INSTRUMENTATION DESIGN AND CHALLENGES AT FRIB*

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Abstract

The Facility for Rare Isotope Beams (FRIB) will use a superconducting linear accelerator to extend the heavy ion intensity frontier for ion species from protons to uranium. The unique design of the twice-folded linac, coupled with the 5 orders of range of beam intensities present new challenges for instrumentation, and machine protection systems. Multi-charge state beams in the low energy linac and dispersive arc regions add complexity to instrumentation systems used for longitudinal tuning and transverse orbit optimization. Beam loss monitoring systems must distinguish losses from the three parallel linac segments sharing the same enclosure. Finally, quick response to abnormal conditions is required to prevent catastrophic damage to beam line components from the high power, heavy ion beams. We present an overview of beam diagnostic systems and detection networks required for the safe tuning, operation, and maintenance of FRIB.

FRIB FACILITY OVERVIEW

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 [2].

The front-end consists of two ECR (Electron Cyclotron Resonance) ion sources, a normal conducting CW (continuous wave) RFQ (Radio Frequency Quadrupole) linac, and beam transport lattices. 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. A multi-harmonic buncher (MHB) precedes the RFQ and impresses the initial 80.5 MHz RF time structure on the beam. The front end is shown schematically in Fig. 2.

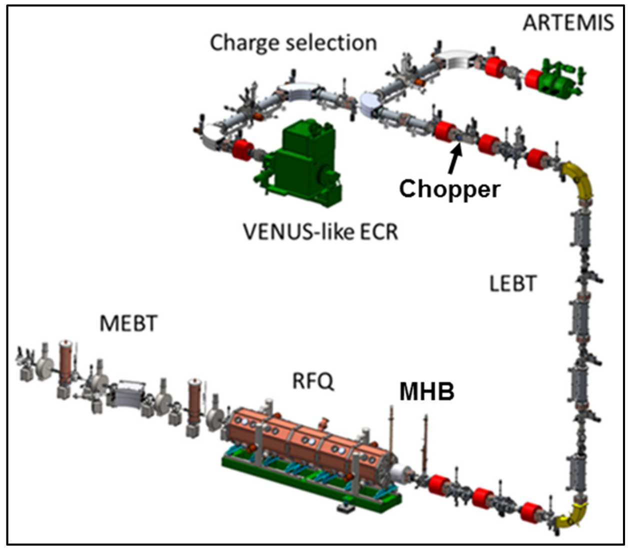

Figure 2: Front end schematic layout.

This paper will first discuss the requirements and specifications of the beam instrumentation systems necessary for FRIB commissioning and operation. Then specific challenges and issues will be presented, along with proposed solutions, which arise from the unique design and operation of this facility.

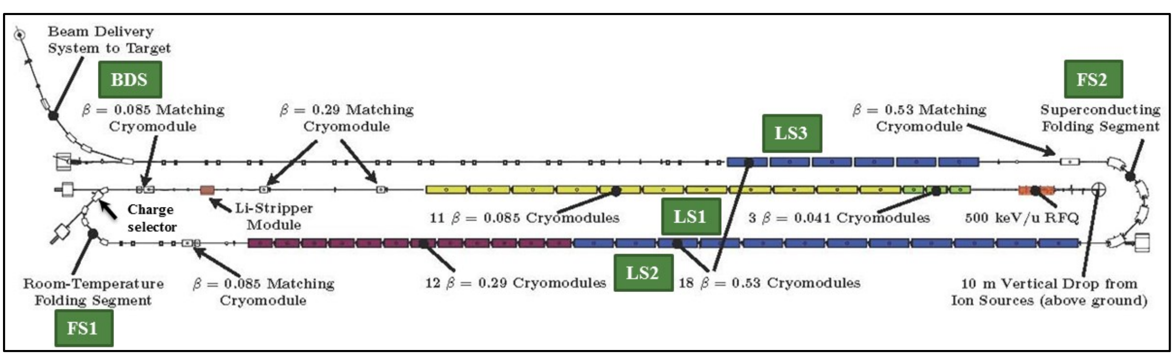

Figure 1: FRIB drive linac schematic layout.

