TECHNICAL CHALLENGES IN DESIGN AND CONSTRUCTION OF FRIB*

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Abstract

The Facility for Rare Isotope Beams (FRIB) will be a world-leading, DOE Office of Science national user facility for the study of nuclear structure, reactions, and astrophysics on the campus of Michigan State University (MSU). A superconducting, heavy-ion, driver linac will be used to provide stable beams of >200 MeV/u at beam powers up to 400 kW (~650 electrical micro-amps for uranium). The stable beams will be used to produce rare isotopes by in flight fragment separation. After fragment selection, the rare isotopes will be used at velocity (~0.5*c*), stopped, or reaccelerated. An overview of the project, project challenges, and mitigating strategies is presented.

SCIENCE

FRIB will produce rare isotopes in substantially greater variety and intensity than anywhere presently available, enabling the nuclear science research community to make major advances in the understanding of nature. FRIB will allow the study of rare isotopes that previously existed only in the most violent conditions in the universe. FRIB will allow studies of both key nuclei and key nuclear reactions. The facility will also produce a broad range of isotopes for research in nuclear medicine, environmental science, nanoscience, and homeland security. Research with FRIB will provide an opportunity for breakthroughs in our understanding of the nature of nuclear matter, the chemical evolution of the cosmos, and the fundamental symmetry laws of nature, and will provide new tools for applied research in other fields. FRIB research will allow scientists to move beyond the greatly restricted perspective of nuclei near the stable isotopes found in nature, from which the existing patchwork of models have emerged, to develop a new, comprehensive theory of nuclei and their interactions.

FRIB FACILITY

Introduction

The FRIB scientific goals require the production and delivery of rare isotopes at high intensity. Layout diagrams and block diagrams of FRIB are shown in Figure 1 and Figure 2, respectively. A superconducting linac accelerates stable isotopes, which are delivered to a fragment production target to produce rare isotopes. The rare isotopes will have approximately the same velocity as the stable beams. At this velocity, a fragment separator is used to isolate the rare isotope of interest, which is then delivered to the experimental areas. Details of the FRIB design can be found in References [1-11].

Placing the FRIB facility next to MSU's existing National Superconducting Cyclotron Laboratory (NSCL) provides benefits derived from the utilization of the extant experimental facilities and facilitates a more fluid transition from the current NSCL operations to one with FRIB's enhanced scientific reach. Concomitant to these benefits are technical challenges in the design and construction of FRIB that include the development of a compact design that cost-effectively meets the FRIB requirements while retaining future upgrade paths.

As shown in Figure 2, the linac delivers stable isotopes with a minimum energy of 200 MeV/u (higher energies for lighter ions) at a beam power of ≤400 kW using a high-performance Electron Cyclotron Resonance (ECR) ion source and multiple charge-state beam acceleration for heavier ions. After production and fragment separation, the rare isotope beams can be used at velocity (fast beams), can be delivered to one of two gas stopping stations, or can be delivered to a solid catcher of complementary design. After stopping, the ions can be extracted and reaccelerated. The experimental equipment for a full program of fast, stopped, and reaccelerated beam research will be included in the facility, along with infrastructure to accommodate the anticipated needs of the users.

Driver Linac

The driver linac is designed to reliably provide intense stable beams for rare isotope production. The FRIB linac is in a tunnel while the supporting equipment is housed in a surface building. The linac is folded such that the three linac segments fit into a compact footprint (Figure 1A). This arrangement reduces the cost for the conventional construction, meets baseline performance requirements, and retains options for future upgrade paths to higher energy (up to 400 MeV/u for uranium or higher for lighter ions). An upgrade path for Isotope Separation On Line (ISOL) rare isotope production with the implementation of an additional target area and light-ion linac is also provided.

