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FRIB

FRIB First Three Years of User Operations and Performance Ramp Up

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On behalf of FRIB Team

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MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT of ENERGY | Office of Science

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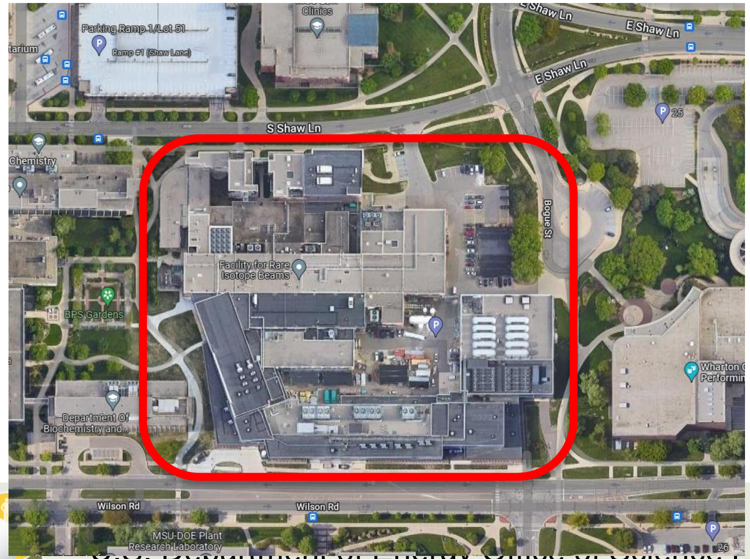
Outline

- FRIB facility and operational status
- Superconducting linac operations and maintenance
- Target and beam dump operations and power ramp-up plan
- FRIB400 energy upgrade plan
- Summary

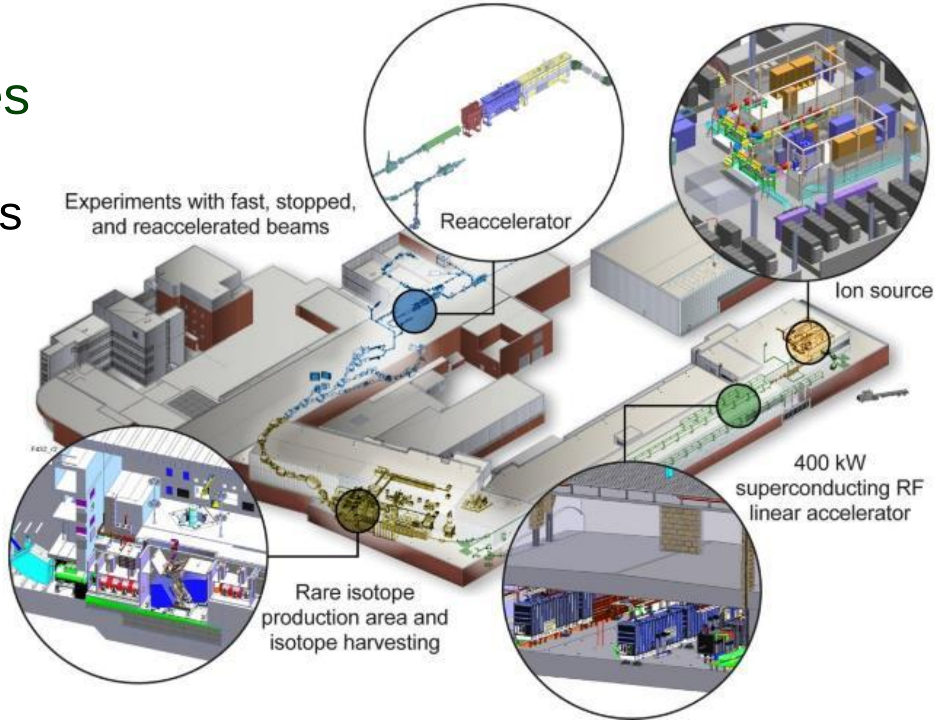
FRIB for Rare Isotope Science

- The world's largest heavy ion SC linac accelerating uranium beam up to 200 MeV/u with an ultimate beam power of 400 kW
- 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

FRIB located in Michigan State University campus



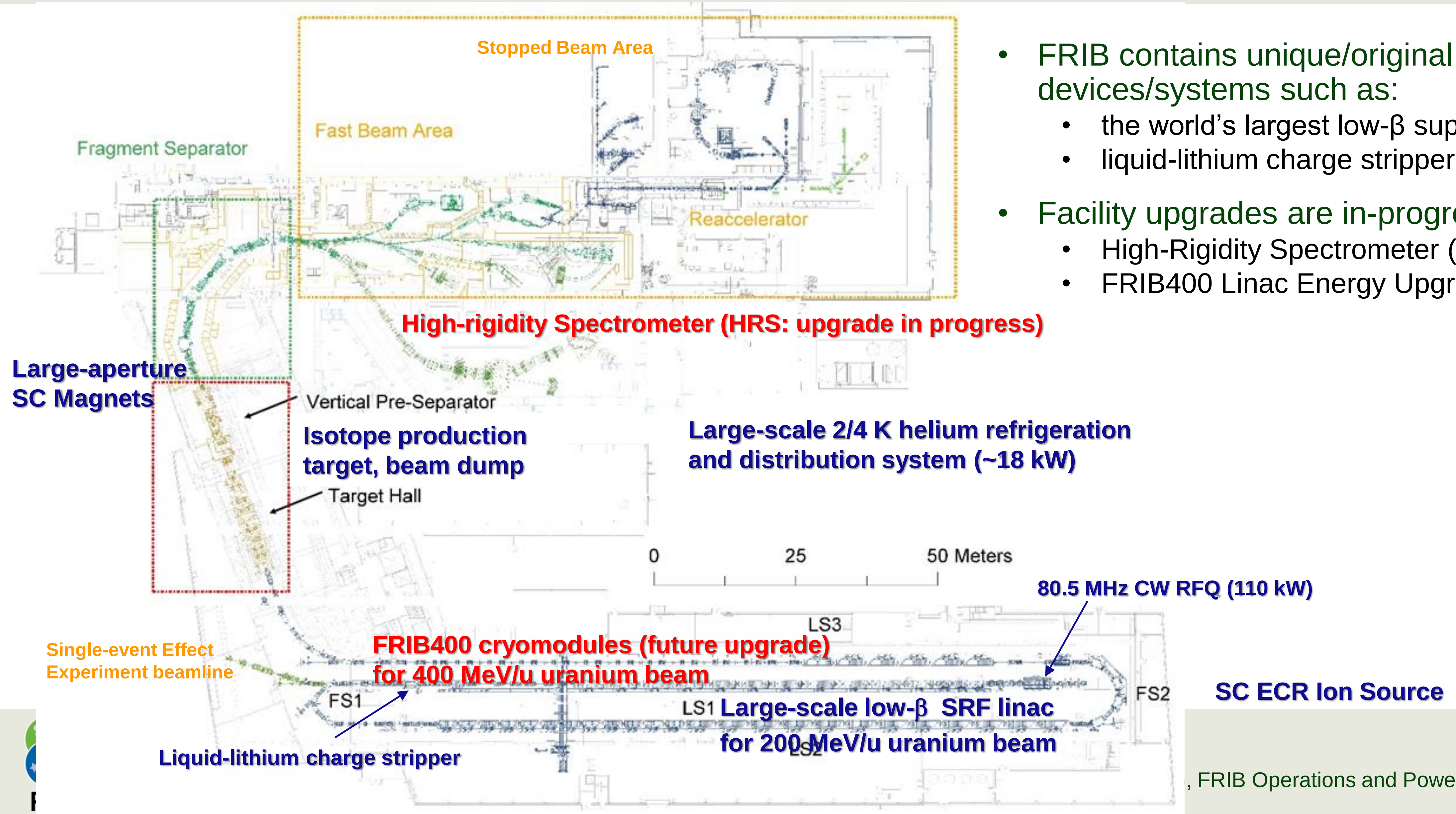
Ion sources, fragment separator, experimental areas including Reaccelerator are on the ground



Linac and isotope production target are 10 m below the ground

- 1963 — Cyclotron Lab Established
- 1982 — First superconducting Cyclotron K500
- Jun 2009 — DOE and MSU signed cooperative agreement
- Sep 2010 — CD-1: Preferred alternatives decided
- Aug 2013 — CD-2/3a: Project baselined and Civil construction started
- Aug 2014 — Start of technical Construction
- May 2021 — Linac construction complete
- Jan 2022 — Project technical construction complete
- Apr 2022 — CD-4
- May 2022 — Start of User Operations

