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WIDE DYNAMIC RANGE DIAGNOSTICS SYSTEM FOR PRIMARY AND SECONDARY BEAMS AT FRIB*

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Abstract

The FRIB diagnostics system covers an extensive range of primary and secondary beam intensities of 14 orders of magnitude and requires continuous improvements. The linac diagnostic system has provided straightforward linac commissioning and supports the development of many primary heavy ion beam species for producing rare isotopes. The diagnostics system for the secondary beam has a unique feature of detecting and measuring low-intensity rare isotope beams. This talk will report on the performance of the FRIB diagnostics system and ongoing improvements.

FRIB FACILITY

The Facility for Rare Isotope Beams (FRIB) is a high power heavy ion accelerator facility presently in operation at Michigan State University [1]. The FRIB is a power frontier accelerator facility aiming to provide two to three orders of magnitude higher beam power than existing heavy ion accelerator facilities. The FRIB linac is designed to accelerate all stable ions to energies above 200 MeV/u with beam power of up to 400 kW with Continuous Wave (CW) operation (see Fig. 1), and carrying intensities up to $\sim 10^{13}$ particles per second (pps) or currents ~100 eμA.

The scientific program generates demands on the functionality and operability of the facility. The ion sources and linear accelerator, and beam transport sections for the primary beam must handle intense, low energy, ion beams with velocities from 0.03c – 0.60c, and with mass-to-charge (A/Q) range 3 – 7. The linac acceptance is designed to permit lossless transport of multi-charge-state beams ($\delta Q/Q \sim 1/16$) [2].

While the FRIB linac operates in Continuous Wave (CW) mode, the electrostatic chopper allows pulsed beam operation for commissioning and tuning. As a high power accelerator, it is important to mitigate excess beam loss during tuning, and the chopper and beam attenuators play key roles to this end by permitting low peak or average power beam generation.

The high power interception devices which include the production target and beam dump, charge strippers and charge selection devices must operate in regimes of large temperature variations and thermal stresses. These are actively monitored for machine protection.

Secondary particles and rare isotopes are produced by the interaction of the primary beam with the target. This large phase space of fragments is filtered and reduced by the fragment separator beamline and instrumentation to isolate the rare isotope of interest, which typically appear at very low production rates.

DIAGNOSTIC AND INSTRUMENTATION REQUIREMENTS

To support the nuclear physics program, experimental runs are performed over periods of up to two weeks. New runs require changes to primary beam species, energy, and intensity. To facilitate these changes, the beam diagnostics and associated instrumentation must maintain sensitivity, accuracy, and speed over the entire range of beam parameters. The range of beam intensities covers many orders of magnitude between production (10^{13} pps) and beam tuning (10^6 - 10^7 pps). Oftentimes, beam tuning is performed with lower duty factor (lower average power) beams, so that signal acquisition modes must allow for short pulse durations and lower repetition frequencies.

Secondary beam production, fragment separation, and particle identification of rare isotope species impose another set of operational demands on diagnostics and instrumentation to facilitate single particle measurements at rates from 10^7 pps to 10^{-2} pps or lower.

Beam losses are a major concern for operation of an intensity-frontier, heavy ion accelerator. Chronic losses must be limited to permit maintenance with negligible impact to the facility's availability while fast losses must be quickly detected and stopped to prevent severe damage. High impact loss events are typically generated by failures in the RF systems or intercepting charge stripper devices. Slower losses may develop from drifts in the ion source output, slow changes to charge stripper thickness, magnet power supplies, etc.

Lastly, a new radiation effects beamline has been built and is currently operating on the FRIB linac [3]. This beamline require measurement and delivery of beam fluxes at low levels, with a minimum $\sim 10^2$ ions/cm^2/s. This has necessitated the development of dosimetry instrumentation.

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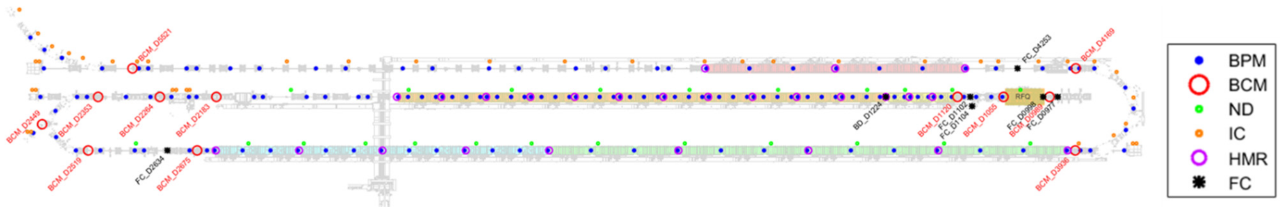

Figure 1. Schematic of FRIB main linac segments, with main diagnostic elements indicated.

