Operational Experience and Challenges with Low-β Superconducting Cavities and Cryomodules in a Large-Scale Heavy Ion Linac

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On behalf of the FRIB Team

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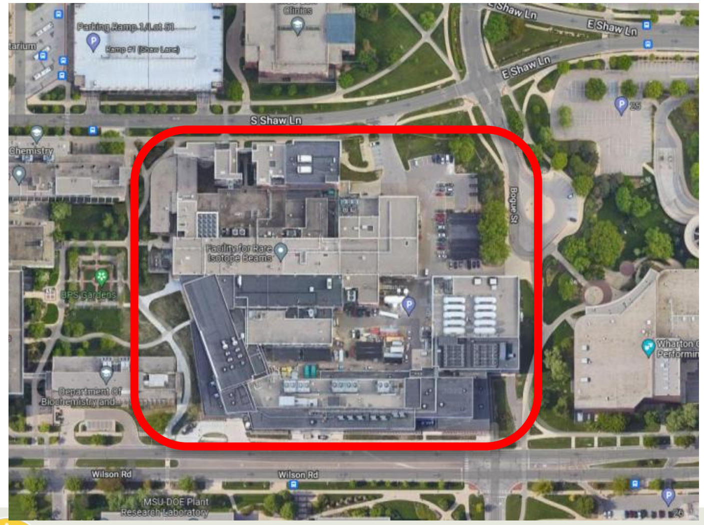
Outline

- Introduction to the FRIB superconducting radio-frequency (SRF) linac
- Challenges with field emission degradation and mitigation thereof
- Experience with microphonics and ponderomotive instability
- SRF R&D for the proposed FRIB energy upgrade
- Summary

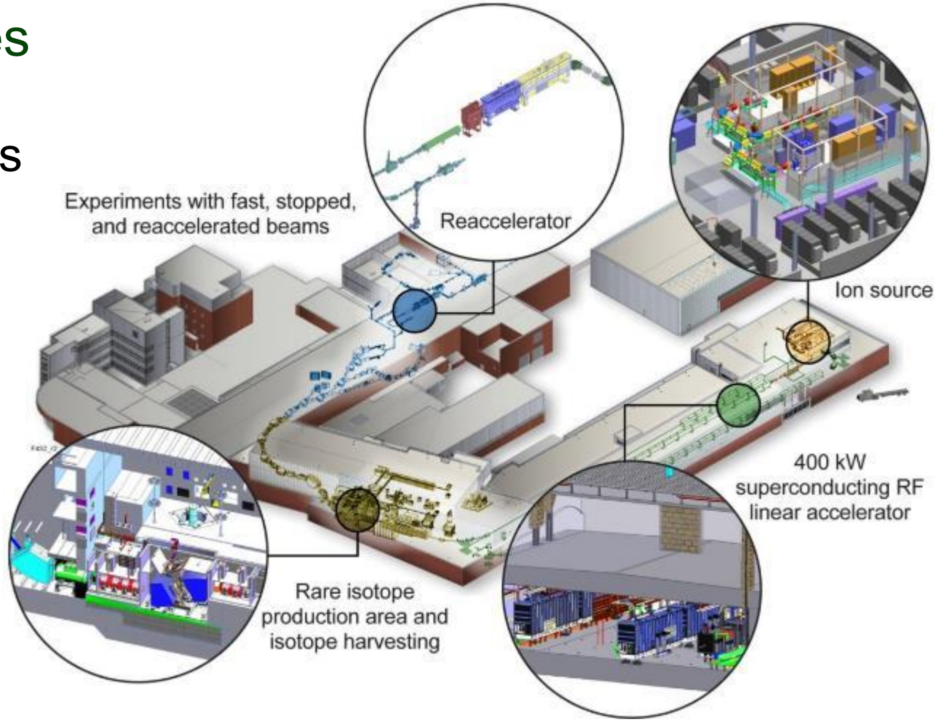
The Facility for Rare Isotope Beams (FRIB): a User Facility for Rare Isotope Science at Michigan State University

- The world's largest heavy ion SRF linac, accelerating uranium beams up to 200 MeV/u; ultimate beam power = 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

Located on the Michigan State University campus



Ion sources, fragment separator, experimental areas, including Re-accelerator: ground level

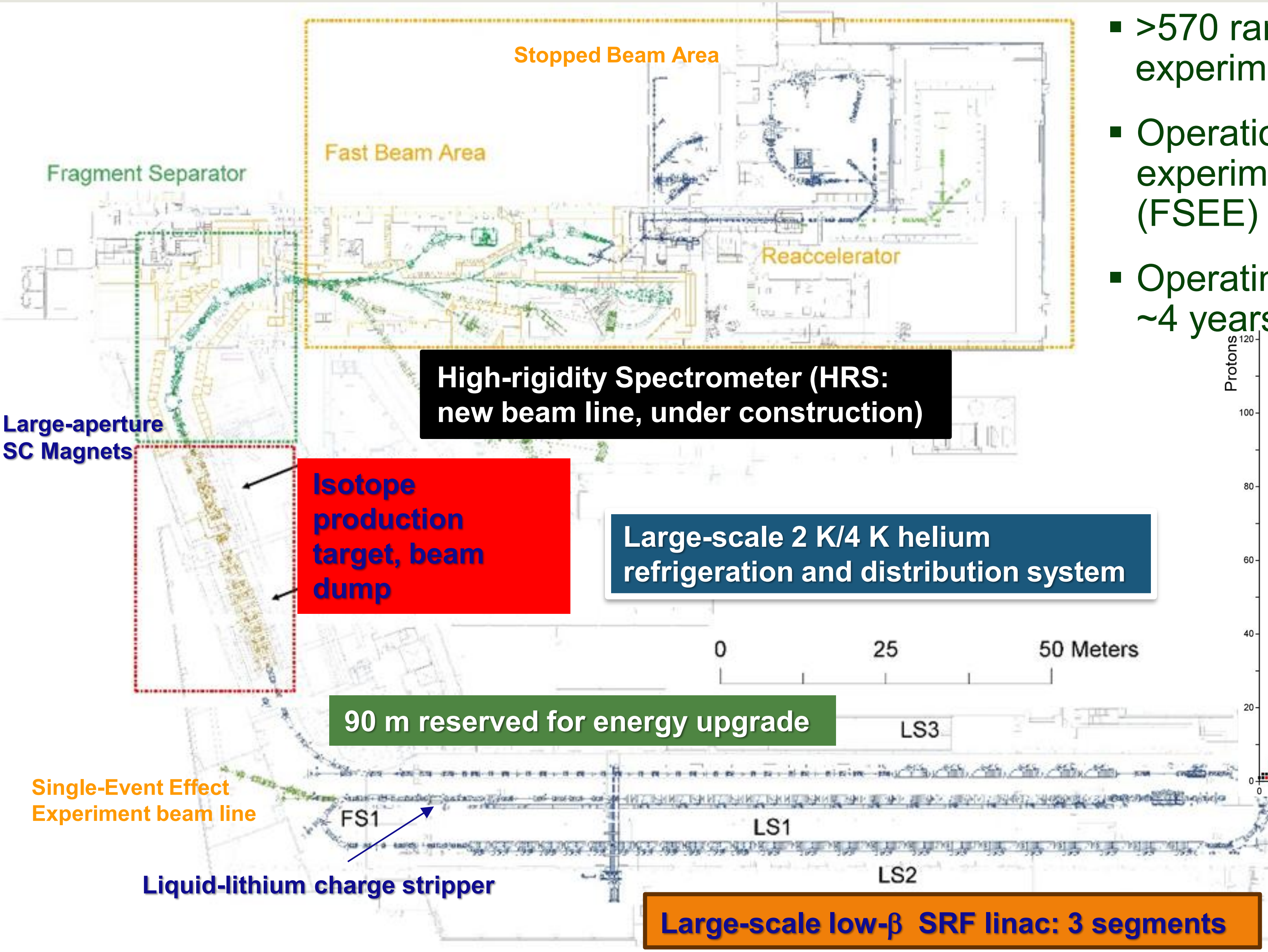


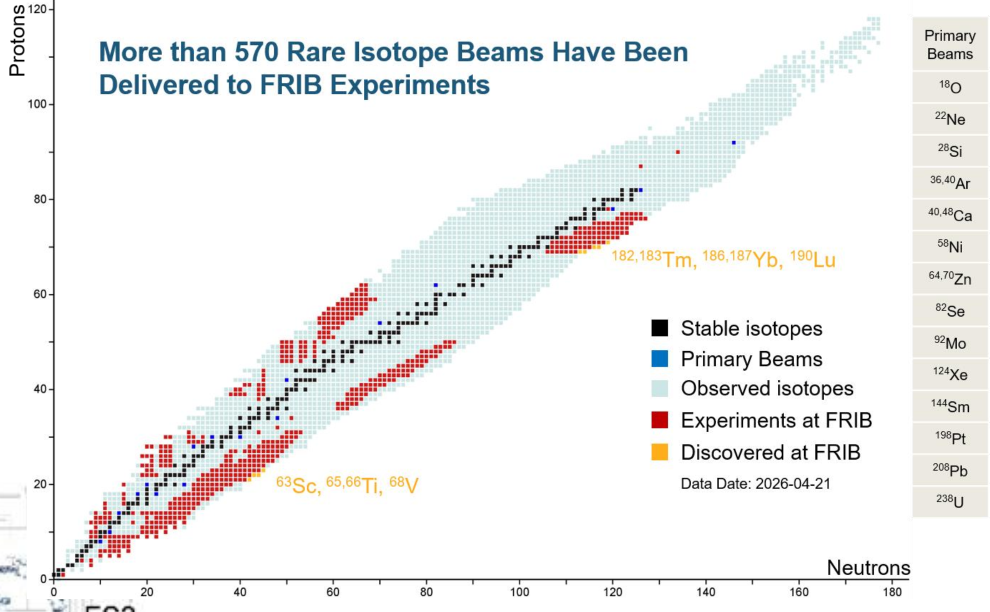
Linac and isotope production target: 10 m below ground

- 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 and User Operation

- >570 rare isotope beams delivered to FRIB user experiments (as of April 2026)
- Operation hours: ~4000 hours for nuclear physics experiment + ~2000 hours for Single-event effect (FSEE) users
- Operating user facility at ~93% availability for last ~4 years





