FRIB: A NEW ACCELERATOR FACILITY FOR THE PRODUCTION OF AND EXPERIMENTS WITH RARE ISOTOPE BEAMS*

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Abstract

The 2007 Long Range Plan for Nuclear Science had as one of its highest recommendations the "construction of a Facility for Rare Isotope Beams (FRIB) a world-leading facility for the study of nuclear structure, reactions, and astrophysics. Experiments with the new isotopes produced at FRIB will lead to a comprehensive description of nuclei, elucidate the origin of the elements in the cosmos, provide an understanding of matter in the crust of neutron stars, and establish the scientific foundation for innovative applications of nuclear science to society." A heavy-ion driver linac will be used to provide stable beams of >200 MeV/u at beam powers up to 400 kW that will be used to produce rare isotopes. Experiments can be done with rare isotope beams at velocities similar the driver linac beam, at near zero velocities after stopping in a gas cell, or at intermediate velocities (0.3 to 12 MeV/u) through reacceleration. An overview of the design proposed for implementation of the DOE national users facility FRIB on the campus of Michigan State University is presented.

HISTORY

A new research facility for creating and utilizing Rare Isotope Beams (RIBs) has been under consideration for some time. In 1999, a subcommittee of the Nuclear Science Advisory Committee (NSAC) produced a report [1] proposing an approach for a RIB-based facility that would utilize a high-intensity (100 kW), high-energy (>400 MeV/u) heavy-ion linac to produce RIBs called the Rare Isotope Accelerator (RIA). RIA was ranked 3rd in the 2003 Department of Energy (DOE) 20-year Science Plan [2]. In the intervening years, a lower-cost alternative based on a lower energy (200 MeV/u) but higher intensity (400 kW) heavy-ion linac was developed called the Facility for Rare Isotope Beams (FRIB). The Rare Isotope Science Assessment Committee (RISAC) of the Academies endorsed FRIB in 2006 [3]. The most recent (2007) NSAC Long Range Plan (LRP) [4] made construction of FRIB the second highest priority for nuclear science.

In 2008, the Department of Energy (DOE) undertook a merit review and evaluation process resulting in the selection of Michigan State University (MSU) to design and build FRIB.

SCIENCE

FRIB will be a critical component of the mission to understand the fundamental forces and particles of nature as manifested in nuclear matter. FRIB will enable the nuclear science research community to make major advances in the understanding of nature by producing key rare isotopes that previously only existed in the most violent conditions in the universe. It will answer compelling questions about the structure of nuclei and the origin and evolution of elements of the cosmos. It will permit sensitive tests of the fundamental symmetries of nature and will address basic questions on the character of the universe. In addition, FRIB will provide a source of rare isotopes for both new and improved applications that benefit from the use of radioisotopes such as those for medicine.

The scientific goal of FRIB is to allow experiments with rare isotopes that answer the overarching questions of the NSAC 2007 LRP. The details of this research will evolve as the research community obtains new information and the new understanding it provides. FRIB will

- Provide the key experimental input needed to develop a more complete understanding of the nuclear force that binds protons and neutrons into stable and rare isotopes.
- Extend the quest for the origin of simple patterns in complex nuclei to rare isotopes out to the limits of existence. With FRIB it will be possible to investigate how regular excitation patterns, unusual shapes and shape transitions, and pairing occur in finite systems, and how these phenomena are influenced by extreme neutron-to-proton ratios.
- Allow the study of key rare isotopes that will help clarify the nature of neutron stars and dense matter by providing nuclear data for the development of reliable models connecting neutron star observations to neutron star properties.
- Allow the measurement of key nuclear properties of nuclei that are involved in nucleosynthesis to help clarify the origin of the elements in the cosmos via the development of reliable and quantifiable astrophysical models.
- Allow the measurement of astrophysically important nuclear processes necessary to determine how energy is generated in stars and stellar explosions.
- Provide rare isotopes that can be used to test fundamental symmetries by allowing tests of parity and time reversal symmetries.
- Provide isotopes for application in a variety of fields ranging from medicine to stockpile stewardship.

