FRIB commissioning and early operations

Jie Wei
On Behalf of FRIB Accelerator Team & Collaboration

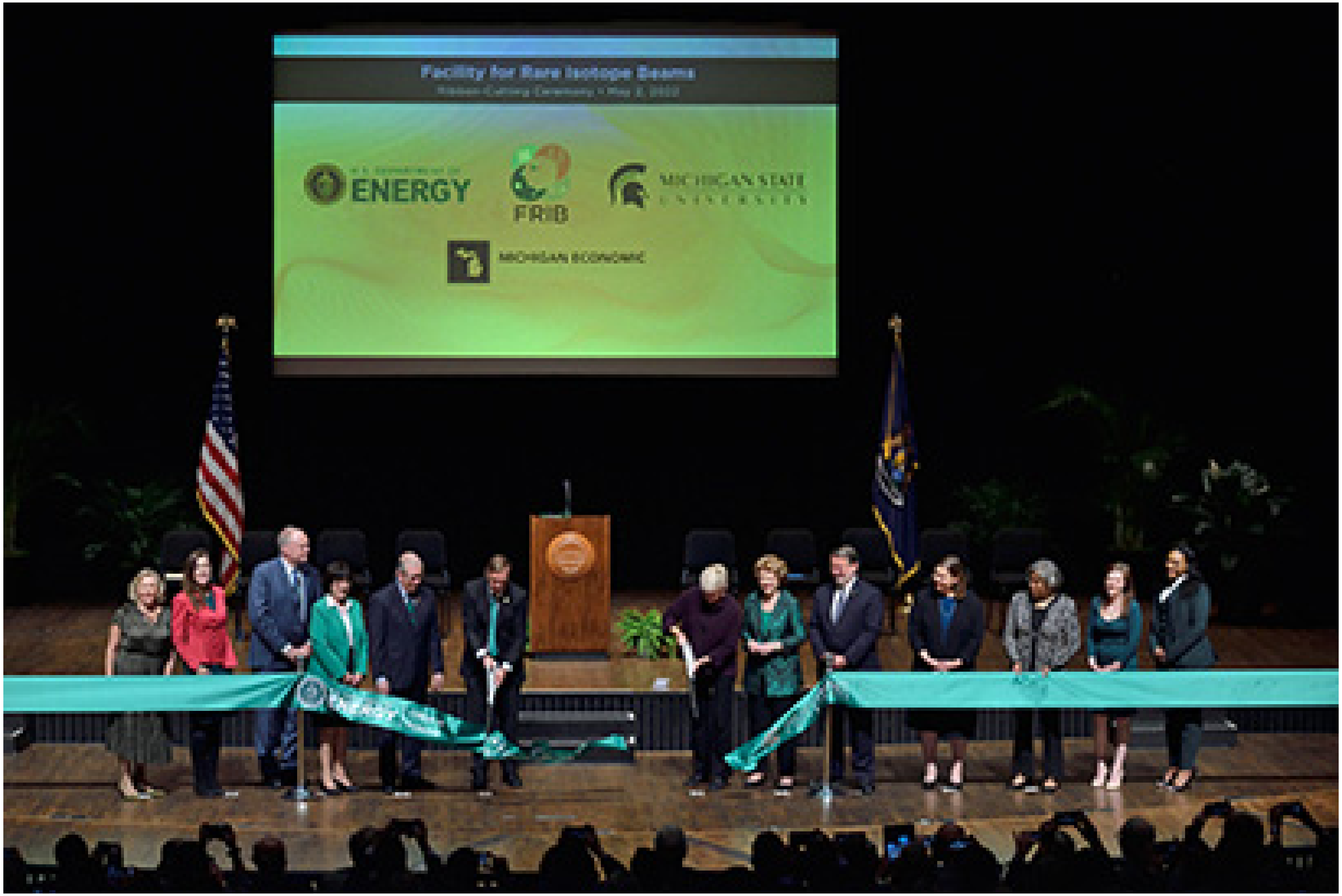
IPAC, Bangkok, June 14, 2022

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661.
Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Outline

- Hot off the press
  - May 2, 2022: FRIB ribbon-cutting
  - May 27, 2022: *Phys. Rev. Lett.* cover article on liquid Li charge stripping at FRIB
- Introduction
- Driver linac commissioning
- Target and fragment separator commissioning
- Early operations
- Summary and lessons learned
- Future perspectives

May 2, 2022 Ribbon-Cutting: Start of FRIB's Scientific Mission



May 27, 2022: *Phys. Rev. Lett.* cover article
“Experimental demonstration of the thin-film liquid-metal jet as a charge stripper”, T. Kanemura *et al.*

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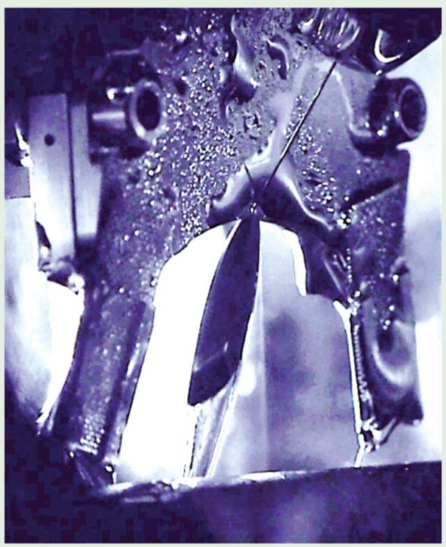
PHYSICAL
REVIEW
LETTERS

Published week ending 27 MAY 2022

PRL 128 (21), 210401–219902, 27 May 2022 (306 total pages)



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Published by
American Physical Society

APS physics

Volume 128, Number 21

Photograph of the liquid lithium film charge stripper in the Facility for Rare Isotope Beams. Selected for a Synopsis in *Physics* [Kanemura *et al.* Phys. Rev. Lett. **128**, 212301 (2022)]

NEWSPAPER

PHYSICAL REVIEW LETTERS

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Articles published 21 May–27 May 2022

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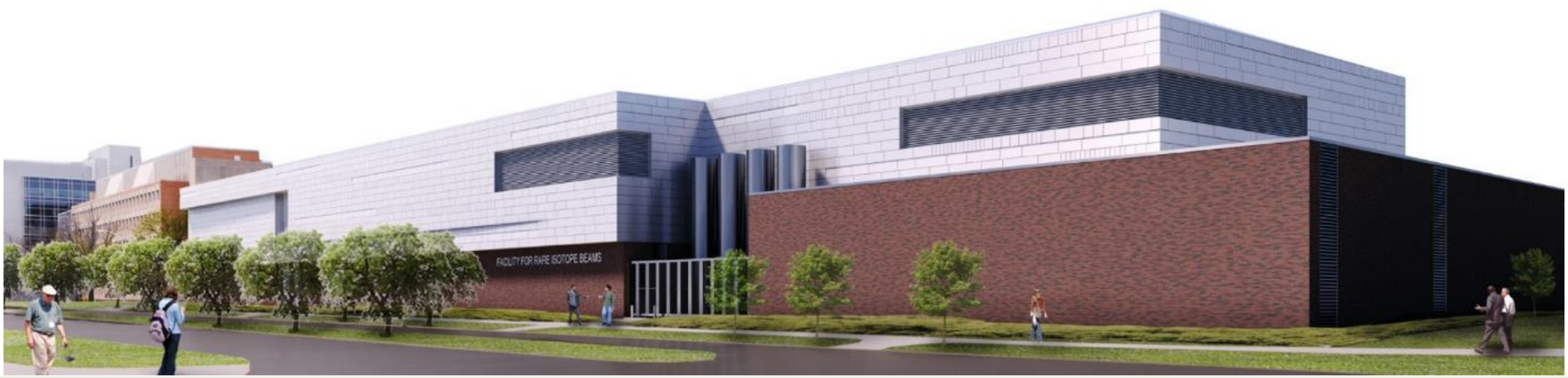
P This paper was highlighted in the APS publication *Physics* (physics.aps.org).
By suggesting a few manuscripts each week, we hope to promote reading across fields. Please see our Announcement Phys. Rev. Lett. 98, 010001 (2007).

0031-9007(20220527)128:21;1-Z

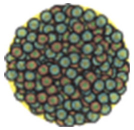
Introduction

FRIB Construction Completed in Jan. 2022 On Cost and Five Months ahead of Schedule

- A $730 million national user facility funded by the U.S. Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan
- FRIB construction completed in January 2022, on cost and five months ahead of schedule
- FRIB is now a DOE-SC scientific user facility for rare isotope research supporting the mission of the Office of Nuclear Physics in DOE-SC

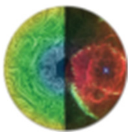


FRIB Enables Scientists to Make Discoveries



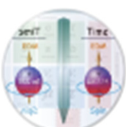
Properties of atomic nuclei

- Develop a predictive model of nuclei and their interactions
- Many-body quantum problem: intellectual overlap to mesoscopic science, quantum dots, atomic clusters, etc.



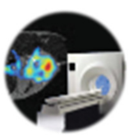
Astrophysics: What happens inside stars?

- Origin of the elements in the cosmos
- Explosive environments: novae, supernovae, X-ray bursts …
- Properties of neutron stars



Tests of laws of nature

- Effects of symmetry violations are amplified in certain nuclei



Societal applications and benefits

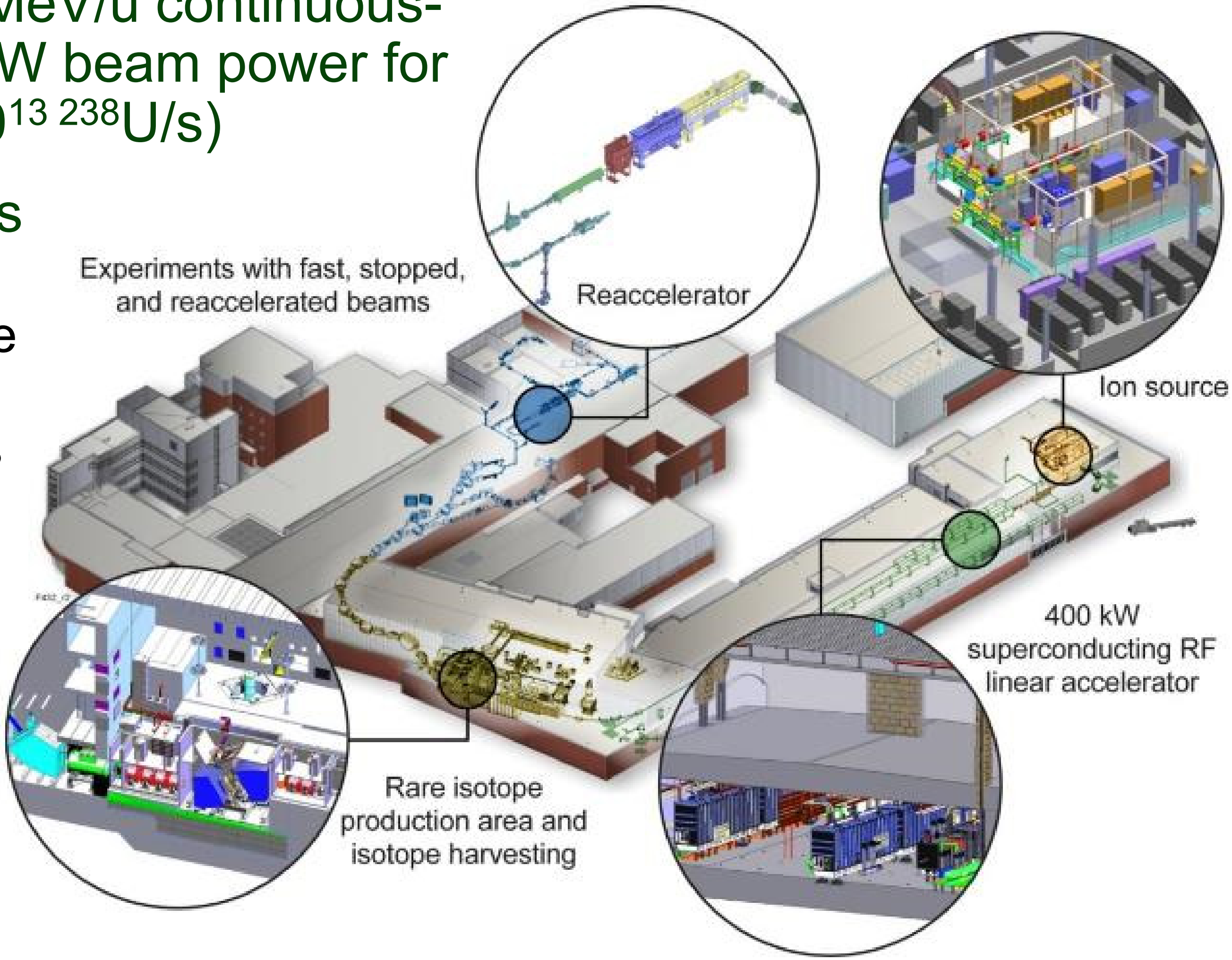
- Medicine, energy, material sciences, national security, work force

Science is aligned with national priorities articulated by

- Nuclear Science Advisory Committee to DOE and NSF *Long Range Plan for Nuclear Science* (2015)
- National Research Council *Decadal Survey of Nuclear Physics* (2012)
- National Research Council *Rare Isotope Science Assessment* report (2006)

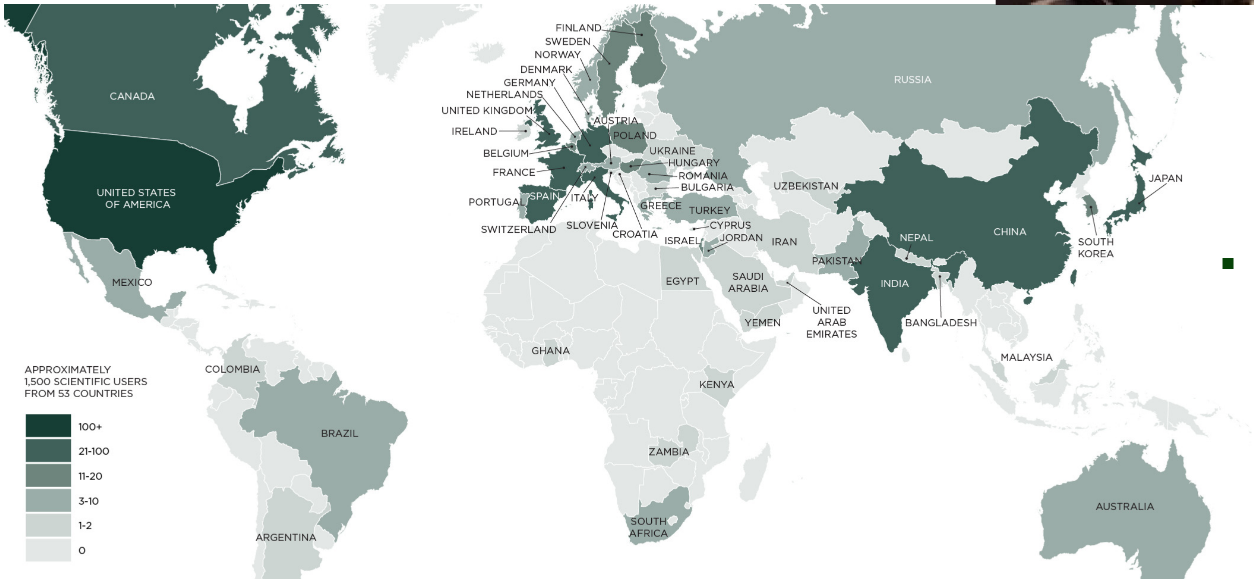
FRIB Optimized for Science
with Fast, Stopped and Reaccelerated Rare Isotope Beams

