FRIB Commissioning and First Operation

October 12, 2022

TTC2022 at Aomori, Japan

Sang-hoon Kim on behalf of FRIB

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Upon completion of FRIB construction and commissioning, FRIB begun delivering rare isotope beams to users May 2022

- FRIB news article (https://frib.msu.edu/news/2022/first-experiment.html)

FRIB'S FIRST EXPERIMENT CONCLUDES SUCCESSFULLY

14 June 2022

The first experiment at FRIB—which studied the beta-decay of calcium-48 fragments that are so unstable that they only exist for mere fractions of a second—concluded successfully. The first experiment was led by Heather Crawford of Lawrence Berkeley National Laboratory (LBNL), with participants from Argonne National Laboratory (ANL), Brookhaven National Laboratory, Florida State University, FRIB, LBNL, Lawrence Livermore National Laboratory, Louisiana State University, Los Alamos National Laboratory, Mississippi State University, Oak Ridge National Laboratory (ORNL), and the University of Tennessee Knoxville (UTK). The spokespersons for the first experiment are James "Mitch" Allmond (ORNL), Crawford (LBNL), Ben Crider (Mississippi State University), Robert Grzywacz (UTK), and Vandana Tripathi (FSU).

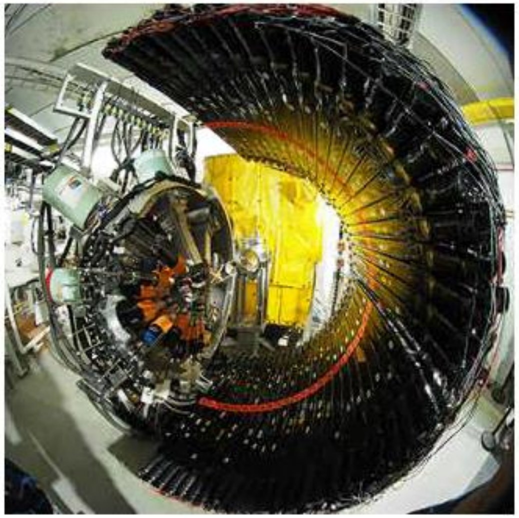
Watching how these exotic nuclei decay away and the products that are produced provides information critical to understand how the atomic nucleus changes from stability to the limits of existence. To perform the study, the rare isotopes were implanted into the center of a very sensitive and granular detector device known as the FRIB Decay Station initiator (FDSi). FDSi is the initial stage of an FRIB Decay Station (FDS), whose science was envisioned in the 2015 Long Range Plan for Nuclear Science.

FDSi integrates the best detectors currently available in the community for FRIB decay studies.

"FDSi is going to be central to the FRIB science program, especially in the first years of operation," said Crawford, staff scientist at LBNL and the contact spokesperson for the first FRIB experiment. "Such a

RELATED INFORMATION

- FRIB Decay Station initiator (FDSi)
- FRIB Decay Station (FDS)
- ORNL, partners launch first experiments using new facility to make cosmic isotopes on Earth
- FRIB announces first PAC-recommended experiments
- ORNL team builds modular, multidetector system



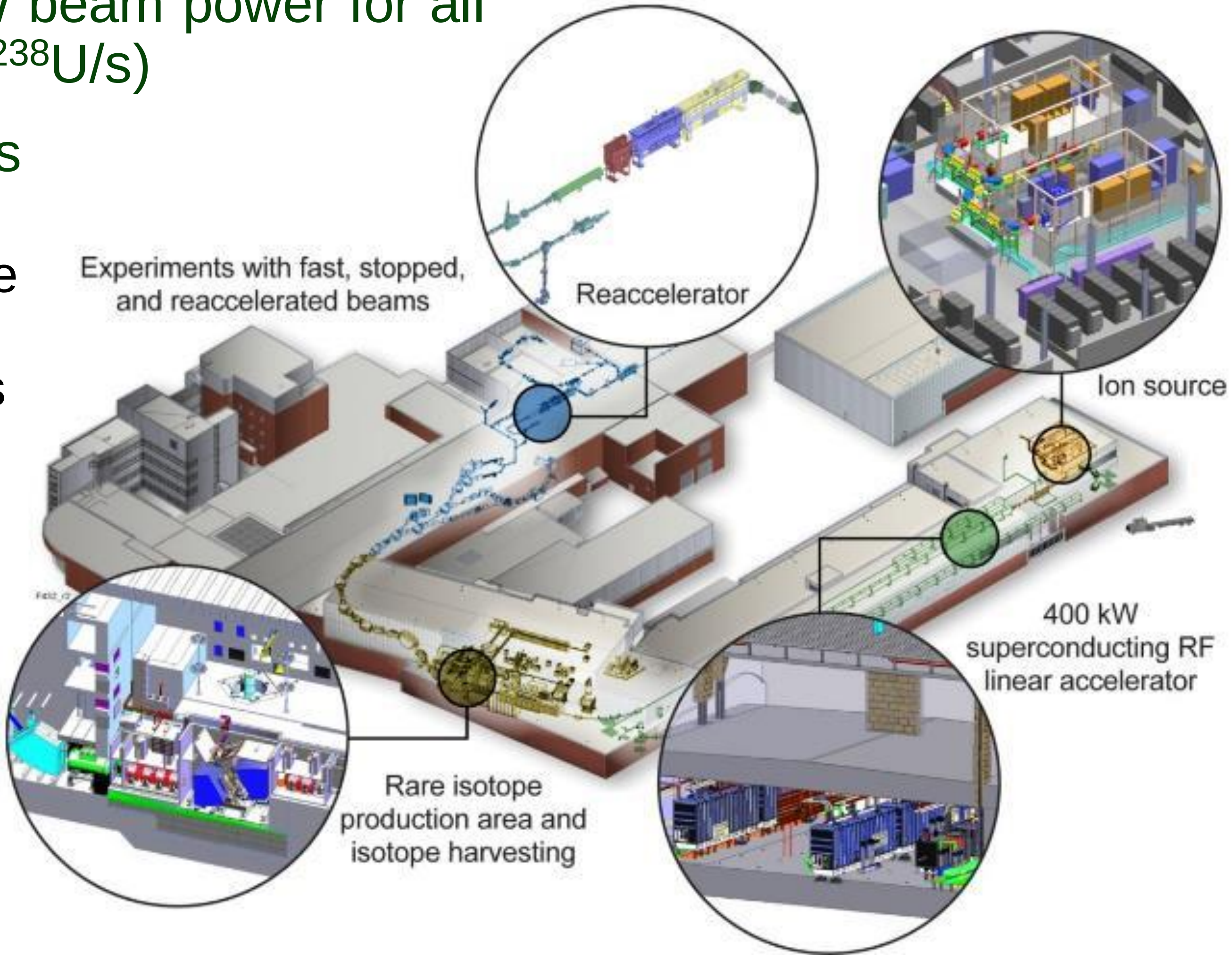
- Publication on the first FRIB experiment was accepted to Phys. Rev. Letter
  - H.L. Crawford et al., "Crossing N=28 toward the neutron drip line: First measurement of half-lives at FRIB"