FRIB FACILITY

Introduction

The FRIB facility will be located on the campus of Michigan State University (MSU). The Facility layout is given in Figure 1. The proposed technical design and

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construction specifications were driven by the scientific goals discussed in the preceding section. The proposed FRIB technical scope includes items that are provided through MSU contributions. These include extant or soon-to-be-added capabilities at the National Superconducting Cyclotron Laboratory (NSCL). The MSU-contributed systems are labeled with an MSU logo MSU in Figure 1.

The FRIB facility described here will be evaluated on numerous occasions by its many stakeholders including the DOE, the FRIB technical team, and the nuclear science community. As a consequence, the detailed design of the FRIB facility is expected to mature from the presently proposed concept. Details on the FRIB design can also be found in the references [5-14].

The FRIB facility is based on a heavy-ion linac with a minimum energy of 200 MeV/u for all ions (higher energies for lighter ions) at a beam power of 400 kW using a high-performance ECR ion source and multiple charge-state acceleration. The facility will have a fully enclosed and remotely handled fragment production area followed by a high-acceptance, fourth-generation, three-stage fragment separator. RIBs 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 which the ions can be extracted and reaccelerated to an energy of up to 12 MeV/u for uranium and up to 20 MeV/u for A<50. Experimental equipment for a full program of fast, stopped, and reaccelerated beam research will be provided, as will the necessary infrastructure and office space to accommodate the anticipated user demand.