- Key feature is a 200 MeV/u continuous-wave linac with 400 kW beam power for all ions (8pμA or 5x10^{13} ^{238}U/s)
- Separation of isotopes in-flight provides
  - Fast development time for any isotope
  - Beams of all elements and short half-lives
  - Fast, stopped, and reaccelerated beams



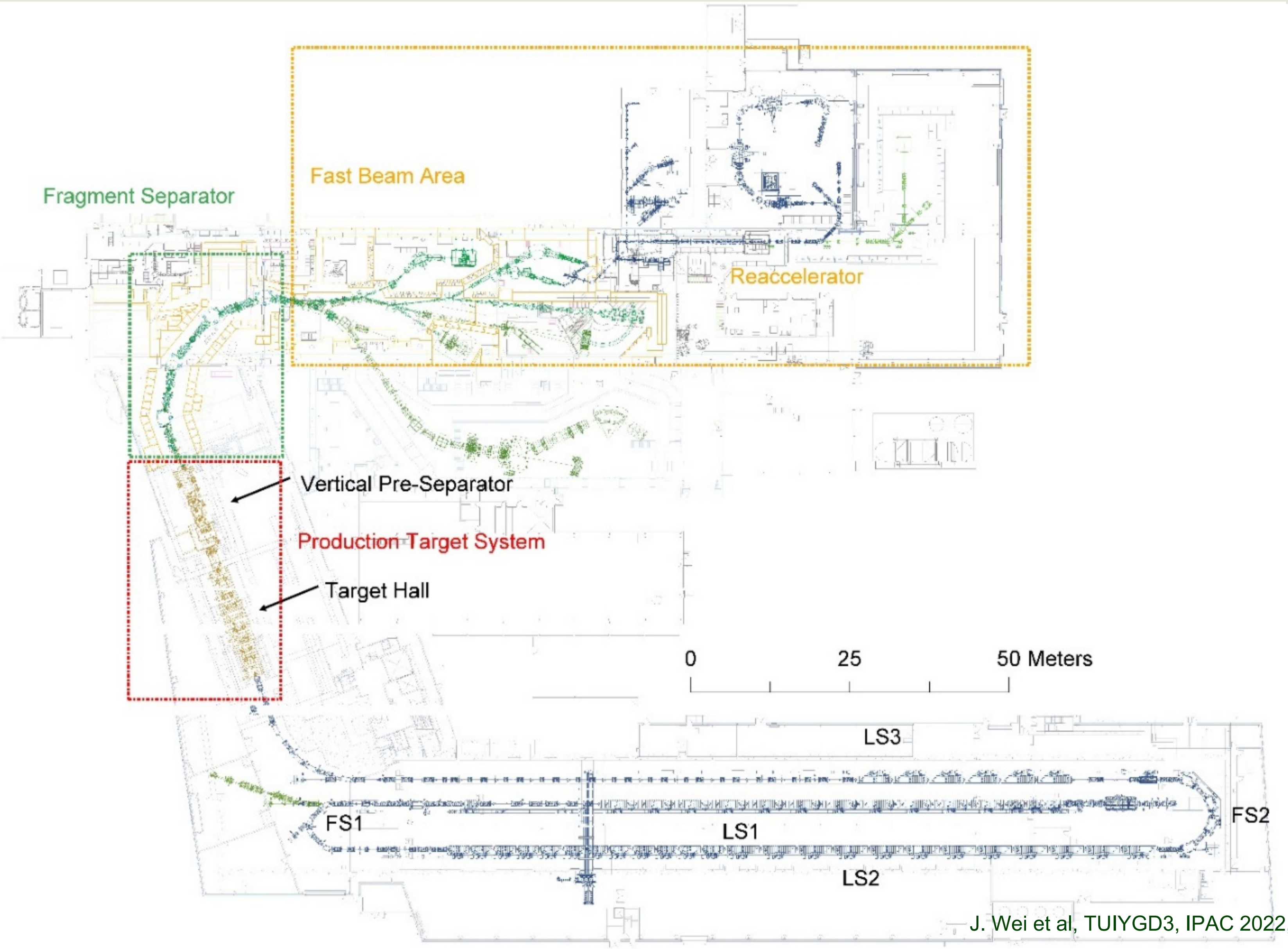
1,600 Users Engaged and Ready for Science
www.fribusers.org

- May 2020: FRIB First Experiments - Proposal Preparation workshop
- November 2020: Call for Proposals
- November 2020-January 2021 Individual Proposal Preparation Meetings
- August 2021: FRIB Program Advisory Committee (PAC1)
- May 2022: First FRIB user experiments



- 1641 members (as of 23 April 2022)
  - 203 U.S. Institutions (38 states)
  - 226 International Institutions (52 countries)

FRIB Accelerator Complex Subsystems



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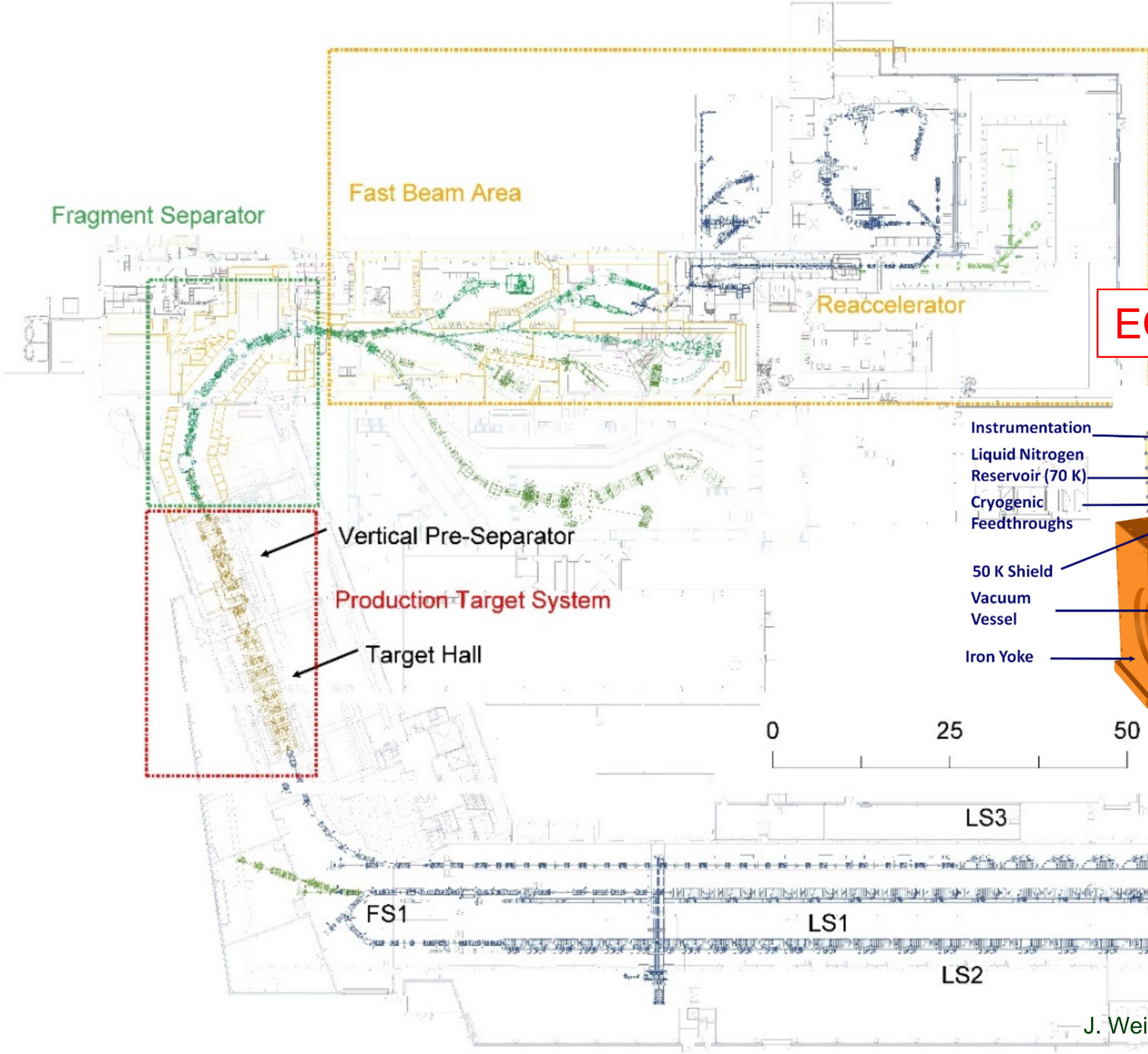
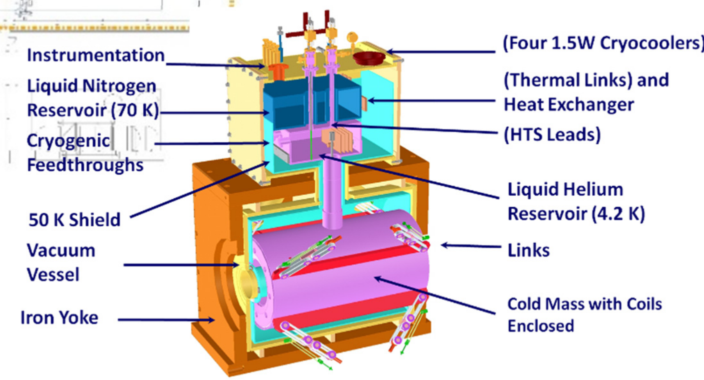
FRIB Accelerator Complex Subsystems



ECR ion source



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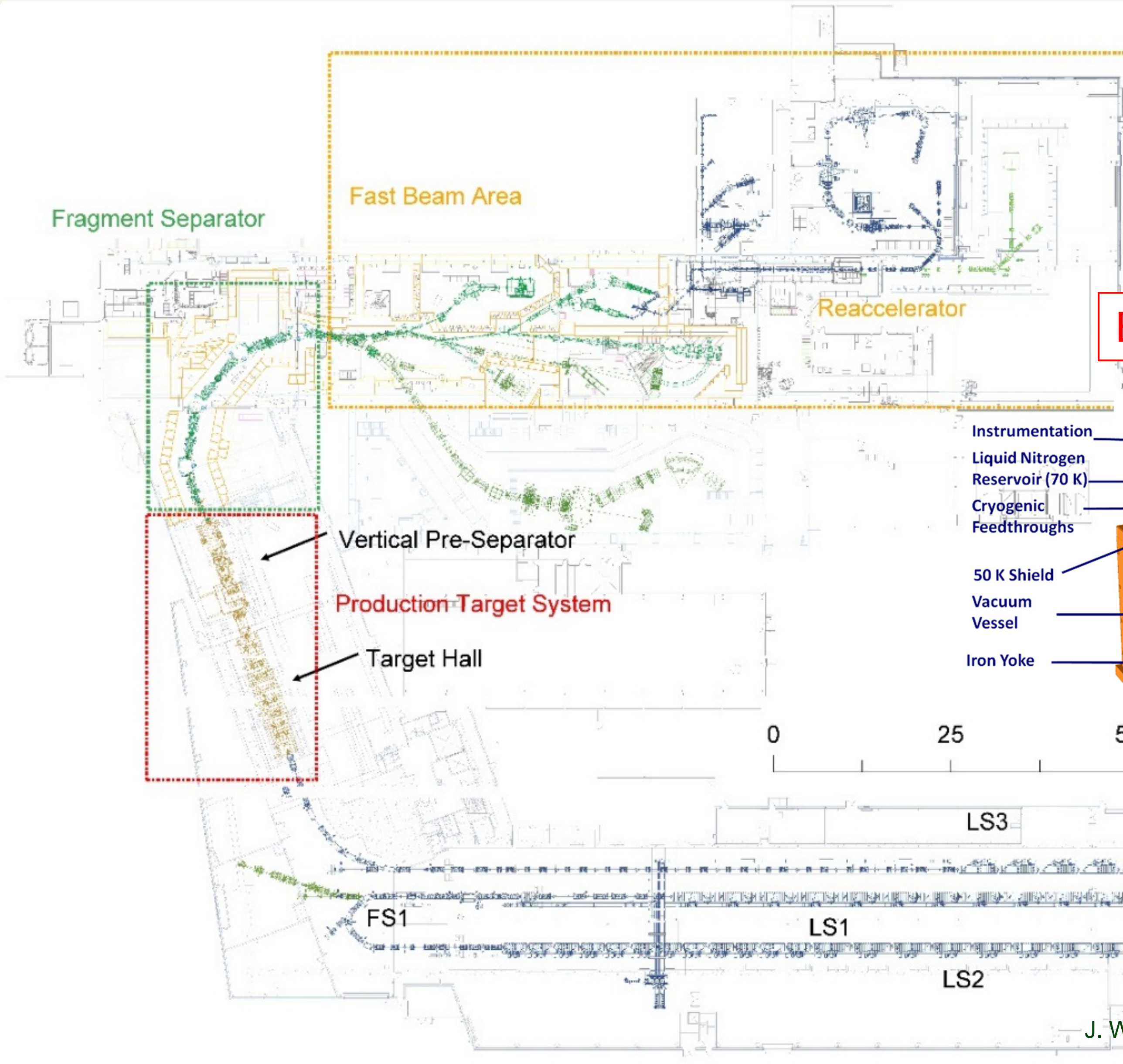
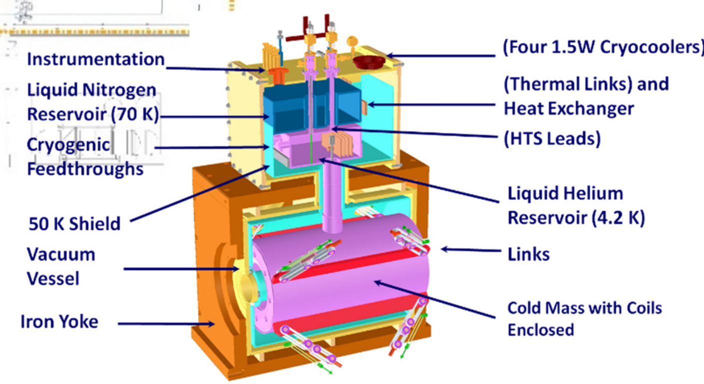
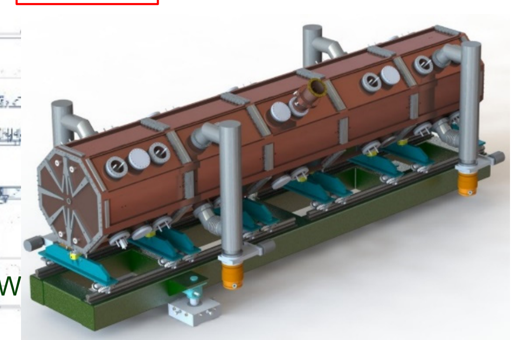
FRIB Accelerator Complex Subsystems