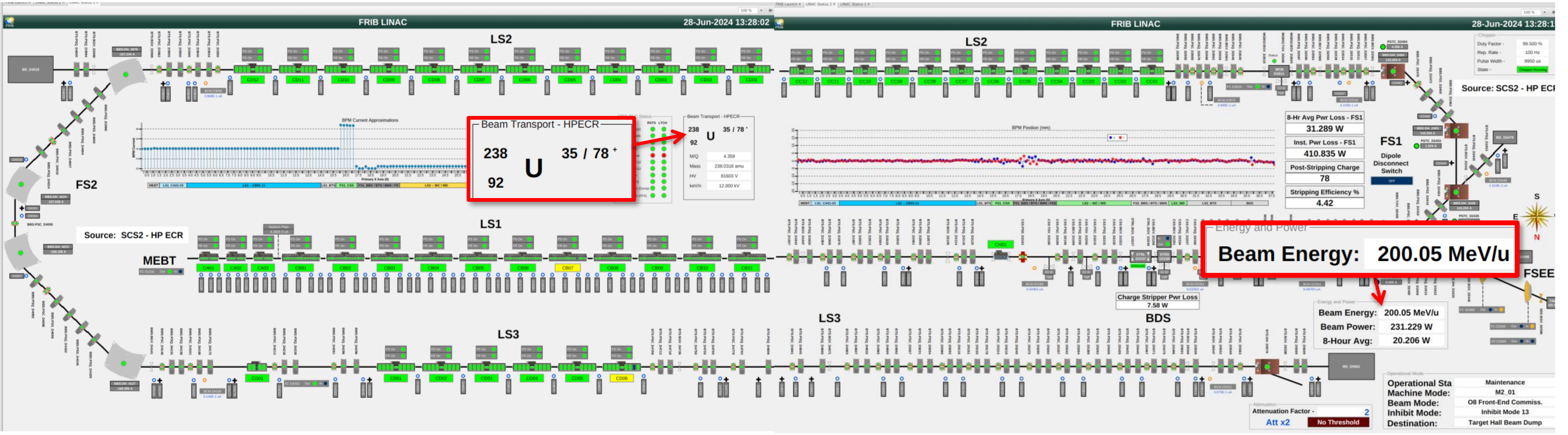
Facility Overview



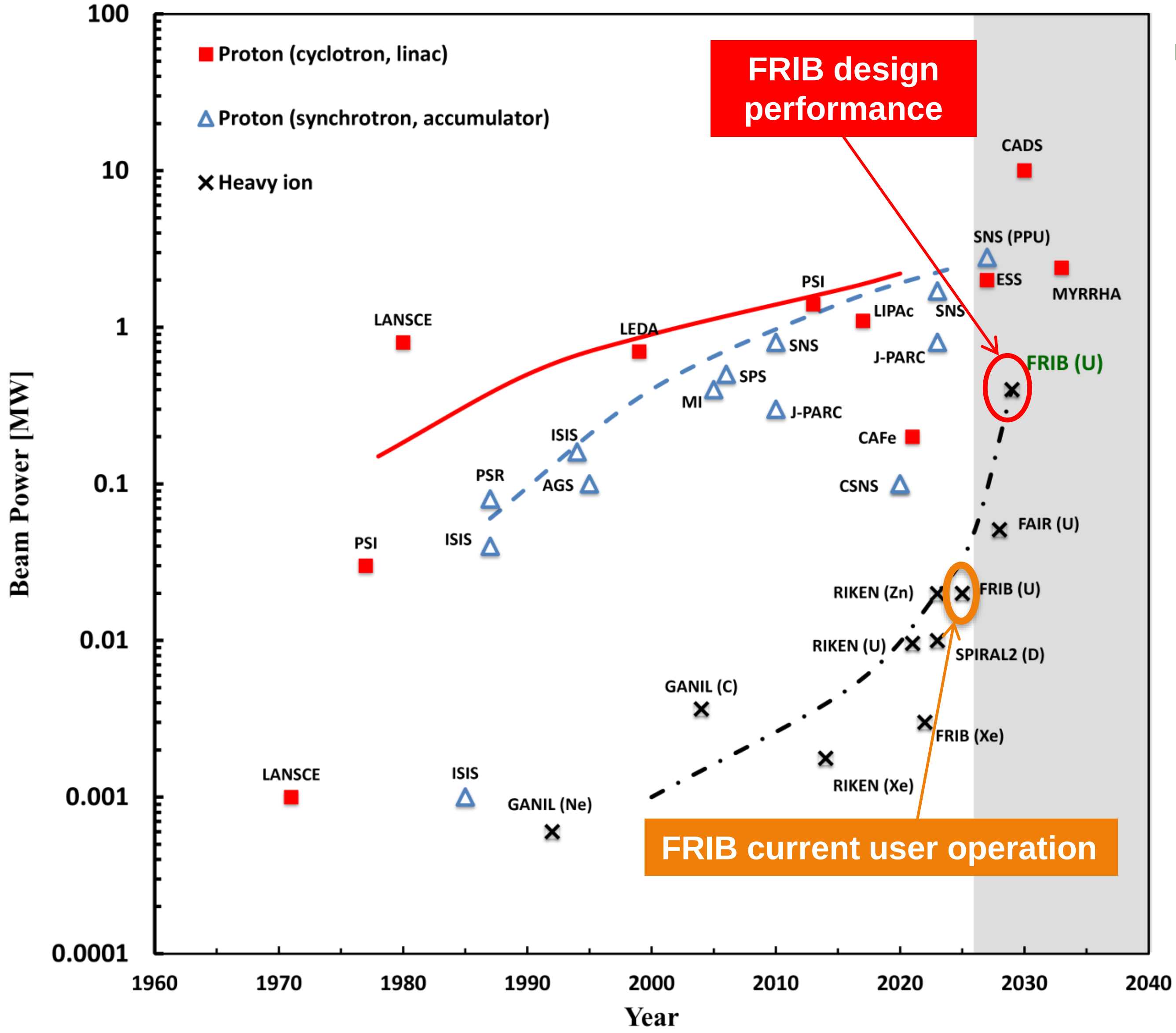
- FRIB contains unique/original accelerator devices/systems such as:
  - the world's largest low-β superconducting linac,
  - liquid-lithium charge stripper.
- Facility upgrades are in-progress/planned:
  - High-Rigidity Spectrometer (in progress),
  - FRIB400 Linac Energy Upgrade (planned).

Demonstrated Acceleration of 200 MeV/u Uranium Beam

- $^{238}U^{78+}$ beam was accelerated to 200 MeV/u
  - Additionally, $^{36}Ar^{18+}$ beam was accelerated up to 300 MeV/u
- 323 out of 324 Linac SRF cavities have been used since FY2023 operation, which were also used for this beam acceleration



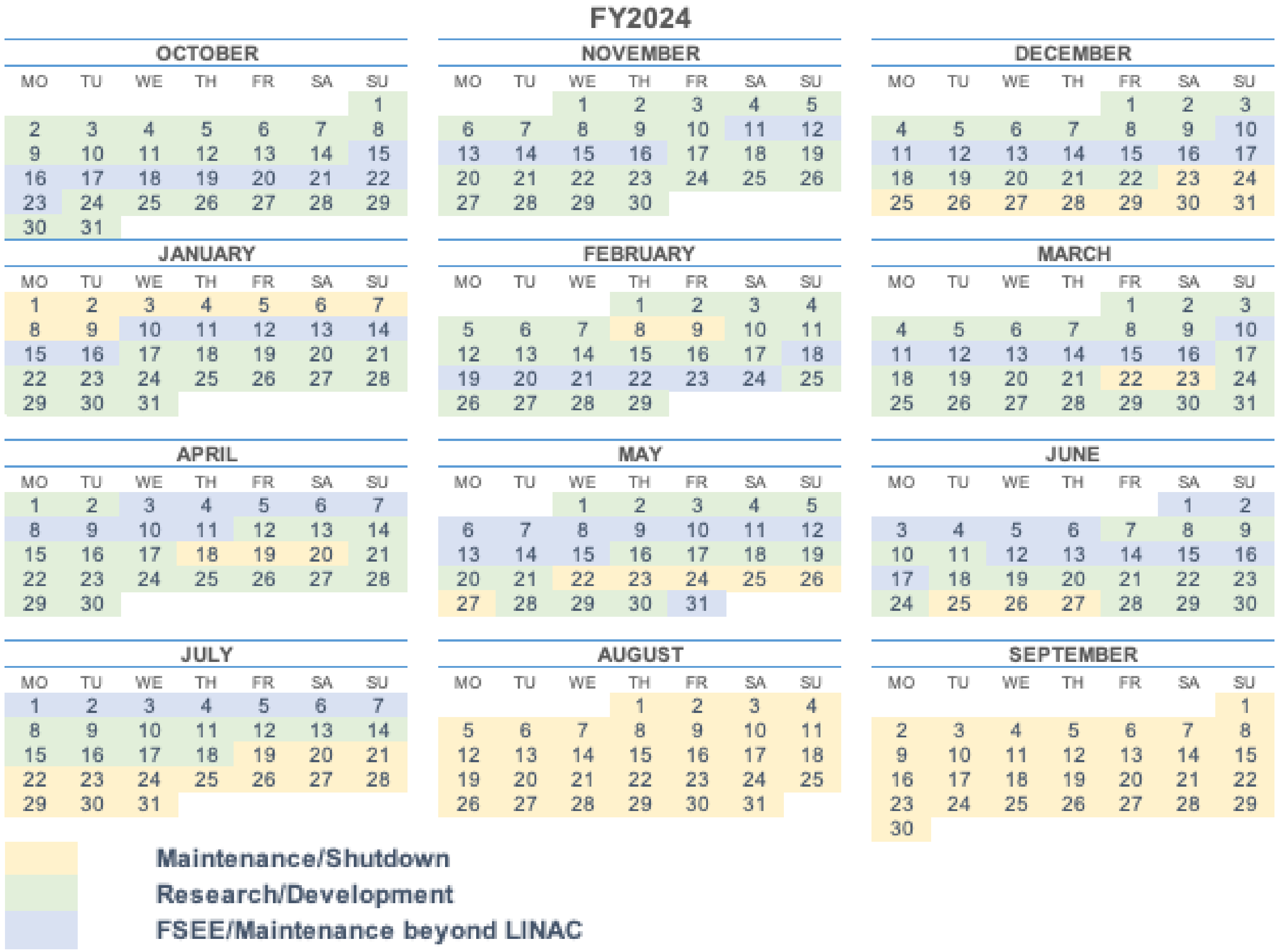
Beam Power Ramp-up in Parallel with User Operations



