DEVELOPMENT OF THE BEAM PERMIT SYSTEM FOR THE RAON ACCELERATOR

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Abstract

The Beam Permit System (BPS) has been implemented as a software-level permit and verification layer for the Rare isotope Accelerator complex for ON-line experiments (RAON), a heavy-ion accelerator being commissioned at the Institute for Basic Science (IBS) in Korea. While the Machine Protection System (MPS) provides fast hardware signal-based protection against beam-induced equipment damage, the BPS complements it by checking software-level conditions such as EPICS Input/Output Controller (IOC) availability, Process Variable (PV) consistency, and operating-mode correctness. By combining IOC monitoring, configuration checks, and mode-based permit logic, the BPS ensures that beam delivery is allowed only when all required operating conditions are satisfied. Commissioning tests in the currently operational RAON section (up to SCL3) confirm that the BPS reliably identifies hardware or software inconsistencies and inhibits beam extraction when necessary, demonstrating the effectiveness of this combined hardware–software protection approach.

INTRODUCTION

The RAON [1] is a heavy-ion accelerator being developed at IBS in Korea. Initial beam commissioning has begun with the low-energy superconducting linac (SCL3), and accelerator operation now involves cryogenic plants, magnets, RF systems, vacuum equipment, diagnostics, and thousands of controllers coordinated through an EPICS-based control system handling nearly 400,000 signals.

Safe and validated beam delivery in this environment requires not only fast hardware protection but also verification of software-layer readiness. The Machine Protection System (MPS) [2] provides microsecond-scale shutdown based on hardware fault triggers such as beam loss, magnet trips, RF failures, and vacuum faults. However, hardware interlocks alone cannot detect software anomalies, including IOC downtime, invalid PV states, or inconsistent operating-mode configurations. Furthermore, the increasing number of operational modes and beam paths necessitates a supervisory mechanism that verifies that only the required subsystems for the selected configuration are enabled. The Beam Permit System (BPS) was developed as a supervisory software-permit layer that evaluates these conditions before beam extraction and feeds the resulting permit state back into the MPS. It integrates EPICS PV–based verification with hardware interlocks, providing a protection framework that is easier to maintain and scalable to complex mode-based structures.

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This paper presents the design, implementation, and commissioning-phase validation of the RAON BPS, demonstrating a combined hardware–software protection architecture for safe and consistent beam operation.

BPS ARCHITECTURE

Overview

The BPS structure is shown in Fig. 1. To the MPS inputs, the BPS adds two subsystem inputs: IOC Monitor (IOCM) and Readiness Manager (RM). These subsystems, including the MPS, are coordinated by mode-based configurations. RAON operates with three mode definitions: Beam Mode, Machine Mode, and Source Mode. For the BPS, Machine Mode is the key operating context because it defines the intended beam path and destination, and therefore determines which software and hardware conditions must be included in the permit decision. Each subsystem covers a different software-state domain: the IOCM monitors network connectivity and IOC error PVs, while the RM evaluates section-based device readiness (setpoint consistency and PV ranges).

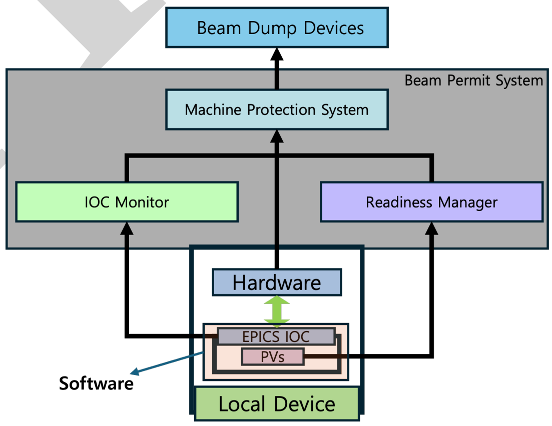


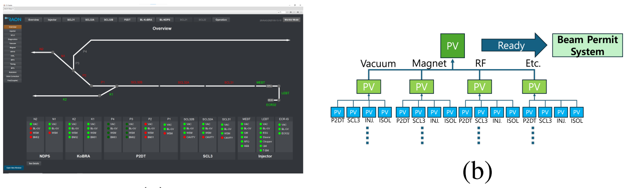
Figure 1: BPS architecture linking EPICS software-state checks with the MPS beam-dump chain.

IOCM

The IOCM uses EPICS “Alive” and “iocmon” as its main modules. These modules evaluate heartbeat PVs and IOC error PVs. The state is evaluated every 1 s; a 15 s heartbeat timeout or unreadable permit PV forces `IOC_OK = 0`.

RM

Readiness PVs are aggregated based on both the Source Mode and Machine Mode. While the Machine Mode defines the active beam-delivery section, the Source Mode focuses on the configuration of the primary beam sources, such as the Electron Cyclotron Resonance Ion Source (ECRIS) or the Isotope Separation ON-Line (ISOL) system. For the selected configuration, the RM evaluates RF readiness, magnet and vacuum equipment settings, and overall control states. The RM interface and the section-based readiness propagation are shown in Fig. 2.



(a) (b)

Figure 2: (a) GUI used to monitor the RM during RAON operation. (b) Section-based device readiness propagation diagram.

