FRIB Power Ramp-Up: Status and Plans

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Outline

- Introduction
- Phased linac improvements
- Phased targetry deployment
- Beam loss budget, radiological control, personnel protection
- Legacy system renovation
- Automation and machine learning
- Summary

Introduction

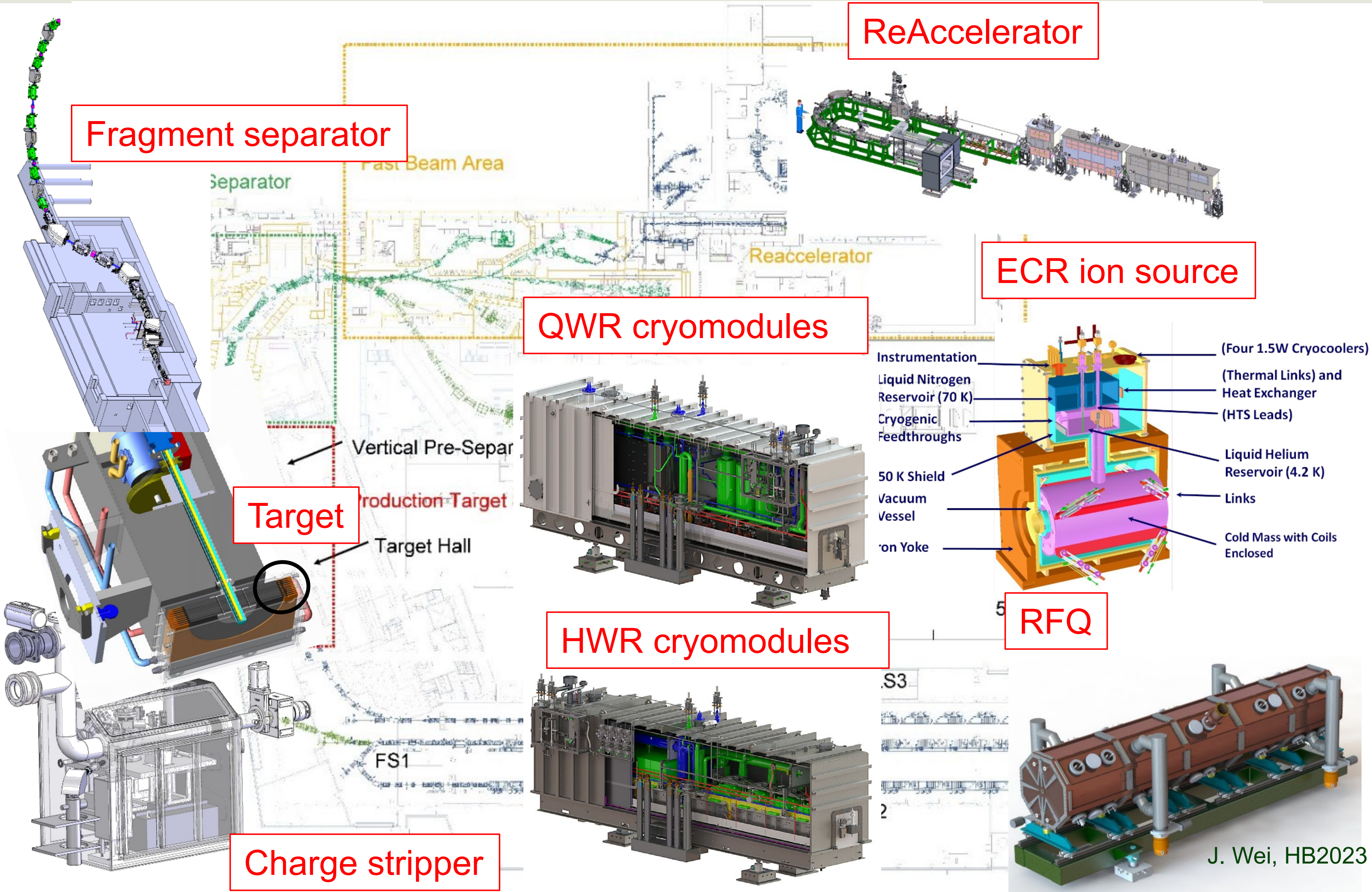
FRIB Project Construction 2014 – 2022

World’s Highest Energy Heavy Ion Linac / CW Hadron Linac

Milestones	Date
DOE and MSU cooperative agreement	Jun 2009
CD-1: preferred alternatives decided	Sep 2010
CD-2/3a: 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
CD-4: project completion	Apr 2022
Start of PAC1 user experiments at 1 kW primary beam power	May 2022
User experiments at 10 kW primary beam power	Oct 2023

- Linac includes front end and 46 SRF 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 charge stripping
- Accelerates all stable ions > 200 MeV/u

Accelerator Complex: In-Flight Isotope Separation; Fast, Stopped, and Reaccelerated Beams



More than 210 Rare Isotope Beams Delivered to FRIB User Experiments for Year 1 with > 5000 Beam Hours

Most Recent Experiments:

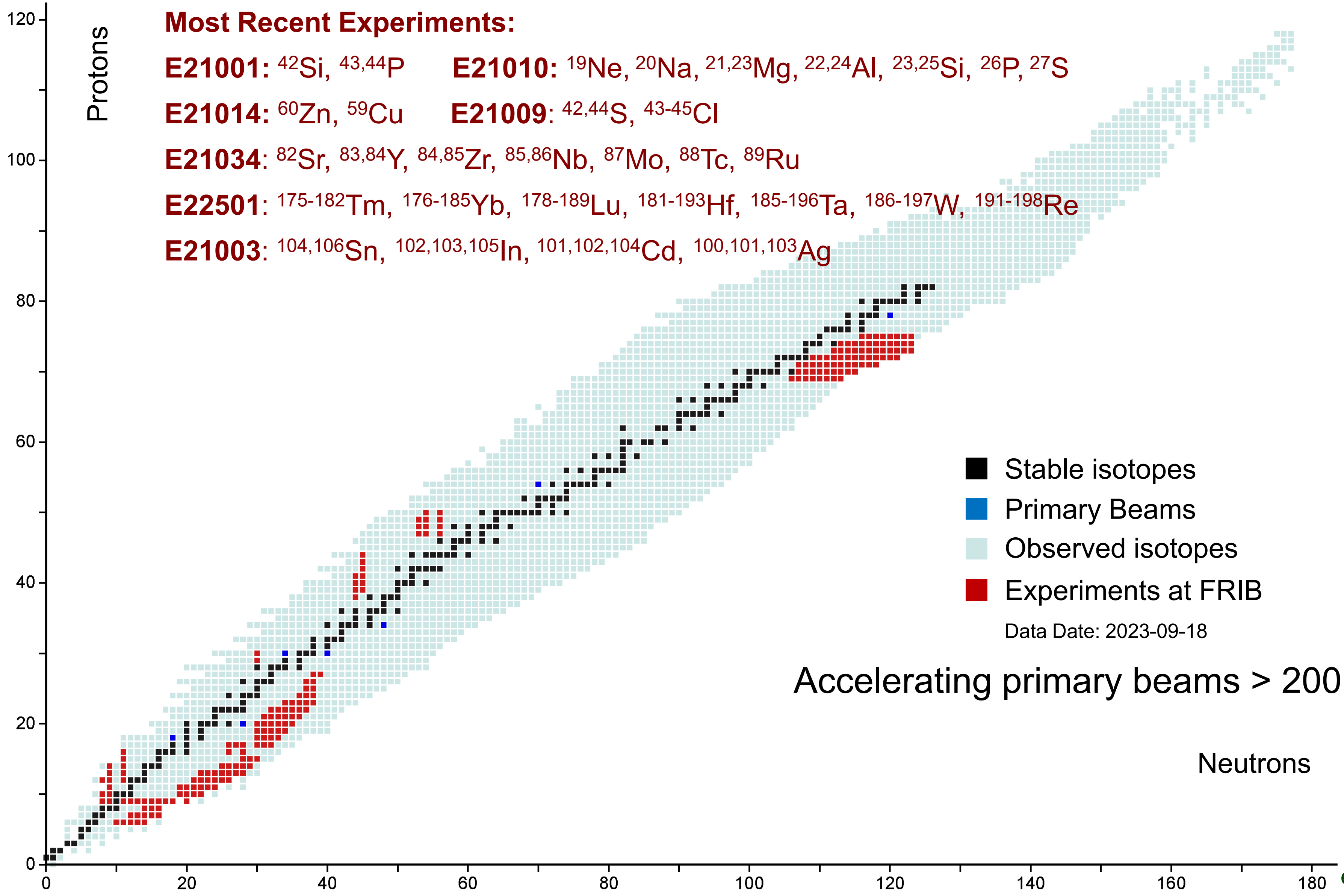
E21001: ^{42}Si, ^{43,44}P **E21010:** ^{19}Ne, ^{20}Na, ^{21,23}Mg, ^{22,24}Al, ^{23,25}Si, ^{26}P, ^{27}S

E21014: ^{60}Zn, ^{59}Cu **E21009**: ^{42,44}S, $^{43\text{-}45}$Cl

E21034: ^{82}Sr, ^{83,84}Y, ^{84,85}Zr, ^{85,86}Nb, ^{87}Mo, ^{88}Tc, ^{89}Ru

E22501: $^{175\text{-}182}$Tm, $^{176\text{-}185}$Yb, $^{178\text{-}189}$Lu, $^{181\text{-}193}$Hf, $^{185\text{-}196}$Ta, $^{186\text{-}197}$W, $^{191\text{-}198}$Re

