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FRIB TRANSITION TO USER OPERATIONS, POWER RAMP UP, AND UPGRADE PERSPECTIVES*

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Abstract

After project completion on scope, on cost, and ahead of schedule, the Facility for Rare Isotope Beams began operations for scientific users in May of 2022. This paper reports on FRIB status and progress, emphasizing complexity, challenges, resolutions and lessons learned from construction to the power ramp-up, along with progress with accelerator improvements and R&D for the upgrades.

INTRODUCTION

The Facility for Rare Isotope Beam (FRIB) project was completed in April 2022, ahead of the baseline schedule established about 10 years ago (Table 1). In December 2021, the project commissioning was completed with acceleration of heavy ions to energies above 200 MeV/nucleon (MeV/u) using 324 superconducting radiofrequency resonators housed in 46 cryomodules, striking a target to produce rare isotope beams [1].

The scientific user program started in May 2022. During the first 12 months of user operations, the FRIB accelerator complex delivered 5250 beam hours, including 1528 hours to nine science experiments conducted with primary beams of ^{36}Ar, ^{48}Ca, ^{70}Zn, ^{82}Se, ^{124}Xe, and ^{198}Pt at beam energies >200 MeV/u; 2724 hours for beam developments, studies, and tuning; and 998 hours to industrial users and non-scientific programs using the FRIB Single Event Effect (FSEE) beam line. More than 200 rare isotope beams were produced by the FRIB target and delivered to user stations (Fig. 1). The facility availability is 92%.

Table 1: FRIB Project Major Milestones

Milestone	Date
DOE & MSU cooperative agreement	Jun. 2009
CD-1: preferred alternatives decided	Sep. 2010
CD-2: performance baseline	Aug. 2013
CD-3a: start of civil construction & long lead procurements	Aug. 2013
CD-3b: start of technical construction	Aug. 2014
CD-4: project completion	Apr. 2022
Start of user experiments at 1 kW	May 2022
User experiments at 5 kW primary beam	Feb. 2023

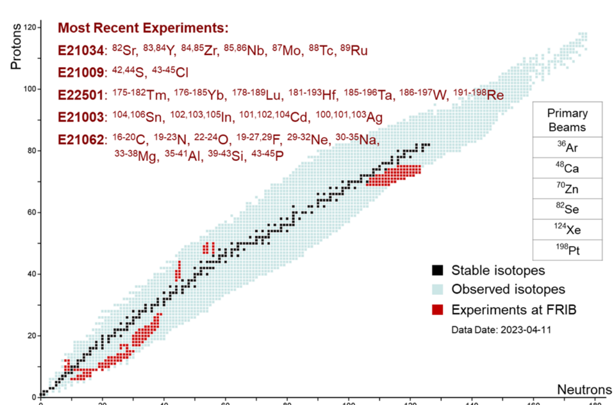

Figure 1: Rare isotopes delivered to FRIB scientific users.

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The ramp-up to the ultimate design beam power of 400 kW is planned over a six-year period (Fig. 2); 1 kW was delivered for initial user runs in 2022, and 5 kW was delivered as of February 2023. In preparation for high-power operations, a liquid lithium charge stripper was used to strip the primary beams [2], and multiple charge states were accelerated simultaneously [3].

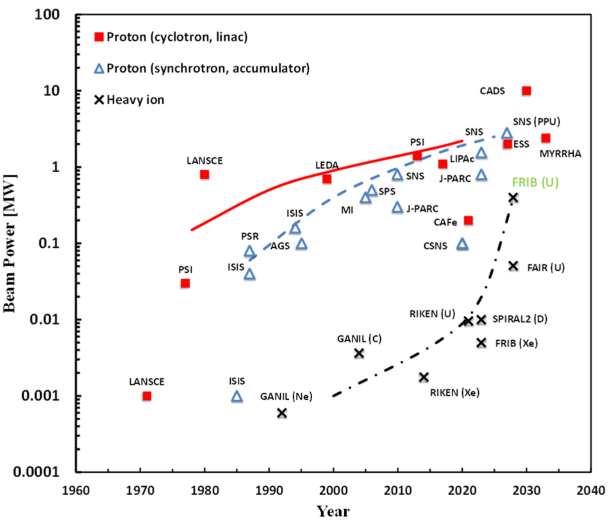

Figure 2: Beam power on target as a function of time for existing (as of May 2023) and planned power-frontier accelerator facilities.