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OVERVIEW OF BEAM DIAGNOSTIC INSTRUMENTATION

The suite of beam instrumentation systems is designed to facilitate initial commissioning and tuning activities

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preceding user operations, and then to monitor beam transport and acceleration function, and to provide sensors for machine protection during operations. Diagnostic systems will be provided to continuously measure beam position and orbit deviations, beam current and transmission at several points, and beam loss induced radiation fields. On-demand diagnostics will produce measurements of beam phase space densities, bunch duration, 1-D beam profiles and 2-D transverse (x-y) or hybrid (x-z) distributions. Time of flight measurements using a dense network of beam position monitors will enable phase and amplitude tuning of the linac sections [3].

Beam Modes

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 modes used for commissioning the front end and fragment separator lack quantitative definition, but may be mapped to one of the other categories. 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).

Overall Requirements and Sensitivities

To meet the demands of the FRIB experimental systems, stringent requirements on the linac driver and beam delivery system are imposed. These are summarized in Table 1.

Table 1: Required beam parameters at target for five-charge-state Uranium

Parameter	Value	Required (% beam)
Beam spot size	1 mm	≥ 90%
Angular spread	±5 mr	≥ 90%
Bunch duration	3 ns	≥ 95%
Energy spread	±0.5%	≥ 95%

Front End

The instrumentation package in the Front End section will enable selection and tuning of two charge states for simultaneous production, acceleration and transport to the first linac segment, while maintaining beam quality. Each source line (Fig. 2) will include a diagnostic station, capable of intercepting up to 300 W of continuous beam power, which includes (i) horizontal and vertical charge-selecting slits; (ii) a Faraday cup; (iii) view screen and optics; and (iv) horizontal and vertical Allison scanners.

The LEBT beamline contains the electrostatic, deflecting mode chopper and Faraday cup monitor for the deflected beam, followed by collimating apertures. A sequence of 1-D profile monitors and pepperpot emittance monitor analyze the beam quality and ensure that the transport lattice and beam distribution are well matched. Following the multi-harmonic buncher and velocity equalizer [3], a stripline fast Faraday cup [4] will be utilized to monitor the longitudinal distribution prior to injection to the RFQ.

Beam current monitors (BCMs, ACCT-type [5]) continuously monitor the beam transmission through the RFQ and at the exit of the MEBT. A 50 µs, 100 Hz current notch or beam gap is imposed by the chopper so that the current baseline can be periodically recovered with the ACCTs. Beam position monitors (BPMs), tuned to a harmonic of the 80.5 MHz cavity frequency, are introduced following the RFQ. Nearly all BPMs in the FRIB lattice use 20-mm diameter, capacitively-coupled buttons to sense beam excursions [6].

Linac Segments

The first linac segment (LS1) accelerates the two-charge-state ion beam from 500 keV/u to 16 MeV/u. Beam position monitors are placed both in the cryogenic assembly between superconducting solenoids and RF cavities (Fig. 3), as well as in the warm sections between cryomodules (Fig. 4). In the remaining two linac segments (LS2 and LS3), BPMs are placed in the warm sections between cryomodules.

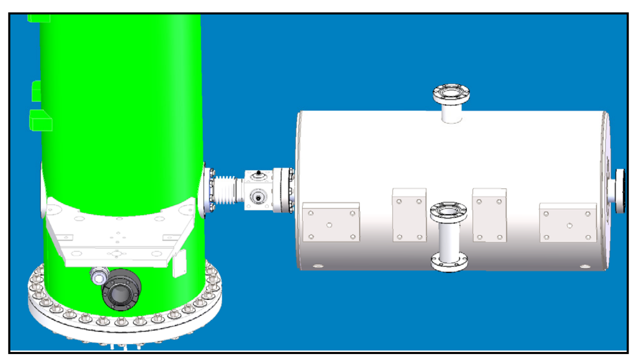

Figure 3: Cryogenic BPM installed between solenoid and cavity in LS1.

Beam current monitors are installed along each straight arm in the folded linac. These are Bergoz AC current transformers (ACCTs) with ~300 kHz high frequency cutoff, and 100 ms droop (*L/R*) time constant. The positions of the unshielded current monitors have been optimized to limit the DC magnetic field

Loss (or Halo) Monitor Rings [7][8] are installed in the warm sections between cryomodules. These niobium rings have apertures that closely match the physical apertures of the cryomodules. They are capacitively-coupled to the

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electrical ground of the diagnostic box and provide a measurement of intercepted current whether from halo scraping or transverse excursions of the beam core.