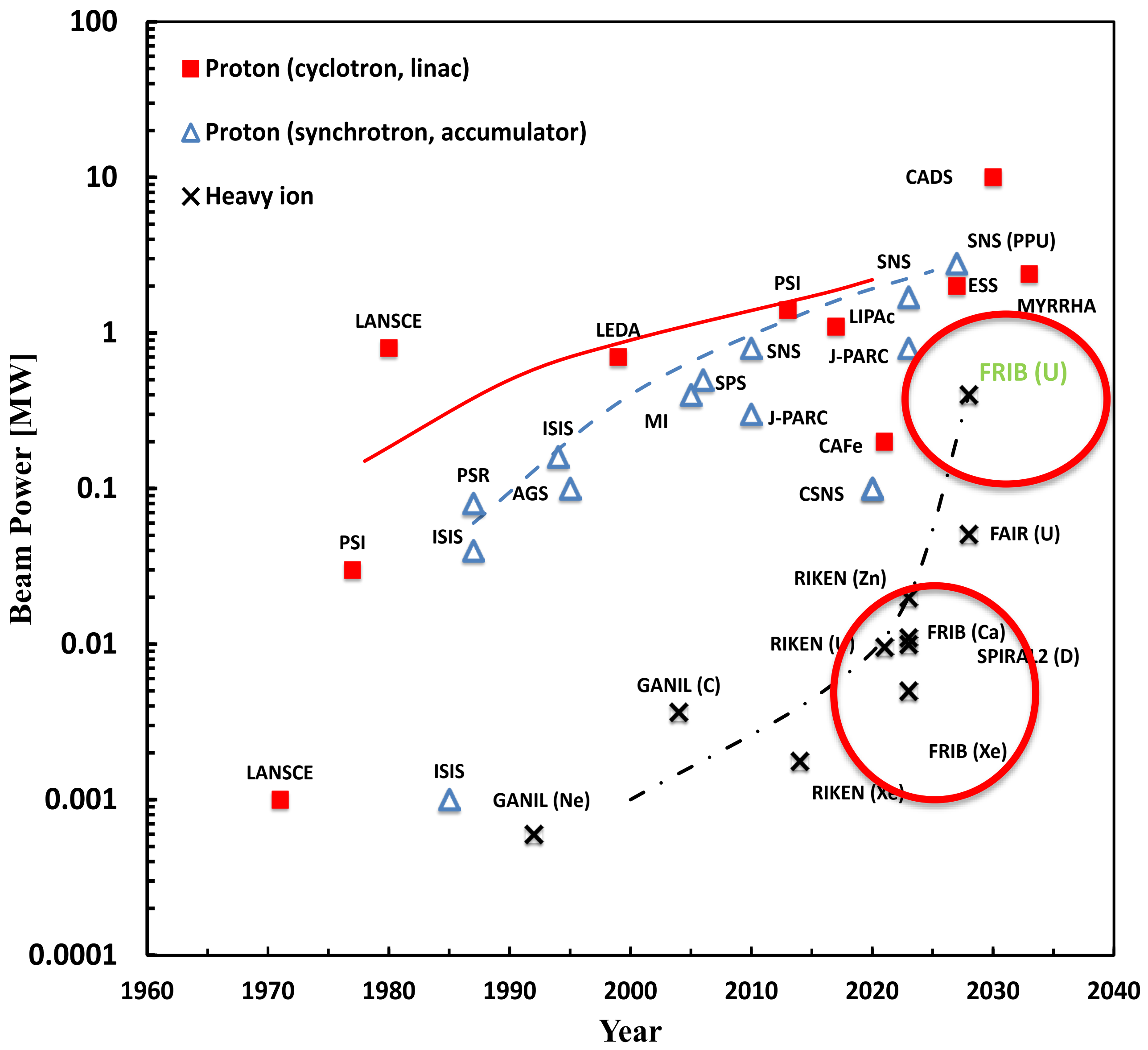
E21003: ^{104,106}Sn, ^{102,103,105}In, ^{101,102,104}Cd, ^{100,101,103}Ag



Accelerating primary beams > 200 MeV/u

Primary Beams
^{36}Ar
^{48}Ca
^{64}Zn
^{70}Zn
^{82}Se
^{124}Xe
^{198}Pt

Evolution of Proton and Heavy Ion Beam Power

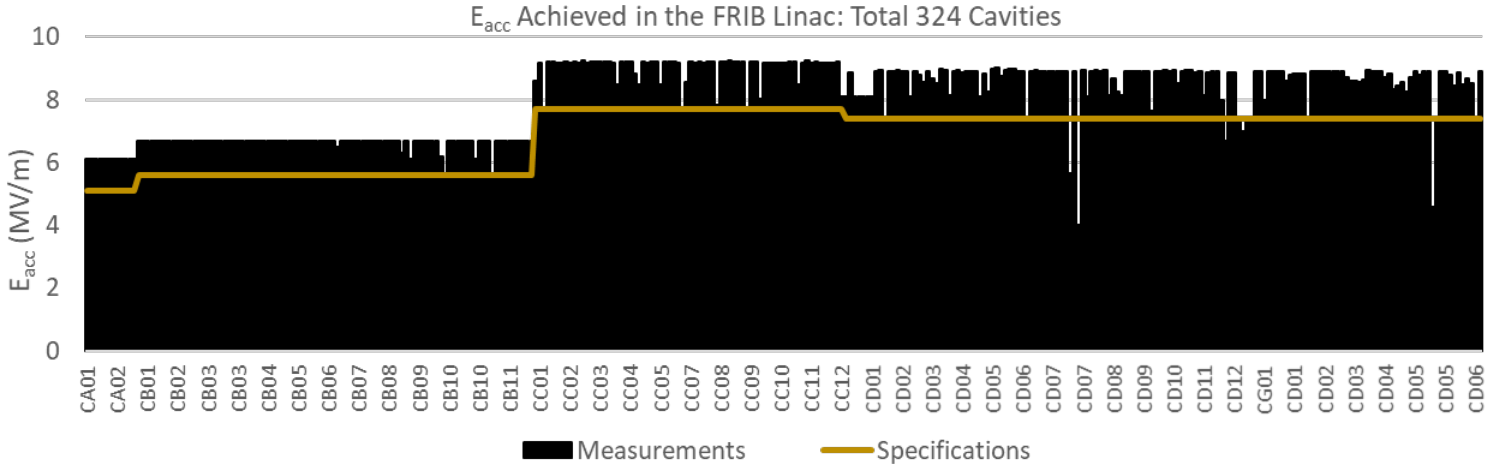


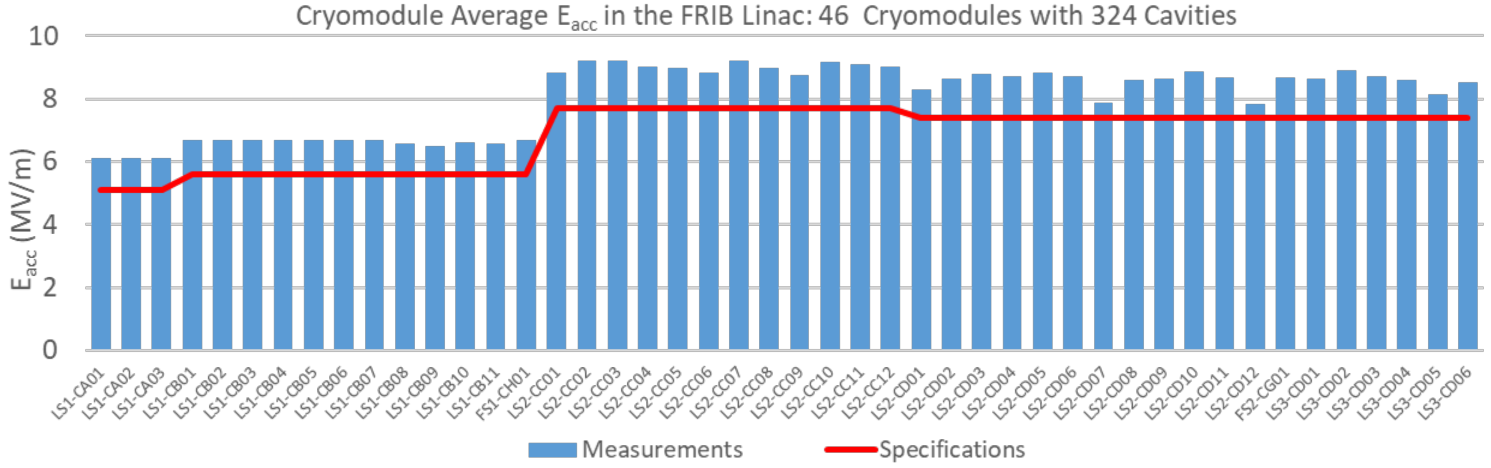
- Compared to proton-based facilities, lower-energy, heavy-ion based facilities face challenges, including high dissipation-power density and high radiation damage
  - FRIB started user operations at 1 kW
  - Progressively increasing the average beam current
  - Currently operating at 10 kW
  - Beam power ramp-up goal: 400 kW in 2028