COMPLEXITY AND LESSONS LEARNED

Comparing with proton-based facilities (Fig. 2), lower-energy heavy-ion based facilities face additional challenges including high power deposition density and high radiation damage. Most challenges were already understood before the project began; additional complexities became clear during facility commissioning and early operation.

Large-scale Low-β Superconducting Linac

To cover a wide energy range of acceleration from 0.5 MeV/u to above 200 MeV/u, the FRIB driver linac uses 324 low-β superconducting radio-frequency (SRF) cavities for β = 0.041, 0.085, 0.29, and 0.53 in 46 cryomodules [4]. An innovative "bottom-up" cryomodule design was developed with the resonators and solenoids supported from the bottom and the cryogenic headers suspended from the top for vibration isolation [5]. An integrated design of the cryogenic refrigeration, distribution, and cryomodule systems facilitated smooth fabrication, assembly, commissioning, and maintenance [6].

Figure 3 shows the maximum accelerating gradient (E_{acc}) reached during linac commissioning. The average E_{acc} per cryomodule exceeded the design goal [5]. The original design operating temperature was 2 K for all cavities; however, since the β = 0.041 and 0.085 quarter wave resonator (QWR) cryomodules (80.5 MHz) can be stably operated at 4.5 K with no microphonics issues [7], we are operating the QWR cryomodules (Linac Segment 1) at 4.5 K. Both β = 0.29 and β = 0.53 half wave resonator (HWR) cryomodules (Linac Segment 2 and 3) at 322 MHz are operated at 2 K. The Q_0 for the HWRs at 2 K is more than 3 times above the design goal, with no observable degradation between the Dewar test, the cryomodule bunker test, and linac commissioning [5]. Amplitude and phase stabilities meet the design goal, peak-to-peak ±1% and ±1° with ample margins [5], which implies stable control of microphonics and other fluctuations by the RF control system and the tuners. Note that FRIB cavities are equipped with only slow tuners, actuated by stepper motors for the QWRs and a pneumatic system for the HWRs.

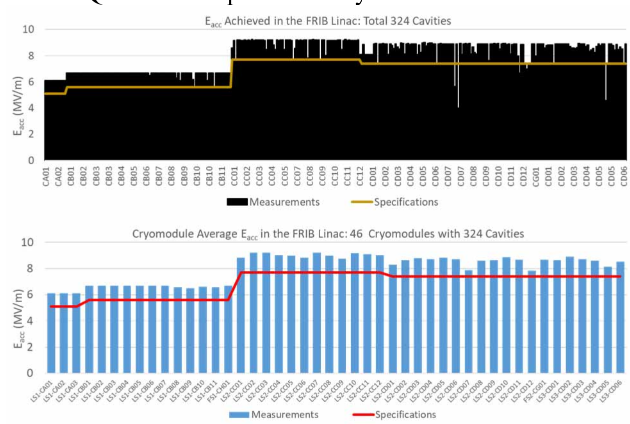

Figure 3: E_{acc} reached in the linac during commissioning for each cavity (top) and averaged over each cryomodule (bottom).

High-power Beam-intercepting Devices

High-power beam-intercepting devices that may limit the attainable beam power of the facility include the charge stripper, the charge selector, the rare-isotope production target, and the beam dump. At this stage, a rotating carbon foil is used for charge stripping of lighter ions, and a liquid lithium film [2] is used for stripping heavier ions for high-power operations (Fig. 4). Moveable water-cooled slits are used to remove unwanted charge states after stripping. A single-slice graphite target upstream of a static beam dump with a 6° incident angle are used for rare isotope production (Fig. 5). The target and dump are both water-cooled; about 22% of the beam power is deposited in the target, with the remained collected in the beam dump. Phased upgrades are planned for the charge selector, target, and beam dump during the beam power ramp-up.

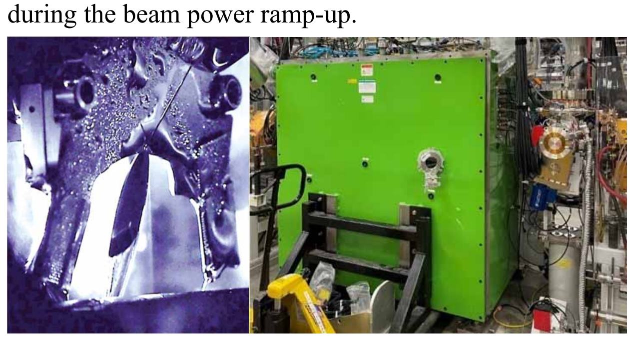

Figure 4: Charge stripper systems: liquid lithium film (left) inside the secondary containment vessel (right, green box) in the FRIB beam line upstream of the rotating carbon foil system (right, on the post).

