Facility for Rare Isotope Beams Update for *Nuclear Physics News*

FRIB Overview

The Facility for Rare Isotope Beams (FRIB) is a major new scientific user facility under construction in the United States for nuclear science research with beams of rare isotopes [1]. FRIB is funded by the United States Department of Energy Office of Science (DOE-SC) and is located on the campus of Michigan State University (MSU), in East Lansing, Michigan, USA. FRIB will support the mission of the Office of Nuclear Physics in the DOE-SC. The total FRIB project cost is $730 million and the facility is scheduled to be completed by 2022. The project has passed the 75% complete mark and is managed toward early completion in 2021. FRIB is estimated to provide access to 80% off all isotopes of elements lighter than uranium.

A key feature of FRIB is the use of a high-power superconducting heavy ion linear accelerator (LINAC) to produce up to 400 kW beams, through simultaneous acceleration of multiple charge states of the beam, at 200 MeV/u for all stable isotopes. The facility is upgradable to 400 MeV/u with the addition of more accelerating cryomodules in space provided in the LINAC hall. A schematic drawing of FRIB is shown in Figure 1. Ions of stable isotopes are produced in an electron cyclotron resonance (ECR) ion source and accelerated by the superconducting LINAC [2]. Rare isotopes are produced in a production area and separated by a three-stage fragment separator [3]. Provisions are made to collect (harvest) unused rare isotopes for research in parallel to experiments with the primary rare isotope beam. The separated beams are delivered to experimental areas that currently exist at the National Superconducting Cyclotron Laboratory (NSCL) [4]. Operation of the current facility, NSCL, is funded by the U.S. National Science Foundation through fiscal year 2021.

A unique feature of FRIB is the provision for in-flight separation of rare isotopes, stopping, and subsequent reacceleration. The combination of in-flight separation followed by reacceleration provides access to rare isotope beams that are chemically difficult to obtain in other ways. Ions are stopped in a helium gas cell, extracted, and charge-bred in an electron-beam ion trap charge breeder to within the range of Q/A from 0.25 to 0.5. At NSCL, currently, the beams can be reaccelerated to 3 to 6 MeV/u using the ReA3 superconducting linear accelerator. An energy upgrade of the ReA3 accelerator will be proposed and space is provided in the facility to add three more cryomodules that would raise the total energy to 12 to 15 MeV/u.

Science of FRIB

FRIB will make possible a range of new scientific opportunities. These opportunities have been well documented in recent years in a variety of publications including the 2012 National Academy of Sciences (NAS) Decadal Study of Nuclear Physics [5] and the 2015 Nuclear Science Advisory Committee's Long Range Plan (LRP) for Nuclear Science [6]. Construction of FRIB was in fact the first recommendation of the NAS report [5]. FRIB was also highlighted in the first recommendation of the