- Conducting user operations and, at the same time, beam power ramp-up (current ramp-up)
  - Currently operating at 20 kW, including uranium beam
  - Approach: phased beam power ramp-up with upgrades of beam intercepting devices such as target and beam dump as well as linac charge selector

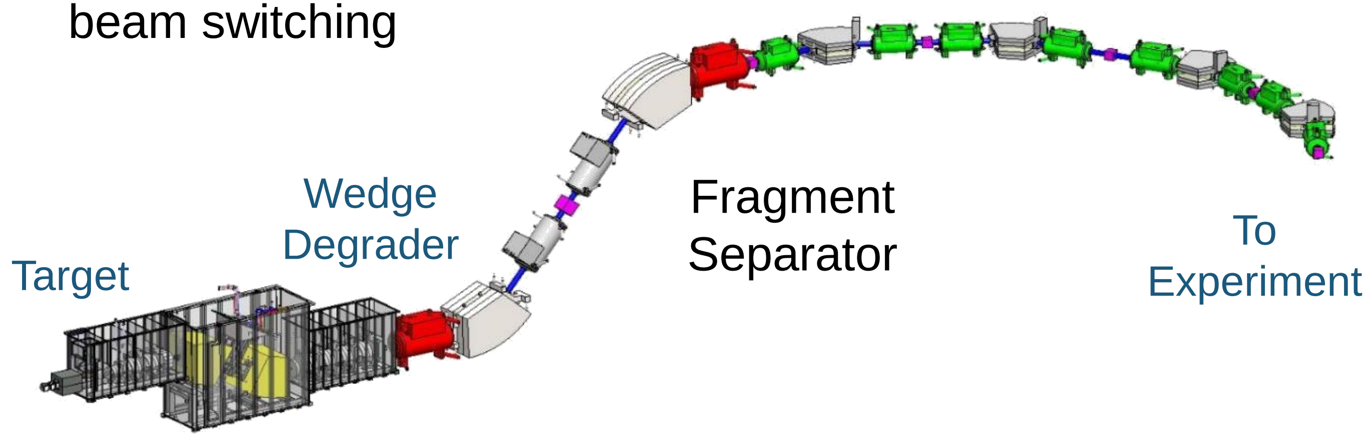
User Operations with High Availability

- Total 6081 Scheduled Operating Beam Hours at 95.7% Availability for FY2024
  - 4242 hours scheduled for FRIB experiments,
  - 1839 hours for FSEE experiments (FRIB Single-Event Effect using Linac Segment 1)
- FSEE experiments scheduled in between FRIB experiments
  - To meet FRIB users' needs for various isotope beams, which requires changes of target/wedge

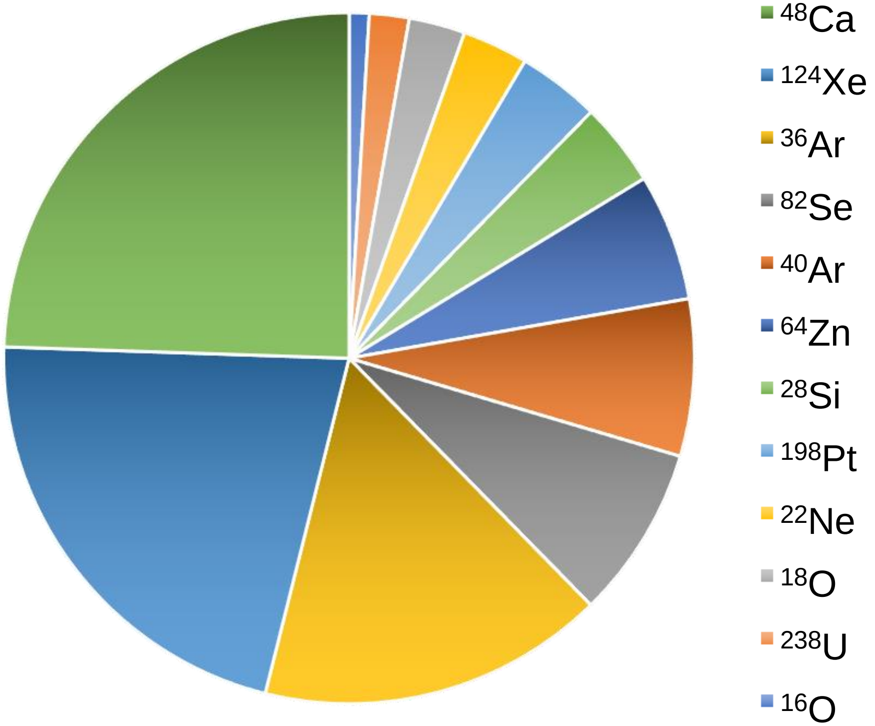


Rare Isotope Production Optimized for User Experiments Requires Frequent Changes of Primary Beams

- Primary beam (isotope and energy), production target, and configuration of the fragment separator need to be optimized for each experiment
  - Changes of target and wedge degrader require replacement of physical devices in hot-cell via remote handling
- Primary beam in the linac also needs to be frequently changed to meet users' need
  - **Stable and reliable SC linac operation** and **high-level beam dynamics tools** are essential for efficient primary beam switching



Primary Beam Statistics Oct 2022 – Apr 2024

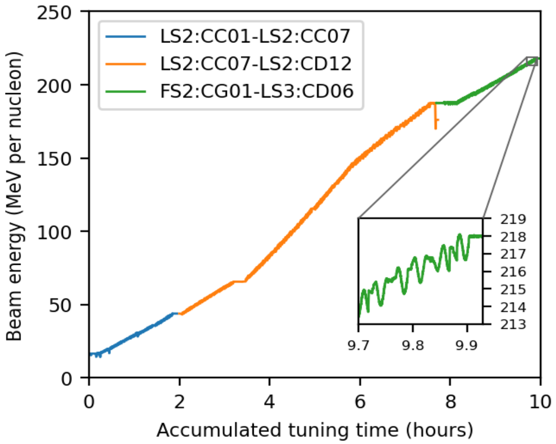


143 primary beam changes, including energy changes

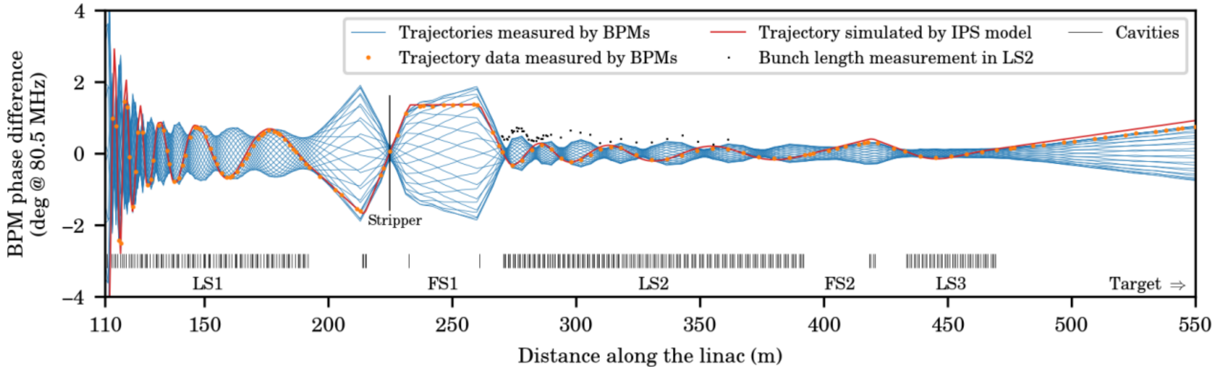
Linac Beam Tuning and SRF Cavity Operation For Efficient User Operations

- Linac phasing and Instant Phase Setting for different m/q beams

Linac phasing example
(220 cavities during ARR05 commissioning)