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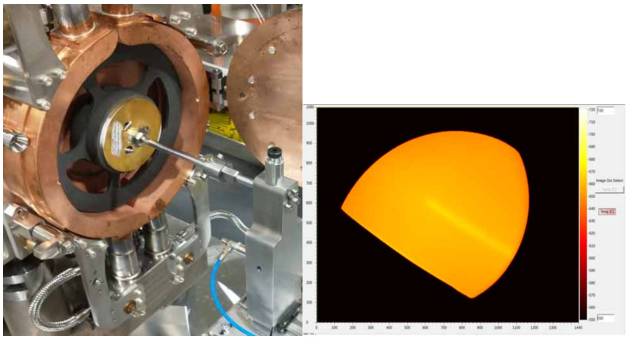

Figure 5: Left: single-slice graphite target inside the water-cooled copper enclosure. Right: thermal image of a 5 kW, 240 MeV/u ^{64}Zn beam on the target rotating at 500 revolutions per minute.

Multiple Charge-State Acceleration

The FRIB driver linac was designed to accept multiple charge states after stripping and simultaneously accelerate them to deliver up to 400 kW to the isotope production target. Simultaneous acceleration of multi-charge-state heavy ion beams resolves two significant issues in high-power accelerators: (1) delivery of high power to the target with limited beam intensity from the ion source and (2) minimizing the power deposition on the charge selector slits after the stripper. The slits intercept the unwanted charge states to avoid uncontrolled downstream beam losses. With multi-charge-state acceleration, the beam losses on the slits are significantly reduced, simplifying the radiation shielding of the charge selector, allowing hands-on maintenance, and reducing radio-activation of air and cooling water. Simultaneous acceleration of a 3-charge-state Xe beam was validated during linac commissioning with detailed measurements [3].

Since the early days of linac operation, we routinely use multi-charge-state acceleration to minimize the power deposition on the selector slits for ^{124}Xe and ^{198}Pt beams. The acceleration of a 3 charge-state platinum beam was especially beneficial due to the limited intensity from the existing ion source for delivery of a 2 kW. However, tuning of multiple charge states in the linac brings additional challenges. Tuning for multiple charge states [8] includes procedures to set up achromatic bends in the folding segments (FS1, FS2) and beam delivery system (BDS):

- Align the transverse position of the central charge state q_0 in each FS1, FS2, and BDS quadrupole by varying fields in the bending magnets.
- Tune charge states $q_0 - 1$and $q_0 + 1$ to the same transverse position after the bend by varying quadrupole settings in the achromatic region with sextupoles off. Neighbouring charge states have a transverse offset from the central charge state after the 180° bend due to the second-order effects, which are proportional to the square of the charge spread.
- Tune sextupoles to minimize the position offsets between all charge states in 6D phase space.

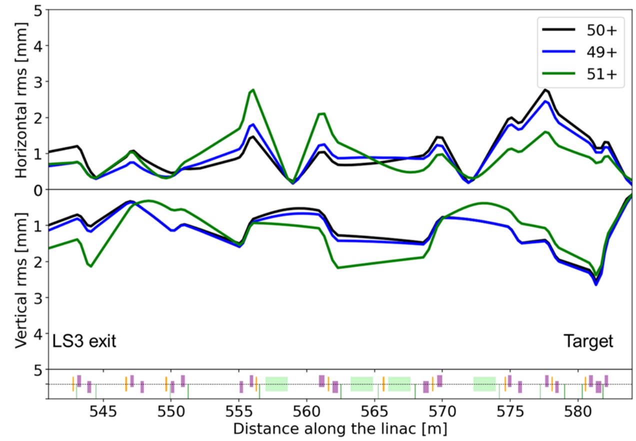

Figure 6: Transverse beam envelopes of 3 charge states of ^{124}Xe in BDS (reconstructed from measured Courant-Snyder parameters) after quadrupole tuning.

To match multiple charge state beams to the target, we measure Courant-Snyder parameters for each charge state and adjust the quadrupole fields to obtain a beam waist at the target with an rms radius of 0.25 mm (Fig. 6).

