PROGRESS TOWARDS THE FACILITY FOR RARE ISOTOPE BEAMS*

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Abstract

The Facility for Rare Isotope Beams (FRIB) is based on a continuous-wave superconducting heavy ion linac to accelerate all the stable isotopes to above 200 MeV/u with a beam power of up to 400 kW. At an average beam power approximately two-to-three orders-of-magnitude higher than those of operating heavy-ion facilities, FRIB stands at the power frontier of the accelerator family - the first time for heavy-ion accelerators. To realize this innovative performance, superconducting RF cavities are used starting at the very low energy of 500 keV/u, and beams with multiple charge states are accelerated simultaneously. Many technological challenges specific for this linac have been tackled by the FRIB team and collaborators. Furthermore, the distinct differences from the other types of linacs at the power front must be clearly understood to make the FRIB successful. This report summarizes the technical progress made in the past years to meet these challenges.

INTRODUCTION

During the past decade, facilities like the Spallation Neutron Source (SNS), the Japan Proton Accelerator Research Complex (J-PARC) and the PSI accelerator advanced the frontier of proton beam power by an order of magnitude to 1 MW level (Fig. 1) [1]. On the other hand, facilities for heavy ions has been at the 1 kW level of average beam power. FRIB currently designed and ready for civil construction at the Michigan State University will advance the frontier of heavy-ion beam power by two-to-three orders-of-magnitude to 400 kW.

On August 1, 2013, the Department of Energy's Office of Science approved Critical Decision-2 (CD-2), Approve Performance Baseline, and Critical Decision-3a (CD-3a), Approve Start of Civil Construction and Long Lead Procurements, for the FRIB construction project. The Total Project Cost for FRIB is $730M, of which $635.5M will be provided by DOE and $94.5M will be provided by Michigan State University. The project will be completed by 2022. "When completed, FRIB will provide access to completely uncharted territory at the limits of nuclear stability, revolutionizing our understanding of the structure of nuclei as well as the origin of the elements and related astrophysical processes."

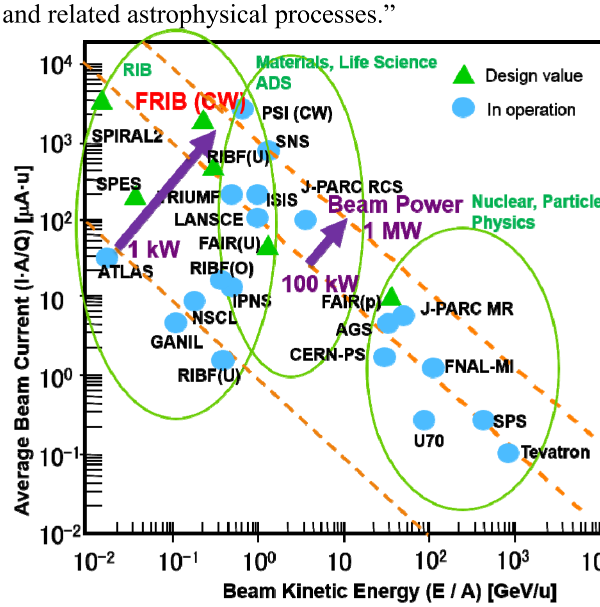

Figure 1: Average beam power as a function of the kinetic beam energy for various operating and proposed proton and heavy-ion accelerator projects.

The FRIB driver accelerator is designed to accelerate all stable ions to energies > 200 MeV/u with beam power on the target up to 400 kW (Table 1) [2]. As shown in Fig. 2, the driver accelerator consists of Electron Cyclotron Resonance (ECR) ion sources; a low energy beam transport containing a pre-buncher and electrostatic deflectors for machine protection; a Radiofrequency Quadrupole (RFQ) linac; linac segment 1 (with Quarter-wave Resonators (QWR) of β_0=0.041 and 0.085) accelerating the beam up to 20 MeV/u where the beam is stripped to higher charge states; linac segments 2 and 3 (with Half-wave Resonators (HWR) of β_0=0.29 and 0.53) accelerating the beam > 200 MeV/u; folding segments to confine the footprint and facilitate beam collimation; and a beam delivery system to transport to the target a tightly

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focused beam. The reaccelerator (ReA) consists of similar β_0=0.041 and 0.085 accelerating structures [3].