Table 1: Front End, Linac, and Target Diagnostic Systems

Device Name	Device Type	Detection Mode	Beam Parameter
BPM	Beam Position Monitor	Button pickup	Position, Energy, Intensity, Longitudinal profile
BCM	Beam Current Monitor	AC-current transformer	Intensity, Fast differential losses
ND	Neutron Detector	Scintillator/PMT	Fast/slow losses, Lattice tune
IC	Ionization Chamber	Current readback	Fast/slow losses, Lattice tune
HMR	Halo Monitor Ring	Current readback	Fast/slow losses, Lattice tune
FC	Faraday cup	Current readback	Intensity
PM	Profile monitor	Current readback	Transverse profile, emittance, lattice tune
Viewer	View screen and camera	Digital image	Transverse profile
BSM	Bunch Shape Monitor	Feschenko-type	Longitudinal phase space
AS	Allison Scanner	Current, Voltage readback	Transverse emittance
FTh	Fast Thermometry detectors	2-10 K RTD	Slow losses
Coll. Slits	Instrumented slits (4-jaw)	Current readback	Intensity
SD	Si(Li) detector	Multichannel analyzer	Intensity, Energy, Contamination
Target Thermal Imaging System	In-vacuum optics and in-air camera	Digital image	Transverse intensity and surface temperature distribution
Fast PD	Fast photodiode	Current readback	Surface temperature

Primary Beams

Primary beam diagnostics are installed in the ion source and Front End, linear accelerator, and Target Hall. The locations of linac systems are indicated in Fig. 1. These and other systems in the linac and Front End are listed in Table 1.

These systems provide detection over a wide range of beam intensities and pulse formats. The non-interceptive beam diagnostics (BPM, BCM, ND, IC, HMR, FTh) present a dense network of several hundred devices along the beamline, providing continuous measurement and monitoring [4].

Beam Position Monitors Beam position monitors (BPMs) have demonstrated the greatest range of applications – providing position, intensity, energy, and longitudinal profile [5] data over a range of beam currents from 100 eμA to 10 enA. Energy measurements are performed using time-of-flight (TOF) techniques with two or three selected BPM signals. This functionality is enabled by verifying the longitudinal position of every BPM, and their relative delays from local RF clock signals, using local beamline clock taps and calibrated, long test cables.

An example of a novel application of the BPM read back is shown in Fig. 2, which illustrates the differential analysis of multiple charge states of ^{129}Xe originating from the injector as ^{129}Xe^{27+}. Also seen in Figure 2 is the horizontal separation of the transmitted charge states due to dispersion in the first Folding Segment.

Beam Current Monitors Beam current monitors (BCMs) are situated to monitor beam intensity, charge stripping efficiency, and transmission losses. Standard AC-CTs from Bergoz Instrumentation are used, with signals collected into a common DAQ chassis for in-chassis analysis and decision-making. These devices are inherently more noisy than the narrowband BPM DAQ electronics. The lower range of current measurements using the BCMs and incorporating significant signal averaging is ~0.5 enA.

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Beam Loss Monitors Beam losses are important to measure and quantify against operational conditions that lead to variations in the anticipated loss distribution along the beamline – ion species and number of transported charge states and beam intensity. Losses are gathered and catalogued for specific beam conditions from measurements: directly in collimating devices (HMRs); or indirectly via detection of secondary radiation (x-rays, gammas, neutrons) in devices bordering the beam line (e.g., IC, ND), via transmission losses (BCM) computed through differential intensities at various beamline locations, and via measured beampipe temperature rises in cryogenic accelerator modules (FTh).

