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The Facility for Rare Isotope Beams

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Abstract. The Facility for Rare Isotope Beams (FRIB) is a United States Department of Energy user facility currently under construction on the campus of Michigan State University. Based on a 400 kW, 200 MeV/u heavy-ion driver linac, FRIB will deliver high-quality fast, thermalized, and re-accelerated beams of rare isotopes with unprecedented intensities to a variety of experimental areas and equipment. New science opportunities at the frontiers of nuclear structure, nuclear astrophysics, fundamental symmetries, and societal applications will be enabled by this future world-leading rare-isotope beam facility.

1 Introduction

Many questions at the frontiers of nuclear structure, nuclear astrophysics and fundamental symmetries can only be answered with increased production of rare isotopes. These isotopes also have the potential to be used in novel practical applications that benefit society. Based on these motivations, the United States low-energy nuclear science community has, for decades, been planning to establish a next-generation user facility for the production of rare-isotope beams [1]. These plans are now being realized with construction of the U. S. Department of Energy's $730M Facility for Rare Isotope Beams (FRIB) underway on the campus of Michigan State University. Figure 1 shows the projected rare isotope fast-beam rates available at FRIB, which are orders of magnitude higher than currently available rates and include thousands of undiscovered isotopes. In this contribution, we briefly review the design of FRIB, report on the status of FRIB construction, and outline selected proposals for major new experimental instrumentation to be used at FRIB.

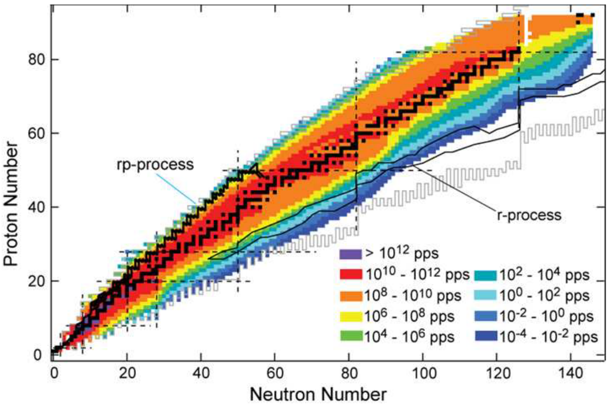

Figure 1. Chart of nuclides showing projected fast rare-isotope beam rates provided by FRIB in particles per second (pps). For reference, stable nuclides (black squares), the traditional closed nuclear shells (dashed lines), estimates of the astrophysical *r*- and *rp*-process paths (solid black lines), and possible nucleon drip lines (solid gray lines) are depicted. A detailed rate calculator can be found at Ref. [2].

2 FRIB Design and Construction

The layout of FRIB is shown in Figure 2. A 400 kW, 200 MeV/u heavy-ion driver linear accelerator (linac) [3], folded into three segments to optimize the use of space, will provide primary beams of stable ions that impinge upon a relatively light production target. Rare isotopes produced by nuclear fragmentation and in-flight fission in the transmission target will be constrained to a forward cone by conservation of momentum, where they will enter a fragment separator. The fragment separator [4] will be tuned to select the rare isotope ions of interest and deliver them either to a fast-beam experimental area, or to a beam stopper [5] that either outputs low-energy thermalized ion beams to experimental areas or to the Re-Accelerator (ReA) [11], which delivers high-quality ion beams of 0.3 to 12 MeV/u to experimental areas.

2.1 FRIB Linear Accelerator

The layout of the subterranean FRIB linac [3] is shown in Figure 3. The front end of FRIB will accelerate stable ions in multiple charge states from rest in an electron cyclotron resonance ion source, through a low-energy beam transport system and a radio-frequency quadrupole (RFQ) accelerator. After the RFQ, a medium-energy beam-transport system will inject the 0.3 MeV/u beam to