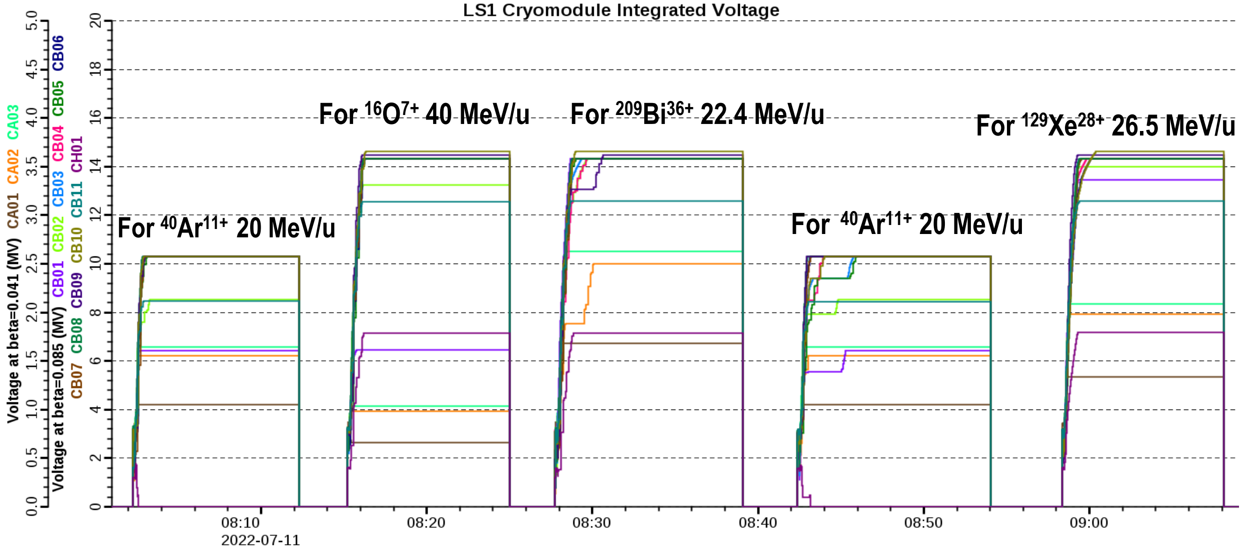
Envelope matching using Instant Phase Setting
(model-based cavity field changes for a different beam)



(Courtesy of P. Ostroumov, A. Plastun)

- SRF cavity operation for nearly instant switch between different m/q beams

LS1 cavity field switching for various beams*
(104 cavities for FSEE experiments)

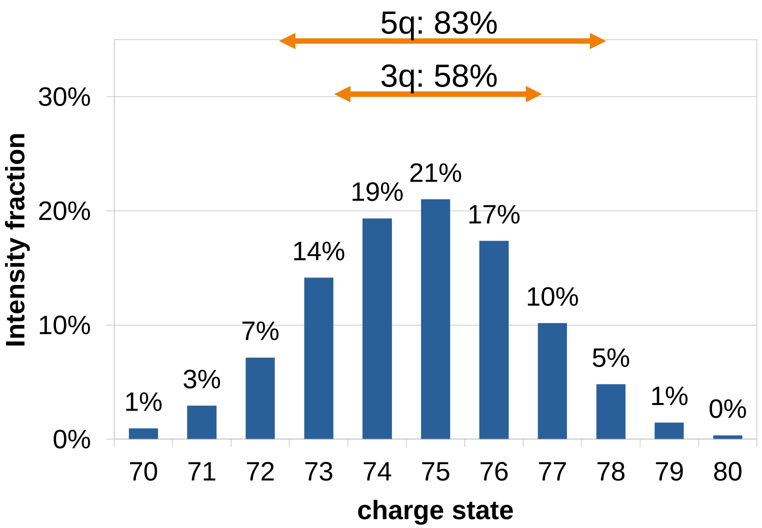


* via dynamic load compensation by cryomodule internal heaters such that the net heat load remained almost constant in each module

Simultaneous Acceleration of Multiple-Charge-State Beam

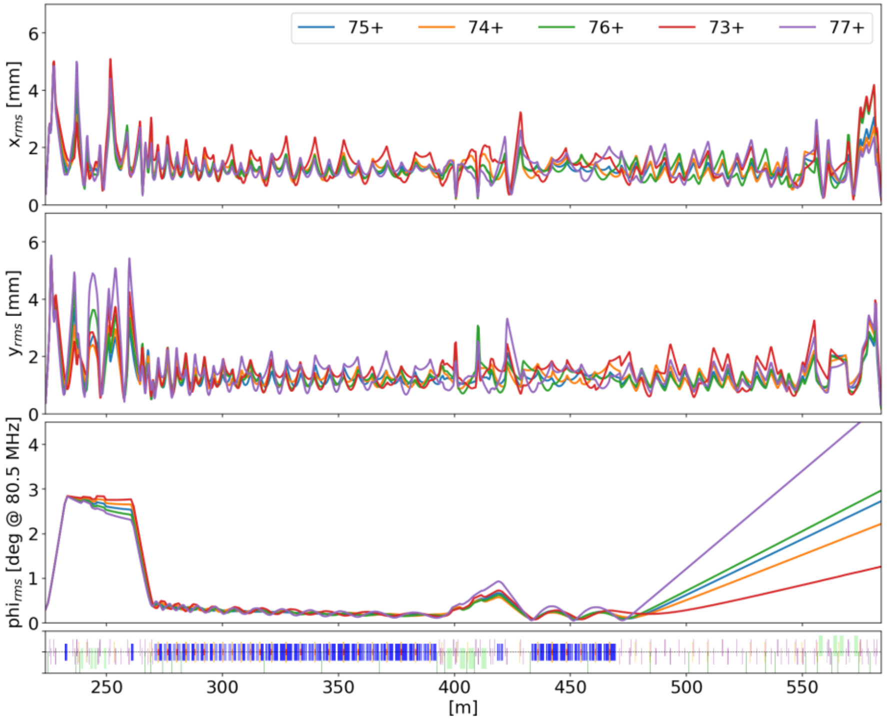
- Multiple-charge-state acceleration: key feature of the FRIB design to obtain the ultimate heavy ion beam current, such as uranium, at the target under the given limitation from the source
- Also helpful to reduce beam losses (heat loads) in the linac FS1 charge selector

Charge State Distribution
17 MeV/u ^{238}U
(Measurement)



Ion	E [MeV/u]	Stripping Efficiency Multi / 1q
$^{48}Ca^{19+,20+}$	225	97% / 71%
$^{64}Zn^{28+,29+}$	240	88% / 70%
$^{82}Se^{32+,33+}$	200	88% / 71%
$^{124}Xe^{48+,49+,50+}$	228	76% / 30%
$^{238}U^{73+ \sim 77+}$	177	83% / 21%

$^{238}U^{5q}$ beam envelope (simulation)



(Courtesy of T. Maruta)

Facility for Rare Isotope Beams
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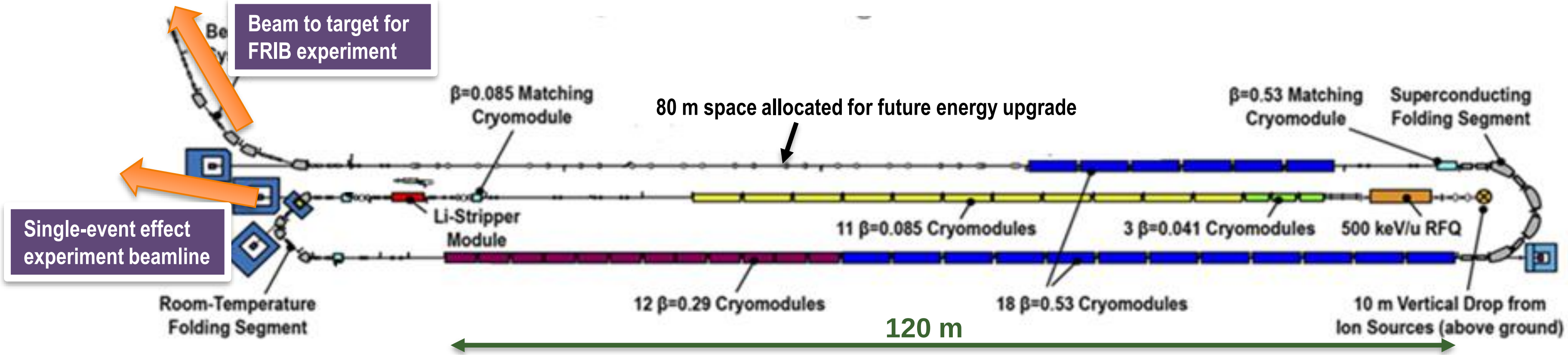
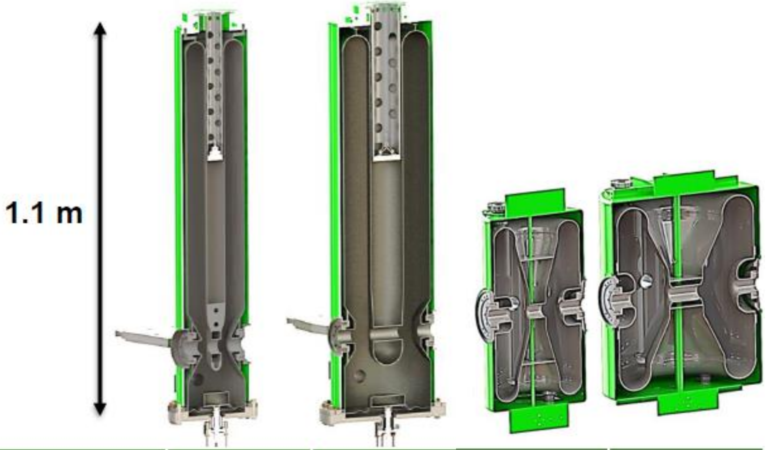
Superconducting Linac with 324 Low-beta Coaxial SRF Cavities in 46 Cryomodules





