Brookhaven National Laboratory | Jefferson Lab | U.S. Department of Energy

Machine-Detector Protection

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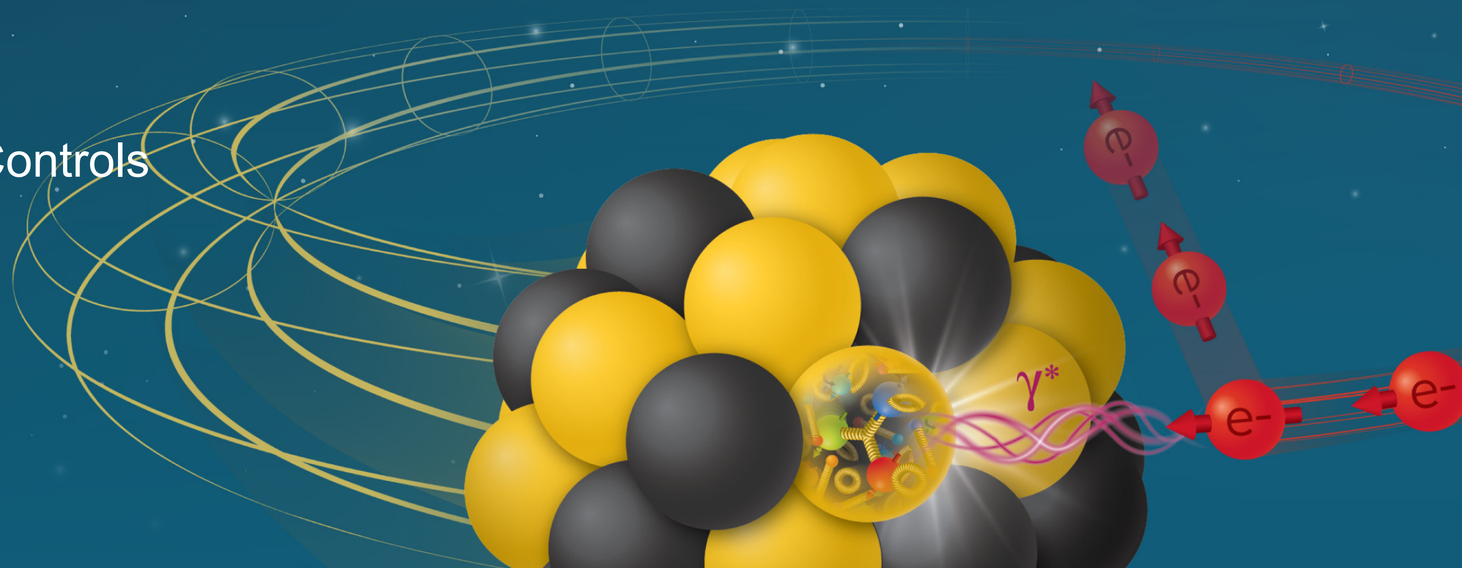
Slow Controls Scope Workshop with EIC Controls