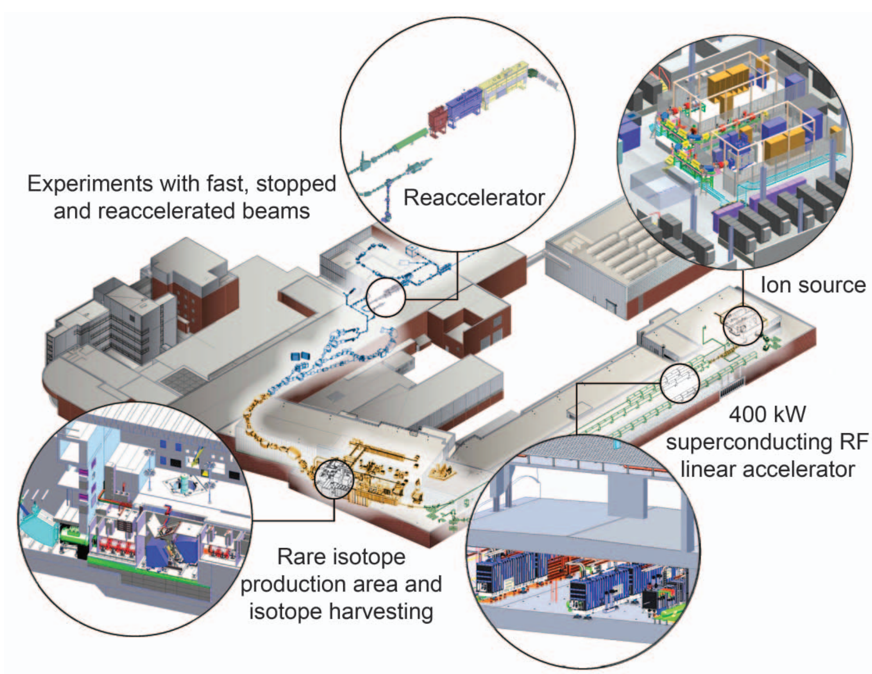

Figure 1. *Schematic drawing of the FRIB facility.*

Figure 2. *FRIB Logo illustrating its scientific program with four areas of inquiry.*

LRP, where it was noted that "Expeditiously completing the FRIB construction is essential. Initiating its scientific program will revolutionize our understanding of nuclei and their role in the cosmos."

There are approximately 300 stable and 3,000 known unstable (rare) isotopes. Estimates are that over 7,000 different isotopes are bound by the nuclear force [7]. It is now recognized that the many yet-undiscovered rare isotopes hold the key to understanding how to develop a comprehensive and predictive model of atomic nuclei, to accurately model a variety of astrophysical environments, and understand the origin and history of elements in the universe. These isotopes also offer the possibility to study nature's underlying symmetries and to explore new diagnostic techniques. The FRIB scientific program supports four areas of inquiry: the study of atomic nuclei, delineation of their role in the cosmos, their use to probe nature's fundamental laws, and the search for new applications of rare isotopes to meet societal problems [5, 6, 8].

The four areas of inquiry of FRIB's scientific program are highlighted in the FRIB logo, shown in Figure 2.

Nuclear Structure—Green Nucleus

The study of atomic nuclei is a core component of modern science, helping to connect the very small (quantum mechanics) with the unimaginably vast (stars, galaxies, and the cosmos). Thanks to a host of productive collaborations between theorists and experimentalists, the last few years have accelerated our understanding of the atomic nucleus. With FRIB and its suite of unique instrumentation, isotopic chains will be accessible from proton drip line to neutron drip line, permitting the study of the isospin dependence of the nuclear force and continuum effects over broad ranges. With the neutron drip line within reach for nuclei as heavy as mass $A = 120$, FRIB will access 80% of all isotopes predicted to exist for elements below uranium and will allow studies of neutron skins three or four times thicker than is currently accessible. Measurements of key properties will support the development of a predictive theory for the properties of atomic nuclei.

Nuclear Astrophysics—Blue Stars

Nuclear physics and astronomy are inextricably intertwined. In fact, more than ever, astronomical discoveries are driving the frontiers of nuclear physics while our knowledge of nuclei is driving progress in understanding the universe. Because of its powerful technical capabilities, FRIB will forge tighter links between the two disciplines. FRIB will provide access to most of the rare isotopes important in astrophysical processes. In particular, FRIB will reach into many key r-process nuclei and provide information about the masses, lifetimes, and detailed internal structure of rare isotopes encountered in stars. With this information, astronomical data can be reliably compared to models and features, or history of astrophysical sites inferred.

Fundamental Symmetries—Olive Mirror Symmetry

Nuclear and particle physicists study fundamental interactions for two basic reasons: to clarify the nature of the most elementary pieces of matter and determine how they fit together and interact. Most of what has been learned so far is embodied in the Standard Model of particle physics, a framework that has been both repeatedly validated by experimental results and is widely viewed as incomplete. Rare isotopes produced at FRIB will provide excellent opportunities for scientists to devise experiments that look beyond the Standard Model.

Potential Benefits—Yellow People

FRIB will provide research quantities of rare isotopes that can be used to develop new medical diagnostics and disease treatments. FRIB's isotopes can also play an important role in understanding small-scale objects by providing isotopes for implantation and probing subtle effects on the atomic scale. Finally, understanding how nuclei interact is essential to national security and design of a new generation of safer nuclear reactors. New applications made possible by rare isotopes have the potential to help solve societal problems.