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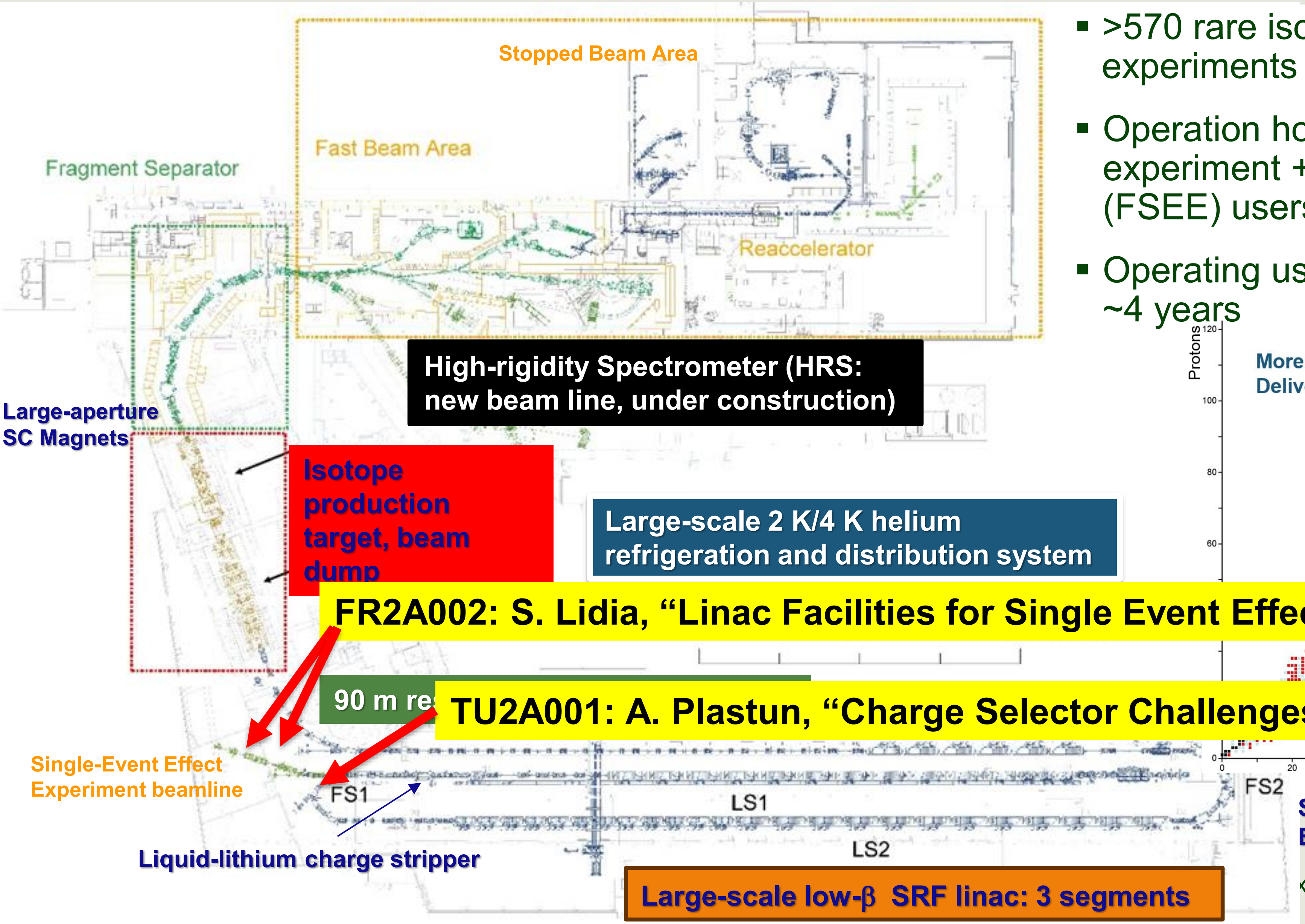
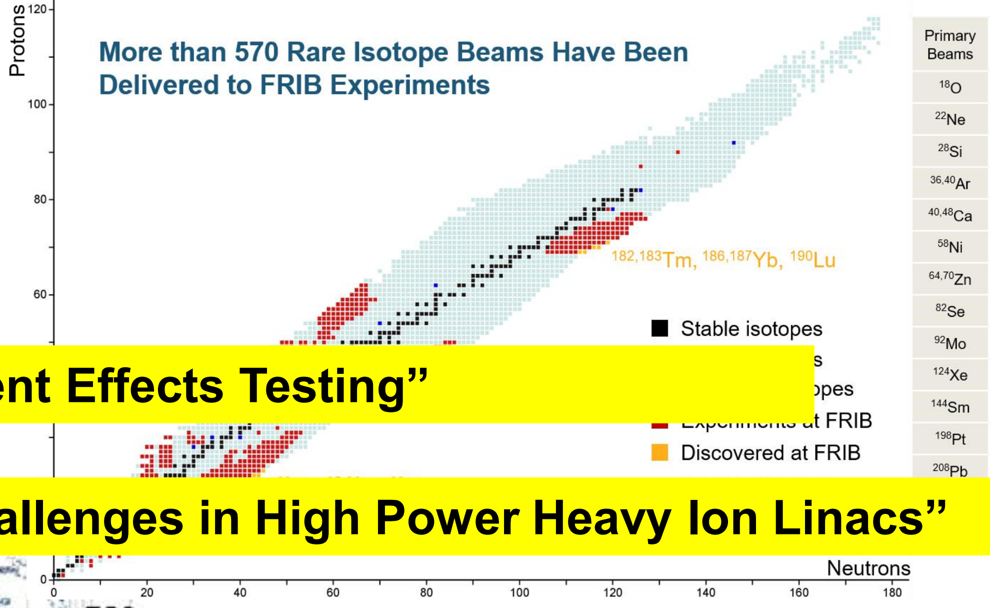
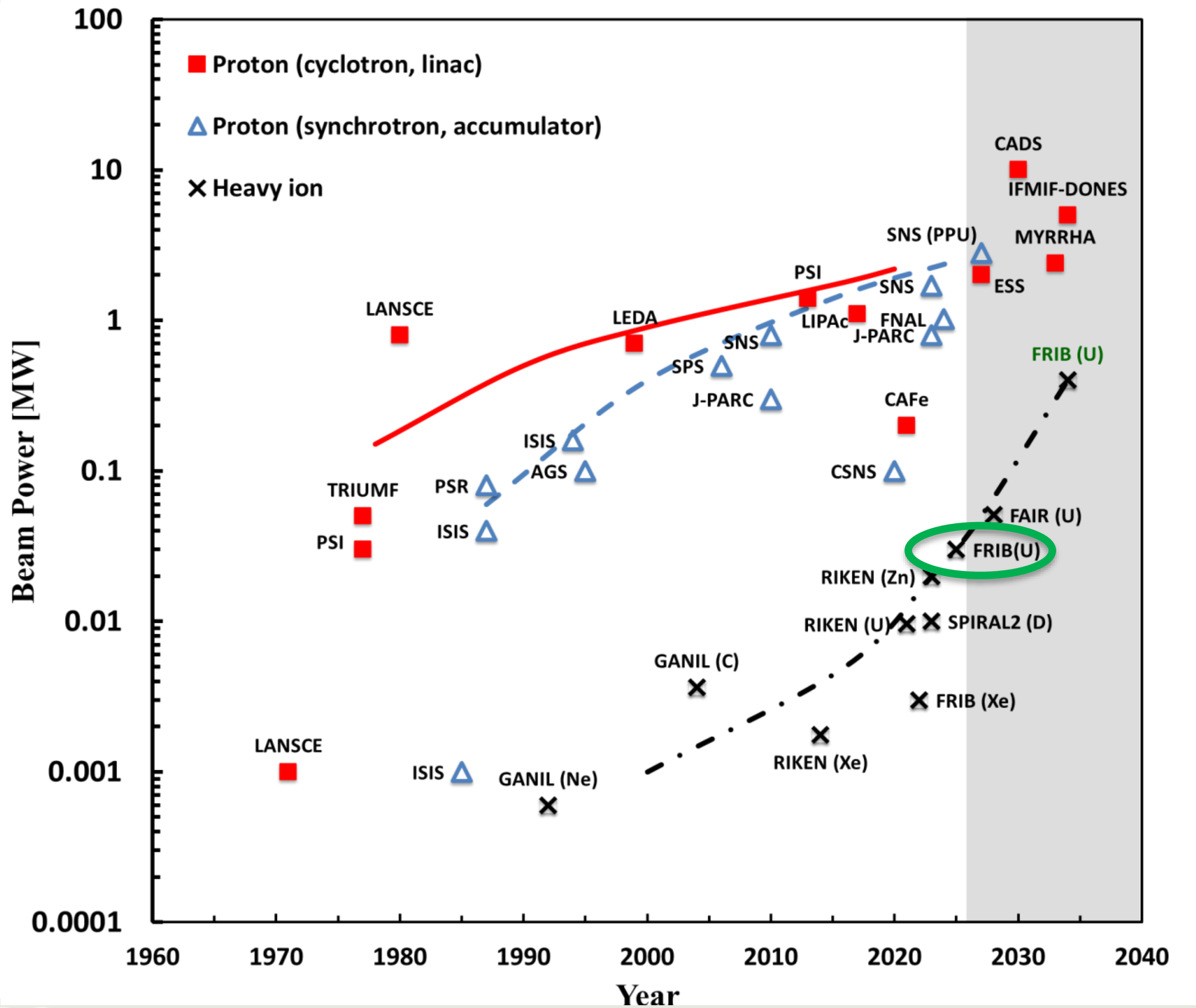
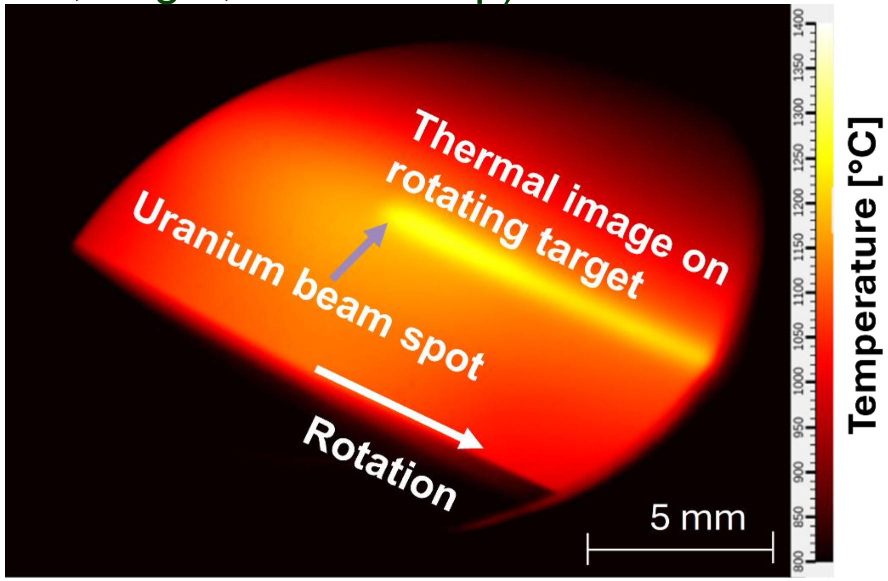




Pushing the Limits of Heavy Ion Beam Power: ~200 MeV/u, 30 kW Uranium Beam: Demonstrated

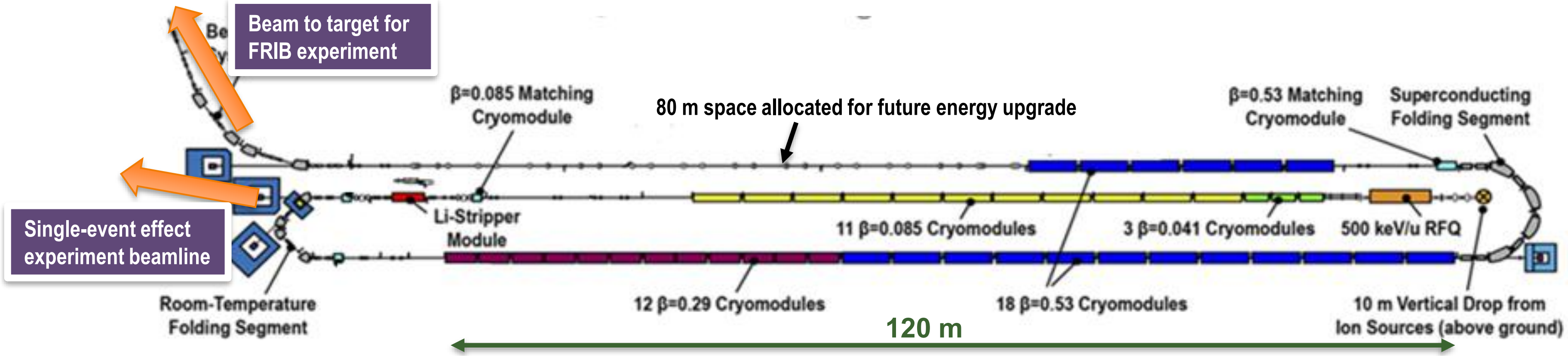


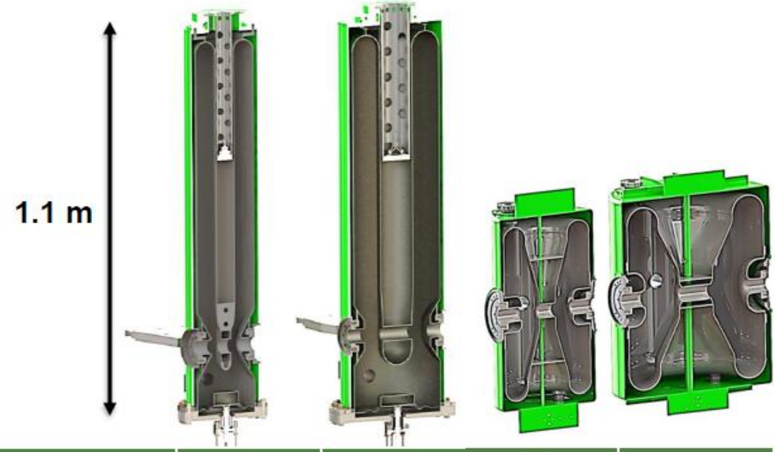
- Have demonstrated 30 kW uranium beam (194 MeV/u); 200 MeV/u uranium beam also demonstrated in the SRF linac
- Beam power ramp-up in progress with development of higher-power beam intercepting devices (charge selector, target, beam dump)