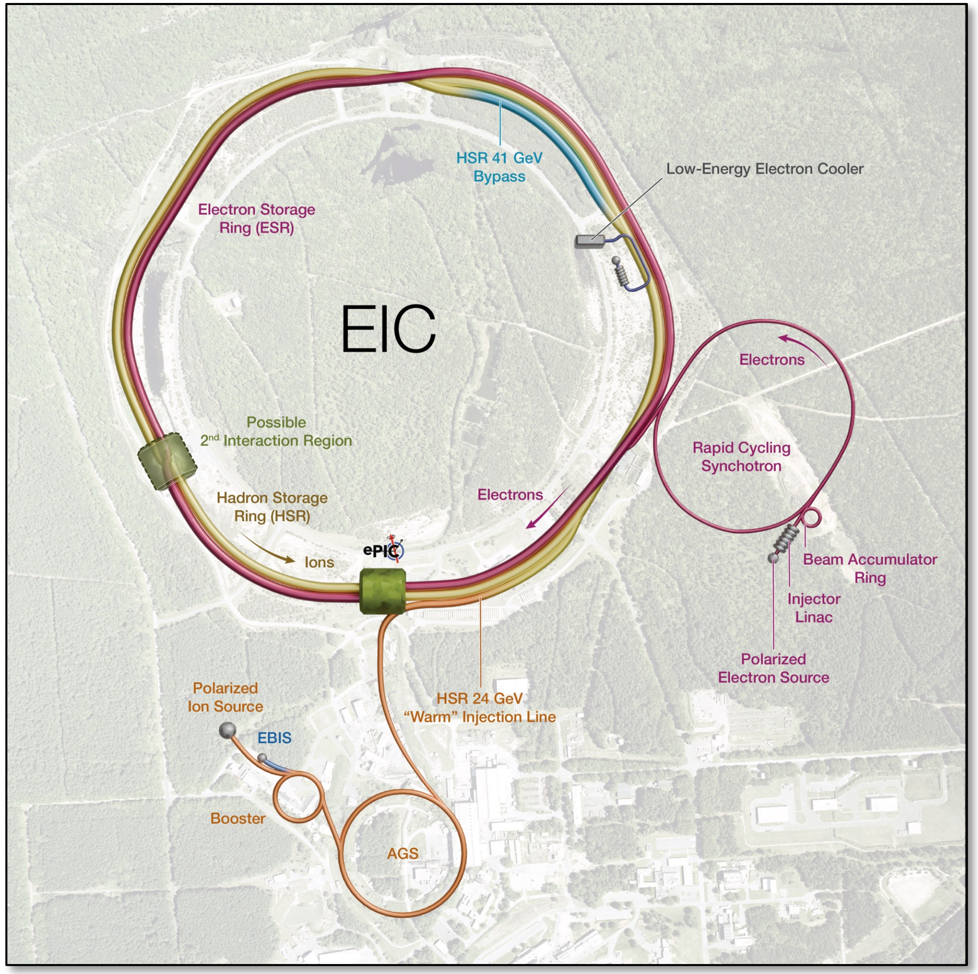
November 13, 2025

Electron-Ion Collider



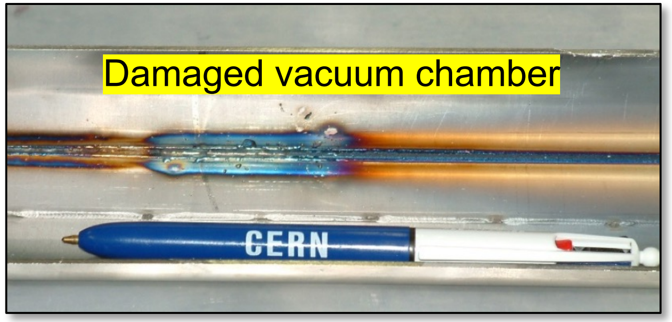
Outline

- Motivation
- Lessons Learned: SuperKEKB
- Scope Definition/Deliverables
- MPS Functional Scheme
- Requirements
- Technical Progress
- Examples: Belle II
- Interface to Slow-Control

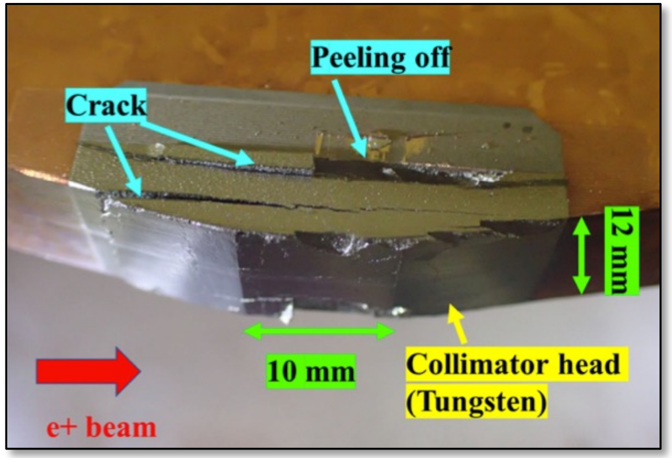


Motivation

- The Machine Protection System (MPS) safeguards the accelerator, detectors, and the beam itself from damage or unnecessary losses.
- Colliders operate with high-intensity, high-energy beams; even a partial uncontrolled loss can **damage hardware or quench magnets**.
- **Goals:**
  - Detect abnormal conditions and trigger fast, reliable beam aborts, while avoiding false or unnecessary aborts that could interrupt stable beam operation.
  - Enable post-mortem analysis after any abort or fault to diagnose causes and improve system performance.
- Ensures **safe operation** across all machine modes: injection, ramp, store, extraction, and machine studies.
- Provides centralized monitoring, diagnostics, and coordinated response across subsystems, balancing equipment protection with beam availability.



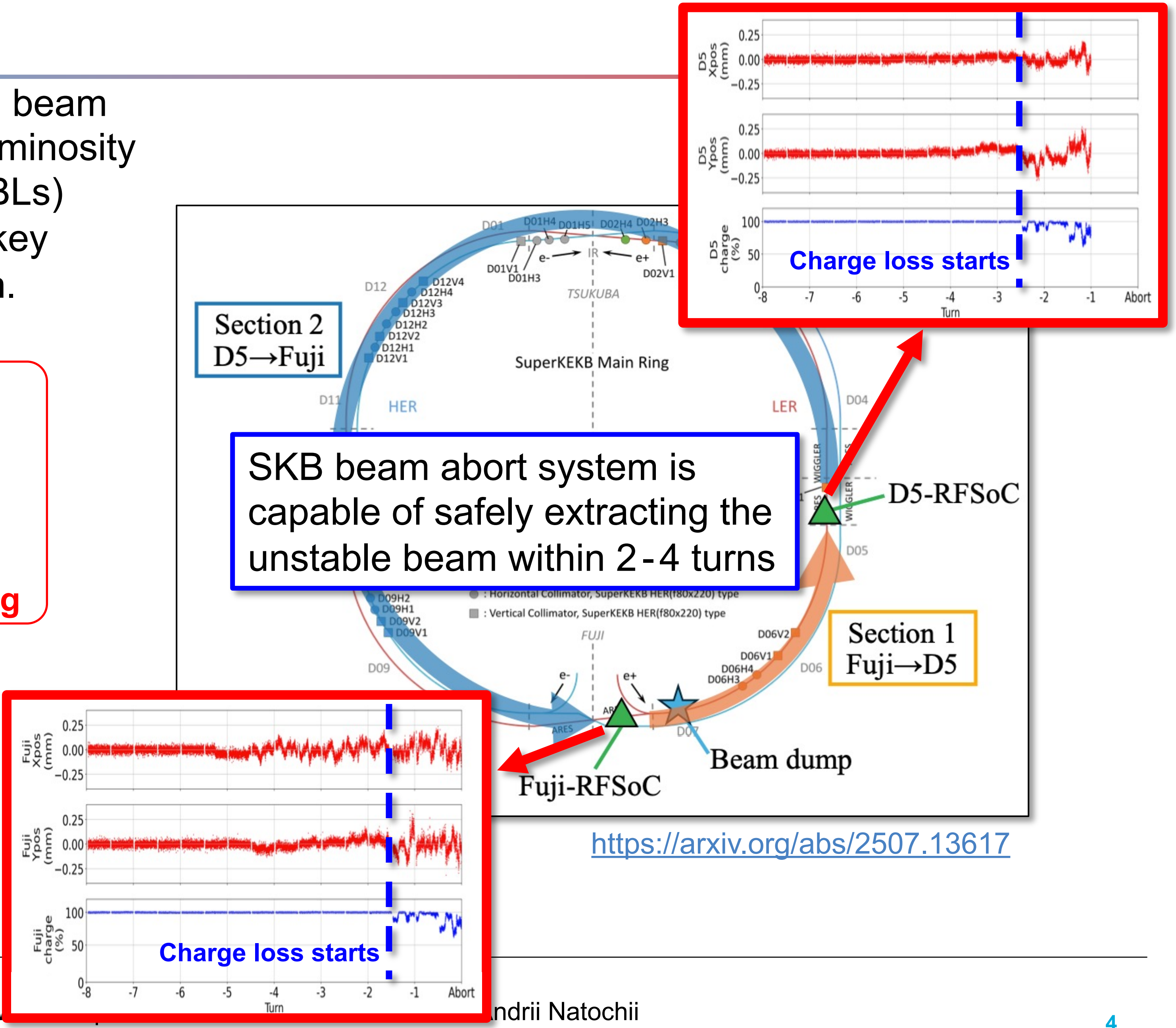
SPS extraction line accident due to a septum magnet failure [link]