FRIB Users

FRIB will be a U.S. Department of Energy Office of Science scientific user facility for research with rare isotopes. It will be open to researchers from around the world based on the merit of their proposals. A program advisory committee will begin to consider proposals for FRIB experiments approximately one year before the facility is operational. Prior to that, researchers have the opportunity to propose experiments at NSCL to establish research programs and equipment. The future and current users of the facility are organized into the FRIB User Organization (FRIBUO). See fribusers.org for details and activities of the organization. Currently the FRIBUO has approximately 1,400 members from more than 50 countries and more than 250 institutions worldwide. The FRIBUO has 19 individual working group preparing for various aspects of the FRIB scientific program. Some of these activities are outlined in the next sections.

FRIB Theory Alliance

Advances in theory provide the essential underpinning to the understanding of nuclei and their role in the cosmos. The FRIB Theory Alliance (FRIB-TA), working together with the theory community, has the goal to enhance theoretical efforts related to FRIB across multiple institutions. The Theory Alliance was highlighted in the 2015 LRP [6], as a new theory initiative: "We recommend the establishment of a national FRIB Theory Alliance. This alliance will enhance the field through the national FRIB Theory Fellow program and tenure-track bridge positions at universities and national laboratories across the U.S." The long-term goals of the FRIB-TA are [9]: (i) to deliver excellent research in theory relevant to the big science questions associated with FRIB; (ii) to serve as a focal point for stimulating continuous interactions between theory and experiment, drawing theory activity toward those problems relevant for the science at FRIB; (iii) to rejuvenate the field by creating permanent positions in FRIB theory across the country; (iv) to attract young talent through the national FRIB Theory Fellow program; (v) to strengthen theory in areas of most need; (vi) to foster interdisciplinary collaborations and build scientific bridges to wider theory communities; (vii) to coordinate a sustainable educational program in advanced low-energy nuclear theory; (viii) to coordinate international initiatives in the theory of rare isotopes. Since the official start of the Theory Alliance on 1 June 2015, a number of activities have been initiated that pave the way toward these long-term goals. See fribtheoryalliance.org for details.

FRIB Major Equipment Plans

FRIB will use a combination of existing experimental equipment available currently at NSCL [4], equipment brought to the facility by users, and new equipment planned or under development. Users have the opportunity to develop equipment and establish programs at NSCL prior to FRIB operation. Existing equipment includes the stopped-beam area and Beam Cooler and Laser (BECOLA) spectroscopy system and Penning traps for mass measurement. Current equipment at NSCL also includes, the High Resolution Array (HiRA), the Summing NaI (SuN) total absorption spectrometer, a liquid-hydrogen target, the active target time-projection chamber (AT-TPC), the Jet Experiments in Nuclear Structure and Astrophysics (JENSA) gas-jet target, the CAESsium iodide ARray (CAESAR) for gamma-ray detection, the S800 Spectrograph, the Modular Neutron Array and Large multi-Institutional Scintillator Array (MoNA-LISA) neutron detection array, and the Low-Energy Neutron Detector (LENDA) array for inverse kinematic charge-exchange studies.

The Separator for Capture Reactions (SECAR) is under construction and will be a recoil separator at NSCL and FRIB that is optimized for measurements of low-energy capture reactions of importance for nuclear astrophysics [10]. SECAR is jointly funded by the DOE Office of Science and the U.S. National Science Foundation and it is currently being installed in the ReA3 low-energy beam area. Early completion for this project could be in 2020. Measurements with SECAR will focus on capture reactions needed to understand stellar explosions, including novae, X-ray bursts, supernovae, and other extreme astrophysical environments such as the interiors of very massive stars. SECAR is designed to have a performance that will allow the full range of direct capture measurements of protons and alpha particles to be measured. It is the flag ship experiment for the FRIB nuclear astrophysics community.