Outline

- Introduction: FRIB beam commissioning and user operation
- SRF performance and operational experience
- SRF R&D for maintenance, improvement, future Energy Upgrade
- Summary

FRIB for Low-energy Nuclear Physics Experiments with Fast, Stopped and Reaccelerated Rare Isotope Beams Produced from Fragmentation Target

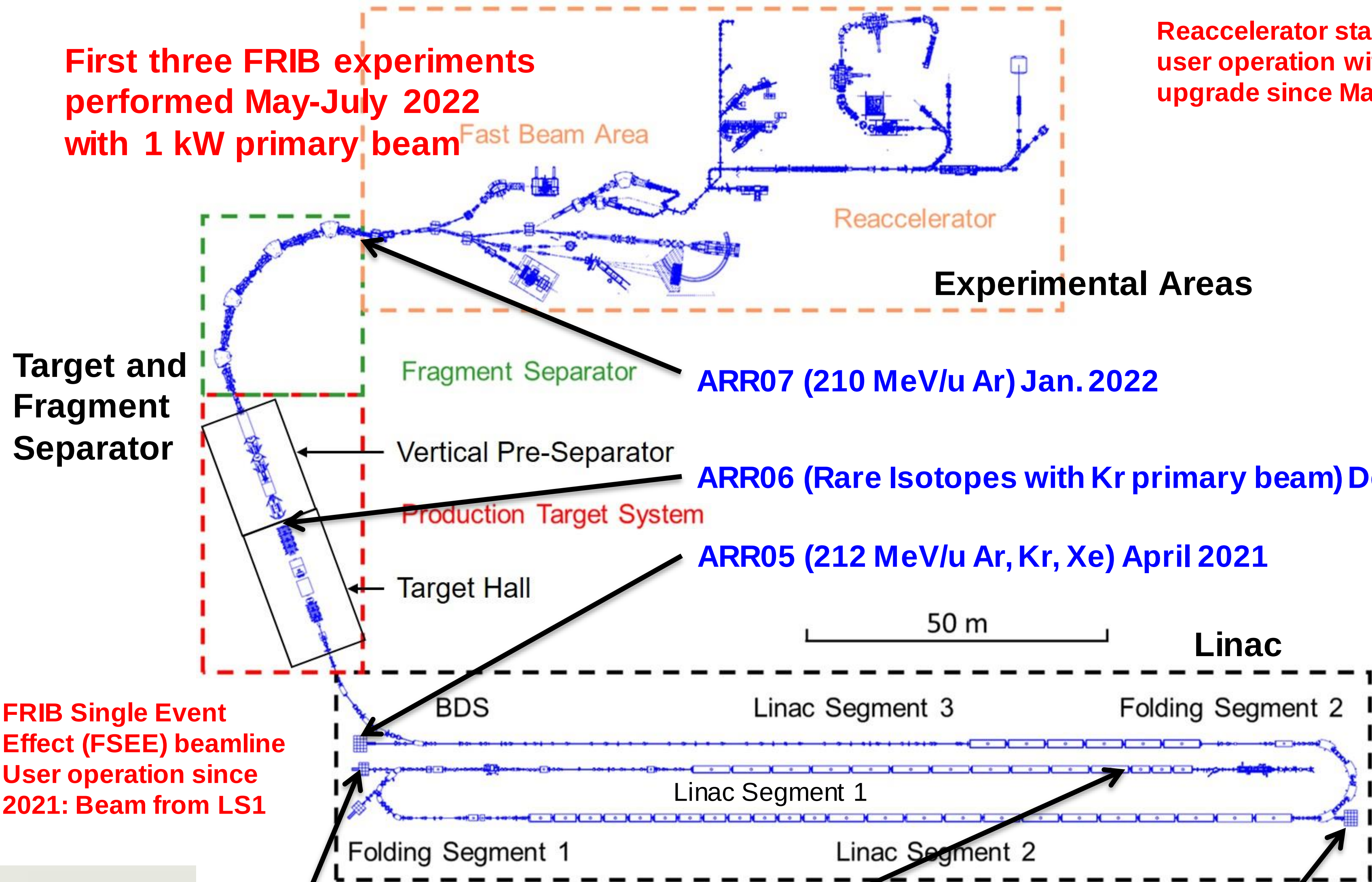
- Key feature is 400 kW beam power for all ions (8pμA or 5×10^{13} ^{238}U/s)
- Separation of isotopes in-flight provides
  - Fast development time for any isotope
  - Beams of all elements and short half-lives
  - Fast, stopped, and reaccelerated beams



