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FRIB PROJECT STATUS AND BEAM INSTRUMENTATION CHALLENGES*

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Abstract

With an average beam power two orders of magnitude higher than operating heavy-ion facilities, the Facility for Rare Isotope Beams (FRIB) stands at the power frontier of the accelerator family. This paper summarizes the status of design, technology development, construction, commissioning, as well as path to operations and upgrades. We highlight beam instrumentation challenges including machine protection of high-power heavy-ion beams and complications of multi-charge-state and multi-ion-species accelerations.

INTRODUCTION

During the past decades, accelerator-based neutron-generating facilities, such as SNS [1], J-PARC [2], PSI [3], and LANSCE [4], advanced the frontier of proton beam power to the 1 MW level, as shown in Fig. 1. FRIB is designed to advance the power frontier for heavy ions by more than two orders of magnitude, to 400 kW [5].

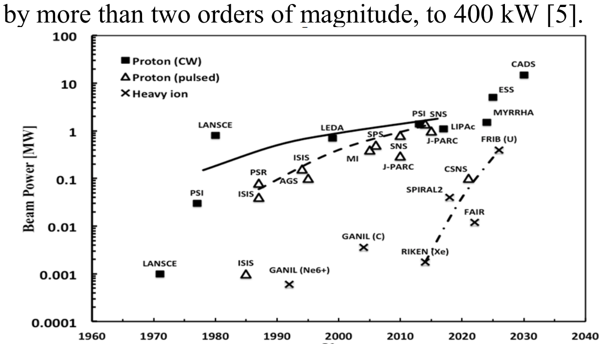

Figure 1: Achieved and planned average beam power on target for proton and heavy ion facilities.

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The FRIB driver accelerator is designed to accelerate all stable ions to energies >200 MeV/u with a beam power on the target of up to 400 kW (Table 1). The driver accelerator consists of a 46 m long Front End [6] containing electron-cyclotron-resonance (ECR) ion sources and a room temperature RFQ followed by a 472 m long SRF linac with quarter-wave-resonators (QWR) of β_0=0.041 and 0.085 and half-wave-resonators (HWR) of β_0=0.29 and 0.53 in a folded layout to facilitate charge stripping and beam collimation and to accommodate the limited real estate footprint in the center of the MSU campus (Fig. 2). Up to 400 kW of the primary beam is focused down to a spot size of 1 mm in diameter striking the production target for rare isotope production. Following the low-loss design philosophy [7], the design average uncontrolled beam loss is below 1 W/m. For heavy ions like uranium at low energies, activation and radiation shielding is of less concern; the 1 W/m limit addresses concerns in damage on superconducting cavity surfaces and in cryogenic heat load [5].

Table 1: FRIB Driver Accelerator Baseline Parameters

Parameter	Value	Unit
Primary beam ion species	H to ^{238}U	
Beam kinetic energy on target	> 200	MeV/u
Maximum beam power on target	400	kW
Macropulse duty factor	100	%
Beam current on target (^{238}U)	0.7	emA
Beam radius on target (90%)	0.5	mm
Driver linac beam-path length	517	m
Average uncontrolled beam loss	< 1	W/m

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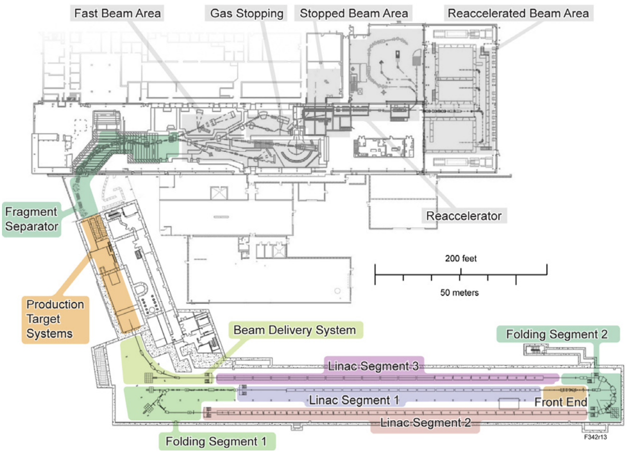

Figure 2: Schematic layout of the FRIB driver accelerator, target, and fragment separator (colored areas) and existing infrastructure (gray).

