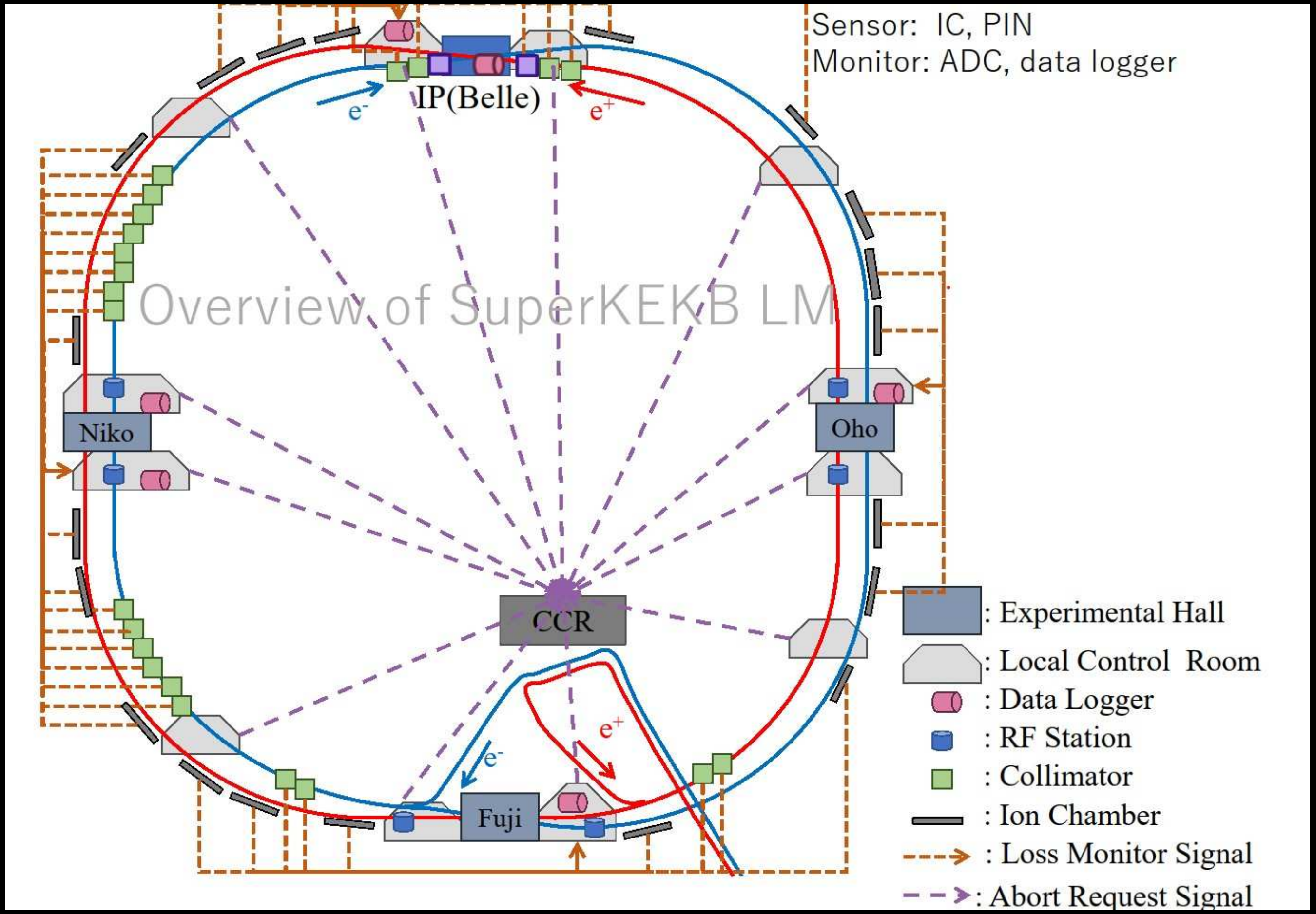
→ **Relax the TMCI bunch current limit.**

Skew sexts (SNLC)





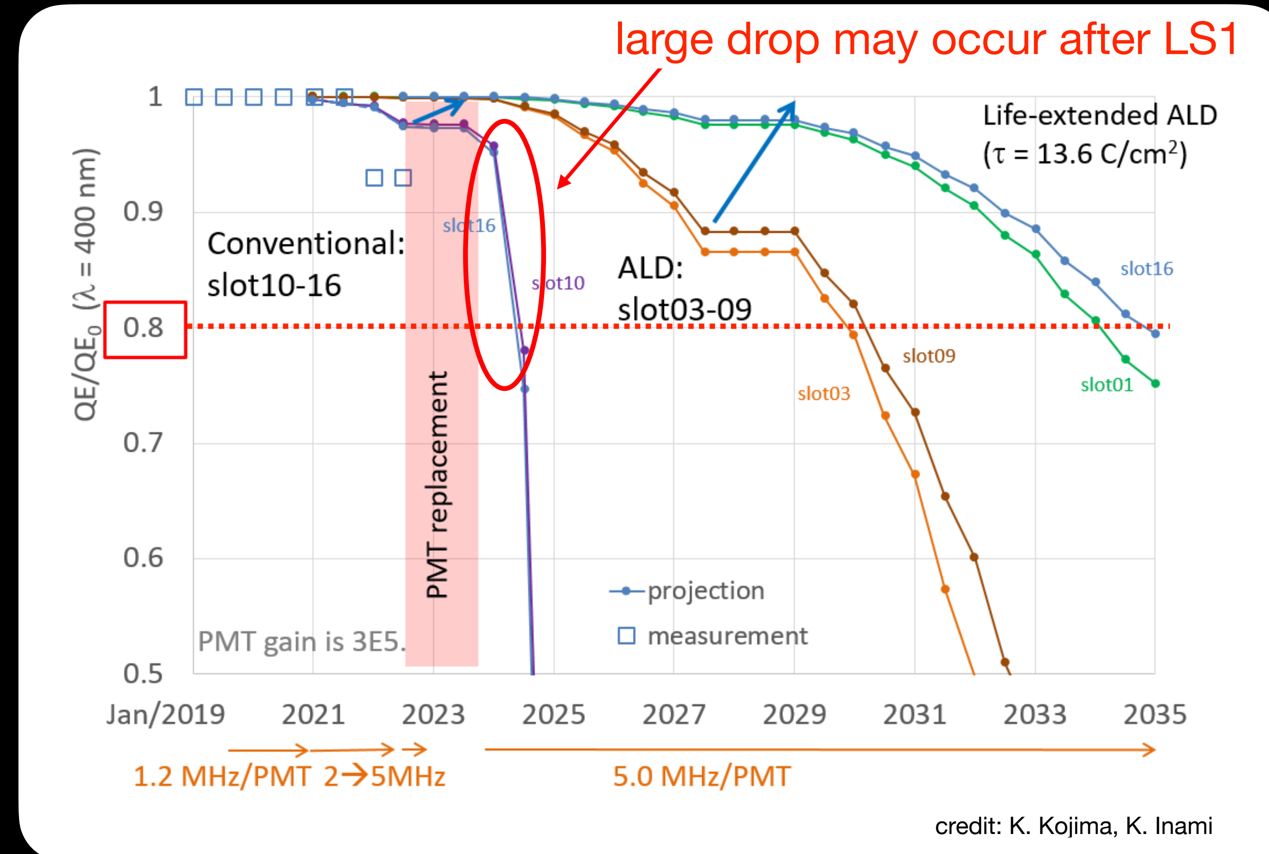
Beam Abort System



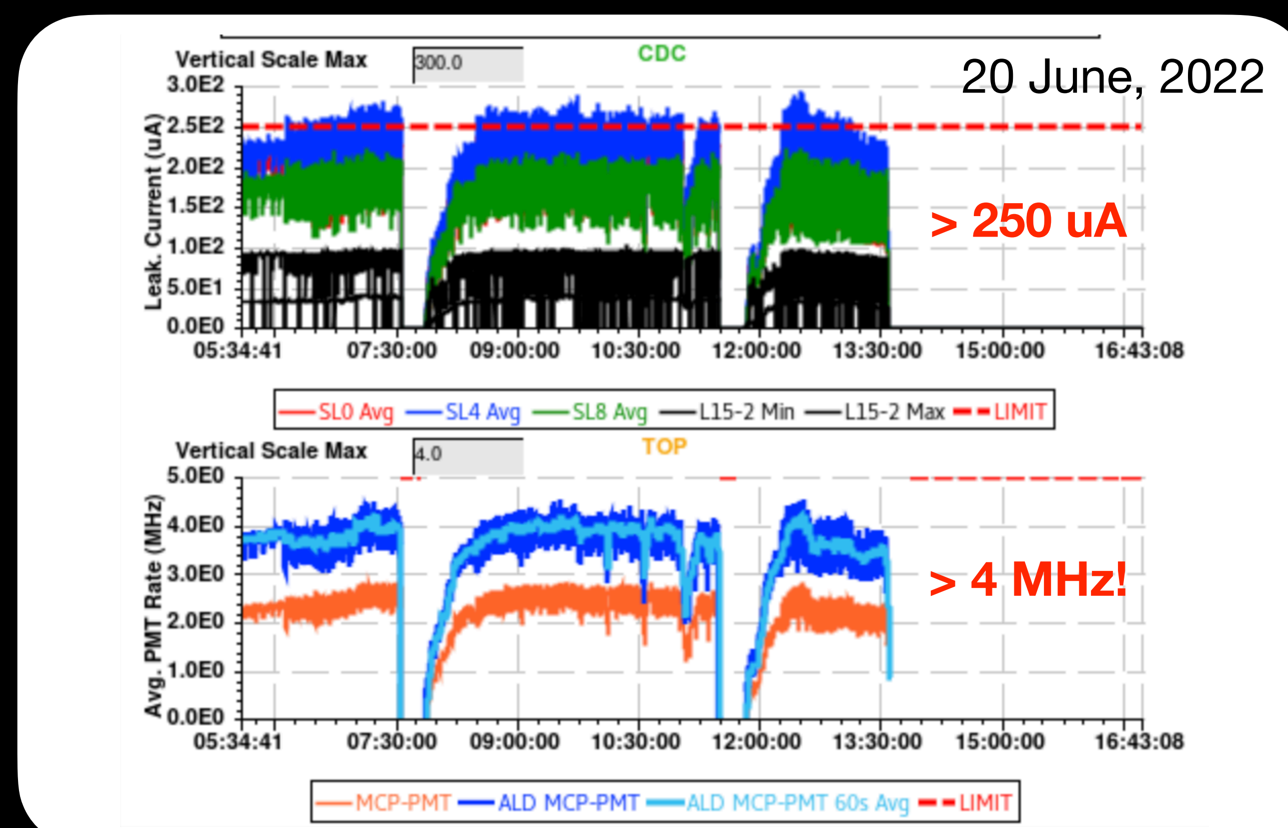
- If abnormal beam loss is detected by various sensors (e.g. PIN diode, diamond), the beam is aborted to protect the Belle II detector or the accelerator components.
- The abort request is sent to the abort kicker via central control room (CCR). **It takes ~20 μs (2 beam turns)**.