30 kW ^{238}U beam on production target

Driver Linac: 324 SRF Cavities in 46 Cryomodules
Linac SRF Operations Since 2018





	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

Quarter Wave Cryomodule				
β	Type	*Component Counts (baseline + spares)*		
		Cryomodules	*Cavities*	*Solenoids*
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

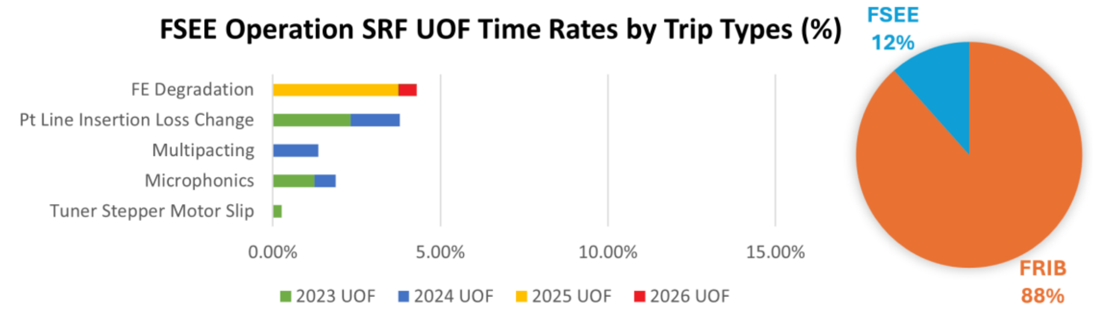
- Linac cool-down, SRF and beam commissioning: phased from 2018 to 2021
  - Majority of cryomodules have been cold for more than 5 years
- 24/7 user operations since 2022
- Thermal cycle (LS1 to ~300 K, LS2 to ~200K) in 2020 to tie in cryo-distribution for target and fragment separator
- LS2 and LS3 full thermal cycle in Summer 2025 for pneumatic tuner preventive maintenance
- One LS1 cryomodule replaced in 2024 maintenance period

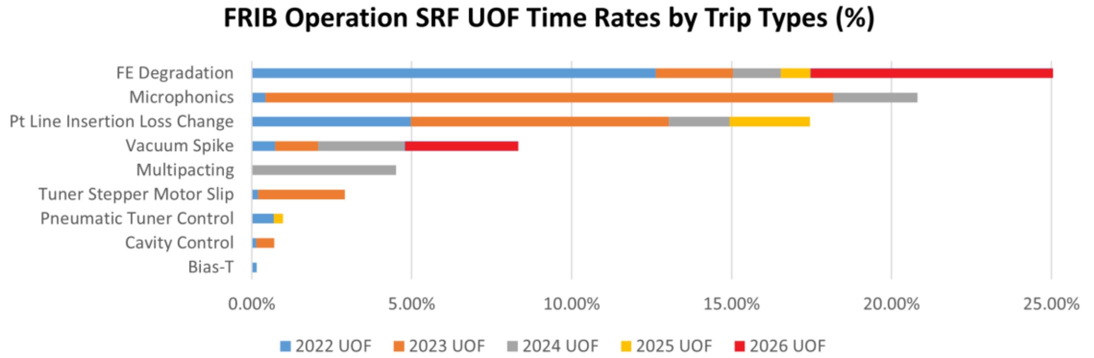
Overall Performance

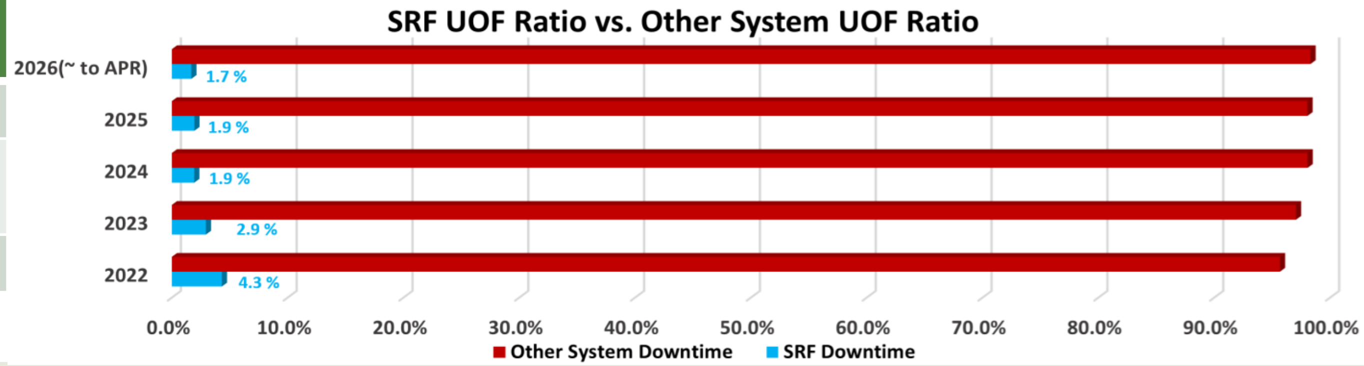
- SRF systems: maintaining high reliability and availability
  - Only one unused cavity out of total 324 over the past 3 years
  - Availability of the SRF systems exceeds 99%:
    - » availability = 1 − (down and recovery time)/(scheduled operating hours)
- The need for cavity field emission management has increased over time, particularly as the beam power increases
- No aging effects have been observed the cryomodule components to date. However, a preventive maintenance plan, including spare components, is in place

Unused cavities (out of 324 total)

Operation Period	Number of Unused cavities	Reason
Commissioning (ARR07)	0 (0%)	-
May 2022 – Jul 2023	4 (1.2%)	HWR tuner blockage (2x), FPC CCG failure (1x), tuning range (1x)
Sep 2023 – Apr 2026	1 (0.3%)	Tuning range







UOF: unscheduled off

Cavity Field Emission Tracking

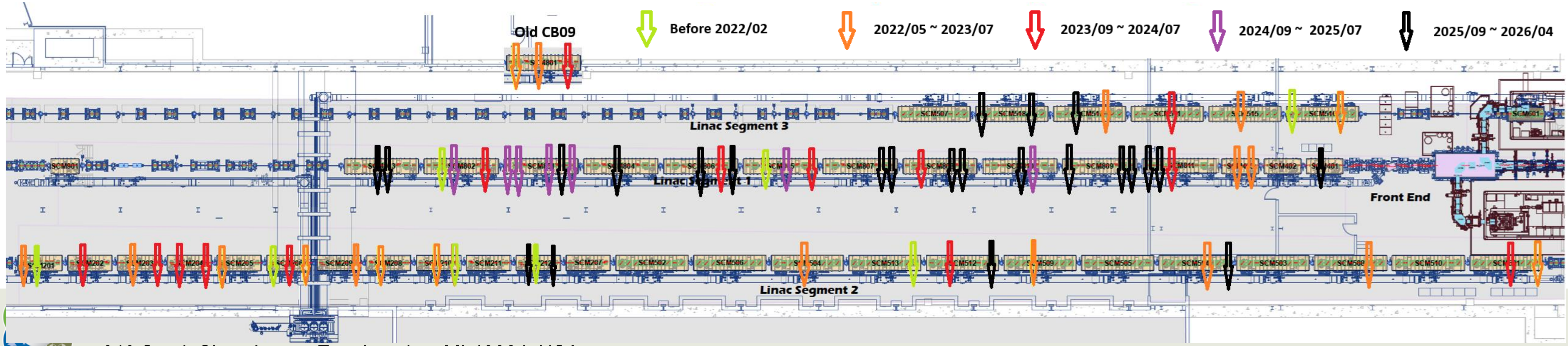
- Tracking methods
  - Two X-ray monitors per cryomodule: X-ray alarms during normal operations and manual measurements in maintenance periods (twice per year)
- Results and impacts to operation
  - No signs of contamination from warm or non-SRF particle free sections
  - We limit the operating gradient (E_a) to maintain X-rays < 30 mR/hr (< 10 mR/hr in most cases)
  - The performance of some cavities has been improved via pulsed RF conditioning
  - ~60% of HWRs operated at 5% above the gradient spec during FY2026

E_a administrative limit

	CA	CB	CC	CD
2022 Oct	95.4%	99.3%	99.7%	98.4%
	-1.4 %		-0.9 %	
2024 Jul	94.0%	99.3%	98.8%	98.4%
	+1.8 % [1]	-0.6 %		+0.2 % [1]
2025 Apr	95.8%	98.7%	98.8%	98.6%
	-1.7 %	-0.8 %	+1.7 % [2]	+2.6 % [2]
2026 Apr	94.1%	97.9%	100.5%	101.2%

(1) Improved by pulse conditioning

(2) Some cavities running 5% above spec



FRIB
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

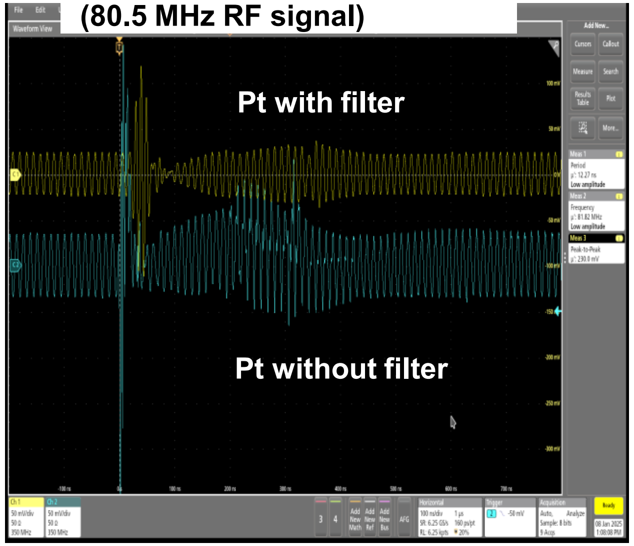
Field Emission: an enduring challenge for SRF accelerators

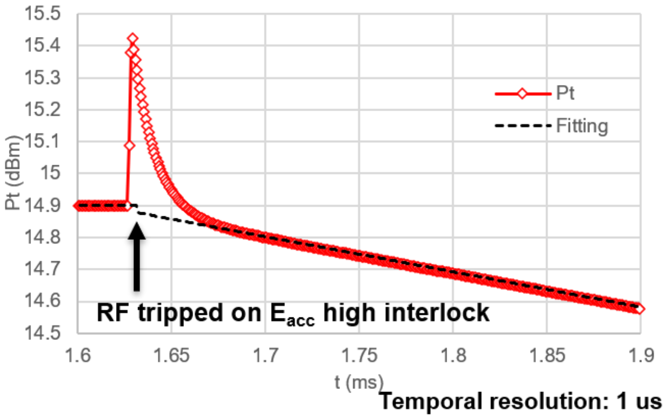
- In general, excessive field emission (FE) is undesirable due to
  - FE-induced *Q*-drop, leading to increased cryogenic loads
  - Thermal or electrical (RF) breakdown, limiting maximum useable gradients
  - FE electrons striking RF coupler ceramic windows, potentially causing damage and vacuum failures
- Approach for FRIB
  - Limit the maximum gradients to keep FE-induced X-rays < 30 mR/hr
    - » Minimize the possibility of FE-induced *Q*-drop or breakdown and their adverse impacts
  - Avoid the possibility of FE electrons directly striking the fundamental power coupler (FPC) RF window by design
- Operational experience at FRIB
  - Even with our conservative FE limits, we have observed RF trips due to cavity field emission

Cavity Field-Emission-Induced RF Trips

- 80.5 MHz QWRs [1]
  - Sharp changes in the transmitted RF power; in the worst case, drops to 0 (but not always)
  - No dc current collected by FPC
  - Pickup RF waveform shows fast disturbance
  - Currently suspecting localized discharge around the cavity pickup induced by cavity FE

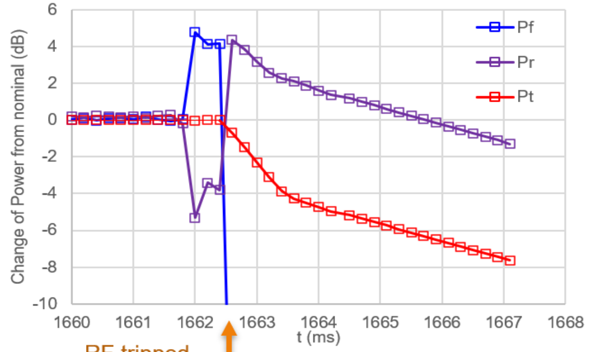
Pt measured on oscilloscope (80.5 MHz RF signal)

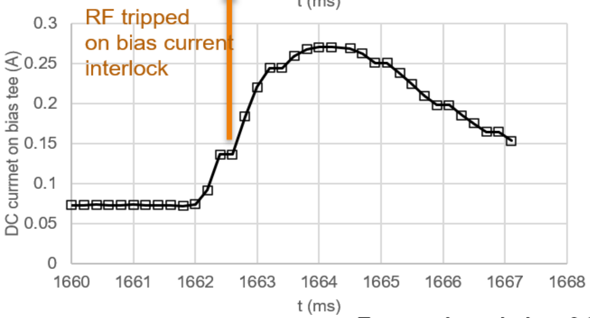




- 322 MHz HWRs [1]
  - FPC: dc current (fast) and vacuum (slow) spikes
  - RF waveforms indicating increased dissipation power
  - These suggests FPC multipacting, enhanced by cavity FE

RF powers and bias current (fast waveforms from LLRF controller)





Temporal resolution: 0.2 ms

Even though the trips are related to ancillaries, they are primarily caused by cavity field emission

[1] W. Chang, “Field Emission Performance of FRIB Linac SRF Cavities During Initial Operations with High-power Heavy Ion Beams,” TTC 2024.

