FRIB MACHINE PROTECTION SYSTEM DESIGN AND VALIDATION STUDIES*

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Abstract

The FRIB heavy ion superconducting linac will become the highest peak power heavy ion beam facility, with beams carrying up to 400 kW power with kinetic energy ≥ 200 MeV/u. Fast protection systems are required to detect and remove beam within 35 μs. Detection of beam losses in the low energy linac segment is confounded by two effects: small fluxes of secondary radiation from beam impacts, and large fluxes due to cross-talk from neighboring, higher energy linac sections. We describe a machine protection scheme based on multiple families of diagnostics and diagnostic networks. On-going fault mode studies are utilized to assess risk and to assist in the definition of specific detection networks for high reliability and responsivity.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) is a high-power, high-brightness, heavy ion facility under construction at Michigan State University under cooperative agreement with the US DOE [1]. The linac will accelerate ions to energies above 200 MeV/u, with up to 400 kW of beam power on target. The linac facility, shown in Fig. 1, consists of a Front End, three Linac Segments (LSs) connected by two Folding Segments (FSs), and a Beam Delivery System (BDS) leading to the production target. Ion sources are located on the ground level and beam from one of two ion sources is delivered to the linac tunnel through a vertical beam drop. An electrostatic chopper upstream of the vertical beam drop is the primary control of the time structure and duty cycle of the ion beam.

The FRIB linac is designed to support multiple operating modes with varying time structure and peak intensity of the ion beams. These modes can be grouped into four general categories:

- Short pulse (<5 – 50 μs), low duty cycle (< ~1 Hz), varying intensity (50 to 650 μA)
- Moderate pulse length (~0.01 s to s), low duty cycle (< ~1 Hz to 5% duty factor), nominal intensity (3 – 10 pμA)
- Approximately CW (50 μs gap @ 100 Hz), low to nominal intensity (<10 to 400 kW)
- Dynamic ramp to high power (variable intensity, pulse duration, and repetition rate) to slowly increase the target temperature (~10 minutes)

Several additional modes are used for commissioning the front end and fragment separator. These modes exhibit a wide range in intensity: 2–650 eμA for Front End commissioning, and 0.0001–30 pnA for fragment separator commissioning and secondary beam development.

MACHINE PROTECTION SYSTEM

Machine protection systems (MPS) exist to avoid prompt and long-term damage to the accelerator and experimental instrumentation, are required to minimize the number of false trips that limit production, and provide evidence of failures or fault events when interlock systems stop beam operation.

Machine failures can derive from several sources. Hardware failures can include power supply trips, magnet or cavity quench, RF trips and loss of low-level control, loss of vacuum, etc. Control system failures may include incorrect calibrations, improper updates of settings, timing distribution errors or mistimed triggers, and feedback malfunctions. Operator actions may introduce tuning and steering errors that generate errant beams.. Beam instabilities at high current or high brightness might develop quickly and damage components.

The time response for MPS interdiction ranges over many orders of magnitude. Fast protection systems (FPS) serve to protect against prompt damage from beam impacts. Typical FPS response times can vary from several to some hundreds of microseconds, and reflect thermodynamic changes of accelerator materials caused by errant beams. Run permit systems (RPS) operate on a slower time scale, from milliseconds to many seconds, and are used to verify machine state and identify conditions that may lead to unintended damage or long term irradiation effects that limit personnel access. As the FRIB accelerator facility may function in many different operating modes with varying thresholds for beam induced damage, the complete machine protection system must be flexible and configurable.

FRIB Challenges

The challenges for the FRIB MPS derive from multiple sources, including physics of the interaction of heavy ions with the vacuum chamber components and the proximity of high energy to low energy linacs The high power and brightness, and short (< mm) Bragg range of the FRIB heavy ion beam places critical importance on the fast protection system to detect and limit prompt beam losses [2]. The performance and lifetime of sensitive superconducting cavity surfaces can be affected by small losses (< 1 W/m) occurring over long durations.