Tuning of a 3-charge-state beam is facilitated by using the central charge state to align the beam to the centers of the quadrupoles and phase all of the cavities. Tuning of a 2-charge-state beam such as $^{64}Zn^{28+,29+}$ is more challenging due to the absence of the central charge state. Theoretically, the charge spread for the Zn beam (2.9%), is smaller than that of a 3-charge-state Xe beam (4%). In practice, scaling of the optics from 28+ to 28.5+ is imperfect due to misalignments. However, we applied steps similar to the Xe beam case to Zn and achieved no-loss beam tuning for the 2-charge-state Zn beam. Cavity phases for Zn were set for the lowest charge state (28+). The beam power deposition onto the slits drops from 420 W to 90 W for a 5 kW ^{64}Zn beam with 2-charge-state acceleration. Multi-charge-state acceleration is now well-established for operations with even and odd numbers of charge states and with both stripper systems.

Advanced Rare Isotope Separator

The Advanced Rare Isotope Separator (ARIS) is designed to collect nearly 100% of the fragments produced at the target and select individual isotopes for delivery to the desired experimental station [9, 10]. This is accomplished with up to three stages of fragment separation using in-flight rigidity selection and selective energy loss in profiled degraders (Fig. 7). The profiled degrader in the pre-separator compresses the momentum/charge acceptance from 10% to 3% for transport to the user station [11]. This is a novel feature, as is the combination of vertical and horizontal separation, which allows momentum compression in the vertical plane and preserves good phase space for gas stopping in the horizontal plane. ARIS is optically corrected to third order and can operate over a rigidity range of 1 to 8 T·m. ARIS performance is in good agreement with simulations done with LISE++ [12].

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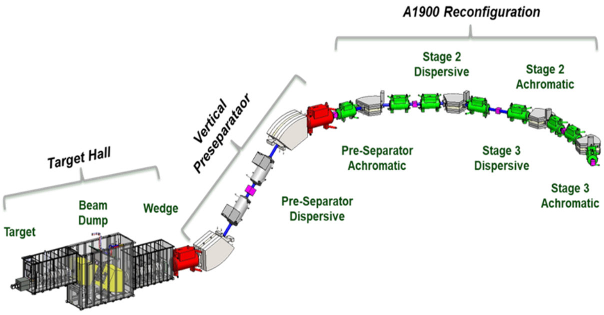

Figure 7: Layout of ARIS.

Legacy System Interfacing and Integration

New construction of the FRIB project includes the driver linac, the target system, and the vertical pre-separator. The rest of ARIS (Fig. 7) and the transfer lines to user stations are reconfigured with aged magnets cooled by legacy cryogenic liquefaction systems. The limited aperture of reconfigured the beam lines reduces the transmission rate. The field errors of these legacy magnets are uncompensated and the reliability of the legacy systems is poor. Significant system improvements are in progress.

Multi-layered Machine Protection

Machine protection is challenging for high power, low energy heavy ions beams due to the short range and high power deposition density. To address this, a multi-layer, multi-time-scale approach is used (Table 2): a fast protection system (FPS) based on signals from e.g. the differential beam current monitor to prevent damage from acute beam loss by quickly inhibiting the beam; a run permit system (RPS1) to continuously query the machine state and provide permission to operate with beam; and a slower but highly sensitive system (RPS2) to prevent slow degradation of cavities due to low beam losses [13].

Table 2: Multi-layered Machine Protection for FRIB

System	Time	Detection	Mitigation
FPS	~35 µs	LLRF controller Dipole current monitor Differential BCM Ion chamber monitor Halo monitor ring Fast neutron detector Differential BPM	LEBT bend electro-static deflector
RPS1	~100 ms	Vacuum status Cryomodule status Non-dipole PS Quench signal	As above; ECR source HV
RPS2	>1 s	Thermo-sensor Cryo. heater power	As above

The FPS mitigates the stray beam within the required 35 µs time duration. The halo monitor rings installed between the cryomodules were highly sensitive to both ion and electron signals at nA level. The fast thermometry sensors installed inside the cryomodule detected beam loss induced heating at 0.1 K level. Devices interlocking includes current monitoring modules for critical magnet power supply inhibition and motor speeds of rotational beam intercepting devices.

