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FRIB COMMISSIONING AND EARLY OPERATIONS*

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Abstract

This paper summarizes the FRIB driver linac commissioning and early operations experience. Strategic planning, operational envelope conformance, technical risk mitigation, and lessons learned are discussed.

INTRODUCTION

Technical construction for the Facility for Rare Isotope Beams (FRIB) was completed in January 2022, five months ahead of the baseline schedule established about 10 years ago [1]. Beam commissioning was done in seven phases starting in 2017 when the normal-conducting ion source and RFQ were commissioned. In April 2021, the driver linac commissioning was completed with acceleration of heavy ions to energies above 200 MeV/nucleon (MeV/u) using 324 superconducting radiofrequency resonators housed in 46 cryomodules. In preparation for high-power operations, a liquid lithium charge stripper was used to strip the primary beams [2], and multiple charge states were accelerated simultaneously [3]. By January 2022, the target and fragment separator commissioning was completed, with rare isotope (RIs) produced and identified [4]. The first user scientific experiment was done in May 2022.

Because of the large project scope (Fig. 1), 8-year technical construction schedule, and state-of-the-art performance goals, FRIB developed a staged beam commissioning strategy. Table 1 summarizes the beam commissioning runs, each lasting for up to two weeks, with specific strategic goals.

Table 1: Beam Commissioning Stages for the FRIB Accelerator Complex

Run	Area with beam	Beam energy (MeV/u); species	Date	Main goals
1	Front end	0.5; Ar, Kr	Jul 2017	Front end and civil integration
2	+ 3 cryomodules	~2; Ar, Kr	May 2018	Cryogenic integration
3	FE + LS1 + FS1	~20; Ar, Kr, Xe, U	Feb 2019	QWR and charge stripping validation
4	+ FS1 + LS2	~200; Ar, Kr, Xe	Mar 2020	2 K cryogenics and HWR validation
5	+ FS2 + LS3 + BDS	~200; Ar, Kr, Xe	Apr 2021	Driver linac validation
6	+ target & beam dump	RI (Se, etc.)	Dec 2021	Targetry and RI production demonstration
7	+ fragment separator	~200; Ar, Kr	Jan 2022	Readiness for user operations

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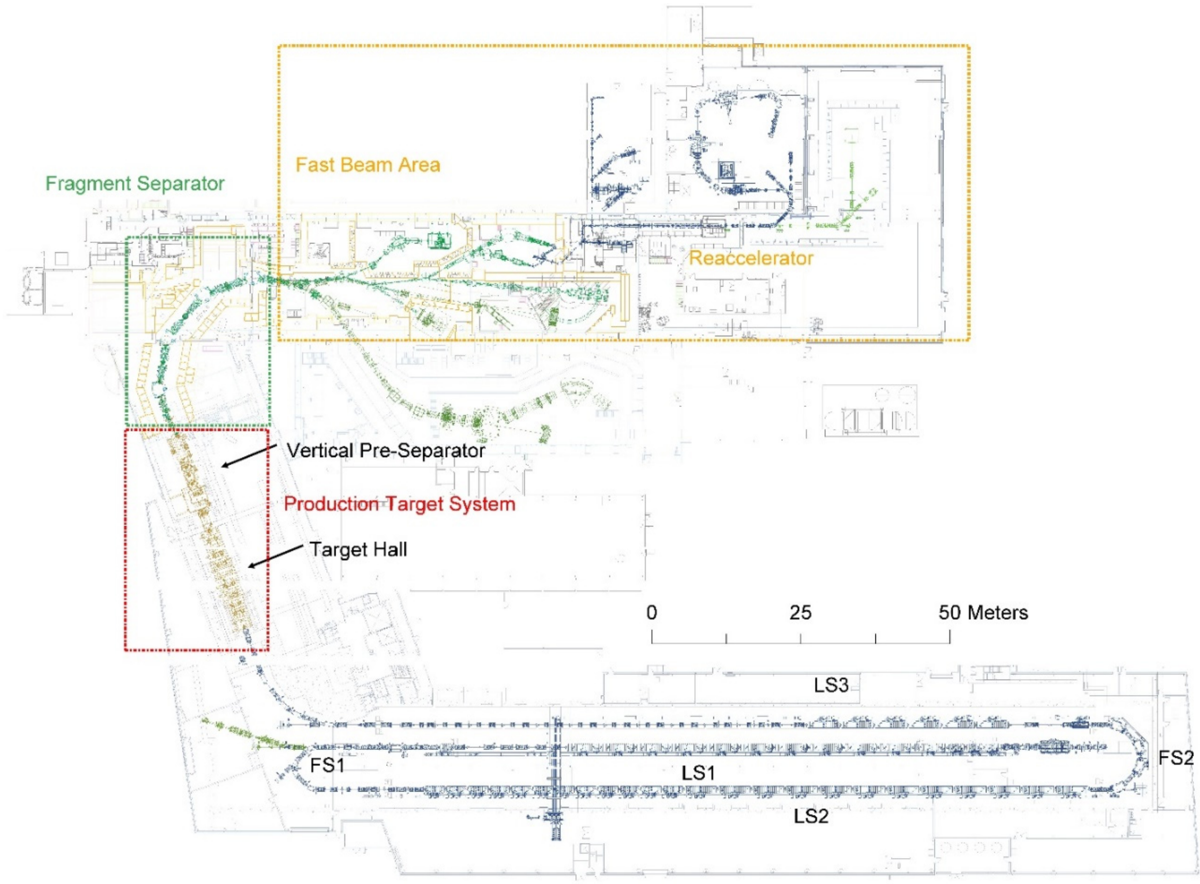