ECR ion source



RFQ



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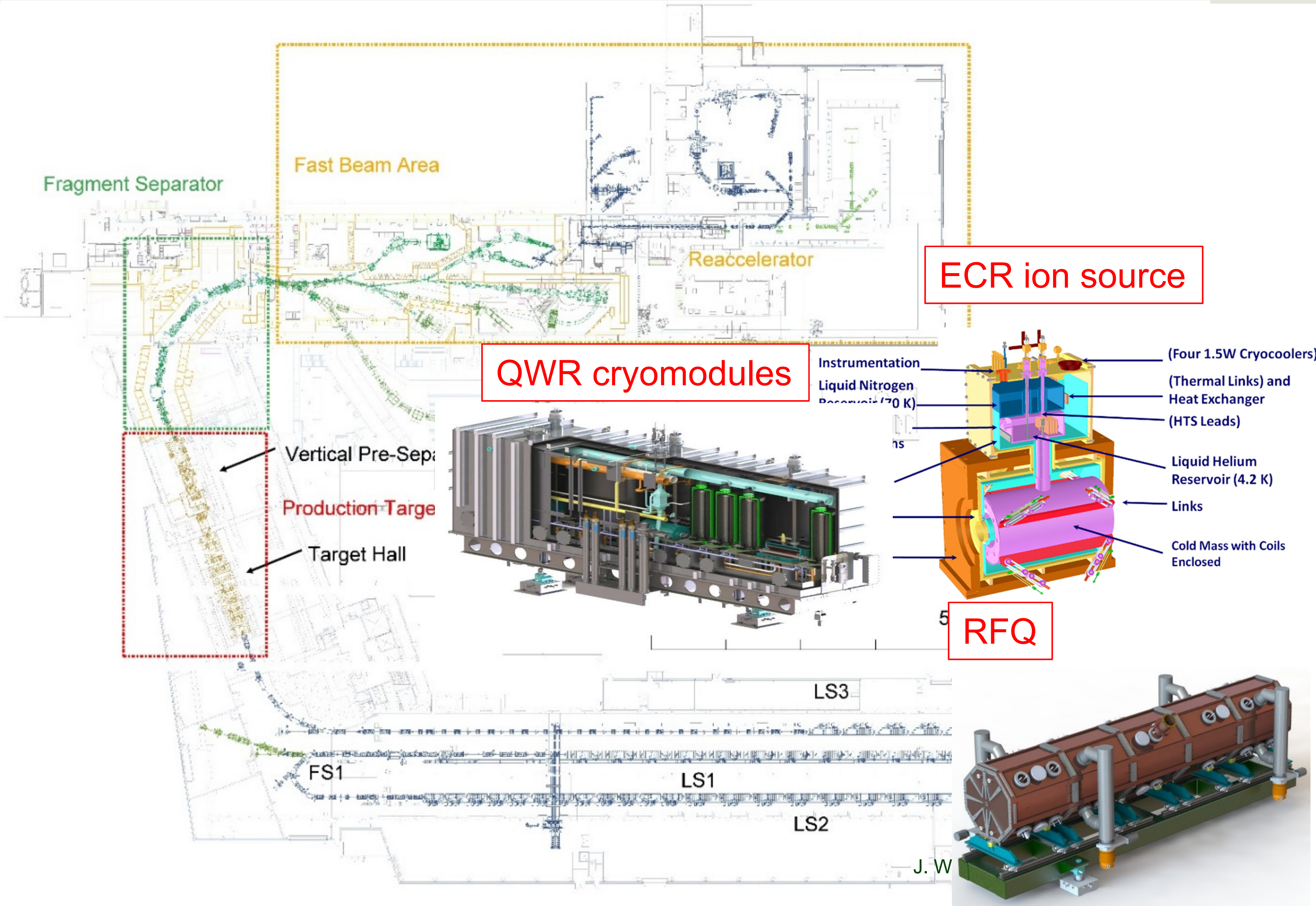
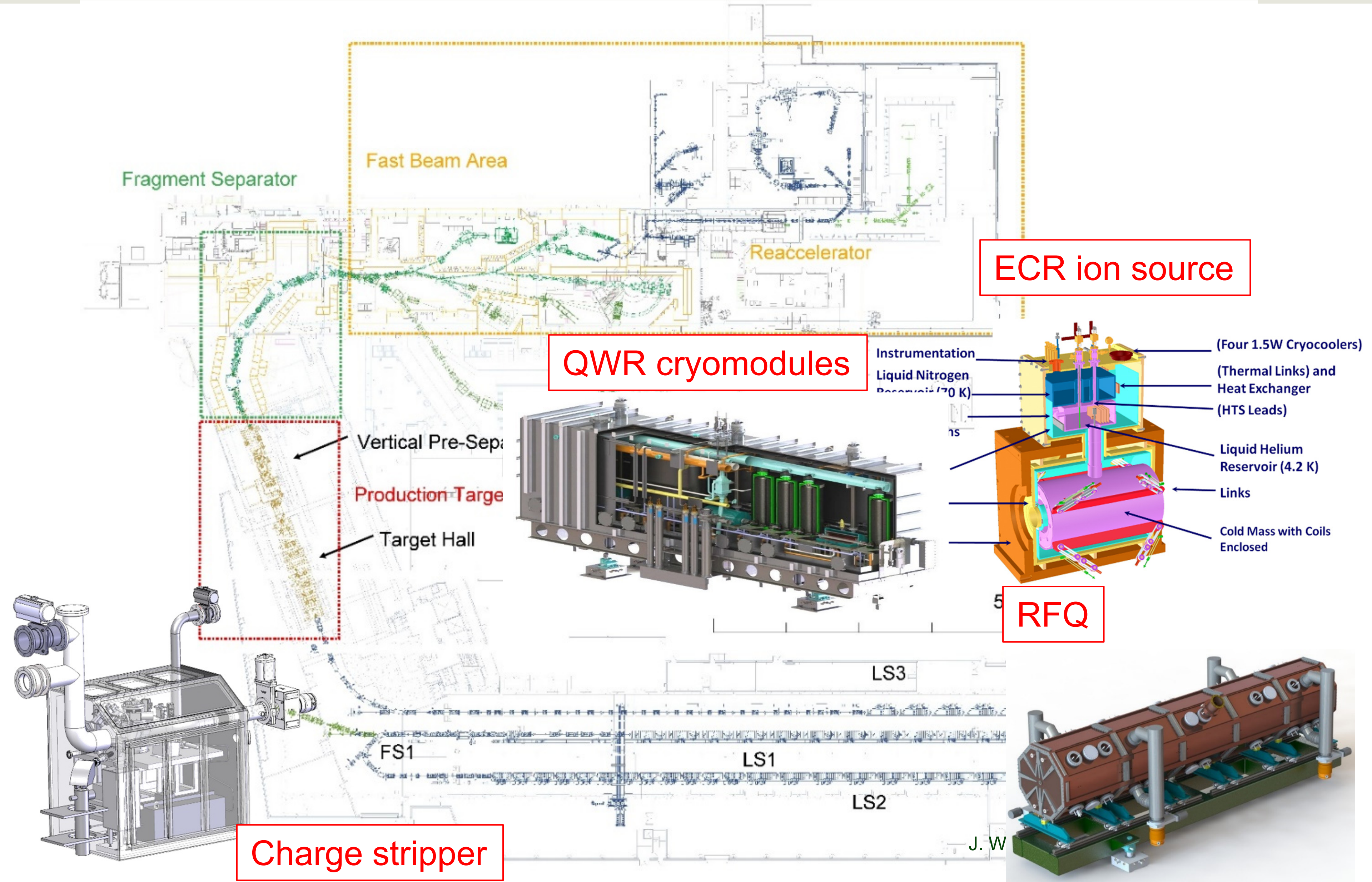
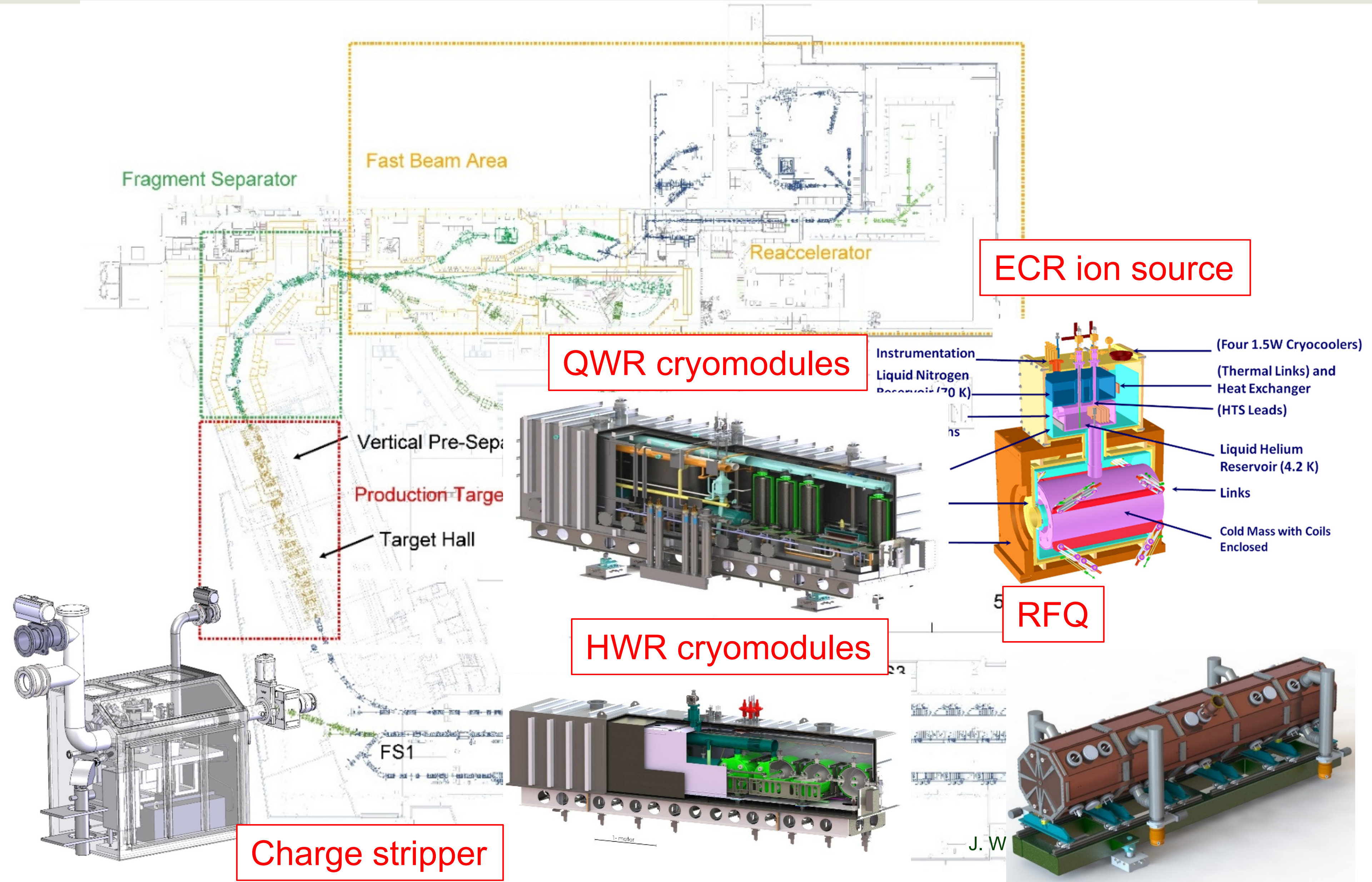
FRIB Accelerator Complex Subsystems