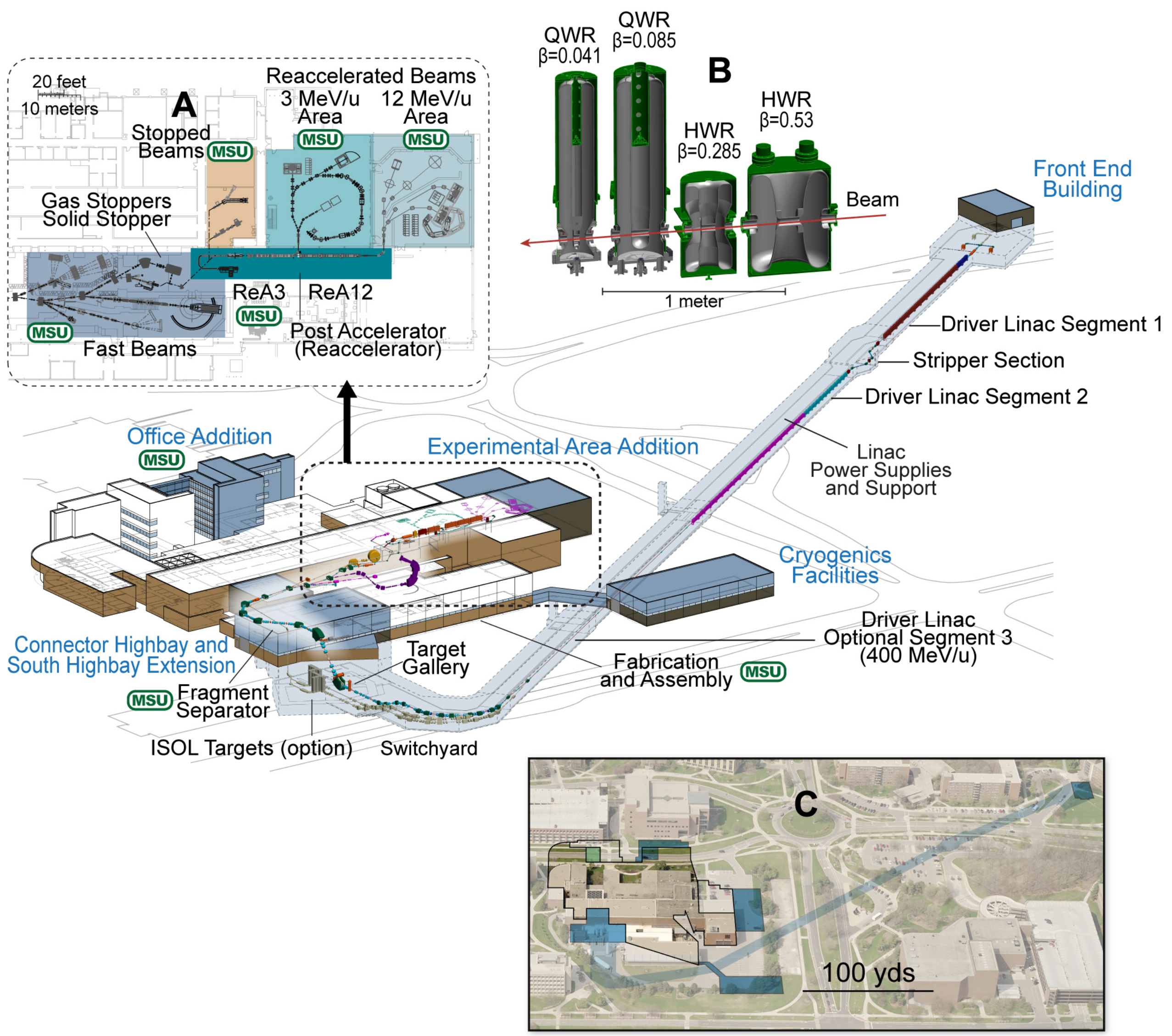

Figure 1: The proposed FRIB facility at MSU showing the driver linac extending from the Front End building through Segment 3. A switchyard will deliver the linac beam to the Target Gallery where the RIBs will be produced and filtered by the Fragment Separator system after which they will be delivered to the experimental area shown in more detail in the magnified region shown in (A). The four superconducting accelerating structures of the baseline design are shown in (B). FRIB overlaid on the MSU campus is shown in (C).

Driver Linac

The design is based on the goal of constructing a reliable accelerator that will ensure production of intense beams for world-class experiments. In addition, possible upgrades have been identified and those possibilities have been incorporated in the design.

Typically the linac accelerating systems (e.g., cavities and focusing elements) are housed in a subterranean structure while the supporting systems (e.g., power supplies and rf drive) are housed in a surface structure. The FRIB linac will utilize two parallel subterranean structures to provide these functions. This allows the linac to extend off the NSCL site, safely passing beneath roads and parking lots. See Figure 1-C.

The driver linac will provide intense beams of exotic nuclei by fragmenting stable ion beams at energies higher than 200 MeV/u at a beam power of up to 400 kW. Beam energies for representative elements are given in Table 1.

Space is included in the linac tunnel to upgrade to a higher beam energy of up to 400 MeV/u for uranium and higher for lighter ions. The beam switchyard for the driver linac will provide high-quality beams at the production target and is capable of transporting the upgraded energy. In addition, space has been provided in the switchyard for the implementation of fast-switching elements to support simultaneous beam delivery to more than one production target.

Table 1. Representative driver linac beam energies.

Ion	**Energy** (MeV/u)
^{238}U	210
^{208}Pb	210
^{86}Kr	265
^{48}Ca	270
protons	610

Front End The driver linac (shown in Figure 1 in relation to FRIB facility) will meet intensity requirements by acceleration of multiple charge states from an Electron Cyclotron Resonance (ECR) ion source. The ions will be transported in a Low Energy Beam Transport system (LEBT) to a Radio Frequency Quadrupole (RFQ) accelerator operating at a frequency of 80.5 MHz. The Medium Energy Beam Transport system (MEBT) will deliver the beam from the RFQ to Segment 1 of the driver linac at an energy of 0.3 MeV/u. 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.

Linac Segment 1 Beam from the linac Front End will be injected into Segment 1 of the superconducting heavy-ion linac shown in Figure 1. Linac Segment 1 will utilize two types of Quarter Wave Resonator (QWR) accelerating cavities operating at a frequency of 80.5 MHz with β_{opt}=0.041 and 0.085 to increase the beam energy to 17.5 MeV/u (β_{opt} is the velocity of an ion relative to the speed of light that will gain the most energy from passage through an accelerating structure.).

Stripping Section The stripping system is located between Segments 1 and 2 and increases the downstream acceleration efficiency (and reduces cost) by increasing the charge state of the beam. It will consist of a stripper and an analysis section. Electrons will be removed from the beam ions by passing through a material (lithium or carbon-based) located at the object point of an achromatic and isochronous analyzing beam line section used to remove unwanted charge states. Unwanted charge states will be removed by aperture slits at the dispersive mid plane of the analyzing section. Local shielding and remote handling systems will be used in this area to accommodate these controlled beam losses of about 20% of the beam power. Simulations indicate that uncontrolled losses will be orders of magnitude less. The remaining analysis-system elements will bring multi-charge state beams (e.g. five charge states for uranium) back to the linac axis in an achromatic and isochronous manner appropriate for acceleration in the driver linac Segment 2. Included in the stripping segment will be accelerating structures to appropriately match the 80.5 MHz beam of Segment 1 to the 322 MHz required for Segment 2. Having only a single frequency shift and having it at a location where appropriate matching systems can be employed will enhance beam quality.