	β=0.041 QWR	β=0.085 QWR	β=0.29 HWR	β=0.53 HWR
f_0 (MHz)	80.5	80.5	322	322
V_{acc} (MV)	0.81	1.8	2.1	3.7
E_{acc} (MV/m)	5.1	5.6	7.7	7.4
E_{pk} (MV/m)	31	33	33.3	26.5
B_{pk} (mT)	55	69	59.6	63.2

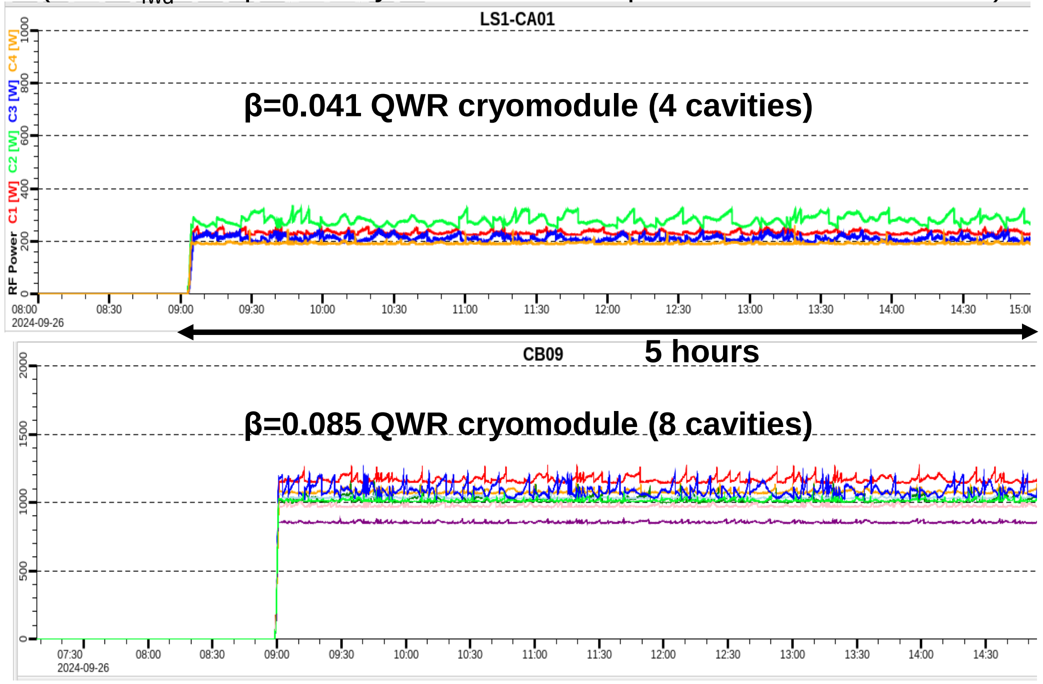
β	Type	Component Counts (baseline + spares)		
		Cryomodules	Cavities	Solenoids
Quarter Wave Cryomodule				
0.041	accelerating	3 + 1	12 + 4	6 + 2
0.085	accelerating	11 + 1	88 + 8	33 + 3
	matching	1 + 1	4 + 4	-
Half Wave Cryomodule				
0.29	accelerating	12	72	12
0.53	accelerating	18	144	18
	matching	1	4	-
TOTALS		46 + 3	324 + 16	69 + 5

Linac Cryomodule Operational Experience

- 80.5 MHz quarter-wave resonators (QWRs; 104 cavities, β=0.041, 0.085)
  - 4K operation is also stable with no microphonics issues

Typical phase lock stability performance of LS1 at 4K:

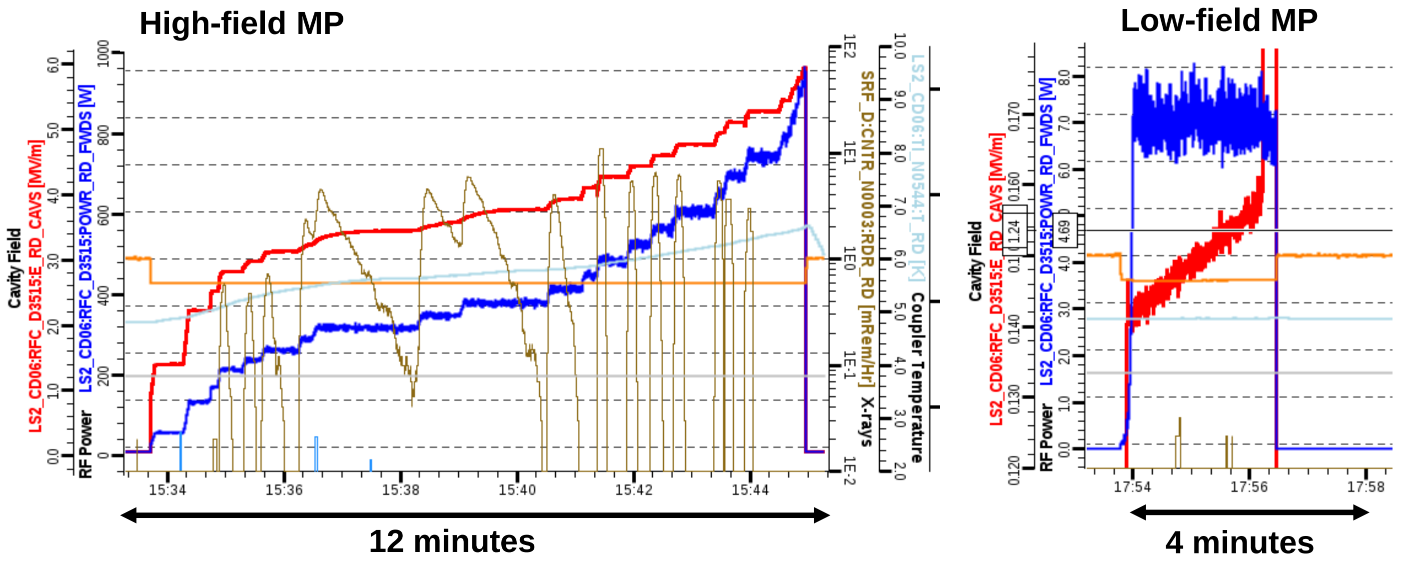
(Max P_{fwd} sampled every ~¼ second and plotted for 7 hour duration)



- 322 MHz half-wave resonators (HWRs; 224 cavities, β=0.23, 0.53)
  - No issues/challenges associated with cavity and coupler multipacting during commissioning and operation: choice of HWR, FPC bias tee

β=0.53 HWR multipacting (MP)

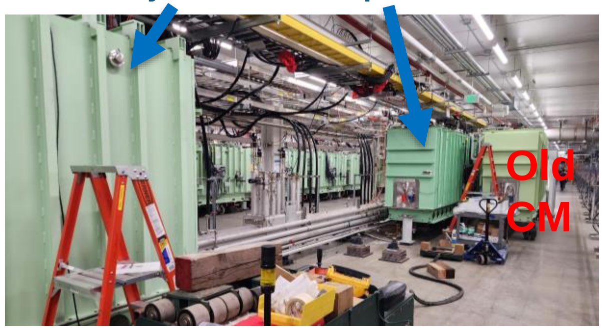
Conditioning in CW mode: typically within 0.5-1 hour



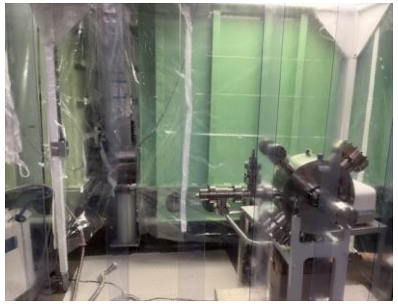
Cryomodule Maintenance Program for Long-term Operation: Spare Cryomodules and In-situ Plasma Processing

- Strategy to address field emission degradation during long-term operation (first-ever experience in high-power heavy ion SC linac): spare cryomodules and in-situ plasma processing

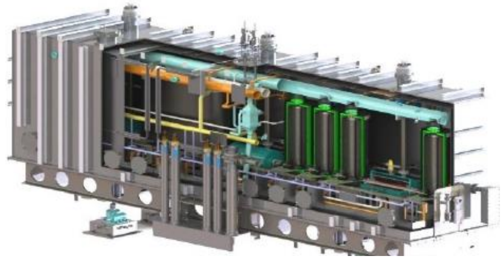
First cryomodule replacement in linac tunnel (2024 summer)