Figure 1: Layout of the FRIB facility. The underground driver linac consists of three straight segments, Linac Segment 1 through Linac Segment 3 (LS1, LS2, LS3), and two folding segments (FS1, FS2), with charge stripping in FS1. The beam delivery system (BDS) delivers beam to the Target Hall at the linac elevation. The vertical pre-separator takes isotope beams to the ground level for transport through the fragment separator to the experimental areas.

DRIVER LINAC COMMISSIONING

Safety is of primary concern in commissioning a new accelerator. Safety envelopes are established to set the boundary for accelerator operations to protect the public and facility personnel. Hazard analyses identify possible adverse events; controls are implemented to mitigate the hazards, including radiation safety controls and oxygen deficiency hazard controls. Furthermore, the run permit and machine protection systems protect the accelerator with interlocks.

Commissioning of the driver linac was done in 5 runs (Table 1). Prior to each run, an accelerator readiness review was conducted to evaluate the readiness of people, hardware, and system documentation. People readiness included defining roles, responsibility, authority, and accountability of the operations staff; staff training; establishing operating procedures; and qualification, certification, and authorization of operators.

Hardware readiness included integrated testing of subcomponents. Individual devices were tested to validate their performance readiness before they were installed. Integrated tests of subsystems ensured hardware readiness for beam commissioning. Tests were preceded by device readiness reviews to ensure proper hazard mitigation, configuration control, and personnel preparation.

System documentation readiness included safety, quality assurance/quality control, access control, work control, training, configuration control, system reviews, recommendation tracking, and safety envelope conformance.

Run 1 commissioned the Front End (FE): the normal-conducting (NC) ion source, radio-frequency quadrupole (RFQ), and associated infrastructure [5]. In 2018, the helium refrigeration plant (Fig. 2a) started operation [6], and Run 2 accelerated Ar and Kr beams to 2 MeV/u through the first 3 superconducting radio-frequency (SRF) cryomodules, each containing four $\beta = 0.041$ quarter-wave resonators (QWRs) and two superconducting (SC) solenoids [7-8]. In the next two years, Run 3 and Run 4 were completed, each raising the beam energy by another order of magnitude, to 20 MeV/u and then to 200 MeV/u. In Run 3, 15 cryomodules were used, containing 104 QWRs (β = 0.041, 0.085) and 39 SC solenoids, all at 4.5 K; at that time, FRIB became the world's highest-energy CW hadron linac. In Run 4, half-wave resonators (HWRs, β = 0.29, 0.53) at 2 K (Fig. 2b) were used to further accelerate the beam through both LS1 and LS2 (Fig. 2c). Detailed results are provided in Ref. [9]. In April 2021, Run 5 concluded linac commissioning with acceleration of ions to >200 MeV/u.