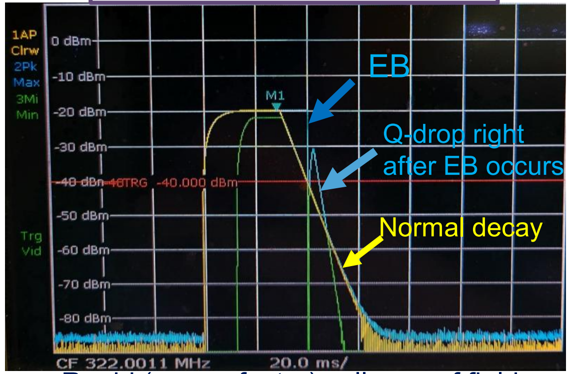
Field Emission Recovery Measures

Method	Pulsed RF Conditioning	Plasma Processing	Cryomodule Refurbishment
Requirements	Duration: 5-10 minutes; can be done with normal operating conditions	Duration: ~1 month; requires a full thermal cycle of the cryomodule	Duration: ~1 year; requires full disassembly, re-processing and/or cleaning of the cavities, and then re-assembly of the cryomodule
Effectiveness	Improvements are limited. In some cases, FE re-appeared after more beam operation (a couple of weeks to several months)	First in-tunnel attempt with a FRIB QWR cryomodule showed promising results. More experience needed.	Expected to be effective

- We are pursing all 3 approaches in parallel, as each has pros and cons
  - Helium processing is in principle another option, but we do not have any recent experience with it

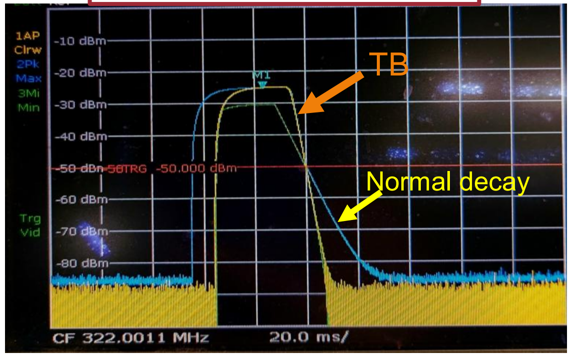
Pulsed RF Conditioning: Observed Limited Improvements in Linac Compared to Offline Initial Cryomodule Tests

Electrical Breakdown (EB)



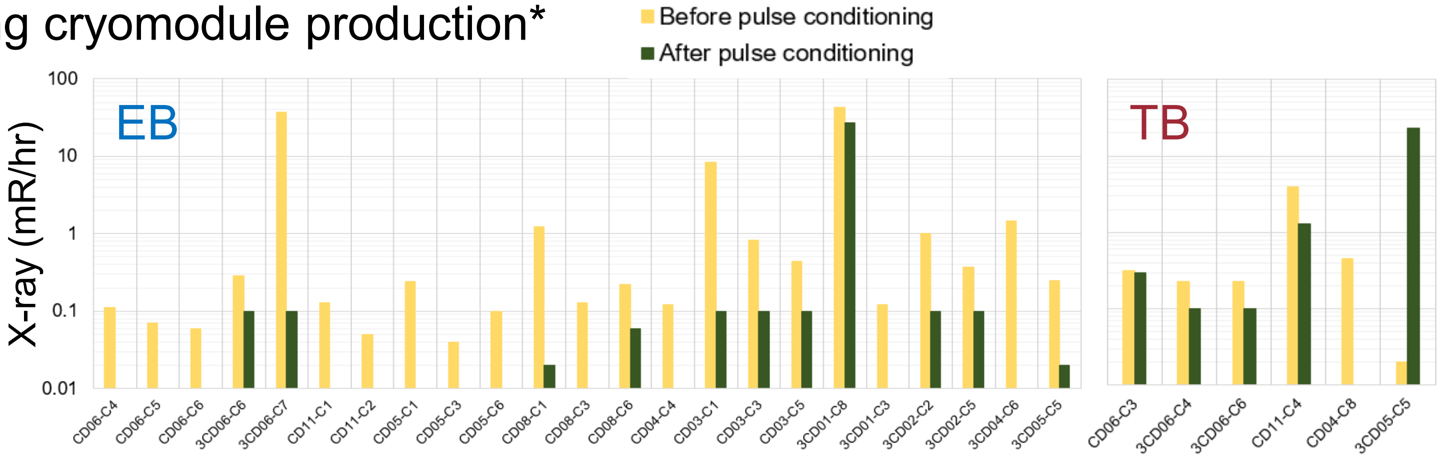
Rapid (~µs or faster) collapse of field.

Thermal Breakdown (TB)

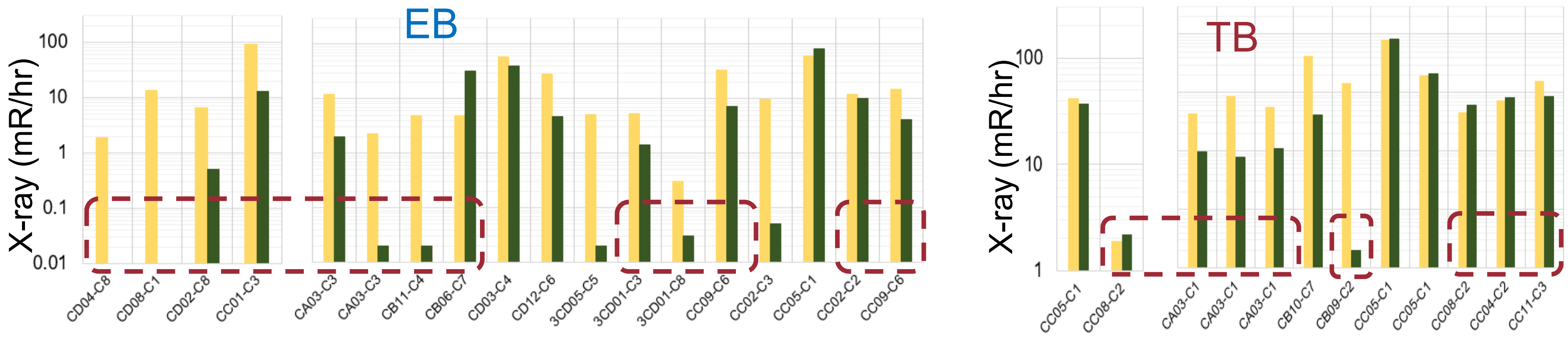


~ms decay time, still faster than normal

Offline tests during cryomodule production*



Linac commissioning and operations (2018 – 2024 Feb)*

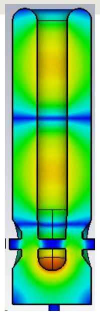


While the improvements in the linac are limited or not permanent, it is still worthwhile to perform this due to its low 'cost'

* Y. Cheon, et al., "RF pulse conditioning to reduce field emission in FRIB SRF cryomodules," LINAC2024

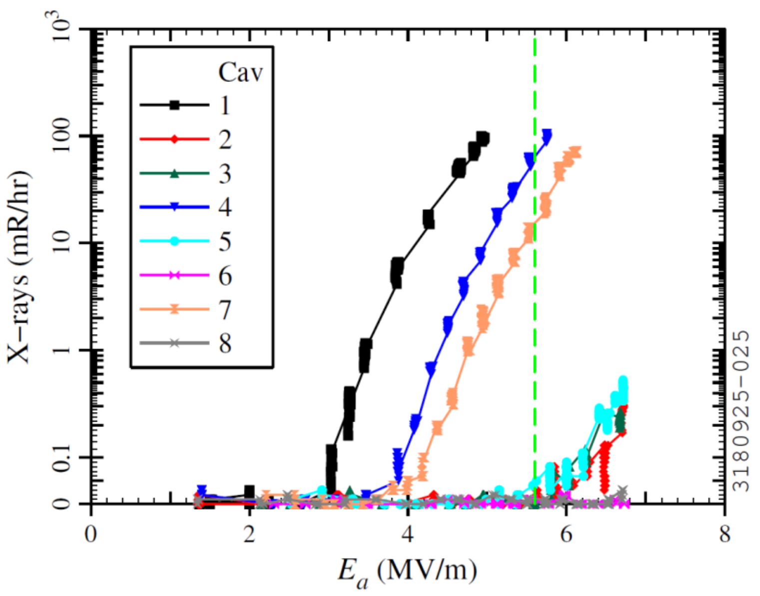
Plasma Processing: Promising initial results, needs further recipe optimization + development for other FRIB cavity types

- FE X-rays are improved after **plasma processing** of one cryomodule (β = 0.085 QWR, 80.5 MHz) + **RF pulse conditioning**
  - Ar/O_2 plasma driven by a higher-order mode (HOM, ~404 MHz) [3, 4]
  - Could not achieve this improvement solely by RF pulse conditioning
- We are tracking the performance as a function of beam operation

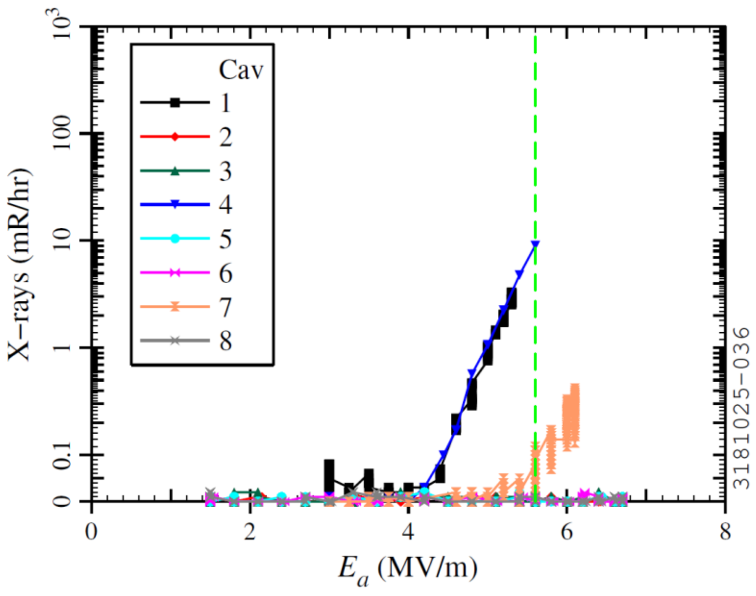


Drive mode

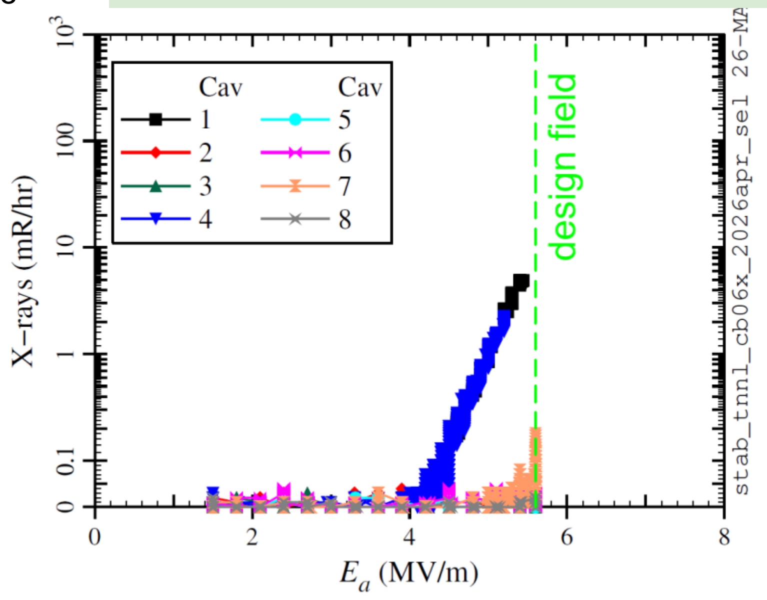
Plasma processing in the linac tunnel



Before plasma (Jul 2025)