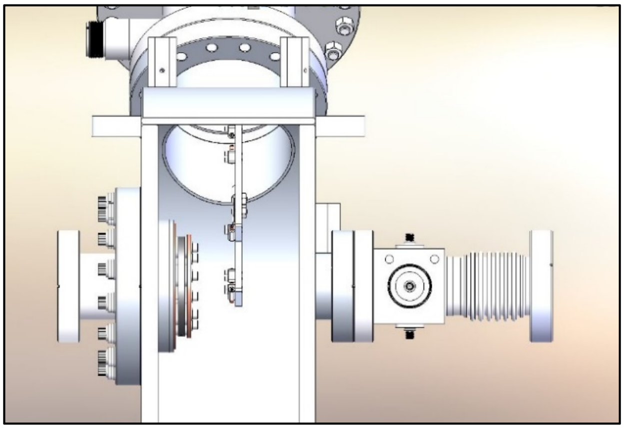

Figure 4: Warm section diagnostic box, with wire profile monitor (PM), BPM, and loss monitor ring (LMR). The profile monitor (shown) is absent in stations connecting cryomodules.

External beam loss monitors (ionization chambers and scintillator-PMT-based, moderated neutron detectors) will be placed along the high energy side of LS2 and along LS3 for prompt detection of x-rays and gammas, and for more sensitive detection of neutron fluxes.

Folding Segments

The low energy (~16 MeV/u) Folding Segment 1 serves several purposes: (i) to provide a warm magnet transport lattice to connect LS1 to LS2; (ii) to strip the two-charge-state ion beam into many charge states, followed by; (iii) selecting up to five charge states for transport and insertion in LS2; and, finally, (iv) to provide a straight-ahead beam dump line for commissioning and tuning LS1. A second beam dump in FS1 is provided to facilitate tuning of the charge state selector and optics. The high energy (~150 MeV/u) Folding Segment 2 provides a superconducting magnetic transport lattice to connect LS2 to LS3, as well as a straight ahead beam dump for LS2 commissioning and tuning.

The basic instrumentation suite includes beam position monitors, transverse profile monitors, and beam current monitors. The charge stripper imposes constraints on the impinging beam distribution to limit the growth in energy spread and beam emittance. A Feschenko-type bunch shape monitor [9] will be used to monitor the transverse and longitudinal bunch profile, enabling upstream tuning to match the stripper admittance.

Beam Delivery System

The final transport lattice which comprises the Beam Delivery System (BDS) serves to deliver the multi-charge-state beam to the target with parameters given in Table 1, for example. The beam instrumentation design includes beam position, transverse profile, and beam current monitoring. A full energy (200 MeV/u), straight ahead beam dump is used for commissioning and tuning of LS3 and the linac-to-BDS transport line, but is not rated for full beam power.

CHALLLENGES FOR BEAM INSTRUMENTATION

FRIB employs a superconducting linac to accelerate the high power, high brightness hadron beam. As such, it shares operational issues with other facilities (SNS, ESS, RHIC, LHC, JPARC, etc.) with regards to power handling and cleanliness of components, restrictive access to the beam line and prohibitions against actuated diagnostics near cryomodules, etc. Several other challenges for beam instrumentation are introduced in the FRIB case due to the low energy of the heavy ion beams, the folded linac geometry, and the requirement to transport multiple charge states simultaneously.

Low-Beta Beam Position Monitoring

The relatively low velocity of the ion beams in the drive linac has implications for accurate beam position monitoring. With low β, the electric field lines spread out resulting in longer, slower image current, and reduced high frequency content. This effect depends on the proximity to the button and produces a position- and velocity-dependent frequency response [6][10][11].

