THE FRIB SUPERCONDUCTING LINAC: STATUS AND PLANS*

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Abstract

With an average beam power two orders of magnitude higher than operating heavy-ion facilities, the Facility for Rare Isotope Beams (FRIB) stands at the power frontier of the accelerator family. This report summarizes the current design and construction status as well as plans for commissioning, operations, and upgrades.

INTRODUCTION

During the past decades, accelerator-based neutron-generating facilities, such as SNS [1], J-PARC [2], PSI [3], and LANSCE [4], advanced the frontier of proton beam power to the 1 MW level, as shown in Fig. 1; the beam-on-target power is the product of the average beam current and the beam kinetic energy [5]. FRIB is designed to advance the power frontier for heavy ions by more than two orders of magnitude, to 400 kW.

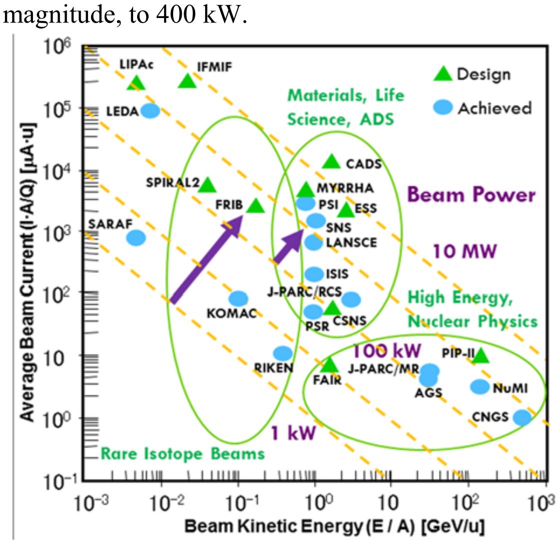

Figure 1: Hadron accelerator power frontier, showing the beam energy, current and average power on target.

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In August 2014, the US Department of Energy's Office of Science (DOE-SC) approved Critical Decision-3b (Approve Start of Technical Construction) for the FRIB project (Fig. 2). The total project cost for FRIB is $730M, of which $635.5M is provided by DOE and $94.5M is provided by Michigan State University (MSU). The project will be completed by 2022. "When completed, FRIB will provide access to completely uncharted territory at the limits of nuclear stability, revolutionizing our understanding of the structure of nuclei as well as the origin of the elements and related astrophysical processes" [6].

In creating this new one-of-a-kind facility, FRIB builds upon the achievements of the National Superconducting Cyclotron Laboratory (NSCL), a National Science Foundation (NSF) user facility at MSU. Starting in 2014, the re-accelerator (ReA3), consisting of a radio-frequency quadrupole (RFQ) and a superconducting radio-frequency (SRF) linac, was constructed and commissioned to accelerate beams of rare isotopes. The FRIB project scope includes a high-power driver accelerator, a high-power target, and fragment separators.

The FRIB driver accelerator is designed to accelerate all stable ions to energies >200 MeV/u with a beam power on the target of up to 400 kW. The driver accelerator consists of a 47 m long Front End containing electron-cyclotron-resonance (ECR) ion sources and a room temperature RFQ followed by a 472 m long SRF linac with quarter-wave-resonators (QWR) of β_0=0.041 and 0.085 and half-wave-resonators (HWR) of β_0=0.29 and 0.53 in a folded layout to facilitate charge stripping and beam collimation and to accommodate the limited real estate footprint in the center of the MSU campus [7].