Phased Beam Commissioning and User Operation

First three FRIB experiments performed May-July 2022 with 1 kW primary beam

Reaccelerator stand-alone user operation with ReA6 upgrade since May 2021



ARR07 (210 MeV/u Ar) Jan. 2022

ARR06 (Rare Isotopes with Kr primary beam) Dec. 2021

ARR05 (212 MeV/u Ar, Kr, Xe) April 2021

FRIB Single Event Effect (FSEE) beamline User operation since 2021: Beam from LS1

(**Front-end** not shown in this map)

ARR03 (20 MeV/u Ar, Kr) May 2018

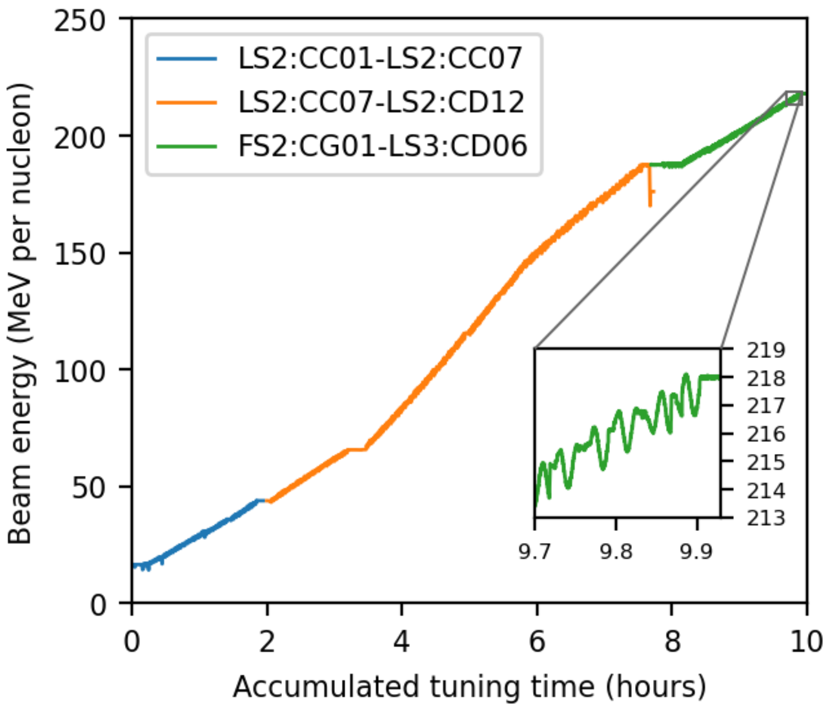
ARR02 (2.2 MeV/u Ar, Kr) July, 2017

ARR04 (204 MeV/u Ar, etc) March 2020

^{36}Ar, ^{86}Kr and ^{129}Xe Accelerated above 200 MeV/u

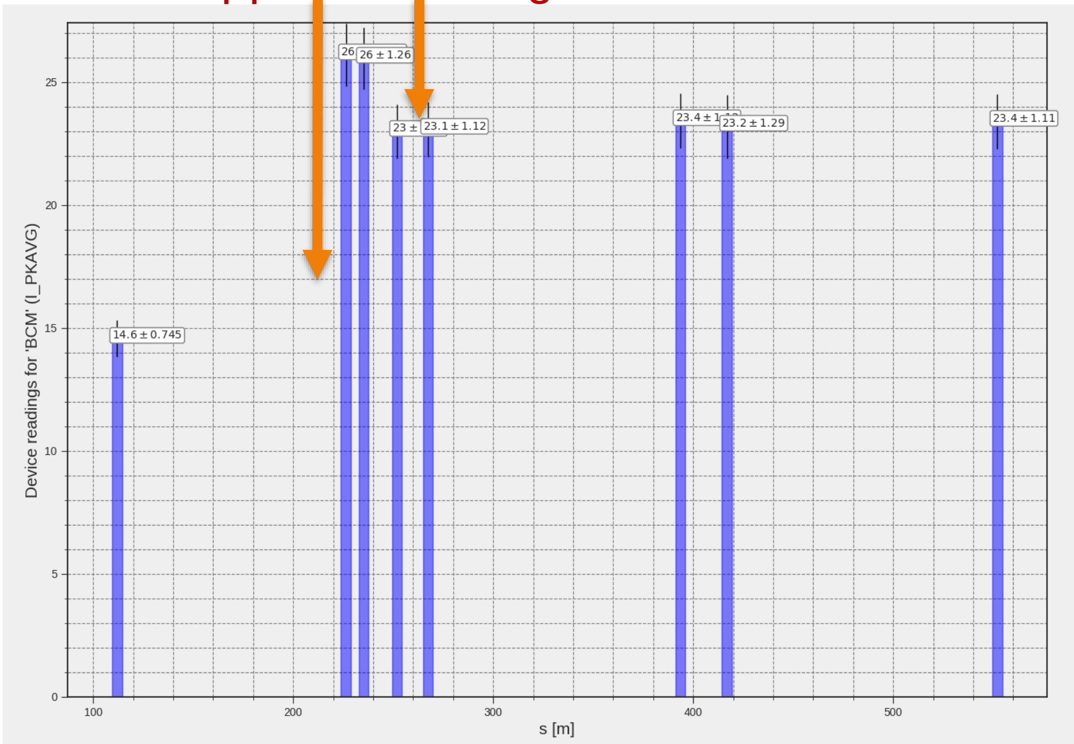
- Three-charge-state $^{124}Xe^{49+,50+,51+}$ and two-charge state $^{86}Kr^{33+,34+}$ were also accelerated and delivered to the beam dump with 100% transmission