After plasma + condition. (Oct 2025)

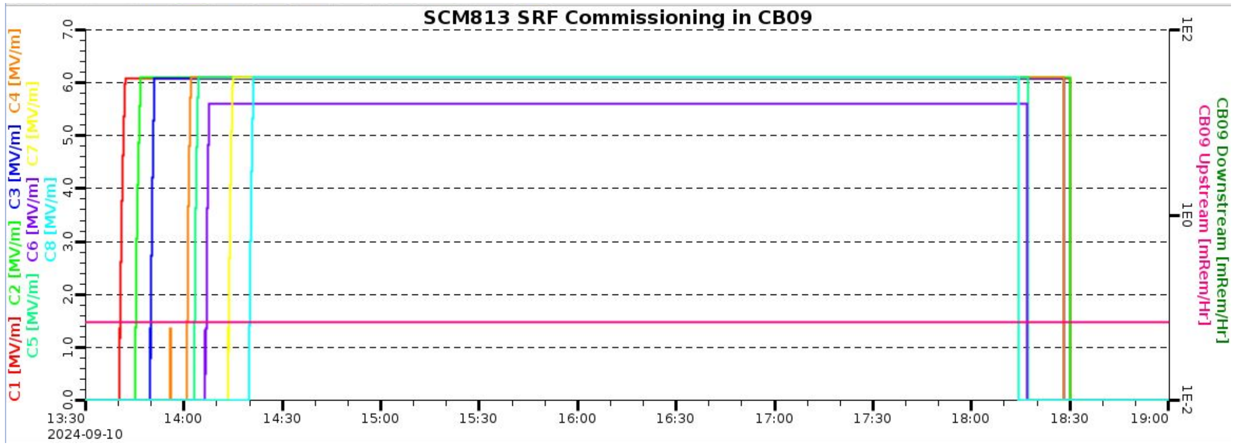


After Linac Ops + condition. (Apr 2026)

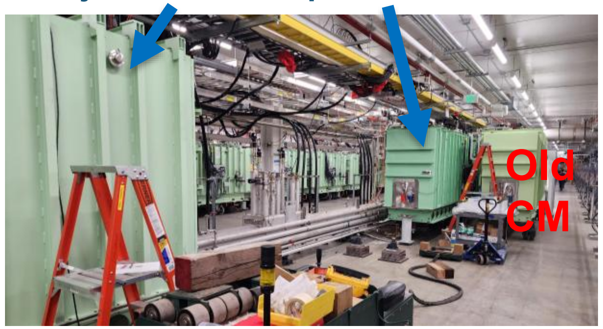
[3] P. Tutt et al., "Plasma processing of FRIB low-beta cryomodules using higher-order modes," SRF2025, TUB05.
[4] W. Hartung et al., "First plasma processing trial of a quarter-wave resonator cryomodule at the Facility for Rare Isotope Beams," *Phys Rev Accel Beams* **29**, 012003 (2026).

Cryomodule Maintenance and Refurbishment Plan

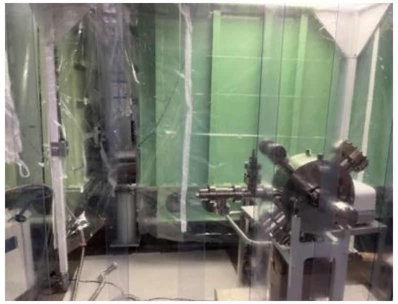
- Spare cryomodules: working toward replacing and refurbishing 1-2 modules per year
- One QWR cryomodule (SCM801) in LS1 slot (CB09) was replaced in with a spare (SCM813) in 2024
  - Plan to add pressure stiffening rings to early production QWRs (SCM801 and 2 other QWR cryomodules)
  - Performance after cryomodule swap: no degradation compared to the cryomodule bunker test



CB09 SRF recommissioning: 7 QWRs out of 8 running at E_{acc} 10% above FRIB spec



1 warm diagnostics box temporarily removed during CM swap

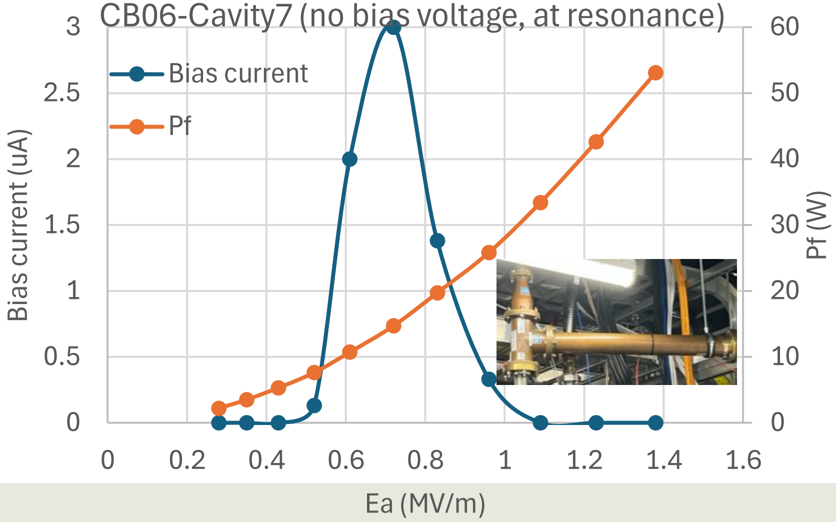


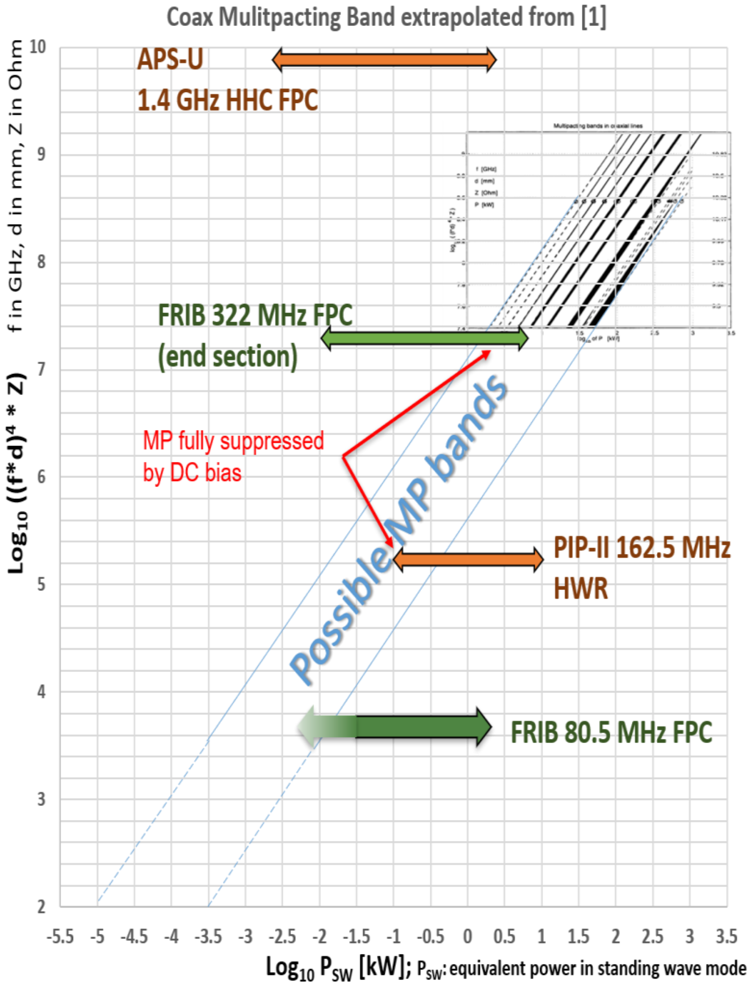
First cryomodule replacement in linac tunnel (Summer 2024)

Lesson from 1st Cryomodule Refurbishment: Weak Multipacting Band Exists in the FRIB QWR FPC

- Oxidation marks were observed on the FPC components of the cryomodule after removal from the linac
  - Warm transitions (Cu-plated thin-wall stainless-steel tubes): 4 out of 8
  - XRF measurements showed no removal of Cu
- Further investigation: FPC multipacting (MP) occurs at low field (low RF power)
- No dc bias is needed
  - The MP barrier is 'weak,' with minimal power dissipation (<1 W)
  - Operation within the MP zone can be avoided

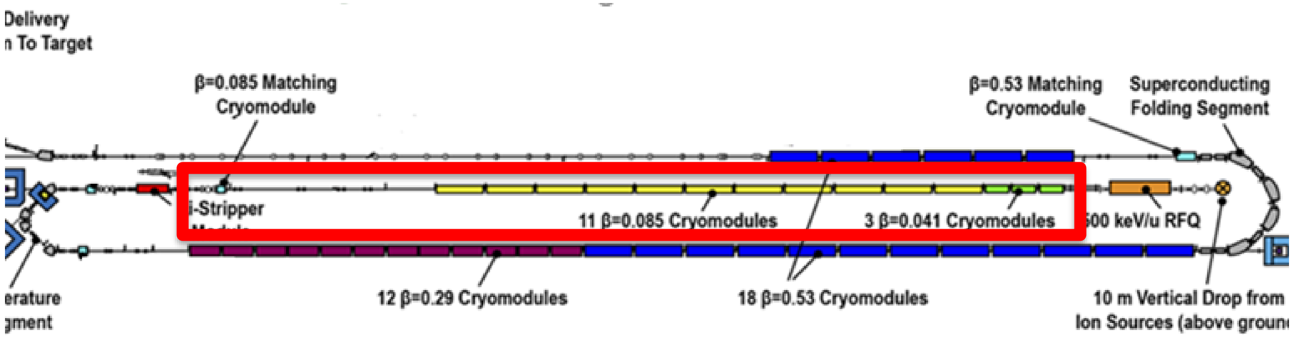
MP current measured on FPC bias tee





Experience with Microphonics: FRIB Linac QWRs Operate Stably at 4 K

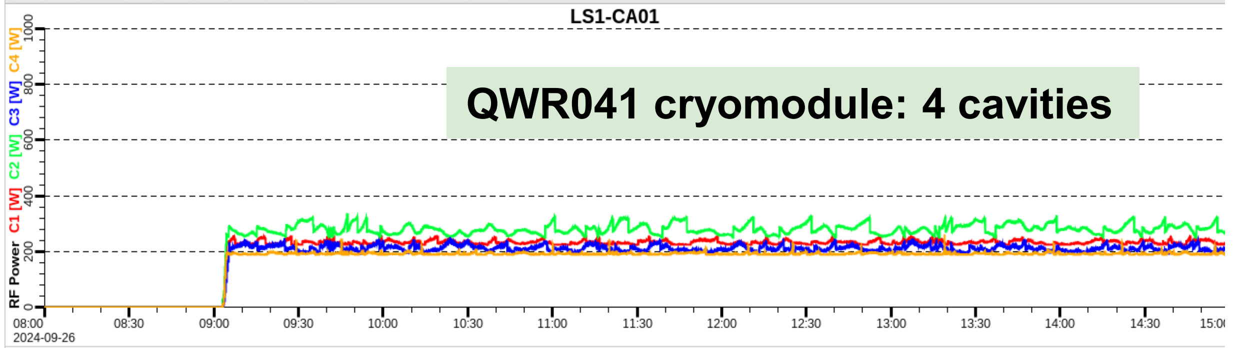
- During phased linac commissioning, Linac Segment 1 (LS1, 80.5 MHz QWRs with Q_L = 2E6) achieved stable operation at 4.4 K
- We have been operating the QWRs at 4.4 K since then; 2 K operation is also possible