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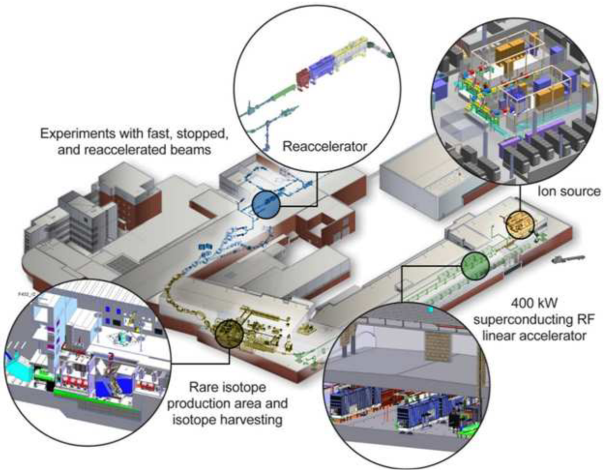

Figure 2. General layout of FRIB.

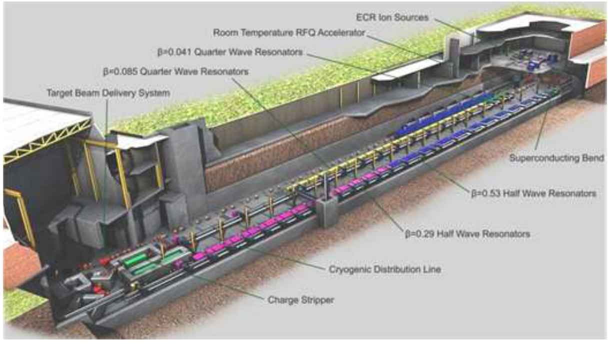

Figure 3. Scale drawing of FRIB's superconducting radiofrequency driver linear accelerator.

the first segment of the driver linac, which will accelerate the beam to at least 17.5 MeV/u using superconducting radiofrequency cryomodules. Following this segment, the beam will pass through a liquid-lithium charge stripper [6, 7] to increase the downstream acceleration efficiency, and enter the first 180-degree folding segment of room temperature magnets. The next segment of the linac will accelerate multiple charge states up to a terminal energy of at least 200 MeV/u for uranium ions (and higher for lighter ions) and include a second folding segment of superconducting magnets. The beam will then effectively coast along a straight path through focusing and diagnostic elements until it reaches magnets that direct up to 400 kW of beam power onto the production target. The coasting region provides space for 12 more cryomodules that could be installed in the future to upgrade the beam energy to 400 MeV/u for uranium.

2.2 FRIB Target Systems

The layout of the FRIB target systems [8, 9] is shown in Figure 4. The main challenges for the FRIB target systems are the high power density of the beam and the high radiation fields produced by its interaction with the target and beam dump. Currently, the target design consists of a multi-slice rotating graphite disk target that distributes the deposited beam power from the 1 mm diameter beam spot over a relatively large effective area. The target systems are designed to accommodate radiation fields that will be present even with the upgraded beam energy. For example, shielding, radiation-resistant materials, air filtering, radiation-detection equipment and personal access systems are incorporated into the design. The radiation fields will be sufficiently high that remote handling of the targets and other components will be necessary; a target change is anticipated to take approximately 24 hours. A potential upgrade option for FRIB is to add a second target that could provide isotope separation online (ISOL) beams in parallel with in-flight ones providing multi-user capability.

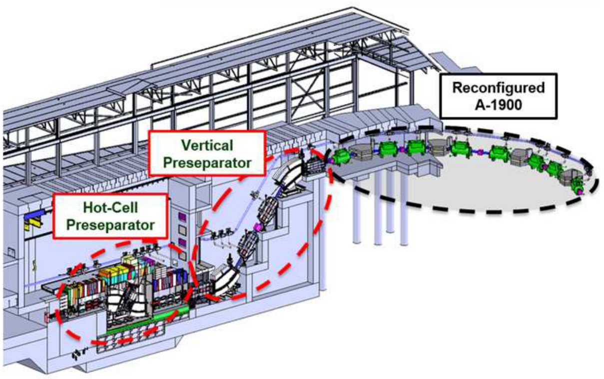

Figure 4. Scale drawing of FRIB's sub-surface production target and surface-level fragment separator.