Phasing of SC cavities
Beam energy vs time



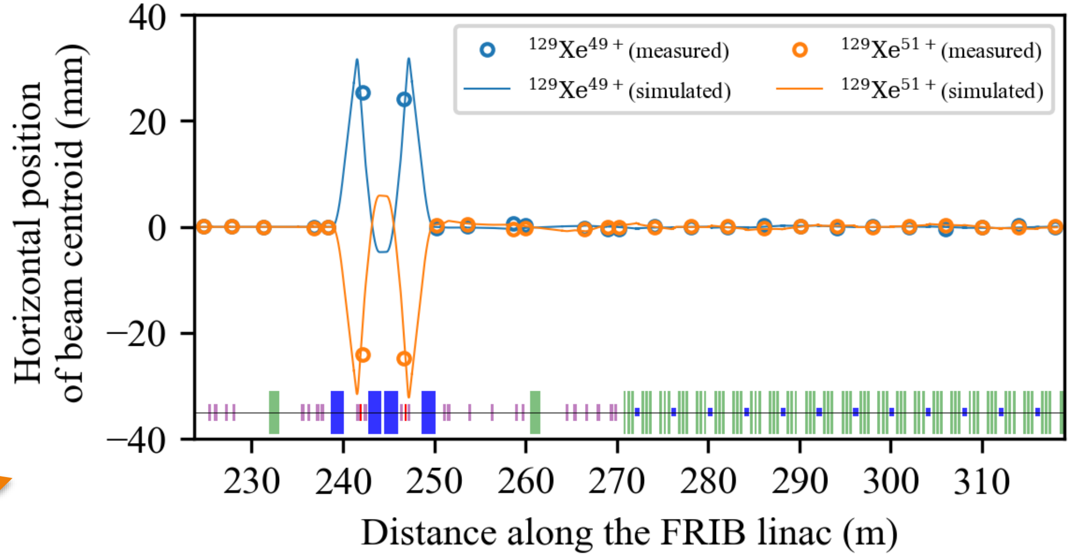
Transmission of ^{36}Ar, beam current in μA

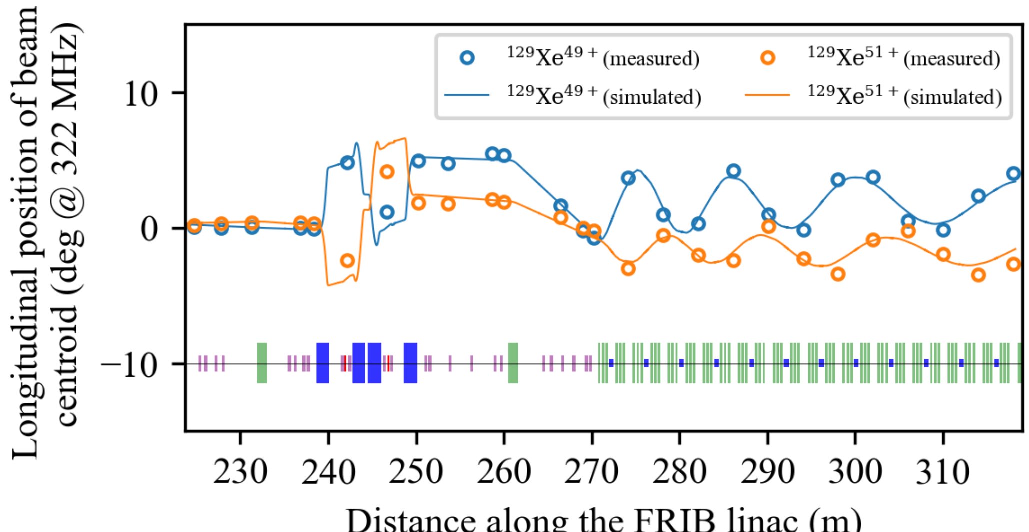
Stripper
Charge Selector



Simultaneous Acceleration of Multiple Charge States Demonstrated

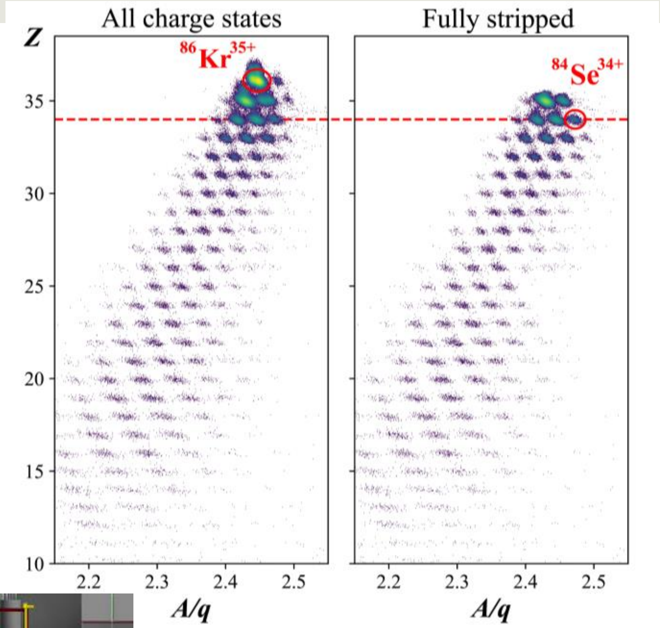
- Three charge states of Xenon beam from stripper to the end of HWR29 cryomodules
- Measured and simulated beam centroids of 51+ and 49+ with respect to 50+
- Transverse
- Longitudinal