CONSTRUCTION STATUS

FRIB long-lead procurements were launched since 2012, two years before start of accelerator construction. They include the high power ECR source, the RFQ, niobium material for SRF cavities, pre-production cavities, the 4.5 K refrigeration “cold box”, and cryogenic distribution.

Since 2013, we started major in-house production infrastructure preparation. The 2500 m^2 “SRF Highbay” at MSU houses areas for material inspection, cavity coordinate measurements and alignment checks, vacuum furnace degassing, parts cleaning, chemical etching, high-pressure water rinsing, SRF coupler conditioning, cavity dewar testing, cold mass assembly, and cryomodule testing. This facility, together with the cryomodule assembly area and the machine shop, supports the production throughput of testing five cavities per week and one cryomodule per month.

During the three years since the start of accelerator technical construction in 2014, FRIB accelerator construction is about 76% complete measured by earned-value project controls. About 65% of the total $303M accelerator construction is for material and work-for-others contracts, and about 35% is for in-house labor. About 94% of baselined major procurements (orders above $50k) have been either spent or committed. In-house work focuses on design, prototyping, system requirements and interface definition, contract statement-of-work and acceptance criteria listing development, vendor technical management, in-house fabrication, installation, testing, and commissioning. Major in-house work includes SRF cavity process and certification, cryomodule assembly, 2 K coldbox and cryogenic pieces.

Accelerator installation (Fig. 3) started before the beneficial occupancy date (BOD). The accelerator commissioning is divided into 8 steps, following the beam trajectory starting from the Front End. Each step of commissioning is contingent upon a successful accelerator readiness review (ARR). Each ARR is preceded by several device readiness reviews (DRR) of subsystems.

Figure 3: FRIB tunnel showing the lower LEBT and RFQ fully installed, and first QWR cryomodules aligned.

The first DRR was conducted in October 2016 allowing the operation of the FRIB room temperature ECR ion source [8]. Upon completion of the third DRR, the Ar beam produced from the ECR ion source was transmitted to the end of Low Energy Beam Transport (LEBT), as shown in Figs. 4 and 5. Presently, the RFQ is being conditioned in preparation for the Front End beam commissioning (ARR01) by September 2017 [6]. Commissioning of the β_0=0.041 superconducting RF section (ARR02) is planned for May 2018 upon completion of the 4.5 K cryogenic system (Fig. 6) [9].

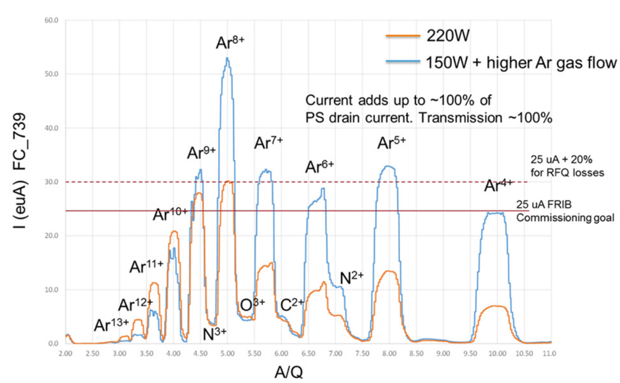

Figure 4: Mass-to-charge (A/Q) scan of Argon ion beam after two weeks of integrated tests showing current recorded on the Faraday Cup (FC_739).

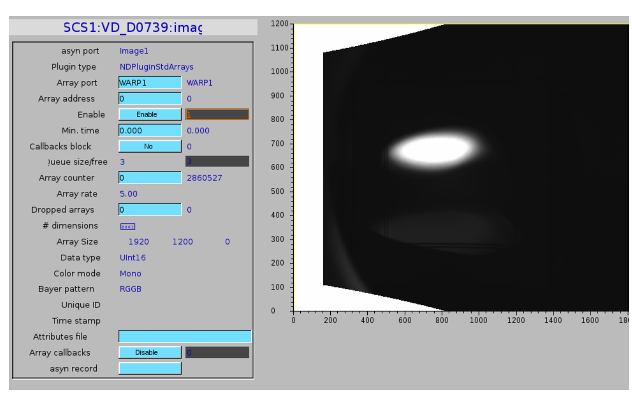

Figure 5: Image of the Ar ion beam on the diagnostics viewer plate near the end of FRIB LEBT.

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Figure 6: 4.5 K coldbox installed in the FRIB cryogenics building [9]. The Floating Pressure Process – Ganni Cycle [10] is implemented to provide efficient adaptation to the actual loads.

