FRIB ACCELERATOR STATUS AND CHALLENGES*

J. Wei#[1], D. Arenius[2], E. Bernard[1], N. Bultman[1], F. Casagrande[1], S. Chouhan[1], C. Compton[1],
K. Davidson[1], A. Facco[1,4], V. Ganni[2], P. Gibson[1], T. Glasmacher[1], K. Holland[1], M. Johnson[1],
S. Jones[1], D. Leitner[1], M. Leitner[1], G. Machicoane[1], F. Marti[1], D. Morris[1], J. Nolen[1,3], J. Ozelis[1],
S. Peng[1], J. Popielarski[1], L. Popielarski[1], E. Pozdeyev[1], T. Russo[1], K. Saito[1], R. Webber[1],
M. Williams[1], Y. Yamazaki[1], A. Zeller[1], Y. Zhang[1], Q. Zhao[1]
[1] Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824, USA
[2] Thomas Jefferson National Laboratory, Newport News, VA 23606, USA
[3] Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA
[4] INFN - Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy

Abstract

The Facility for Rare Isotope Beams (FRIB) at MSU includes a driver linac that can accelerate all stable isotopes to energies beyond 200 MeV/u at beam powers up to 400 kW. The linac consists of 330 superconducting quarter- and half-wave resonators operating at 2 K temperature. Physical challenges include acceleration of multiple charge states of beams to meet beam-on-target requirements, efficient production and acceleration of intense heavy-ion beams from low to intermediate energies, accommodation of multiple charge stripping scenarios (liquid lithium, helium gas, and carbon foil) and ion species, designs for both baseline in-flight fragmentation and ISOL upgrade options, and design considerations of machine availability, tunability, reliability, maintainability, and upgradability. We report on the FRIB accelerator design and developments with emphasis on technical challenges and progress.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB), baselined as a 7-year, US$680 million construction project, is to be built at the Michigan State University under a corporate agreement with the US DOE [1]. FRIB driver accelerator is designed to accelerate all stable ions to energies above 200 MeV/u with beam power on the target up to 400 kW (Table 1). As shown in Figure 1, 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 $\beta=0.041$ 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 $\beta=0.29$ and 0.53) accelerating the beam above 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 focused beam. The reaccelerator (ReA) consists of similar $\beta=0.041$ and 0.085 accelerating structures [2].

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

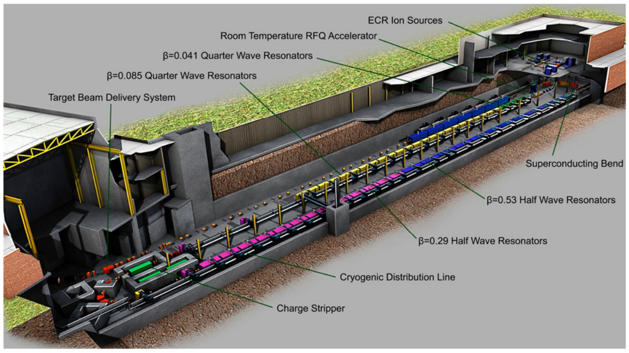

Figure 1: Layout of the FRIB driver accelerator.

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 very low energy (500 keV/u) with practically sized cavity bores by housing both the cavities and solenoids in a cryomodule. A two-cell scheme is chosen throughout the entire linac providing both efficient acceleration and focusing. Developments of digital low-level RF control and solid-

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#wei@frib.msu.edu

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.
- Reliability: A Machine Protection System (MPS) minimizes component damage and operational interruption (e.g. magnet quench and cryogenic load increase) caused by both acute (fast) and chronic (slow) beam losses. Upon acute beam loss, the MPS response time is 35μs (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- scraping rings in the warm interconnect sections and possible thermal sensors at cold regions are planned for more sensitive loss detection [3].
- 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 above 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 above 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 [1]. 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 Spallation Neutron Source (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 [4]. 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 [3]. 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 longitudinal and transverse focusing in the superconducting acceleration structure, focusing 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 [4] was based on the ANL work on a liquid-lithium high-power thick target where it was demonstrated power deposition of 20 kW (from an electron beam) with the liquid lithium operating well in an accelerator environment [5]. During the last couple of years the stability of a thin liquid film with the correct thickness for the FRIB stripper (~600 $\mu g/cm^2$) was achieved (Figure 2). The next step is to show that the power deposited by the primary beam on the moving film (~ 1 kW) will not destroy or perturb it.