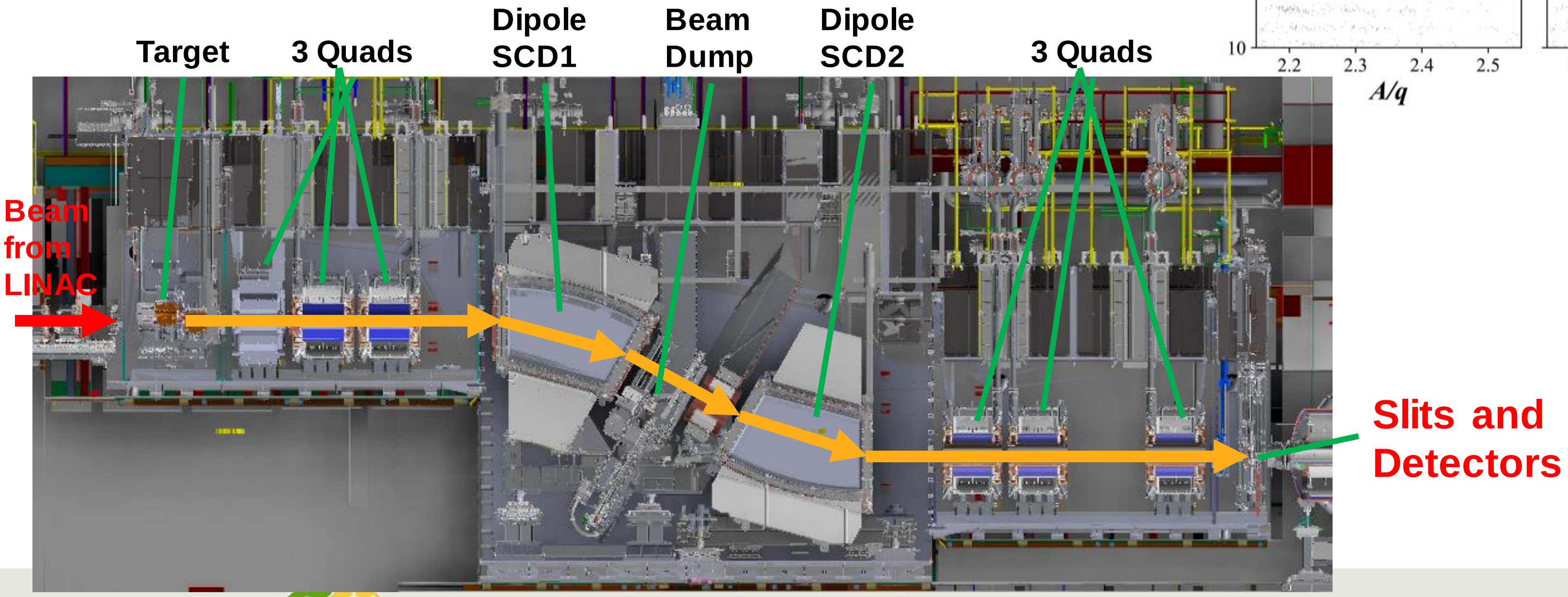




Identified Selenium Isotopes

- Produced isotopes from ^{86}Kr primary beam and detected ^{84}Se: achieved final key performance parameter of the FRIB project





