FRIB ACCELERATOR: DESIGN AND CONSTRUCTION STATUS*

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Abstract

With an average beam power approximately two to three 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.

INTRODUCTION

In August 2014, the Department of Energy's Office of Science approved Critical Decision-3b (CD-3b), Approve Start of Technical Construction, one year after approving CD-2 (Approve Performance Baseline) and CD-3a (Approve Start of Civil Construction and Long Lead Procurements) for the FRIB construction project (Fig. 1). 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" [1].

FRIB will be a new national user facility for nuclear science. Under construction on campus and operated by MSU, FRIB will provide intense beams of rare isotopes (that is, short-lived nuclei not normally found on Earth). FRIB will enable scientists to make discoveries about the properties of these rare isotopes in order to better understand the physics of nuclei, nuclear astrophysics, fundamental interactions, and applications for society.

In creating this new one-of-a-kind facility, FRIB builds upon the expertise and achievements of the National Superconducting Cyclotron Laboratory (NSCL), a National Science Foundation (NSF) user facility at MSU. Since 2001, NSCL's coupled cyclotron facility, one of the world's most powerful rare isotope user facilities, has been conducting experiments on rare isotopes. Since 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 consists of a high-power driver accelerator, a high-power target, and fragment separators.

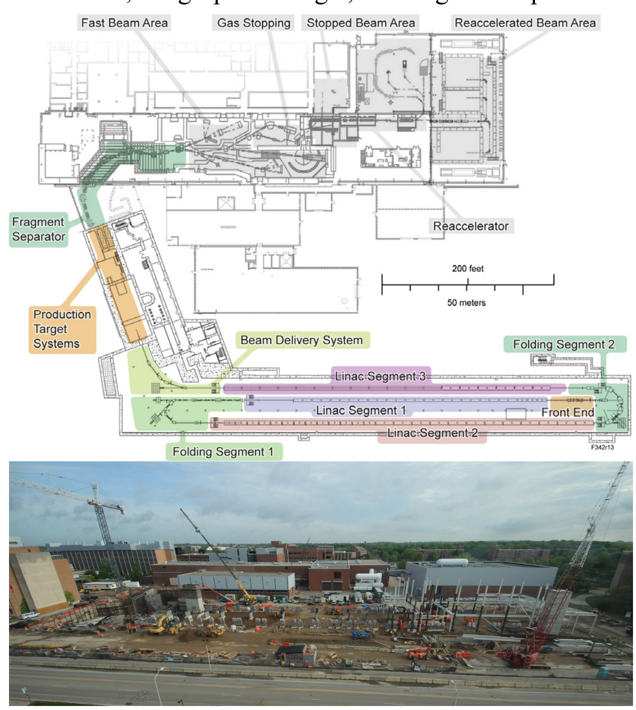

Figure 1: Layout of the FRIB driver accelerator, target and fragment separator (colored areas) and existing infrastructure (top); photograph showing FRIB civil construction (bottom).

The FRIB driver accelerator is designed to accelerate all stable ions to energies >200 MeV/u with beam power on the target up to 400 kW (Table 1). The driver accelerator consists of electron-cyclotron-resonance (ECR) ion sources; a low energy beam transport containing a pre-buncher and electrostatic deflectors for

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machine protection; a radiofrequency quadrupole (RFQ) linac; Linac segment 1 with quarter-wave-resonators (QWR) of β_0=0.041 and 0.085, to accelerate the beam to 20 MeV/u, where the beam is stripped to higher charge states; Linac segments 2 and 3 with half-wave-resonators (HWR) of β_0=0.29 and 0.53, to accelerate the beam to >200 MeV/u; folding segments to confine the footprint and facilitate beam collimation; and a beam delivery system to transport to the target [2].

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 Tsinghua University. The cryogenics system is developed in collaboration with the JLab cryogenics team. The recent experience gained from the JLab 12 GeV cryogenic system design is utilized for both the refrigerator cold box and the compression system designs. 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 is collaborating with ANL on RF coupler and tuner developments, assisted by JLAB for cryomodule design, and by FNAL and JLab on cavity treatments. FRIB is collaborating with LBNL on the development of VENUS type ECR ion source.

Table 1: FRIB Driver Accelerator Primary Parameters

Parameter	Value
Primary beam ion species	H to ^{238}U
Beam kinetic energy on target	> 200 MeV/u
Maximum beam power on target	400 kW
Macropulse duty factor	100%
Beam current on target (^{238}U)	0.7 emA
Beam radius on target (90%)	0.5 mm
Driver linac beam path length	517 m
Average uncontrolled beam loss	< 1 W/m

MAJOR TECHNOLOGY DEVELOPMENT

Major accelerator R&D and subsystem prototyping are completed. These systems include integrated cryogenics, “bottom-up” cryomodule, SRF technologies for low-β acceleration, charge stripping and machine protection for high-power, low-energy heavy ion beams.