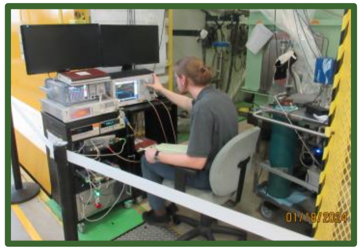


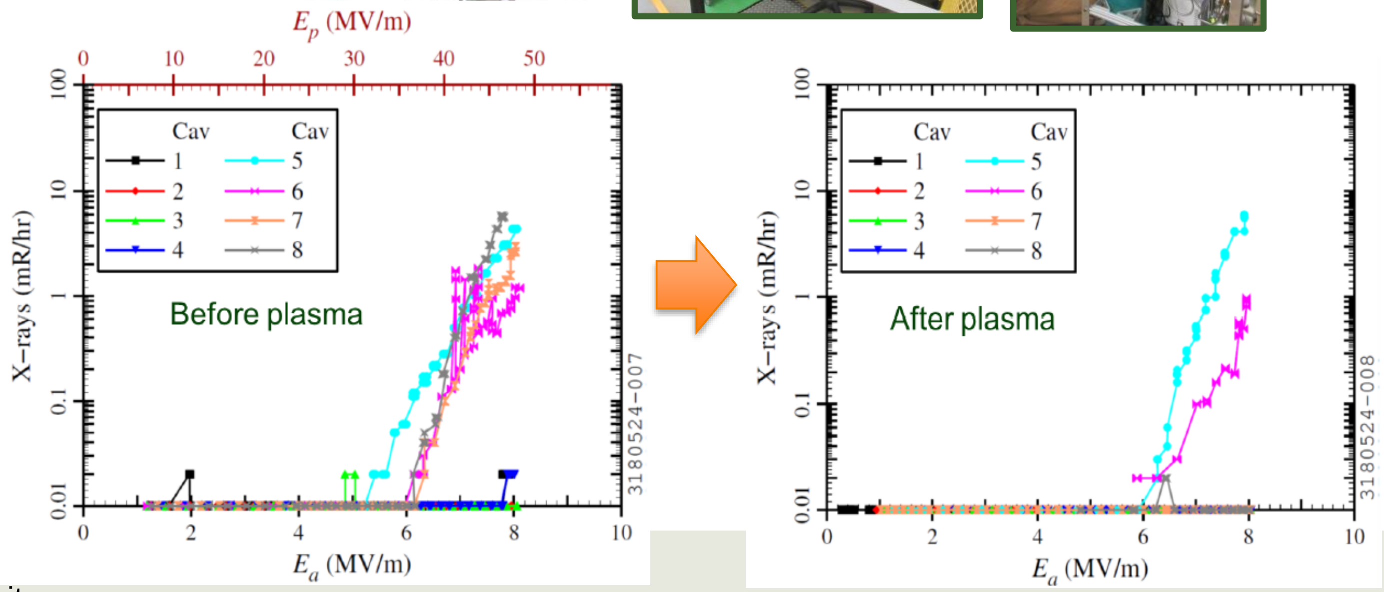
A warm diagnostics box temporarily removed during CM swap



QWR cryomodule plasma processing (PP)
(first time in-situ PP in low-beta cryomodules)

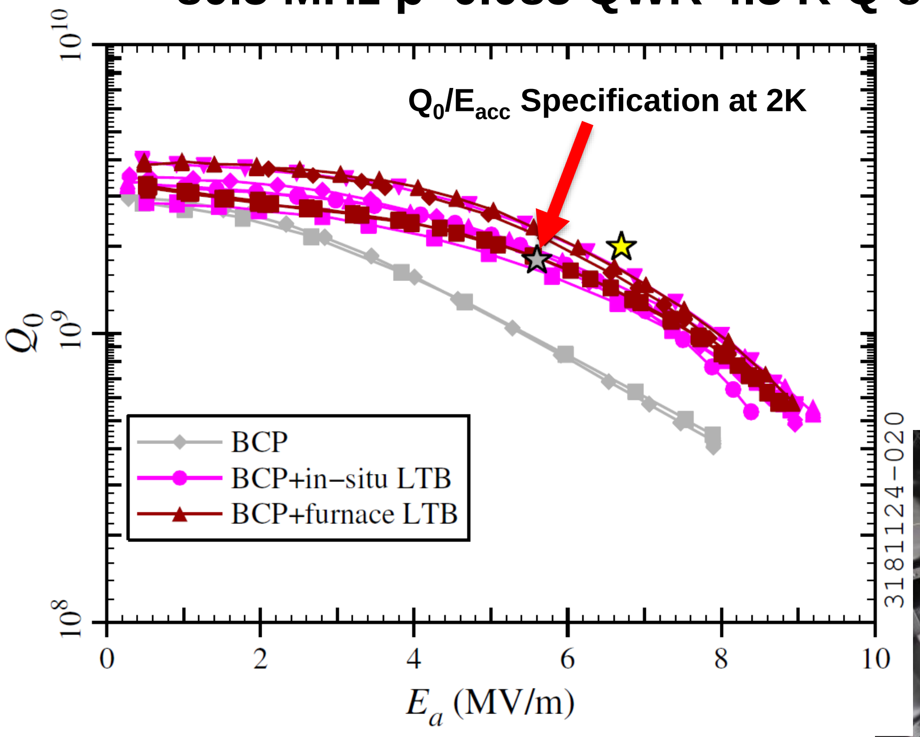






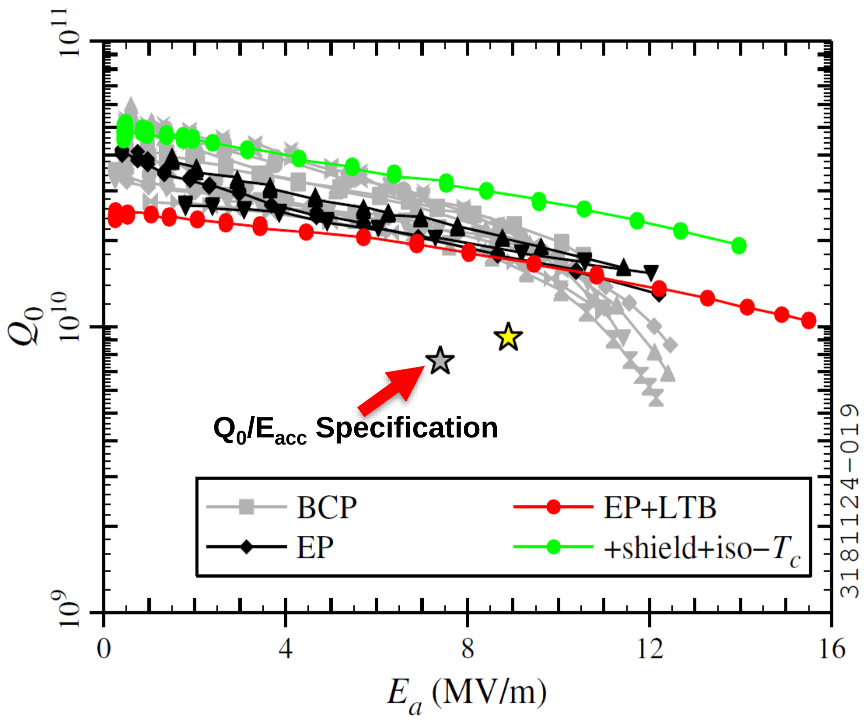
SRF Development for Higher Q0/Gradient Spare Cryomodules

80.5 MHz β=0.085 QWR 4.3 K Q curves



- Buffer Chemical Polishing (BCP) + 120 deg.C low-temperature baking (LTB) is superior to BCP-only for 4K operation
- **BCP + furnace LTB (120⁰C for 48 hours)** is a recipe for spare cavities

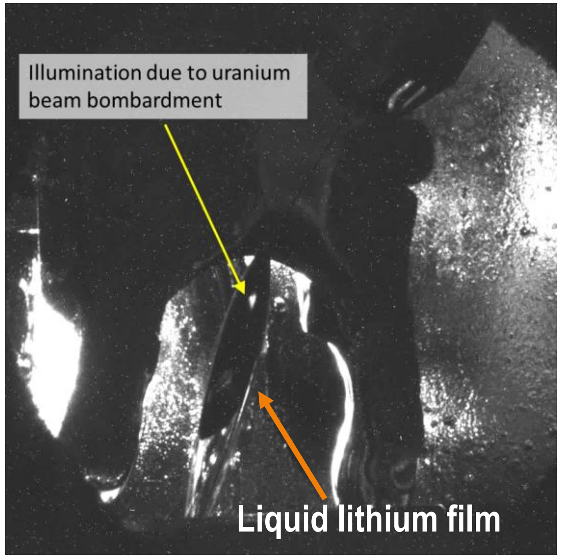
322 MHz β=0.53 HWR 2.0 K Q curves



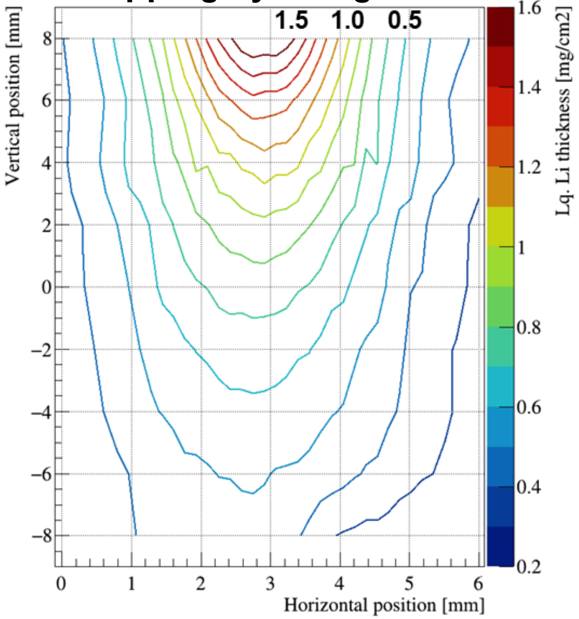
- Observed improvement of high-field Q-slope in electropolishing (EP) and EP + LTB, compared to BCP
- **EP or EP + LTB** is a recipe for spare cavities