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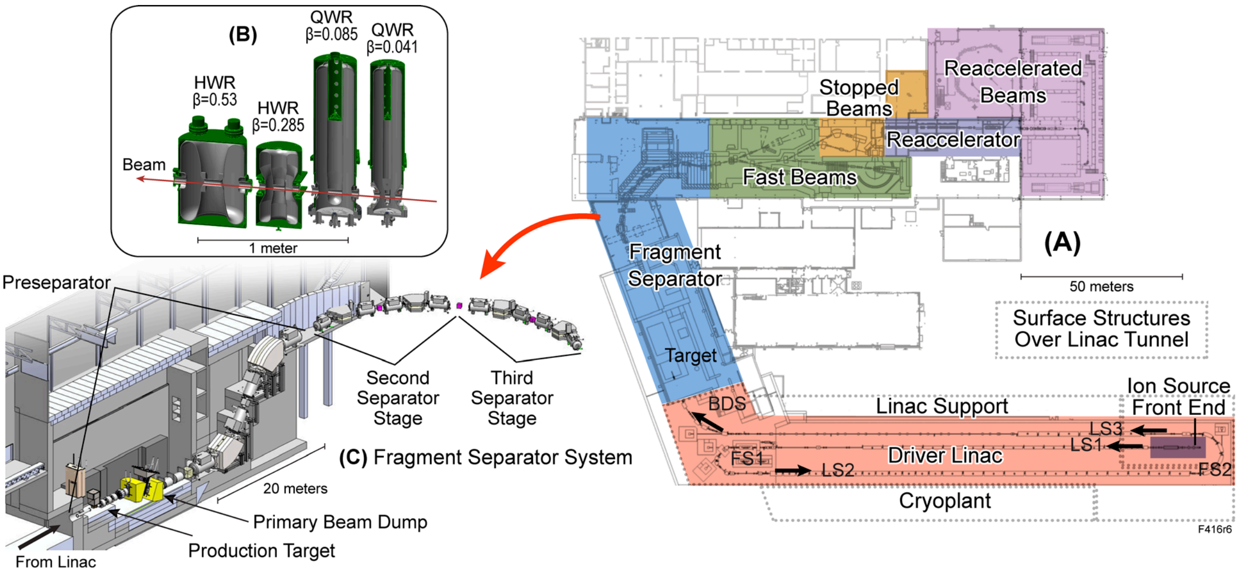

Figure 1: (A) The proposed FRIB facility at MSU showing the driver linac extending from the Front End through Linac Segments (LS1,LS2,LS3), connected by Folding Segments (FS1, FS2) followed by the beam delivery system (BDS), production target, Fragment Separator, and experimental areas. (B) Superconducting quarter-wave resonators (QWRs) and half-wave resonators (HWRs) for the linac. (C) The Fragment Separator System filters the rare isotopes after the production target.

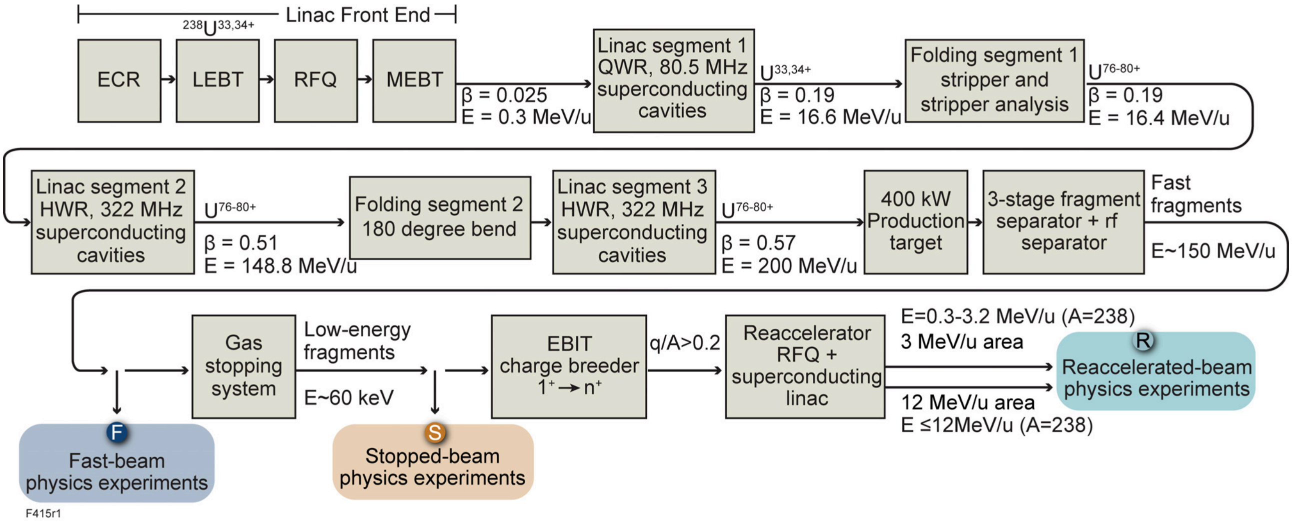

Figure 2: Conceptual schematic of FRIB. The block diagram represents the items within the FRIB technical scope. Sample beam parameters for uranium are included.