Belle II Backgrounds

- **TOP PMT lifetime**
  - To retain QE of MCP-PMT, beam background such as beam-gas and Touschek needs to be suppressed to an acceptable level
  - It may limit the luminosity performance



- **Leakage current in drift chamber**
  - The leak current increases as beam injection background goes high
  - It may eventually cause HV trip

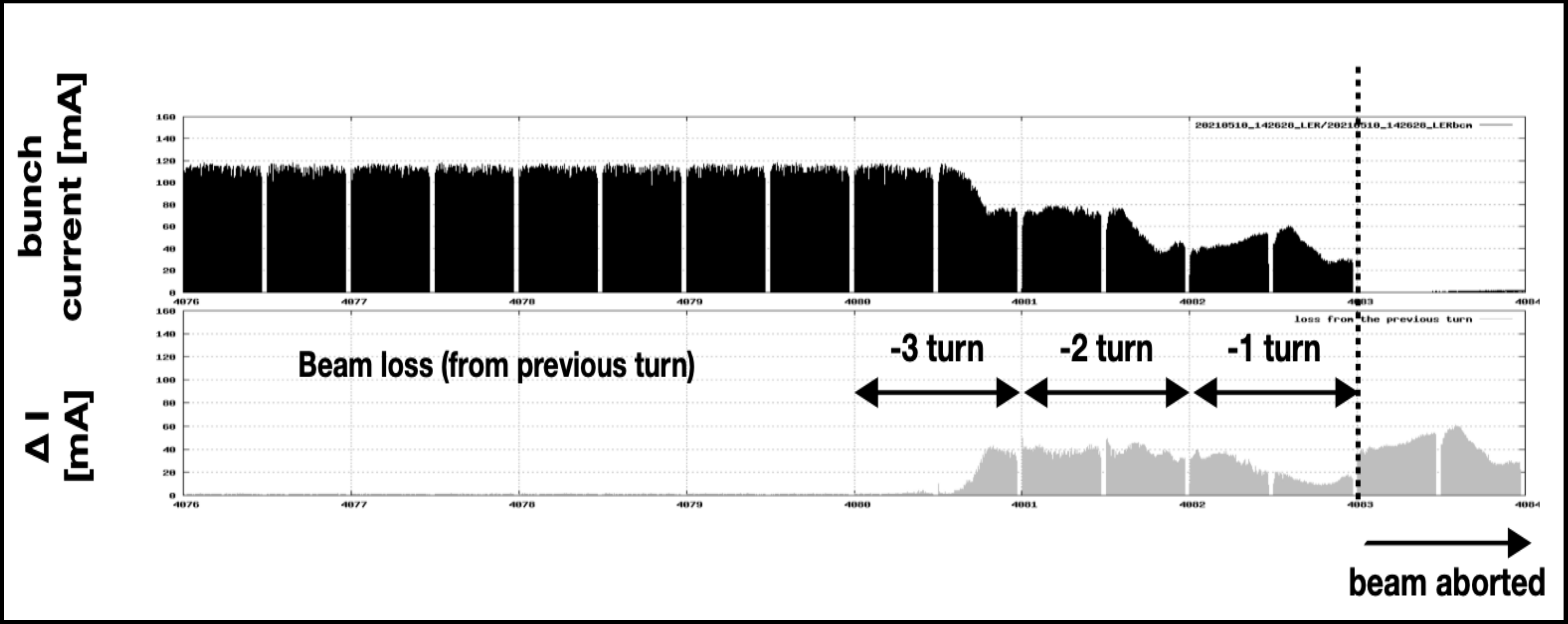


- Synchrotron radiation introduces non-uniform hit pattern in PXD sensor

Beam Instability

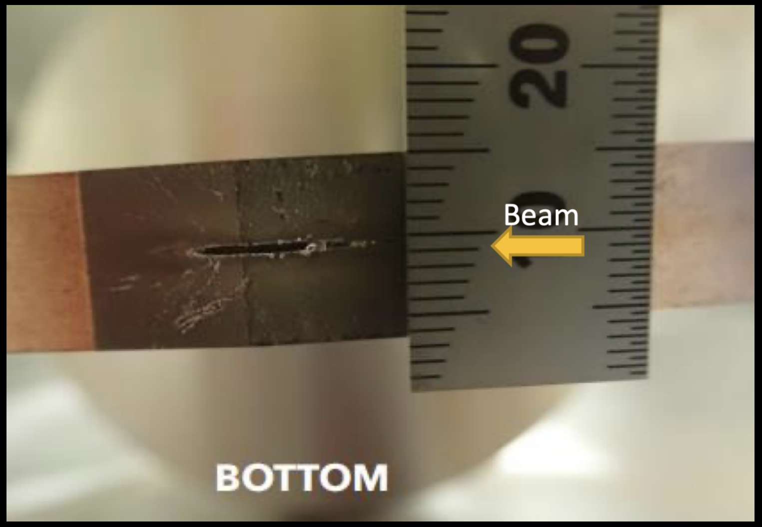
- SBL
- Beam Diagnostics
- Advanced Abort System

Sudden Beam Loss (SBL)



The stored beam is lost within just a few turns due to unknown causes. This occassionally leads to a QCS quench, potentially damaging a collimator head or the Belle II detector.

→ **Significant limitation for machine operation**



Main Objectives

Belle II and SuperKEKB have focused their joint efforts since 2021 on the following.

1. Fast LM system for beam diagnosis

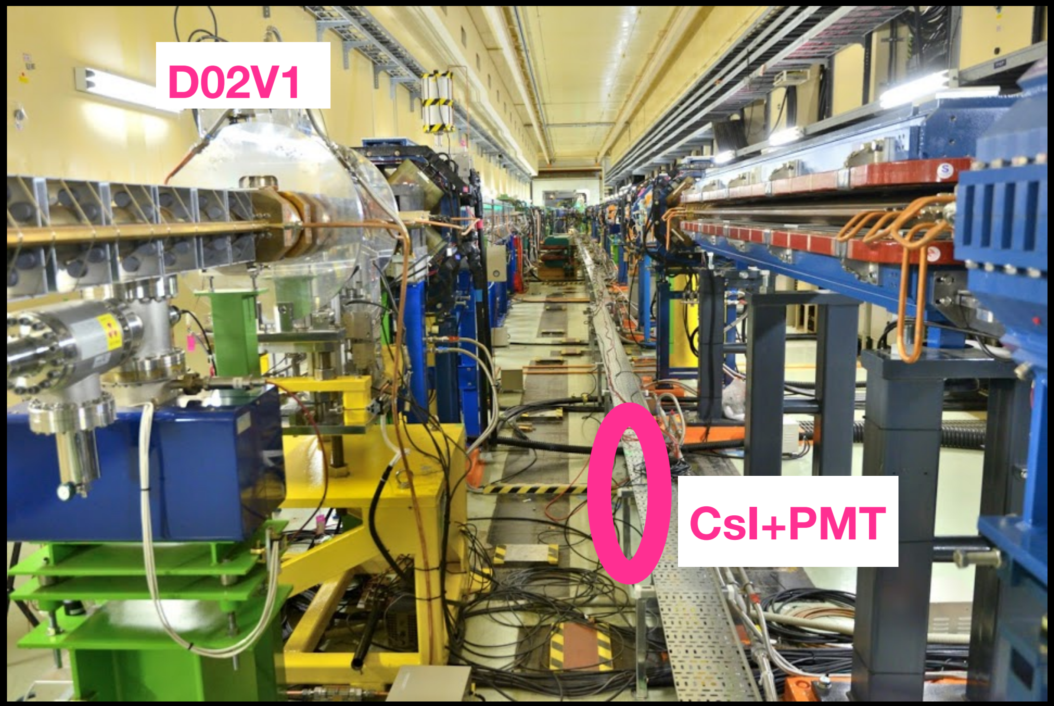
- Can we pinpoint the location of the initial beam loss? Adding more loss monitors might provide insights into the SBL mechanism

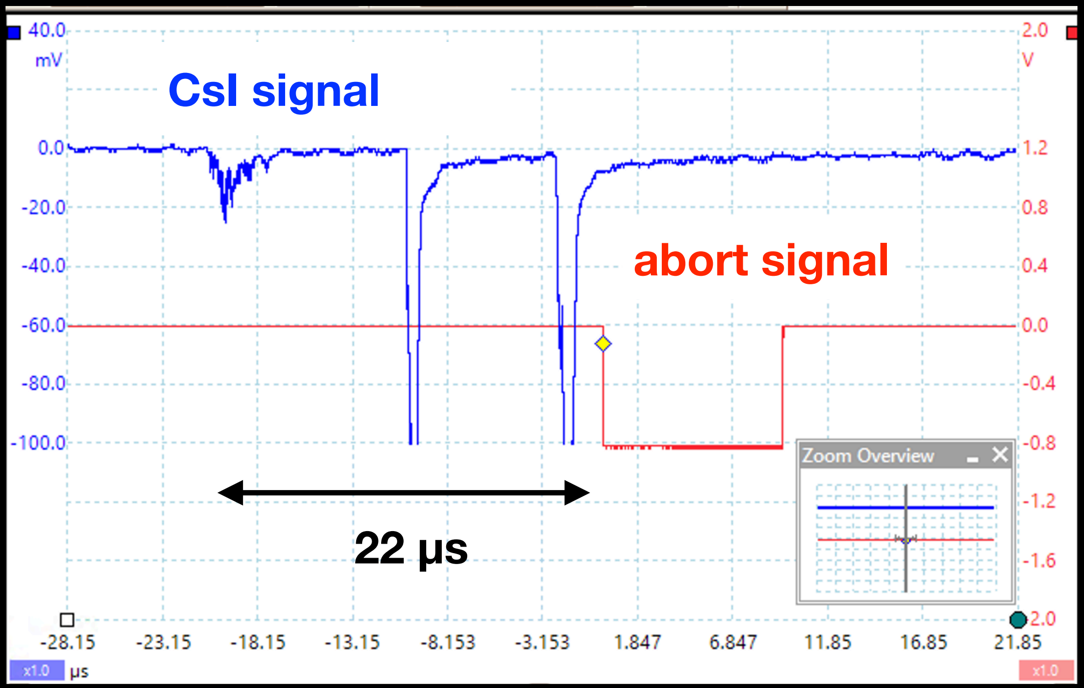
2. Advanced beam abort system

- To protect hardware and the detector from SBL, we must improve the speed of the beam abort system, reducing the radiation dose lost in the ring

Enhancing Detection Capabilities for SBL

- A new beam diagnosis system (loss monitors + time sync system), has been developed to accurately pinpoint the location of beam losses with an accuracy of 20 m (~100 ns)