High-power Beam Intercepting Devices: Linac Charge Stripper, Isotope Production Target and Beam Dump

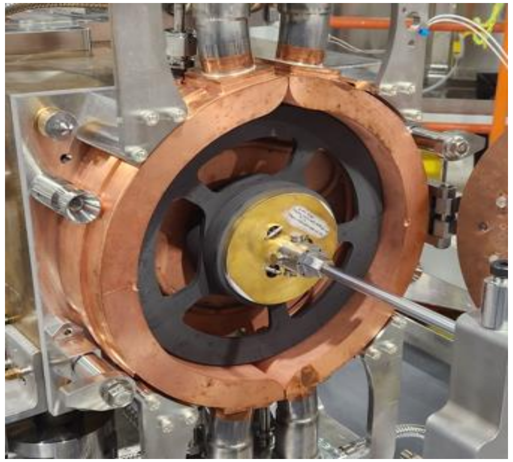
Liquid-lithium (linac) charge stripper

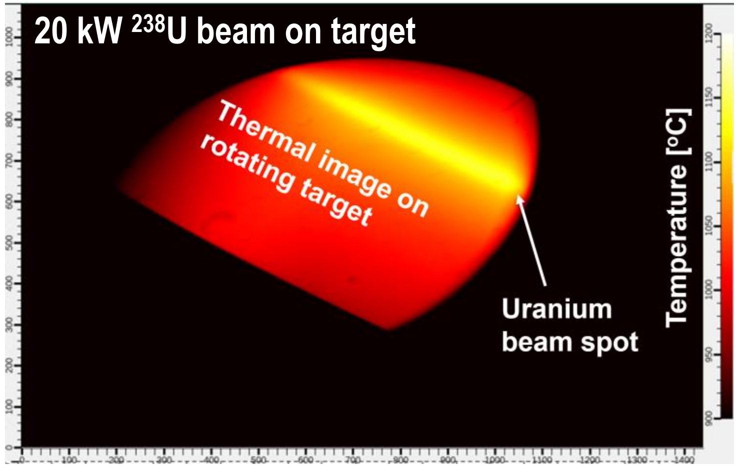


Lithium film thickness mapping by using beam

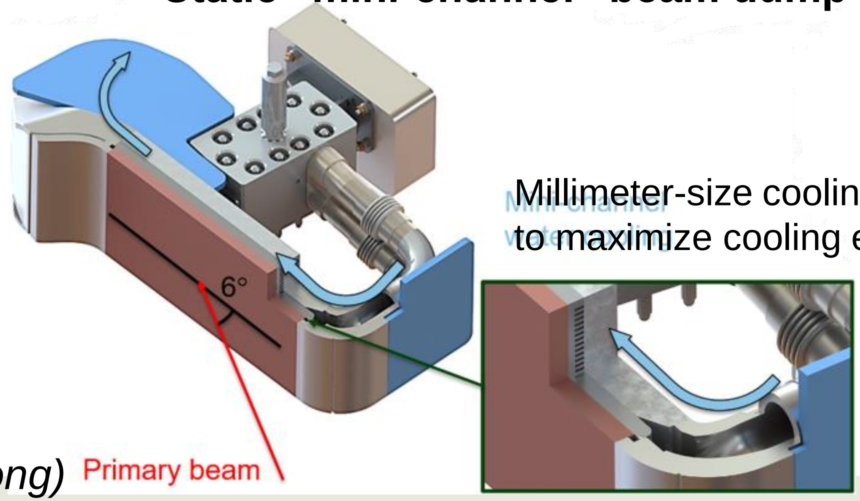


Single-slice rotational graphite target





Static "mini-channel" beam dump



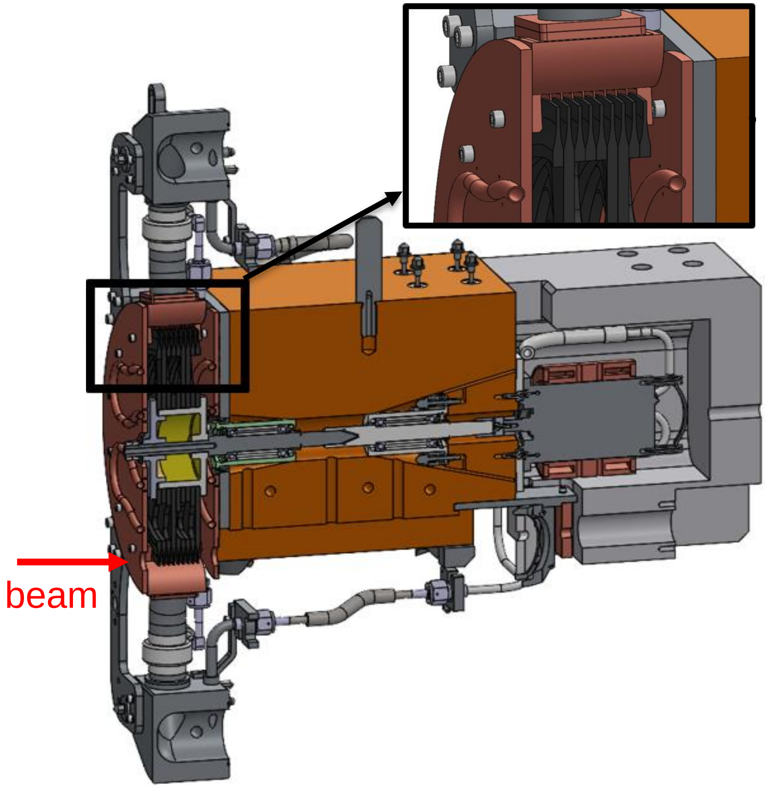
Millimeter-size cooling channel array to maximize cooling efficiency

(Courtesy of T. Kanemura, P. Ostroumov, J. Song)

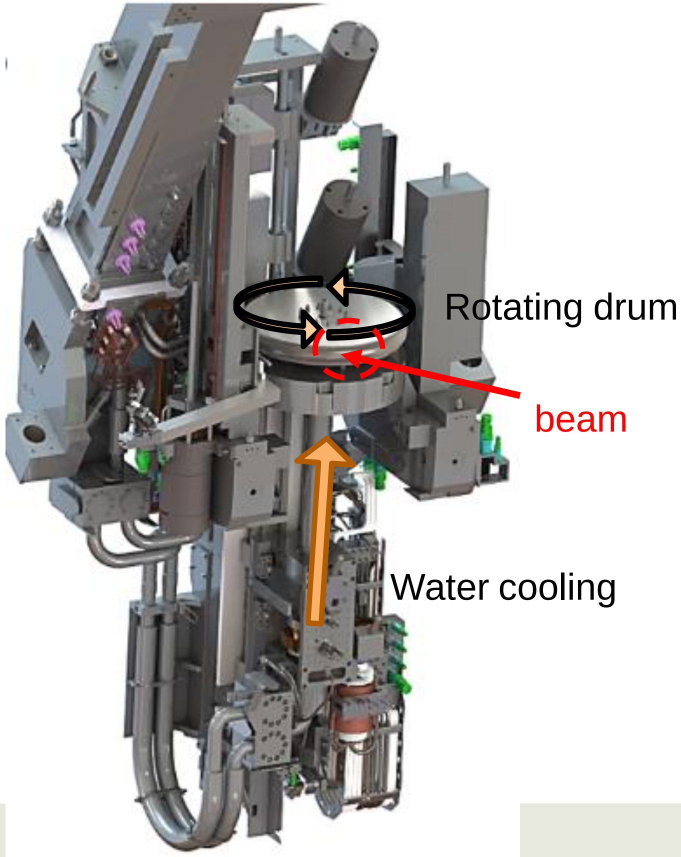
Target and Beam Dump Plan for Power Ramp-up

- Phased deployment of high-power targetry devices is planned; the devices are under development based on operational experience with high-power heavy ion beams