FRIB Facility Challenges and Complexity

- Large-scale low-β superconducting linac
- High-power beam-intercepting devices
  - Charge stripping and charge collection
  - Target and beam dump
- Multiple charge-state acceleration
- Advanced and complex fragment separation
- Legacy system interfacing and integration
- Multi-layered machine protection

Large-scale Low-β Superconducting Linac: in Operation

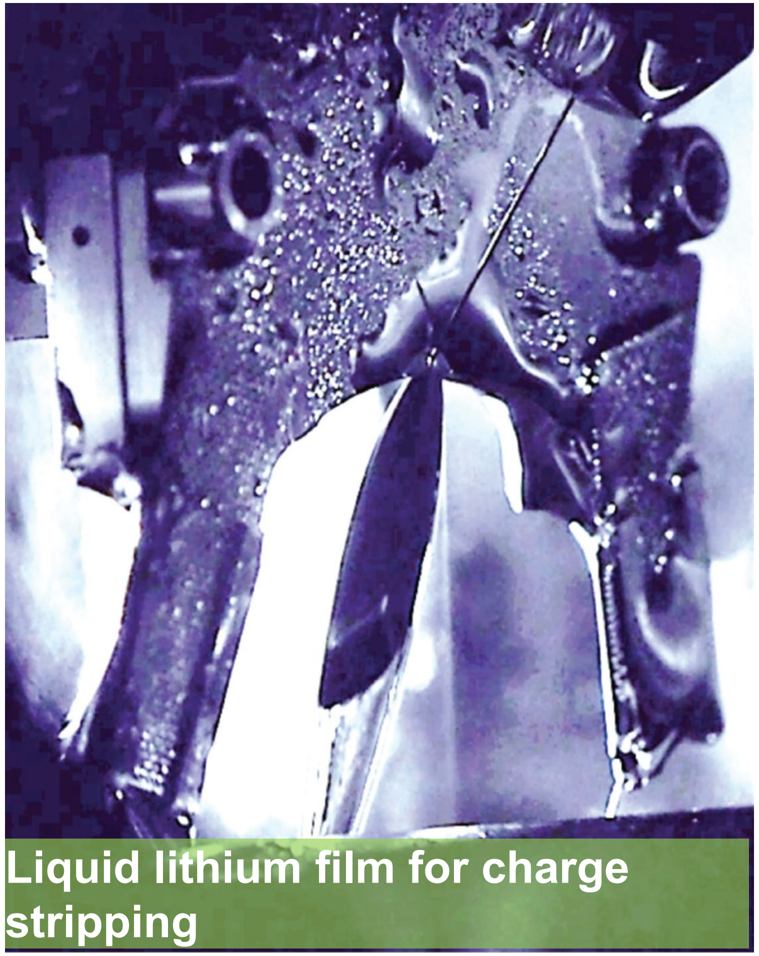




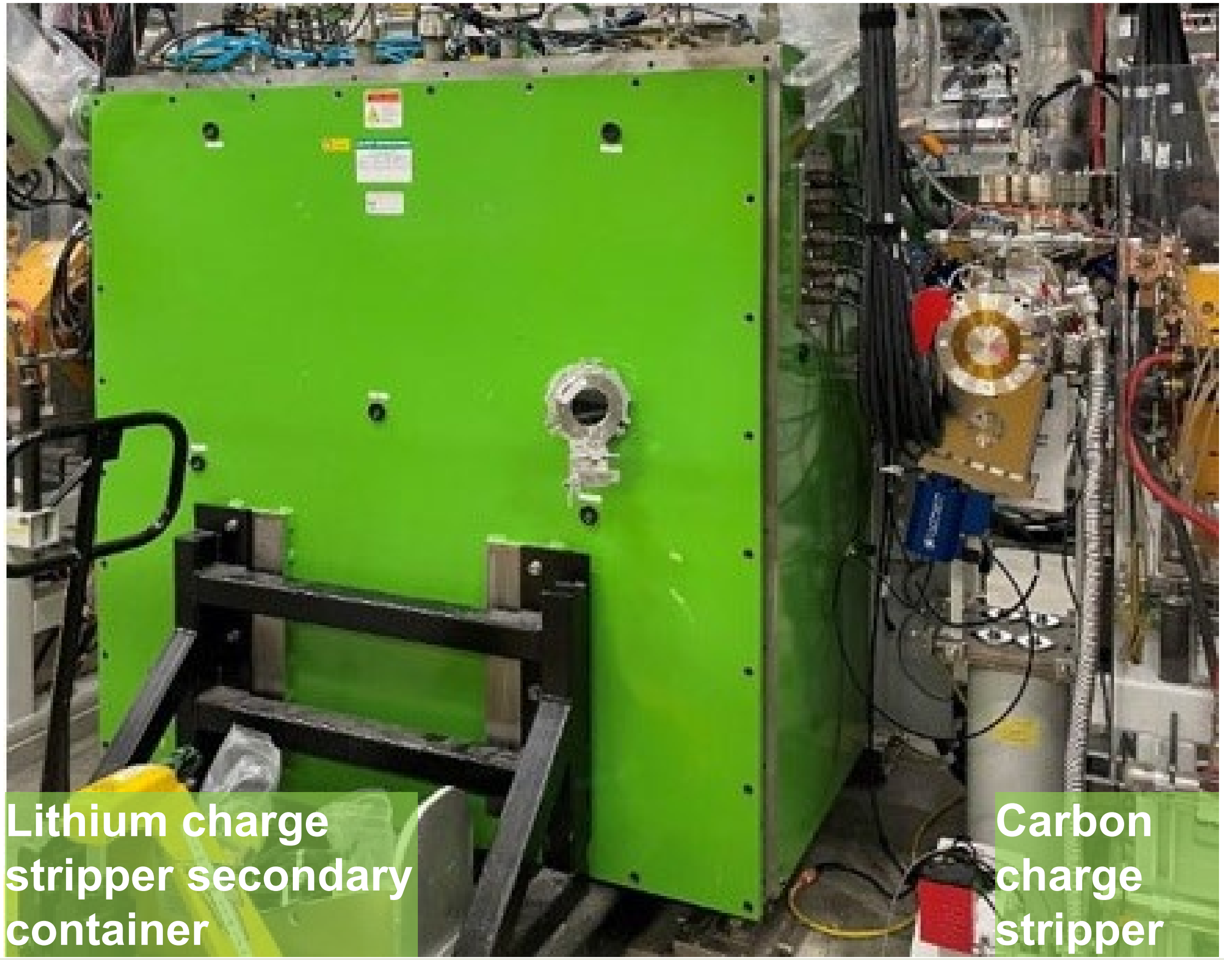
- Integrated design of cryogenics, cryo-distribution, and cryomodules
- All resonators can operate at either 2 K or 4.5 K
- Operations: HWR runs at 2 K, while QWR and SC magnets run at 4.5 K
- All cryomodules operating at or above design goal
- No obvious signs of beam-induced degradation

High-power Charge-stripping Devices: Pioneered at FRIB

- Operating with charge strippers of either liquid-lithium film or rotating carbon foil (for light ions)