Shafer's analysis of low-β beam pickups [11] identified a correction factor determine position. With BPM buttons *A* and *B* centered on the midplane (with separation *D*), the beam position is estimated as

$$\Delta x \cong \frac{1}{1+G}\frac{D}{\pi}\frac{A-B}{A+B}, \tag{1}$$

where

$$G = 0.0347\left(\frac{\omega}{\beta c}\frac{D}{\gamma}\right)^2 - 0.00181\left(\frac{\omega}{\beta c}\frac{D}{\gamma}\right)^3. \tag{2}$$

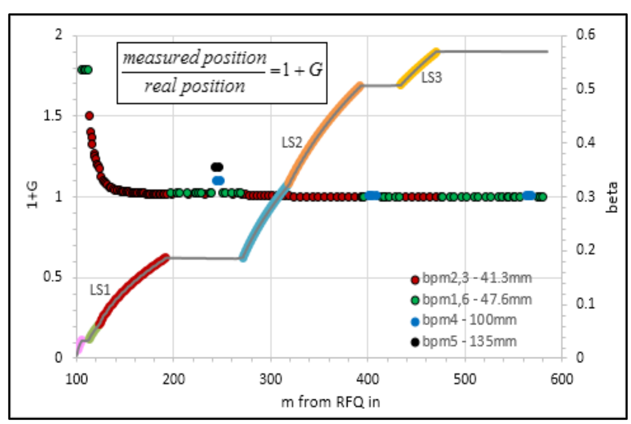

Figure 5: Linear correction factor for low-β. [6]

The linear correction factor for the FRIB BPMs are shown in Fig. 5. The effect is pronounced for position measurements in the MEBT, the lower energy region of LS1, and the large dispersion region of FS1 which requires large aperture BPMs.

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Multiple Charge State Beams

The acceleration, transport and delivery of a multiple charge state composite beam presents particular complications to the beam instrumentation design and functionality for establishing the machine tune. Representative ion species for FRIB are listed in Table 2, where Q1 is the beam charge state in the Front End and LS1, and Q2 is the beam charge state following the stripper and charge selector in FS1. In the case of Uranium, two charge states are transmitted to the stripper, with five states selected for additional acceleration and target delivery.

Table 2: Representative Ion Species in FRIB

Ion Species	A	Emax (MeV/u)	Q1	Q2-center	Q2-spread
U	238	200	33, 34	78	76-80
Xe	136	242	24	51	50-52
Kr	86	262	17	35	35
Ca	48	268	12	20	20
Ar	36	318	10	18	18
O	16	319	3	8	8

From a beam dynamics perspective, the effect of multiple charge states is homologous to a momentum spread: $\Delta Q/Q \sim \Delta p/p$. In the case of Uranium beams, the charge state spread ($\Delta Q/Q$) is ~3% before the stripper and ~6% following the selector. Differential focusing and acceleration is required to remove different charge-state-induced phase space offsets.

Uranium beams undergoing low energy acceleration in LS1 will execute synchrotron oscillations. Due to the large $\Delta Q/Q$ separation between charge states they will orbit about different stable phase points. The result is an overall oscillation in the longitudinal emittance (Fig. 6).

The challenge to beam instrumentation is to spatially resolve the phase dispersion of the two charge states along the linac. This can be accomplished by utilizing the network of BPMs and measuring phase differences between the fundamental and 3rd harmonic of the bunch frequency, for example.

A separate issue with multi-charge state beams arises in FS1 due to dispersion. Figure 7 shows the effect near the position of maximum dispersion for the ideal lattice case. Here, the beam distribution at the BPM following the charge selector is dispersed horizontally by up to ~80 mm. A large (150 mm) aperture, elliptical, split plate BPM design (Fig. 8) provides a larger linear response regime [12].