2.3 FRIB Fragment Separator

The layout of the FRIB fragment separator [4] is shown in Figure 4. The separator is designed to have a large acceptance for secondary rare-isotope beams produced by interaction of the primary beam with the production target, to direct the un-reacted primary beam ions to a beam dump, and to output a high purity beam of a particular rare isotope. The hot-cell pre-separator will employ radiation-resistant magnetic components that direct the un-reacted primary beam to a rotating water-filled beam dump. The vertical pre-separator will make a coarse initial selection of isotopes from the broad (A, Z) distribution of fragments produced by reactions in the target and deliver them to a separator at ground level. The ground-level separator will be comprised of reconfigured components from the existing A1900 fragment separator at the National Superconducting Cyclotron Laboratory (NSCL) [10] and deliver in-flight beams of unprecedented purity and intensity into the current NSCL building, which will be subsumed by FRIB. The separator design will also incorporate provisions for isotope harvesting.

2.4 FRIB Thermalized and Re-accelerated beams

Thermalized and re-accelerated FRIB beams are closely linked to the current NSCL facility [10], where the equipment and techniques needed to provide and utilize these beams are already being developed *in situ*. A linear gas cell to thermalize fragmented beam ions and extract them has already been installed and successfully tested with in-flight beams at NSCL [5, 13]. Complementary beam-thermalization techniques [5] are also being actively developed including a cyclotron gas-stopper (for light elements), a cryogenic linear stopper (for enhanced efficiency), and a solid stopper (for particularly intense beams of certain elements). Thermalized beams can be delivered to experiments involving ion trapping or laser spectroscopy, for example, or charge-bred [12] and injected into the re-accelerator, ReA [11].

ReA is a linear accelerator based on the same superconducting radiofrequency cryomodules as FRIB that will provide high-quality rare-isotope beams between 0.3 and 12 MeV/u (for uranium) to two experimental halls (Figure 2). The first stage of ReA has already been built and will accelerate rare-isotope beams into the ReA3 experimental hall, which will accept beams between 0.3 and 3 MeV/u. In the future, ReA will be extended using more cryomodules to deliver beams of up to 12 MeV/u to the existing ReA6/12 experimental hall.

2.5 FRIB Technical Developments and Construction

Many technical milestones related to FRIB have been reached in the past few years including the construction of a new high bay [14] for the manufacture of superconducting radiofrequency cavities for the linac, tests of pre-produced resonant cavities with quality factors that already exceed FRIB performance goals [6], validation of the liquid lithium charge-stripping scheme [6, 7], building and testing of a prototype production target with high-power electron beams [15], installation and commissioning of the linear gas catcher [5, 13], construction of the cyclotron gas catcher [16], and the re-acceleration of a rare-isotope beam into the ReA3 hall [17].

The most conspicuous advancement is the breaking of ground that signified the beginning of FRIB civil construction on March 3^{rd}, 2014. 1400 cubic yards of Earth have been excavated to a depth of approximately 3 stories and the first foundational concrete was poured on July 23^{rd}, 2014 (Figure 5). Technical construction is scheduled to begin in October, 2014.

3 Selected Proposals for Major New FRIB Instrumentation from FRIB Users

At the time of CGS15, the growing independent FRIB Users Organization (FRIBUO) [19] had 1386 members from 55 countries. The existing NSCL facility is already providing early science opportunities for FRIB users with fast, thermalized, and re-accelerated beams enabling the ongoing development of experimental equipment and techniques that will be applied at FRIB. Users have many creative ideas for new experimental equipment to be placed in the 47000 sq. ft. of experimental area at FRIB, with upgrade space of more than 60000 sq. ft. In this section we touch upon four proposals for major new experimental instrumentation at FRIB: GRETA, HRS, ISLA, and SECAR[1].

Figure 5. Photograph of FRIB's first foundational concrete being poured on July 23^{rd}, 2014. The eastward view toward the future position of the ion source shows the subsurface space that will house the linear accelerator. Real-time images of the FRIB construction site can be found at Ref. [18].