MPS

The MPS receives fault and interlock signals from beam diagnostics and accelerator equipment and propagates them through the beam-dump path. The `Hardware_OK` signal represents the state where no equipment failures are present and no beam anomalies are detected by diagnostic devices. `IOC_OK` and `Readiness_OK` are converted into hardware-level digital signals and integrated into the MPS input path. This keeps the microsecond-scale hardware response speed for beam faults while adding a supervisory point for software-state permission.

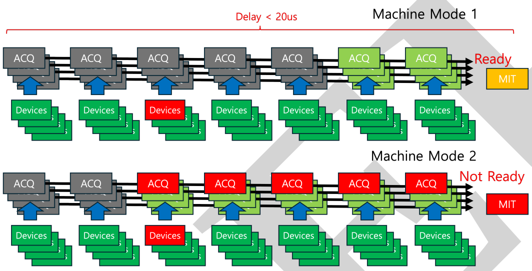


Figure 3: Mode-based permit logic used by the MPS.

MODE BASED PERMIT LOGIC

The top-level beam permit is issued only when the hardware interlock state, device readiness, and IOC availability are simultaneously valid:

$$\begin{aligned} \text{Permit} &= \text{MPS\_OK} \\ &= \text{Hardware\_OK} \wedge \text{Readiness\_OK} \wedge \text{IOC\_OK}. \end{aligned} \tag{1}$$

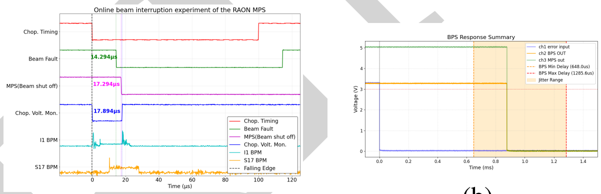
Device readiness is evaluated by the Readiness Manager (RM), which monitors whether equipment follows predefined operational conditions. A device is considered "Ready" (`Readiness_OK`) when its current values match the required setpoints, or when specific Process Variables (PVs) remain within their designated tolerance ranges. Similarly, the IOC Monitor (IOCM) generates the `IOC_OK` signal by verifying both the network connectivity of the controllers and the state of specific "IOC error PVs" that indicate internal software or communication faults.

Machine Mode defines the active accelerator section and determines which PVs and readiness states are evaluated. For example, during SCL3 operation, excluded downstream faults do not remove the permit, while SCL3 and injector section related IOC or PV inconsistencies generate a beam-dump condition.

Although the MPS inherently operates in a chain structure, its core concept is to monitor only the targets corresponding to the active monitoring section using the Machine Mode, while masking others (Fig. 3). This concept is equally applied to the RM and IOCM for configuring and evaluating the monitored PVs.

PERFORMANCE EVALUATION

The following results evaluate the standalone MPS dump-path response and the BPS (including MPS) response integrated with the BPS software modules (IOCM and RM).



(a) (b)

Figure 4: (a) Standalone MPS beam-dump validation and (b) measured BPS response with IOCM/RM integration.

Response times from the SCL3 end to the injector section chopper were evaluated by injecting faults and measuring signal propagation. As shown in Fig. 4(a), a deterministic hardware latency of approximately 3 μs was confirmed for the standalone hardware MPS. For the integrated BPS shown in Fig. 4(b), which involves software-state verification and network propagation through the gateway, the mean response time was 895.83 μs (including MPS latency) with a standard deviation of 106.70 μs over 100 trials. The observed latency is essentially a reflection of the network propagation delay across the software and gateway layers.

OPERATIONAL RESULTS

The BPS demonstrated its operational reliability during SCL3 commissioning by successfully managing and validating real-world beam-dump events. Analysis of these events—categorized into RFrelated (61%), magnetrelated (6%), and user-driven faults (7%)—confirmed that the BPS consistently maintained the integrity of the permit chain.

A representative case involved an LLRF fault: the BPS immediately detected the setpoint inconsistency, the RM triggered an automated state transition from `BEAM ON` to

BEAM PREPARATION, and the resulting inhibition signal was successfully propagated to the chopper through the MPS. This operational sequence confirms that the BPS-to-MPS protection chain functions as a unified supervisory layer, ensuring that no beam extraction occurs under unverified or inconsistent software states. The web-based log system (see Fig. 5) provides full traceability of these software-state transitions and permit changes.

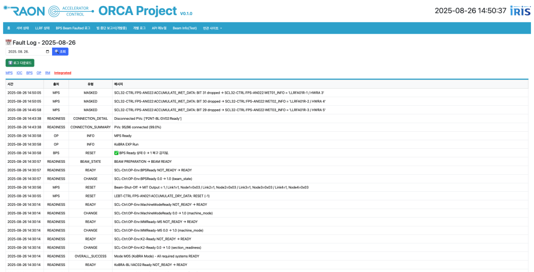


Figure 5: The web-based log system provides full traceability of software-state transitions and permit changes.

CONCLUSION

The RAON BPS successfully integrates a software-state verification layer into the existing hardware-level MPS. Key findings from SCL3 commissioning include:

- Seamless Integration: Software-state verification (IOCM/RM) was successfully integrated into the hardware MPS dump path.
- Reliable Performance: Confirmed microsecond-scale hardware response (3 μs) and 1-millisecond software permit latency.

ACKNOWLEDGEMENT

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