Front End The driver linac (see Fig. 1 in relation to the FRIB facility and schematically in Fig. 2) will meet the beam intensity requirements by accelerating multiplecharge states from ECR ion sources on the ground level. A Low Energy Beam Transport (LEBT) system brings the ions to the linac tunnel and to a Radio Frequency Quadrupole (RFQ) accelerator operating at a frequency of 80.5 MHz. The Medium Energy Beam Transport (MEBT) system delivers the beam from the RFQ to Linac Segment 1 of the driver linac at an energy of 0.3 MeV/u.

The technical challenges for the Front End include the production of sufficient beam intensity to meet the high beam power (400 kW) requirement. This intensity requirement is particularly challenging for the heavier ions (~ ≥Xe) and will be met by utilizing two charge states (e.g. 33+ and 34+ for uranium) in the Front End. Multi-charge state acceleration effectively represents a larger longitudinal emittance, and as a consequence, a premium is placed on the minimization and preservation of the longitudinal emittance through the linac. In the Front End, emittance preservation is provided by an RFQ with an external buncher [3] upstream and matching into the linac (by the MEBT) downstream.

The Front End will rely on room temperature-based technology for acceleration. Superconducting technology will be used for downstream elements of the driver linac since it most efficiently achieves the 100% duty factor operation needed to reach the required beam power [4].

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Superconducting Cavities To minimize R&D costs, engineering costs, acquisition costs, and technical risk, the driver linac has a minimum number of cavity types [5-6]. Because two-gap structures will be used, only four cavity types are needed to efficiently cover the required velocity range (Figure 1B). Each cavity type is identified by its optimum β (β_{opt}). The component counts are given in Table 1.

Table 1: Driver Linac Cavity, Superconducting Solenoid, and Cryomodule Counts. Numbers in brackets are for matching cryomodules; numbers not in brackets are for accelerating cryomodules.

Type	λ/4	λ/4	λ/2	λ/2	Total
β_{opt}	0.041	0.085	0.29	0.53	
Cavities	16	96	78	144	345
	[0]	[4]	[4]	[3]	
Solenoids	8	36	13	18	75
	[0]	[0]	[0]	[0]	
Cryomodules	4	12	13	18	52
	[0]	[2]	[2]	[1]	

The rf drive power for the cavities will be supplied by solid state amplifiers that will be fabricated by combining smaller units each of approximately 2 kW capacity. The necessary rf power increases with β_{opt}. The rf power required is approximately 2, 4, 4, and 8 kW for β_{opt} = 0.041, 0.085, 0.29, and 0.53 respectively.

The technical challenges for the superconducting cavities include demonstrating performance and implementing acquisition strategies that will achieve the necessary performance on schedule. The performance demonstration for the Quarter Wave Resonators (QWRs) will be provided through their utilization in the MSU-funded reaccelerator (ReA3) [7]. The driver linac requires a large number of β_{opt} = 0.53 Half Wave Resonators (HWRs). Dewar testing of 5 of these HWRs is in progress. A full systems test of a prototype cryomodule with two β_{opt} = 0.53 HWRs and a superconducting solenoid is scheduled to be completed in 2011. The β_{opt} = 0.29 HWR design will be largely based on the successful 0.53 HWR design and will be verified with Dewar testing. Because of the relatively more complex geometry of the QWR and HWR compared to the more common elliptical cavities, industrialization steps are being implemented prior to the acquisition of production cavities.

Linac Segment 1 Beam from the Front End is injected into Linac Segment 1, which uses two types of QWRs operating at a frequency of 80.5 MHz with β_{opt} = 0.041 and 0.085. Linac Segment 1 accelerates the uranium beam energy to about 17 MeV/u (or higher for lighter ions).

The technical challenges for Linac Segment 1 include ensuring performance of the QWRs and making appropriate beam trajectory corrections, given the enhanced sensitivity to alignment errors in the earliest stages of acceleration. The QWR performance contingency will be enhanced by operation at 2 K, which reduces the decrease in quality factor with rf field ("*Q*-slope") and mitigates microphonic issues by providing a substantially more stable helium bath pressure. Since the *Q* increase with decreasing temperature has been found to be similar to the reduction in refrigeration efficiency, operation of the QWRs at 2 K in lieu of 4.5 K (the temperature traditionally used for cavities at this frequency) results in very little change in the cryogenic plant requirements.

A central trajectory correction scheme under consideration would use an admixture of both cold beam position monitors (BPMs) near the superconducting solenoids and room temperature BPMs between the cryomodules to provide a more robust solution than can be obtained with only room temperature BPMs.