Linac Segment 2 After stripping, Segment 2 of the driver linac will accelerate up to five charge states to energies of at least 200 MeV/u for uranium with a beam power of 400 kW. Linac Segment 2 will use two types (β_{opt} = 0.285 and 0.53) of Half Wave Resonators (HWRs) operating at a frequency of 322 MHz.

Linac Segment 3 Segment 3 of the driver linac will initially have only focusing and diagnostic elements. This space will allow for additional cryomodules to be installed later to reach 400 MeV/u for uranium, providing an increase in the production rates of many rare isotopes by up to a factor of 10. These additional cryomodules would provide protons at an energy of 1 GeV.

Beam Switchyard The beam transport system from the end of the linac (shown in Figure 1 as Segment 3) to the production target will accommodate a beam energy of up to 400 MeV/u for uranium 79+ and correspondingly higher energies for lighter ions. The ion-optical design is based on a low beam-loss symmetrical solution. The system is achromatic and can deliver up to five charge states of uranium within a beam-spot diameter of less than 1 mm. Space is provided to add additional lines and a microbunch-beam distribution system to provide full-power beams to up to three target stations (e.g., one fragment separator target and two ISOL targets).

Beam Dynamics Only four types of accelerating structures (two types of 80.5 MHz QWRs and two types of 322 MHz HWRs, as shown in Figure 1-B) are required thereby simplifying construction and operational considerations including an appropriate inventory of spares. The accelerating cavities will be packaged with focusing solenoids into cryomodules. The design will use four basic cryomodule configurations. The transverse focusing will be provided by 9 T solenoids with additional coils to produce two steering dipoles for beam-centroid corrections. Active shielding of the cavities from solenoid magnetic fields will be provided by four additional coils in series with the main solenoid coil. Niobium and cryoperm shrouds around the solenoids will provide additional passive shielding.

End-to-end simulations of the linac design have been performed to verify that uncontrolled losses are less than 1 W/m. None of the over 10^8 simulated test particles were lost along the linac, even allowing for misalignment and tuning errors. We performed 300 different simulations each with 10^6 particles, starting in the LEBT, to the end of Segment 2 of the driver linac. Two charge states of uranium were included in Segment 1; nine charge states were included after the stripper, until the collimation area where five charge states were selected. The effect of RF errors and misalignments was included. The superconducting cavities and solenoids were misaligned according to a uniform distribution with maximum displacements of ±0.5 mm at each end. The room temperature dipoles, quadrupoles, and sextupoles in the stripper section were misaligned with a uniform distribution of errors with maximum values of ±0.2 mm for displacements at each end and ±1 mrad angular rotation. The RF systems powering the cavities had amplitude errors of σ=0.5% and phase errors of σ=0.5° both from a Gaussian distribution. Steering dipoles were used to correct the beam centroids based on beam position monitors with position errors of σ=0.5 mm from a Gaussian distribution. The Gaussian distributions used to generate errors were truncated at 3σ. The error limits correspond to tolerances that are readily achieved.

Cryogenic Facilities The FRIB superconducting elements will require a refrigerator system (cryogenic plant) to cool down and to maintain superconducting temperatures. The load to the cryogenic plant from the driver linac will primarily be due to the dynamic RF losses in the superconducting cavities, with an additional smaller contribution from the static heat leak of the cryomodules. A design value for the intrinsic quality factor (Q_0) of each cavity was used to calculate the dynamic load per cavity. The design Q_0 was based on the theoretical Q_0 for the cavity shape and experimental results for prototype cavities. The static heat leak was calculated from the cryomodule design, with predictions verified via measurements on prototype cryomodules.