Liquid lithium film for charge stripping

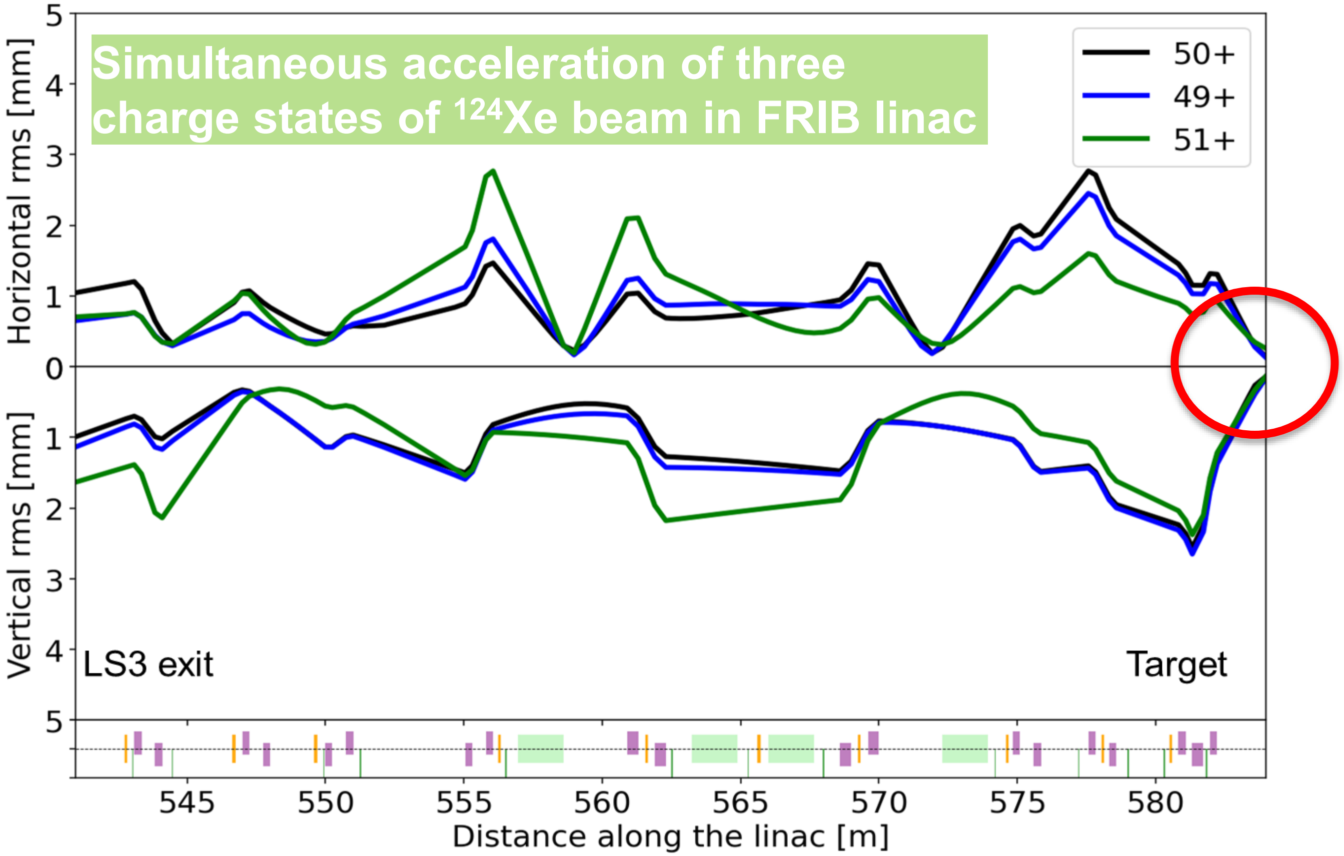


Lithium charge stripper secondary container

Carbon charge stripper

Multiple Charge-state Acceleration: Partly Realized

- Routinely accelerating up to 3 charge state simultaneously to enhance beam intensity and reduce controlled beam loss downstream of charge stripper

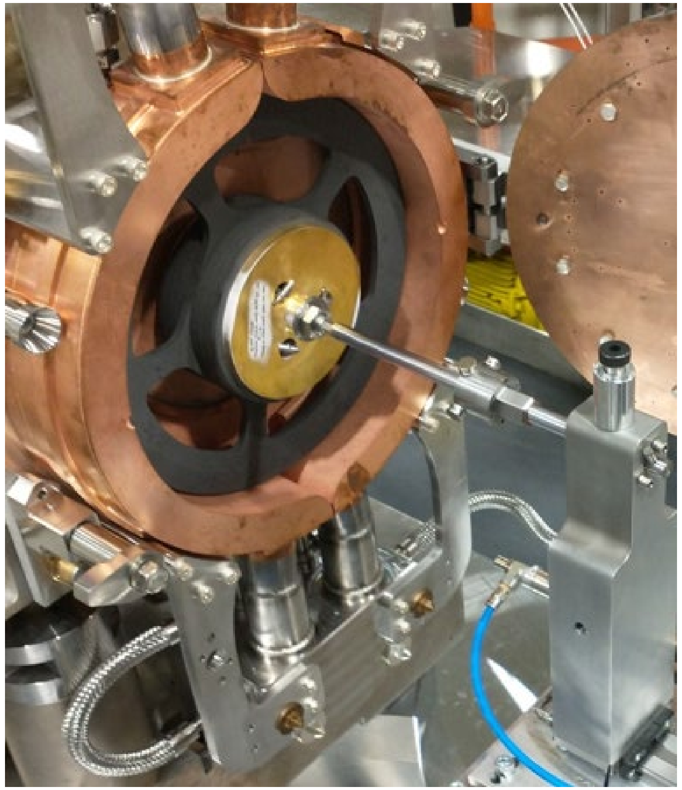


- Multi-charge-state beams tuned to overlap at specified locations
  - Target (present)
  - Charge stripper (future)
- Plan to accelerate multi-charge state beams in Linac Segment 1 (upstream of charge stripper)

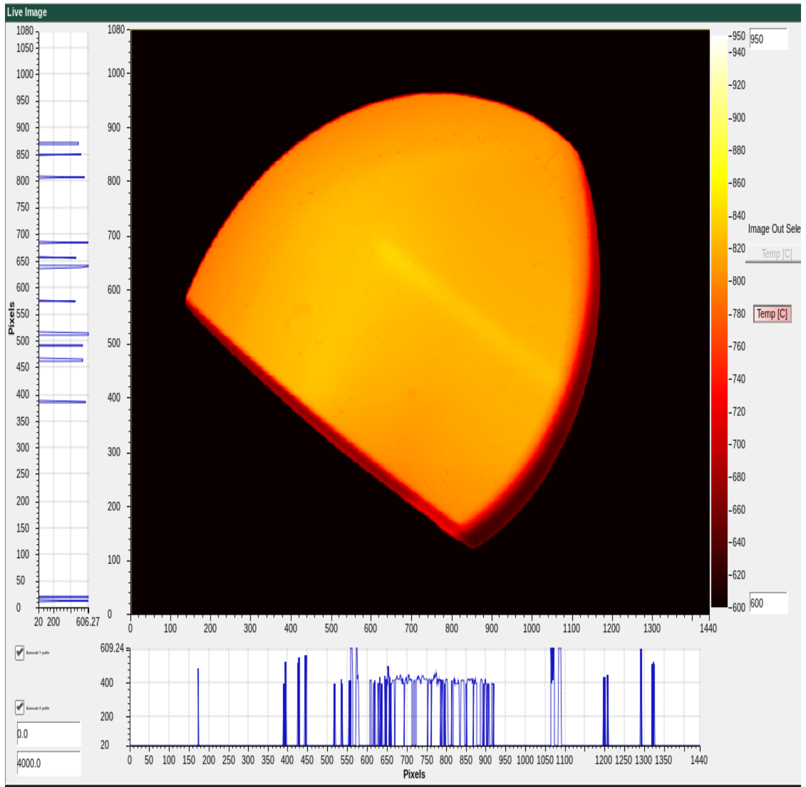
High-power Targetry Devices: in Phased Deployment

- Rotating, single-slice graphite target for rare isotope production
  - Absorbs ~ 25% beam power; accommodate small (Ø ~ 1 mm) beam size
- Static beam dump with shallow beam incident angle
  - Absorbs ~ 75% beam power; consideration of radio-activation in water and surroundings

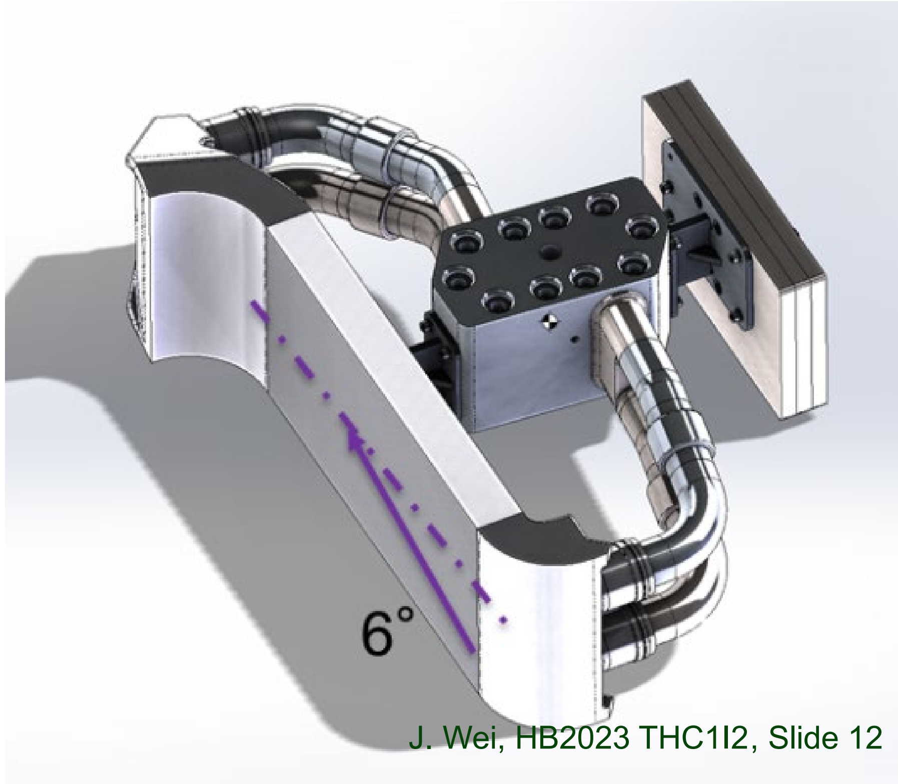
Single-slice graphite production target



10 kW, 217 MeV/u ^{48}Ca beam on target rotating at 500 r.p.m.