Table 1: FRIB Accelerator Primary 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	mA
Beam radius on target (90%)	0.5	mm
Driver linac beam-path length	517	m
Average uncontrolled beam loss	< 1	W/m

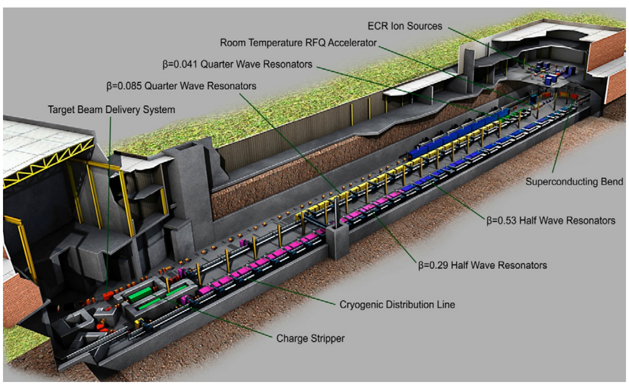

Figure 2: Layout of the FRIB driver accelerator.

DESIGN PHILOSOPHY

Full-energy linac technology is chosen to deliver primary beam that can meet the FRIB requirements of rare-isotope productivity and separation accuracy. Up to 400 kW of beams are focused to a diameter of 1 mm (90%), energy spread of 1% (95% peak-to-peak), and bunch length of < 3 ns (95%) on the target.

Superconducting (SC) technology is the energy-efficient choice for the CW linac. SC acceleration of heavy-ion beams is feasible from low energy (500 keV/u) with practically sized cavity bores by housing both the cavities and solenoids in a cryomodule. A two-gap scheme is chosen throughout the entire linac providing both efficient acceleration and focusing. Developments of digital low-level RF control and solid-state RF amplifier technologies have made individual cavity powering and control reliable and cost efficient.

Furthermore, high availability, maintainability, reliability, tunability, and upgradability are especially required for the FRIB accelerator to operate as a national scientific user facility.

- Availability: The accelerator is designed with high beam-on-target availability accommodating normal, alternative, and fault scenarios. In the normal scenario, a liquid lithium stripper is used to raise the average charge state of ^{238}U beam to 78+ for efficient acceleration. Alternatively, helium gas confined by plasma windows with differential pumping can be used to strip the ^{238}U beam to a lower average charge state of 71+. Fault scenarios include the situation when superconducting (SC) cavities underperform by up to 20% of the design gradients. Furthermore, key components and subsystems are implemented with spares and design redundancies.
- Maintainability: The average uncontrolled beam loss is limited to below 1 W/m level for all ion species from proton to uranium, to facilitate hands-on maintenance. For a proton beam at high energy, this level corresponds to an average activation of about 1 mSv/h measured at a distance of 30 cm from the beam chamber surface, 4 hours after operations shutdown. 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. To facilitate maintenance of individual cryomodules, warm interconnect sections are used between cryomodules, and U-tubes with bayonet connections are used for cryogenic distribution. Furthermore, identical, interchangeable cryomodules are used for each β type of the cavities.
- Reliability: A Machine Protection System (MPS) minimizes component damage and operational interruption caused by both acute (fast) and chronic (slow) beam losses. Upon acute beam loss, the MPS response time is 35 μs (including diagnostics, signal processing, and residual beam dumping). MPS responding to slow beam loss is complicated by low sensitivity of conventional ion chamber loss detection to low-energy heavy ions and beam-loss signal background from adjacent linac segments with which beam energies are significantly different. Beam-halo-monitor rings in the warm interconnect sections and possible thermal sensors at cold regions are planned for more sensitive loss detection [4].
- Tunability: The accelerator is designed to be easily tunable during both beam commissioning and operations. In linac segment 1, where beam transverse-phase advance is large, cold beam-position monitors (BPM) are implemented in the cryomodules. Efforts are made in establishing beam-tuning strategies based on virtual accelerators and on-line models under normal and fault conditions.
- Upgradeability: Space is reserved in linac segment 3 to house another 12 cryomodules to readily increase the energy of ^{238}U beam > 300 MeV/u. If cavities with 35% higher accelerating gradient are used in linac segments 2 and 3, the beam-on-target energy can be raised > 400 MeV/u for ^{238}U. The linac tunnel allows future expansion so that a dedicated light-ion injector can be added supporting rare isotope production using the isotope separation on-line (ISOL) method [2]. Using an RF deflector cavity and a Lambertson septum magnet, $^{3}He^{+}$ beam supplying protons to the ISOL target can share cycle with the

^{238}U beam feeding the fragmentation target; thus simultaneous users are supported. Furthermore, space is reserved to house instrumentations including non-destructive diagnostics and sub-harmonic buncher that are compatible with future user demands of experiments.