SuperKEKB collimator head damaged due to the accidental injection kicker firing [link]

Lessons Learned

- At **SuperKEKB**, currently operating at high beam currents (~1 A), energies (4/7 GeV), and luminosity (~10^{35} cm^{-2} s^{-1}), **sudden beam losses** (SBLs) occurring within **1–2 turns** are among the key **challenges for stable and safe operation**.
- Consequences of SBLs include:
  - **Superconducting magnet quenches**
  - **Silicon detector damage**
  - **Collimator deformation or damage**
  - **Vacuum degradation**
  - **Long interruptions to physics data taking**
- The team demonstrated that **high-speed BLMs and BPMs are essential** for precise SBL source localization and beam dynamics studies
- **Early beam extraction is critical** to prevent irreversible damage to machine and detector components.



SKB beam abort system is capable of safely extracting the unstable beam within 2-4 turns

https://arxiv.org/abs/2507.13617

Scope Definition/Deliverables

WBS Scope	WBS Deliverables
Included: defining system requirements, system architecture, interlock logic, protection algorithms, interface and integration specifications, and technical documentation **Included in 6.04.04.04 WBS – Controls Systems:** design, procurement, and installation of the MPS distribution infrastructure for the IR subproject	- **System Architecture & Documentation:** *requirements, interlock diagrams, protection algorithms, interface specifications, and integration documentation*
Included: oversight of component design and procurement, acceptance testing, installation planning, and support equipment	- **Beam Abort & Collimator Systems:** *design, simulation, procurement, assembly, installation support, protection logic implementation, testing, and validation*
Included: integration with accelerator subsystems and machine-detector interfaces, with definition, implementation, and testing of fault detection algorithms, abort triggers, and protection logic	- **Commissioning Support:** *coordination with subsystems and machine-detector interfaces, functional testing, and operational readiness verification*
Included: MPS dedicated sensors, development of post-mortem analysis capabilities, centralized monitoring and logging, and operator interface screens to support diagnostics, commissioning, and operational readiness	- **Monitoring & Post-Mortem Analysis:** *centralized monitoring, logging, diagnostics, and post-mortem analysis tools for event reconstruction and protection logic refinement heavily overlap with the Controls Systems WBS*