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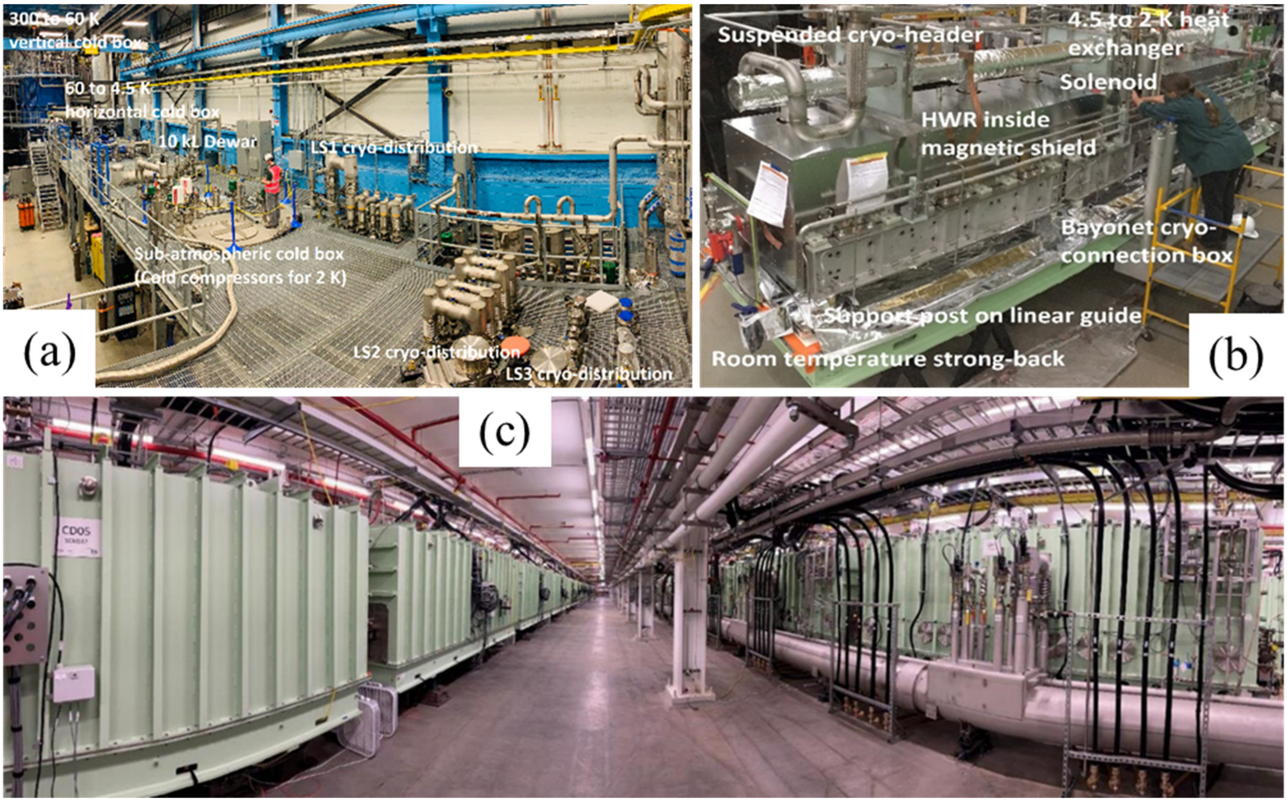

Figure 2: (a) FRIB helium refrigeration plant. (b) Partially-assembled FRIB $\beta = 0.53$ cryomodule. (c) FRIB driver linac tunnel, about 10 m underground (left: LS2; right: LS1).

The 324 accelerating cavities are controlled independently so that the RF amplitude and phase can be adjusted for beams with different charge-to-mass ratios. Automated phase scans reduced the tuning time. Automated cavity turn-on algorithms were developed to enable the low-level RF, tuner control loop, amplitude control loop, and phase control loop in sequence. Automation of cavity turn-on and phase scans will help to prepare for routine operation with high reliability and availability, which is critical to the success of a large-scale user facility.

The transverse beam dynamics [10] for the entire linac are predicted with the second-order code FLAME [11]. With pre-calculated settings, the measured normalized root-mean-square (rms) emittance in x and y for 212 MeV/u Kr and Xe beams is less than 0.3 π mm·mrad, allowing for a 0.3 mm rms beam spot size on the target.