Major accelerator R&D and subsystem prototyping are completed. These systems include integrated cryogenics, "bottom-up" cryomodules of low-β cavities and solenoids, charge stripping, and machine protection for high-power, low-energy heavy ion beams.

Integrated Cryogenics and SRF Cryomodule

An integrated design of the cryogenic refrigeration, distribution, and cryomodule systems is key to efficient SRF operations [9, 10]. The prototype distribution module and cryomodule have been successfully cold-tested together for both 4.5 K and 2 K operations. Integrated test with the 4.5 K cryogenic system at the upper-level cryogenic building (Fig. 6), the cryogenic transfer line from the refrigerator to the tunnel, the modular cryogenic distribution sections inside the tunnel, and the β_0=0.041 SRF cryomodules is planned before the ARR02 beam commissioning in May 2018.

To facilitate efficient assembly, simplify alignment, and allow U-tube cryogenic connections for maintainability, FRIB adopted an innovative bottom-up cryomodule design with the resonators and solenoids supported from the bottom [11, 12], as shown in Fig. 7. The cryogenic headers are suspended from the top for vibration isolation. By July 2017, all types of production QWR and HWR cavities in such "bottom-up" configurations are successfully validated.

Liquid Lithium Charge Stripping

FRIB uses a liquid lithium film moving at a speed of ~50 m/s. Tests with a proton beam produced by the LEDA source demonstrated that power depositions similar to the FRIB uranium beams are achievable without destroying the film [13]. In April 2017, the electromagnetic pump was successfully tested for lithium circulation. The production charge stripper along with the safety system will be fabricated by March 2018, as shown in Fig. 8.

Figure 7: Pre-production β_0=0.53 cryomodule under assembly, with 8 SRF cavities operating at 2 K and a solenoid operating at 4.5 K temperature, respectively.

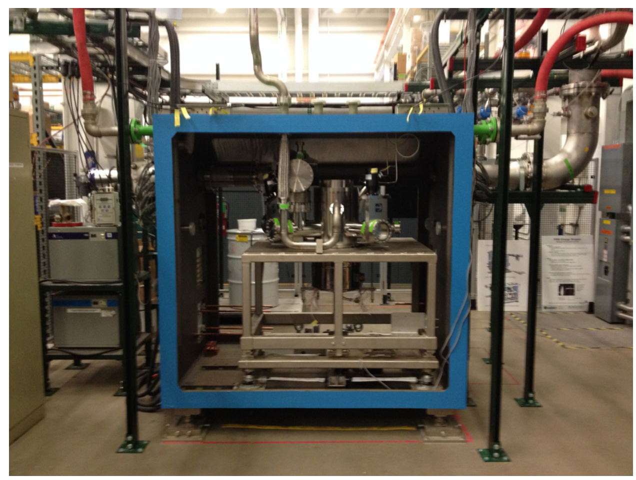

Figure 8: Liquid lithium charge stripper under assembly. The charge stripper assembly is contained in a sealed vessel that can be instantly filled with Ar gas. This vessel is a "credited engineered control" for hazard mitigation.

BEAM INSTRUMENTATION CHALLENGES

This section lists some examples of challenges in FRIB accelerator beam instrumentation and diagnostics.

Multi-layered Machine Protection

Machine protection is challenging for FRIB's intense low-energy heavy ion beams due to the low detection sensitivity and high power concentration in a short range. FRIB adopts multi-time scale and multi-layer approaches (Table 2). The fast protection system (FPS) is required to mitigate beam loss within 35 µs (10 µs for detection, 10 µs for controls processing, 5 µs for inhibit action, and 10 µs for beam clearing) to prevent damage to beam line components [14]. Primary detection methods include Low-level RF (LLRF) monitoring, differential beam current monitoring, halo monitor rings for high-sensitivity loss

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detection (Fig. 9), and current-monitoring modules for critical magnet power supply inhibition. The fast beam inhibit is achieved by independently disabling both the upper and lower 90° electrostatic bends in the LEBT. Addition mitigation at a slower time scale is to disable the ECR ion source high voltage.