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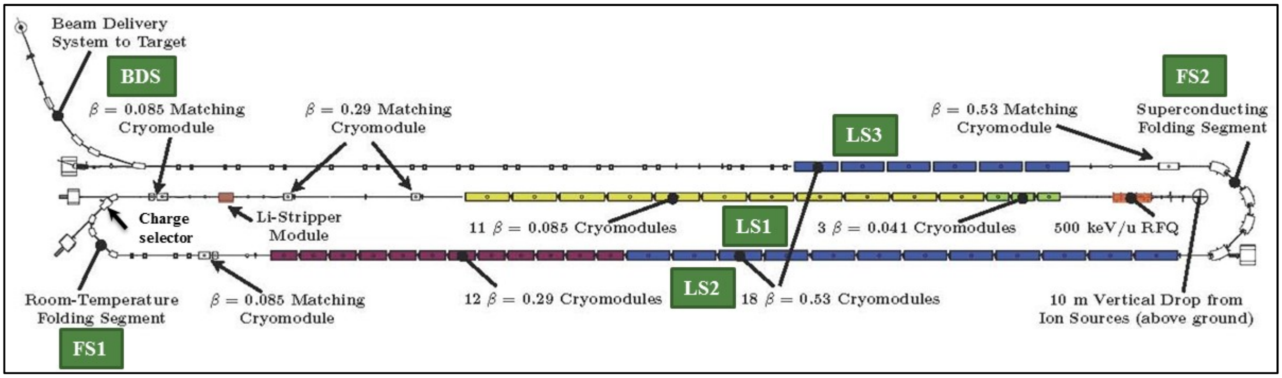

Figure 1: FRIB accelerator layout.

The twice-folded geometry of the FRIB linac places the high energy linac segment in close proximity to the low energy linac segment. Traditional loss monitors, eg. ionization chambers and scintillation-based neutron detectors, will be unable to differentiate the low-amplitude loss signals arising in LS1 from the high-amplitude signals generated in LS3 due to radiation cross-talk [3]. Additionally, x-ray background sources originating from field emission in the RF cavities might also overwhelm the relatively low-amplitude beam-generated signals in the low energy linac modules.

MPS Controls and Mitigation

The MPS network for detection and mitigation employs an optical fiber network to establish communication between an FPS Master and multiple Slave nodes, and the beam inhibit devices. The FPS Master queries and receives input from 7 chains of FPS Slave nodes every 8 µs. Each chain is composed of 8 Slave nodes. The input to each Slave node is a single RS-422 bit, which originates from beam or component monitoring systems.

The FPS Master activates the MPS interlock whenever the status bit changes from OK to NOK, as reported by the FPS Slave nodes or the RPS monitoring system. The time budget for activating the beam mitigation system is 10 µs from the first instance of a NOK signal from any Slave node. The primary beam inhibit is to initiate a fast (< 1 µs) HV switch to de-energize the electrostatic dipoles in the Low Energy Beam Transport section (see Fig. 2). Defense-in-depth requires a reach-back to the ion source HV platforms which terminate beam production. A secondary reach-back to the electrostatic chopper power supply can be used to direct beam to a local beam dump in the vacuum chamber.

BEAM LOSS DETECTION METHODS

Multiple overlapping and redundant systems will continuously monitor the state of individual beamline components and power supplies, control feedback, and beam sensing diagnostics.

The RPS (100 ms scale) continuously queries the machine state and controls permission to operate with beam.Fast loss detection methods are integrated with the FPS to terminate the beam within 35 µs. These schemes limit damage from acute beam loss by quickly activating the beam inhibit device. They require sensitivity for fast detection of large losses (~10% - 100%). Additionally, slow losses are detected and measured with high sensitivity over longer time scales (sec to hours) to prevent slow degradation of SRF system under small beam loss. FPS mitigation is activated once a loss threshold is exceeded.

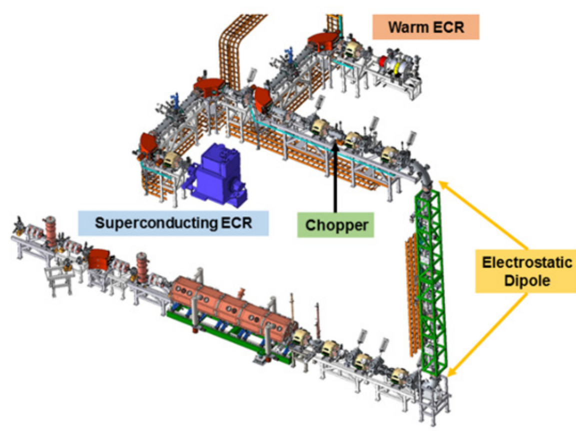

Figure 2: Front End beamline schematic.