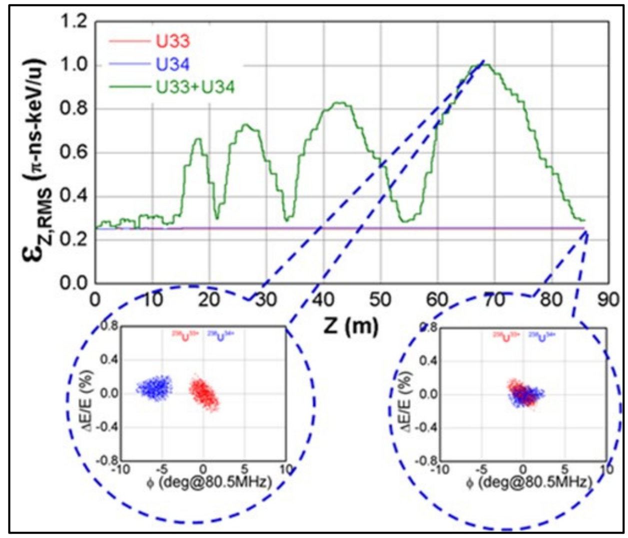

Figure 6: Longitudinal emittance evolution of two-charge-state beam in LS1

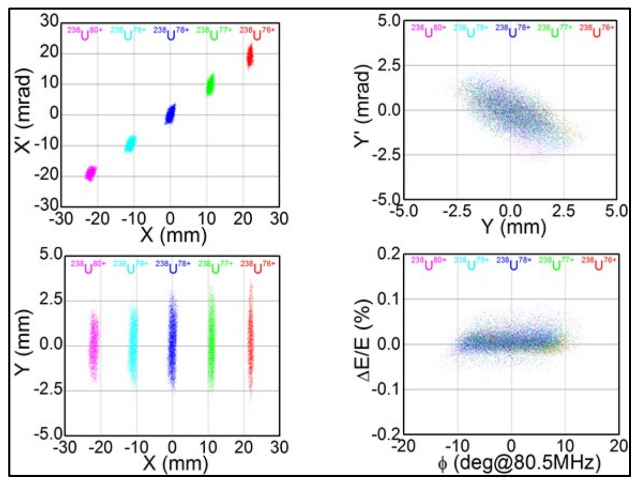

Figure 7: Five-charge-state beam dispersion in FS1.

Large Dynamic Range of Beam Intensity

The previously discussed beam modes define the range of conditions that the beam instrumentation must serve. Beam instrumentation is required to detect beam currents ranging from ~1 mA to ~1 μA, with bandwidths sufficient to provide sensitivity over orders of magnitude in duty cycle or pulse duration (CW to 50 μs pulse duration at 1 Hz). Additional operating modes (albeit a small fraction of the operating schedule) require lower peak intensities and average beam power. The baseline resolution requirements for the diagnostic systems assumes CW operation with 100 μA beam current. Operationally, for reduced average beam currents, longer integration or averaging times may be used to restore resolution. In the extreme case of ion beam fluxes ~100 pfA, intercepting diagnostics may be utilized with long integration times to acquire flux density information on the transported beams.

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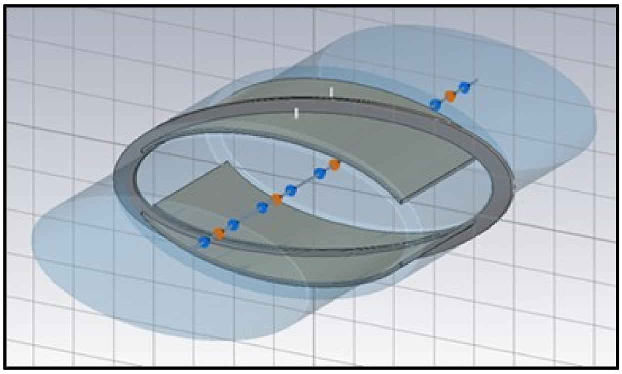

Figure 8: Large aperture, elliptical, split-plate BPM in FS1.

Machine Protection Issues

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 mitigate against prompt beam losses [13]. The performance and lifetime of sensitive superconducting cavity surfaces can be affected by small losses (< 1 W/m) occurring over long durations.

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 [14]. Additional x-ray background sources originating from the RF cavities themselves can also overwhelm the relatively low-amplitude beam-generated signals in the low energy linac modules.

Table 3: FRIB Beam Loss Detection Layers

		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/Temp	HMR	HMR/Temp	BLM	BLM	BLM	BLM
> 100 ms	Secondary	HMR/Temp		HMR/Temp	HMR/Temp	HMR	HMR/Temp	
	Tertiary	Cryo		Cryo	HMR/Temp		HMR/Temp	
					Cryo		Cryo	

The loss monitor network scheme for FRIB is shown in Table 3. Fast and slow losses, in each segment of the accelerator chain, are separated, and the primary as well as backup detection schemes are indicated. The primary fast detection schemes are based on direct monitoring utilizing differential beam current monitors (DBCMs) [15]. Secondary radiation monitoring appears only as the primary beam energy increases to a suitable production threshold. The slow loss schemes are based on time averaged loss ring monitoring as well as thermal drift monitoring in cryomodules.

SUMMARY

The beam instrumentation design for the FRIB linac has been presented, and has been shown to satisfy the requirements for measuring and tuning of the expected high power, high brightness hadron beams. Issues and challenges to beam instrumentation specific to the FRIB linac facility have been described, and proposed solutions presented.

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