Table 2: Machine Protection for the FRIB Driver Linac

Mode	Time	Detection	Mitigation
FPS	~35 µs	LLRF controller Dipole current monitor Differential BCM Ion chamber monitor Halo monitor ring Fast neutron detector	LEBT bend electro-static deflector
RPS (1)	~100 ms	Vacuum status Cryomodule status Non-dipole PS Quench signal	As above; ECR source HV
RPS (2)	>1 s	Thermo-sensor Cryo. heater power	As above

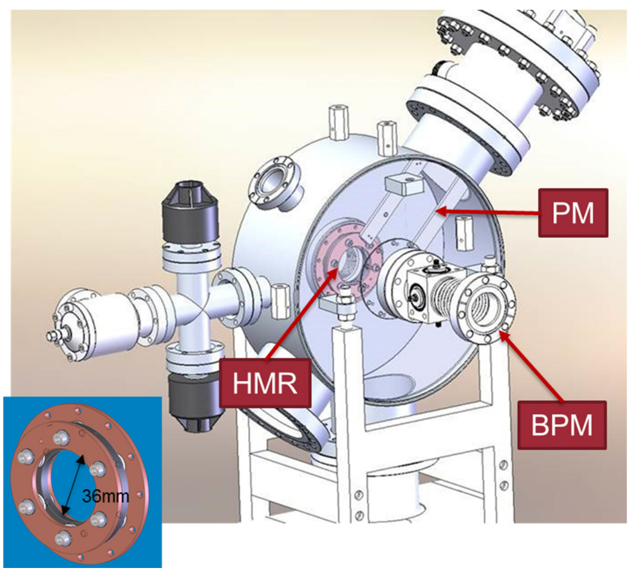

Figure 9: Room-temperature diagnostics section containing beam position (BPM) and profile (PM) monitors and halo monitoring ring (HMR, insert).

Low-loss Detection for SRF Performance

The machine protection system needs to function not only at a fast time scale to stop acute beam loss, but also at slow time scales to mitigate small, chronic beam loss (Table 2). Experience at SNS indicates correlation between chronic beam loss and performance degradation of the SRF cavities. Figure 10 shows the thermometry sensors installed in the cryomodule to detect beam loss at 1 W/m level at a response time scale of seconds.

Multi-charge-state, Multi-Species Diagnostics

To reach the design high beam intensity, FRIB driver linac simultaneously accelerates up to five charge states ($^{238}U^{76+}$, $^{238}U^{77+}$, $^{238}U^{78+}$, $^{238}U^{79+}$, $^{238}U^{80+}$) with a momentum spread of ~±2.6%. FRIB upgrade requires simultaneous acceleration of both heavy and light ions (e.g. $^{238}U^{79+}$, H_3^+). Beam instrumentation must accommodate wide momentum aperture in particular at the high-dispersion folding segments (Fig. 11) and residual dispersion under normal and fault conditions, and ensure tightly focused beam spot (~ 1 mm) at locations of charge stripper and the production target.

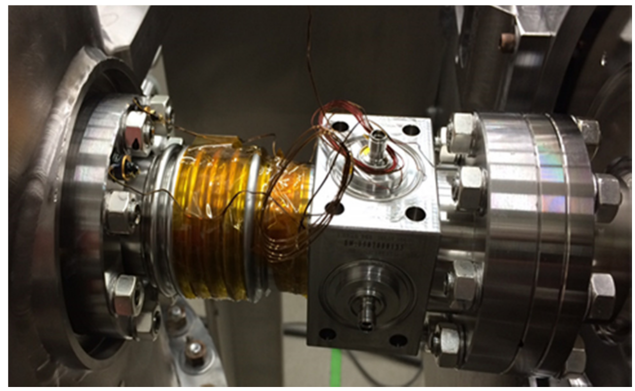
Figure 10: Cold BPM and thermometry sensors (resistance temperature detectors, RTDs) installed along the beam line in the FRIB SRF cryomodule.

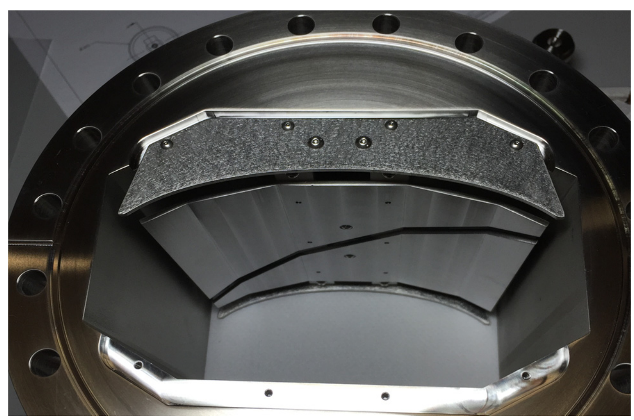
Figure 11: Elliptical beam position monitor for multi-charge state beam in Folding Segment dispersive section. The 150 mm wide horizontal aperture accommodates up to five uranium beam charge states over 80 mm spread.