Accelerator Construction: Lessons Learned

Lessons from FRIB technical design, construction, and commissioning include [1]

- Recruit worldwide and retains key subject matter experts (own the best people);
- Develop and mature key technologies in time to support the project schedule (own the technology);
- Align interests for infrastructure investment to support key construction steps and future research (align interests, invest in infrastructure);
- Closely collaborate with US national labs and worldwide partners for knowledge transfer and project support; rigorously manage collaboration (collaborate without losing control);
- Strategically facilitate phased commissioning to stagger the work force, validate the design principles, feedback on improvements, and meet the schedule (phase the scope for optimization);
- Conduct rigorous external reviews, inviting the best experts to critique the work (review rigorously);
- Engage with industrial providers via exchange visits, weekly meetings, and extended stays (intimately engage vendors);
- The original “turn-key” approach to procure the large-scale cryogenic helium system from industry exposed the project to serious risks in budget and scope (avoid “turn-key” on large-scale cryogenics);
- Early shortcuts taken in QWR sub-component validation was costly (avoid shortcuts);
- Shared vacuum vessels in the target area complicate maintenance (consider maintenance);
- Lack of diagnostics and correctors in the 3D geometric layout complicates fragment separation (ensure adequate diagnostics and adjustments);
- Conduct systematic R&D for novel technology, e.g. bottom-up cryomodule (systematic R&D);
- Thorough testing is needed for all major technical equipment, e.g. SRF sub-components, cryomodules, superconducting magnets (test thoroughly);
- Pro-actively facilitate critical system validation, e.g. for liquid Li stripper (facilitate critical validation).

USER OPERATIONS

Program Delivery

FRIB is a scientific user facility with the imperative of safe operation guided by five paradigms:

1. Operate with > 85% availability for user satisfaction;
2. Ramp up the beam power to enhance discovery opportunities;
3. Automate to increase the machine time available for science;
4. Foster an engaged user community; and

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5. Deliver opportunities for all areas of science enabled by FRIB.

FRIB is on track, annually delivering 4400 scheduled hours for scientific programs at above 83% availability. Additionally, FRIB plans to offer about 2000 hours annually for industrial users and other programs with the FSEE beam line.

Down Time, Performance, and Reliability

As shown in Fig. 8, the leading causes of accelerator down time over 6 months were due to legacy cryogenic and magnet system failures. Other major down periods were associated with known ancillary system issues to be improved and non-technical procedural issues.

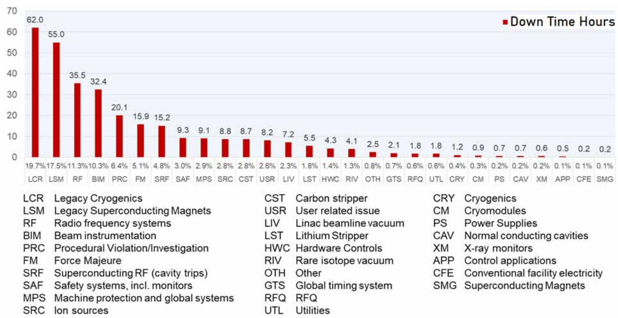

Figure 8: Down time by category for facility operations during between October 2022 and March 2023.

Figure 9 shows the maximum gradient (E_{acc}) for all of the linac cavities as of May 2023. Four out of 324 cavities are not being used for operations; recovery of 3 of these cavities is planned in the 2023 maintenance period via replacement of a failed fundamental power coupler (FPC) cold cathode gauge and removal of contamination from the pneumatic tuner gas lines for 2 cavities. A 4th cavity is unused because the pneumatic tuner operating pressure is close to the lower limit of the gas return line.

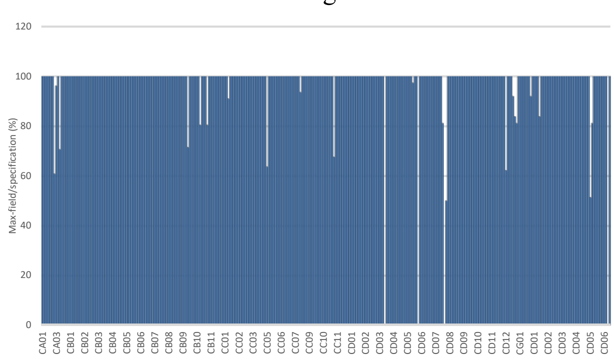

Figure 9: Maximum E_{acc} for each cavity as of May 2023.

We plan to swap 1 or 2 cryomodules per year to maintain reliable FRIB operations. This plan will facilitate repair of broken components or recovery of cavity performance degradation, as such degradation may happen in long-term operation. The FRIB cryomodule and cryo-distribution systems allows for warm-up and cool-down of a single cryomodule. In addition to cryomodule swapping plans, we are developing plasma processing, which has been found to be effective for improving SRF cavity performance in-situ, e.g. in the SNS linac [14]. A development effort is needed because FRIB uses coaxial cavities with relatively weak coupling for continuous-wave (CW) operation, leading to a large cavity-coupler mismatch at room temperature.