Integrated Cryogenics

An integrated design of the cryogenic refrigeration, distribution, and cryomodule systems is key to efficient SRF operations [3, 4]. The FRIB refrigeration system adopts the floating pressure process Ganni Cycle [5] for efficient adaptation to the actual loads. Distribution lines are segmented and cryomodules are connected with U-tubes to facilitate staged commissioning and maintenance (Fig. 2). The 4-2 K heat exchangers are housed inside the cryomodules for enhanced efficiency. Figure 2 shows the FRIB prototype β_0=0.085 cryomodule developed at MSU and the prototype cryogenic distribution developed by JLab.

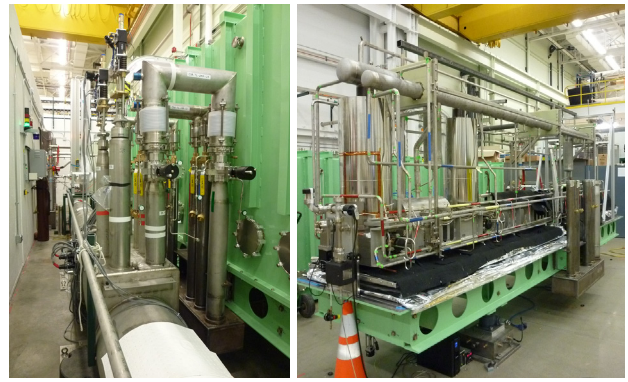

Figure 2: Left: test bunker with cryogenic distribution via U-tube connections. Right: prototype β_0=0.085 cryomodule housing 2 cavities and a solenoid.

Bottom-up Cryomodule Design

Low-β cryomodules built for MSU’s 3 MeV/u Reaccelerator (ReA3) [6] use traditional “top-down” design, with the cavities and solenoids hanging from a “strong-back”. To facilitate assembly efficiency, simplify alignment, and allow U-tube cryogenic connections for maintainability, FRIB adopted an innovative “bottom-up” cryomodule design (Fig. 3) with the resonators and solenoids supported from the bottom [7]. The cryogenic headers are suspended from the top for vibration isolation. In May 2015, the β_0=0.085 prototype cryomodule was cold tested (Fig. 2). It exceeded all FRIB design specifications, including mechanical stability, alignment accuracy, 2 K and 4 K cryogenic stability, RF bandwidth, phase and amplitude control (24-hour RF lock at full power), static and dynamic heat loads at full accelerating gradient, solenoid operation at full field, and susceptibility to ground noise and vibration. The local magnetic shielding design was validated, with remnant field controlled below 1.5 μT.

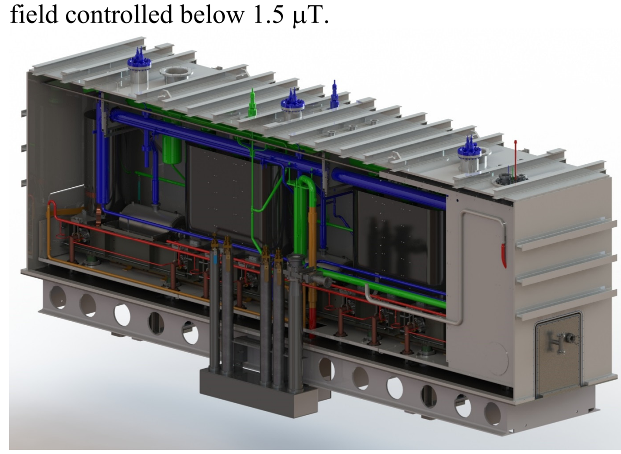

Figure 3: “Bottom-up” β_0=0.085 cryomodule design containing 8 cavities and 3 solenoids.

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Low-β Superconducting RF Acceleration

The FRIB driver linac uses 330 low-β cavities. The cavity design is optimized for both optimum performance and low production cost. This requirement guided the choice of the cavity geometries, material, and mechanical solutions, avoiding complicated shapes, minimizing the amount of electron beam welds, eliminating bellows, and optimizing construction and surface treatment procedures. FRIB cavities operate in superfluid helium at 2 K. The increase in cavity Q_0 at the operating field more than compensates for the lower efficiency of the 2 K cryogenic system. This innovative choice for a low-β linac allows operation of the cavities in stable pressure conditions with a high safety margin on the maximum surface fields [8].