Folding Segment 1 A stripping system [8-9] is located in Folding Segment 1 to increase the downstream acceleration efficiency by increasing the charge state of the beam. Local shielding and remote handling systems will be used in this area to accommodate controlled beam losses of about 20% of the beam power during collimation, which is needed to truncate the range of charge states to be further accelerated. Simulations indicate that uncontrolled losses in the linac will be orders of magnitude less. The remaining beam line elements will match the multi-charge state beams (e.g. five charge states for uranium) in a manner appropriate for acceleration in Linac Segment 2.

The technical challenges for Folding Segment 1 include the stripping of intense heavy-ion beams to higher charge states, selection of the post-stripping charge states for further acceleration, and matching into Linac Segment 2 within a compact footprint. The stripping of heavy-ion beams at FRIB intensities is a technical challenge largely because of the high power densities (~1 kW/mm^2) created when the heavy ions interact with matter. The primary solution being developed in the FRIB R&D program will utilize a jet of liquid lithium. A secondary solution is also being developed that would utilize a helium gas stripping system. Space has been allocated to allow the implementation of either solution. Additional space has been allocated for collimation, where the technical challenge again derives from the high power densities obtained with heavy ion and matter interaction. To preserve the beam quality, transverse focusing and longitudinal bunching is provided by matching elements upstream of Linac Segment 2.

Linac Segment 2 After liquid lithium charge stripping, Linac Segment 2 will accelerate up to five charge states to energies of at least 149 MeV/u. Linac Segment 2 will use two types (β_{opt} = 0.285 and 0.53) of Half Wave Resonators operating at a frequency of 322 MHz.

Folding Segment 2 This segment connects Linac Segments 2 and 3. The elements of Folding Segment 2 provide the folded geometry and full 6-dimensional phase matching of the multiple charge states from Linac Segment 2 into Linac Segment 3.

The technical challenges for Folding Segment 2 stem from the need to reliably meet the full 6-dimensional phase space matching necessary to maintain beam quality within a compact footprint. Since the footprint of Folding

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Segment 2 sets the tunnel width, its design impacts the conventional construction costs. Beam dynamics evaluations have been used to confirm the efficacy of the proposed approach. In support of these efforts, the magnetic element designs are used to make sure appropriate space is provided. The magnetic element field quality is included in these evaluations to ensure performance, which is particularly important because the large momentum spread of the multi-charge state beam causes larger beam sizes in the segment's dispersive regions.

Linac Segment 3 Linac Segment 3 will accelerate up to five charge states to energies of at least 200 MeV/u using $\beta_{opt} = 0.53$ Half Wave Resonators at 322 MHz.

The technical challenges for Linac Segment 3 derive from the requirement of at least 200 MeV/u, which could be at risk either because of lack of HWR performance or because of the need to implement a gas stripper system. A gas stripper would deliver lower mean charge states, so that acceleration in Segments 2 and 3 would be less efficient. To mitigate these possibilities, space is allocated in Segment 3 for additional cryomodules, should they be required.

The upgrade path to higher (≥400 MeV/u) energies can be provided through the replacement of the HWRs with cavities of enhanced performance (~35% gradient increase); such a performance improvement is compatible with technology advancements in recent decades.

Beam Delivery System The beam transport system from the end of the linac (Figure 1) to the production target will be achromatic to deliver up to five charge states of uranium within a beam-spot diameter of less than 1 mm, as required to achieve the resolution necessary for the downstream fragment separator system. Extra space is allocated to accommodate an additional beam delivery system for a possible future implementation of an ISOL target.

Beam Dynamics The accelerator design uses four basic cryomodule configurations (one for each cavity type), with three additional cryomodule configurations for longitudinal matching in Folding Segments 1 and 2. The transverse focusing is provided by 9 T superconducting solenoids with integrated horizontal and vertical steering dipoles for beam-centroid corrections.

End-to-end simulations of the linac design have been performed, including error studies [10-11]. To maintain hands-on machine maintenance, the specification for uncontrolled beam loss was set at less than 1 W/m.

The technical challenges for the FRIB linac beam dynamics are the preservation of the beam to meet the uncontrolled beam loss requirement and to meet the spot size requirement (1 mm) on the production target, even with the relatively large emittance of heavy ion beams and the large momentum spread due to the multiple charge states. The effectiveness of the design approach is ensured via end-to-end simulations beginning with experimentally-based ion source phase spaces and including machine errors (e.g., misalignment and mispowering), three-dimensional electromagnetic fields, and the effects of charge stripping.

Cryogenic Facilities The cryogenic plant will have a capacity of approximately 15 kW at 4.5K, corresponding to a 50% overcapacity to ensure reliable operations. The cavities will operate at 2 K, while the superconducting magnets will operate at 4.5 K. The conversion from 4.5 K to 2K will be done inside the cryomodules.