Layering Strategy for Beam Loss Monitors

Beam diagnostics systems supplying inputs to the Machine Protection System offer a range of sensitivities and time responses to beam losses incurred along an accelerator chain. To mitigate risk and increase the probability of a robust detection scheme, a network of sensors is established. Redundant loss monitor systems for both fast and slow losses will be implemented. In many cases, the signals from the same physical monitor will be analyzed over multiple time scales with varying sensitivity.

The loss monitoring scheme for FRIB is shown in Table 1. Fast and slow loss detection methods are shown for each segment of the accelerator, and primary as well

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as backup detection schemes are indicated. At low energy, the primary fast detection schemes are based on direct beam monitoring. Secondary radiation monitoring methods only come into play as the primary beam energy increases to a suitable production threshold. The slow loss schemes are based on time-averaging of signals as well as thermal monitoring in cryomodules.

Table 1: Beam Loss Monitor Network (DBCM – Differential Beam Current Monitor; HMR – Halo Monitor Ring; BLM – beam loss monitor; FTS – Fast Thermometry Sensor; Cryo – Cryogenic System Monitors)

		LS1	FS1	LS2 Low Energy	LS2 High Energy	FS2	LS3	BDS
Fast Loss	Primary	DBCM	DBCM	DBCM	DBCM	DBCM	DBCM	DBCM
< 35 µs	Secondary	HMR	HMR	HMR	BLM	BLM	BLM	BLM
	Tertiary				HMR	HMR	HMR	
Slow loss	Primary	HMR	HMR	HMR	BLM	BLM	BLM	BLM
> 100 ms	Secondary	FTS		FTS	HMR	HMR	HMR	
	Tertiary	Cryo		Cryo	Cryo		Cryo	

A multi-time scale signal processing scheme for the Halo Monitor Rings is shown in Fig. 3.

In Vacuum Monitors

The direct measurement of beam properties, on a suitably fast basis, can directly inform the machine protection system to cease beam production and to dump stored beam. Robust monitoring of beam current at the 1-10% level of the normal current on a fast time scale (several µs) is required to detect changes in the beam intensity that may require MPS interdiction. Beam position monitors, capacitive pickups, and current sensing interceptive devices near the limiting beam aperture can also provide reliable detection sensitivity. Modern FPGA electronics systems are gaining wide acceptance for fast and flexible beam loss detection and interface to MPS decision and control systems.

Differential Beam Current Monitoring

Differential beam current monitoring (DBCM) for MPS has been demonstrated at SNS using AC-coupled current transformers (ACCTs) [4]. ACCTs generally have higher frequency response than DC-coupled current transformers and so can better detect relatively fast changes in beam current (<10 µs). However, lacking DC response, an ACCT signal must be periodically re-baselined to define the 'no current' condition and additional signal conditioning is necessary to compensate for signal 'droop'. [5].

A network of 12 ACCTs will be deployed at FRIB to provide fast detection of beam losses throughout the linac segments and transport arcs. The individual ACCT beam current monitor (BCM) signals will be acquired, conditioned, digitized, and analysed with Struck 8300-L2 digital cards and Struck 8900 MTCA.4 RTM boards [6]. A single pair of boards will receive 4 BCM signals. A single MTCA.4 chassis will house the 3 pairs of boards, and provide a fast digital link to daisy chain the FPS status to the FPS slave node.