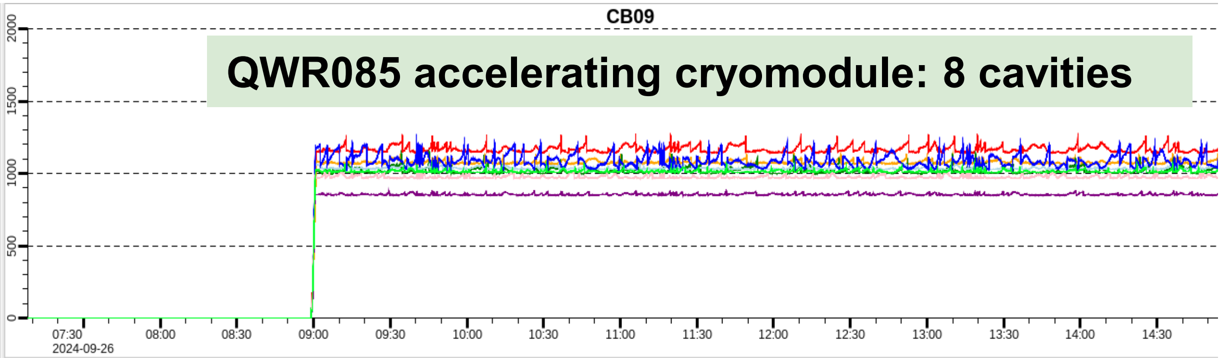


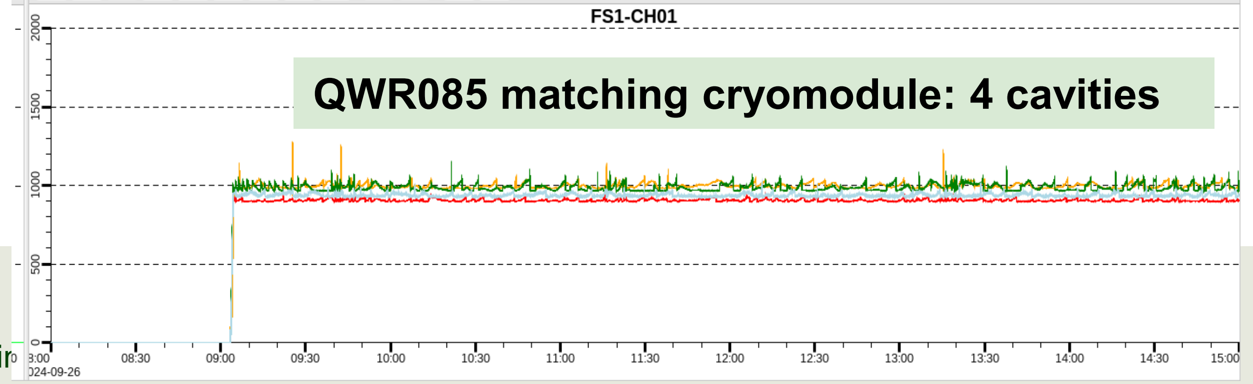
LS1: 104 QWRs to accelerate beam to 20 MeV/u in uranium case

Typical phase lock stability for LS1 at 4.4 K

Max Pf sampled every ~¼ sec, plotted for 7 hours







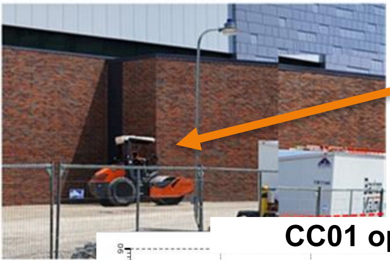
Experience with Microphonics: Overcoming challenges from impacts due to on-campus construction

- Initially observed impacts from outside construction activities in LS2 (322 MHz HWRs operated at 2 K with Q_L = 5E6, 1E7) in 2024
- Further investigation and testing suggested that the root cause was the vibrating roller. After replacing the vibrating roller, we were able to run during construction activities such as drilling, compacting, and excavating
- We Work closely with the FRIB and MSU civil construction teams to minimize the impact of construction activities on linac operation

Construction areas

FRIB superconducting linac

August 7

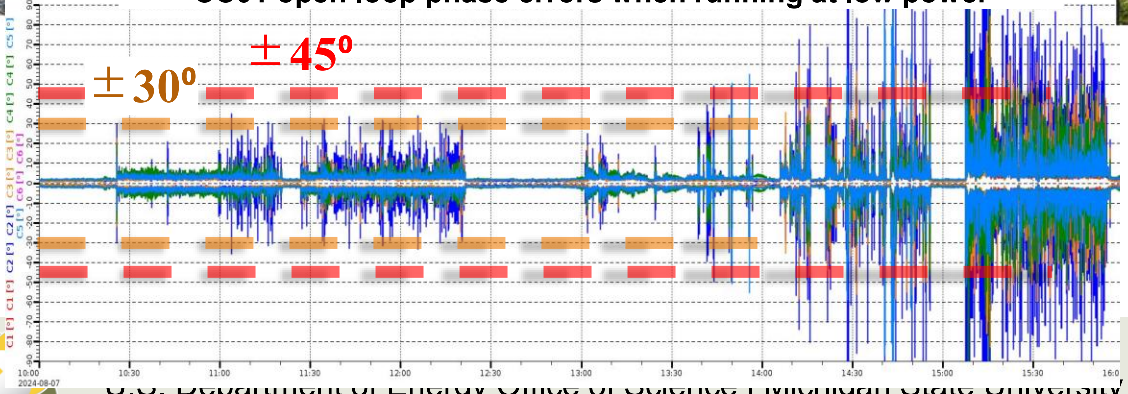


Old vibrating roller

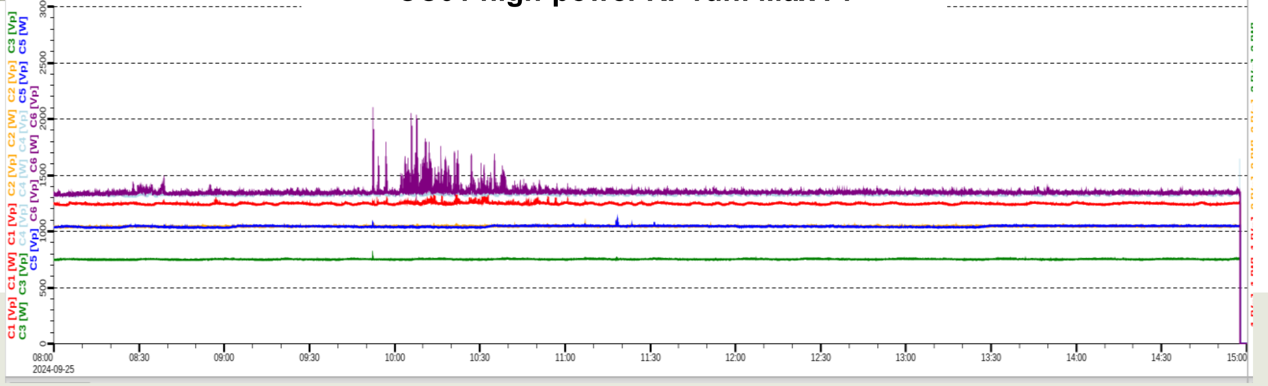
September 25

New vibrating roller

CC01 open loop phase errors when running at low power

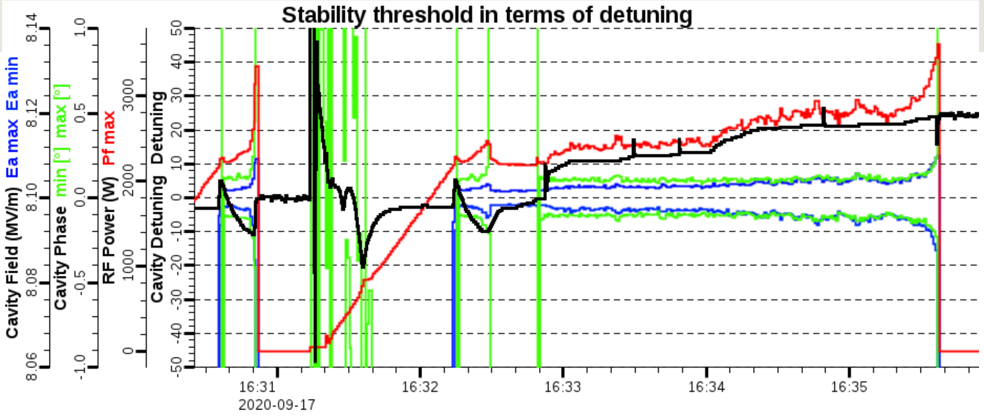


CC01 high-power RF run: Max Pf

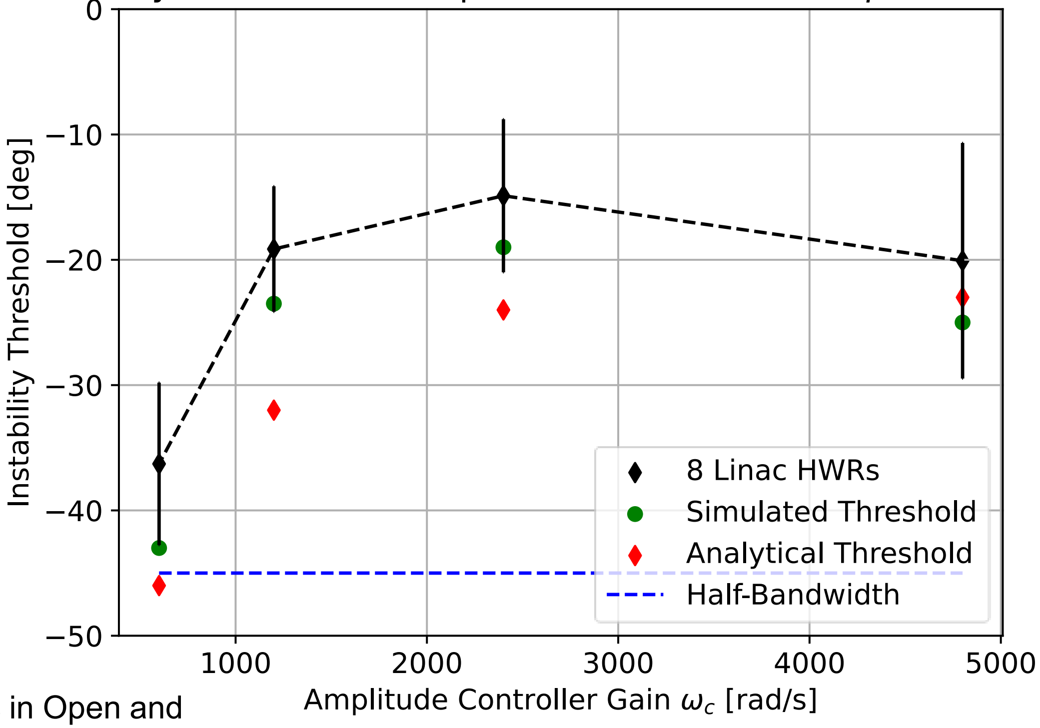


Experience with Ponderomotive Instabilities

- Observed instability-like behavior during cryomodule production and offline testing
  - Investigated LLRF feedback control and experimentally identified better control parameters to move the potential instability threshold beyond our operating conditions
- Further in-depth theoretical modeling and experimental studies suggest that this is a ponderomotive instability, this finding has enabled further optimization of LLRF parameters [5]
  - This work will help push the operating gradients of high-performing HWR53 cavities and support the development of future energy-upgrade cryomodules



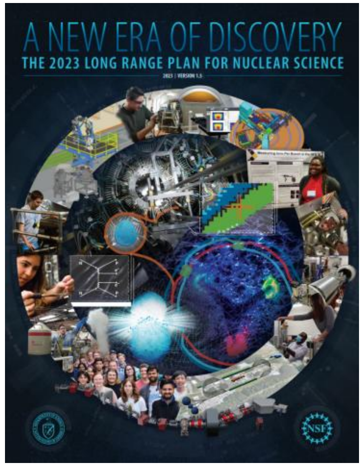
Instability Threshold v. Amplitude Controller Gain: $\beta = 0.53$ HWRs [5]



[5] J. Brown et al., “The Ponderomotive Effects of Narrow-band, Superconducting Resonators in Open and Closed Loop,” https://arxiv.org/abs/2607.28806 (2026).