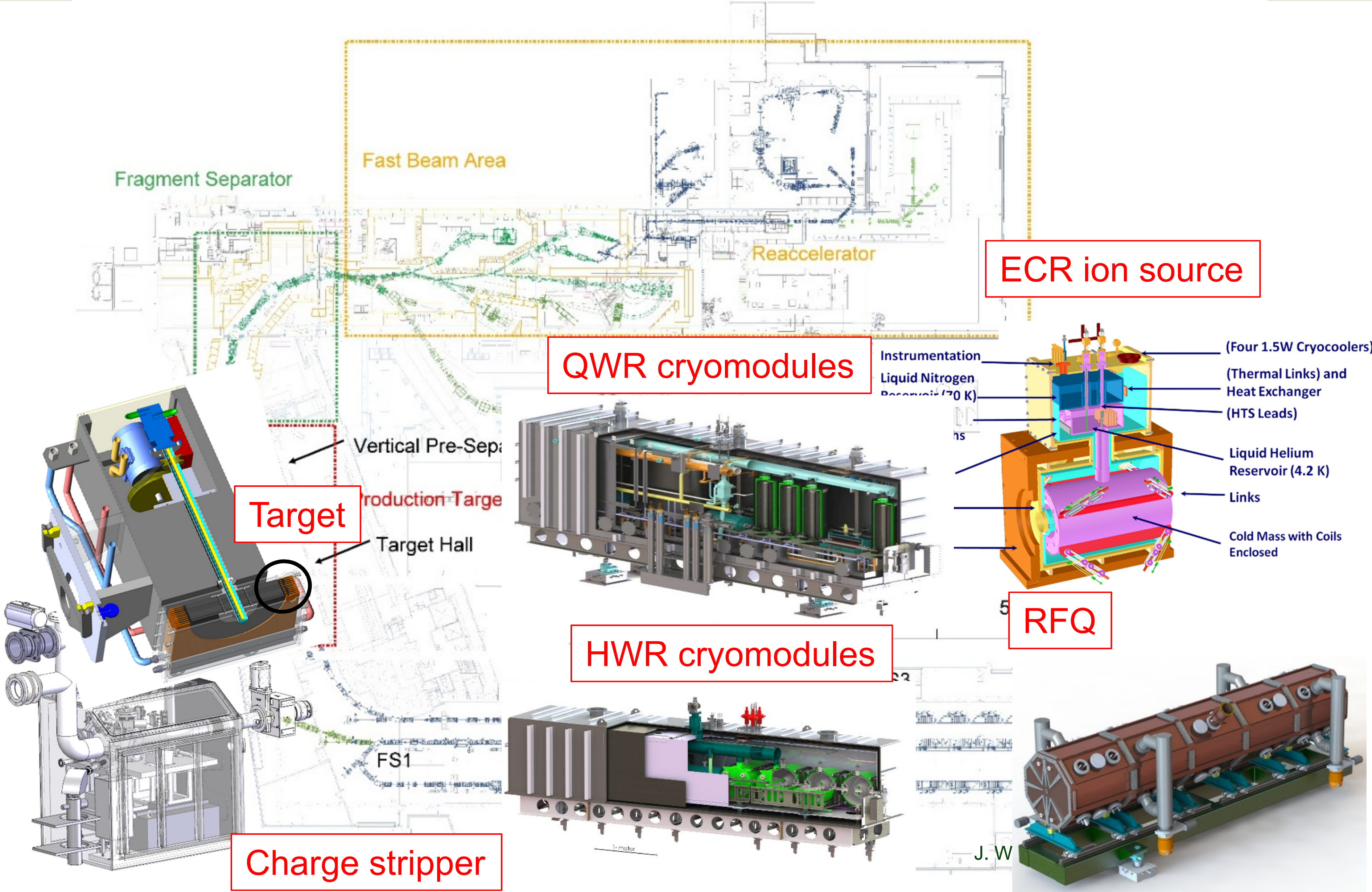
FRIB Accelerator Complex Subsystems



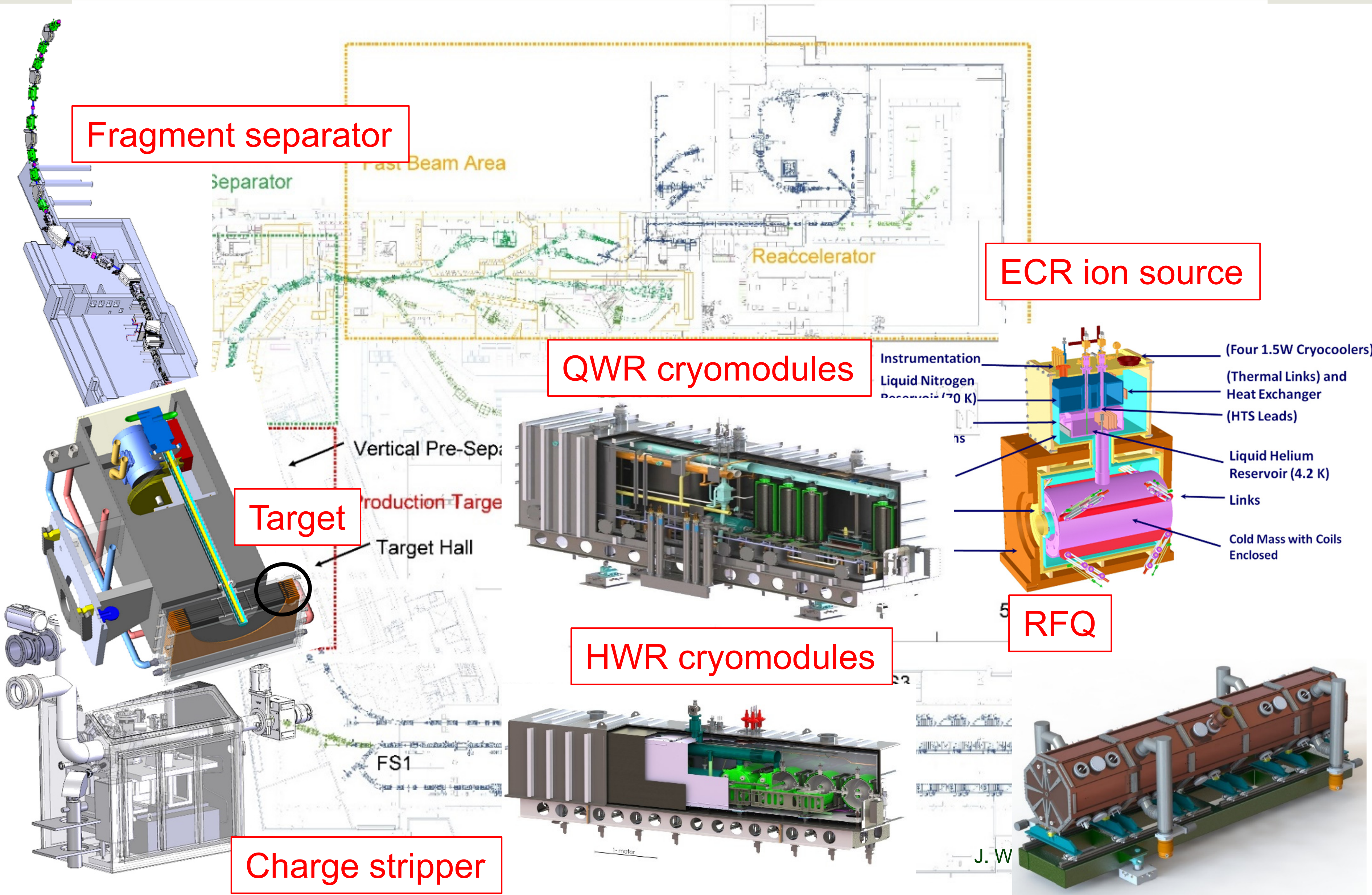
FRIB Accelerator Complex Subsystems



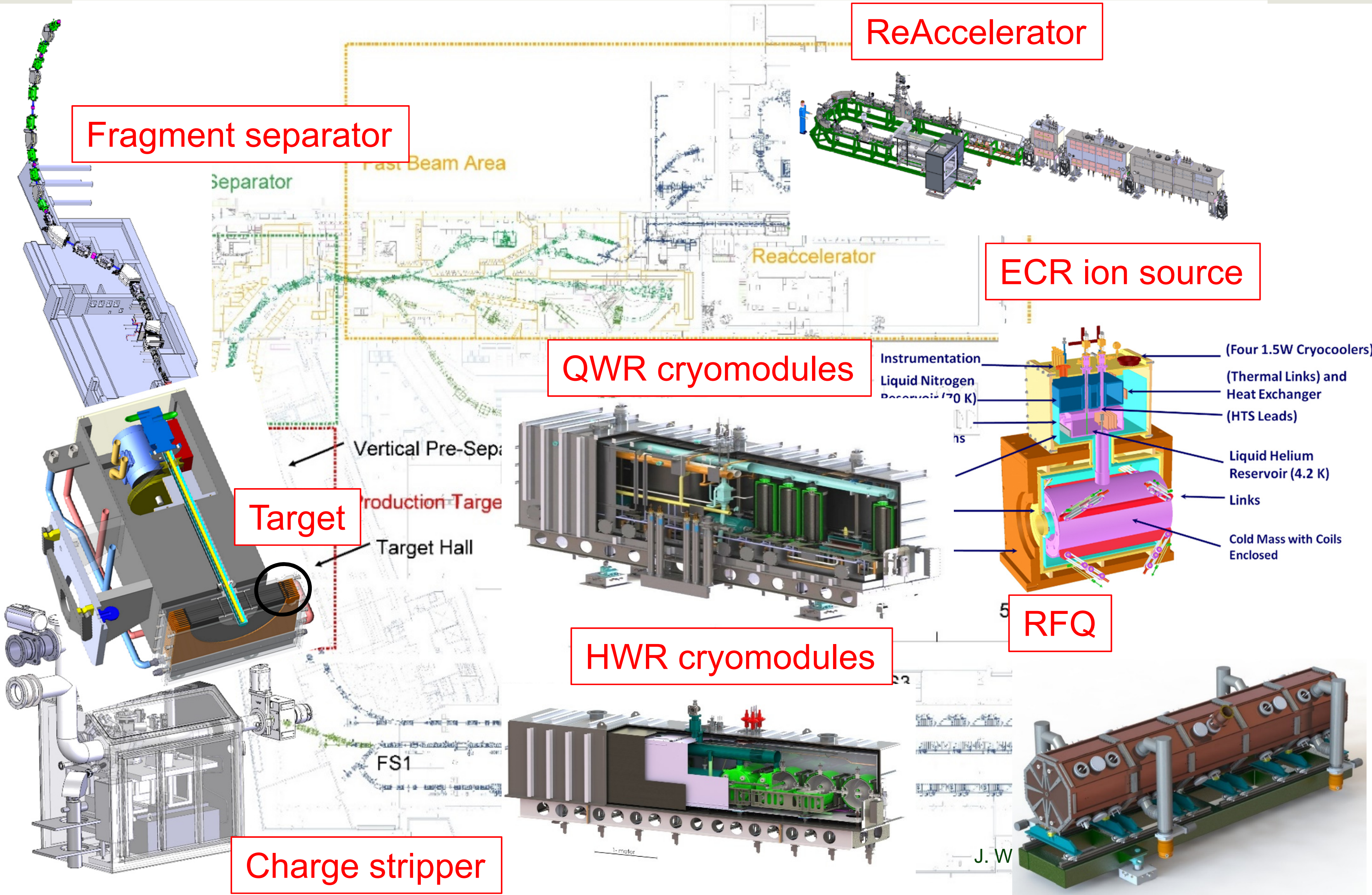
FRIB Accelerator Complex Subsystems



FRIB Accelerator Complex Subsystems

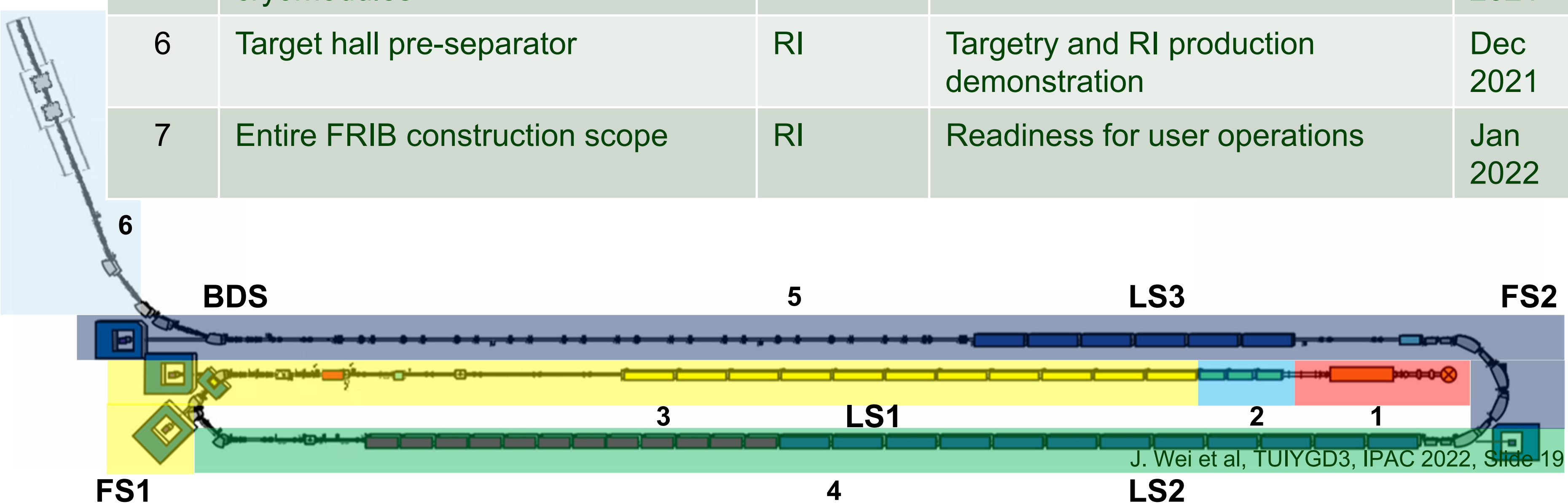


FRIB Accelerator Complex Subsystems



Strategically Planned Beam Commissioning: 7 Phases over 5 Years

Run	Area with beam	Energy [MeV/u]	Goal	Date
1	Ion source, LEBT, RFQ, MEBT	0.5	Front end and civil integration	Jul 2017
2	Linac Segment 1 with β=0.041 cryomodules	2	Cryogenic integration	May 2018
3	LS1 with β=0.041 and 0.085 cryomodules	20	QWR and charge stripping validation	Feb 2019
4	Linac Segment 2 β=0.29 and 0.53 cryomodules	200	2 K cryogenics and HWR validation	Mar 2020
5	Linac Segment 3 β=0.53 cryomodules	> 200	Driver linac validation	Apr 2021
6	Target hall pre-separator	RI	Targetry and RI production demonstration	Dec 2021
7	Entire FRIB construction scope	RI	Readiness for user operations	Jan 2022



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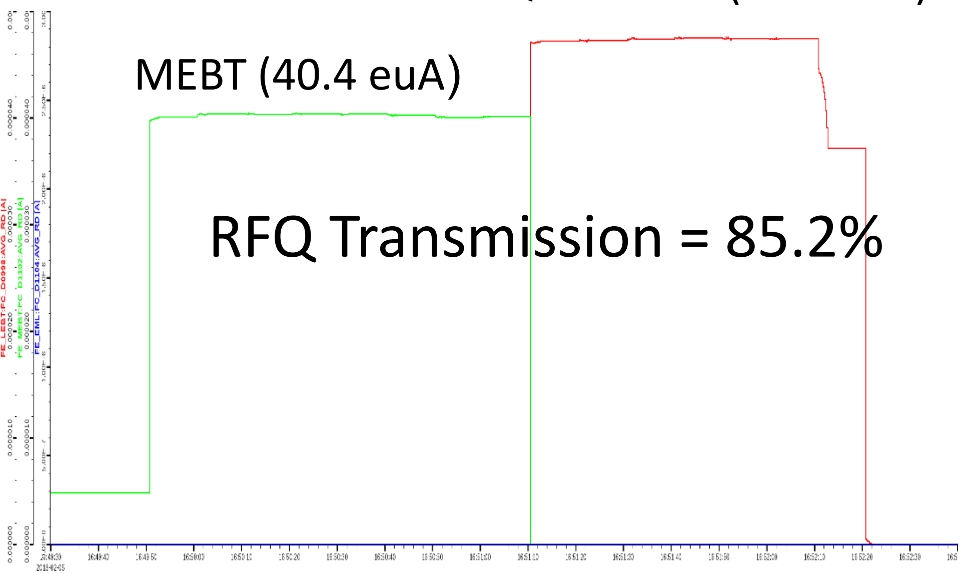
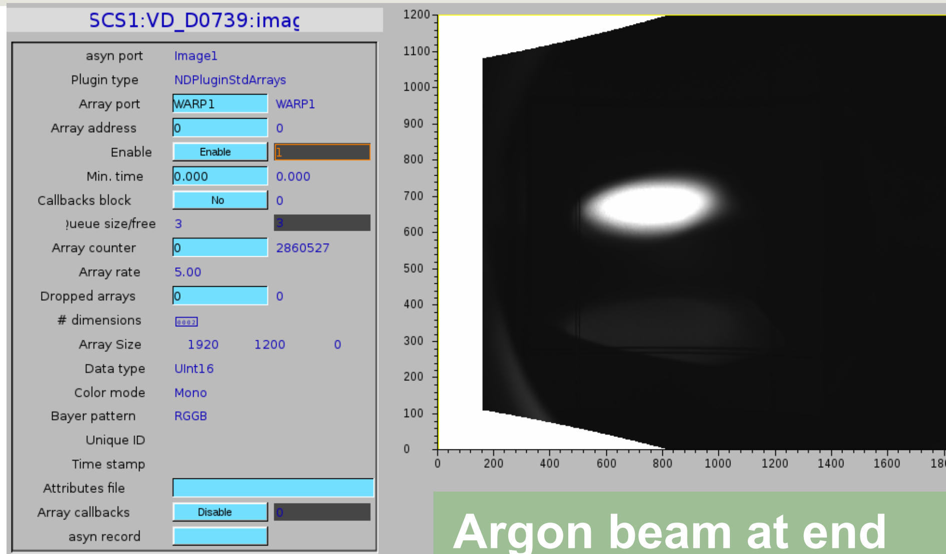
Driver linac commissioning

2017: Front End Beam Commissioned (Run 1)