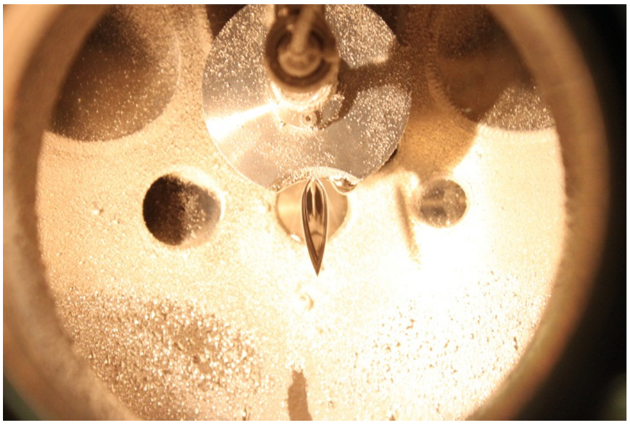

Figure 2: Liquid lithium film established at ANL.

A second option for the stripper consisting of a helium gas cell enclosed by plasma windows was considered. The RIKEN group has shown [6] that helium gas produces a higher average charge state than a nitrogen gas stripper. The purpose of the plasma windows is to limit the helium gas leaking out of the gas cell [4].

Superconducting RF

FRIB driver linac is the first full-size SC linac using a large quantity (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. FRIB cavities work with superfluid helium at 2 K. The increase in cavity Q more than compensates the energy required for the 2 K cryogenic system operation. 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 [7].

After a 10-year development, the 2nd generation QWR prototypes are used in the ReA3 linac (7 with β_0=0.041 in operation and 8 with β_0=0.085 under installation). 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, in order to remove a critical thermal problem in the design. The new tuning plate includes slots and undulations to increase its maximum elastic displacement and thus its tuning range, and a “puck” whose length can be adjusted for cavity tuning before final welding. Concerning the β_0=0.53 HWR prototype, which is similar in design to the β_0=0.29 cavity, 4 units of the 2nd generation have been built by 2 different vendors in addition to the one built in house. After positive test results, the β_0=0.085 QWR and the HWRs designs are further refined in a 3rd generation design with increased diameter that takes maximum advantage of the space available in FRIB cryomodules.

Test results and production cost considerations led to the choice of buffered chemical polishing (BCP) for FRIB cavity’s surface treatment. The effort was concentrated in the development of a reliable procedure able to produce field-emission free, high gradient cavities. The treatment includes the following BCP steps: 1) bulk etch (~150μm removal), 2) differential etching in QWRs for final cavity tuning if required, 3) light etch (~30 μm removal). Thermal treatment in high vacuum at 600 °C is applied before step 3) for Hydrogen removal to prevent Q disease. High pressure water rinsing (HPR) is applied before cavity final installation. To assure surface cleanliness, dust particle count is performed on resonator surfaces during cavity assembly in the clean room and the water purity is continuously monitored during HPR. During BCP both the cavity and acid temperatures are stabilized to control the removal rate and to avoid excess of hydrogen absorption in Nb. The acid flow path in the β_0=0.53 HWR was studied by means of simulations and experiments to obtain homogeneous removal over the entire inner resonator surface. The implementation of the 120°C final thermal treatment showed negligible improvement of the Q-slope at 2 K but significant reduction at 4.2 K [8].

The 2nd generation prototypes of β_0=0.085 QWR and 0.53 HWR have been tested in vertical dewars at 2 K exceeding FRIB design specifications. The residual resistance measured in the prototype families was below 5 nΩ up to about 100 mT in QWRs, and about 80 mT in

HWRs. Considering that the FRIB specified limits are 11 nΩ and 70 mT, a large safety margin exists for upgrades.

The 3rd-generation cavity 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 could be moved below the safe values of 35 MV/m and 70 mT in all cavities. The design gradients of the β_0=0.085 QWR and β_0=0.29 HWR are raised by 10% without increasing the total cryogenic load, allowing a reduction of two cryomodules. The apertures of all QWRs were enlarged from 30 to 34 mm, and their bottom rings were modified for efficient tuning-plate cooling using a low-cost design. The HWR designs were optimized to facilitate the mechanical construction and tuning procedure. In all cavities, the helium vessel is made of titanium to avoid brazed Nb-to-stainless-steel interface.

The Technology Demonstration Cryomodule (TDCM) consists of two 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 tested [9] at the design cryogenic temperatures demonstrating excellent cryogenic and LLRF control stabilities. Multipacting was found to impede the performance of the cavities and the coupler [9]. Future tests are planned on magnetic field and shielding studies, mechanical-type and pneumatic-type tuner evaluations, multipacting mitigation, and integrated tests with both β_0=0.29 and β_0=0.53 HWRs.