The cryogenic load at 4.5 K will be 1.7 kW from the QWR cryomodules; 1.5 kW from the superconducting magnets, transfer lines and 50 K cold gas; and an additional 1.3 kW at 2 K from the HWR cryomodules (corresponding to approximately 3.9 kW at 4.5 K) for a total of 7.1 kW at 4.5 K. The cryogenic plant will have a capacity of approximately 10.7 kW corresponding to a 50% overcapacity to ensure reliable operations. Additionally, the cryogenic plant cooling water capacity and building will be sized so that additional compressors can be added to increase capacity. Further increases in capacity are possible with modifications to the cold box.

Target Facilities

Isotope production facilities will be located in a well-shielded area, accommodating all production components that must withstand high radiation fields or that could become highly activated. The baseline design includes rare isotope production by projectile fragmentation with ISOL beam production or a second fragmentation line as upgrade options. The target building will be equipped with shielding designed to accept the full power of the primary beam at the upgraded energy of 400 MeV/u for uranium, 500 MeV/u for lighter ions, and 1000 MeV protons, with room for additional target locations. Air handling and high-efficiency particulate air (HEPA) filtering systems, water cooling systems, radiation detection equipment, and personnel access systems will be integrated into the design.

The magnitude of the radiation fields in the first separator stage and the level of air and component activation are such that remote handling is essential. A target service area and hot cell for maintenance will be equipped with an overhead crane that can lift each of the shielding modules and transport them to the component handling and waste removal area. A remote manipulator will be used for component changes. Remote handling will also be used to change the fragment separator wedges and detector systems downstream from the target production area. A component handling and waste removal area with truck access will provide the main removal path for radioactive material.

The design goal is to ensure that the system is fully compatible with the implementation of additional target stations. The base facility will include infrastructure so that no high-radiation areas will be disturbed by the installation of additional stations.

The production targets for fast-ion beams must be able to sustain high power densities to accommodate 400 kW operations and a 1 mm diameter beam spot size. The science goals require a wide range of primary beams and production target thicknesses with up to 50% of the primary beam power dissipated in the target.

Fragment Separator

FRIB will employ a new three-stage projectile fragment separator (PFS) that is optimized to have a large, adjustable acceptance for secondary beams, to separate and contain the intense primary beam at a well-defined location, and to provide excellent secondary-beam purity. The FRIB fragment separator will be a fourth-generation device. The beam purity from the new separator will be at least two orders of magnitude higher than that possible from even the most modern one-stage separators.

The first stage of the PFS, called the preseparator, will provide the initial rough-cut on the broad distribution of fragments, provide a well-defined primary beam dump, and deliver the secondary fragments to the object point of the main separator without significant aberrations. The preseparator will be made up of new magnets designed to operate in the high-radiation environment.

The projectile fragments will pass from the preseparator into two subsequent high-resolution stages using magnetic elements obtained by reconfiguration of the existing robust superconducting magnets in the third-generation separator operating at the NSCL.

Experimental Systems

A full complement of experimental systems will be situated downstream of the fragment separator for the science program with fast (RIB particle velocities similar to that of the driver linac beam), stopped, and reaccelerated beams. Because of the long-standing and ongoing NSCL program, many of the experimental systems are or soon will be in place. Because the NSCL has stable primary beams that largely differ only in intensity, the experimental systems that will ultimately become elements of FRIB will be fully commissioned and will be producing science before FRIB is completed.

The fast beam systems will largely rely on existing NSCL facilities. An MSU funded area to stop RIBs using one of several methods including gas- and solid-based systems is currently under construction. Experiments with stopped RIBs will use ion traps and laser-spectroscopy systems. Beginning in 2010, a reaccelerator system will be available to provide RIB reacceleration from 0.3 to 3 MeV/u. This reaccelerator system will be augmented within the FRIB project to achieve reacceleration up to 12 MeV/u for uranium. Adjacent research areas will also be available to support concomitant experimental programs. Initially about 47,000 square feet of experimental floor space is planned with the possibility to double this footprint by adding additional experimental halls.

FRIB PROJECT

The present Total Project Cost is approximately $550M. The primary initial activities will be associated with the continuation of an R&D program, the initiation of National Environmental Policy Act (NEPA) evaluations, and the development of a Conceptual Design Report (CDR). Subject to the availability of funds, the FRIB project could become operational in approximately 2017.

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