Scope Definition/Deliverables

WBS Scope

Included: defining system requ
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specifications, and technical do
Included in 6.04.04.04 WBS –
procurement, and installation o
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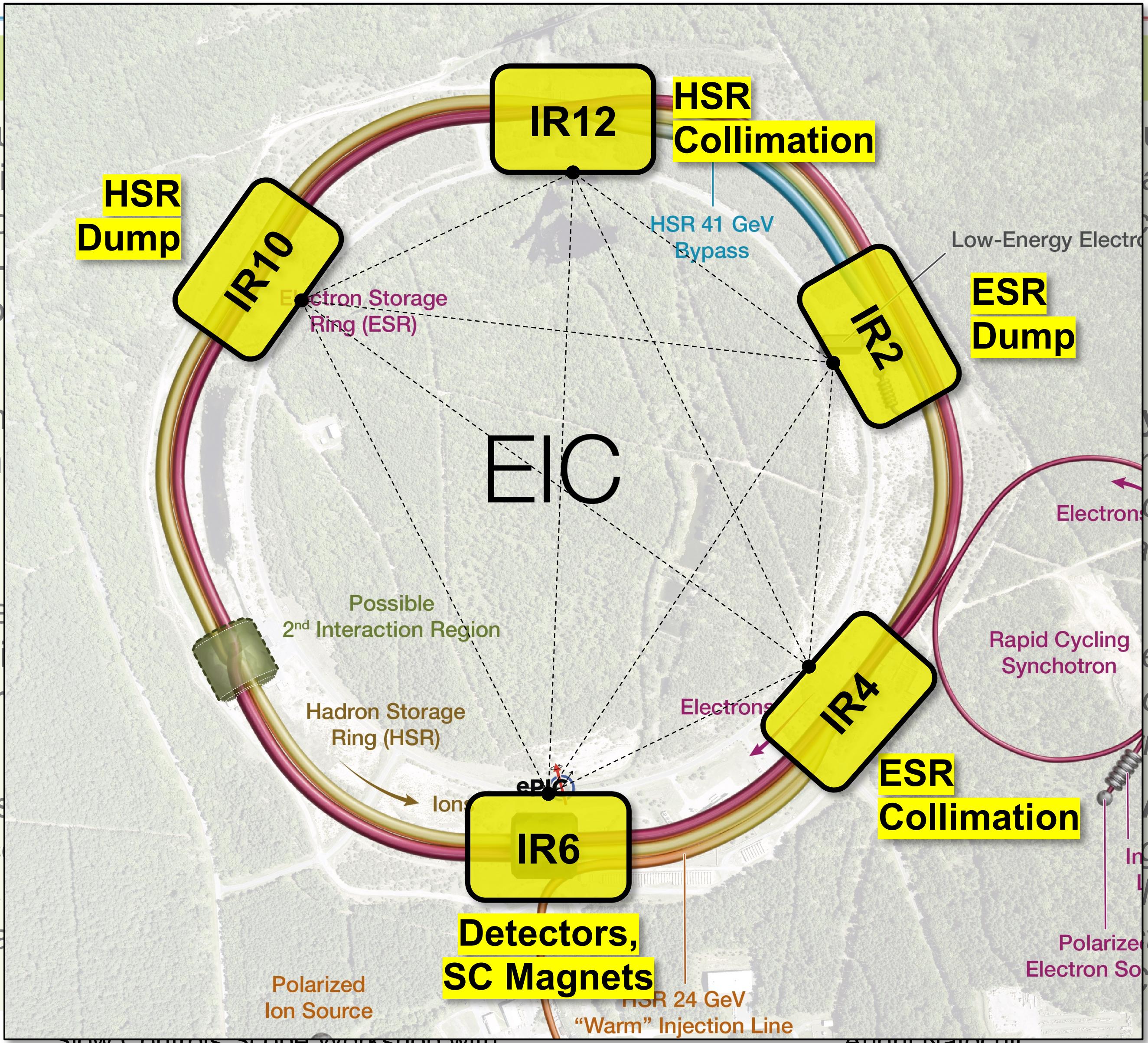

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MPS Functional Scheme

Failure Event

- Single Turn (≤ 1 turn)
  - *Kicker mis-fire / pre-fire*
  - *Extraction/injection mistiming / wrong phase*
  - *Extremely fast hardware failure (electrical arcing, connector failure)*
- Fast (≈10-100 turns)
  - *Beam instabilities*
  - *Power supply trip*
  - *RF fault / cavity trip or phase jump*
  - *Fast vacuum burst*
  - *Kicker waveform error / partial discharge*
  - *SR flash heating from sudden orbit change*
- Slow (> 100 turns)
  - *Operational settings error*
  - *Thermal drifts / heat-induced alignment shifts*
  - *Vacuum deterioration / slow leak*
  - *Collimator creep / position drift*
  - *Component aging*
  - *Ground motion / alignment drift*

Passive Protection

Movable Collimators, SynRad Masks, Absorbers, Shielding

- Limit and localize beam losses, shielding sensitive machine and detector components from secondary and synchrotron radiation.
- Provides passive containment and energy absorption — the first line of defense before active systems react.

Beam/Vacuum Changes

- Beam size blow-up
- Orbit drift/jump/mis-steering
- Energy/phase shift
- Severe beam-gas collision
- Large beam losses due to aperture hit
- SR flash heating from sudden orbit change

Beam Extraction

- Injection stopped
- ePIC detector power off
- Dump the beam

Monitoring System

- Hardware status *(power, current, aperture)*
- Machine parameters *(settings, vacuum)*
- Beam parameters *(losses, position, current)*

Interlock System

- Injection/extraction permit
- Data transmission
- Interfaces

Beam Abort System

- Extraction magnets (kickers, DC, septum)
- Beam dump

Active Protection

MPS must detect and mitigate across all timescales – from single-turn fast aborts to slow operational corrections.

Requirements

Subsystem / Function	Key Requirements & Rationale
Collimation System	- **Protect** sensitive accelerator and detector components from uncontrolled beam losses - **Precisely adjustable jaws** with micrometer-level **position accuracy and wide movable range** - **Active cooling** to handle beam-induced heating - **Low impedance design** to minimize beam instabilities - **Radiation-hard materials** to ensure long lifetime - Localize beam losses in **well-shielded and predefined regions**
Synchrotron Radiation Masks	- **Absorb synchrotron radiation** before it reaches the IP vacuum chamber - Maintain acceptable SR power density on downstream components - Designed for high thermal load and minimal outgassing
Radiation Shielding	- **Maintain dose rates and heat loads** in superconducting coils and cold mass **below quench limits** - Ensure detector background levels are within operational tolerances - Use optimized shielding geometry and material selection for effective attenuation
Interlock and Abort System	- **Fast acquisition and propagation of abort signals** from critical components: *BLMs, BPMs, magnet and RF power supplies, vacuum gauges, temperature and flow sensors, kickers, etc.* - End-to-end abort response (signal + decision + dump) in < 4 turns - Robust infrastructure and redundancy to cover all key MPS inputs - Prevent false or premature aborts through logic validation and fault discrimination - Protect against kicker misfire or prefire scenarios
Centralized Monitoring & Post-Mortem Analysis	- Continuous **monitoring of system status**, faults, and interlock states - Automatic **data logging and event reconstruction** for fault analysis - Integrated tools for machine diagnostics and operational optimization - Centralized operator interfaces for MPS health overview
System Integration & Coordination	- Seamless **interface with accelerator control system** and IR detector systems - **Coordination with RF, vacuum, magnet protection, and cryogenics** - Defined latency, reliability, and redundancy requirements & regular testing and validation procedures