FRIB accelerator systems design and construction have been facilitated under work-for-others agreements with many DOE-SC national laboratories including ANL, BNL, FNAL, JLab, LANL, LBNL, ORNL, and SLAC, and in collaboration with institutes worldwide including BINP, KEK, IHEP, IMP, INFN, INR, RIKEN, TRIUMF, and

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Tsinghua University. The cryogenic system is developed in collaboration with JLab. The recent experience gained from design of the cryogenic system for the JLab 12 GeV upgrade is used in the design of both the refrigerator cold box and the compression system. The liquid lithium charge stripping system is developed in collaboration with ANL. BNL collaborated on the development of the alternative helium gas stripper. The SRF development benefited greatly from the expertise of the low-β SRF community. FRIB has been collaborating with INFN on resonator development and with ANL on RF coupler and tuner development, and is assisted by JLAB on cryomodule design, by KEK on superconducting solenoids, and by FNAL and JLab on cavity treatments. FRIB is collaborating with LBNL on the development of VENUS-type ECR ion sources.

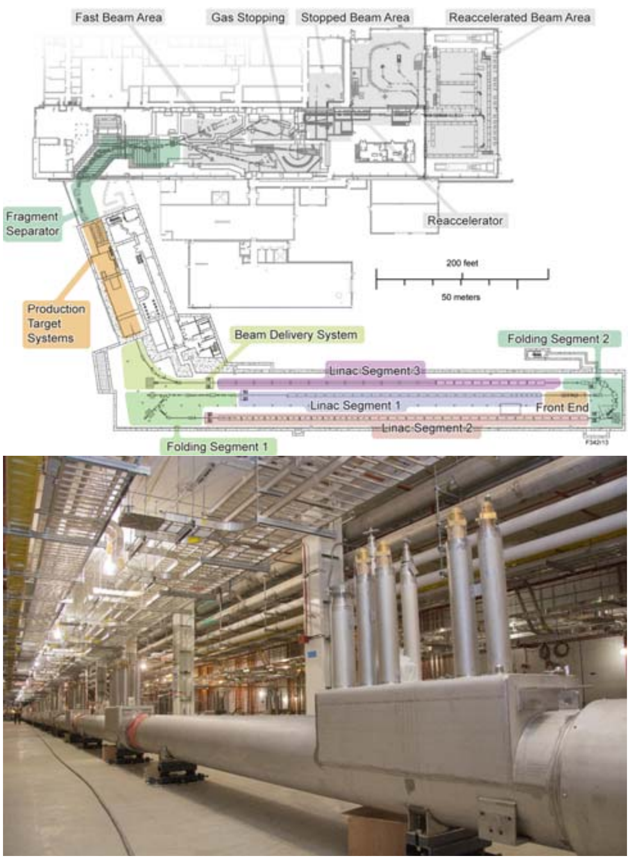

Figure 2: Top: layout of the FRIB driver accelerator, target, and fragment separator (colored areas) and existing infrastructure (gray). Bottom: photograph of the FRIB tunnel under construction for the SRF driver linac.

MAJOR TECHNOLOGY DEVELOPMENT

Major accelerator R&D and subsystem prototyping are completed. These systems include integrated cryogenics, "bottom-up" cryomodules of low-β cavities and solenoids, charge stripping, and machine protection for high-power low-energy heavy ion beams.

Integrated Cryogenics and SRF Cryomodule

An integrated design of the cryogenic refrigeration, distribution, and cryomodule systems is key to efficient SRF operations. The prototype distribution module and cryomodule have been successfully cold-tested together (Fig. 3) [8].

Low-β cryomodules built for MSU's 3 MeV/u Reaccelerator (ReA3) use a traditional top-down design, with the cavities and solenoids hanging from a strong-back. To facilitate efficient assembly, simplify alignment, and allow U-tube cryogenic connections for maintainability, FRIB adopted an innovative bottom-up cryomodule design with the resonators and solenoids supported from the bottom [9]. The cryogenic headers are suspended from the top for vibration isolation. This design was successfully tested and validated in 2015.

Figure 3: Top: test bunker with FRIB-type cryogenic distribution connections to β_0=0.085 cryomodule. Bottom: pre-production β_0=0.53 cryomodule under assembly, with 8 cavities and one solenoid.