For high-energy high-power beams, charge stripping at ~ 17 MeV/u is needed. We have developed a liquid metal stripper based on a molten lithium film with a thickness of 10 to 20 µm, flowing at ~60 m/s in the ultra-high vacuum environment (Fig. 3) [2]. During system commissioning, we experimentally confirmed that the thin windowless liquid film can effectively strip $^{36}Ar^{10+}$, $^{124}Xe^{26+}$, and $^{238}U^{36+}$ beams.

A 3-charge-state ^{124}Xe beam was accelerated successfully to 180 MeV/u after stripping [3]. Subsequently, 3 charge states (49+, 50+, and 51+) of ^{124}Xe were accelerated to 212 MeV/u. The Xe beam intensity was increased by a factor of 2.5 relative to a single-charge-state stripped beam. This also demonstrated the design capability of accelerating a 5-charge-state ^{238}U beam.

Successful beam commissioning of the driver linac [12] validated the accelerator systems design. Strategically planned, interlacing accelerator installation and beam commissioning over a period of five years was both challenging and rewarding.

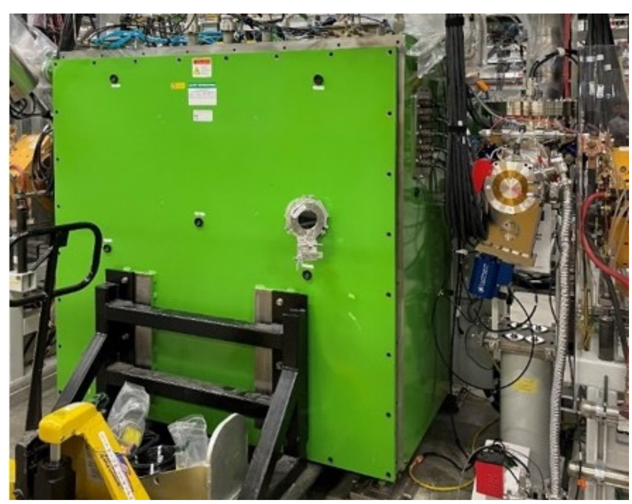

Figure 3: The liquid lithium charge stripper (left) and carbon charge stripper (right) in FS1. The green box is a secondary containment vessel enclosing the entire Li loop.

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TARGET AND FRAGMENT SEPARATOR COMMISSIONING

After linac beam commissioning, two more commissioning runs were conducted for downstream systems. In Run 6, beam was delivered to an RI production target, with the primary beam stopped in a downstream beam dump (Fig. 4, Fig. 5a) after the first separator dipole. Detectors were installed at the focal plane of the pre-separator for identification of rare isotopes. In Run 7, the primary beam was transported through the whole fragment separator complex (Fig. 5b).

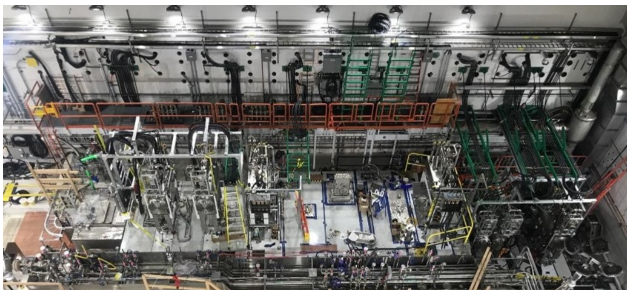

Figure 4: FRIB Target Hall, including the production target, beam dump, and wedge systems, with vessels and radiation shielding.

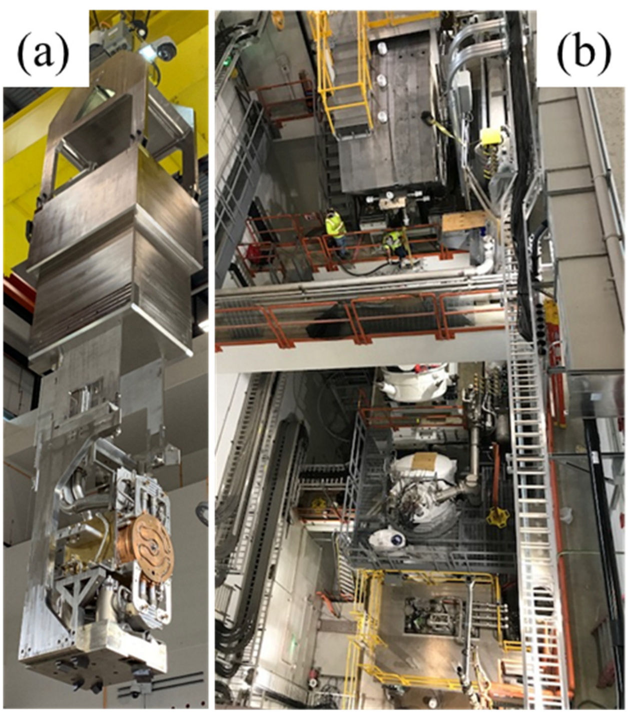

Figure 5: (a) Production target assembly before installation. (b) Vertical pre-separator area.