Integrate Warm Systems with New Civil Infrastructure





Argon beam at end of U-LEBT $^{40}Ar^{9+}$

- Beam based measurement & RF calibration in agreement within 1%

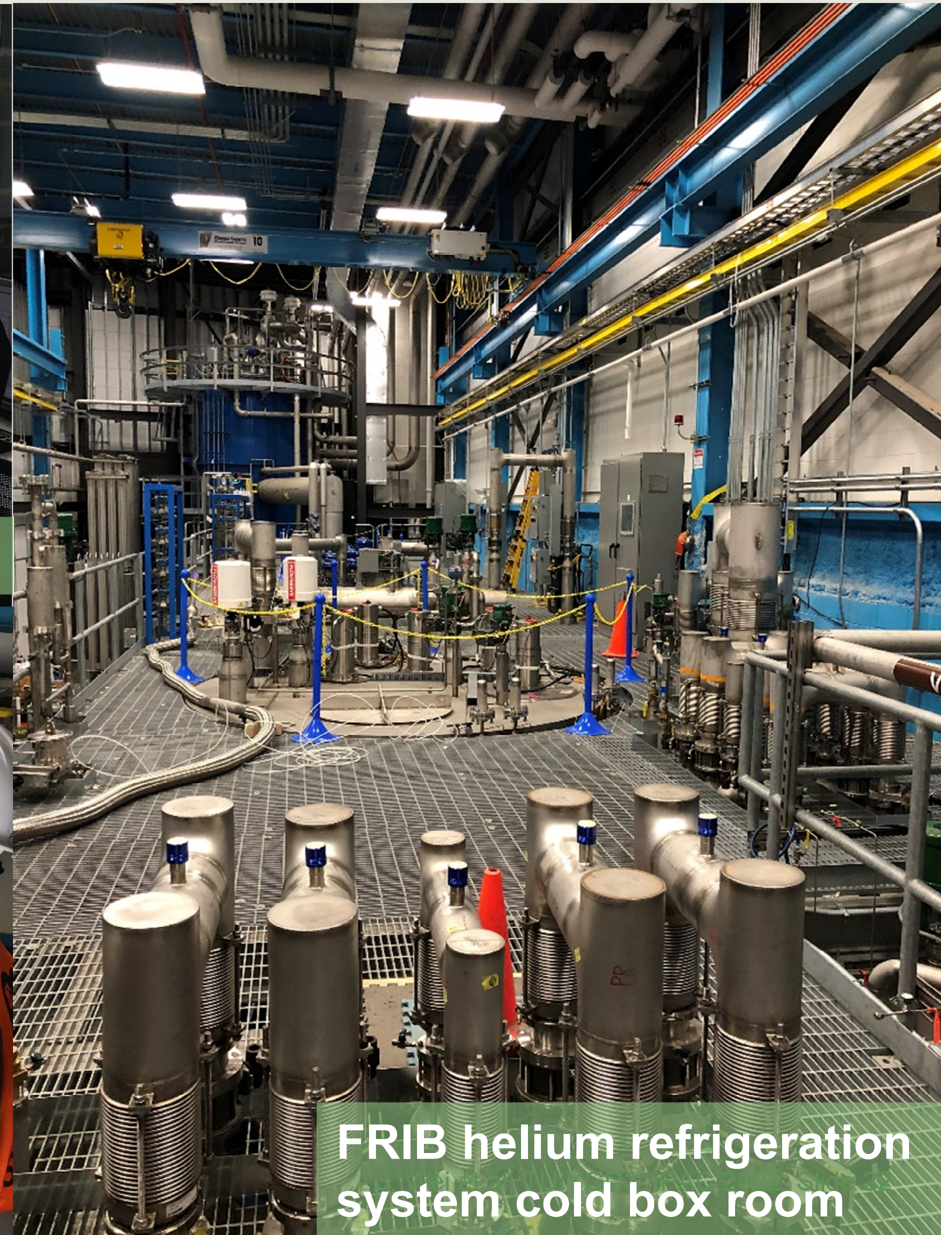
FRIB Lower LEBT, RFQ, MEBT, and the three β=0.041 cryomodules

Helium Refrigeration System Operational

Keeping Cryomodules Cold at 4.5 K or 2 K Temperatures since 2018

2 K cold box commission, Dec. 2018

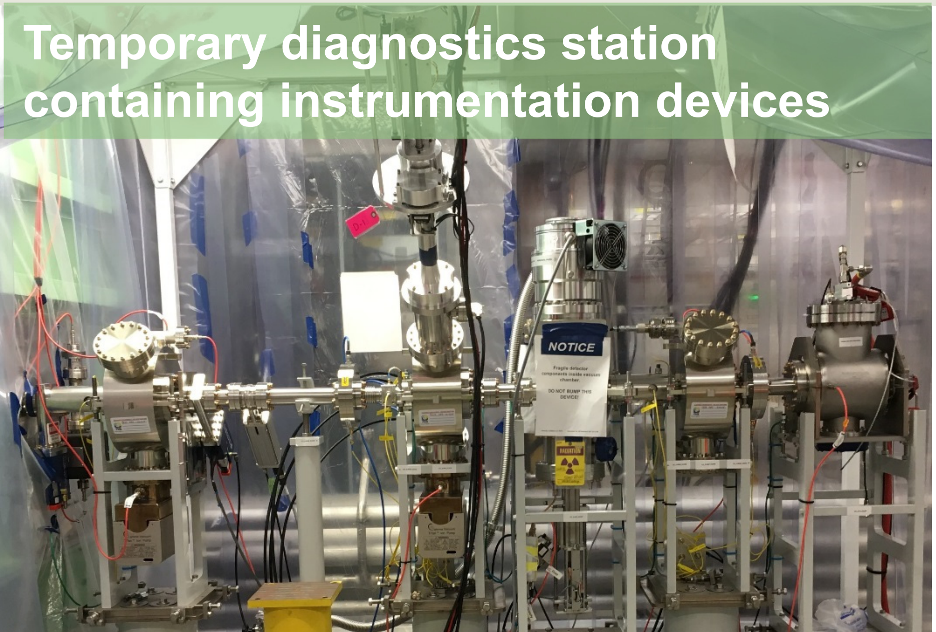
2 K cold box installation, Aug. 2018

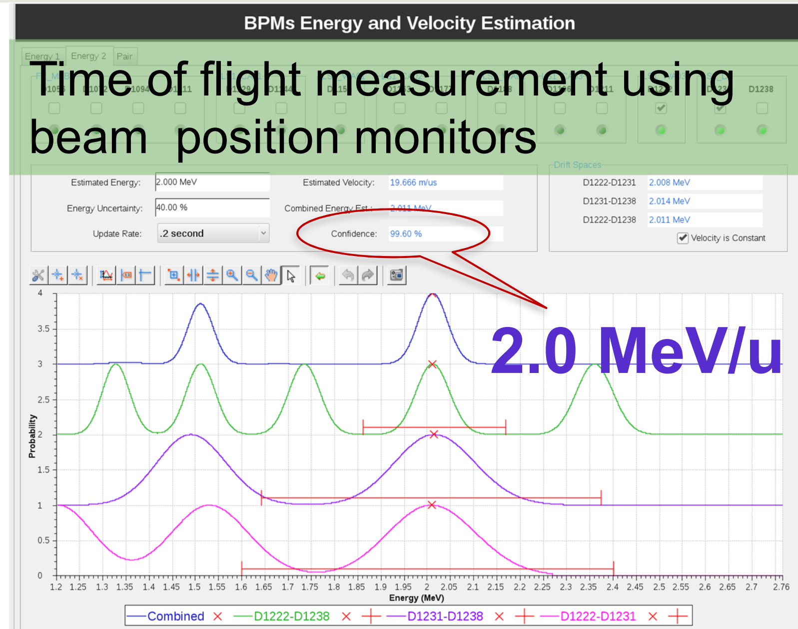


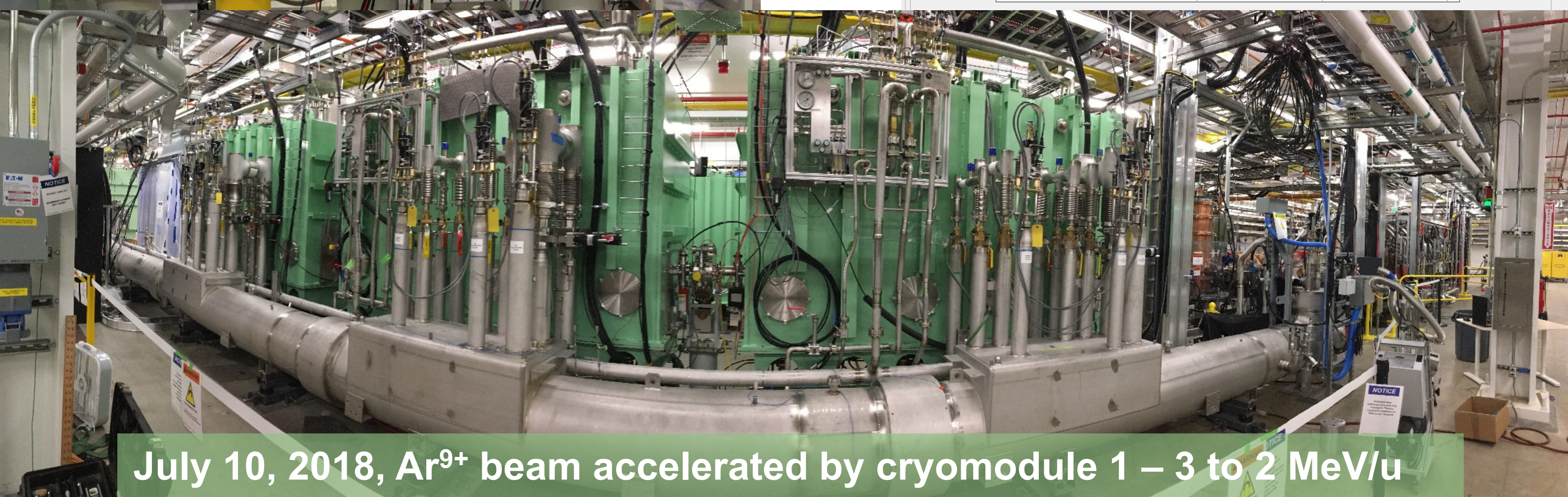
FRIB helium refrigeration system cold box room

2018: Accelerated Beams > 2 MeV/u (Run 2)

Integrated Cryogenic and Cryomodule Systems



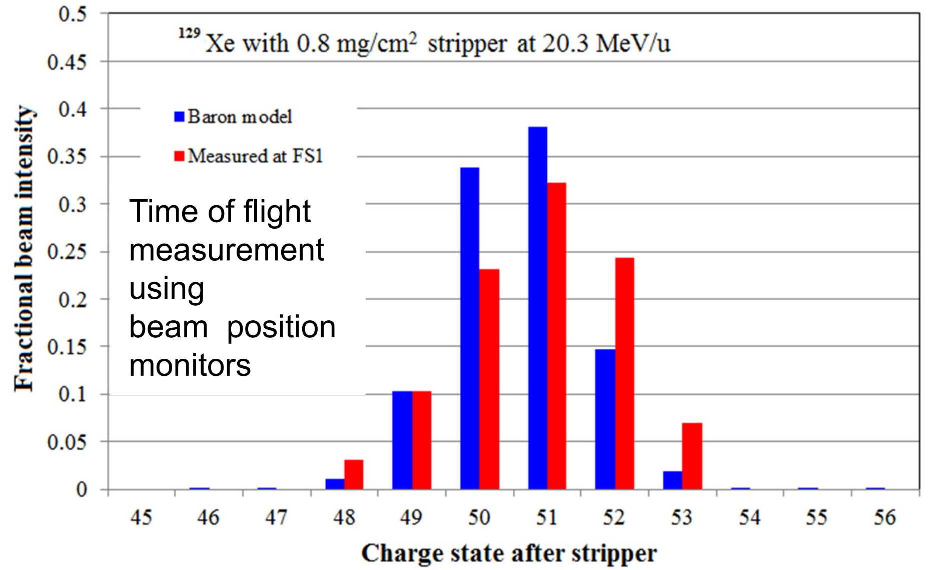




2019: Accelerated Beams > 20 MeV/u (Run 3)

FRIB Became World's Highest Energy CW Hadron Linac

FRIB Linac Segment 1 containing 15 SRF cryomodules



Feb 14, 2019, Ar^{9+} beam accelerated by cryomodule 1 – 14 above 20 MeV/u

2020: Accelerated Beams > 200 MeV/u (Run 4)

Conducted During the Week before COVID-19 Executive Order

- Using two linac segments operating at both 2 K and 4.5 K temperature
- Three-day shift to accelerate ^{36}Ar beam above 200 MeV/u
  - Day 1: removed safety locks and conducted interlock re-validations
  - Day 2: steered beam around folding segment 1 with 100% transmissions
  - Day 3: tuned linac segment 2 to accelerate beam to the full energy

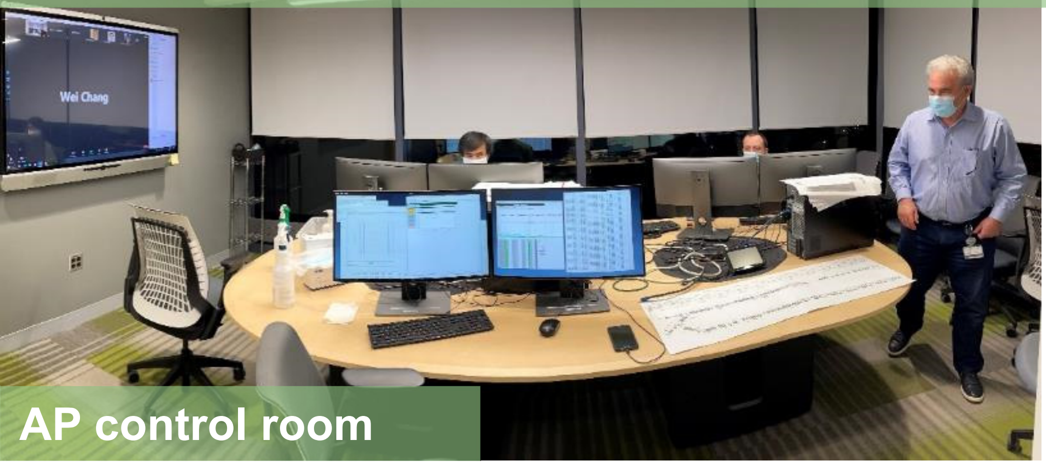
On 04:17, 19 March 2020, ^{36}Ar beam was accelerated to 204 MeV/u using 37 cryomodules. LS2 beam commissioning at the FRIB Main Control Room

2021: FRIB Linac Fully Commissioned (Run 5)

Continued Precautions for COVID-19

- Distributing commissioning staff to five individual control rooms to comply with MIOSHA workplace safeguards under COVID-19

On 21:32, 25 April, 2021 the ^{86}Kr beam was accelerated to 212 MeV/u using all 46 cryomodules. FRIB driver linac commissioning at five distributed control rooms