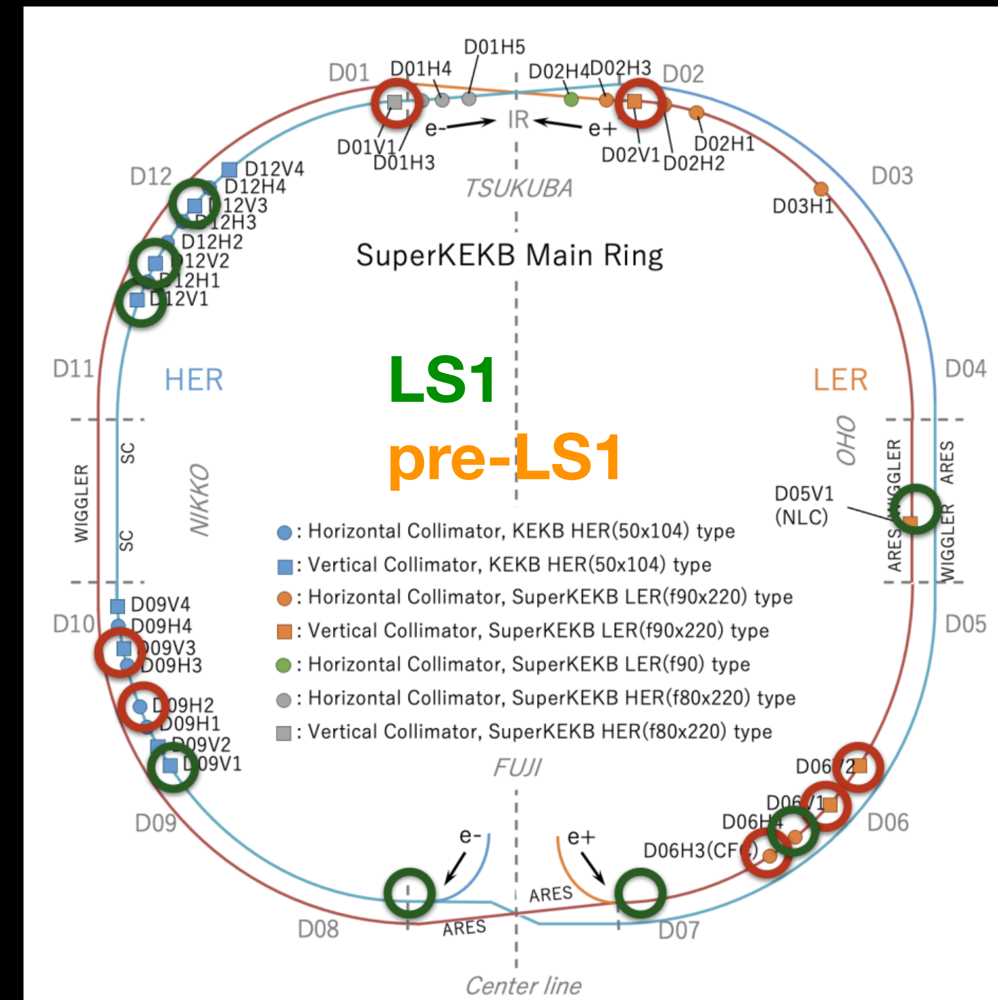




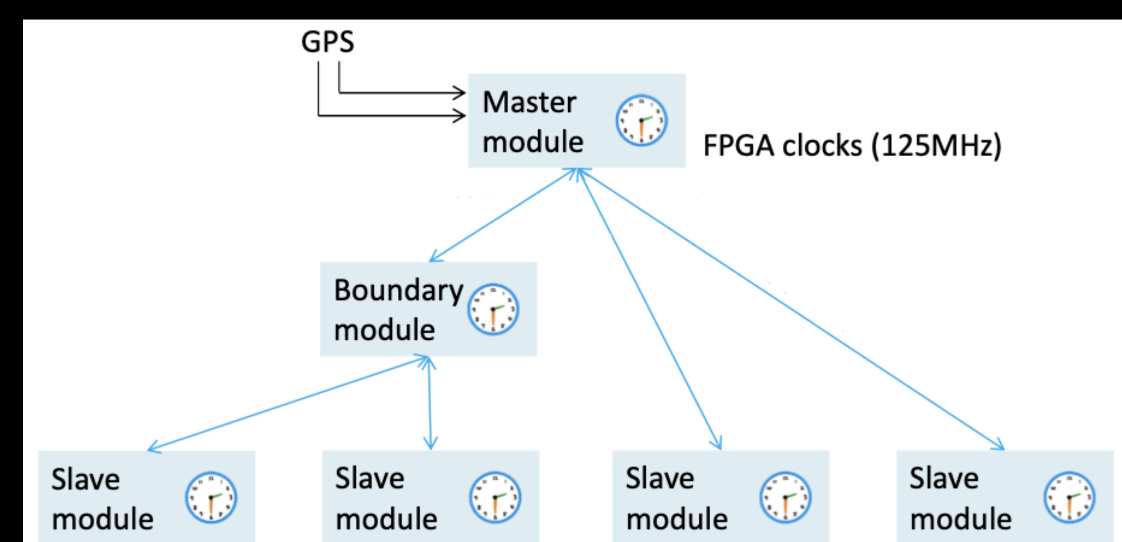
- At the end of 2021b, a CsI (pure) + PMT was installed at D02V1, where it successfully detected a significant beam loss

Fast LM system for beam diagnosis

- 15 loss monitors (CsI+PMT, EMT) have been installed around collimator locations (i.e. smallest aperture in the ring) since the summer of 2021.

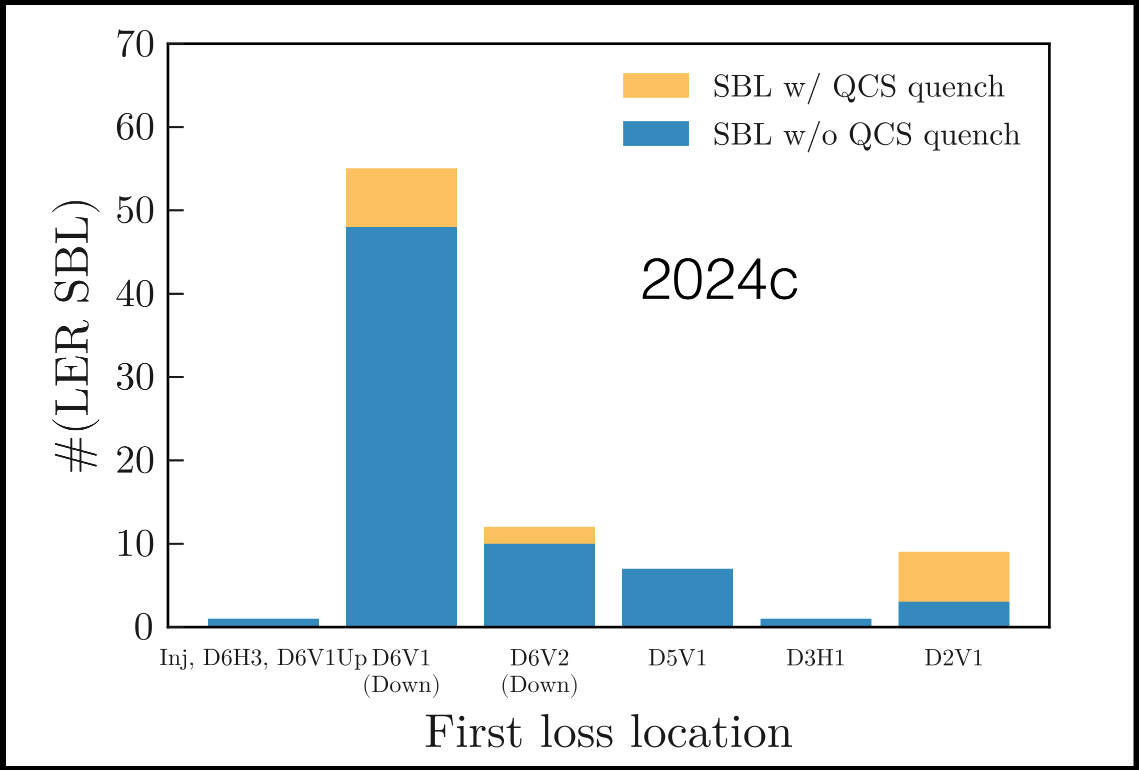


- White Rabbit (WR) time synchronization system, developed by CERN, has been employed.