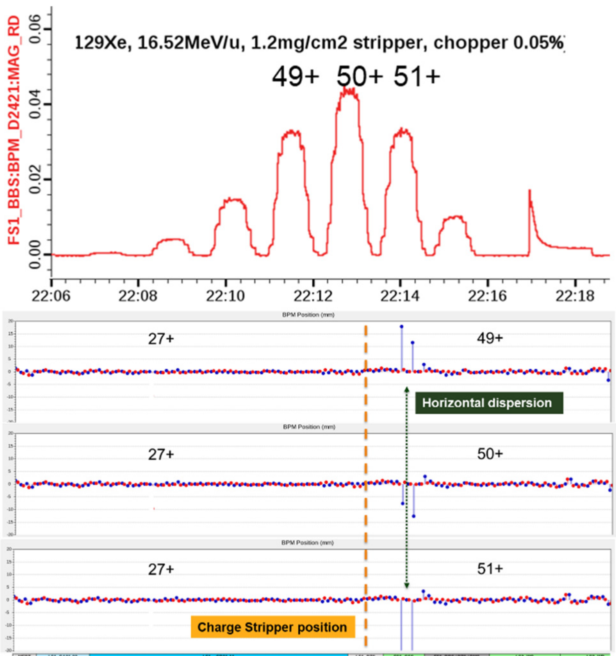

Figure 2. (Top) Intensity distribution of ^{129}Xe charge states downstream of charge stripper in Folding Segment 1, obtained by narrow scanning of the high-power charge selection slits transversely across the beam. (Bottom) Horizontal (blue) and vertical (red) beam offsets along LS1 and LS2, for different charge states (obtained individually).

Beam losses are monitored in various time increments from 15 µs to multiple seconds to provide monitoring of fast onset events as well as drifts that occur over long time scales. Fast losses of significant fractions of the beam power are detected and arrested within 35 µs to prevent catastrophic loss of vacuum containment. Slower losses are detected and mitigated to prevent longer term degradation to SRF cavities and to limit activation of beamline components.

Different loss measurement modes can provide higher sensitivity or faster detection times. BCMs can provide fastest detection for the larger beam currents anticipated in production, but are limited in accuracy and response time for lower peak currents. This is ameliorated in practice by performing (low power) tuning operations with a low duty factor (typically 5 Hz rather than the nominal 100 Hz) and short pulse durations (eg. 100 µs rather than 9950 µs), but with production-scale peak intensities.

High loss sensitivity is obtained with diagnostics that respond to beam interception. Halo monitor rings (HMRs) are collimating devices attached to sensitive picoammeters that detect diffuse halo or tails of mis-steered beams. Secondary radiation monitors likewise operate with high amplification and are sensitive to low event rates. The Fast Thermometry system can measure changes in the cryogenic beam pipe temperature to 0.1 K or less, and can observe losses in the ~1 W/m range. These higher sensitivity detectors are useful for establishing beam tunes and transport conditions for single charge state beams, and are invaluable for monitoring transmission of multiple-charge-state beams.

Detection and Mitigation of Beam Instabilities Charge stripping is inherent for high power ion accelerators such as the FRIB LINAC. At high power, strippers require motion to prolong the operational life of the stripping media, or by flowing a liquid Lithium film. The charge stripping process introduces energy losses that vary with the actual film thickness, which results in observable beam losses along the tuned beamline, if not adequately mitigated. BPM phase feedback is used in real-time to compensate for these effects, controlling upstream RF cavities in order to maintain a constant beam energy and phase post-stripper, which significantly reduces beam energy fluctuations [6].

Target Imaging The beam target is one of the intercepting devices that receives the full beam intensity during rare isotope production. The graphite target typically rotates at 500 RPM to distribute the (up to) 30% fraction of primary beam power along its surface. Visible and infrared imaging is established to provide on-line read back of the profile and/or the thermal signature of the beam on the target [7]. An example is shown in Fig. 3.

Readout Instrumentation Beyond the sensitivity of the diagnostic sensors themselves, the ultimate performance of the measurement is determined by the analog and digital signal processing and data acquisition system (DAQ).

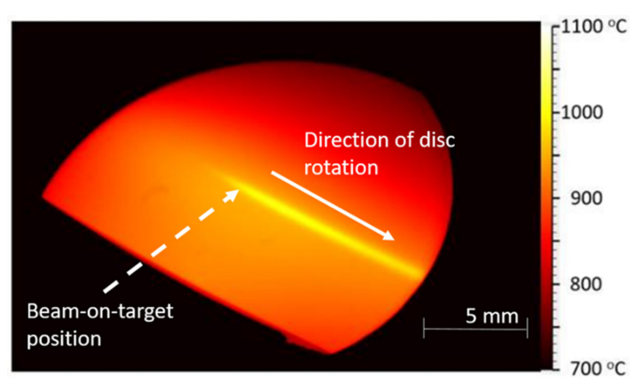

Figure 3. Thermal image of 10.5 kW, 177 MeV/u, ^{238}U onto graphite target rotating at 500 RPM.