AP control room

Main control room

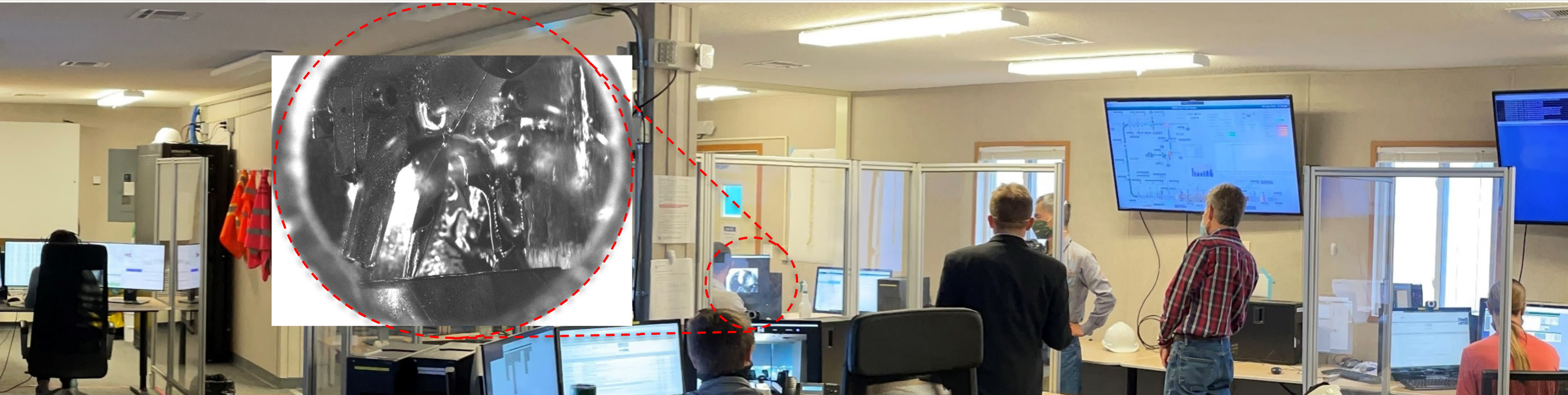
Cryo control room

BIM control room

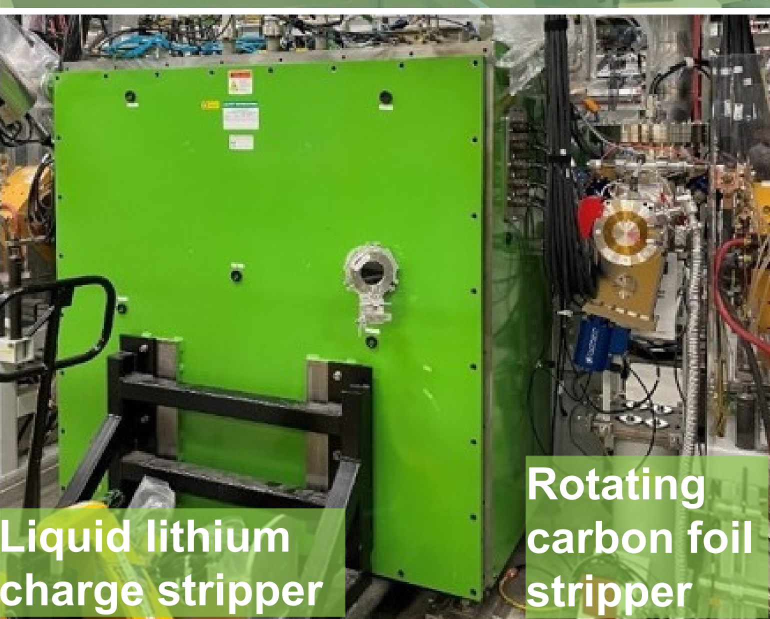
RF control room

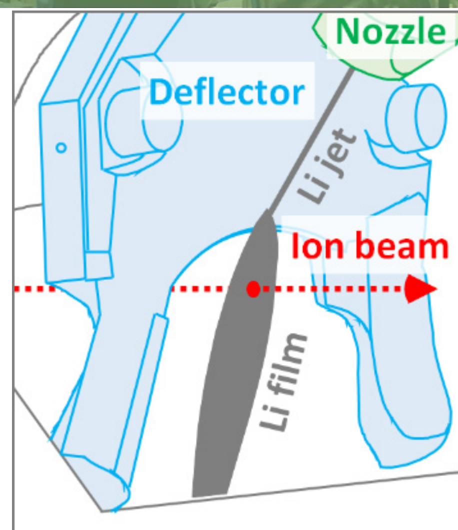
Liquid Lithium Strips Heavy Ions

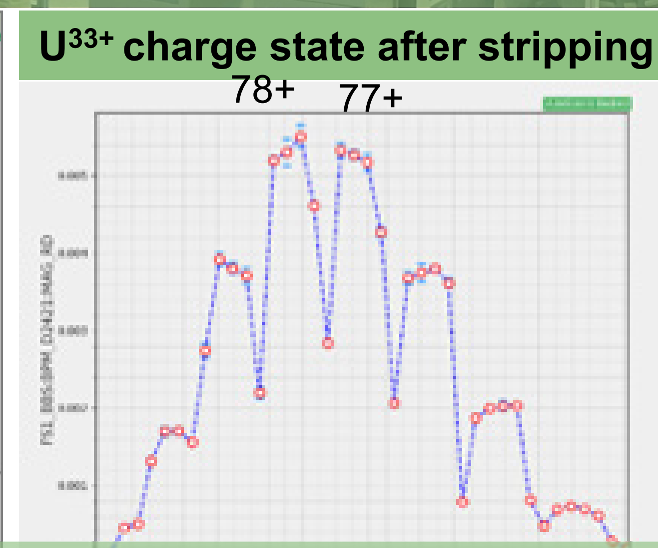
Lithium Jet at 60 m/s Strikes Deflector to Produce Li Film



On 17:22, 8 April 2021, the $^{124}Xe^{26+}$ beam was accelerated to 17 MeV/u and stripped by liquid lithium charge stripper (beam commissioning at FRIB Main Control Room)







T. Kanemura, *et al.*, *Phys. Rev. Lett.* **128**, 212301 (2022)

Simultaneous Multi-charge-state Acceleration

Acceleration of 3 Beams of ^{129}Xe in LS2 with 100% Transmission

- Simultaneously accelerated $^{129}Xe^{49+}$, $^{129}Xe^{50+}$, $^{129}Xe^{51+}$ to 180 MeV/u
- Transmission after charge stripping is 100%
- Factor of 2.5 increase of beam intensity with three charge states acceleration as registered at LS2 beam dump

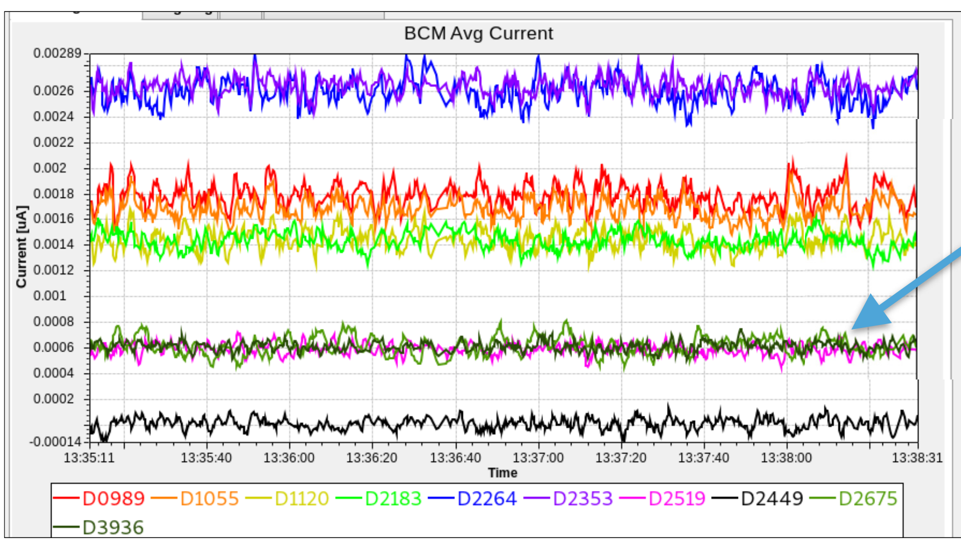
P. N. Ostroumov, *et al., Phys. Rev. Lett.* **126**, 114801 (2021)

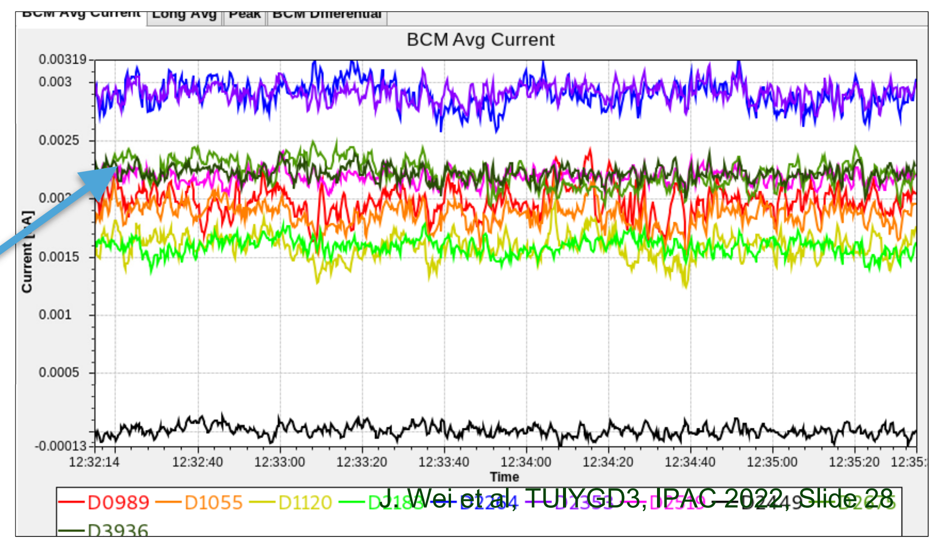
Charge state 50+

Stripping efficiency into 50+: 30.5%

Charge state 49+,50+, 51+

Stripping efficiency into 49+,50+, 51+: 76.5%



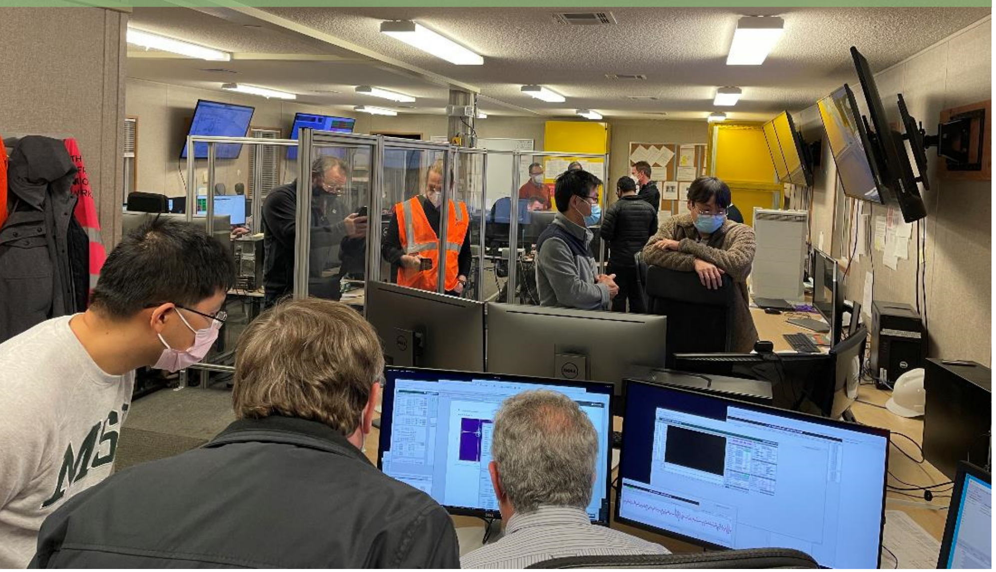


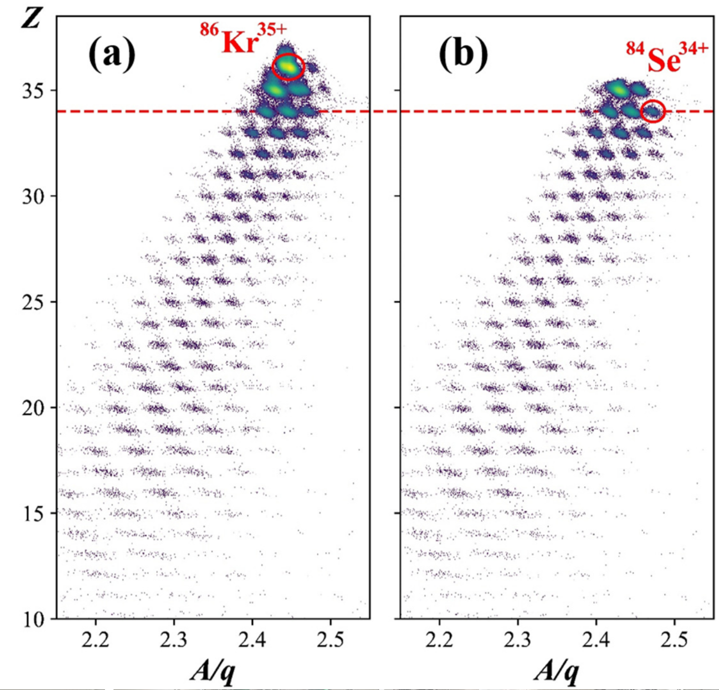
Target and fragment separator commissioning

2021: Rare Isotope Beams Produced (Run 6)

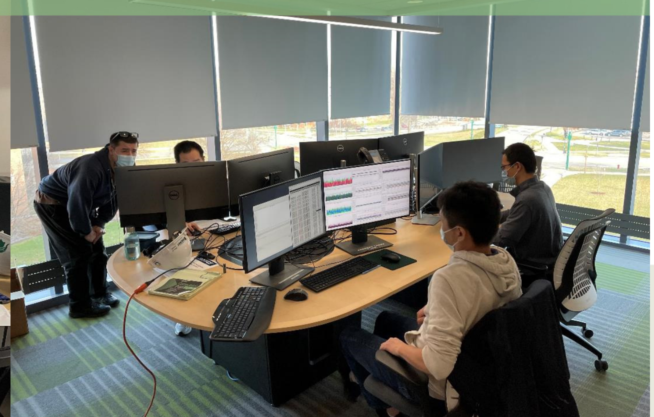
Target and Beam Dump Systems Commissioned with Beam

On 17:46, 11 December, 2021, ^{84}Se isotopes were produced from a primary ^{86}Kr beam, separated, identified at FRIB





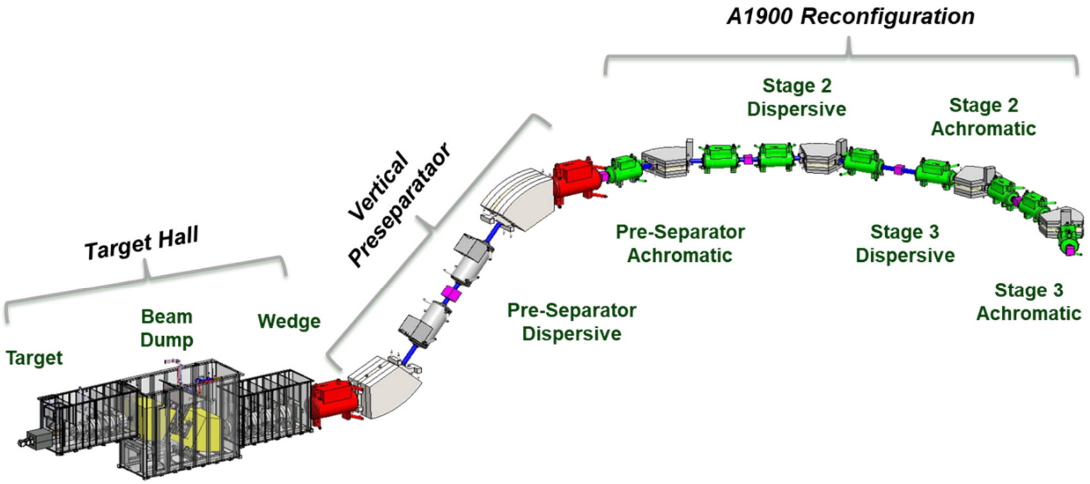
FRIB commissioning at four distributed control rooms



Resolving beam blockage due to installation issue

2022: Beam to Destination Focal Plane (Run 7)

Completing FRIB Technical Project Scope by January 2022



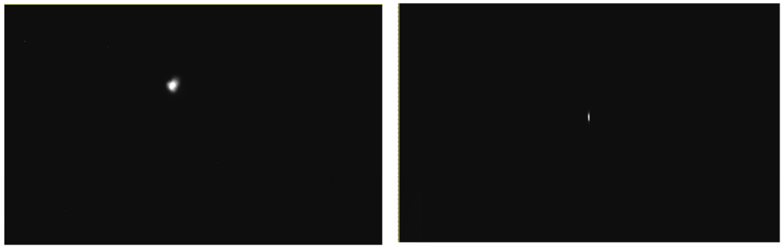


Figure 2. Screenshot of the beam images on the target (left) and DB5 (right) viewers.