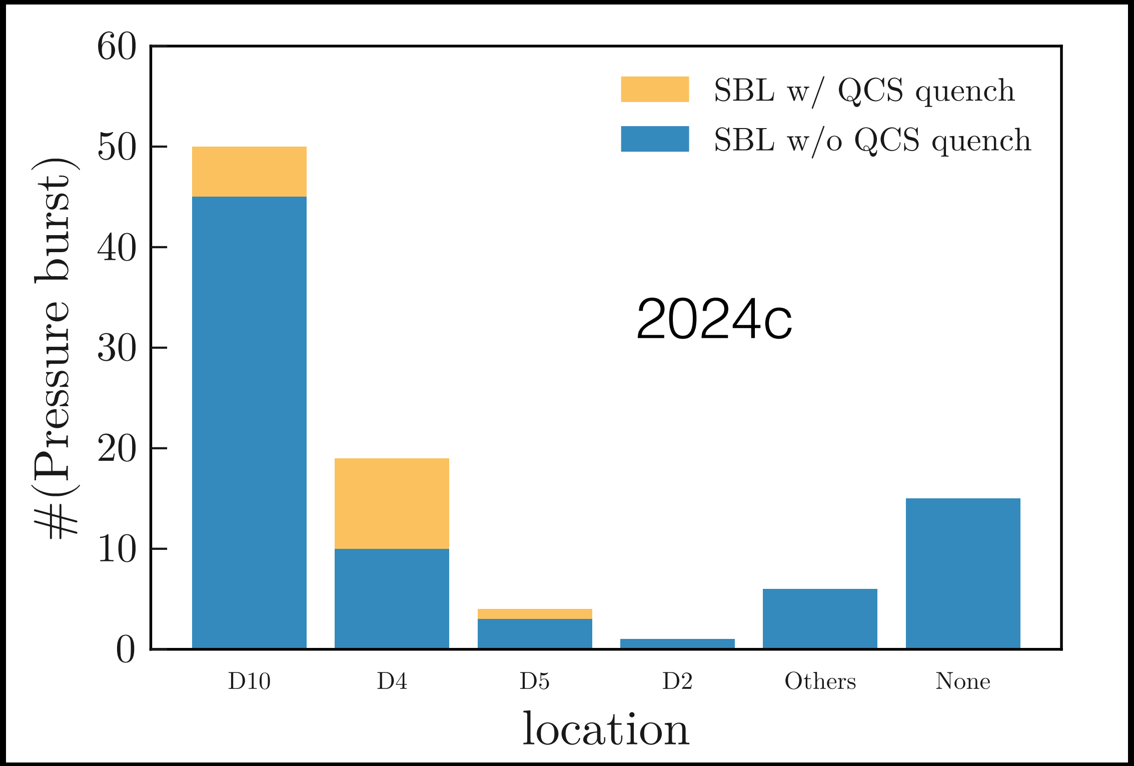


SBL Analysis

First beam loss

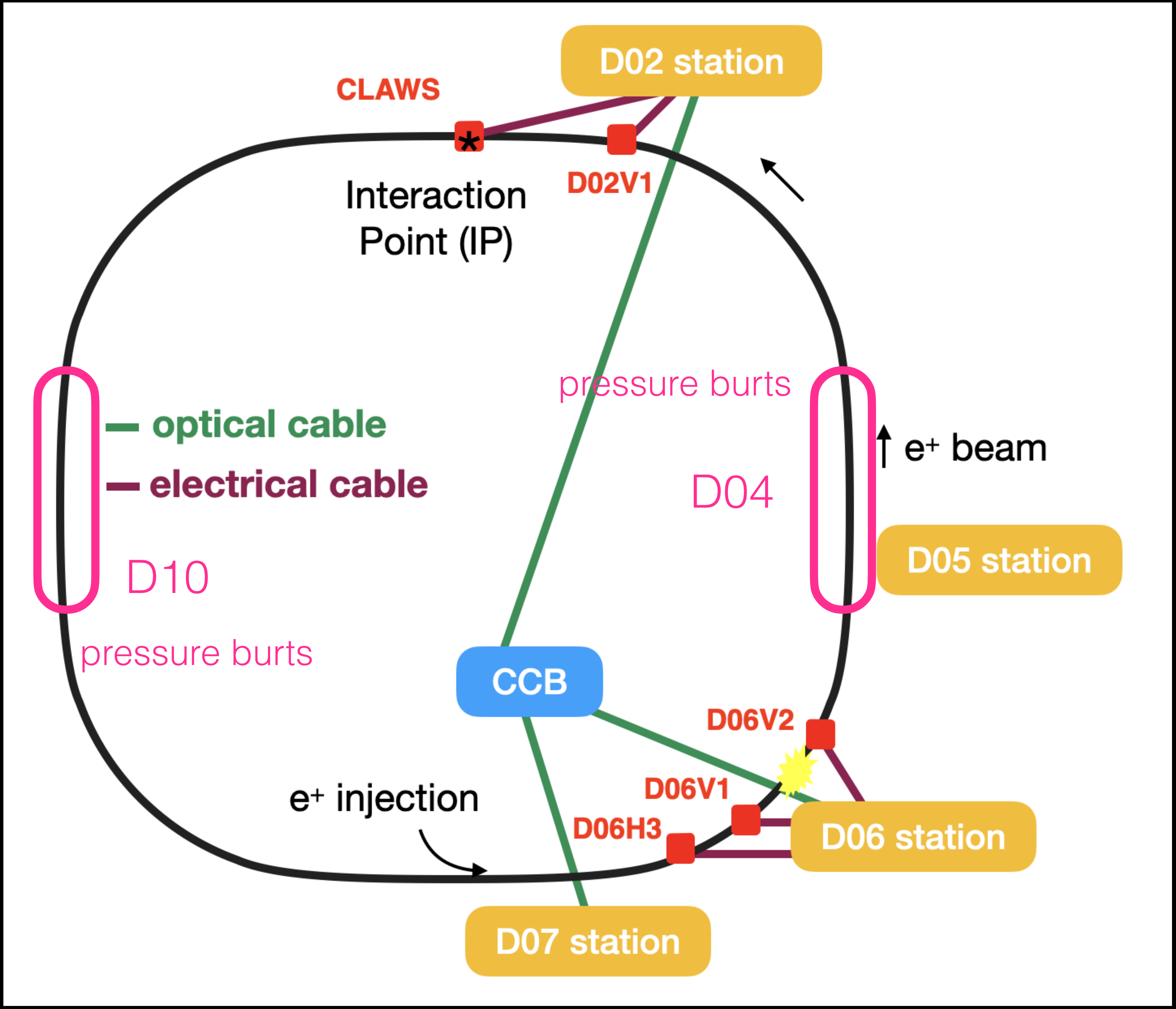


Pressure Burst



- The analysis primarily focused on LER. The losses were often detected at D06V1 and D06V2 (or D05V1 in 2024).
- High QCS quench probablitiy was linked to first losses detected at D02V1.
- SBL events found to be highly correlated with **pressure bursts** in certain sections (**D04 and D10**) in 2024.

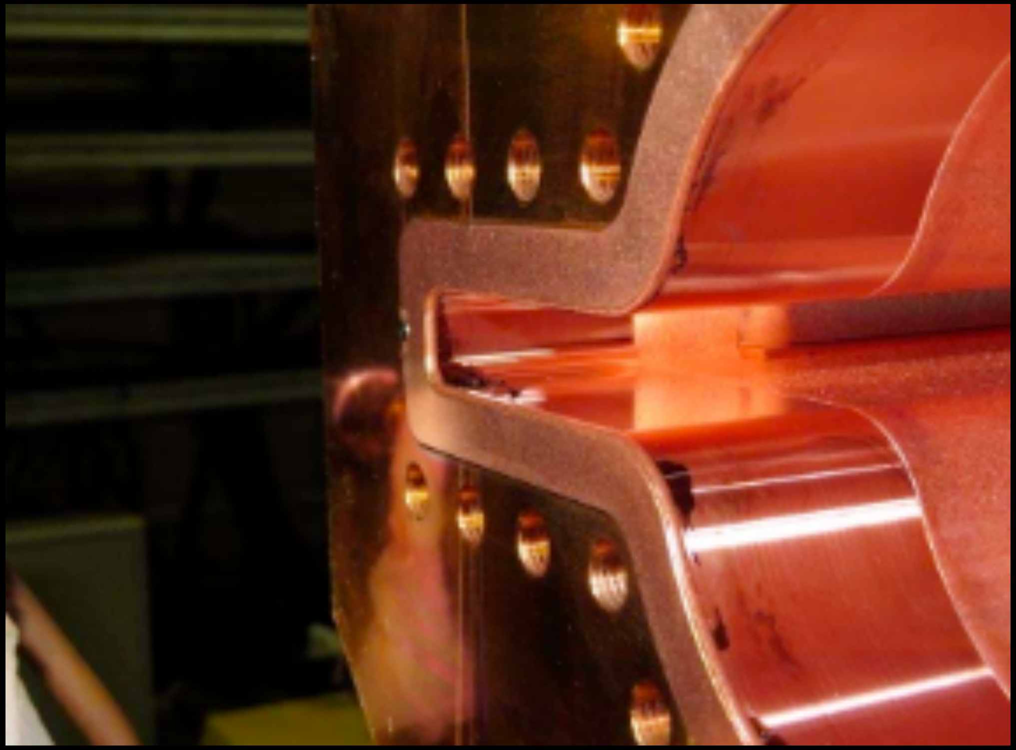
SBL Locations



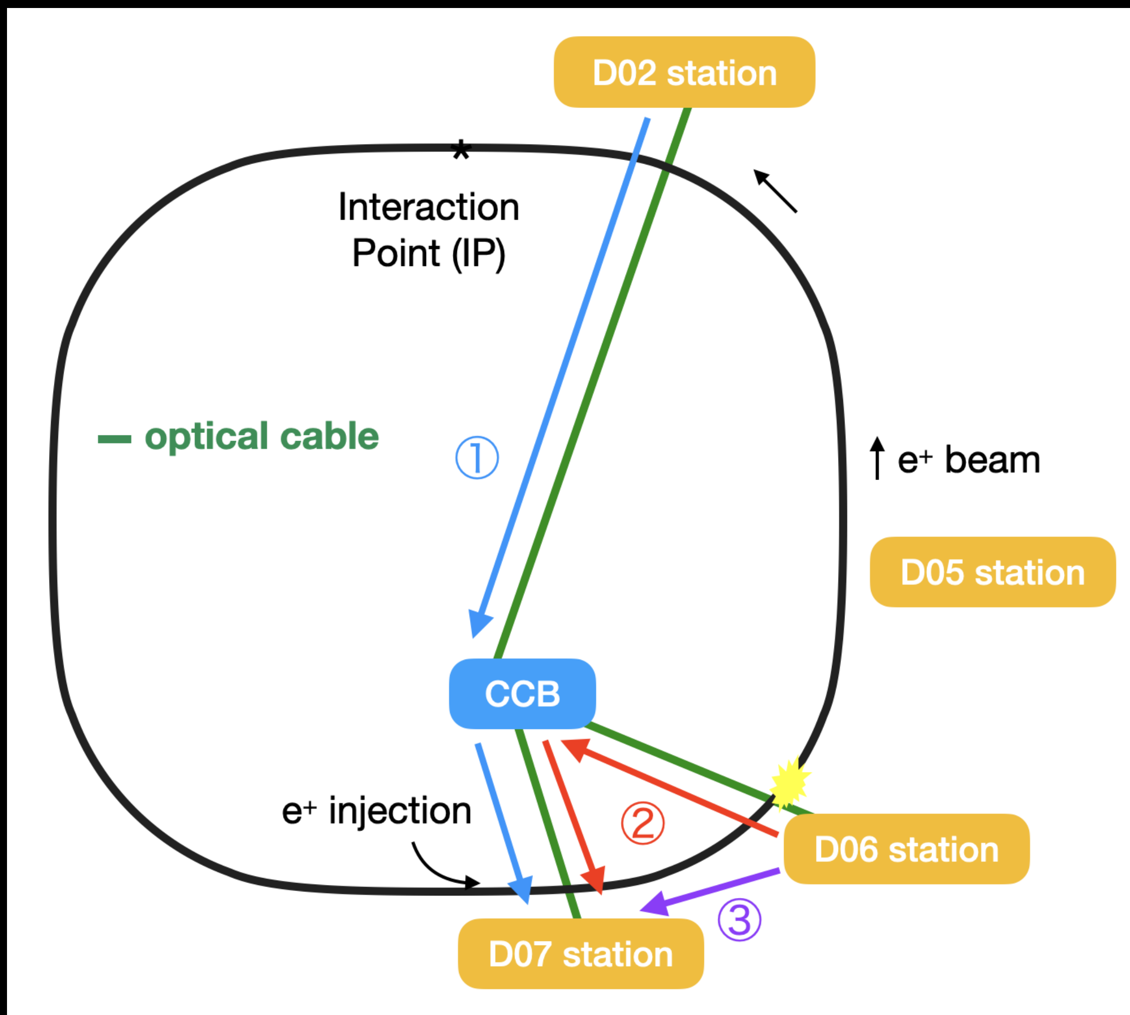
SBL Investigation (After Summer 2024)