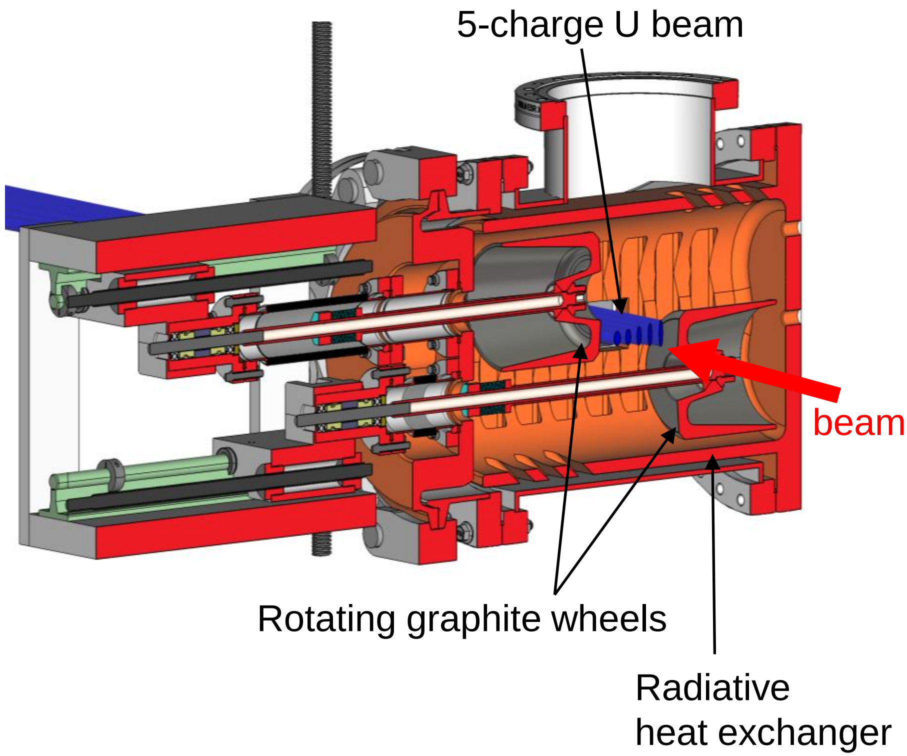
Multi-slice rotational graphite target



Rotational water beam dump

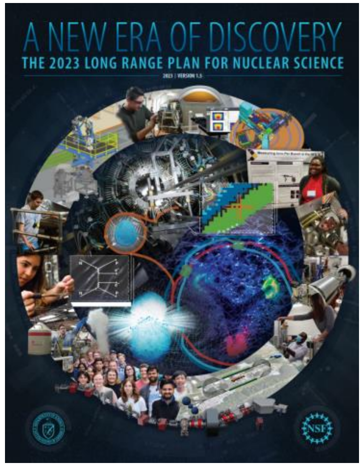


Linac rotational graphite charge selector



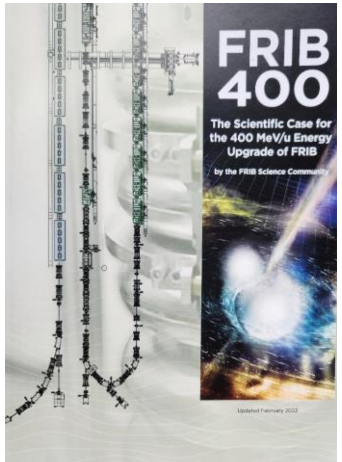
FRIB400 Energy Upgrade

2023 NSAC Long Range Plan

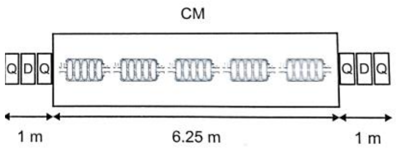


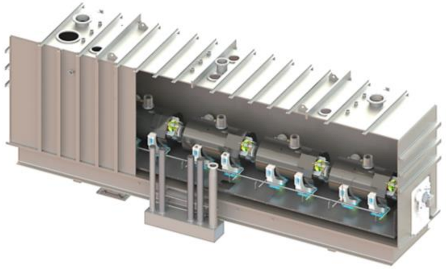
- Will double FRIB's beam energy, 400 MeV/u for uranium beam, using 644 MHz β=0.65 5-cell elliptical cavities
  - To expand the scientific impact by increasing the yield of many rare isotopes tenfold
- Highlighted in the 2023 Long Range Plan for Nuclear Science (2023 LRP) as one of the strategic opportunities to advance discovery science of tomorrow
- FRIB's approach for future FRIB400
  - Developing two-cavity cryomodule as a spare buncher of the existing linac
  - Performing R&D for high Q_0 recipes, plasma processing
  - The linac energy upgrade project has not started yet

FRIB400 White Paper (2018)



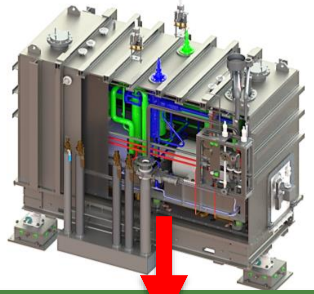
5-cavity FRIB400 accelerating cryomodule



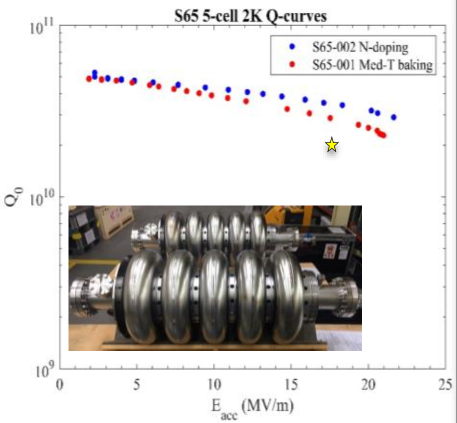


Parameter	Quantity
Number of Cryomodules	11
Cavity Per Cryomodule	5
Total Cavities	55

2-cavity S65 buncher cryomodule (FS2 buncher spare)



Technical Roadmap for Development of FRIB400 Cryomodule



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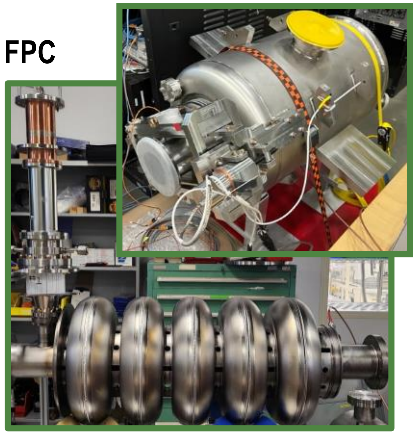
Cavity design and fabrication

- **Unjacketed 5-cell cavity vertical test: Achieved Q_0 = 3.5x10^{10} @ 17.5 MV/m**
- Validated unjacketed cavity design
- Built a jacketed cavity

tuner

FPC



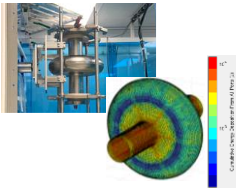
Tuner and coupler design and fabrication

- Built a tuner and performed room-temperature test
- Built fundamental power couplers (FPC) and performed low-power RF test

Surface preparations optimization

- Optimize High-pressure rinsing (HPR), clean assembly, other surface cleaning methods for field-emission-free performance

1-cell HPR



Jacketed cavity vertical test

- Validate jacketed cavity design together with surface preparation process

Integration test in Test Cryomodule

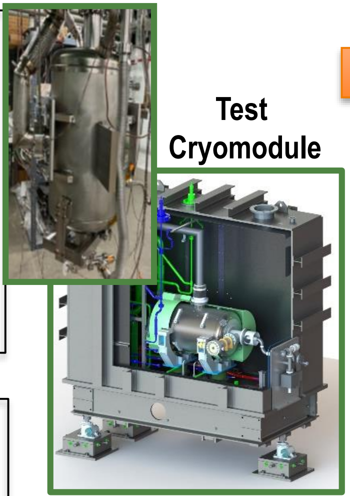
Goal: Q_0 > 2e10 @ 17.5 MV/m,

Q_L = 2x10^7, Max 15 kW CW

- Validate all subsystems design

Jacketed cavity

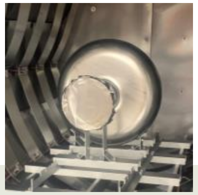
Test Cryomodule



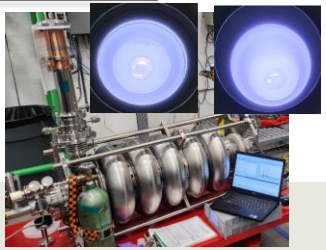
Advanced SRF R&D

- Develop alternative high Q0 recipes
- Develop plasma processing method
- Study potential RF instability and develop mitigation methods
- Develop field emission mapping systems

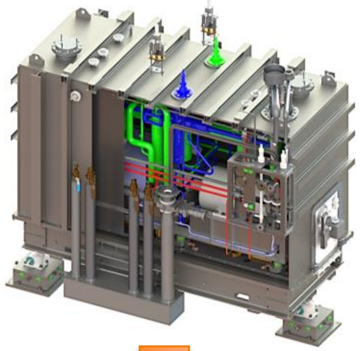
1-cell Nitrogen doping



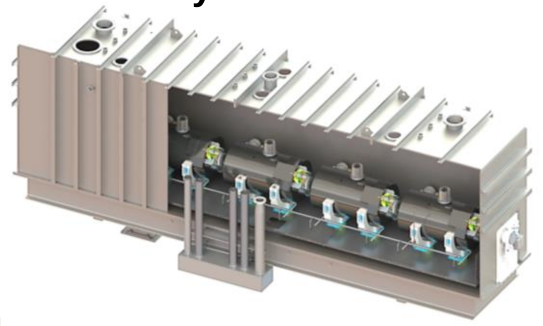
5-cell plasma processing with FPC



S65 buncher cryomodule



FRIB400 accelerating cryomodule



Summary

- FRIB has been conducting user operations since May 2022, providing rare isotope beams to nuclear physics experiment users more than ~4000 hours per year, with a high reliability (>95%)
- Currently operating with a beam power of 20 kW. Plan to ramp up the beam power with phased deployment of higher-power beam intercepting devices such as target, beam dump, linac charge selector
- Maintenance program to keep such a high reliability is in place. In case of superconducting linac, we are building spare cryomodules with higher performance, and developing in-situ plasma processing to address field emission degradation in future long-term operation
- Additionally, FRIB400 energy upgrade, doubling the linac beam energy with new medium-velocity elliptical cavity cryomodules, is planned. Currently conducting SRF development for cavities, subsystems, and cryomodules