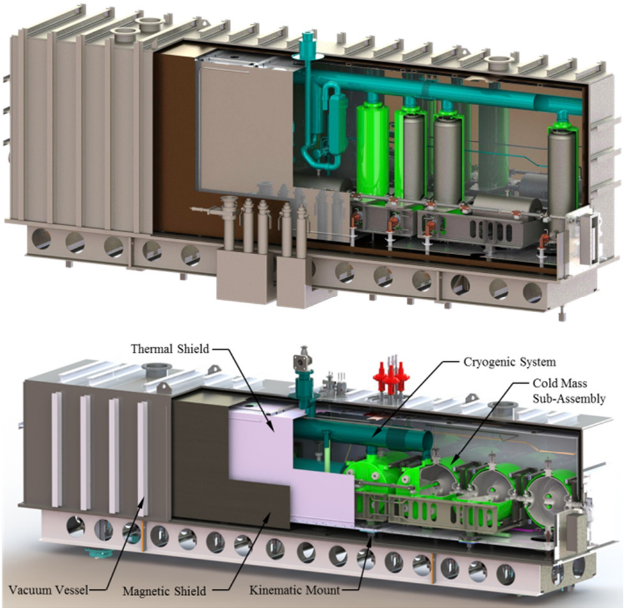

Figure 3: FRIB "bottom-up" cryomodule designs. The top cryomodule incorporates 8 β=0.085 QWRs, 3 solenoids, and 3 cold beam position monitors; the bottom cryomodule incorporates 8 β=0.53 HWRs and a solenoid.

The FRIB cryomodule design has evolved significantly from the "top-down" ReA3 style to a "bottom-up" design [10]. Key features including rail system, support system, heat and magnetic shields are simplified along with improvements in assembly and alignment. Figure 3 shows the current design incorporating a torque-resistant structural frame made of stainless steel. We incorporate machined fiberglass compression posts supporting the coldmass in the cryomodule vacuum vessel. Three posts on linear roller bearings oriented towards the center of thermal contraction serve as 6-degree-of-freedom kinematic supports. This design controls the alignment of the coldmass while allowing thermal contraction. Cavity and solenoid attachment points to the rails are all machined after welding to ensure assembly consistency.

DESIGN & ACQUISITION

A summary of the accelerator design status was given in Ref. [1] including the front end, linac segments, folding segments, beam-delivery system, and reaccelerator. Also discussed was subsystem status including the cryogenics, cryomodule, RF, ion source, RFQ, magnet and power supply, diagnostics, vacuum and alignment, controls, and utilities [1]. After the project baseline in April 2012, the FRIB project entered into its final design phase when detail-engineering designs are performed at MSU. While critical processing and assembly are to be performed in house, fabrication of a large quantity of repetitive components is planned through mass production and out-sourcing by industrial providers [11].

The FRIB project plans to place approximately 450 procurements valued at more than $50k each. The sum of all technical equipment procurements amounts to $217M excluding conventional facility construction. We have implemented a procurement strategy that strives to reduce vendor risks for the best value to the FRIB project:

- We work directly with the vendors understanding their individual risk concerns and proposing mitigations:
    - Perform certain tasks in-house if the vendor lacks capability;
    - Adjust engineering designs to allow vendor to implement familiar fabrication approaches;
    - Identify key-personnel bottlenecks at the vendor, and provide technical support where necessary;
    - Work closely with the vendor in mass-production planning and subsequent quality monitoring;
    - Accept components on mechanical (dimensional) properties instead of functional (e.g. electromagnetic, RF) performance;
    - FRIB to purchase high-cost materials that expose to market fluctuations (e.g., Nb).
- We evaluate how the project fits into the supplier's total capabilities and long-term business plans to gauge supplier management's commitment to solve production challenges and risks.
- 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.

So far we have implemented this strategy to negotiated favorable prices for all the SRF material purchases and the production of 174 β=0.53 HRWs [9].

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 [12] 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 1 to 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.

The SRF development benefit greatly from the expertise of the low-β SRF community. Weekly teleconferences are held with participations from INFN, TRIUMF, JLAB, and ANL. FRIB is collaborating with ANL on the coupler and tuner developments, and assisted by JLAB on cavity processing.

FUTURE PERSPECTIVES

The FRIB accelerator design is advanced towards beginning 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, to acquire cryogenic distribution equipment that needs to be installed before accelerator tunnel completion, and to acquire SRF components to be assembled in the pre-production cryomodules. Upon fabrication, installation, and integrated tests, early beam commissioning is expected to be staged from 2017 to 2019. The facility is scheduled to meet key performance parameters supporting user operations before 2021. Full design capability is expected to be reached 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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