ACCELERATOR PHYSICS CHALLENGES

The FRIB accelerator design combines the complexity of heavy ion accelerators with the engineering challenges of high-power accelerators. Due to the low charge-to-mass ratio, heavy ion acceleration is often not efficient. Uncontrolled beam loss, which usually is not an issue for low-power heavy ion machines, is of primary concern for the FRIB accelerator. Comparing with high-power proton machines like the SNS linac where apertures of the elliptical SC cavities are large and beam amplitude reaches maxima in the warm locations of the focusing quadrupole magnets, the apertures of the FRIB QWR and HWR accelerating structures are small and beam amplitude reaches maxima in the cold solenoid locations inside cryomodules. Requirements on beam halo prevention, detection and mitigation are stringent.

To maximize beam intensity on the target, beams of multiple charge states are accelerated simultaneously (2 charge states of 33+ and 34+ before stripping, and 5 charge states of 76+ to 80+ after stripping for ^{238}U). Bends of second-order achromatic optics are used to fold the beams, and cavity phases are adjusted so that beams are longitudinally overlapping at the charge stripper.

Conventional charge strippers like solid carbon foils are not sustainable at the power of a ^{238}U beam at 17 MeV/u during normal operations. FRIB accelerator lattice needs to accommodate beam acceleration of different charge states resulting from various stripping methods including liquid lithium and helium gas (average charge state from 63+ to 78+ for ^{238}U). Buncher cavities of fundamental (80.5 MHz and 322 MHz) and double (161 MHz) linac RF frequencies are strategically placed in the folding segments to preserve beam quality.

Due to the short stopping distance in surrounding materials, uncontrolled beam loss of the low-energy heavy ions can cause damage to the surface of accelerating structures much more easily than a proton beam. On the other hand, due to the low level of radio-activation, losses of low-energy heavy-ion beams are difficult to detect [4]. Beam-loss detection and machine protection often rely on beam scraping. On the other hand, scraping of partially stripped ions may lead to higher ionization further complicating beam collimation and machine protection.

Due to requirements of frequent transverse focusing in the superconducting acceleration structure, solenoids are placed inside cryomodules adjacent to cavities. Alignment tolerance of these solenoids is ±1 mm under cryogenic conditions. Horizontal and vertical steerers are needed to thread the beam and correct the beam orbit.

Stringent beam-on-target requirements demand tight optical control, error control, and advanced beam diagnostics. The primary beam of 400 kW needs to be focused into a diameter of 1 mm with below ±5 mrad transverse angular spread. The desired range of beam power variation on target is 8 orders of magnitude. Orbit stability needs to be controlled at 0.1 mm level.

TECHNOLOGY CHALLENGES

Charge Stripper

The FRIB baseline design of charge stripping is a liquid lithium film moving in front of the beam at high speed of about 50 m/s. During the last couple of years the stability of a thin liquid film with the correct thickness for the FRIB stripper was achieved at ANL. Tests with a proton beam produced by the LANL LEDA source were conducted in 2013 demonstrating that power depositions similar to the FRIB uranium beams could be achieved without destroying the liquid film (Fig. 3) [5].

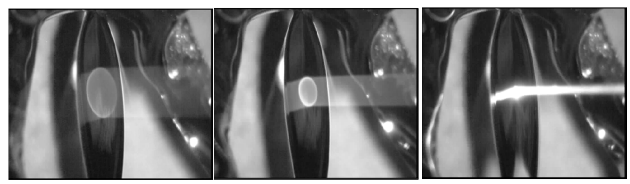

Figure 3: Liquid lithium film flowing at high speed (~ 50 m/s) intercepting a proton beam of about 60 kV at ANL. The test produced power deposition densities similar to the FRIB uranium beams.

An alternative option for the stripper consisting of a helium gas cell enclosed by plasma windows was considered. The BNL work has demonstrated that a conductance reduction of about 10 can be obtained with an aperture of 6 mm diameter [6].