3.1 The Gamma Ray Energy Tracking Array (GRETA)

The Gamma Ray Energy Tracking Array (GRETA) [20] is a next-generation array of germanium detectors optimized for γ rays emitted following reactions of fast rare-isotope beams with energies of to up 200 MeV/u (Figure 6). This 4π sr array consists of 30 segmented detector modules with 4 crystals per module and 36 electrical segments per crystal. GRETA will enable tracking of Compton scattered γ rays through the segmented germanium crystals enabling reconstruction of the position of first interaction with 2 mm resolution and summing of the energy deposition from all interactions. The position resolution allows for an improved Doppler correction over current-generation arrays, which improves the γ-ray energy resolution. The large solid-angle coverage and summing capabilities improve the full-energy peak efficiency and the peak-to-background ratio. The Gretina array, consisting of GRETA modules covering over 1π sr, has already been commissioned at Lawrence Berkeley National Laboratory, used in a successful campaign of 25 experiments at NSCL, and is currently being used in a campaign at Argonne National Laboratory's ATLAS facility.

3.2 The High-Rigidity Spectrometer (HRS)

The High-Rigidity Spectrometer (HRS) [21] will enable experiments with the most rigid and neutron-rich rare-isotope beams at peak intensities produced by the FRIB

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[1] The broad suite of existing and proposed equipment to be used at FRIB is too extensive to review comprehensively in this short contribution. Due to these constraints, the author made a subjective and incomplete selection of proposed devices to discuss.

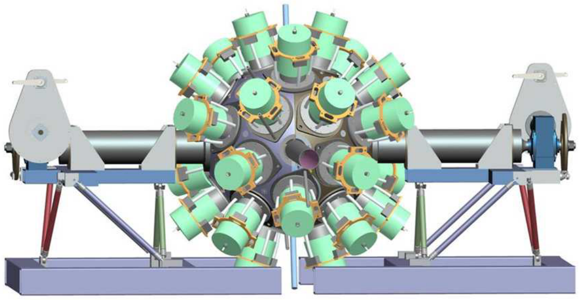

Figure 6. Technical drawing of the Gamma Ray Energy Tracking Array (GRETA).

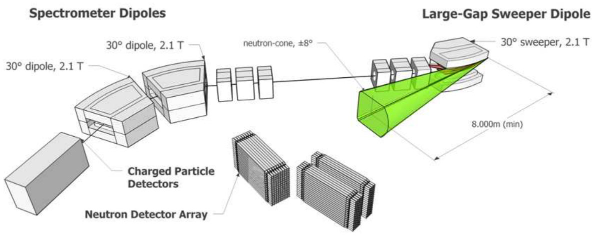

Figure 7. Conceptual drawing of the High-Rigidity Spectrometer (HRS)

fragment separator. In addition to addressing key scientific drivers for the construction of FRIB, it also extends scientific opportunities to experiments with rare-isotope beams at the highest energies available at FRIB ($\approx 200 - 250$ MeV/u). In Figure 7, a pre-conceptual design of the HRS is shown. It consists of a sweeper stage, which separates the charged particles produced at the reaction target from fast neutrons, and a spectrometer stage, which is used to momentum analyze and identify the charged fragments up to high mass ($A \approx 200$). The HRS will be fed by a large-acceptance beam line from the FRIB fragment separator in order to minimize transmission losses prior to the reaction target. An important consideration for the design of the HRS is the capability to place a wide variety of auxiliary detectors around the target station, such as GRETA or charged-particle and neutron detectors. In addition, the sweeper dipole magnet will have a large gap to ensure unperturbed transmission of fast neutrons to neutron detection arrays [22], as shown in Figure 7.

3.3 The Isochronous Separator with Large Acceptance (ISLA)

The Isochronous Separator with Large Acceptance (ISLA) [23, 24] is a general-purpose M/Q magnetic separator consisting of four dipoles that is designed for use with re-accelerated rare-isotope beams with energies on the order of 10 MeV/u in the ReA12 hall (Figure 8). High-quality beams at these energies are appropriate for studies of transfer reactions, multi-step Coulomb excitation, massive transfer in deep inelastic scattering, and fusion reactions. To this end, ISLA has a dispersive focal plane following the first two dipoles and an isochronous achromatic focal plane following the final magnet, providing excellent particle identification and rejection of un-reacted beam. The M/Q resolving power will be greater than 1000. Large acceptances including 64 msr for solid angle and ±10 % for momentum will make optimum use of the beams. The target position will have space for detector arrays such a GRETA and an incoming beam swinger will allow for operation off zero degrees without moving ISLA. The focal plane will be compact to facilitate decay studies of residues and a low-energy radio-frequency kicker will allow physical separation of the reaction products by M/Q.