Interface to Slow Control System - SCS

Technical Progress

Collimation System

- Developed particle tracking code
- Define the baseline configuration for ESR and HSR collimators → effective IR6 beam loss reduction
- Prepared preliminary designs of collimators

Synchrotron Radiation

- Developed X-ray tracking code in the IR6 vacuum
- First SR masks prototypes reduce ePIC detector background by x1000 → further reduction is needed due to noticeable ePIC performance degradation
- Proposed high-Z shielding to keep IR6 cryostat cold mass heat load below limits

Beam Abort System

- Designed a septum-based ESR abort extraction configuration and robust dump
- Defined the HSR beam abort system upgrade plans: reuse the dump, implement solid-state switchers for kicker power supplies, upgrade kickers, additional shielding, design a new misfire prevention system

Monitoring

- The common EIC beam monitoring system is under the Beam Instrumentation Systems (WBS 6.04.03.06)
- The MPS-dedicated fast beam loss monitor (fast-BLM) prototypes were successfully tested at RHIC in 2025; see next slides

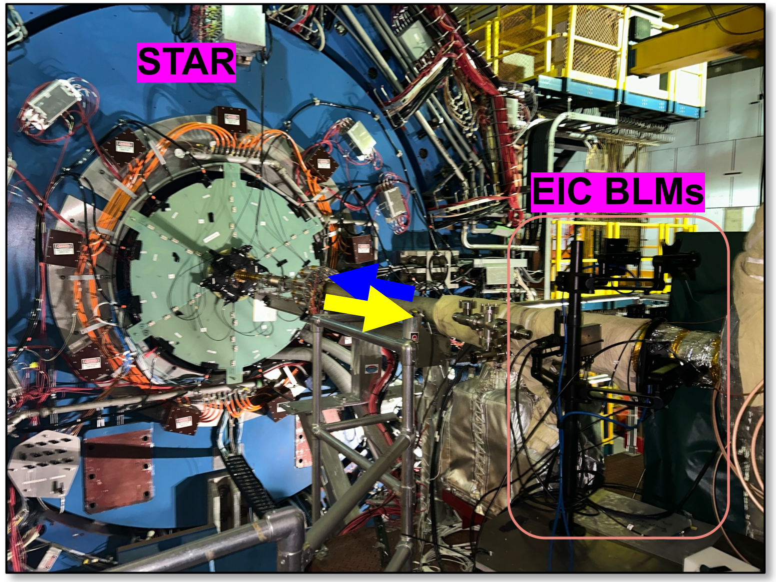
Interlock Infrastructure

- Base the MPS communication infrastructure on the EIC Common Platform developed under 6.04.04.04 WBS – Controls Systems
- Pre-defined ESR and HSR beam abort signal propagation network; see next slides

Technical Progress: Fast BLMs for EIC

Why Fast BLMs are Essential for MPS?

- Failure scenarios can cause **beam losses in μs–ms**
  → ***SC magnet and/or detector damage***
- Collimators cannot fully absorb such sudden losses
  → **fast detection is critical**
- Fast BLMs provide **real-time signals** to MPS:
  - Trigger beam abort within microseconds
  - Prevent localized damage and quenches



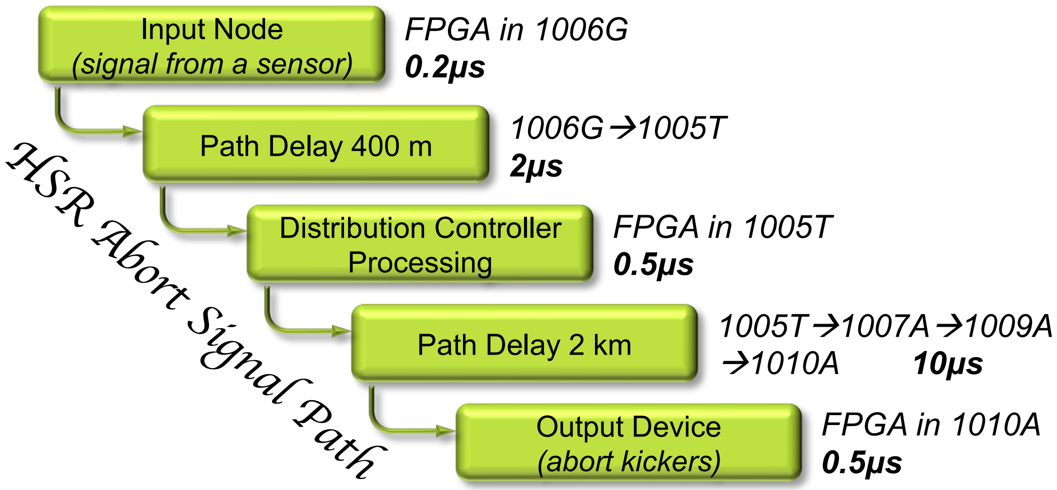
Can be installed @ EIC near critical equipment (e.g., detectors, SC magnets)

A new setup near STAR at RHIC (since July 2025):