Experimental Systems

FRIB's experimental systems include the facilities needed for the production and separation of fast Rare Isotope Beams (RIBs) and equipment to allow their utilization at velocity (Fast), to stop them for experiments at rest (Stopped), and to provide low energy beams by reacceleration (Reacceleration) of the stopped beams. Experimental halls for FRIB experiments with fast, stopped, and reaccelerated beams are planned.

Rare Isotope Production The FRIB production target facilities will provide rare isotope beams from projectile fragmentation and in-flight fission of a wide variety of primary beams on suitable targets. The well-shielded target building will accommodate all production components that must withstand the high radiation fields, including the last beam transport elements for the primary beam, the production target itself, and a magnetic fragment preseparator with a high-power beam dump. The FRIB facility design also provides space for a later upgrade of the facility to rare isotope production via target fragmentation and fission (ISOL). The target building will provide space for a remote handling gallery for target changes and the maintenance of highly activated components.

Figure 1C shows the overall layout of the fragment separator. Three stages of separation will be employed to obtain the high resolving power needed to achieve sufficient rare isotope beam purity. The first stage, the preseparator, provides an initial rough-cut on the broad distribution of fragments emerging from the target, provides a well-defined location where the primary beam and most of the unwanted fragments can be collected, and delivers the secondary beam to the second stage of the fragment separator located at ground level. The preseparator efficiently collects projectile and fission fragments produced at 200 MeV/u by utilizing a large acceptance (5 msr, and 10% momentum acceptance) and a maximum magnetic rigidity of 8 T·m. The last two separation stages will be obtained by reconfiguring the A1900 fragment separator presently in use at NSCL.

The technical challenges for the experimental systems largely stem from the rare isotope beam production using a stable ion beam power of 400 kW. The targets for the production of in-flight separated beams must be able to sustain very high power densities with the consequent thermal stress and radiation damage. Isotope production requirements include a maximum target thickness of ~50 mm with a 1mm beam spot diameter, the ability to absorb (and dissipate) a continuous power of up to 200 kW (energy lost in the target), and a target lifetime

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of more than one week (the anticipated duration of a typical FRIB experiment). R&D to establish a target design that can deliver these features is underway; a rotating multi-disk graphite target with radiative cooling is under active study.

The beam dump for stopping the primary beam after the first separation stage must be able to absorb up to 400 kW of beam power. Different dump alternatives have been investigated as part of the R&D program and a concept based on a water-filled rotating cylinder has been chosen for further development.

Beam Stopping, Reacceleration, and Experimental Areas FRIB will capitalize on the benefits of rare-isotope production by projectile fragmentation with in-flight separation. The rare isotopes will be provided at velocity (Fast), at low-energy (Reaccelerated), and at rest (Stopped). Gas stopping has been recognized as the best approach to bring the fast ions to rest. Capitalizing on the on-going NSCL program, the gas stopper systems will be functioning well before FRIB starts operation. An additional solid-catcher ion-source system will be implemented for high-intensity beams of readily extracted elements.

An MSU-funded reaccelerator, ReA3, capable of accelerating uranium to 3 MeV/u and ^{48}Cr to 6.2 MeV/u is under construction. A singly-charged (1+) ion beam from one of the beam stoppers will be sent into a high-current Electron Beam Ion Trap (EBIT) to selectively and efficiently produce ions with a charge-to-mass ratio of $Q/A = 0.2$ to 0.5. An RFQ and a compact superconducting linac will accelerate the ions to energies ranging from 0.3-12 MeV/u for uranium and 0.3-20 MeV/u for $A<50$ once a planned upgrade (ReA12) is in place.

A full complement of experimental equipment for the FRIB science program will be situated downstream of the fragment separator. The continued operation of NSCL provides the unique opportunity for pre-FRIB science with fast, stopped, and reaccelerated beams. Of particular importance will be ReA3, which will make MSU at present the only place in the world to offer reaccelerated beams of rare isotopes produced by projectile fragmentation. Because of its long-standing and ongoing program, a number of experimental systems are in place at NSCL that will be available for FRIB. With the addition of a new experimental area for reaccelerated beams from ReA12, initially about 4,500 square meters of experimental floor space will be available at FRIB. In response to future science needs, adding additional experimental halls could double this footprint.

FRIB PROJECT STATUS AND PLANS

The FRIB project has in 2010 received Critical Decision 1 approval from DOE (establishing the preferred design and the associated cost and schedule ranges). Project completion is planned for 2020. The project intends to manage to an early completion in 2018, subject to availability of funds.

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