Designs are validated by vertical Dewar tests of individual cavities; by integrated tests of the cavity, power coupler, tuner, and ancillary systems (Fig. 4); and by assembled cryomodule testing in the bunker.

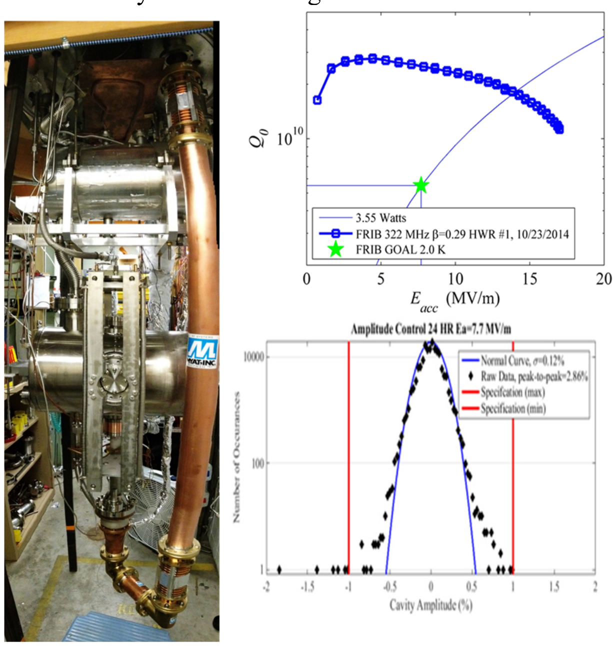

Figure 4: Preparation for 24-hour integrated test of β_0=0.29 cavity (left); Q_0 vs. E_{acc} performance measured at 2 K (top right); and measured RF amplitude control performance at 2 K (bottom right).

Liquid Lithium Charge Stripping

Intense heavy ions at low energies may cause severe damage to stripping material. FRIB uses a liquid lithium film moving at ~50 m/s speed. Tests with a proton beam produced by the LEDA source (Fig. 5) demonstrated that power depositions similar to the FRIB uranium beams could be achieved without destroying the film [9].

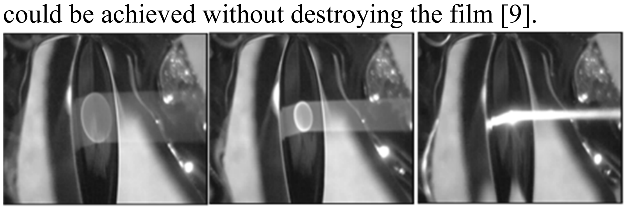

Figure 5: Liquid lithium film intercepting a proton beam of ~ 60 kV for a beam power survival test.

Multi-layered Machine Protection

Machine protection is challenging for intense low-energy heavy ion beams due to the low detection sensitivity and high power concentration/short range. Furthermore, due to the folded geometry of the driver linac, beam loss at high energy interferes with loss detection of low-energy beams [10]. Innovative techniques include the halo monitor ring [11] for high-sensitivity loss detection and current monitoring modules for critical magnet power supply inhibition. FRIB adopts multi-time scale, multi-layer approaches: the fast protection system (FPS) prevents damage from acute beam loss by quickly activating the beam inhibit device; the run permit system, RPS (1), continuously queries the machine state and provides permission to operate with beam; the even slower but highly sensitive RPS (2) prevent slow degradation of SRF system under low beam loss (Table 2).

Table 2: 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

DESIGN STATUS

Major design reviews are conducted at the preliminary, intermediate, and final design stages. The preliminary design stage corresponds to the project baselining (CD-2) three years after the completion of the conceptual design (CD-1 in 2010). At the intermediate design stage, system requirements, specifications and interfaces are finalized and safety hazards identified and mitigated. At the final design stage, models and/or drawings are produced ready for procurement, the statement of work and acceptance criteria listing are developed, the procurement strategy is defined, and installation and commissioning plans are developed. Design maturity of each major subsystem is assessed according to the follow six questions:

- Are requirements and interfaces defined?
- Is appropriate prototyping completed?
- Do prototypes meet specifications?
- Is the detailed design completed?
- Has the design been reviewed?
- Does a procurement/fabrication plan exist?

Presently, all major technological developments and subcomponent prototyping have been successfully

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completed, including cryogenic refrigeration and distribution [3], cryomodule and SRF subcomponents [6-8], RF [12], power supply [13], controls [14, 15], diagnostics [16], charge stripping [9], ion source [17], RFQ [18], and personnel and machine protection [10]. According to the measures defined by the FRIB Final Design Plan, the overall accelerator systems design is currently about 80% complete [19].