Beam position monitor analog data is processed through front-end low-pass or band-pass filters, then sampled at

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119 MSPS then digital down conversion to target the second beam harmonic, resulting in IQ data. This IQ data is averaged and decimated to 1 MHz and 100 Hz data rates. This sampling rate collects and organizes up to 5 harmonics of the fundamental 40.25 MHz beam bunch frequency into a single Nyquist zone without overlap. Table 2 lists the performance of BPM electronics at 80.5 MHz with typical beam parameters for tuning (peak current 4.5eμA, average current 6.7enA), with 1-second data averaging.

Table 2: BPM Signal Parameters at the 80.5 MHz Harmonic Frequency

Area	Analog Input Bandwidth (MHz)	Phase Noise (deg, rms)	Position Noise (mm, rms)
MEBT	400	0.064	0.022
LS1	400	0.037	0.019
LS2	90	0.064	0.031
LS3	90	0.096	0.053

Charge-measuring devices form a large class of diagnostics in the Front End and linac. This class includes Faraday Cups, Halo Monitor Rings, Wire-intercepting Profile Monitors, Ionization Chambers, Neutron Detectors, instrumented Beam Stops and Collimating Slits. We have standardized the DAQ electronics on one of two instruments. For detectors that must respond to fast changes in current (eg. for machine protection), we use the 8-channel PICO-8-AMC [8] in a custom 35kHz input analog bandwidth configuration, with 1 MSPS acquisition rate. For higher sensitivity devices, such as Faraday cups, without the need for higher acquisition rates, we use the PICO-8-AMC in 10kHz bandwidth or the 4-channel TetrAmm [9] with 300 Hz input bandwidth and 100 SPS acquisition rate. Additional decimation and averaging is performed in software. A multiplexer has been designed and integrated to permit both instruments to acquire data selectively from specific beam diagnostics.

Secondary Beams

Nuclear fragmentation reactions between the incoming stable primary beam and the graphite target produce a large population of nuclear fragments. The purpose of the Fragment Separator beamline is to characterize the fragments and isomers that survive for several microseconds and may be delivered to experiments, and to filter out all but the rare isotope of interest for an individual experiment. The Advanced Rare Isotope Separator (ARIS) beamline [10] is shown in Fig. 4.

Secondary rare-isotope beams produced by in-flight projectile fragmentation have relatively large beam emittances and are often a mixture of several isotopes. The presence of cocktails of isotopes in the beam is advantageous for efficiently measuring reactions on more than one rare isotope simultaneously, as long as reactions involving different components in the cocktail beam can be identified by using detector in the beam line. Therefore, depending on the specific experiment to be performed, a variety of diagnostics and tracking detectors are required.

Fragment separation and particle identification in ARIS is performed via the established Bρ-ΔE-ToF technique [11]. The beamline is divided into dispersive and achromatic focal planes, where interception and diagnostic devices at these locations provide capability for single particle characterization. Properties of these detectors are listed in Table 3.

Tracking detectors are required for measuring the momenta and angles of beam particles in the achromatic beam transport mode. The momentum resolving power for the incoming beam must be compatible with that specified for the experimental programs. For the determination of the angle at the reaction target in front of the Spectrometer Section of the incoming beam particles a resolution of 5 mrad must be achieved. This is particularly important for experiments where stringent angular cuts are necessary (e.g., for heavy-ion Coulomb excitation) or where the accurate knowledge of the reaction angle is critical for reducing the uncertainties in the kinematical reconstruction (e.g., in invariant-mass spectroscopy).

Delay-line Parallel Plate Avalanche Counters (DPPACs) [12] are used extensively as tracking detectors due to their sensitivity to light and heavy ions, and their high rate capabilities. A dedicated gas handling systems (GHS) is designed for the operation of the DPPAC by providing up to 20 sccm gas flow to the detectors, and maintaining a constant gas pressure (typically 5 Torr).

Time-Of-Flight detectors for the particle identification and to provide trigger signals utilizes plastic scintillators, such as ELJEN type EJ-230 with a light output of 64% anthracene and a rise time of 0.5 ns, have an active area that matches that of the tracking detectors. Thinner scintillator detectors are used for heavier ion species. The scintillation light emitted by the scintillator is read out by vacuum photomultipliers. For high-precision timing measurements, required for ToF-Bρ mass-measurements, specialized systems will be adopted, such as small plastic scintillators fitted with two or more photomultipliers.

Energy loss measurement for particle identification (PID) may be achieved using a thin (≤500 micron) silicon PIN diode or with a gas-filled, multi-segment ionization chamber.