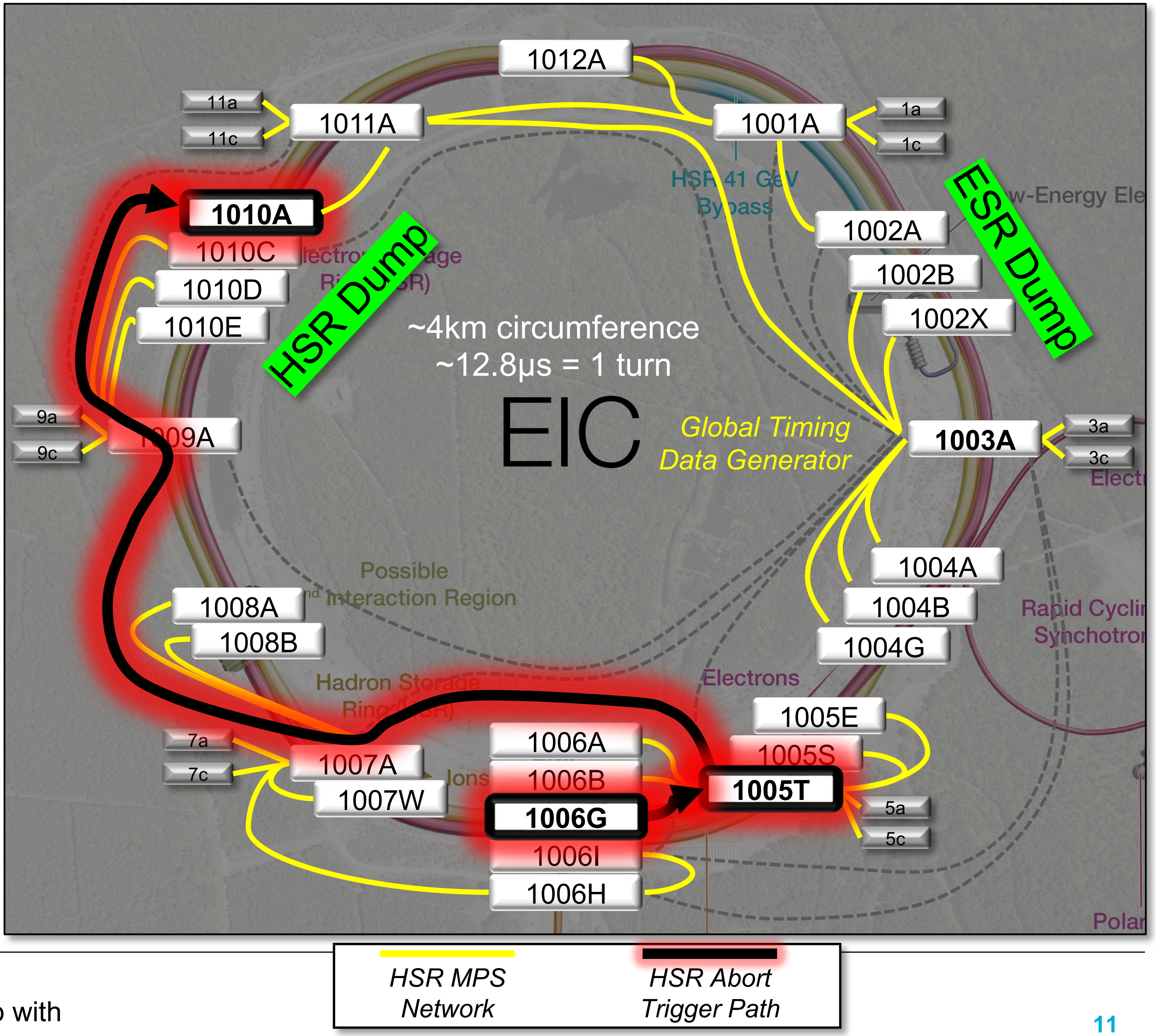
- Goal: Test different prototypes with hadron beam losses
- Sensors: **Plastic scintillators** (CLAWS – used at SuperKEKB – sensitive, fast, portable), **CVD diamonds** (fast, radiation hard), and **Diamond powder scintillators** (fast)
- Readout: GS/s USB oscilloscopes and Mach-Zehnder electro-optical modulator
- Status: Successfully collecting data (**bunch-by-bunch losses**), characterizing RHIC local losses (normal operation, beam aborts)