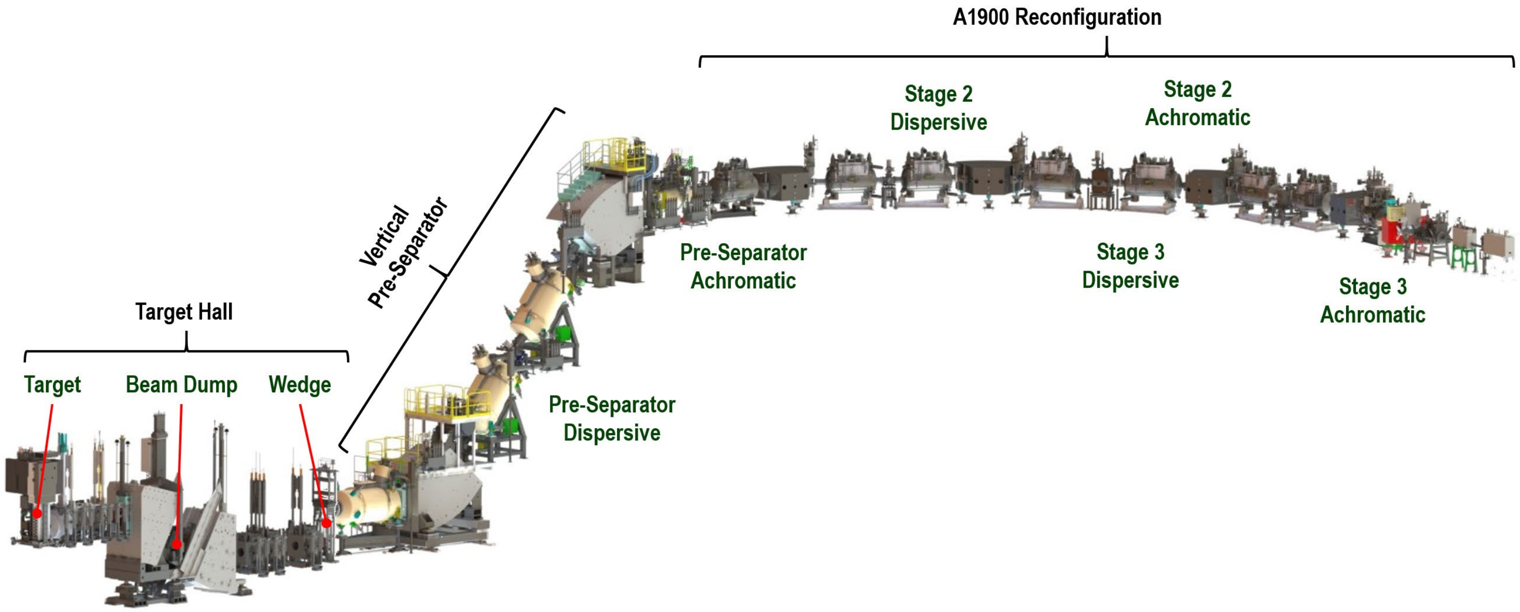


Static beam dump with 6º incident angle for incoming beam



Advanced Rare Isotope Separator Complexity

- Collects ~ 100% of fragments produced at the target; selects individual isotopes for delivery to desired experimental station
  - Three stages of fragment separation
    - » In-flight rigidity selection and selective energy loss in profiled degraders
  - Combination of vertical and horizontal separation
    - » Momentum compression in the vertical plane
    - » Preserves good phase space for gas stopping in the horizontal plane
  - Optically corrected to 3rd order and operate over rigidity range of 1 to 8 T·m



- Issues:
  - Newly constructed vertical pre-separator meets legacy reconfigured beam lines
    - » Aperture-limited
    - » Some magnet aberrations are not compensated for
    - » Lack of diagnostics and correctors

Multi-layered Machine Protection for Heavy Ion Beams

- High power, low-energy ions beams: short stopping range and high power density
- Must mitigate both acute & chronic beam loss (by beam inhibition)

System	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
RPS1	~100 ms	Vacuum status Cryomodule status Non-dipole PS Quench signal	As above; ECR source HV
RPS2	>1 s	Thermo-sensor Cryo. heater power	As above

- Used extensively in driver linac
- Need to extend use to high-power targetry systems

A Safe Power Ramp-Up with Phased Deployments

over 6 years, progressively raising the average beam current

EPOCH	1		2		3		4		5		6
Beam Power	10 kW		20 kW		50 kW		100 kW		200 kW		400 kW
ARTEMIS, light ion beams from gas	■	■	■	■	■	■	■	■			
ARTEMIS, heavy ion beams from metal	■	■	■	■							
High Power ECR, gas beams	■	■	■	■	■	■	■	■	■	■	■
High Power ECR, metal beams	■	■	■	■	■	■	■	■	■	■	■
Intermediate power charge selector in FS1					■	■	■				
High power charge selector in FS1								■	■	■	■
Post-stripper chicane							■	■	■	■	■
Additional beam collimation in FS2, BDS							■	■	■	■	■
Dual charge state heavy ions upstream of the stripper (velocity equalizer)									■	■	■
Rotatable target, 1 slice	■	■	■	■	■						
Rotatable target, multi-slice						■	■	■	■	■	■
Post-target shield							■	■	■	■	■
Beam dump 6º slant (S-shape)	■	■	■								
Beam dump 6º slant (S-shape), better cooling				■							
Rotatable beam dump, 1-mm wall					■	■	■	■	■	■	
Rotatable beam dump, 0.5-mm wall											■
Medium power ladder wedge system with adjustable slits (hands on)	■	■	■	■	■						
High power wedge system (remote handling)						■	■	■	■	■	■
PPS upgrade with fast ionization chambers	■	■	■	■	■	■	■	■	■	■	■

- Experience must be gained to safely handle increased radiological impacts
  - Prompt radiation and radio-activation in devices, ground water, and exhaust
- Extensive machine studies and beam tuning: needed to minimize uncontrolled beam losses
- High-power targetry systems and beam-intercepting devices: in phased deployment, along with ancillary systems, including non-conventional utilities, and remote handling
- Accelerator improvements and renovations to aging legacy systems: being implemented in parallel

Phased Linac Improvements

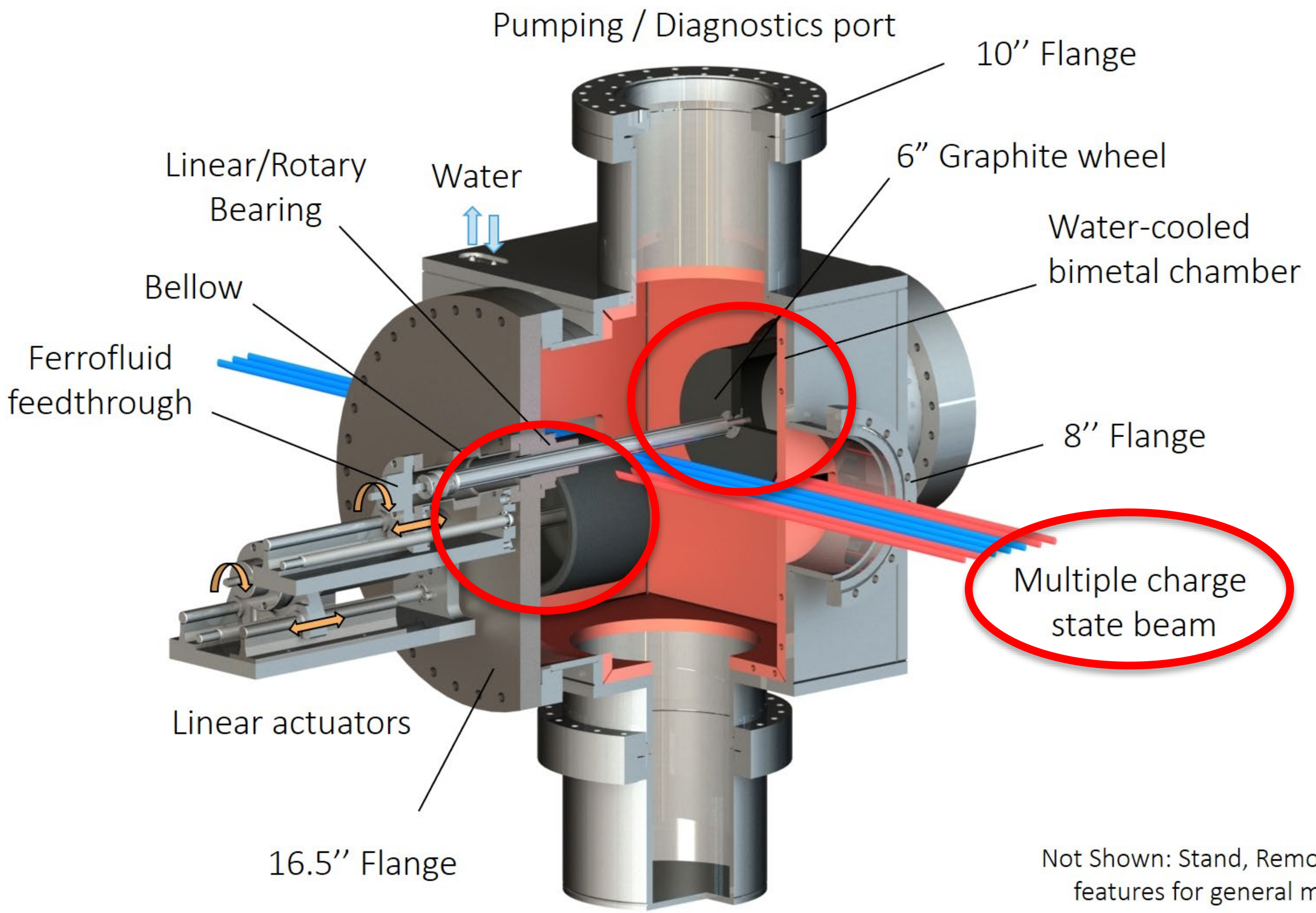
Liquid Lithium Film Thickness

Water film produced by colliding two jets from 1-mm diameter nozzles for to produce thicker film