A key component of the FRIB scientific program will be gamma-ray spectroscopy at high beam energies and with reaccelerated beams. The key instrument for these studies will be the 4π γ-ray tracking array GRETA (Gamma-Ray Energy Tracking Array) [11]. GRETA will be a 4π shell made of 120 hexagonal germanium crystals, tapered and shaped to enable close packing. The first phase of the GRETA project, led by researchers from Lawrence Berkeley National Laboratory, is the existing GRETINA array, which is approximately one-quarter of the full GRETA array, and has run experimental science campaigns at Argonne National Laboratory (ANL) and NSCL. GRETA and GRETINA mark a major advance in the development of γ-ray detector systems and provide order-of-magnitude gains in sensitivity compared to non-tracking existing arrays. A photograph of the GRETINA array at the target position of the NSCL S800 spectrograph is shown in Figure 3. Gamma-ray tracking with the array uses highly-segmented hyper-pure germanium crystals together with advanced signal processing techniques

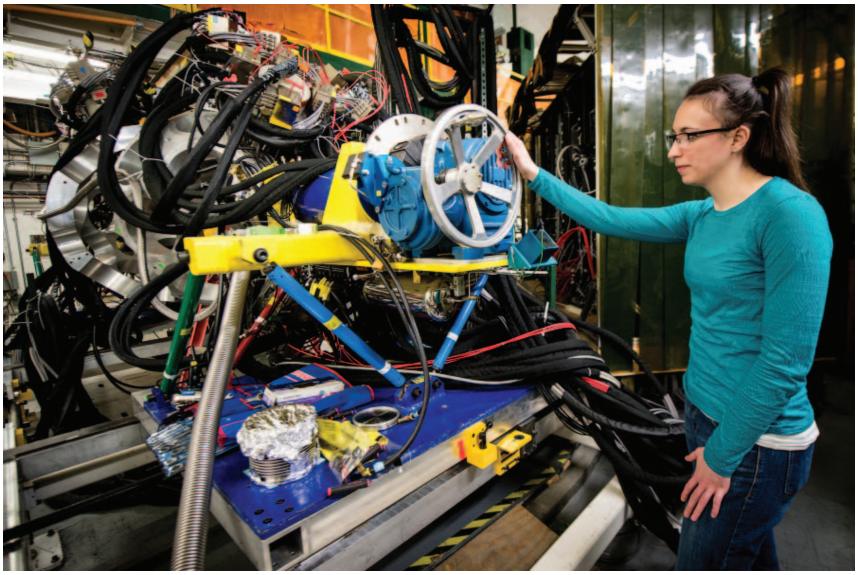

Figure 3. *NSCL student Rachel Titus with the GRETINA array located at the target position of the S800 at NSCL.*

to determine the location and energy of individual γ-ray interactions, which are then combined to reconstruct the incident γ-ray first interaction point and direction.

The planned High Rigidity Spectrometer (HRS) will be the centerpiece of FRIB's fast-beam program [12]. It is needed because the current spectrograph, the S800, is limited to a bending power of 4 T-m, which limits the top energy and often intensity of the most neutron-rich beams. The HRS will have an 8 T-m limit and large solid angle and momentum acceptance, which will provide an order-of-magnitude higher sensitivity for key beams such as ^{60}Ca. The high magnetic rigidity of the HRS will match the rigidities for which rare-isotope production yields at the FRIB fragment separator are maximum across the entire chart of nuclei and enable experiments with the most exotic, neutron-rich nuclei available at FRIB. The first element of the HRS after the target station is the sweeper dipole, which diverts charged particles toward a focusing beam-line that transports particles to the spectrometer dipoles and the focal plane detectors. The spectrometer dipoles provide the precise exit channel characterization with momentum and particle identification resolutions required for the broad scientific program with the HRS. It is anticipated that GRETA and MoNA-LISA will often run in coincidence with the HRS. A large collaboration of scientists from across the United States is involved in the design of this device.

Decay spectroscopy will be one of the primary discovery tools at FRIB. It will allow the characterization of nuclear properties at the limits of stability where new phenomena are expected. The FRIB Radioactive Decay Station Working Group, led by researchers from the University of Tennessee and Oak Ridge National Laboratory, is investigating the design and construction of a new system that will take advantage of the exciting opportunities provided by FRIB. The plan is to build-up an efficient, state-of-the-art detection station equipped with instruments capable of characterizing various forms of radiation such as gamma rays, conversion electrons, beta particles, protons, alpha particles, and neutrons that will be required for decay studies at FRIB.