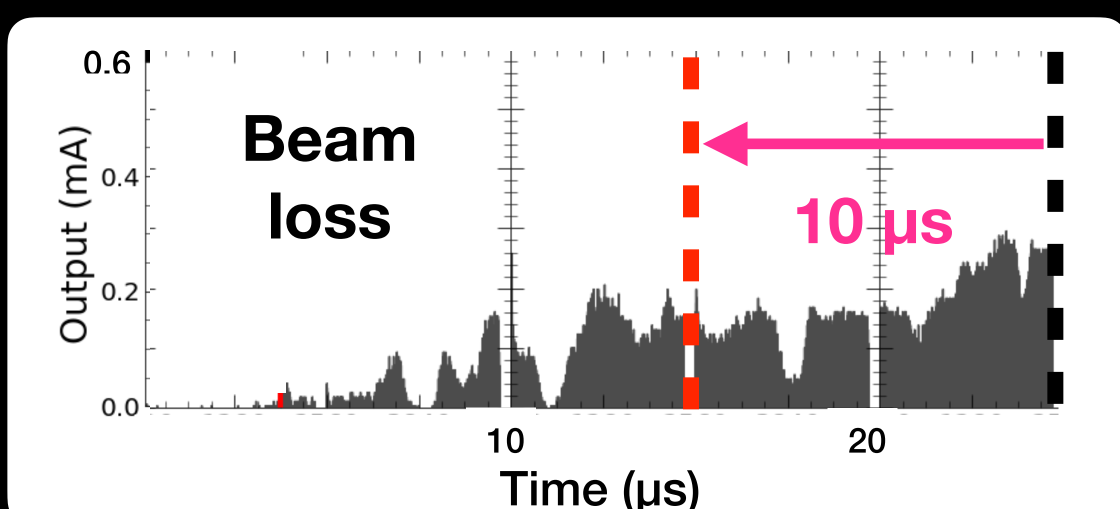
- Upon opening the beam pipe in the D10 L02/L03 sections, **black stains** were discovered.
- These stains were identified as burnt silicon, most likely originating from the degradation of **vacuum sealants (VACSEAL)**.

- After cleaning the affected pipes (D10 L02/L03), SBLs were completely eliminated in that section.
- **However SBLs continue to occur in the D04 section, necessitating further clearning/monitoring.**



Advanced Beam Abort System



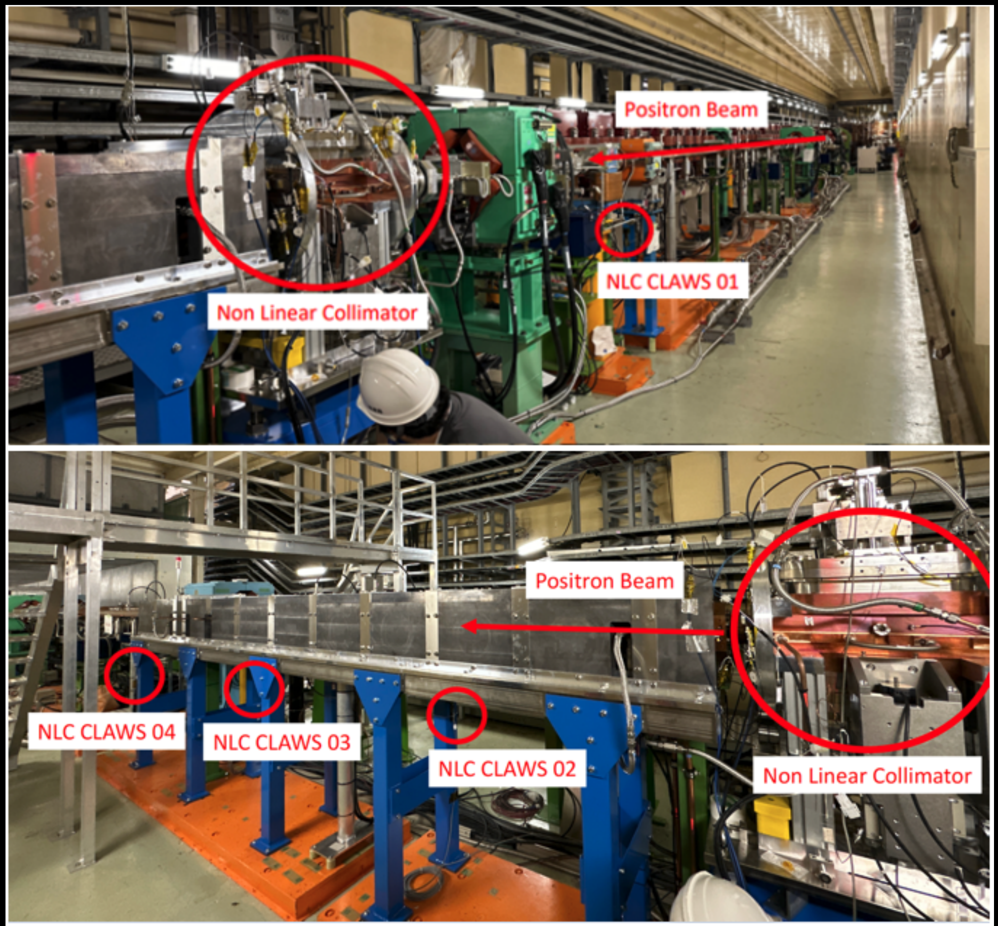


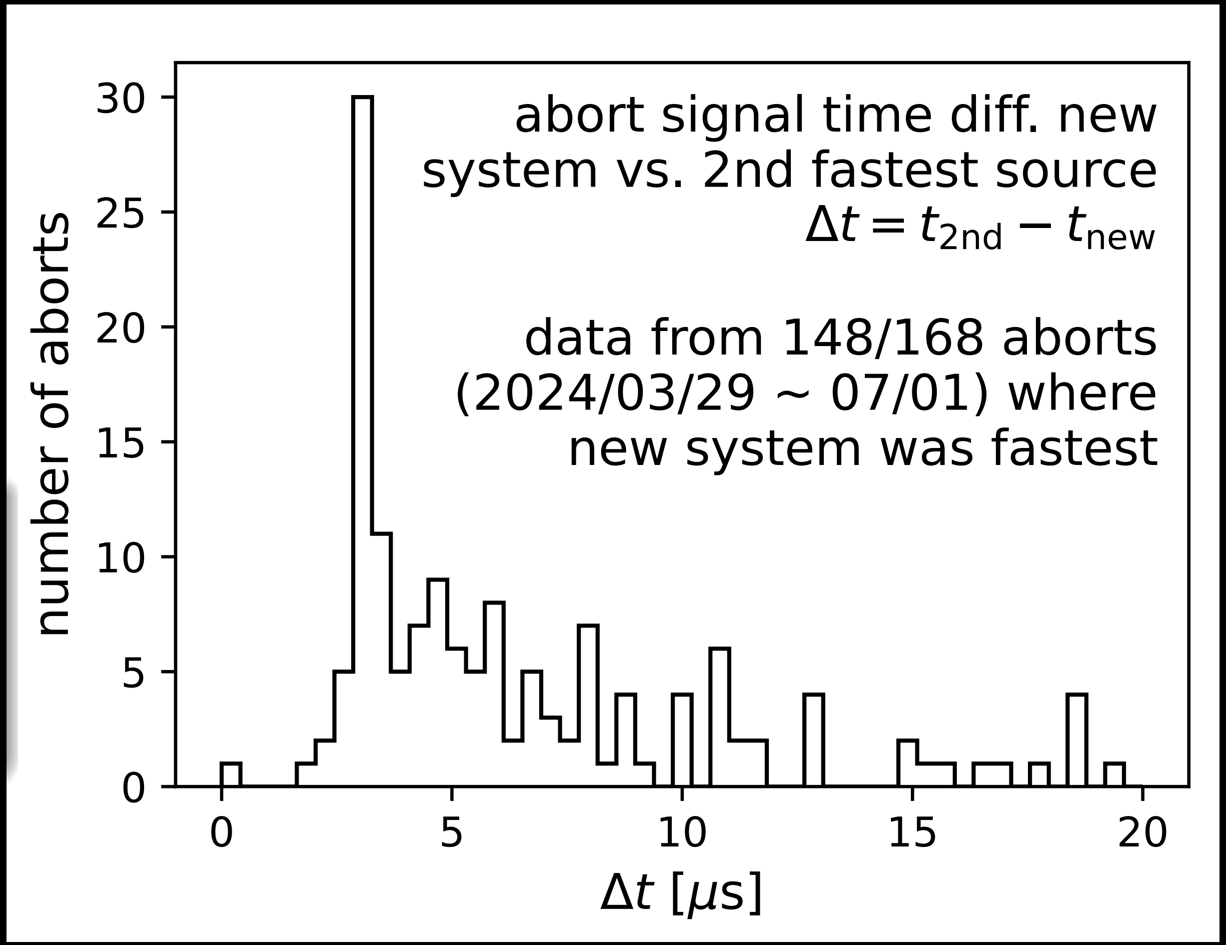
In 2022, most SBL events triggered abort requests from CLAWS (IR). The timing of these aborts can be improved by:

1. **Optimizing sensor placement**
2. **Reducing transmission path length (bypassing CCB)**

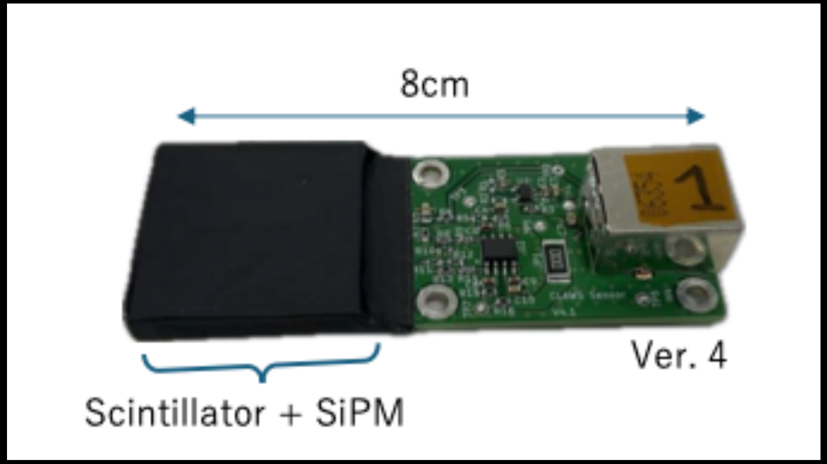
In 2022, we demonstrated that optimizing sensor placement at D06V1 allowed the abort signal to be issued 1-2 abort gaps earlier.