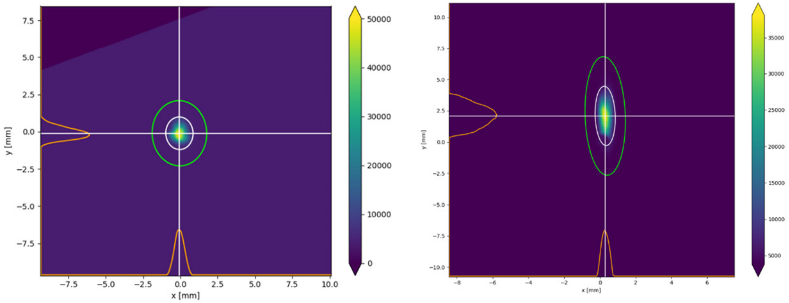
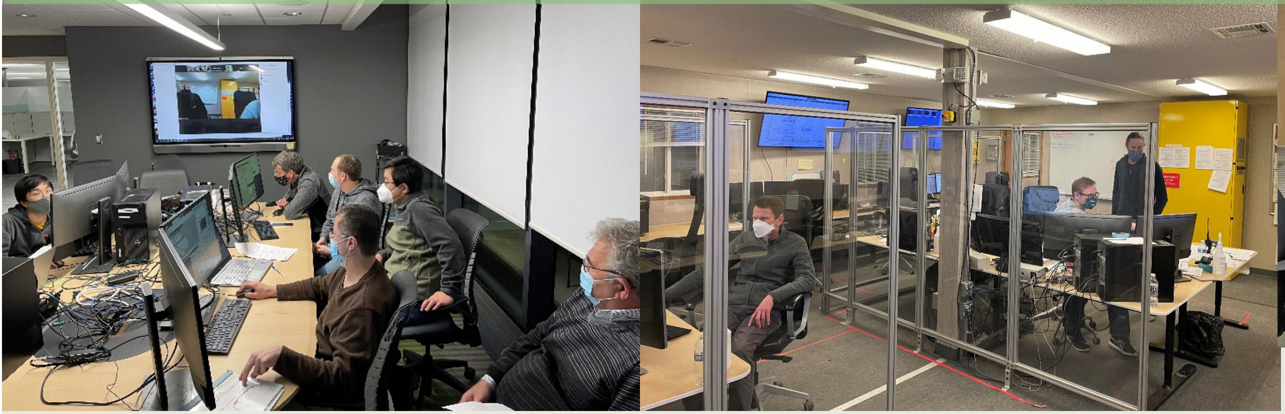


Figure 3. Beam distribution on the target (left) and DB5 viewers (right). The root mean square (rms) beam size on the target is 0.3 mm in both horizontal and vertical directions. The rms size of the beam on the DB5 viewer is 0.2 mm and 0.8 mm in horizontal and vertical planes respectively.

On 14:22, 25 January, 2022, delivery of a 210 MeV/u ^{36}Ar beam to the ARIS focal plane



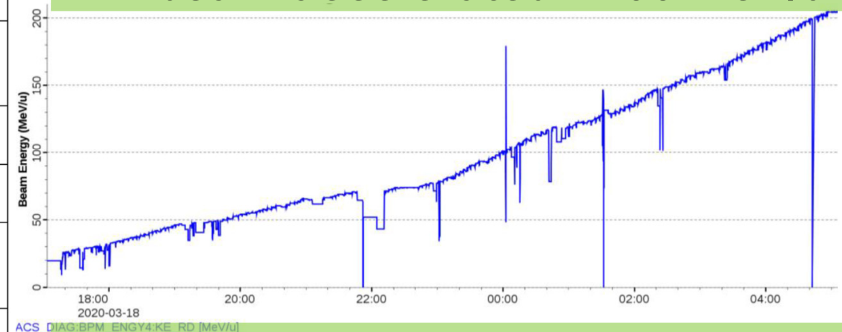
Attained Key Performance Parameters

Table 5.1.1 FRIB Threshold Key Performance Parameters at CD-4

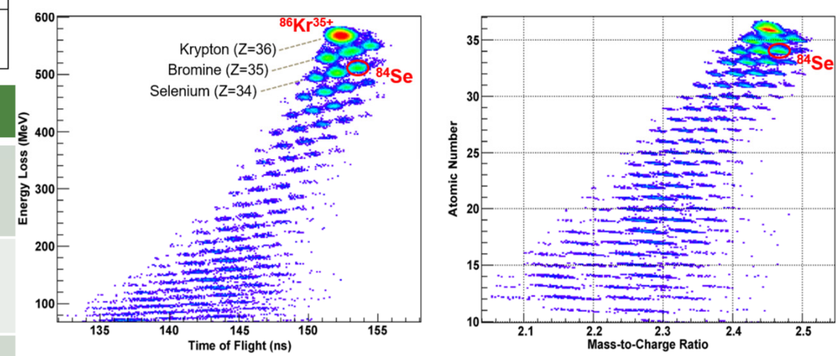
System	Parameter	Performance Criteria
Accelerator System	Accelerate heavy-ion beam	Measure FRIB driver linac ^{36}Ar beam with energy larger than 200 MeV/nucleon and a beam current larger than 20 pnA
Experimental Systems	Produce a fast rare isotope beam of ^{84}Se	Detect and identify ^{84}Se isotopes in FRIB fragment separator focal plane
	Stop a fast rare isotope beam in gas and reaccelerate a rare isotope beam	Measure reaccelerated rare isotope beam energy larger than 3 MeV/nucleon
Conventional Facilities	Linac tunnel	Beneficial occupancy of subterranean tunnel structure of approximately 500 feet path length (minimum) to house FRIB driver linear accelerator
	Cryogenic helium liquefier plant – building and equipment	Beneficial occupancy of the cryogenic helium liquefier plant building and installation of the helium liquefier plant complete
	Target area	Beneficial occupancy of target area and one beam line installed and ready for commissioning

Objective Measures	Date
Measure FRIB driver linac ^{36}Ar beam with energy larger than 200 MeV/nucleon and a beam current larger than 20 pnA	Mar 2020
Detect and identify ^{84}Se isotopes in FRIB fragment separator focal plane	Dec 2021
Measure reaccelerated rare isotope beam energy larger than 3 MeV/nucleon	Sep 2015

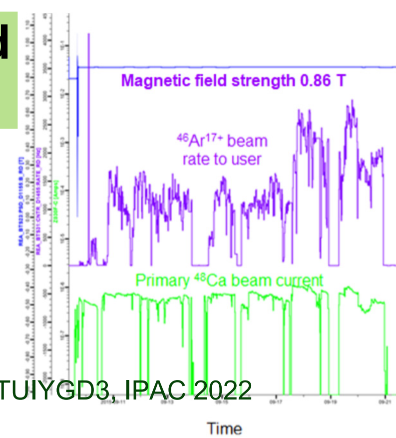
^{36}Ar beam accelerated >200 MeV/u



Rare isotope $^{84}Se^{34+}$ identified



^{46}Ar re-accelerated > 3 MeV/u



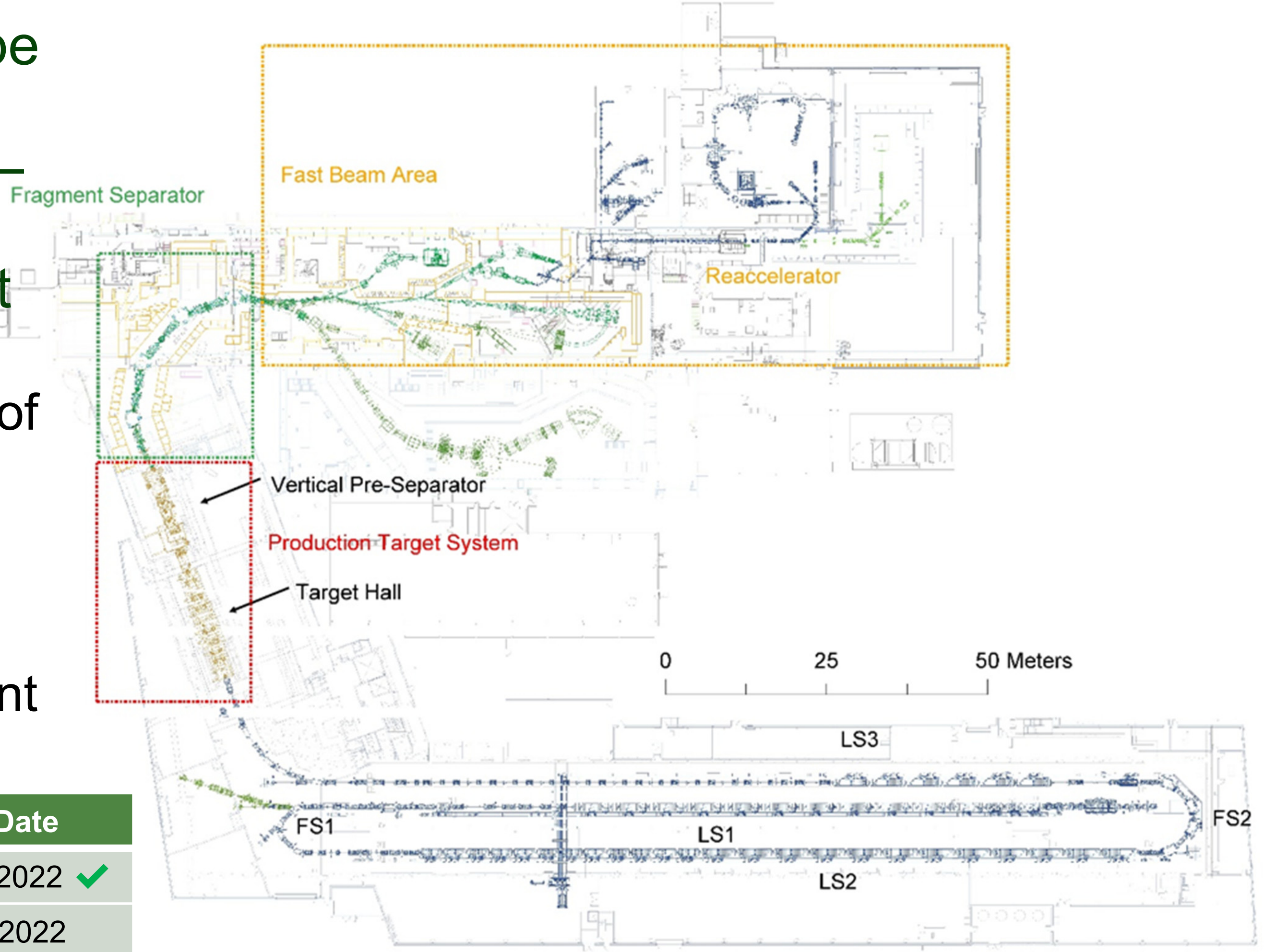
- 3/2020: ^{36}Ar beam accelerated above 200 MeV/u in FRIB driver linac
- 12/2020: $^{84}Se^{34+}$ ($q = Z$) is identified using all three measured parameters
- 9/2015: ^{46}Ar isotope beam from CCF, stopped, re-accelerated to 4.6 MeV/u at ReA3

J. Wei et al, TUIYGD3, IPAC 2022

Early operations

Readiness for Beam Operations
Start PAC1 User Program May 11, 2022

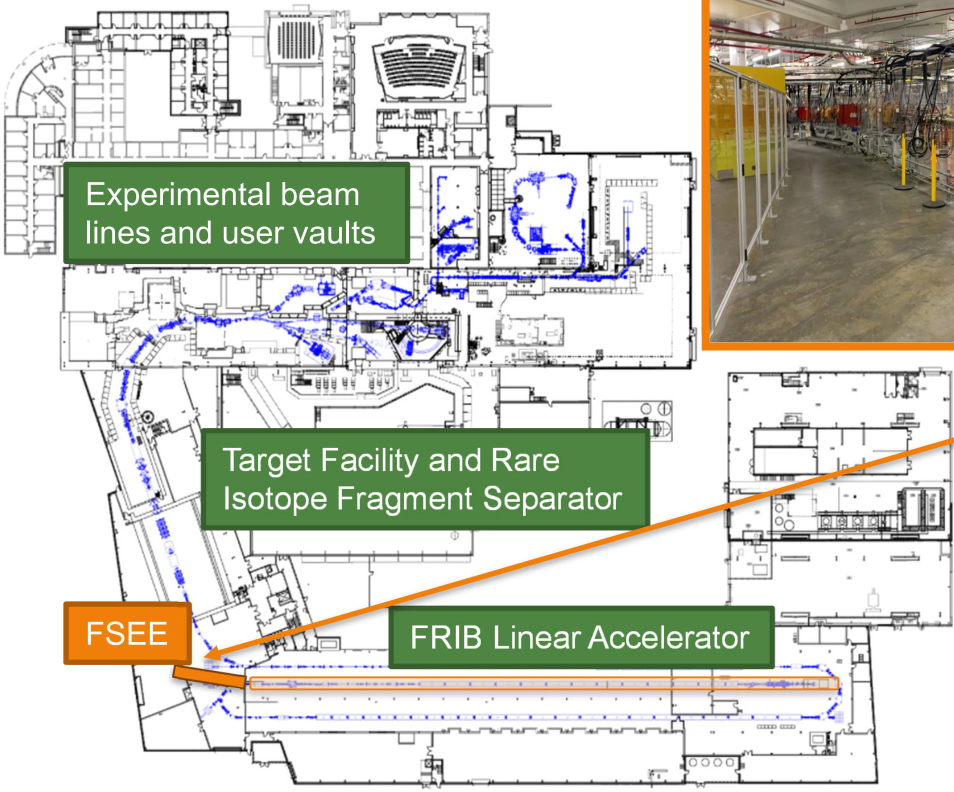
- FRIB provided isotope beam to the decay station from May 11 – 18 for the first PAC approved experiment #21062
  - Primary beam: 1 kW of ^{48}Ca
  - RI beams: ^{42}Si was delivered to the experiment for the most of the experiment time

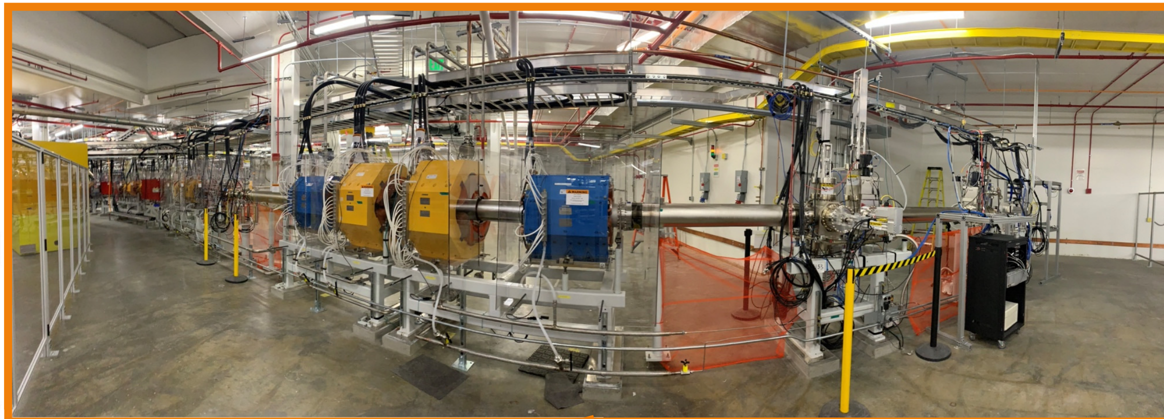


Objective Measures	Date
FSEE user operation start	Jan 2022 ✔
New Main Control Room in use	Mar 2022 ✔
Beam commissioning on user run	May 2022 ✔
1st user experiment at FDSi	May 2022 ✔

H. Crawford, *et al*., FRIB experiment e21062, Accessed 2022, https://userportal.frib.msu.edu/Pac/Experiments/PublicList
M. Almond *et al*., “FRIB decay station,” Accessed 2022, http://www.ornl.gov/project/frib-decay-station

FRIB Single Event Effects Beam Line Operating: Industrial User Program Started





FSEE uses the ion source, Front End, and first segment of the FRIB linac.