PRODUCTION INFRASTRUCTURE

To support the acceptance, processing, assembly and tests of production SRF subcomponents and cryomodules, a building is newly constructed with an area of 2500 m^2 as shown in Fig. 6. This "SRF Highbay" houses areas for material/subcomponent inspection, cavity coordinate measurement and alignment assessment, degassing furnace, parts cleaning and high pressure rinsing, chemical processing, power coupler conditioning, vertical test Dewars, cold mass assembly and tests, and cryomodule test bunkers. A 900 W cryoplant is dedicated to this building to supply liquid helium at 2 K. Once fully commissioned, this facility is expected to support the production throughput of testing five cavities per week and one cryomodule per month [20].

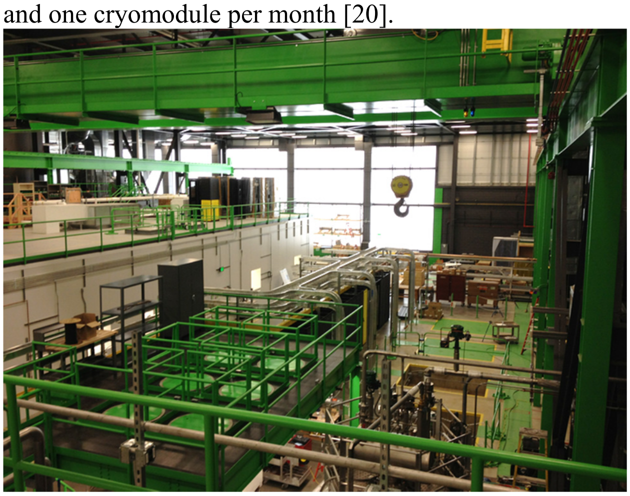

Figure 6: Newly constructed SRF Highbay at MSU.

CONSTRUCTION STATUS

FRIB construction officially started in 2013 upon the approval of CD-2 and CD-3a. Major accelerator long-lead procurements prepared prior to this date include the 4.5 K cryogenic refrigeration "cold box", the cryogenic distribution, the niobium material for SRF cavities, pre-production of the SRF cavities, the RFQ (Fig. 7), and the Electron Cyclotron Resonance ion source (ECR).

Full-scale technical construction started in 2014 upon the CD-3b approval. While critical processing and assembly are planned to be performed in house, fabrication of large quantities of components are planned through mass production by industrial providers. Approximately 35% of the accelerator scope is for in-house labor and 65% is for material, work-for-others efforts at partner laboratories, and procurements from industries.

Presently, about 65% of baselined major procurement funds 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.

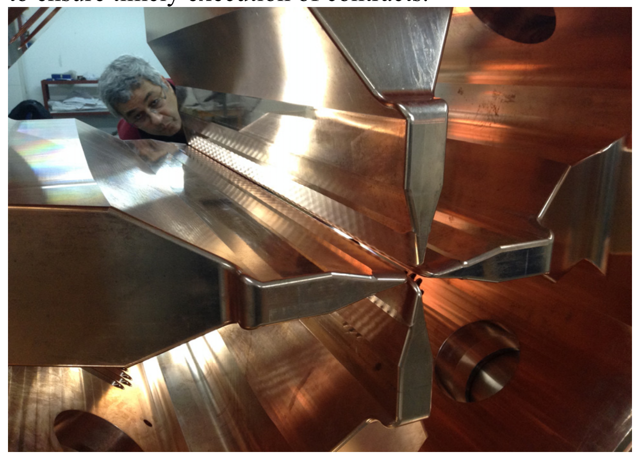

Figure 7: First segment of the RFQ at the vendor site.

OUTLOOK

Figure 8 shows the high-level FRIB Integrated Master Schedule. The present critical path consists of 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 the conventional facility construction.

Upon fabrication, installation, and integrated tests, early beam commissioning is expected to occur from 2017 to 2020, starting with the Front End. The facility is expected to meet key performance parameters and support routine user operations before June 2022 (CD-4). We plan to reach the full design capability within 4 years after beginning routine operations. Science driven upgrade options may be pursued at any stage.