Superconducting RF

FRIB driver linac is the first full-size SC linac using a large number (340) of low-β cavities. Cavity design is optimized not only for optimum performance but also for low production cost. This requirement guided the choice of the cavity geometries, materials and mechanical solutions, avoiding complicated shapes, minimizing the amount of electron beam welds, eliminating bellows, optimizing construction and surface treatment procedures. All FRIB cavities work with superfluid helium at 2 K. This innovative choice in a low-β linac allows operation of cavities in stable pressure conditions with high safety margin on the maximum surface fields.

After several years of development, the 2nd generation QWR prototypes are used in the ReA3 (7 of β_0=0.041 in operation and 8 of β_0=0.085 in construction). This cavity type underwent modifications including the displacement of the RF coupler from the bottom plate to the resonator side and an increased distance between the tuning plate and the inner conductor tip to remove a critical thermal problem in the design. The new tuning plate includes slots and undulations to increase its maximum elastic

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displacement and thus its tuning range, and a "puck" whose length can be adjusted for cavity tuning before final welding [7]. The 11 2nd generation prototypes of β_0=0.085 QWR have been tested in vertical dewars at 2 K exceeding FRIB design specifications (Fig. 4a).

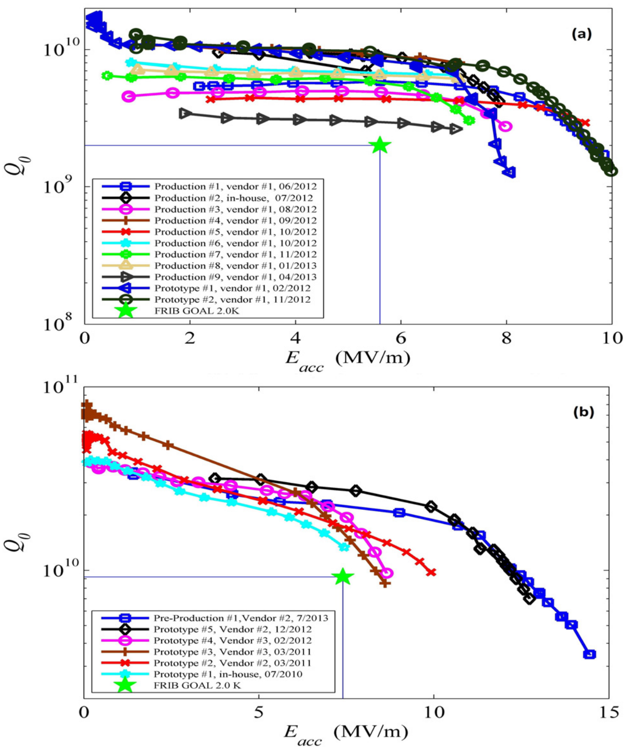

Figure 4: Q_0 vs. E_{acc} performance tested at 2 K for (a) β_0=0.085 QWR prototypes used in the ReA3, and (b) the prototype and pre-production β_0=0.53 HWR.

After testing 5 units of 2nd generation HWR prototype, the first production-design, 3rd generation β_0=0.53 HWR fabricated by an industrial supplier was tested in vertical dewars at 2 K exceeding FRIB design specifications (Fig. 4b). The 3rd-generation design optimization resulted in significant improvement of peak fields E_p/E_{acc}, B_p/E_{acc} and shunt impedance R_{sh}, with consequent reduction of the overall linac cost and operational risk. E_p and B_p in operation are below the safe values of 35 MV/m and 70 mT in all cavities. The apertures of all QWRs were enlarged from 30 to 36 mm, and their bottom rings were modified for efficient tuning-plate cooling using a low-cost design. In all cavities, the helium vessel is made of titanium to avoid brazed Nb-to-stainless-steel interface.

A "Technology Demonstration Cryomodule" was developed consisting of 2 β_0=0.53 HWRs operating at 2 K and a 9 T solenoid operating at 4.5 K arranged in a "top-down" configuration. The cryomodule was demonstrated excellent cryogenic and LLRF control stabilities. Local magnetic shielding was verified and adopted [8].

The FRIB cryomodule design has evolved significantly from the "top-down" ReA3 style to a "bottom-up" design (Fig. 5) [9]. An "Engineering Technology Cryomodule" containing the rail and support, vacuum, cryogenics for liquid nitrogen cooling and wire-position monitor was fabricated and successfully validated alignment requirements. Presently, the full-scale "bottom-up" prototype (ReA6 cryomodule) is under development starting with 2 production-design β_0=0.085 QWRs, a solenoid, 2 K cryogenics and full shieldings.