Goal: larger film thickness for better stripping efficiency

Charge Selector Upgrade with Rotating Drums

Intermediate-power charge selector design (1" = 25.4 mm)



Not Shown: Stand, Remote handling features for general maintenance

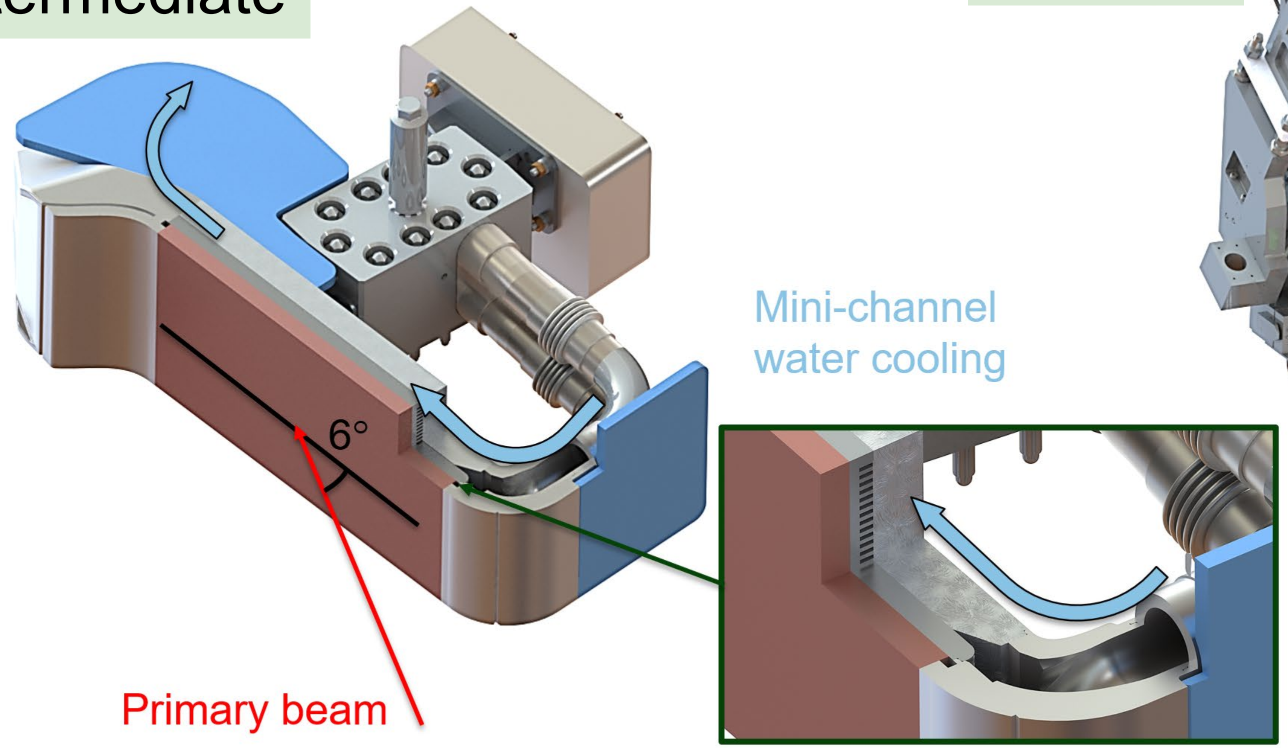
- Charge selector cleans up unwanted charge states downstream of charge stripper
  - ^{238}U: 5 charge states kept for acceleration, the rest removed by charge selector
- Present charge selector: adjustable static water-cooled jaws
- Next phase: 2 rotating graphite drums

Phased Targetry Deployment

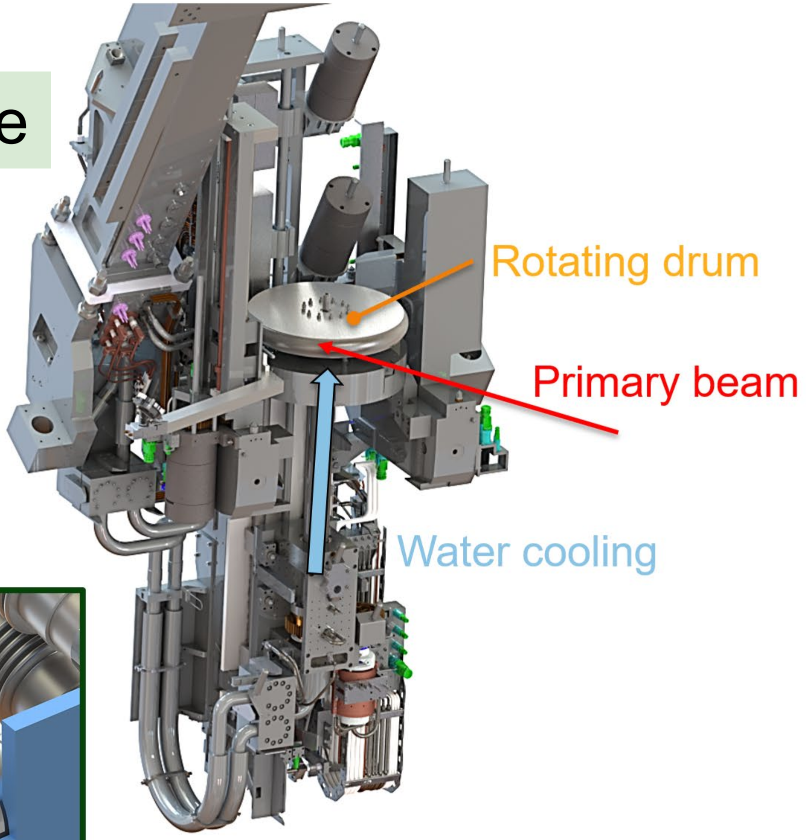
Phased Beam Dump Deployment

- Beam dump absorbs ~75% beam power
- Present beam dump: water-cooled static aluminum plate with beam incident at 6º angle
- Next phases: (a) bi-metal plate with mini-channel cooling; (b) static and rotating thin-wall water-filled drums
  - Challenge: “non-conventional utility”

Intermediate



Ultimate



Beam Loss Budget
Radiological Control
Personnel Protection

Beam Loss Budget: Basis for Radiological Control, ES&H Impact Management, and Remote Handling Design

Table 3: Estimated Controlled Primary Beam Loss for Typical 400 kW Operation

Mechanism	Location	Power [kW]
Front end beam tuning	MEBT F-cup	0.1
β = 0.041 beam tuning	LS1 Nb plate	0.002
LS1 beam tuning	FS1a dump	0.015
LS1 beam tuning	FS1b dump	0.5
Charge stripping loss	FS1 stripper	1.3
Unwanted beam collection	FS1 selector	7-12
Unwanted charge state and ion contaminants collection	FS1 45° dipoles	0.1-0.4
Beam halo and ECR ion contaminants interception	Collimator 1-5	0.1-1.7
Charge exchange halo	Collimator 6-7	0.02
LS1 beam tuning	FS1 F-cup	0.03
LS2 beam tuning	FS2 dump	0.14
LS2 beam tuning	FS2 F-cup	0.03
Linac beam tuning	BDS dump	0.14
Targetry protection	Collimators	0.1
RI production	Target	< 80
Spent beam	Beam dump	< 320

Table 4: Estimated Controlled Secondary Beam Loss for Typical 400 kW Operation

Mechanism	Location	Power [kW]
Target scattering	Post-target shield	< 15
RI beam cleaning	Fragment catchers	< 20
Post-target scattering	Thermal armors	< 17
Post-target scattering	Collimators	< 9
RI beam	Wedge	< 2
RI beam cleaning	Wedge slits	< 3
RI beam cleaning	Separator slits	< 5
RI beam cleaning	Focal plane slits	< 2

Table 5: Estimated Uncontrolled Beam Losses for Typical 400 kW Operation

Mechanism	Location	Power
Stripper scattering	Downstream of stripper	<3 W/m at 17 MeV/u
Uncontrolled loss	All locations	< 1 W/m

Legacy System Renovation

Legacy System Interfacing, Renovation and Integration

FRIB's state-of-the-art, high efficiency central helium refrigeration system

- NSCL "green cold box" is < 30% efficient, high in (nitrogen, helium) consumption, and less reliable than FRIB cryoplant
- FRIB experimental area cryogenics are designed to a higher pressure rating to recover helium from magnet quenches and for increased availability
- FRIB 35 – 55 K shield: compatible with HTS (high temperature superconductor) magnets