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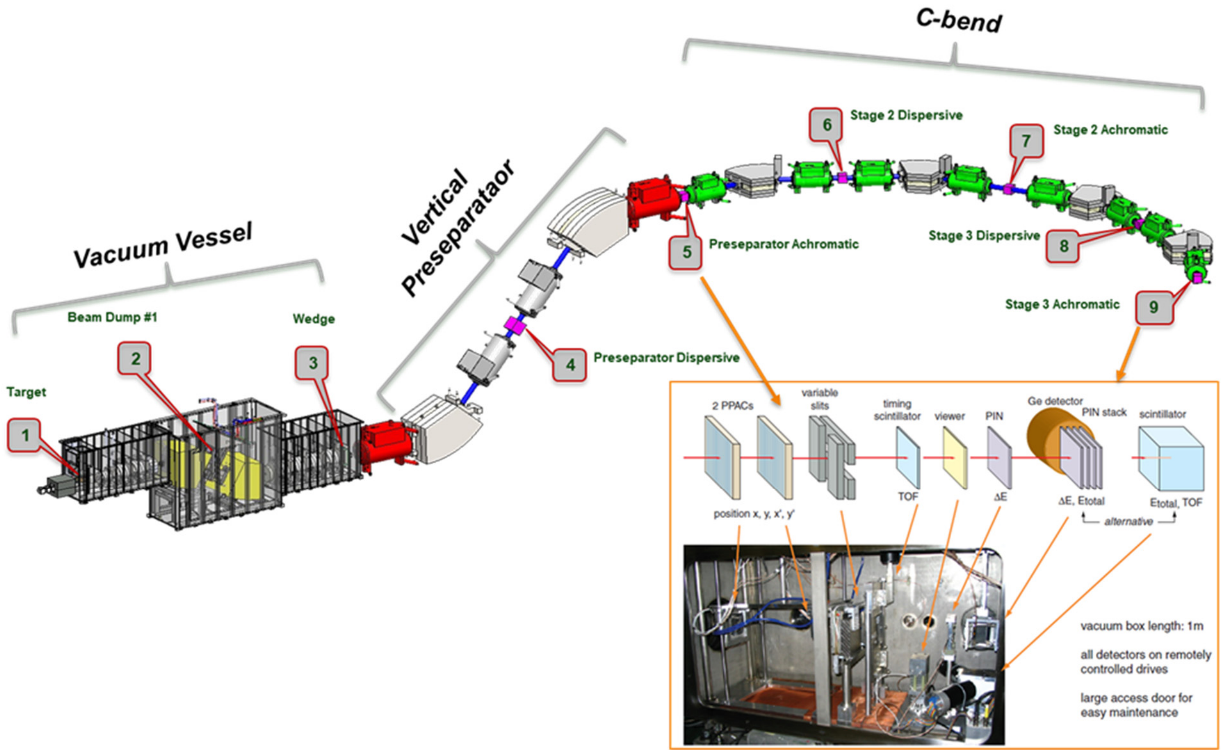

Figure 4. Schematic of FRIB target facility and ARIS fragment separator beamline, and layout of diagnostics.

Table 3: ARIS Diagnostic and Detector Systems

Function	Detector	Property	Position or Energy resolution (σ)	Time resolution (σ)	Rate Limit
Tracking	DPPAC	x/y position, angle	0.5 mm	< 100 ps	>100 kHz
Time of Flight	Thin Scintillator/PMT	Arrival time		< 100 ps	1 MHz
ΔE	Si PIN detector	Energy loss	< 5% (5.9 MeV α)		Few kHz
TKE	Si PIN stack, Thick scintillator/PMT	Total energy loss	< 5% (5.9 MeV α)		1 MHz

Future Needs and Improvements

Continuous assessment and improvements to the diagnostic and instrumentation systems are needed to reach the full scientific productivity of the facility as the beam power delivered to the target climbs towards 400 kW.

- Developing non-interceptive beam profile monitors [13].
- Improving radiation hardness of detectors and closely-sited electronics.
- Increased integration of digital electronics and processing capabilities in particle detection and tracking, and time of flight systems.
- Develop large format tracking detectors, optical tracking and energy loss detectors, and gaseous (or liquid) Xenon detectors for high mass states (A > 50) [14]

Conclusions

We have discussed the range of beam measurements and diagnostic systems in use at FRIB to support the wide dynamic range of intensities and needs imposed by the scientific program.

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