Technical Progress: Latency

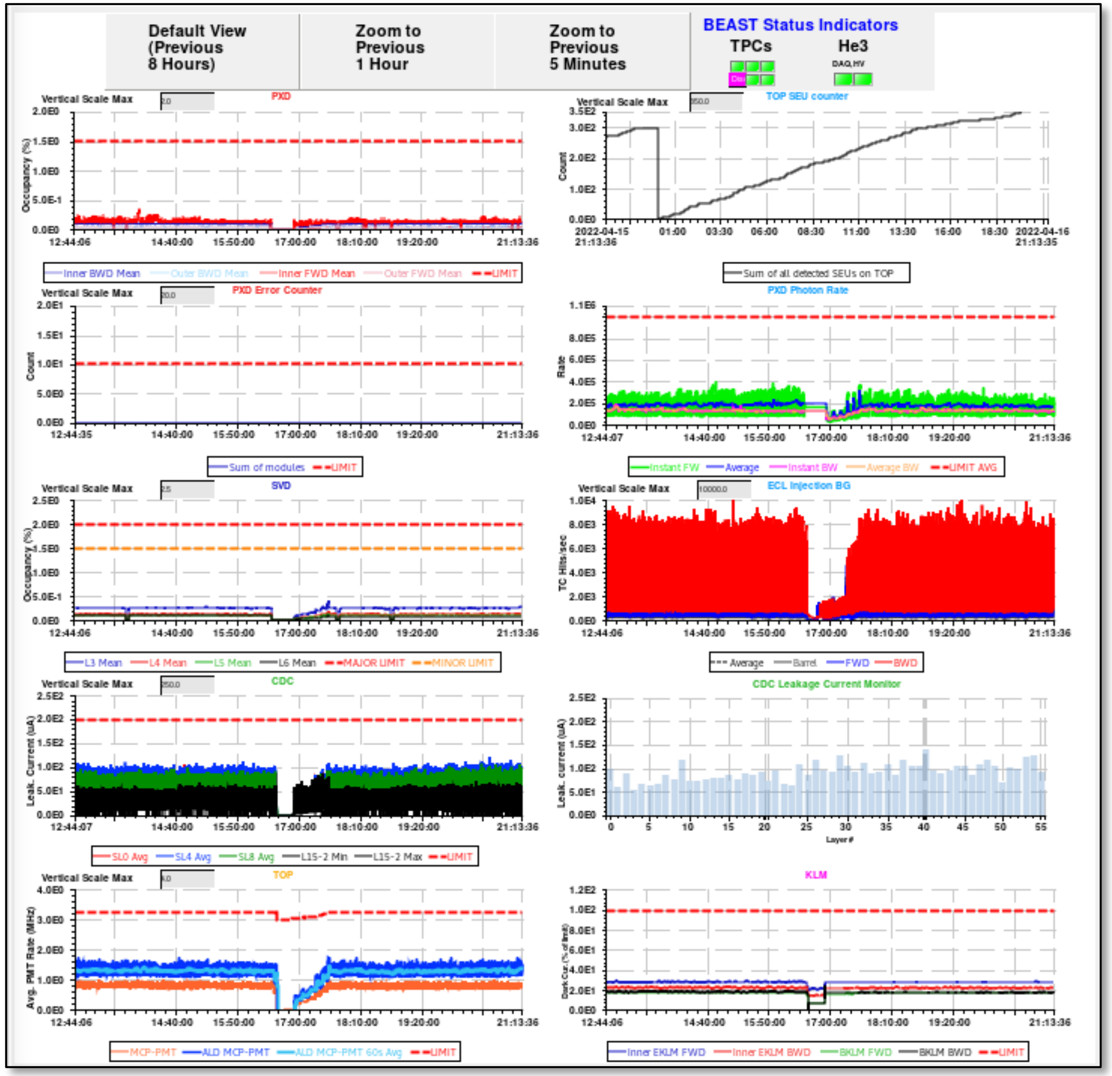
- Worst-case scenario latency *(example)*:



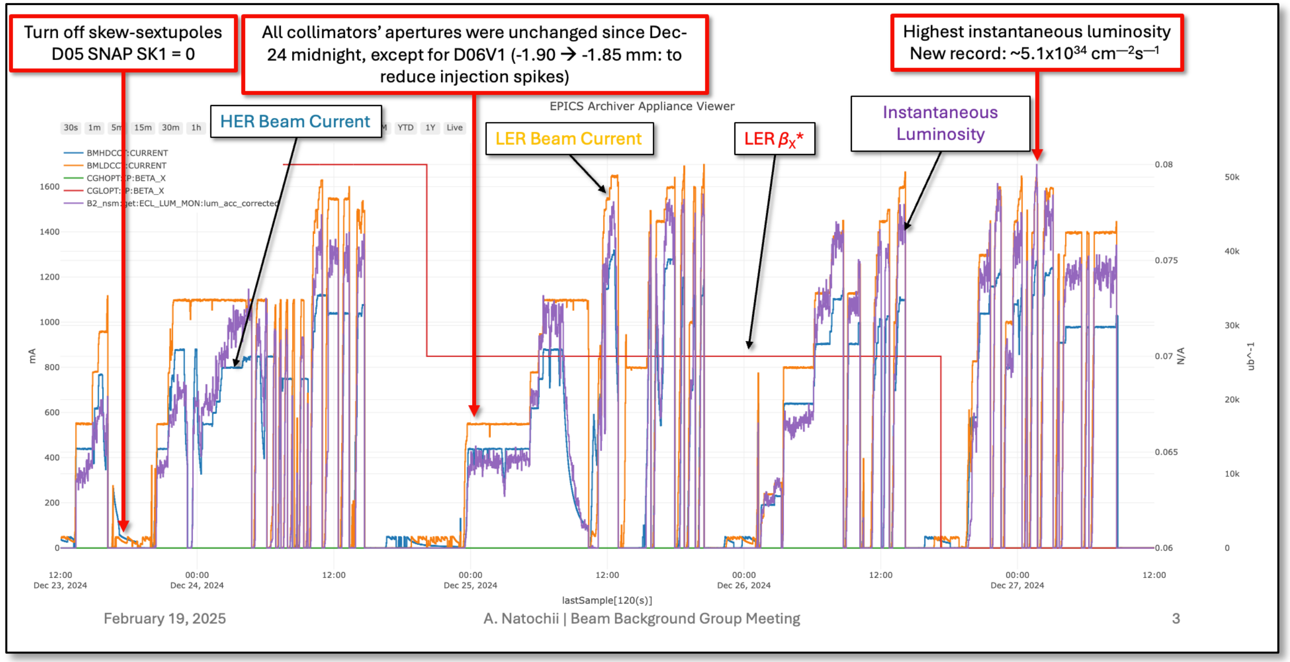
- Total delay of **~14μs (1.1 turns)**
  + 1 turn for abort gap alignment
  + 1 turn for beam extraction
  ≈ **3.1 turns < 4 turns requirement**
- The same latency is expected for the ESR