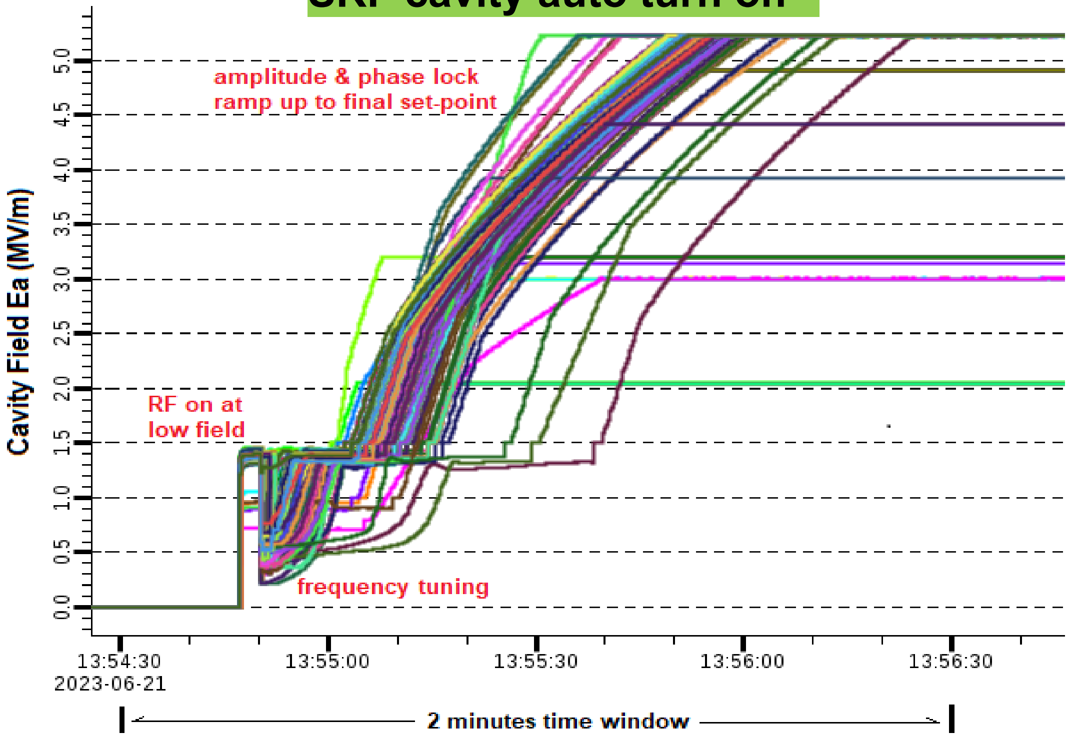
Legacy NSCL "green cold box" supporting experimental cryogenic distribution / devices

Automation and Machine Learning

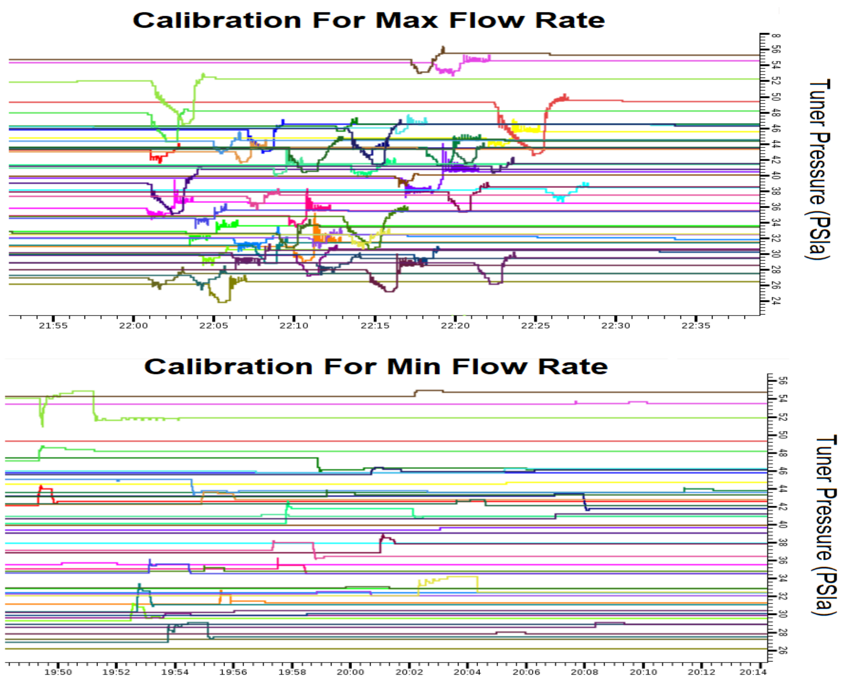
SRF Cavity, SC Magnet Auto-on / Auto-off

- All 324 SRF cavities can be turned on in ~ 2 minutes; turned off in ~ 2 seconds: facilitating frequent user access to experiments
  - SRF HWR pneumatic tuner control valve calibration is required (440 valves in total) for successful frequency tuning
    - » Auto calibration for all cryomodules in parallel reduces 3 days of human effort to 2 hours of machine effort
  - Input/output controller (IOC) level implementation facilitates stable automation, resolves possible conflicts between multiple workstations, and ensures secure access

SRF cavity auto turn on

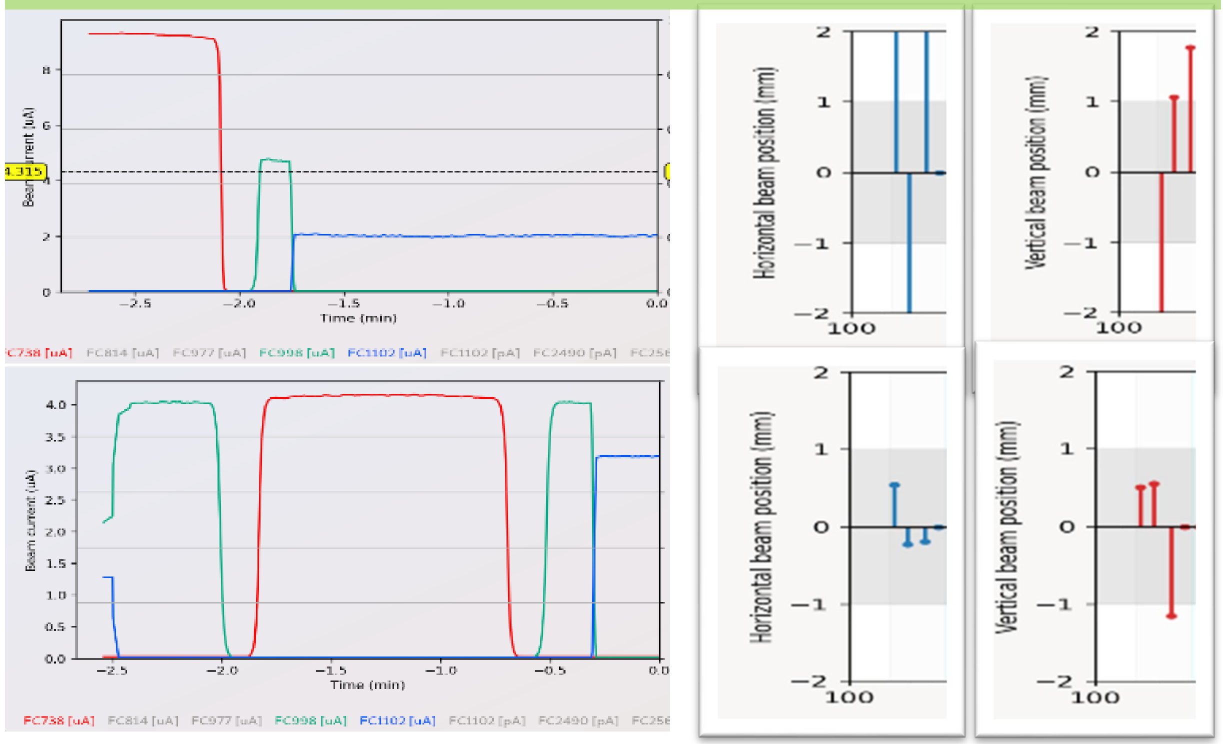


Auto pneumatic tuner valve calibration

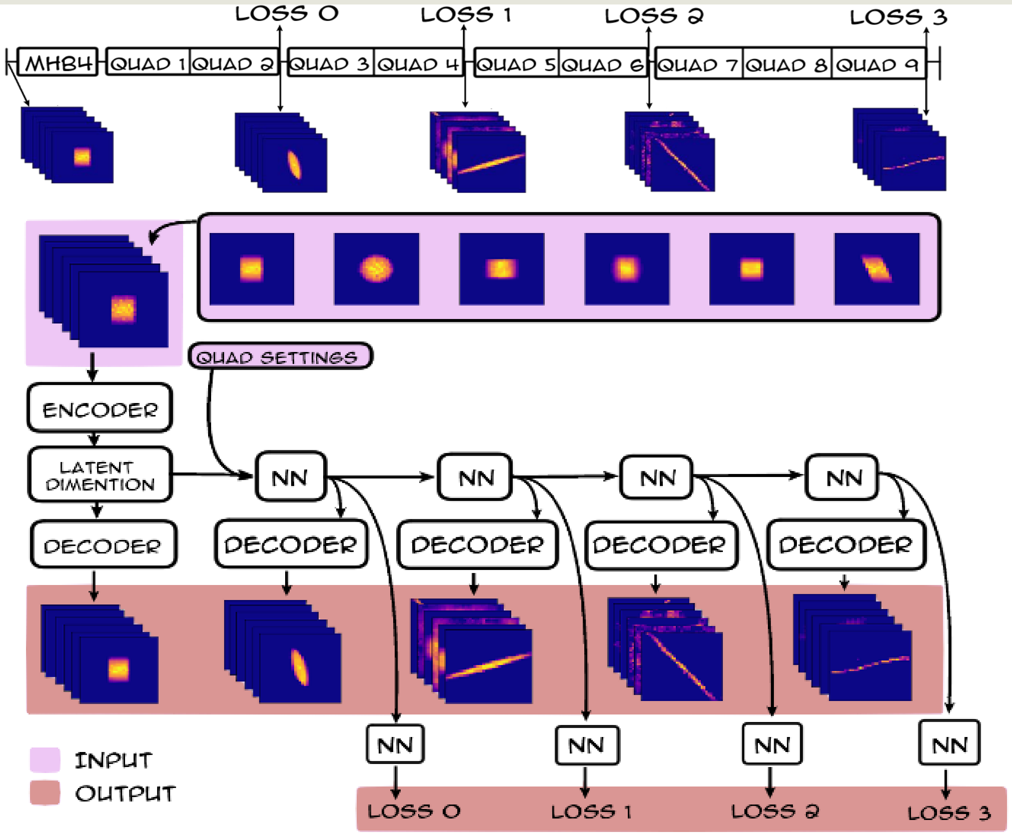


Artificial Intelligence and Machine Learning: in Development

Proof of principle test in orbit tuning to optimize front-end beam transmission: from 25% to 80%