Liquid Lithium Charge Stripping

As a conventional stripping foil is not an option for intense heavy ions, FRIB uses a liquid lithium film moving at a speed of ~50 m/s. Tests with a proton beam produced by the LEDA source demonstrated that power depositions similar to the FRIB uranium beams are achievable without destroying the film [10]. Present work focuses on component fabrication (Fig. 4), including the electromagnetic pump for lithium circulation.

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Figure 4: Main vacuum chamber of the liquid lithium charge stripper under assembly.

Multi-layered Machine Protection

Machine protection is challenging for FRIB's intense low-energy heavy ion beams due to the low detection sensitivity and high power concentration in a short range. Furthermore, due to the folded geometry of the driver linac, beam loss at high energy interferes with loss detection for low-energy beams [11]. Innovative techniques include the halo monitor ring [12] for high-sensitivity loss detection and current-monitoring modules for critical magnet power supply inhibition. FRIB adopts multi-time scale and multi-layer approaches (Table 1).

Table 1: Machine Protection for the FRIB Driver Linac

Mode	Time	Detection	Mitigation
FPS	~35 µs	LLRF controller Dipole current monitor Differential BCM Ion chamber monitor Halo monitor ring Fast neutron detector Differential BPM	LEBT bend electro-static deflector
RPS (1)	~100 ms	Vacuum status Cryomodule status Non-dipole PS Quench signal	As above; ECR source HV
RPS (2)	>1 s	Thermo-sensor Cryo. heater power	As above

LONG-LEAD PROCUREMENTS

FRIB long-lead procurements were launched in 2012, two years before start of construction. They include the high power ECR source, the RFQ (Fig. 5), niobium material for SRF cavities, pre-production cavities, the 4.5 K refrigeration "cold box" (Fig. 6), and cryogenic distribution. These programs are progressing towards timely delivery to meet the project construction and commissioning schedule.

Figure 5: The FRIB 80.5 MHz, 5-segment, 4-vane RFQ after brazing, assembly, leak checking, and tuning.

Figure 6: The upper 4 K cold box installed at FRIB.

PRODUCTION INFRASTRUCTURE

The 2500 m^2 "SRF Highbay" at MSU houses areas for material inspection, cavity coordinate measurements and alignment checks, vacuum furnace degassing, parts cleaning, chemical etching, high-pressure water rinsing, SRF coupler conditioning, cavity Dewar testing, cold mass assembly, and cryomodule testing (Figs. 7 and 8). This facility, together with the cryomodule assembly area and the machine shop, supports the production throughput of testing five cavities per week and one cryomodule per month [13].

Figure 7: Newly commissioned SRF Highbay at MSU.

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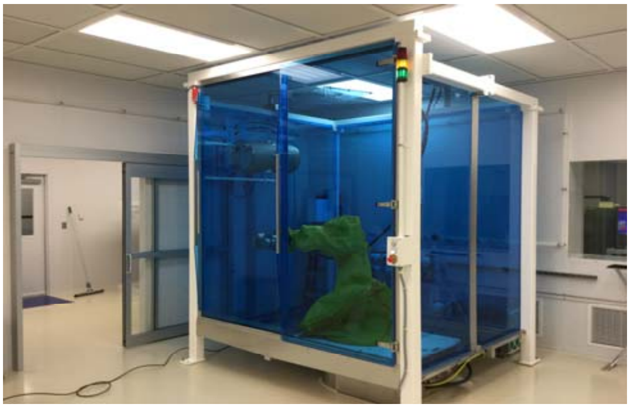

Figure 8: The robotic high-pressure water rinsing system equipped with liquid particle counting in the clean room.

CONSTRUCTION STATUS

Measured by earned-value project controls, FRIB accelerator construction is more than 50% complete. About 65% of the total $289M accelerator construction is for material and work-for-others contracts, and about 35% is for in-house labor. At the peak of construction, a total of about 160 full-time-equivalent staff manage technical aspects of the procurements and perform in-house work in the areas of accelerator physics and integration, controls (hardware, high level, personnel protection, machine protection, and global timing), mechanical engineering, electrical engineering (RF, power supply, diagnostics, and electronics), cryogenics, cryomodule, front end, and installation (Figs. 9-13).