Example: Background vs Machine Settings



- The Belle II Slow-Control System enables machine and detector operators to maintain detector backgrounds below predefined limits, ensuring detector longevity and performance
- Archived EPICS data are continuously used for online and offline analyses to optimize luminosity while maintaining safe and stable machine and detector operation
- A similar approach should be adopted for the ePIC/EIC



Example: AI/ML for Online Background Decomposition

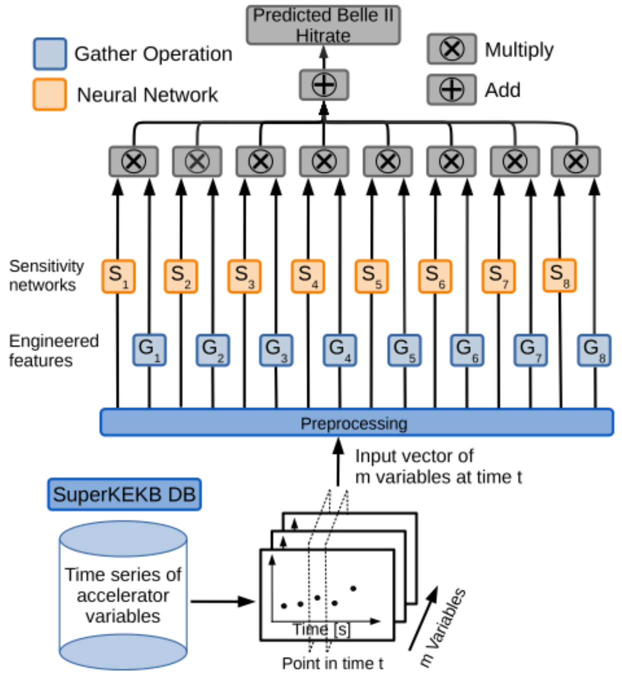


Fig. 1. Flow diagram for BGNet: The output of the network is the total predicted background at a time t for a Belle II sub-detector.

B. Schwenker, L. Herzberg, Y. Buch, A. Frey, A. Natochii, S. Vahsen, H. Nakayama, "*A neural network for beam background decomposition in Belle II at SuperKEKB*", NIM-A (2023), https://doi.org/10.1016/j.nima.2023.168112

A B S T R A C T

We describe a neural network for predicting the background hit rate in the Belle II detector produced by the SuperKEKB electron–positron collider. The neural network, BGNet, learns to predict the individual contributions of different physical background sources, such as beam-gas scattering or continuous top-up injections into the collider, to Belle II sub-detector rates. The samples for learning are archived 1 Hz time series of diagnostic variables from the SuperKEKB collider subsystems and measured hit rates of Belle II used as regression targets. We test the learned model by predicting detector hit rates on archived data from different run periods not used during training. We show that a feature attribution method can help interpret the source of changes in the background level over time.

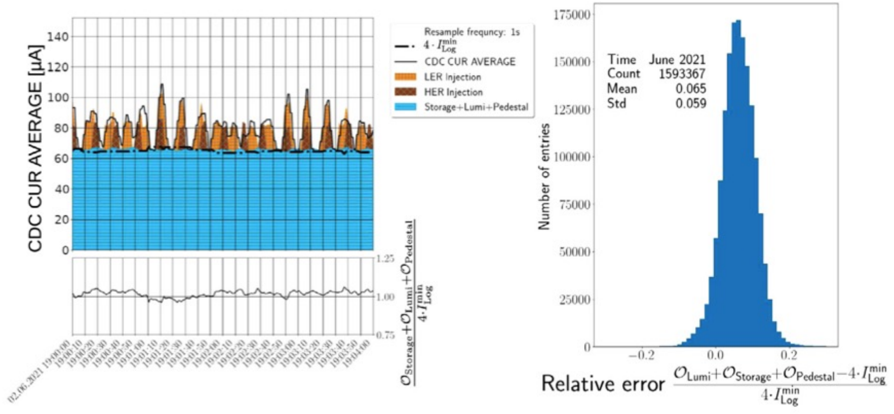


Fig. 6. Left: Top-up injections in a 4 min time window. The storage, luminosity and pedestal components are combined and displayed together with the injection background components of HER and LER rings. The fast CDC current logger variable is used to gauge the ability of BGNet to differentiate between the sum of storage and luminosity backgrounds and injection backgrounds. Right: Histogram of the relative error between the fast CDC current logger variable and the predicted storage and luminosity backgrounds plus the pedestal over the month of June 2021.

MPS ↔ SCS Interface

Function	Direction	Description
Configuration and threshold settings	SCS → MPS	Slow Control sets operational parameters (e.g., BLM thresholds, beam current limits) that MPS uses in real time
Status and diagnostics	MPS → SCS	MPS reports interlock status, trip sources, and diagnostic data to SCS for display, logging, and analysis
Interlock commands	MPS ↔ SCS	SCS can enable/disable certain interlock channels or define operational modes (with protection logic approval)
Timing synchronization / event logging	Both	Shared timestamps or event builders ensure post-mortem analysis and correlation with beam events

The MPS must remain independent and fail-safe:

- SCS can configure but not override safety-critical logic
- MPS logic continues to function even if the control system fails

The MPS protects the machine in real time, while the SCS supervises, configures, and logs its operation without compromising safety.