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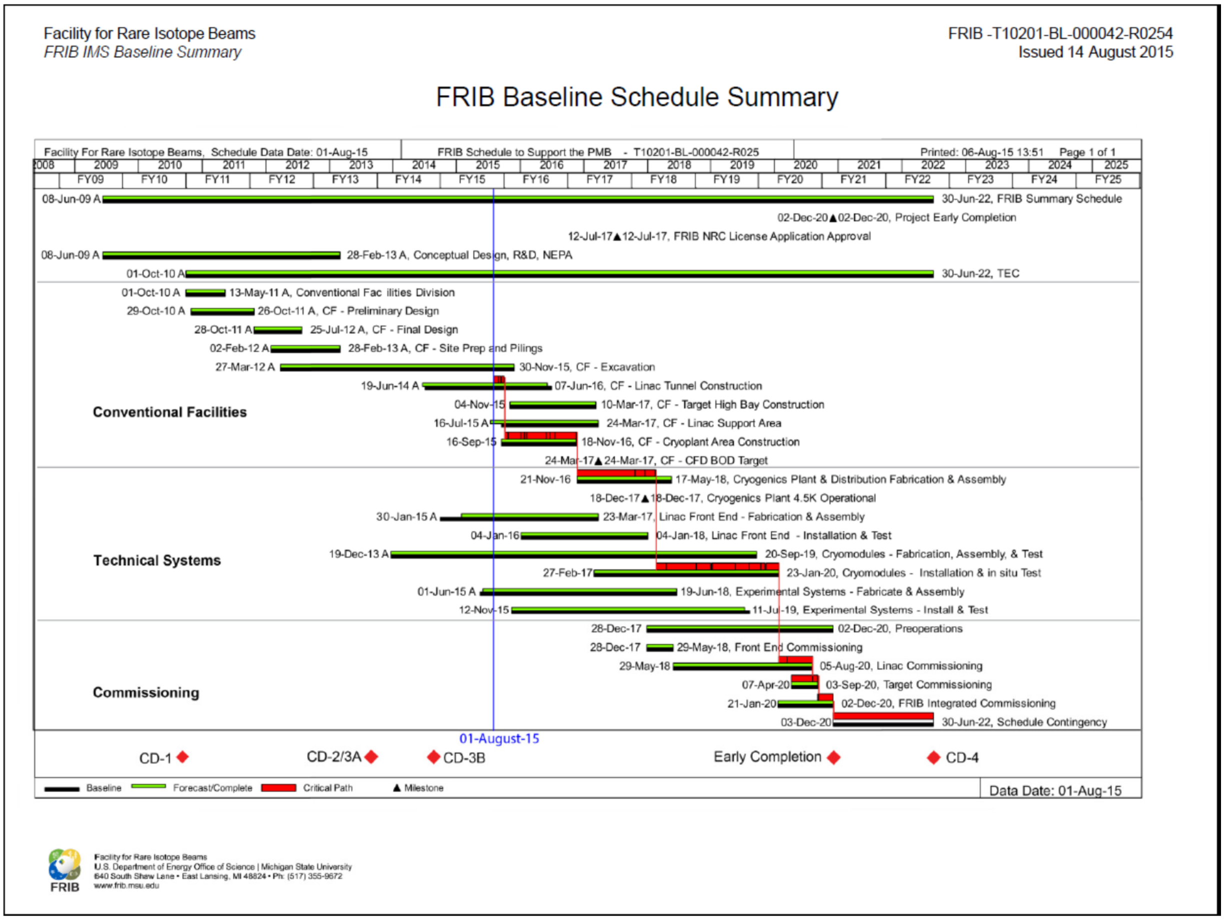

Figure 8: A snapshot of the FRIB Project Integrated Master Schedule showing the current critical path.

J. Preble, J. Price, D. Raparia, A. Ratti, T. Roser, M. Ross, R. Ruland, J. Sandberg, R. Schmidt, W.J. Schneider, D. Schrage, I. Silverman, K. Smith, J. Sondericker, W. Soyars, C. Spencer, R. Stanek, M. Stettler, W.C. Stone, J. Stovall, Y. Than, J. Theilacker, J. Tuozzolo, V. Verzilov, R. Vondrasek, P. Wanderer, P. Wright, H. Xu, L. Young, and A. Zaltsman, and colleagues who advised and collaborated with the FRIB team including A. Burrill, A.C. Crawford, K. Davis, X. Guan, P. He, Y. He, K. Hosoyama, A. Hutton, S.H. Kim, P. Kneisel, K. Macha, G. Maler, E.A. McEwen, S. Prestemon, J. Qiang, T. Reilly, R. Talman, J. Vincent, X.W. Wang, J. Xia, Q.Z. Xing. The FRIB accelerator design is executed by a dedicated team of the FRIB Accelerator Systems Division with close collaboration with the Experimental Systems Division headed by G. Bollen, the Conventional Facility Division headed by B. Bull, the Chief Engineer's team headed by D. Stout, and supported by the project controls, procurements, ES&H of the FRIB Project, by NSCL, and by MSU.

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