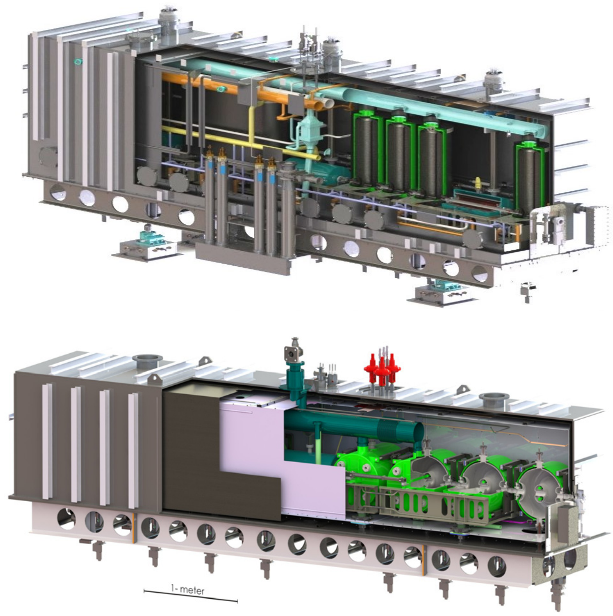

Figure 5: FRIB "bottom-up" cryomodule designs. The top cryomodule contains 8 β_0=0.085 QWRs, 3 solenoids, and 3 cold beam position monitors; the bottom cryomodule contains 8 β_0=0.53 HWRs and a solenoid.

ACQUISITION

After project baseline, the FRIB project entered into its final design phase when detail-engineering designs are performed. While critical processing and assembly are to be performed in house, mass production by industrial providers is facilitated as much as feasible. The FRIB accelerator project plans to place more than 100 procurements valued at more than $50k each. A procurement strategy is implemented for the best value to the FRIB project:

- For most procurements multiple providers are identified and competitions encouraged through strategic Request for Information/Proposal processes.
- FRIB evaluates how the project fits into the supplier's total capabilities and long-term business plans to gauge supplier management's commitment meeting production challenges. We develop long-term supplier relationships for mass production. Phasing of procurements from prototypes to production sensitizes vendors to be able to successfully produce the unique components at reasonable prices.
- Both FRIB technical and business staff works directly with the vendors' understanding their individual risk concerns and proposing mitigations. Weekly teleconferences and frequent site visits are maintained for most active procurements.

So far, we have implemented this strategy to some major procurements including all the SRF material [8], the production of 174 β_0=0.53 HRWs [9], part of the liquid helium refrigerator [10], and the RFQ [11].

COLLABORATION & PARTNERSHIP

FRIB accelerator systems design has been assisted under work-for-others agreements by many national laboratories including ANL, BNL, FNAL, JLab, LANL, LBNL, ORNL, and SLAC, and in collaboration with many institutes including BINP, KEK, IMP, INFN, INR, RIKEN, TRIUMF, and Tsinghua University.

The cryogenics system is designed in collaboration with the JLab cryogenics team. The refrigeration process incorporates the cumulative experience from both JLab and SNS cryogenic systems. The recent experience gained from the JLab 12 GeV cryogenic system design is utilized for both the refrigerator cold box and the compression system designs. The Floating Pressure Process – Ganni Cycle is to be implemented to provide efficient adaptation to the actual loads.

The charge stripping system is under development in collaboration with the ANL Physics Division. We borrowed the LEDA ion source and LEBT from LANL to modify the optics to obtain a 3 mm diameter beam spot on the liquid-lithium film at MSU. Once the new optics is checked on a new platform that is matched to the ANL lithium loop, the device will be moved to ANL for the integrated test. 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 is collaborating with ANL on the coupler and tuner developments, and assisted by JLAB on cavity processing and cryomodule developments.

FUTURE PERSPECTIVES

The FRIB accelerator design is advanced towards beginning technical construction in 2014. Early procurements before 2014 is strategically planned to establish the front end test stand to demonstrate critical components of the ECR ion source and the fully powered RFQ, to contract on long lead-time cryogenic refrigeration subcomponents, and to acquire SRF components to be assembled in the pre-production cryomodules. Upon fabrication, installation, and integrated tests, early beam commissioning will be staged from 2018 to 2020. The facility is scheduled to meet key performance parameters supporting user operations before 2022. We plan to reach full design capability in 4 years after the beginning of operations. Science driven upgrade options may be pursued at any stage of the project.

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