Automation of linac operation helps to reduce the time needed for turn-on, tuning, and turn-off and hence allows more time for user experiments and beam development. One example is compensation of the cavity dynamic heat loads by cryomodule internal heaters, which allows for fast adjustment of the cavity fields for different beam species [15]. Heater compensation is very helpful for FSEE experiments as well, as frequent access to the user station in the linac tunnel is needed for sample changes.

Beam Power Ramp Up

Present operation is with a primary beam power of 5 kW on the target. Table 3 outlines the power ramp-up stages and associated system improvements: operation at 10 kW is planned by the end of 2023 (Epoch 1). In forthcoming years, the power will be progressively increased by raising the beam current as operational experience is accumulated, aiming for 400 kW in 2028 (Epoch 6 and Fig. 1). To facilitate a safe power ramp up, several major systems improvements will be deployed in phases, including beam interception systems, personnel protection systems, and radio-activation control. The power ramp-up with constant beam energy without the need for higher cavity fields.

Table 3: Phased Deployment of System Improvements for the Beam Power Ramp Up

EPOCH	1	2		3		4		5		6
Beam power	10 kW	20 kW		50 kW		100 kW		200 kW		400 kW
ARTEMIS, light ion beams from gas	■	■	■	■	■	■	■			
ARTEMIS, heavy ion beams from metal	■	■	■							
High power ECR, gas beams	■	■	■	■	■	■	■	■	■	■
High power ECR, metal beams	■	■	■	■	■	■	■	■	■	■
Intermediate power charge selector in FS1				■	■					
High power charge selector in FS1						■	■	■	■	■
Post-stripper chicane						■	■	■	■	■
Additional beam collimation in FS2, BDS						■	■	■	■	■
Dual charge state heavy ions upstream of the stripper (velocity equalizer)								■	■	■
Rotatable target, 1 slice	■	■	■	■						
Rotatable target, multi-slice					■	■	■	■	■	■
Post-target shield						■	■	■	■	■
Beam dump 6° slant (S-shape)	■	■								
Beam dump 6° slant (S-shape), better cooling			■							
Rotatable beam dump, 1-mm wall				■	■	■	■	■	■	
Rotatable beam dump, 0.5-mm wall										■
Medium power ladder wedge system with adjustable slits (hands-on)	■	■	■	■						
High power wedge system (remote handling)					■	■	■	■	■	■
PPS upgrade with fast ionization chambers	■	■	■	■	■	■	■	■	■	■

IMPROVEMENTS AND INVESTMENTS

Accelerator improvement projects and capital equipment investments (Table 4), production of operational spares and standby systems, and R&D (Table 5) will play an essential role in updating aged legacy systems in the laboratory that predate the FRIB project; maintaining high availability during the beam power ramp up; addressing new operational complexity; and maximizing the productivity of the facility to meet evolving user demands.

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Table 4: Examples of FRIB Accelerator Improvement Projects (AIP) and Capital Equipment (CE) Investments (SC: superconducting; ReA: reaccelerator.)

Helium preservation & cryogenics legacy mitigation
Next-generation coil dominated SC magnets
Next-generation fragment separator beam dump
Improved lithium pump circuit
Intermediate power charge selector
Optimized shielding in fragment separator
Legacy cryogenics system: nitrogen savings plan
Variable degrader wedge system
β = 0.65 buncher cryomodule
ARIS corrector magnets
Feedback system for charge stripper
ReA beam cleaning chopper and power supply
Machine Protection System: loss detection
High intensity multiple charge state equipment
Secondary beam line controls legacy digital hygiene
High power secondary beam diagnostics
Beam interception device utility activation control
Beam line for third ion source

Table 5: Examples of Planned FRIB Accelerator R&D

High power targetry and material
Model-based automatic tuning
Secondary beam efficiency optimization
Advanced technology for liquid lithium stripper
Detectors for high-rate particle identification/tracking
ARIS automation
Cryogenic technology and infrastructure
SRF technology and infrastructure
SC magnets for heavy-ion spectrometry
Fast beam loss detection and protection
Instrumentation for high intensity beam diagnostics
Physics of multi-charge-state ion beams

SRF technology and infrastructure development is being conducted to support sustainable operation of the FRIB linac and prepare for preventive/proactive maintenance. Highlights of recent achievements include