A primary beam of $^{86}Kr^{35+}$ was focused on the target with an rms size of 0.3 mm. A 2 mm slit (part of the wedge system) was used to separate isotopes vertically. Carbon and beryllium targets were used to produce rare isotopes. The upstream magnets of the Advanced Rare Isotope Separator (ARIS) [13] were used to select fragments produced in the target with mass-to-charge ratio (A/q) near 2.4. A telescope containing eight PIN diodes of various thicknesses was placed directly behind the slit for isotope detection. The detection system and particle identification were calibrated with the primary beam. The magnet setting was centered on the momentum distribution for $^{84}Se^{34+}$ ions, based on LISE++ [14] calculations. To identify the different RIs, we measured the energy deposited in each detector and the time of flight from target to detectors. These measurements were used to determine the proton number Z, the mass-to-charge ratio A/q, and the ion charge state q for each particle. The experimental methods are described in more detail elsewhere [15, 16]. Results are shown in Fig. 6.

Identification of $^{84}Se^{34+}$ marked the delivery of the last of the FRIB "key performance parameters":

- Accelerate ^{36}Ar to > 200 MeV/u with a beam current > 20 particle nA: attained March 2020;
- Produce and identify ^{84}Se isotopes: attained December 2021;
- Measure reaccelerated RI beam energy > 3 MeV/u: attained September 2015.

With the completion of commissioning Run 7, all of the technical scope of the FRIB baseline was completed.

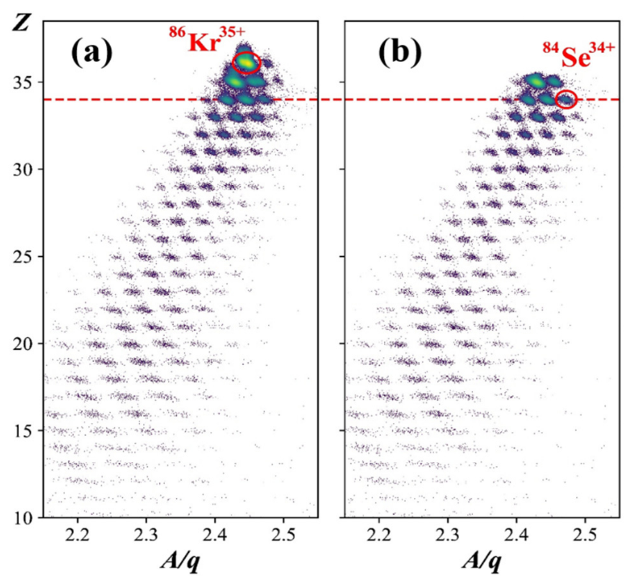

Figure 6: Particle identification for nuclei produced by a $^{86}Kr^{35+}$ beam in a 3.3 mm-thick Be target with selection by upstream ARIS magnets: (a) without charge state selection; red circle: charge state +35 of the primary beam, the most intense component; (b) showing only fully stripped ions, as determined by the measured total kinetic energy; red circle: $^{84}Se^{34+}$, the desired isotope.

EARLY OPERATIONS

The first FRIB Program Advisory Committee approved 34 scientific experiments with 9 different primary ion beams starting in 2022; the first experiment [17] was conducted in May 2022. Under the current operational safety envelope, up to 1 kW of the ^{48}Ca primary beam was accelerated, striking a beryllium target. RI beams were produced at the optimum settings for ^{42}Si, separated from the

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other fragments, and transported to a decay station [18] for the experiment.

The FRIB industrial user program started in 2021 with the commissioning of the FRIB Single Event Effects (FSEE) beam line at the end of LS1 in the linac tunnel (Fig. 7). Beams of ^{16}O, ^{40}Ar, ^{129}Xe, or ^{209}Bi were accelerated to energies of up to 40 MeV/u for FSEE users [19].