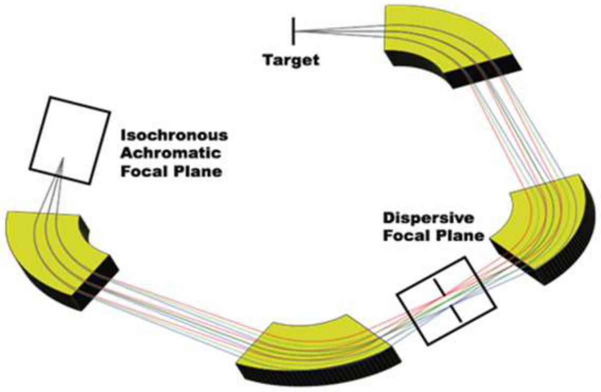

Figure 8. Conceptual drawing of the Isochronous Separator with Large Acceptance (ISLA). Dipole magnets are shown in yellow and ion paths are shown with solid lines.

3.4 The Separator for Capture Reactions (SECAR)

The Separator for Capture Reactions (SECAR) [25] is an electromagnetic separator that is specialized to measure the radiative captures of protons and alpha particles on proton-rich rare isotopes at the energies encountered in explosive astrophysical environments such as classical novae and type I x-ray bursts (Figure 9). Re-accelerated rare-isotope beams of several hundred keV/u from ReA3 will be incident upon a windowless gas target of H or He [26]. Reaction products and un-reacted beam have effectively the same momentum as they exit the target but the ratio is typically between $1{:}10^{11}$ and $1{:}10^{15}$ due to the low reaction cross sections making their separation a challenge. Since their mass differs, their velocity also differs and two stages of Wein velocity filters can be used to select the reaction products after a charge state is selected using dipole magnets. The products in that charge state can be transmitted with 100% efficiency to the end of the separator, where any scattered beam that may have leaked through the separator is cleaned up with one more section of dipoles followed by focal-plane detectors. Further discrimination of reaction products from leaky beam can be accomplished using coincidences with prompt γ-ray detectors around the target and/or time of flight through SECAR.

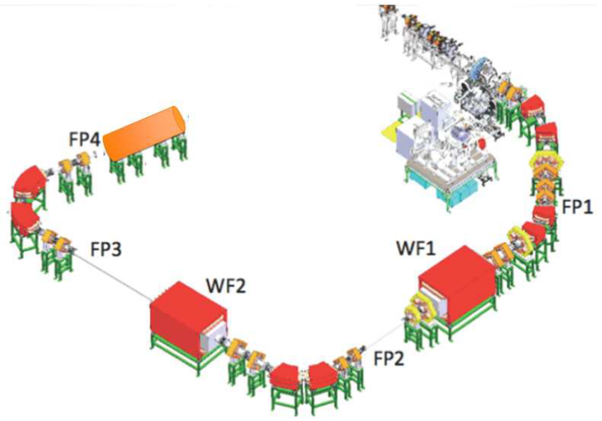

Figure 9. Technical drawing of the Separator for Capture Reactions (SECAR). Wien filters are denoted by "WF" and focal planes are denoted by "FP".

4 Conclusions and Outlook

In summary, FRIB is a United States Department of Energy user facility on the campus of Michigan State University that is currently under civil construction with technical construction scheduled to begin in October, 2014. The existing NSCL facility will be subsumed by FRIB, but will continue to operate independently during FRIB construction until the two are physically connected. FRIB is scheduled to be completed in June, 2022 and managed to early completion by December, 2020. Upon completion, FRIB will provide fast, thermalized, and re-accelerated rare isotope beams to a growing international community that numbers 1386 as of the CGS15 conference in August, 2014, yielding scientific advances in nuclear structure, nuclear astrophysics, fundamental symmetries, and societal applications.

5 Acknowldegments

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