High-power Charge Selection and Scraping

Charge selection requires up to several tens of kW of heavy ion beams of unwanted charge states to be scraped at energy near 18 MeV/u. Rotating scrapers of graphite discs, a scaled-down version of the FRIB production target [15], will be used to withstand the power.

Target Beam Position Monitoring

Beam instrumentation must withstand the high radiation environment near the production target monitoring the 400 kW heavy ion beam focusing onto a spot of 1 mm diameter

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striking the production target [15]. Figure 12 shows the radiation-cooled, multi-slice graphite target of 30 cm diameter that rotates at 5000 rpm. Target diagnostics include optical thermal imaging and beam position monitoring. Shielding is carefully designed to block the "back shine" from the target ensuring proper operation of accelerator magnets and diagnostics for beam delivery.

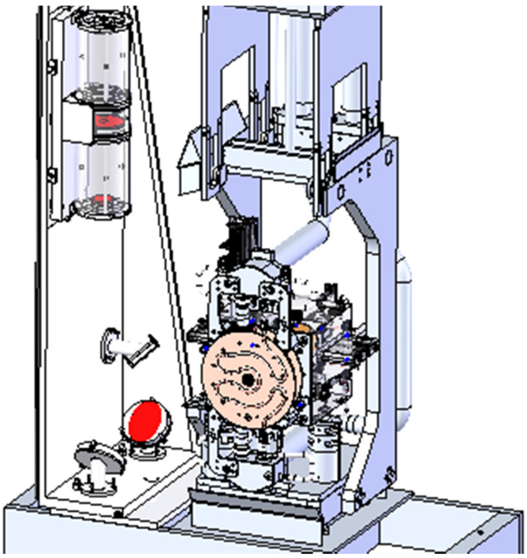

Figure 12: Schematics of the production target insert. The thermal imaging optics is located on the left side.

Folded Accelerator Geometry Complications

The folded accelerator lattice causes radiation cross-talk issue from high-energy linac sections that confound low-energy beam loss measurements. Local shielding is likely needed to raise signal-to-noise ratio in low-energy section of the driver linac. Sensitive loss monitors will be used during tuning of the low energy section upon staged beam commissioning and diagnose.

Beam Structure and Dynamic Range

Both continuous-wave (CW) and pulsed beams are to be accelerated in the linac. The CW beam is notched with beam gaps of 50 μs at 100 Hz to facilitate diagnostics. Beam instrumentation is designed to function over wide intensity and charge-state range from 50 eμA and 50 μs beam pulses during commissioning to full intensity (e.g. 700 eμA ^{238}U) CW beams [16].

User Cycle Flexibility

Table 3 shows user requested operational weeks per year during commissioning and initial operations [17]. The linac must be easily tuneable to allow fast user cycle change. The ion source is located at surface level with adequate instrumentation in the LEBT (Fig. 13) to allow easy maintenance and fast tuning.

Table 3: User Requested Operational Weeks Per Year for Various Types of Primary Beams Upon Operation Start

Beam type	Needed date	Weeks/year
^{36}Ar, ^{86}Kr	Commissioning	As needed
^{238}U	Starting year 1	12
^{48}Ca	Starting year 1	7
^{78}Kr	Starting year 1	3
^{124}Xe	Starting year 1	2
^{18}O, ^{16}O	Starting year 1	2
^{82}Se	Starting year 2	6
^{92}Mo	Starting year 2	3
^{58}Ni, ^{22}Ne, ^{64}Ni	Starting year 2	3

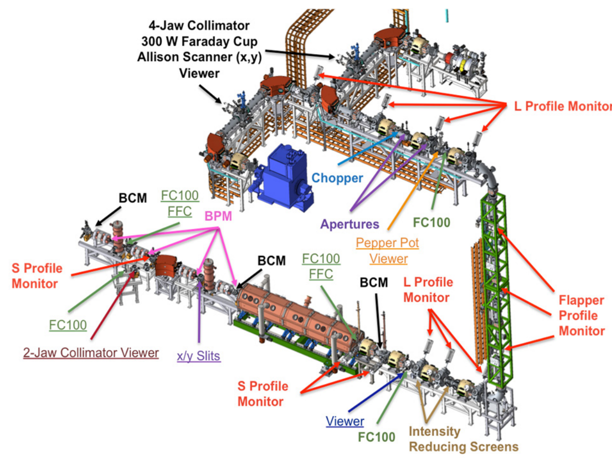

Figure 13: Front End beam instrumentation and diagnostics containing 12 types of 49 devices, as partly listed in Table 3.