Figure 7: FSEE beam line in the linac tunnel.

SUMMARY AND LESSONS LEARNED

Fourteen years after the site selection in 2008, the FRIB baseline was delivered on cost and five months ahead of schedule (Table 2).

Lessons from FRIB technical design, construction, and commissioning include

- Recruit worldwide and retains key subject matter experts (own the best people);
- Develop and mature key technologies in time to support the project schedule (own the technology);
- Align interests for infrastructure investment to support key construction steps and future research (align interests, invest in infrastructure);
- Closely collaborate with US national labs and worldwide partners for knowledge transfer and project support; rigorously manage collaboration (collaborate without losing control);
- Strategically facilitate phased commissioning to stagger work force, validate design principles, feed back on improvements, and meet schedule (phase the scope for optimization);
- Conduct rigorous external reviews, inviting the best experts to critique the work (review rigorously);
- Engage with industrial providers via exchange visits, weekly meetings, and extended stays (intimately engage vendors);
- The original "turn-key" approach to procure the large-scale cryogenic helium system from industry exposed the project to serious risks in budget and scope (avoid "turn-key" on large-scale cryogenics);
- Early shortcuts taken in SRF/QWR sub-component validation was costly (avoid shortcuts);
- Shared vacuum vessels in the target area complicate maintenance (consider maintenance);
- Lack of diagnostics and correctors in the 3D geometric layout complicates fragment separation (ensure adequate diagnostics and adjustments);
- Conduct systematic R&D for novel technology, e.g. bottom-up cryomodule (systematic R&D);
- Thorough testing is needed for all major technical equipment, e.g. SRF sub-components, cryomodules, superconducting magnets (test thoroughly);
- Pro-actively facilitate critical system validation, e.g. for liquid Li stripper (facilitate critical validation).

Table 2: FRIB Project Major Milestones

Milestone	Date
DOE & MSU cooperative agreement	Jun 2009
CD-1: preferred alternatives decided	Sep 2010
CD-2: performance baseline	Aug 2013
CD-3a: start of civil construction & long lead procurements	Aug 2013
CD-3b: start of technical construction	Aug 2014
FRIB linac construction completion	May 2021
Project technical construction completion	Jan 2022
Start of scientific user experiments	May 2022

FUTURE PERSPECTIVES

FRIB will operate as a scientific user facility with the imperative of safe operation, guided by five paradigms:

1. Operate with > 85% availability for user satisfaction;
2. Ramp up the beam power to enhance discovery opportunities;
3. Automate to increase the machine time available for science;
4. Foster an engaged user community; and
5. Deliver opportunities for all areas of science enabled by FRIB.

In subsequent years, the primary beam power will be progressively increased as operational experience is accumulated, aiming for 400 kW in 2028 (Fig. 8, [4]). Accelerator improvement projects will play an essential role in updating aged systems in the laboratory that predate the FRIB project and maximizing the productivity of the facility. Work is also proceeding in preparation for future upgrades, including a doubling of the primary beam energy to 400 MeV/u to enhance the scientific reach of the facility.

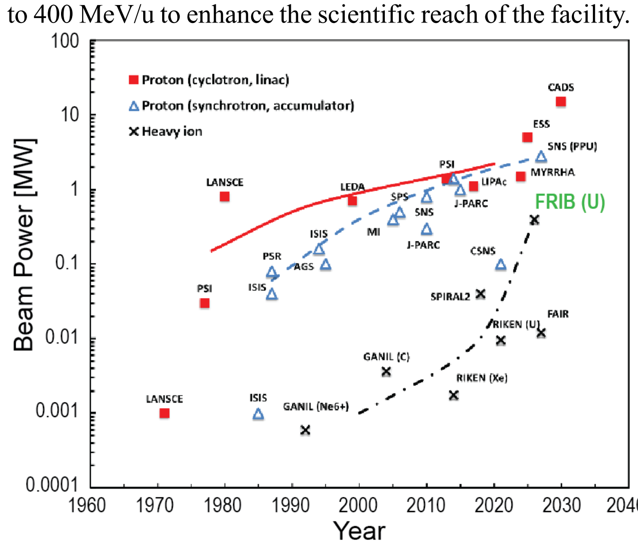

Figure 8: Beam power on target as a function of time for existing and planned power-frontier accelerator facilities.

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