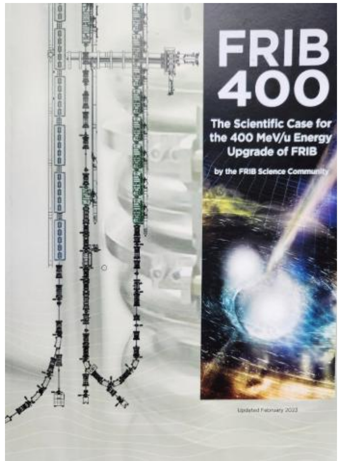
Proposed FRIB Energy Upgrade

2023 NSAC Long Range Plan



- Will double FRIB's beam energy to 400 MeV/u for uranium beam using 5-cell elliptical cavities (β=0.65, 644 MHz)
  - 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
- FRIB approach
  - SRF R&D since 2017: cavity high-Q_0 recipes, plasma processing
  - SRF infrastructure upgrades, including electropolishing, N-doping, surface inspection
  - Prototyping and cryomodule design: in progress

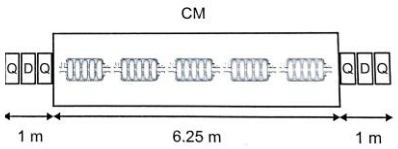
FRIB400 White Paper (2018)

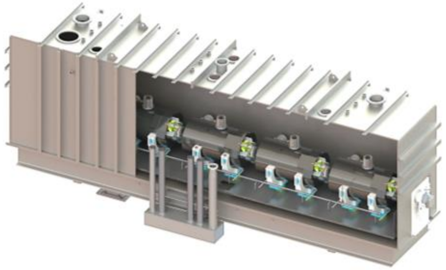


Upgrade cavity key parameters

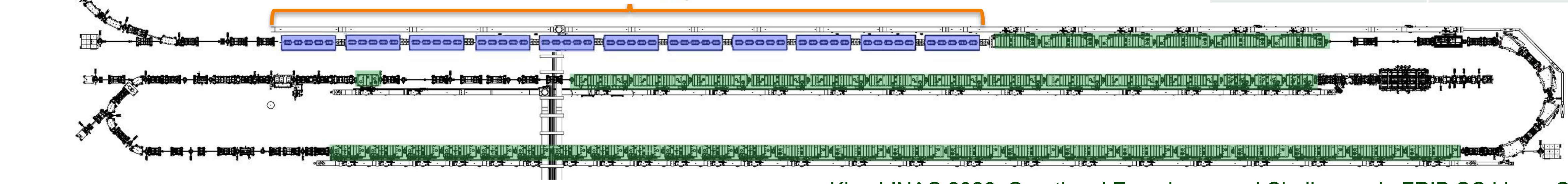
Parameter	Value
E_{acc}	17.5 MV/m (V_{acc} = 12.4 MV)
Q_0 in cryomodule	1.5e10
FPC Q_{ext}	2.0e7 (loaded bandwidth = 32 Hz)
Forward RF power	19.3 kW (max)

5-cavity upgrade accelerating cryomodule



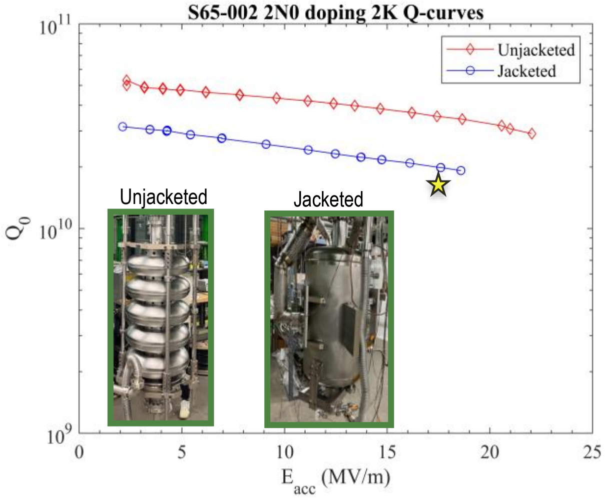


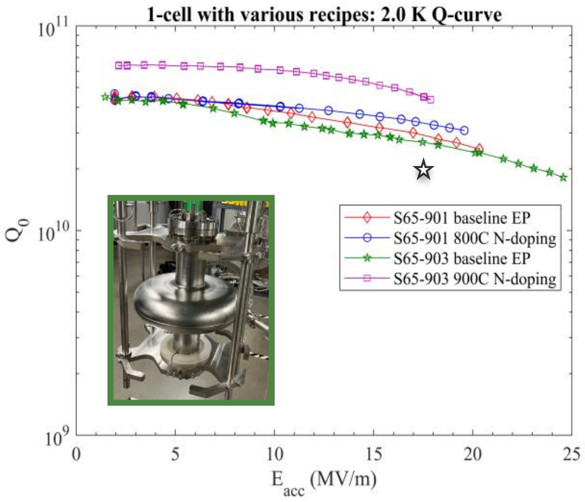
Parameter	Quantity
Number of Cryomodules	11
Cavity Per Cryomodule	5
Total Cavities	55



Energy Upgrade: SRF R&D and Prototyping

- SRF R&D Effort
  - Demonstrated the design goals in a jacketed 5-cell cavity
  - Continuing recipe studies for more margin in Q_0 using 1-cell [6]
  - Developed HOM plasma processing RF recipe with the full FPC assembly [7]
- 1-cavity prototype cryomodule test: assembly in progress
  - To validate the design of all subsystems
  - To verify performance: microphonics, pondermotive instability, plasma processing capability

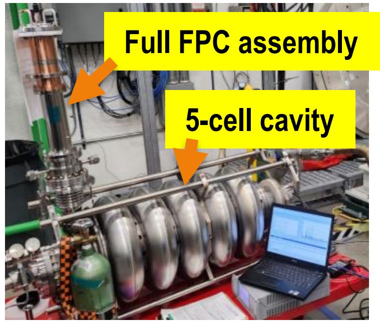




S65 Test Cryomodule: Cavity, FPC, tuner, rail, hood

644 MHz 20 kW amplifier installed at SRF bunker

HOM plasma processing demonstrating hydrocarbon removal



[6] S. Moskaitis et al., "Investigation of RF Surface Resistance in Sub-GHz Superconducting Elliptical Cavities Processed with Various Nitrogen-Doping Surface treatments," IPAC 2026, TUP7326.
[7] Y. Cheon et al., "Feasibility study of plasma processing for the FRIB energy upgrade 5-cell superconducting cavity," HIAT 2025, TUP24.

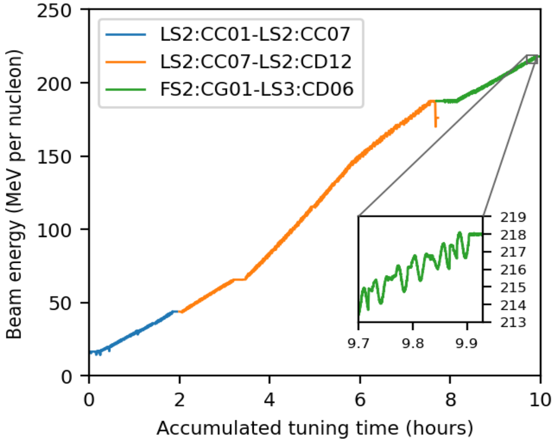
Summary

- FRIB superconducting driver linac cryomodules have been in operation since 2018 for cryogenic and SRF operations and since 2022 for user operations
- We continue efforts to maintain high reliability and high availability. Examples include field emission tracking and recovery from performance degradation via pulsed RF conditioning, plasma processing, and cryomodule refurbishment
- We are pursuing SRF R&D and prototyping for the proposed linac energy upgrade using medium-velocity elliptical cavities

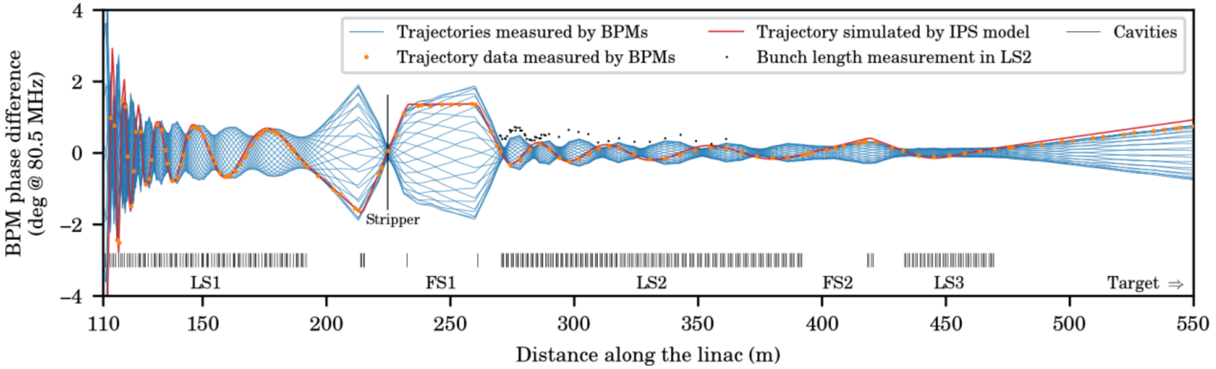
Backup: Linac Beam Tuning and SRF Cavity Operation For Efficient User Operations

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

Linac phasing example
(220 cavities during ARR05 commissioning)



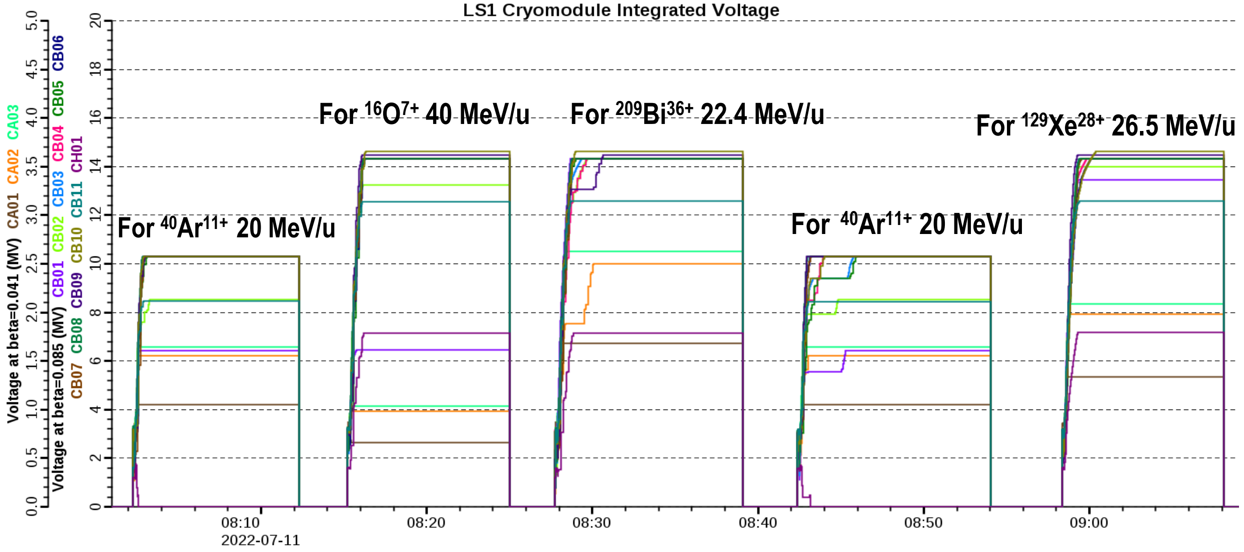
Envelope matching using Instant Phase Setting
(model-based cavity field changes for a different beam)



(Courtesy of P. Ostroumov, A. Plastun)

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

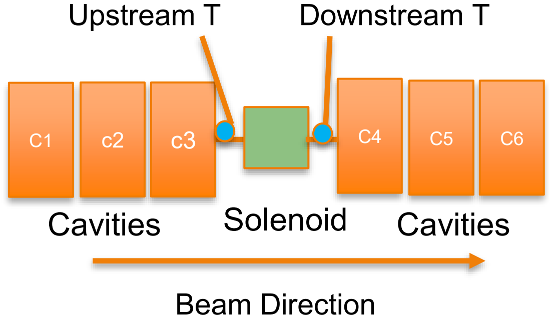
LS1 cavity field switching for various beams*
(104 cavities for FSEE experiments)