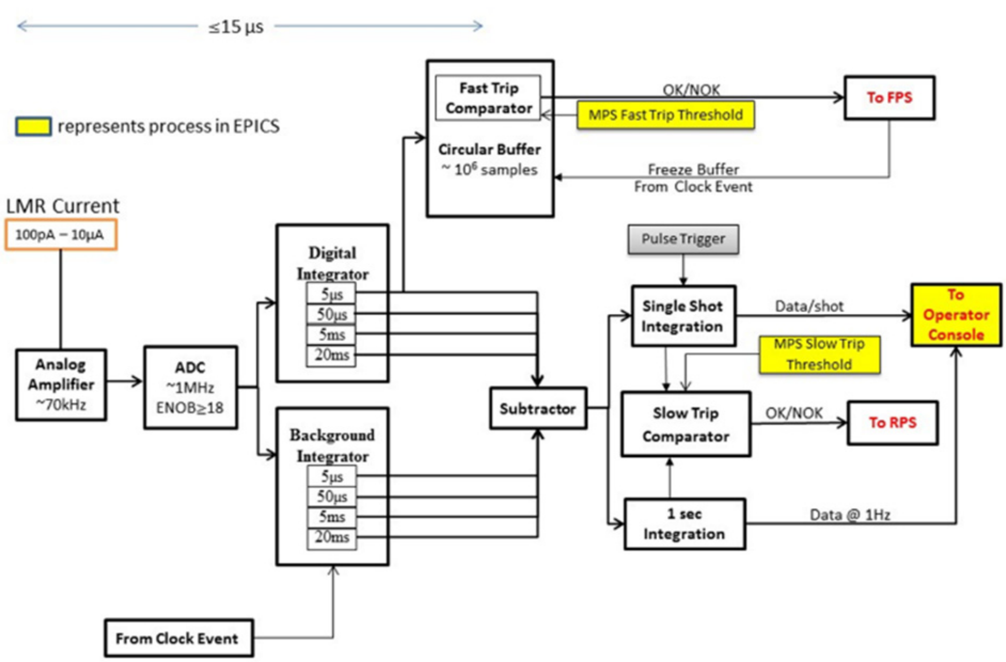

Figure 3: Halo ring signal processing scheme.

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The halo monitor ring (HMR) was designed as a minimally interceptive device [3], with high sensitivity (~0.1 nA) to small losses and fast response (<10 μs) to large losses. The HMR is designed to be mounted within a diagnostic box between two cryomodules, with inner aperture that approximately matches the limiting beam aperture in the cryomodule. Tests of the loss ring sensitivity were performed at the National Superconducting Cyclotron Laboratory. The FRIB HMR design is shown in Fig. 4.

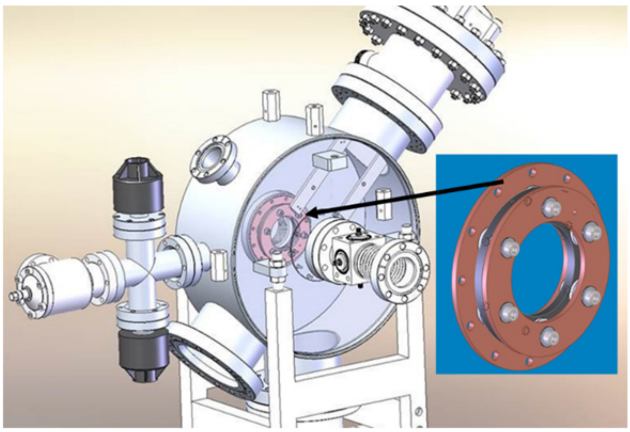

Figure 4: FRIB halo monitor ring implementation.

Secondary Radiation Monitoring

Beam loss monitors (BLMs) based on detection of radiation from primary beam losses will be used extensively. Sensitive, pressurized gas ionization chambers will be used in the warm transport areas and along LS3 for fast and slow monitoring. Scintillator based neutron monitoring will be used along LS2 and LS3 for overall background radiation monitoring. During commissioning, they will be deployed along LS1 for fast and slow loss monitoring.

Cryomodule-Based Monitors

Low intensity, chronic beam losses are a prime factor in the degradation of superconducting RF cavity performance. Losses of primary beam interact thermodynamically with the cryomodule system. Systems employing fast thermometry or calorimetry have been developed to monitor the temperature of cryogenic components and beamlines [7][8]. Resistance temperature detectors (eg. Cernox RTDs) are employed to monitor the surface temperature of components.

Fast thermometry techniques are currently being explored to detect low level, slow beam losses at limiting apertures in cryomodules [9]. ANSYS models can predict the magnitude and rate of change in component temperature under thermal loading conditions due to beam loss [10] (Table 2).