SRF Performance and Operational Experience

FRIB Driver Linac
Segment 1 and 3

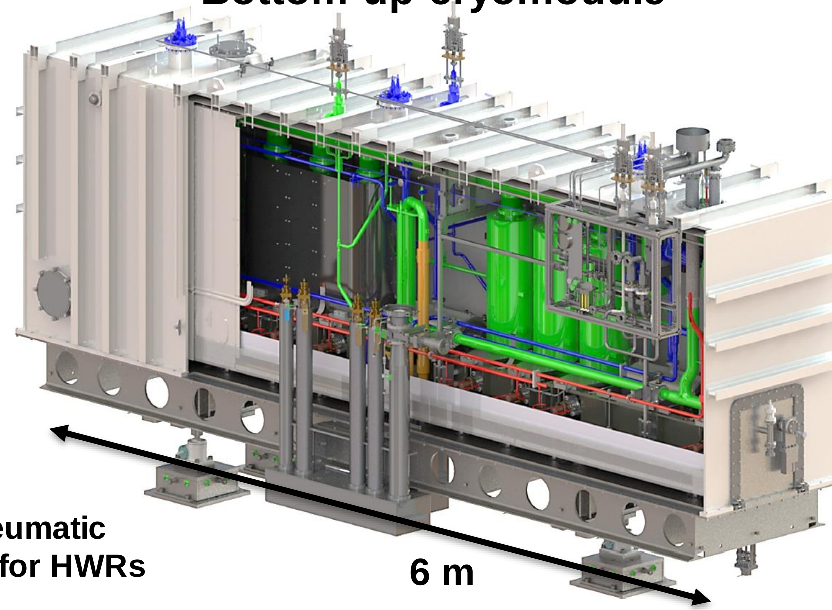
SRF Cavities and Cryomodules

All 104 QWRs and 220 HWRs commissioned with beam

80.5 MHz QWRs

322 MHz HWRs

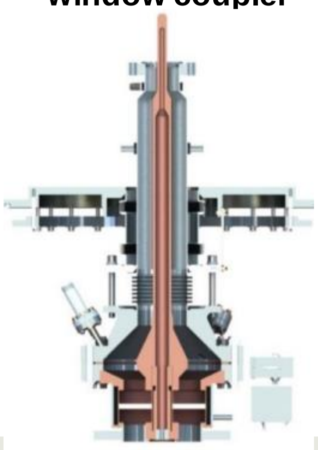
Bottom-up cryomodule



80.5 MHz double window coupler

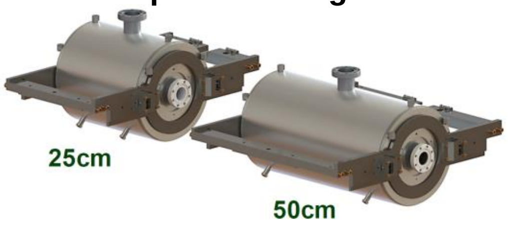
Stepper motor tuner for QWRs

322 MHz single window coupler



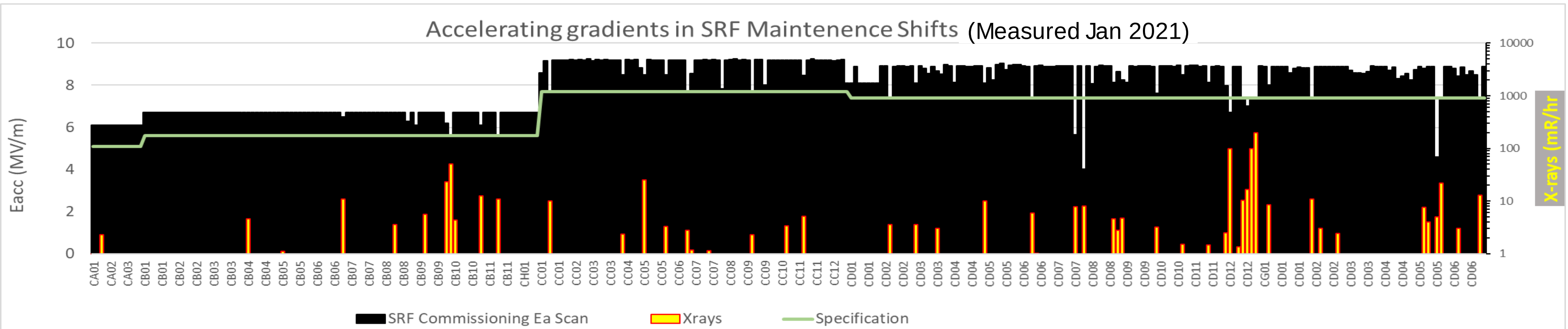
Pneumatic tuner for HWRs

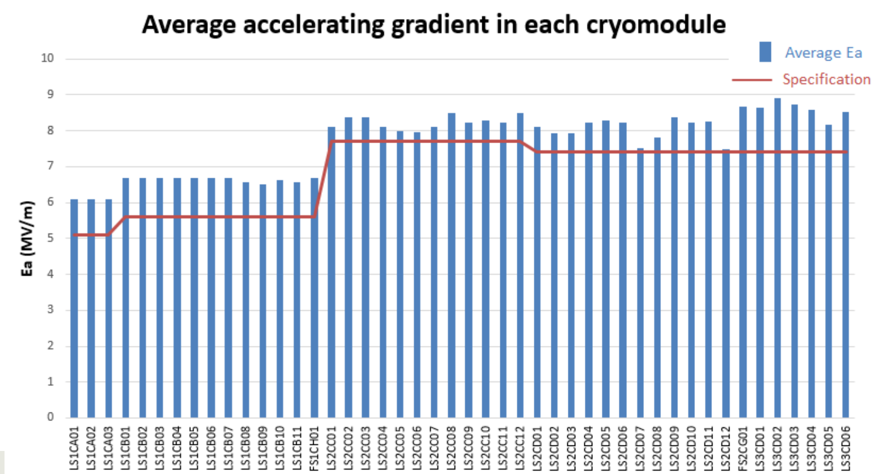
8 T SC solenoid integrated with XY dipole steering coils



Accelerating Gradient in Linac Cryomodules

- Total accelerating voltage exceeds the FRIB specifications, which provides operational margins





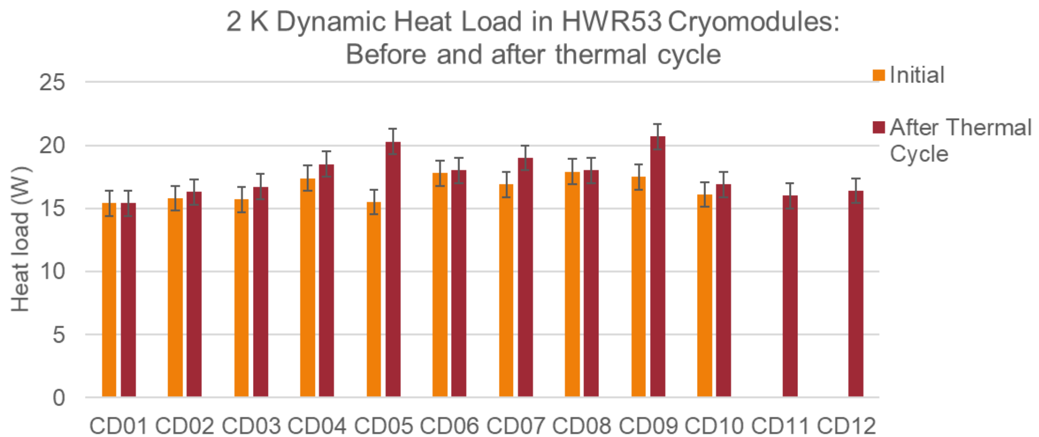
Cavity Q0 in Linac Cryomodules

- Offline cryomodule bunker test results: ample margins in Q0

		4.5 K Static [W]		2K Static [W]		Q_O in CM at 2K		
CM Type	CM Tested	Spec	Measured*	Spec	Measured*	Spec	Measured*	Heat load** [W]
QWR041	4	12.8	14.1	3	4.0	1.2E+09	3.3 E+09	0.5
QWR085	11	20.5	20.0	4	7.3	1.8E+09	3.3 E+09	2.1
HWR29	12	13.1	11.0	5.1	6.4	5.5E+09	1.9 E+10	1.0
HWR53	18	16.1	16.7	6.3	8.5	7.6E+09	2.5 E+10	2.4