Bayesian optimization applied to beam tuning



AI/ML-based tomography and beam loss prediction

- Accelerator R&D supports FRIB AI/ML for more efficient operation
- Complemented by separate grant from DOE Office of Nuclear Physics on accelerator auto-tuning and optimization methods: “Online Autonomous Tuning of the FRIB Accelerator Using Machine Learning”

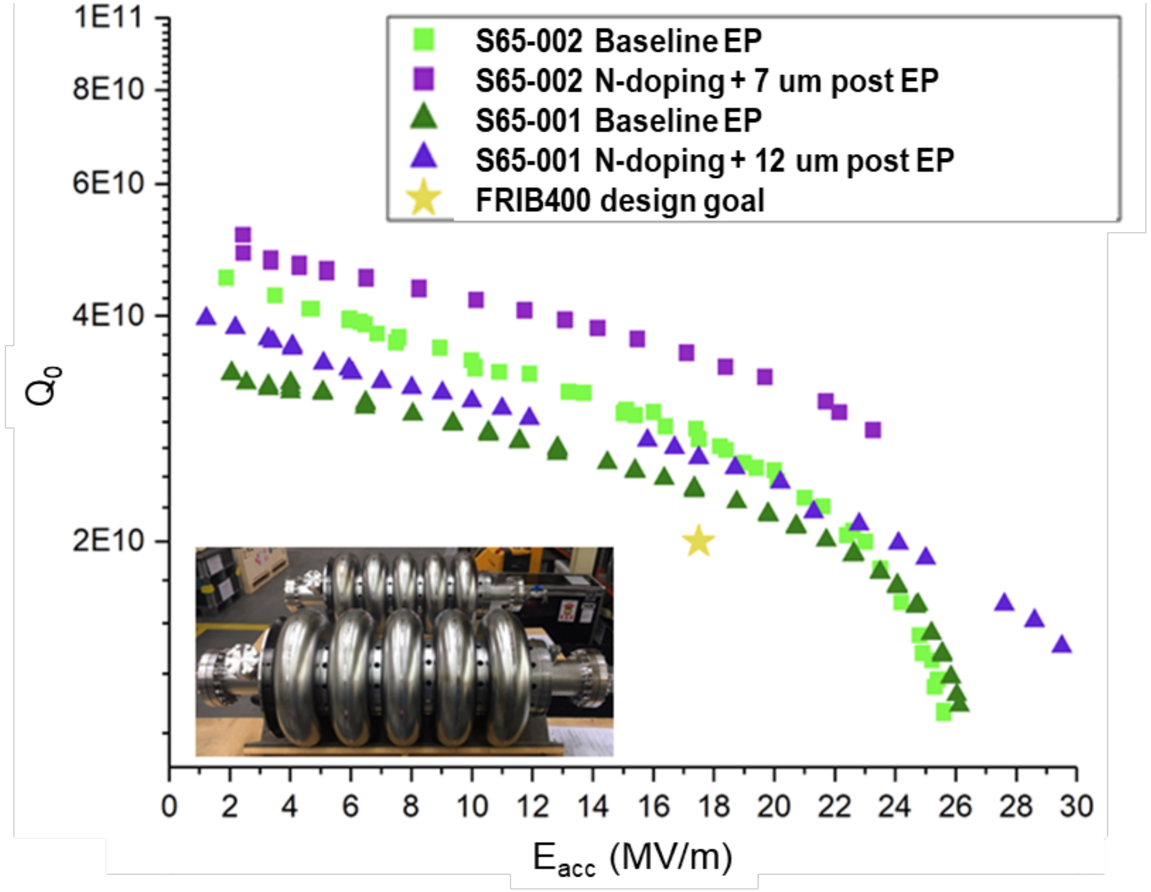
Summary

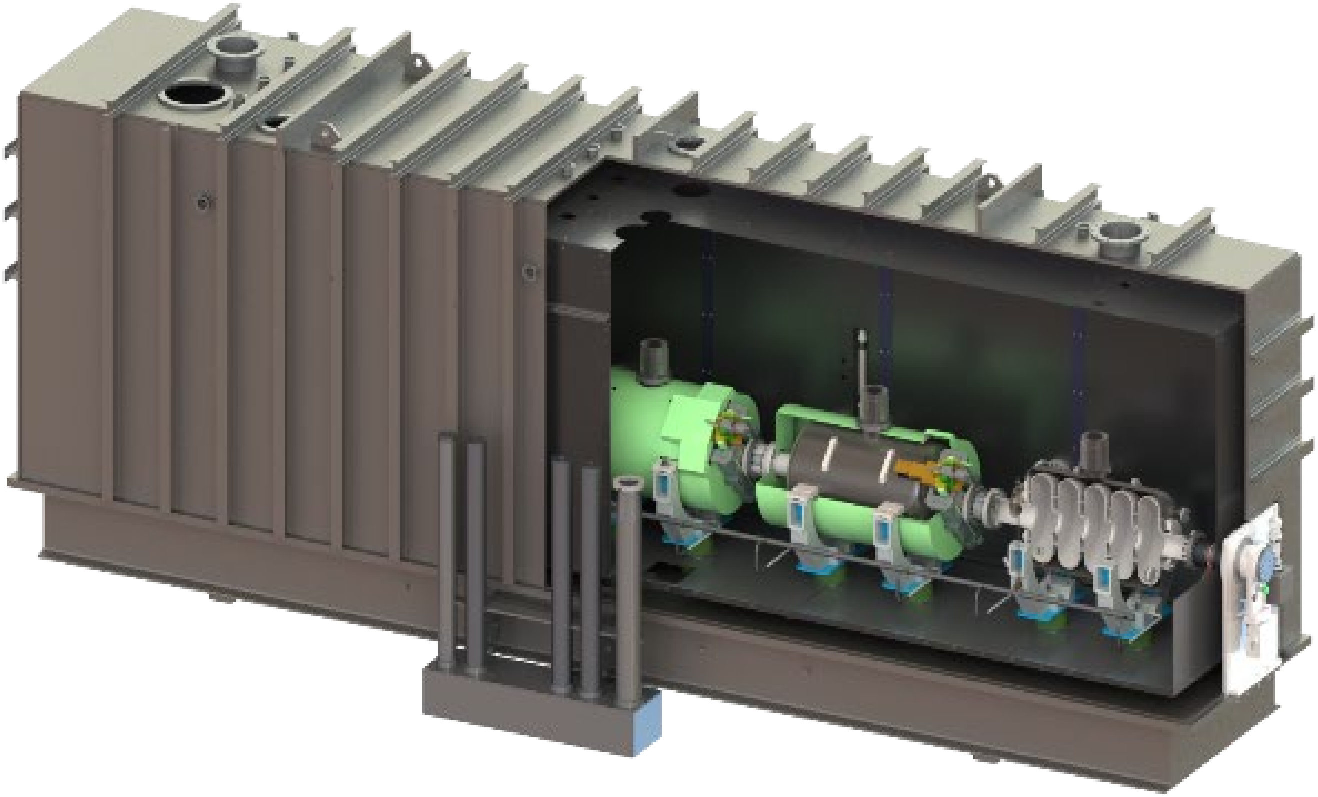
Lessons Learned during FRIB Construction

- Recruit worldwide and retain 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, magnets (**test thoroughly**)
- Pro-actively plan critical system validation, e.g. for liquid Li stripper (**facilitate critical validation**)

FRIB400: Extend Scientific Reach and Discovery Potential

- Doubles linac beam energy (to 400 MeV/u for uranium) by adding 11 cryomodules, each containing 5 (β = 0.65) cavities at 644 MHz
  - Fill reserved slots in FRIB tunnel; expand cryo-distribution
- R&D and design: in progress





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

Summary

- The FRIB project was completed in 2022 on scope, on cost, and 5 months ahead of schedule baselined > 8 years ago
- FRIB has been operating for > 1 year, delivering > 5000 hours of beam time for both scientific and industrial experiments with 92% availability
- The primary beam power is being steadily raised from 1 to 10 kW
- To ramp up to the ultimate design beam power of 400 kW, efforts are focused on phased linac improvements, phased targetry system deployments, control of beam loss, radiological impacts, legacy system renovation, automation, and machine learning
- The power ramp-up campaign and the proposed FRIB upgrade to double the primary-beam energy to 400 MeV/u will significantly enhance FRIB's discovery potential
- More detailed FRIB work were presented by Prof. Peter Ostroumov (MOA1I2) and Dr. Takuji Kanemura (WEC2I2) at this conference

Co-authors

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Thank you!