Additional Sensor installation



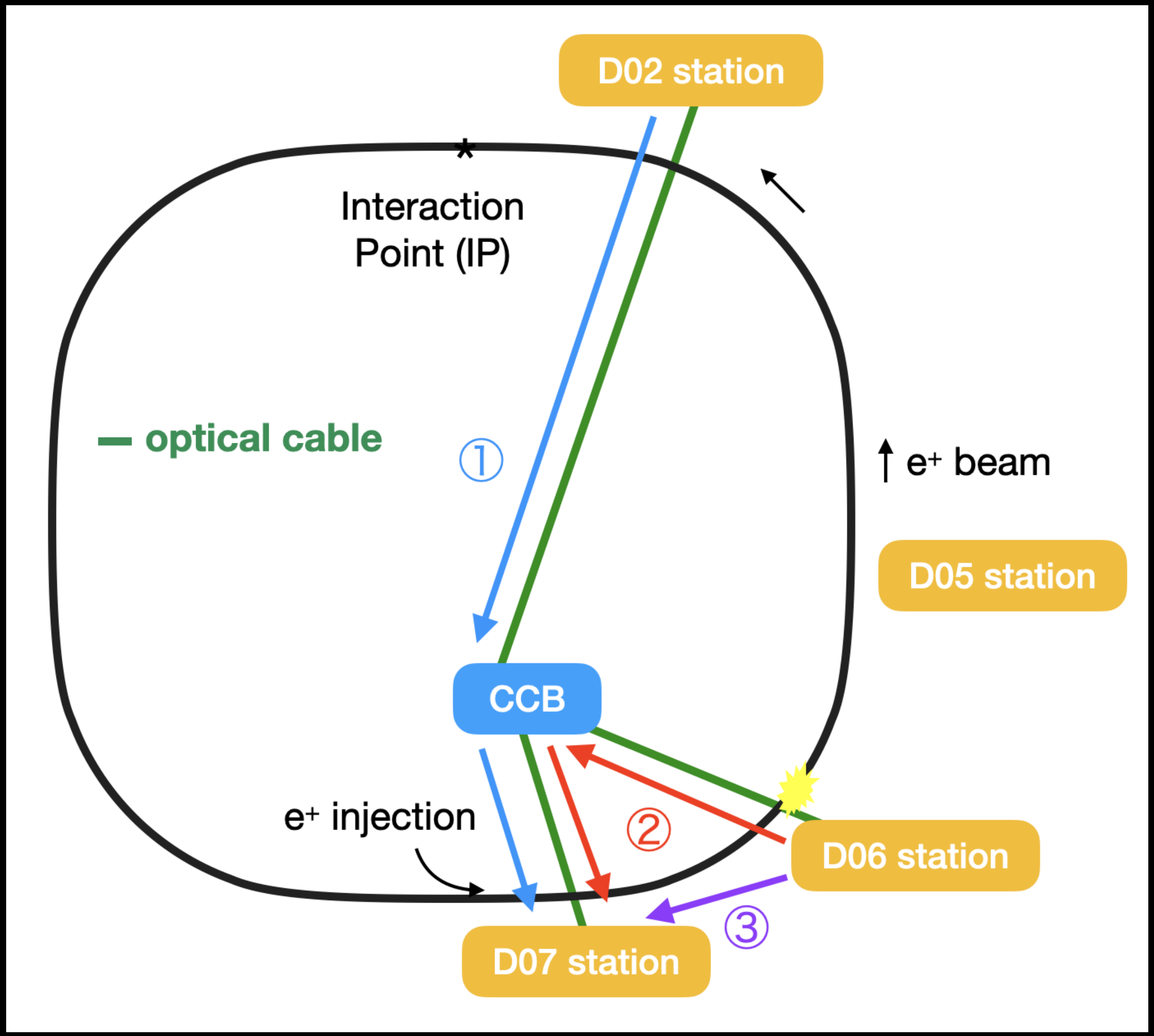


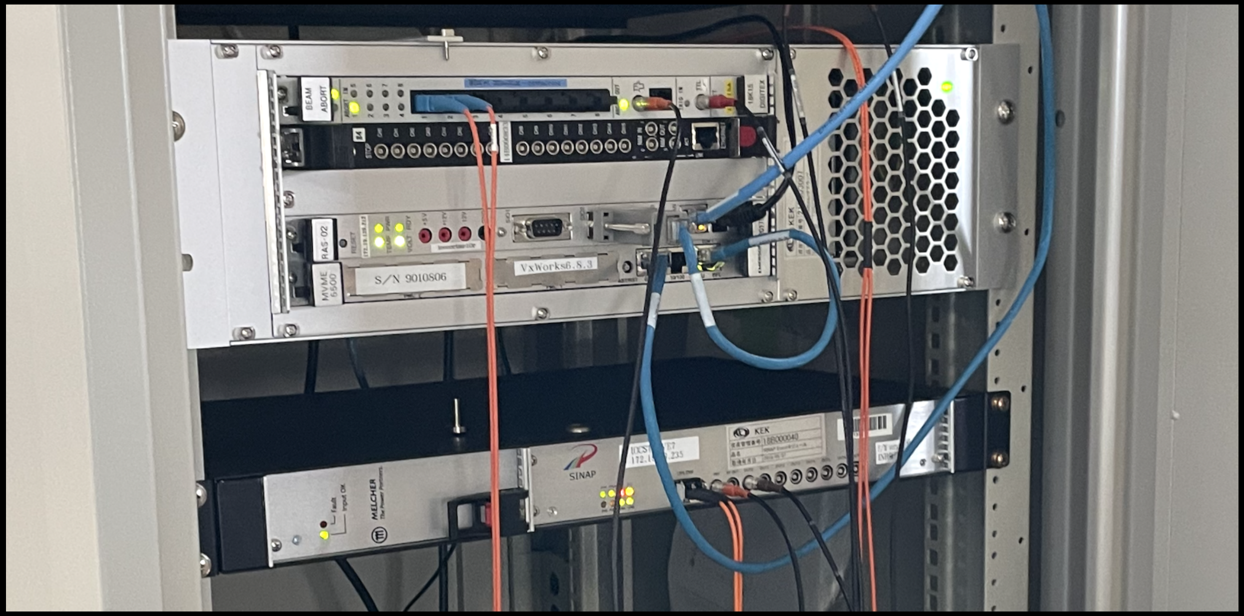
- An additional CLAWS sensor was installed at D05V1, where the NLC was placed during LS1.
- 148 out of 168 SBL events in 2024 (by summer) were triggered by the D05V1 CLAWS sensor.
- Another CLAWS was installed at D06V1 after summer.



CLAWS sensor

Expansion of Abort Module

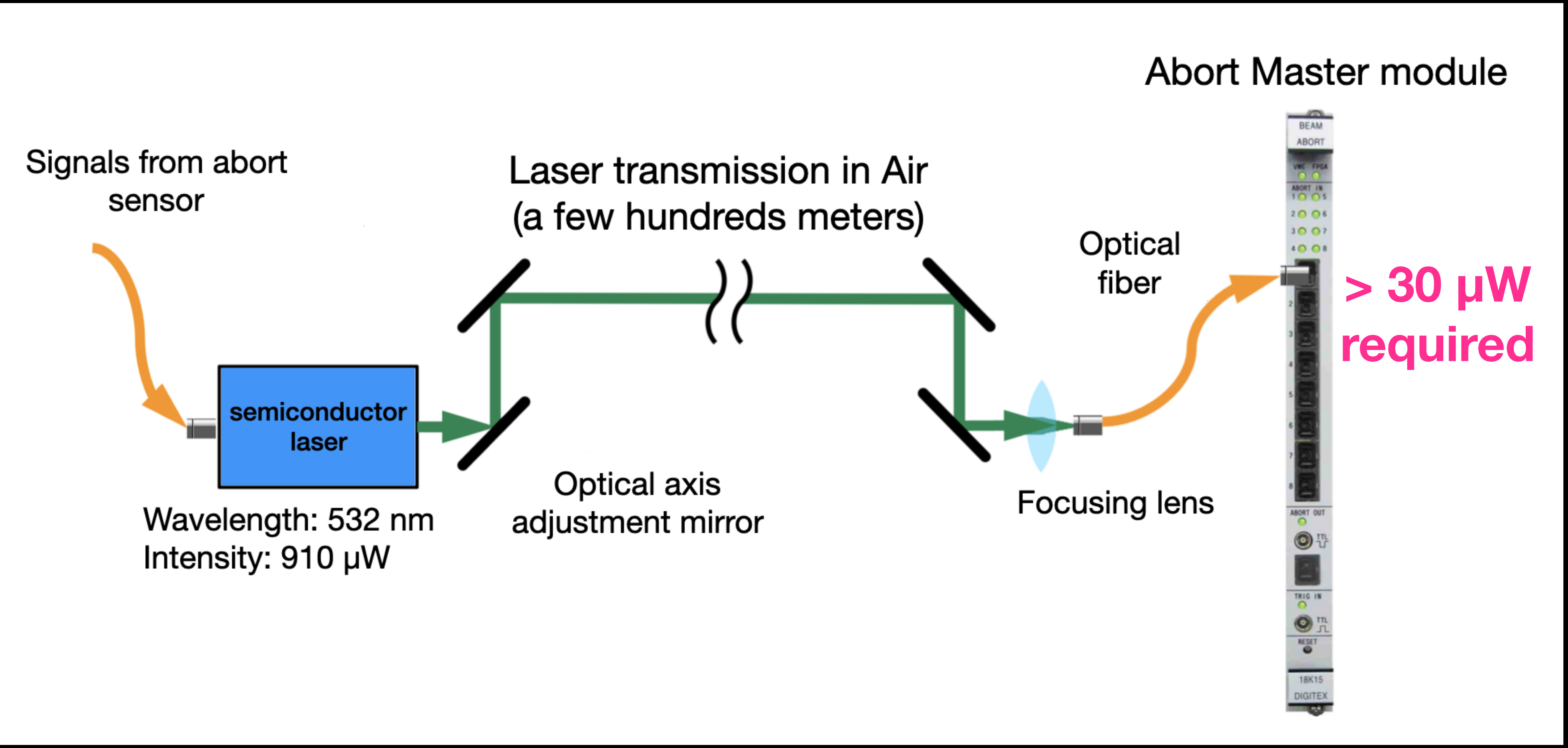




Second abort master module and abort kicker magnet trigger circuit at D07.