- Plasma processing [16]: a reduction in field emission (FE) was observed in several FRIB β = 0.085 QWRs after processing with the FPC using a neon-oxygen plasma (Fig. 10). A higher-order mode (HOM) was used to reduce the cavity-FPC mismatch.
- Optimization for 4 K operation: with a low-temperature (120 °C) bake-out (LTB) after buffered chemical polishing (BCP), the quality factor of β = 0.085 QWRs at 4.3 K is almost doubled, allowing us to reach the 2 K design goal at 4.3 K (Fig. 11).
- High-field performance improvement for HWRs [17]: production β = 0.53 HWRs showed high-field *Q*-slope (HFQS) starting at E_{acc} ~ 8 MV/m after BCP. Electro-polishing (EP) and LTB can mitigate HFQS and allow for operation at higher gradient with a tolerable cryogenic load. An initial test using the new FRIB EP station showed improved performance (Fig. 12), similar to higher-frequency elliptical cavities.
- In-situ swapping of FPC RF windows [18]: a preliminary test was done in a setup which simulates the cryomodule environment in the linac (Fig. 13). The cavity was cold-tested before and after the RF window swap. There was no change in FE X-rays up to E_{acc} = 9 MV/m (E_{peak} ~ 30 MV/m).

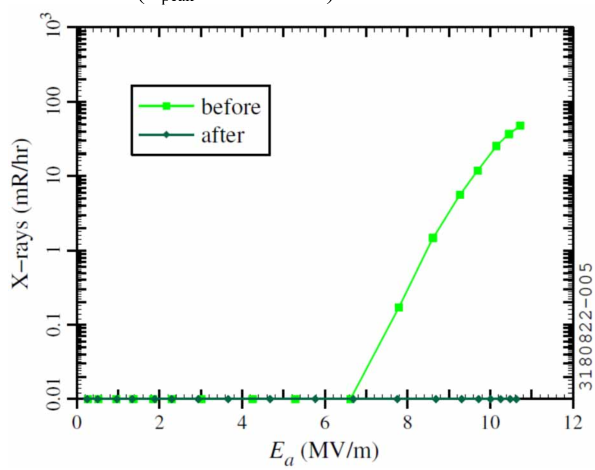

Figure 10: Example of FE X-rays reduction after plasma processing of a FRIB β = 0.085 QWR with the FPC.

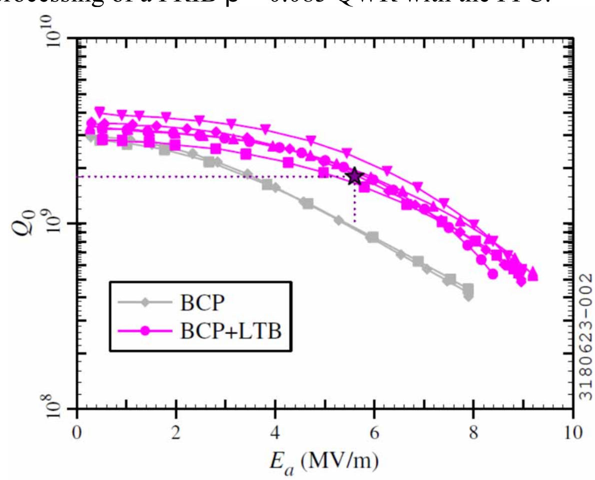

Figure 11: Measured quality factors at 4.3 K for FRIB β = 0.085 QWRs with BCP (gray, 2 cases) or BCP + LTB (magenta, 5 cases) LTB.

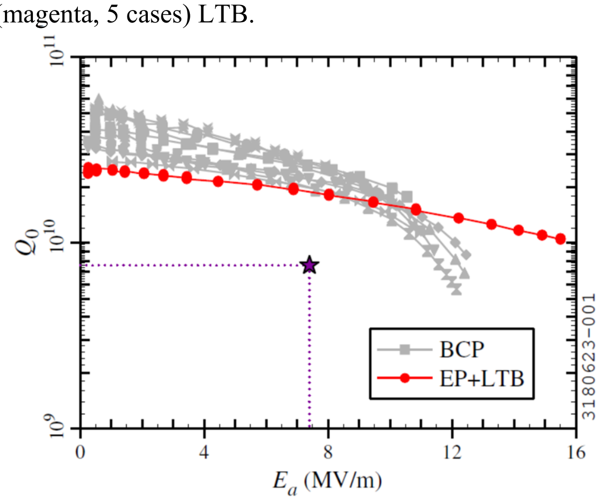

Figure 12: Measured quality factor at 2 K for FRIB β = 0.53 HWRs with BCP (gray, 8 cavities) or EP + LTB (red).