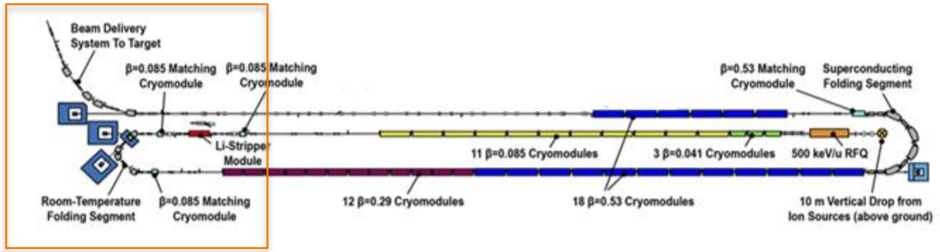


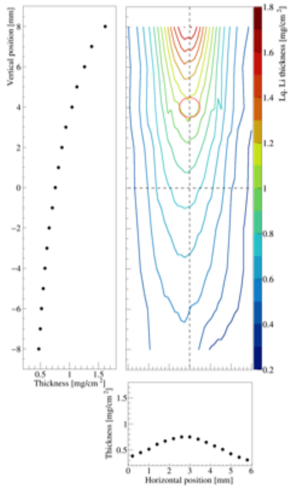
* via dynamic load compensation by cryomodule internal heaters such that the net heat load remained almost constant in each module

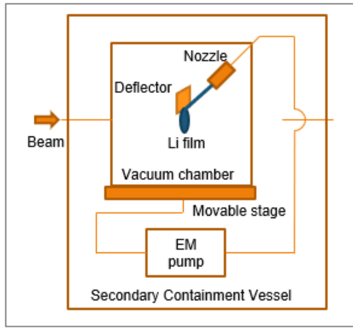
Backup: Minimize Beam Losses Downstream of Liquid Lithium Charge Stripper

- Fast thermometry (slow protection): temperature sensors attached on cryomodule internal beam-pipes
  - Most sensitive beam-loss diagnostic, particularly for HWR cryomodules (CC) after first bend (FS1)
- Lessons learned
  - Detected the beam losses in CC cavities due to charge stripper (liquid Li film thickness fluctuation)
  - Found correlation between temperature rise (beam losses) and FE degradation in CC cavities
  - Energy compensation by buncher and stripper thickness feedback control implemented to mitigate fluctuations



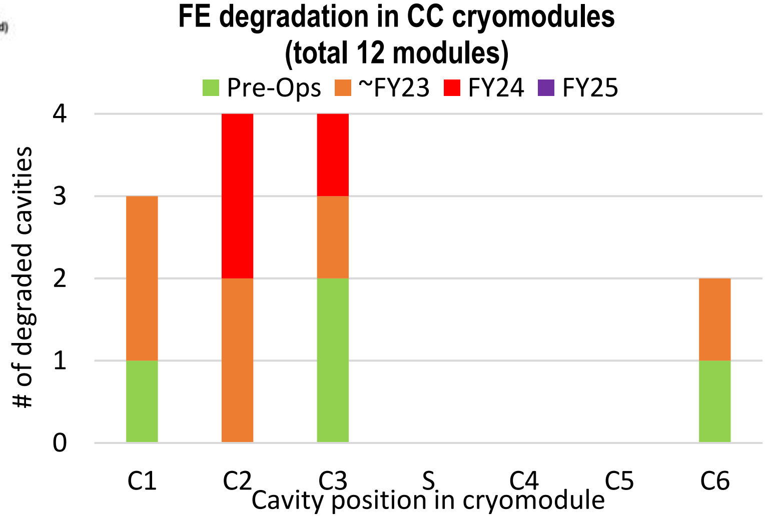


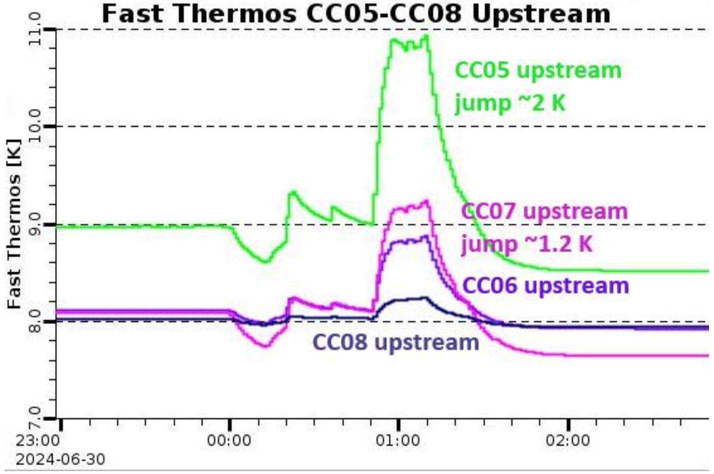




Vacuum chamber is on a stage movable with motors (vertical & horizontal)

Liquid lithium stripper





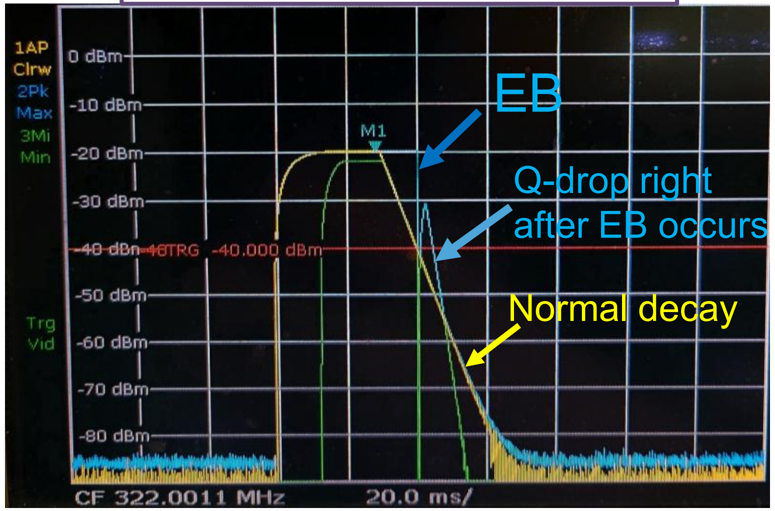
Backup: Breakdown during RF Pulse Conditioning

- In the FRIB case, **RF pulse conditioning** has been a useful technique **to reduce FE X-rays and maintain accelerating gradient in FRIB cryomodules** for beam commissioning and user operations**.**
- Chose ~50 ms pulse length, 1 Hz repetition rate.

During conditioning, we observed two types of rapid drops in the transmitted RF power by using spectrum analyzer.

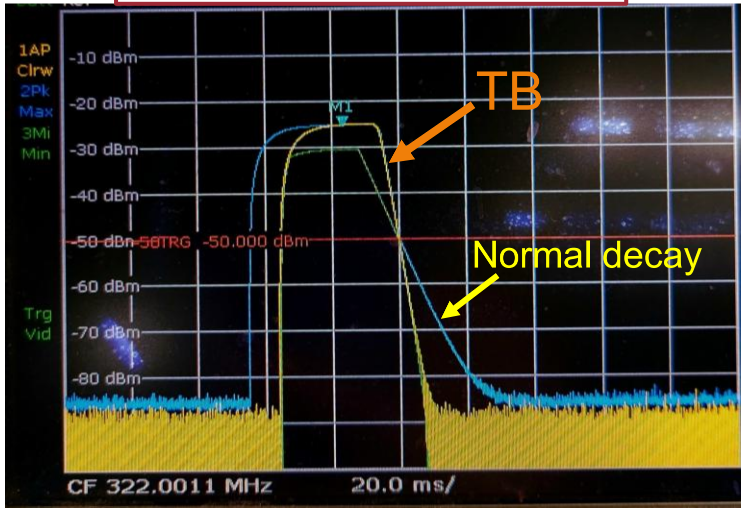
Pt [dBm] ; transmitted power from cavity (Log scale) vs time (20 ms division)

Electrical Breakdown (EB)



Rapid (~µs or faster) collapse of field.

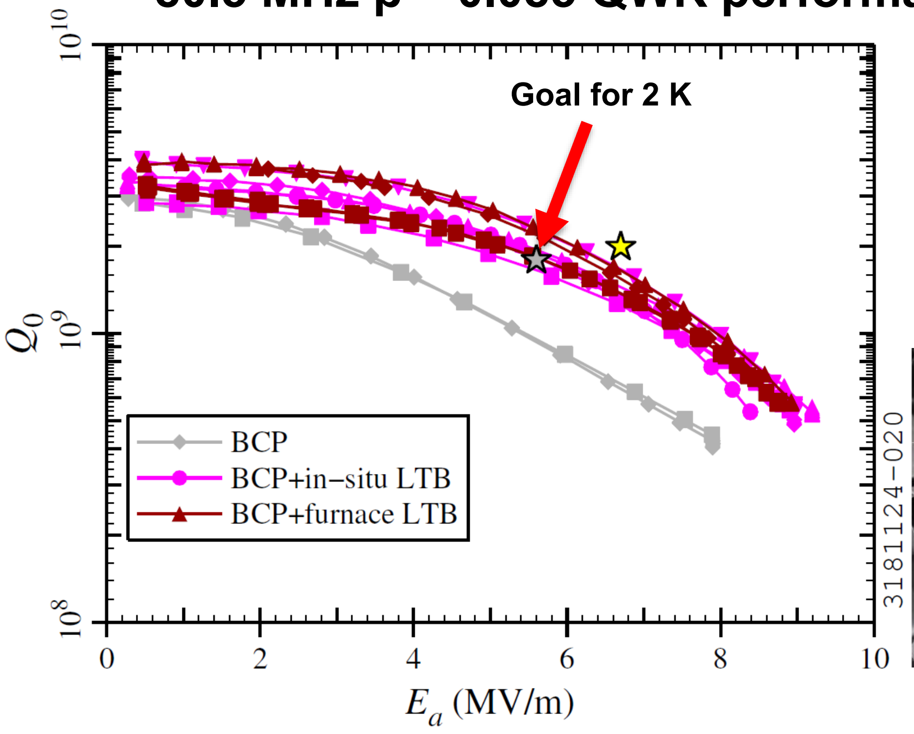
Thermal Breakdown (TB)



Relatively slow (~ms) decay time, still faster than the normal decay set by FPC Q_{ext} (with matched condition from circulator)

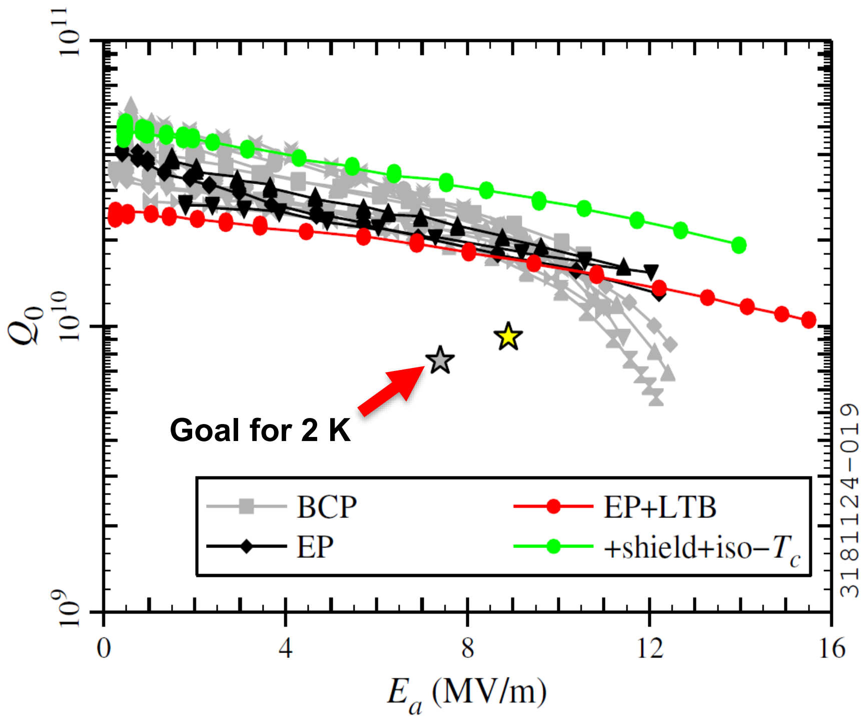
SRF Development for Higher Q_0/Higher Gradient Spare Cryomodules

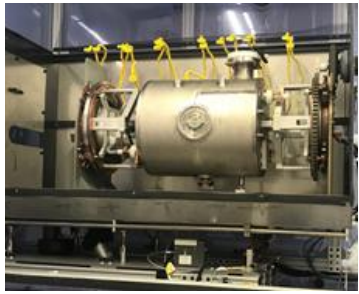
80.5 MHz β = 0.085 QWR performance at 4.3 K



Furnace LTB

322 MHz β=0.53 HWR performance at 2 K





EP

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

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