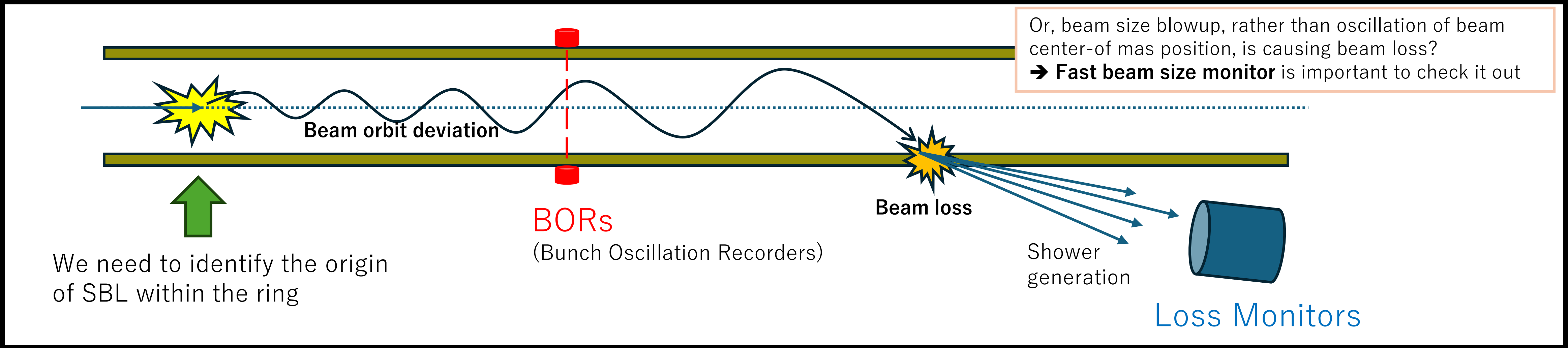
- A secondary abort trigger system was installed at D07 to bypass the CCB (i.e. Path ③)
- This setup offers a 15% (D05) or 20% (D06) chance that the beam abort will be executed **1 abort gap** (5 μs) earlier.

Laser Abort System



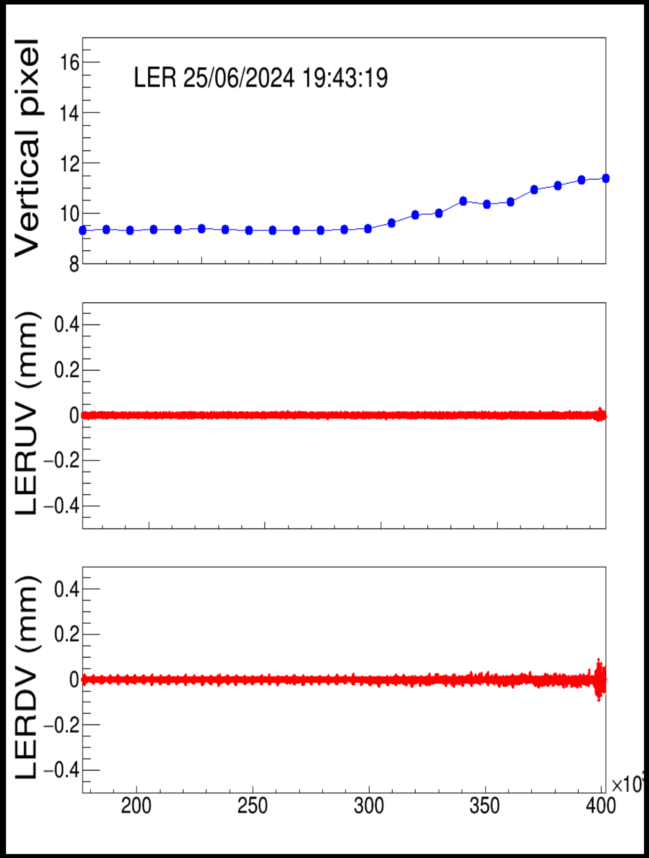
- We consider directional lasers for transmitting abort requests, which can transfer signals 1.5 times faster in air (refractive index 1.5 → 1.0)
- Transported laser was focused into the fiber with more than 90% efficiency.

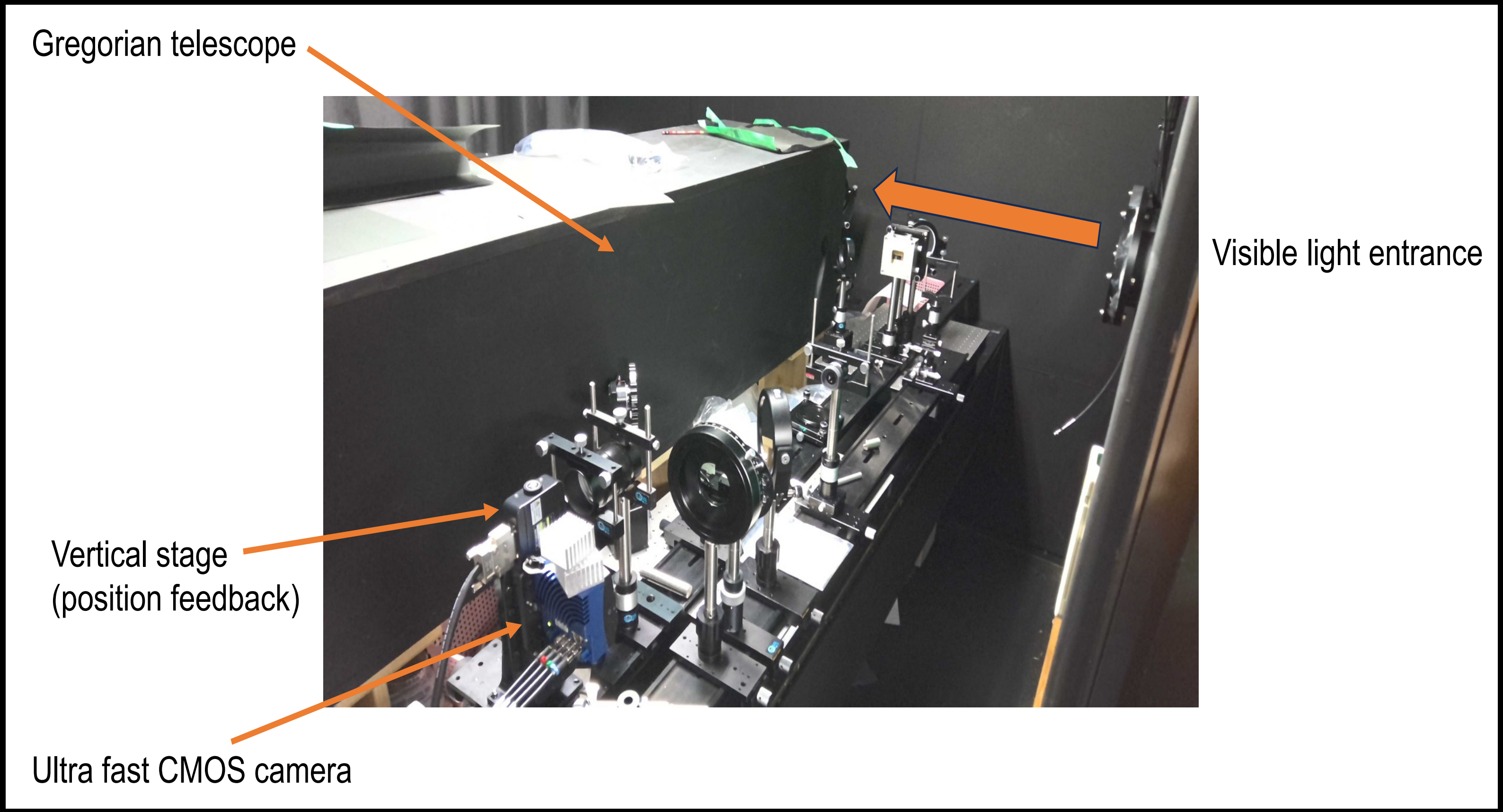
Future Direction: Bunch Oscillation Recorder (BOR)



- BOR can measure beam oscillations on a bunch-by-bunch basis, allowing precise analysis of beam's central position.
- Beam oscillations often begin **a few beam-cycles before losses are detected**. A multi-BOR system can identify the ring section where the SBL originates.
- By placing BORs at different betatron phases (e.g., 90-degree phase difference), the betatron phase at which an SBL is introduced can be estimated.

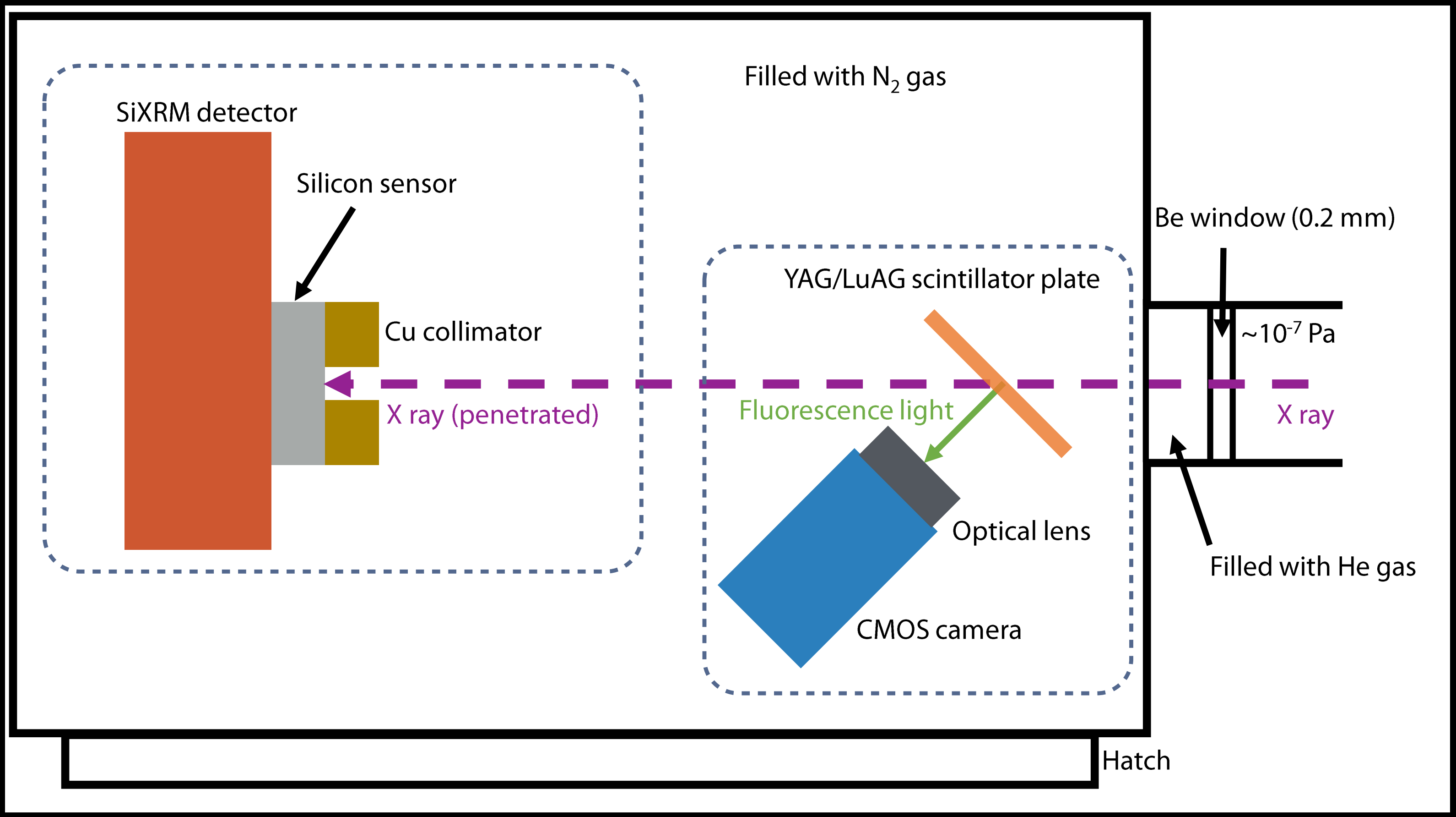
Future Direction: Visible Light Monitor System (SRM)