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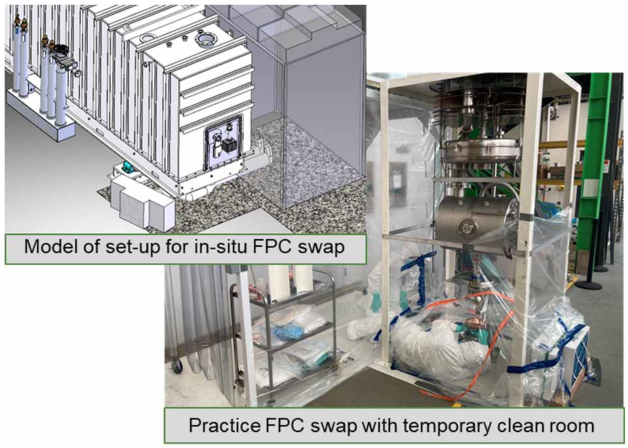

Figure 13: A special setup was developed as a mock-up for an FPC swap in the linac tunnel.

FRIB ENERGY UPGRADE

The proposed FRIB energy upgrade (FRIB400) would increase the on-target energy from 200 MeV/u to 400 MeV/u for uranium ion beams. The upgrade would further extend the scientific reach and discovery potential of FRIB, in alignment with the overarching intellectual challenges articulated in the 2015 Nuclear Science Advisory Committee (NSAC) Long Range Plan and the National Research Council (NRC) Decadal Study [19].

FRIB400 uses 644 MHz β = 0.65 5-cell elliptical cavities [20]. As part of the development effort, we built two unjacketed 5-cell prototype cavities. We achieved Q_0 = $3.5 \cdot 10^{10}$ at E_{acc} = 17.5 MV/m with nitrogen doping (Fig. 14), which is the first demonstration for such a cavity type [21]. The next steps for FRIB400 R&D include (1) achieving a high Q_0 in a prototype cryomodule, (2) developing subsystems such as the FPC and tuner, and (3) integrated testing of a cavity with tuner and FPC. A total of 55 cavities in 11 cryomodules are needed for FRIB400; 80 m of space in the linac tunnel are allocated for FRIB400 cryomodules (Fig. 15).

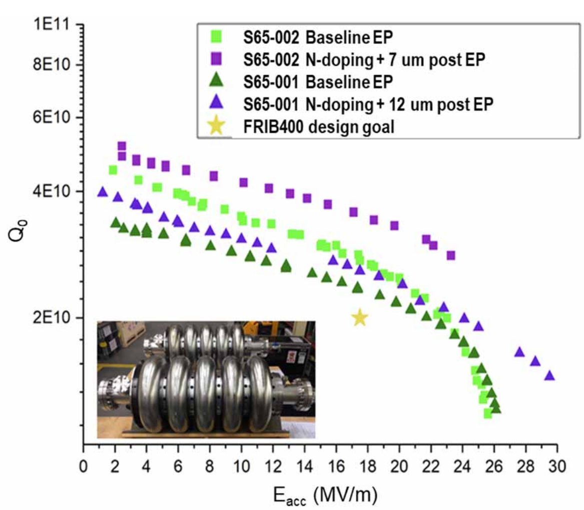

Figure 14: Measured quality factors at 2 K for 5-cell FRIB400 cavities after EP and nitrogen doping.

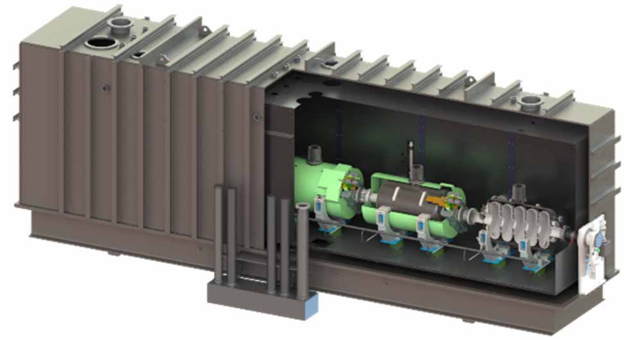

Figure 15: Preliminary FRIB400 cryomodule design.

SUMMARY

The Facility for Rare Isotope Beams has been operating for a year, delivering beams for both scientific and industrial experiments with the desired reliability and availability. The primary beam power has been steadily raised from 1 to 5 kW. Accelerator improvement projects, capital equipment investments, and R&D projects are in progress to renovating legacy systems and maintain high availability during the beam power ramp-up. R&D work for an energy upgrade is underway.

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