* Average of tested cryomodules, ** Dynamic heat load per cavity

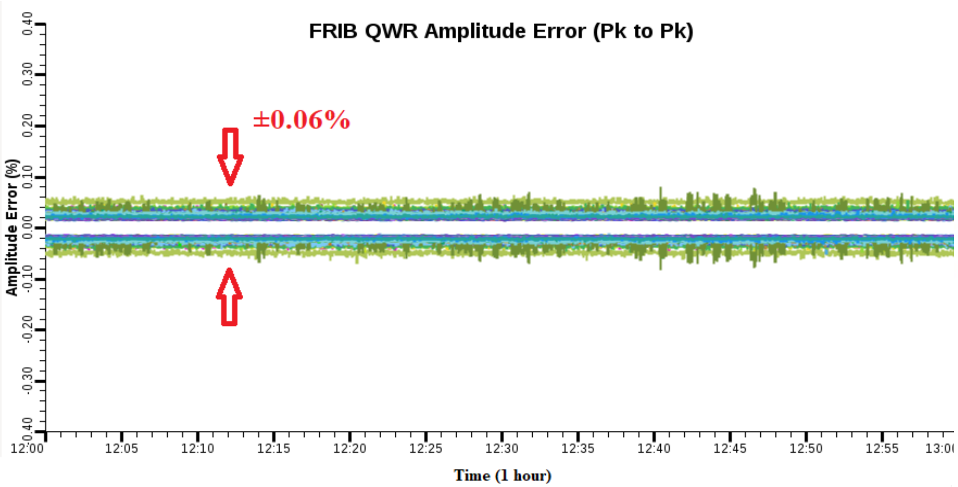
- Performance in Linac: LS2 HWR53 case
  - Equivalent to bunker test results
  - In addition, no degradation after thermal cycle (partial warm up to ~170 K and stay in 50-to-170 K zone for 21 days). Cavities were hydrogen-degassed at 600ºC.

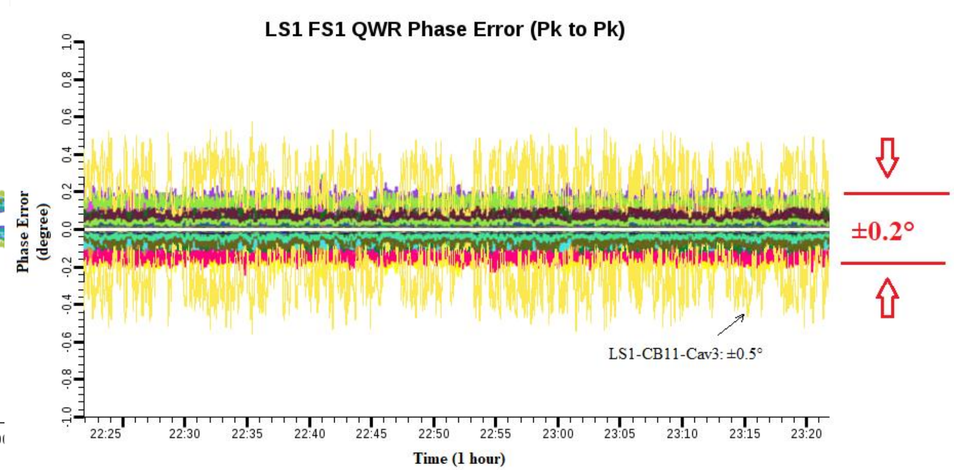


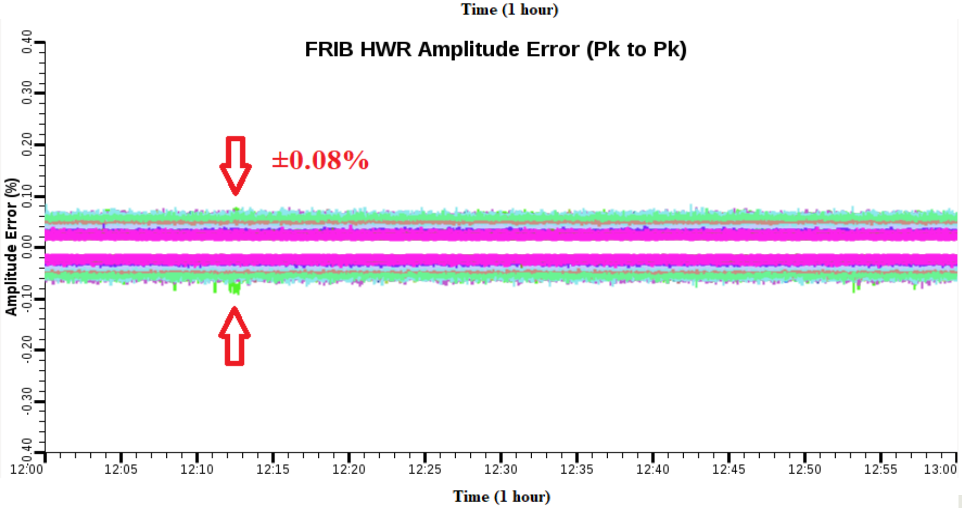
E_{acc} (MV/m)	CD01	CD02	CD03	CD04	CD05	CD06	CD07	CD08	CD09	CD10	CD11	CD12
Initial	7.4	7.4	7.4	7.4	7.4	7.4	6.8	7.4	7.4	7.4	n/a	n/a
After T-cycle	7.6	7.5	7.5	7.7	8.0	7.9	7.4	7.7	8.0	7.9	8.0	7.0