About 90% of baselined major procurements (orders above $50k) have been either spent or committed. Both domestic and foreign industrial providers are engaged based on best-value practices. Intense vendor follow-up is in place to ensure timely execution of contracts.

In-house work focuses on design, prototyping, system requirements and interface definition, contract statement-of-work and acceptance criteria listing development, vendor technical management, in-house fabrication, installation, testing, and commissioning. In-house fabrication includes preparation and testing of SRF cavities, cryomodule assembly, and controls algorithm development.

Figure 9: The FRIB general-purpose digital board (FGPDB) shared by several systems, including machine protection, controls, diagnostics, and low-level RF.

Figure 10: Test of the pneumatic control valve for the Low Energy Beam Transport (LEBT) beam plug as part of the Personnel Protection System.

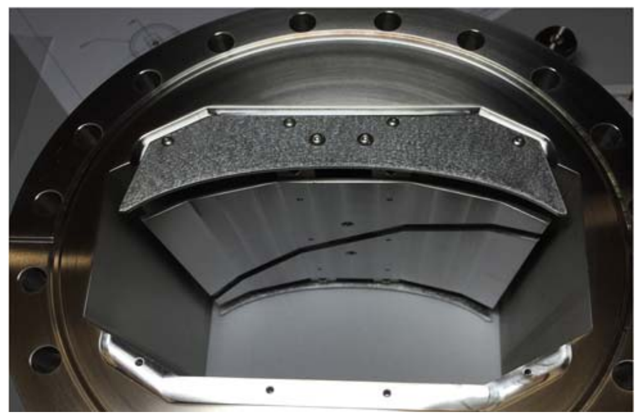

Figure 11: Elliptical beam position monitor for multi-charge state beam in Folding Segment dispersive section.

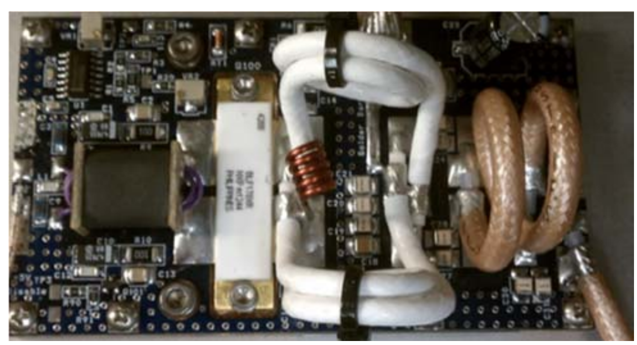

Figure 12: High-efficiency variable-bias solid-state push-pull RF amplifier for SRF cavities.

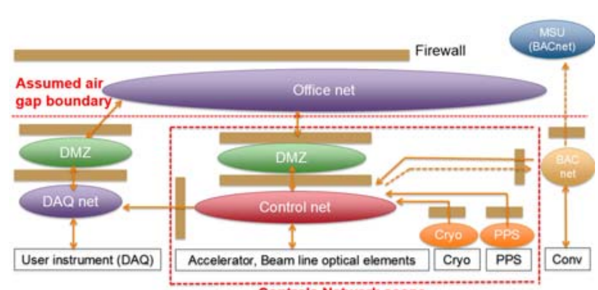

Figure 13: FRIB controls network layout with consideration of cyber security.

INSTALLATION AND COMMISSIONING

FRIB project critical path items include linac tunnel construction, cryogenic area construction, cryogenic plant and distribution fabrication and assembly, cryomodule test and installation, and linac commissioning. Accelerator installation has started in parallel with conventional facility construction before the beneficial occupancy date. Installation is performed in four main categories (mechanical engineering, electrical engineering, cryogenics, and controls) starting with the Front End and the cryoplant (Figs. 14-17).