Summary and lessons learned

FRIB Technical Construction 2014 – 2022

Beam commissioning scope completed January 2022

FRIB driver linac in accelerator tunnel

Milestones	Date
DOE and MSU cooperative agreement	Jun 2009
CD-1: preferred alternatives decided	Sep 2010
CD-2/CD-3a: performance baseline, start of civil construction & long lead procurement	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

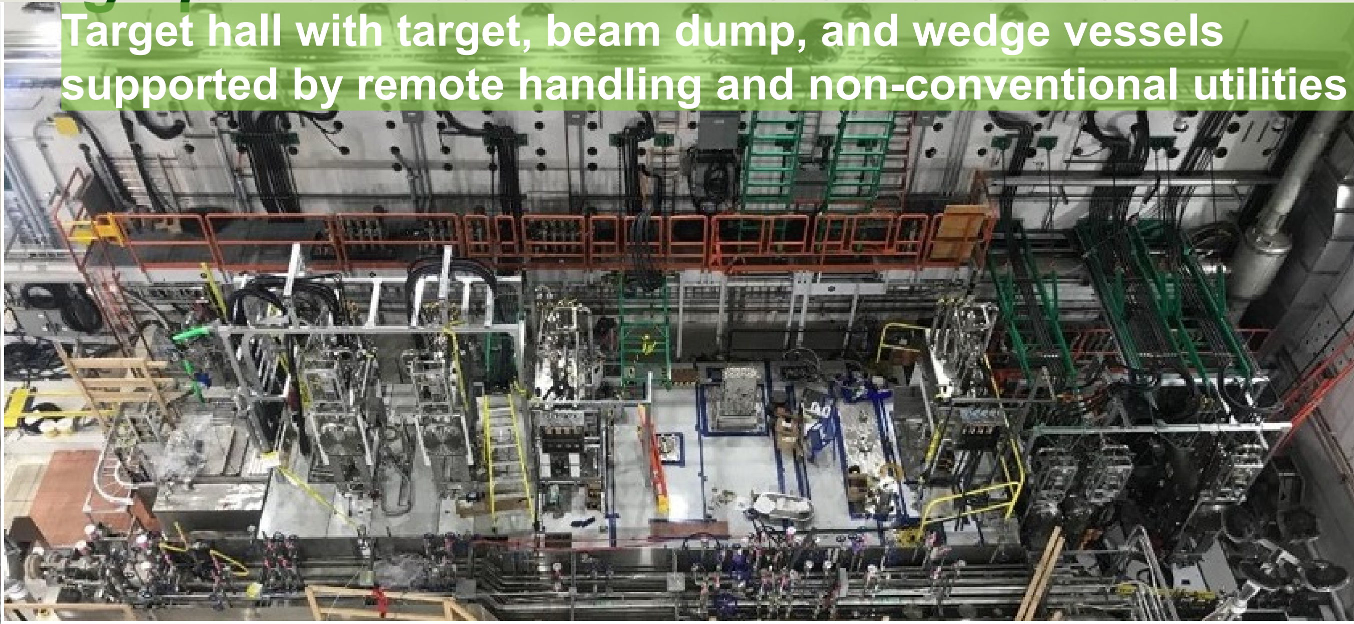
- FRIB linac includes the front end and 46 superconducting RF cryomodules
  - ECR ion sources, RFQ
  - 324 SRF cavities in 46 cryomodules with velocity β from 0.041 to 0.53
  - 208 cold magnets, 350 warm magnets
- Liquid helium for 2 K, 4 K operations
- Liquid lithium and rotating carbon for charge stripping

Experimental Systems Deployed in Phases

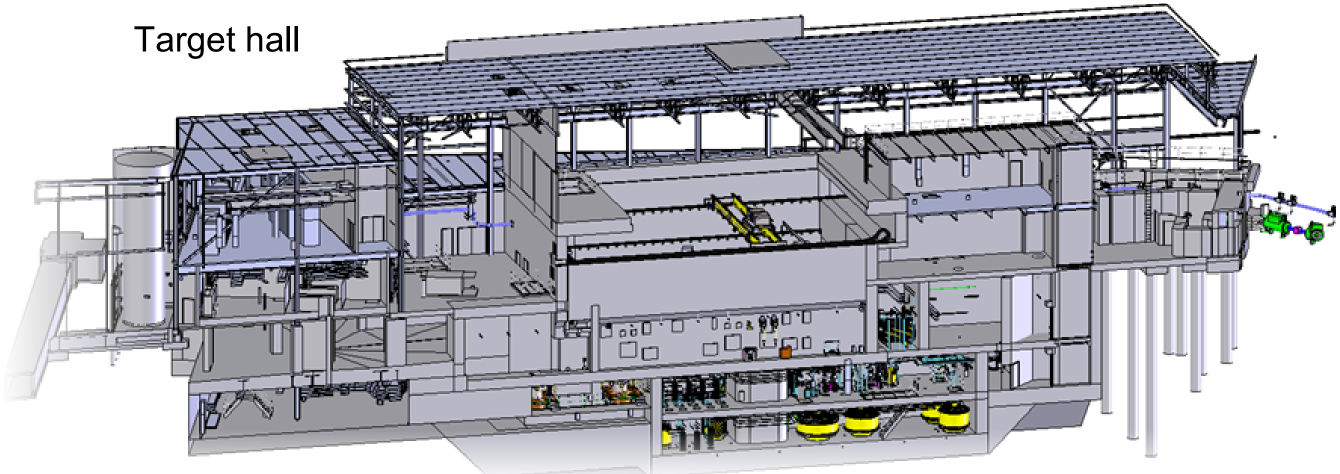
3-stage fragment separator for rare isotope production at high rates with high purities to maximize science reach

Vertical pre-separator containing a series of SC magnets weighing up to 180 Ton each

Target hall with target, beam dump, and wedge vessels supported by remote handling and non-conventional utilities



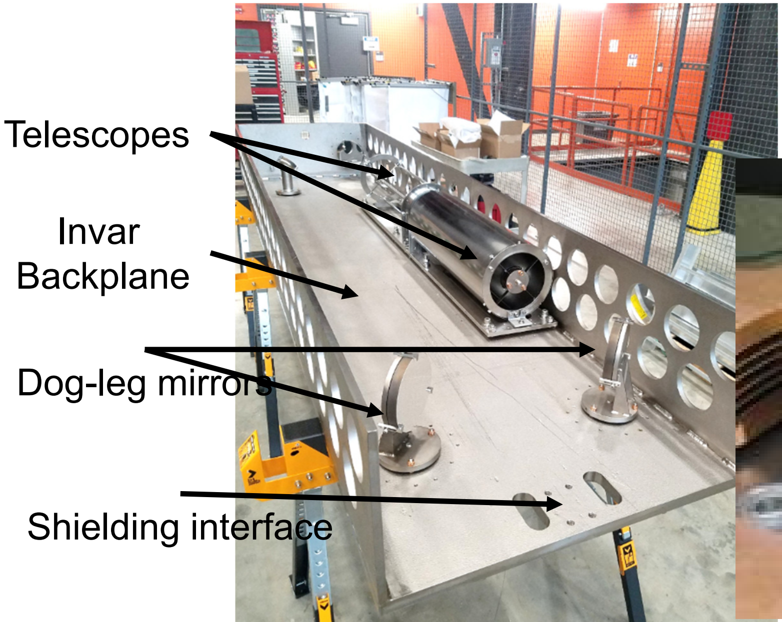
Target facility design

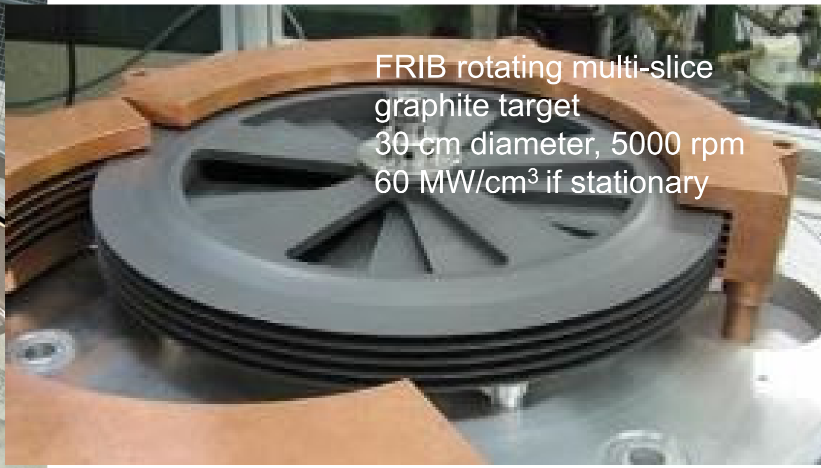


Target, Beam Dump, Wedge, Diagnostics
In Preparation for User Programs and Power Ramp Up

- Starting with static target disc and beam dump for initial commissioning
- Continue with single-slice rotating target for PAC1 user runs
- Final target and beam dump designed for 100 kW and 300 kW heavy ion beam power, respectively
- Rotating multi-slice graphite target 30 cm diameter, 5000 rpm (~ 60 MW/cm^3 if stationary)

Target thermal imaging system





Experience and Lessons Learned

- 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**)

Collaboration with National Laboratories and International Partners: Key to Success

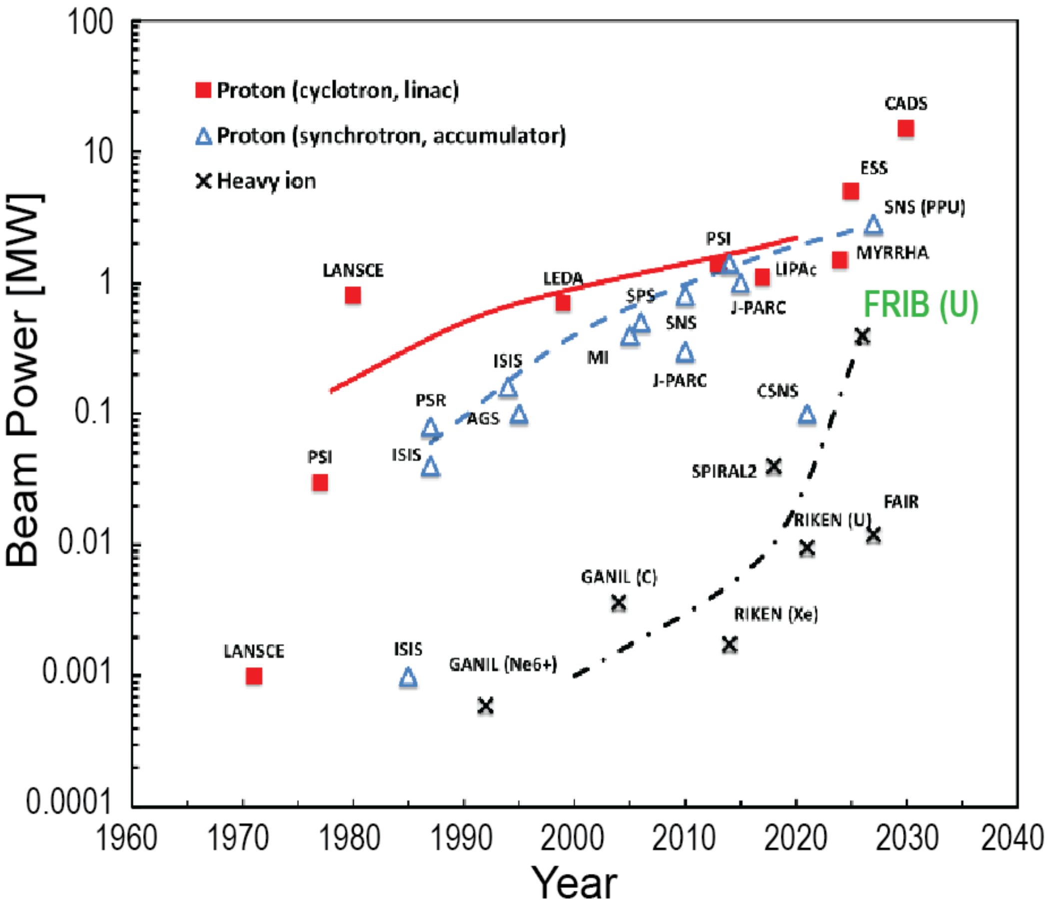
- ANL
  - Liquid lithium charge stripper
  - Beam dynamics verification ; β=0.29 HWR processing and testing ; SRF tuner validation ; beam dump ; SRF components development
  - RF couplers for multi-gap buncher
  - SOLARIS
- BNL
  - Plasma window & charge stripper, physics modeling, magnets
- FNAL
  - Diagnostics, SRF processing
- JLab
  - Cryoplant; cryodistribution design & prototyping
  - Cavity hydrogen degassing; e-traveler
  - HWR processing & certification
  - QWR and HWR cryomodule design and engineering support for production
- LANL
  - Proton ion source
- LBNL
  - ECR coldmass; beam dynamics
- MIT
  - CRIS
- ORNL
  - Remote handling, diagnostics; large-vessel vacuum, cryoplant controls
  - FDSi
- SLAC
  - Cryogenics, SRF multipacting, physics modeling

- RIKEN
  - Helium gas charge stripper
- TRIUMF
  - Beam dynamics design, physics modeling SRF, QWR etching
- INFN
  - SRF technology
- KEK
  - SRF technology, SC solenoid prototyping
- IMP
  - Magnets
- Budker Institute, INR Institute
  - Diagnostics
- Tsinghua Univ. & CAS
  - RFQ
- ESS
  - Accelerator physics
- DTRA
  - RFQ power supply
- CSNSM-JaNNUS
  - Nuclear recoil damage to materials
- RaDIATE
  - Nuclear recoil damage to materials
- GANIL
  - Rare isotope physics, target development
- GSI
  - Rare isotope physics, fragment separators
- U Notre Dame
  - Recoil implantation testing of materials

Future perspectives

Catching Up with World Leaders in Beam Power Frontier

- RIKEN is leading the heavy ion beam power frontier
  - Successfully operating at ~ 10 kW level at ~ 345 MeV/u
- FRIB just starts the 6-year planned power ramp up to 400 kW while preparing for energy upgrade to 400 MeV/u



- Example: phased deployment of targetry systems
  - Beam dump: (1) static 20º slanted; (2) static 6º slanted … (3) 1 mm shell rotating; (4) 0.5 mm shell rotating, as we learn to manage NCU
  - Target: (1) static multi-position; (2) single-slice rotating; (3) multi-slice rotating
  - Wedge: (1) wedge ladder; (2) 2nd wedge station; (3) nonlinear wedge …

Conclusion

- Fourteen years after the site selection in 2008, the FRIB baseline was delivered on cost and 5 months ahead of schedule
- Strategically planned beam commissioning in 7 phases over 5 years successfully led to the start of user operations
- In subsequent years, the primary beam power will be progressively increased as operational experience is accumulated, working toward 400 kW
- 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

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- We thank industrial partners worldwide for their support to FRIB during the design, R&D, construction, commissioning, and early operations
- We are looking forward to continued collaboration towards FRIB's future improvements, expansion, and upgrades

We Are Looking for Energitic and Ambitious Scientists, Engineers, Students to Join FRIB

- During the past years, scientists, engineers, and post docs of a wide range of disciplines joined FRIB from national laboratories, universities and industrial companies worldwide (more than 30 countries) – their decidation and ingenuity made FRIB successful
- Students joined Michigan State University to pursue their career with FRIB (e.g. MSU cryogenic initiative, Accelerator Science and Engineering Traineeship program, MSU graduate school)
- We are looking for more energitic and ambitious scientists, engineers, and students to join our journey while extending their career with a state-of-the-art accelerator facility, and ambitious and challenging programs for future developments
  - High-power accelerator physics, rare isotope beam physics, high-power targetry, machine learning and automation, cryogenics, superconducting RF, superconducting magnets, controls, diagnostics, detector and data acquisition, mechanical engineering, electrical engineering, radiation and remote handling, large-project management …

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Thank You!