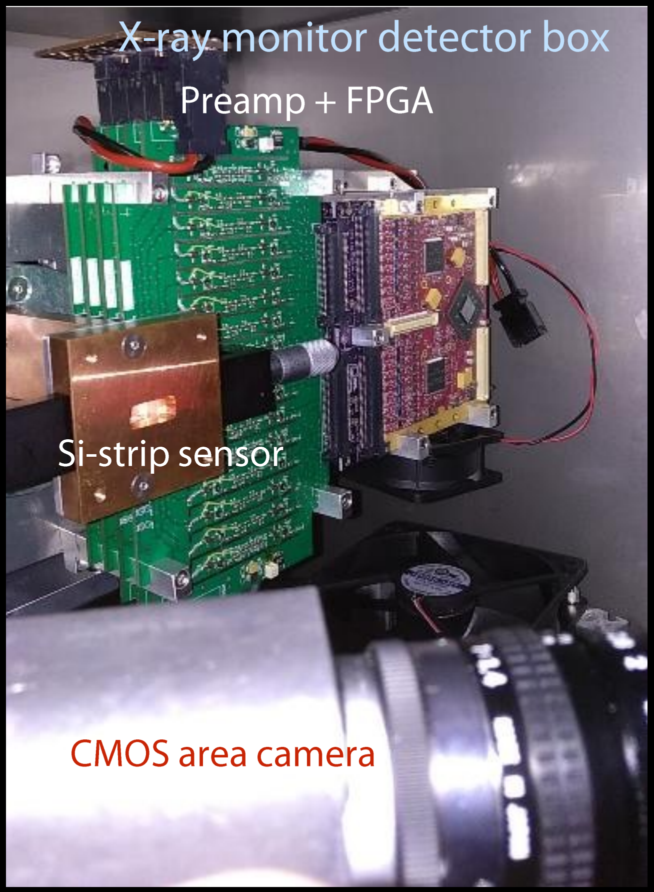




- Visible Light Monitor System measures the beam size every 2 turns (limited by light exposure and processing time), complementing BOR.
- **Vertical beam size blow-up is often observed during SBL** events, occuring many turns earlier than when oscillations become visible in the BOR system.

Future Direction: X-Ray Radiation Monitor (XRM)





- XRM can also measure vertical beam size, enabling single-shot, **bunch-by-bunch measurements**.
- The XRM silicon sensor (depletion length of 75 μm) has 128 channels and features a fast sampling (2.7 Gsps). Ideal for fast beam diagnositcs.

Beam Injection

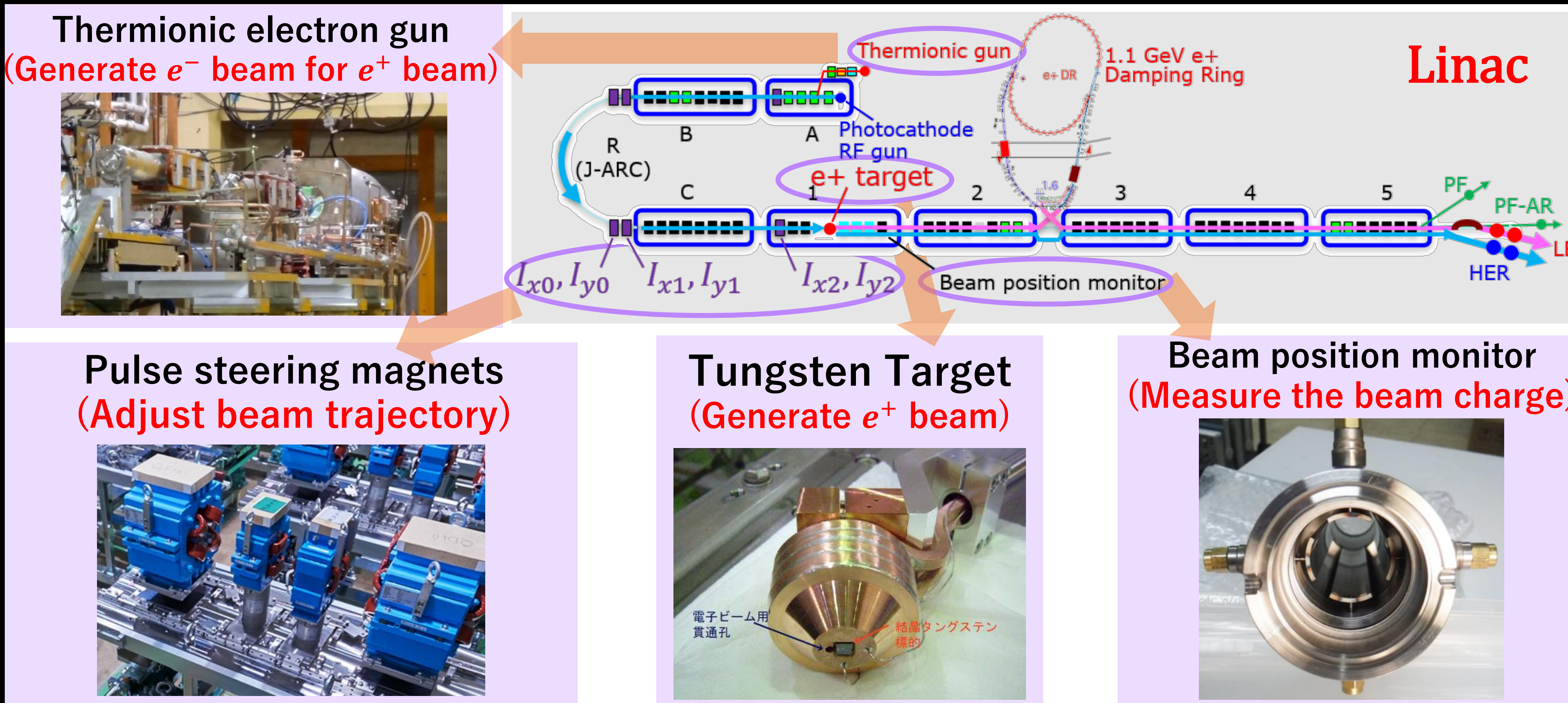
Beam Injection

- In 2022, only ~66% of SuperKEKB operation time was used for physics due to **frequent beam tuning**.

- The more beam is squeezed, the shorter its lifetime becomes. Therefore, achieving high-quality beam injection is essential for maintaining or increasing the beam current in future operations.

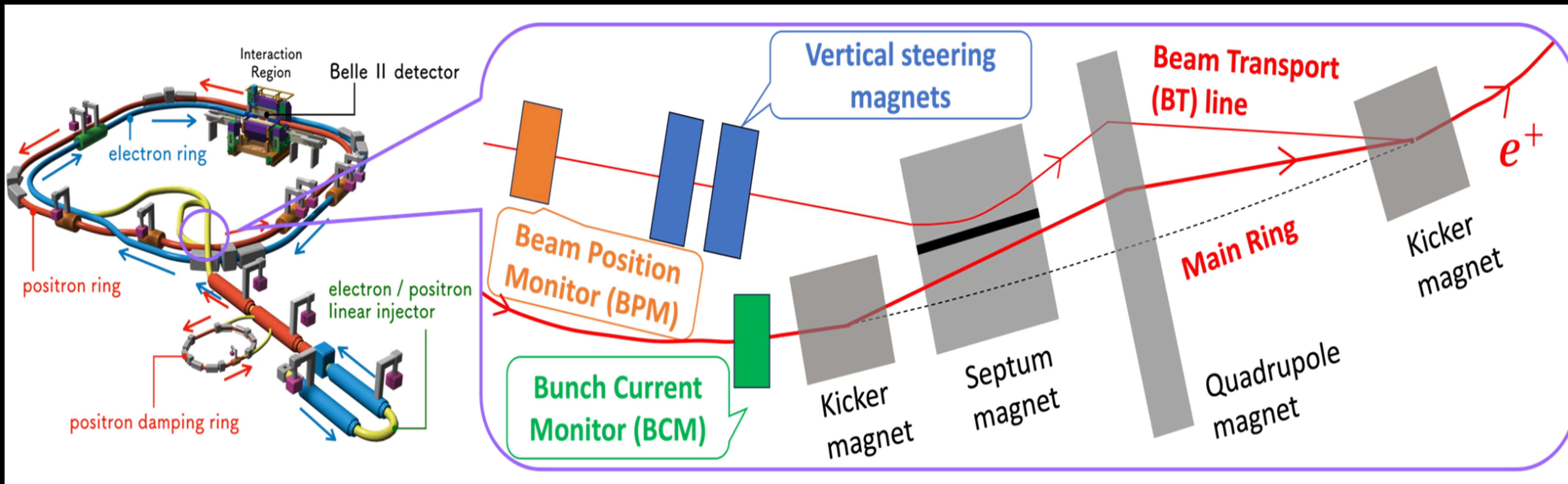
  - **High injection efficiency**
  - **Low injection background** (especially critical for CDC)

LINAC Tuning



- Positron beam optimization using 6 steering magnet currents.
- Evaluation based on beam charge measured by Beam Position Monitors (BPM)
- Bayesian Optimization (BoTorch) iteratively maximizes positron yield.

Beam Injection Tuning



- Bayesian Optimization (BoTorch) is used for injection tuning.
- Two vertial steering magnets were selected as tuning knobs.
  - Initial values are selected based on past expert's experience
- Injection efficiency measured by BPM and BCM was used as the optimization target.
  - LER Eff. : 88 →98%, HER Eff. : 41 →46%

Summary

- The MDI group promotes collaboration between Belle II and SuperKEKB, working on a variety of topics:
  - Beam Background
  - Beam Instability (e.g., SBL, Beam Diagnostics, Abort System)
  - Beam Injection
- We are expanding our efforts to achieve more stable operation and higher luminosity at SuperKEKB.
- **Many additional topics weren't covered today. If you're intersted, please don't hesitate to contact us — we warmly welcome your participation!**

Thank you!

Backup