Table 2: Cryogenic Beam Loading Response

Rising time for 0.1K temperature difference from beam loss		
Beam loss in cryomodule	0.1 W/m	1 W/m
0.1K rising time	1 min	7 sec
Maximum temperature rising	1.83 K	8.9 K
Total rising time	30 min	20 min

Measurements of thermal loading and RTD pickups were conducted at FRIB [9]. Initial sensor response is encouraging for detection of several mK temperature rise with a time response of 10's seconds. Improvements to the sensitivity and time response are expected with higher sampling and averaging rates (1-10kHz).

A fast thermometry system (FTS) [7] will be installed in the cryomodules in LS1 (Fig. 5) and the low energy portion of LS2 to provide enhanced beam loss detection. Pairs of resistance temperature detectors (RTDs) will be installed at the entrance and exit of each cryogenic solenoid in these cryomodules to detect changes in local temperature from beam interception. Fast (~10 kHz) signal conditioning and digitizing modules provide sensitivity to 0.1 K temperature changes on a seconds-order time scale.

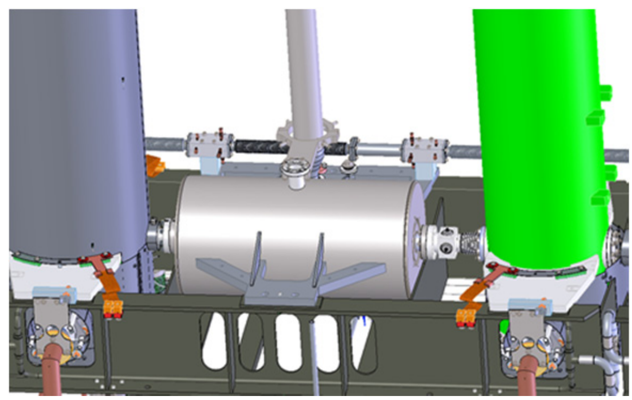

Figure 5: FRIB β=0.085 cryomodule segment.

Additional methods are under consideration to monitor the heat load in the 2K (cavity) and 4.5K (solenoid) cryogenic circuits due to beam loss. Such signals include the cavity/solenoid vessel temperature sensors (CERNOX 1010), vessel heater supplies, and the 2K/4/.5K bath pressure. These can provide temperature sensitivity to 0.1K but may require long time averaging (1000s seconds).

Fault Mode Studies to Improve Network Response

Fault mode and errant beam studies are being conducted to assess the risk of large beam energy density deposition from component failure or operator error. A beam and accelerator model is used to generate distributions of beam power and energy density deposition along the beamline due to discrete fault conditions [11]. Particular cases under study are single cavity and solenoid magnet failures from quench and

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room temperature magnet mis-powering and steering errors.

Fault mode and errant beam loss patterns are used to identify high risk loss events and then analyse the responses of BLM sensors (using secondary radiation) as well as BCM, BPM, and HMR fast responses. This data can then be used to optimize the network density of FPS-serving sensors and improve the robustness of beam loss decision making algorithms [12][13].

COMMISSIONING AND VALIDATION SCHEME

During the initial FRIB commissioning phases, the peak and average beam intensity will be limited. Increasing the average beam power to the design value will require validation of machine and personnel protection mechanisms. It is currently envisioned to progressively validate and commission the FPS systems in three stages.

The first stage has sufficiently low peak and average beam power that safe operation requires no fast MPS response. MPS will only be needed to inhibit the next pulse in case of a fault situation. In this stage, the DBCM, HMR, and BLM diagnostic systems will be established to terminate the beam within 50 ms.

In the second stage, MPS is required to terminate the beam within 50 ms. The diagnostic systems have been established and demonstrated in the previous stage. In this second stage, fast DBCM, HMR, and BLM systems will be verified to terminate beam within 500 μs. The increased sensitivity provided by slow HMR and BLM monitoring systems and by cryomodule temperature monitoring will be initially demonstrated.

The third stage requires fast MPS systems, starting with 500 μs response times. Further demonstration and verification of beam termination within 35 μs will be performed before full power beam production is allowed.

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