The accelerator commissioning is divided into 8 steps, following the beam trajectory starting from the Front End. Each step of commissioning is contingent upon a successful accelerator readiness review (ARR). Each ARR is preceded by several device readiness reviews (DRR) of subsystems. The very first DRR was recently conducted on the FRIB room-temperature ion source.

Successful completion of commissioning of the entire FRIB facility is defined by achieving the Key Performance Parameters (KPP) (Critical Decision-4, CD-4) that include accelerating a heavy ion beam of ^{36}Ar with energy >200 MeV/nucleon and a beam current >20 pnA, producing a fast rare isotope beam of ^{84}Se, stopping a fast rare isotope beam in gas, and reaccelerating a rare isotope beam.

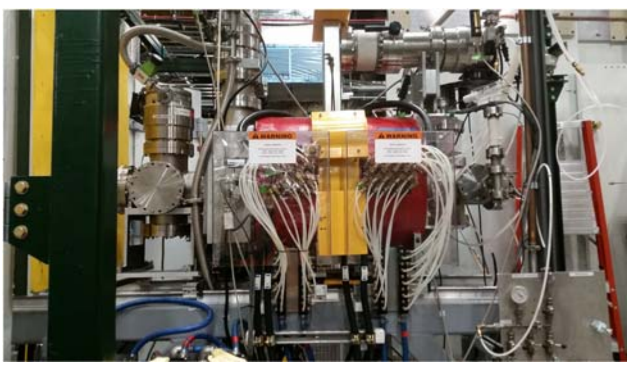

Figure 14: ARTEMIS 14 GHz ECR ion source installed on the high-voltage platform.

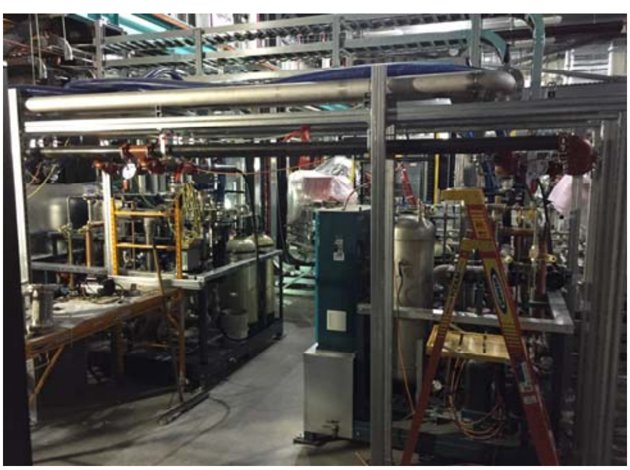

Figure 15: RFQ water-cooling skids installed in the service building.

Figure 16: Left: ion source isolation transformer (350 kVA, 100 kV). Right: facility electrical distribution gear installed in the service building.

Figure 17: Warm compressors for the refrigeration system installed in the cryogenic building.

OPERATIONS AND UPGRADES

After reaching the project CD-4 milestone for routine operations as a user facility, we expect to steadily increase the beam power and raise the machine availability, reliability and tuneability to the full design capability in 4 years. Beam power ramp up consists of three elements: fine-tuning of components dedicated for high power beam operation, including the high power ion source, liquid lithium charge stripper, and high power charge selector; tuning for multi-charge-state beam acceleration; and beam quality improvement, including beam loss mitigation. In 2016, a review was conducted by DOE-SC's Office of Nuclear Physics to assess the operating cost of the FRIB complex.

Science-driven upgrade plans include doubling the linac output energy by filling the vacant slots in the linac tunnel with higher-β_0 cryomodules (e.g. β_0=0.65), simultaneous heavy ion and light ion acceleration, an ISOL (Isotope Separation On-Line) option for rare isotope production, and storage rings for rare isotopes [14]. Design studies and prototyping efforts for the energy upgrade have been initiated.

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