A critical piece of experimental equipment for the reaccelerated beam program will be a recoil separator that can filter out unreacted beam particles and separate and characterize the reaction residues of interest for experiments above the Coulomb barrier. A novel concept for a very large acceptance device has been selected by the user community as the solution for FRIB. Engineering studies are underway for the Isochronous Separator with Large Acceptance (ISLA). Researchers from Bucknell University, MSU, and ANL are leading the design. ISLA will consist of four large dipoles arranged in a circular configuration and ions will be identified by their time of flight. The advantages of the proposed system are a large solid-angle, large momentum, and charge-state collection, high mass resolving power, variable incoming beam angle, and operation with high-rigidity beams. Physical separation of isotopes can be obtained by deflection of unwanted ions that arrive at other times. The plan is to design the device to accommodate major detector systems such as GRETA and allow the incoming beam angle to be varied by up to 40 degrees.

FRIB Construction

FRIB is overall more than 75% complete and beneficial occupancy of all civil construction is planned for March 2017. Prior to building completion, an increasing number of technical installations has already begun including major parts of the FRIB cryoplant.

The FRIB Project began in 2008 when the DOE-SC selected a site and initiated the project. In August 2013, the DOE-SC approved Critical Decision 2/3a (project baseline and start of civil construction). Civil construction

Figure 4. *View of construction site on groundbreaking day in March 2014. The tent that held the groundbreaking-ceremony guests is shown on the far right.*

Figure 5. *View of construction site in March 2015.*

Figure 6. *View of construction site in March 2016.*

Figure 7. *View of the construction site as of December 2016.*

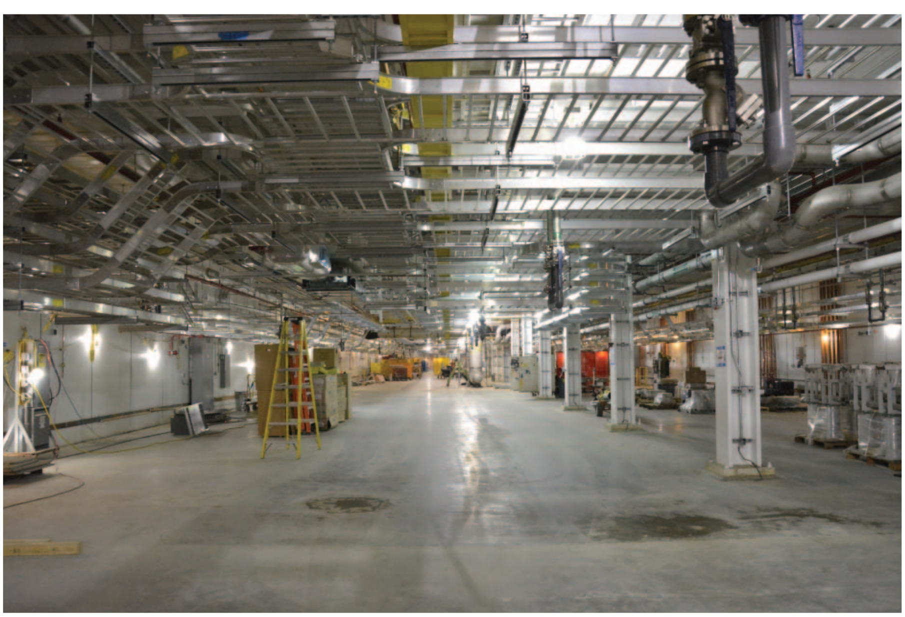

Figure 8. *A view inside the linear accelerator tunnel in June 2016.*

began in March 2014 with a groundbreaking ceremony, and technical construction began in October 2014. The project team began moving technical equipment into the front-end building (where the ion sources start the beam) in 2016, and extracted a first beam in 2016—12 months earlier than planned.

The following series of photographs (Figures 4–8) illustrate the progress in FRIB construction from the ground breaking in March 2014 to the status of the construction site in December 2016. Civil construction was substantially completed in March 2017 and technical installation continues. Commissioning of the first parts of the FRIB accelerator chain has begun already in 2016.

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