Automated Tuning for Machine Availability

As a national user facility with over 1400 registered users, FRIB accelerator must operate with high availability (~ 90%) and reliability. Automated lattice tuning assisted by virtual accelerator modelling is being developed taking advantage of flexibility of the SRF linac. Table 4 shows the main diagnostics devices to be installed in the linac to facilitate operational availability [16]. In addition to permanently installed devices, a temporary diagnostics station is being prepared for staged beam commissioning starting from the first SRF linac section. As shown in Fig. 14, this temporary station contains two timing calibrated beam position monitors, a wire scanner, a Silicon detector, a bunch length monitor, halo monitor rings, and a beam current monitor.

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Table 4: Main Permanently Installed Diagnostic Devices (560 in total) Located in the Front End (FE), Linear Segments 1, 2, and 3 (LS), and Folding Segments and Beam Delivery Segment (FS) of the FRIB Driver Linac

Device	FE	LS	FS	Total
Position monitor, BPM	4	103	43	150
Current monitor, ACCT	3		9	12
Current monitor, DCCT	1			1
Loss monitor, halo ring		17		17
Loss monitor, ion chamber		15	32	47
Loss monitor, neutron detector	1	22	1	24
Loss monitor, thermometry		192	48	240
Profile monitors	14	6	22	42
Bunch shape monitor			1	1
Allison emittance scanner	2			2
Pepper pot emittance meter	1			1
Faraday Cup; fast Faraday Cup	7, 2			9
Viewer plate	5			5
Selecting slits, 300 W	5			5
Collimation aperture, 100 W	2			2
Intensity reducing screen	2			2

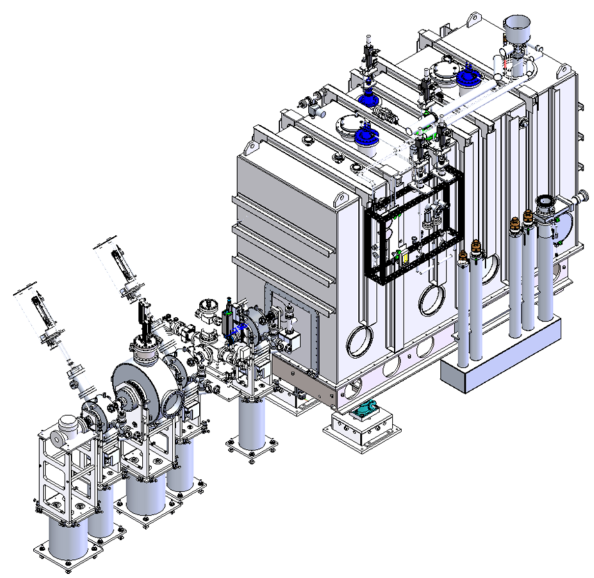

Figure 14: The temporary diagnostics station to be used for staged beam commissioning of the SRF linac containing two timing calibrated beam position monitors, a wire scanner, a Silicon detector, a bunch length monitor, halo monitor rings, and a beam current monitor.

TEAM AND COLLABORATIONS

FRIB accelerator is fortunate to attract many excellent technical leaders and subject matter experts worldwide with cultural background of more than 20 countries. At the peak of construction, a total of about 160 full-time-equivalent staff manage technical aspects of the procurements and perform in-house work. Efforts are made to form FRIB culture with project discipline, resource sharing (Fig. 15), and rigorous peer reviews.

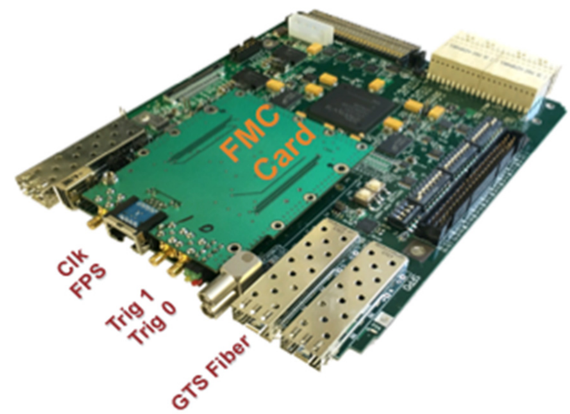

Figure 15: The FRIB general-purpose digital board (FGPDB) shared by several systems, including machine protection, controls, diagnostics, and low-level RF.

FRIB accelerator systems design and construction have been facilitated under work-for-others agreements with many DOE-SC national laboratories including ANL, BNL, FNAL, JLab, LANL, LBNL, ORNL, and SLAC, and in collaboration with institutes worldwide including BINP, KEK, IHEP, IMP, INFN, INR, RIKEN, TRIUMF, and Tsinghua University. The cryogenic system is developed in collaboration with JLab. The recent experience gained from design of the cryogenic system for the JLab 12 GeV upgrade is used in the design of both the refrigerator cold box and the compression system. The liquid lithium charge stripping system is developed in collaboration with ANL. BNL collaborated on the development of the alternative helium gas stripper. The SRF development benefited greatly from the expertise of the low-β SRF community. FRIB has been collaborating with INFN on resonator development and with ANL on RF coupler and tuner development, and is assisted by JLAB on cryomodule design, by KEK on superconducting solenoids, and by FNAL and JLab on cavity treatments. FRIB is collaborating with LBNL on the development of VENUS-type ECR ion sources.

Experienced industrial suppliers worldwide have been assisting FRIB accelerator construction following established procurement processes.

FUTURE PERSPECTIVE

Following beam commissioning of the FRIB Front End, early operation is expected to start in 2018 with ECR ion source user program developments. As rest of the accelerator is built and installed, project construction completion (CD-4) is expected in 2022.

After reaching the project CD-4 milestone for routine operations as a user facility, we expect to steadily increase the beam power and raise the machine availability, reliability and tuneability to the full design capability in 4 years. Beam power ramp up consists of three elements: fine-tuning of components dedicated for high power beam operation, including the high power ion source, liquid lithium charge stripper, and high power charge selector;

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tuning for multi-charge-state beam acceleration; and beam quality improvement, including beam loss mitigation.

Science-driven upgrade plans include doubling the linac output energy by filling the vacant slots in the linac tunnel with β_0=0.65 cryomodules, simultaneous heavy ion and light ion acceleration, an ISOL (Isotope Separation On-Line) option for rare isotope production, and storage rings for rare isotopes. Design studies and prototyping efforts for the energy upgrade have been launched.

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REFERENCES

[1] J. Galambos, in *Proc. PAC'13*, Pasadena, 2013, p. 1443.
[2] K. Hasegawa *et al.,* in *Proc. IPAC'13*, Shanghai, 2013, p. 3830.
[3] M. Seidel *et al.,* in *Proc. IPAC'10*, Kyoto, 2010, p. 1309.
[4] R.W. Garnett *et al.,* in *Proc. PAC'11*, New York, 2011, p. 2107.
[5] J. Wei *et al.,* in *Proc. LINAC'12*, Tel-Aviv, 2012, p. 417.
[6] E. Pozdeyev *et al.*, in *Proc. PAC'13*, Pasadena, 2013, p. 734.
[7] J. Wei, *Rev. Mod. Phys.* 75, 2003, p.1383.
[8] G. Machicoane *et al.*, in *Proc. PAC'09*, Vancouver, 2009, p. 432
[9] F. Casagrande, presented at IPAC'15, Richmond, 2015, Talk THYB1.
[10] V. Ganni *et al.*, *CEC-ICMC 59*, 323 (2013).
[11] T. Xu *et al.,* in *Proc. LINAC'16*, East Lansing, 2016, p. 673.
[12] A. Facco *et al.*, *Proc. IPAC'12*, New Orleans, 2012, p. 61.
[13] J. Nolen *et al.,* FRIB Report FRIB-T30705-TD000450, 2013.
[14] M. Ikegami, in *Proc. IPAC'15*, Richmond, 2015, p.2418.
[15] F. Pellemoine, *Nucl. Instrum. Meth.* B317, 369 (2013).
[16] S. Lidia *et al.*, in *Proc. IBIC '15*, Melbourne, 2015, p. 226.
[17] T. Glasmacher, presented at LINAC'16, East Lansing, 2016, Paper FR3A02.