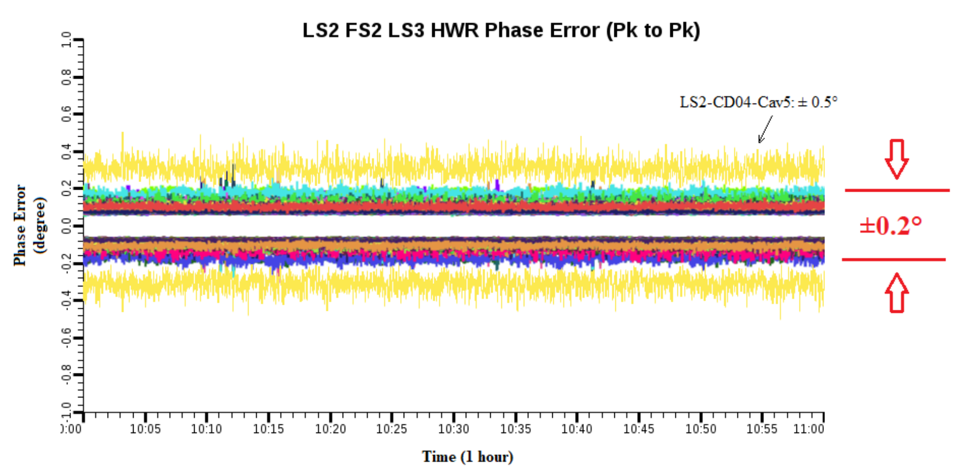
Amplitude and Phase Stabilities

- Amplitude and Phase Stabilities Meet the FRIB Specifications, ±1% pk-to-pk and ±1º pk-to-pk, with Ample Margins









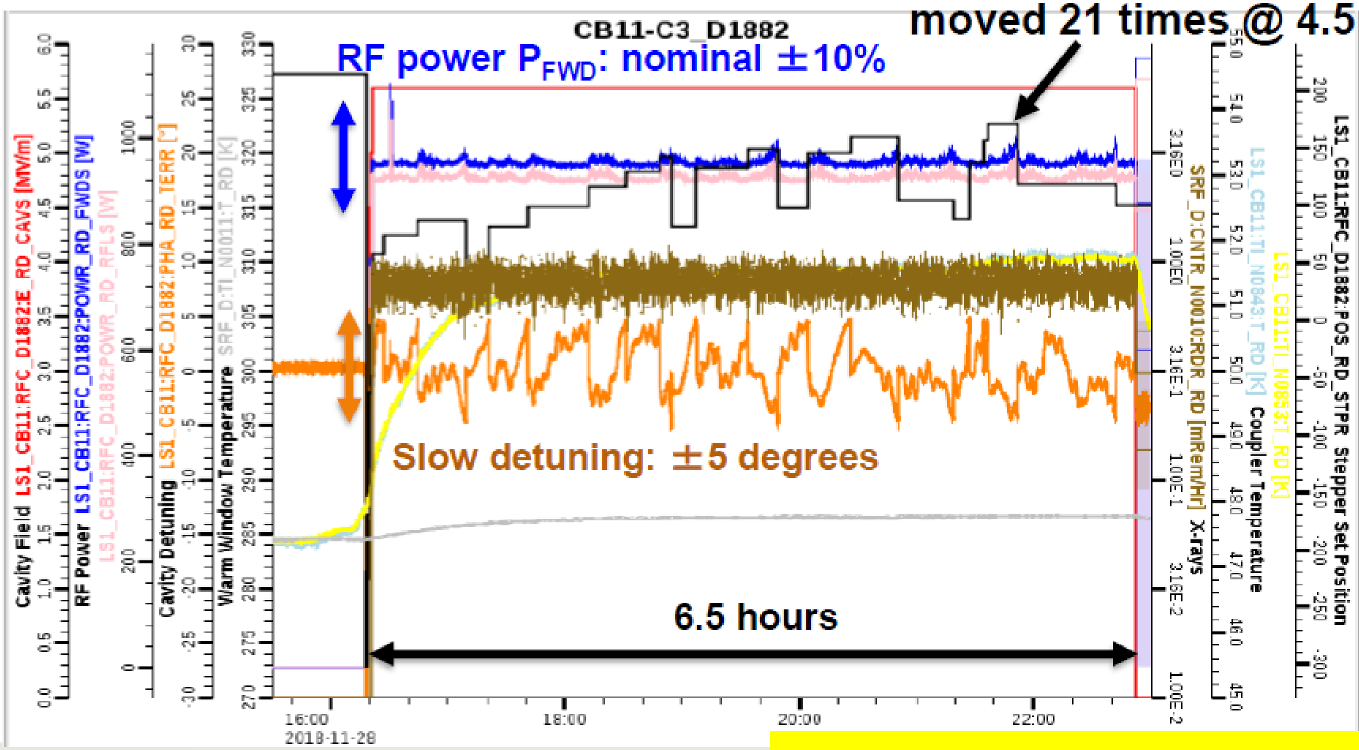
Resonance Control Performance at 4.5 K

80.5 MHz QWRs were stable at 4.5 K

- Pool boiling effect is negligible: with -2 to -5 Hz/Torr df/dp, <8 W wall dissipation power, 40 Hz bandwidth in QWR085
- Microphonics resonant with the cavity mechanical mode: managed not to be excited
- Stepper motor frequency tuner: moves a few times per hour with on-off control with the hysteresis band

CB11-C3 @ 5.6 MV/m, 4.5 K

Tuner stepper set point: moved 21 times @ 4.5 K



WG2, Chang/Kim, "Experience with resonance control with slow tuners in low-beta CW linac

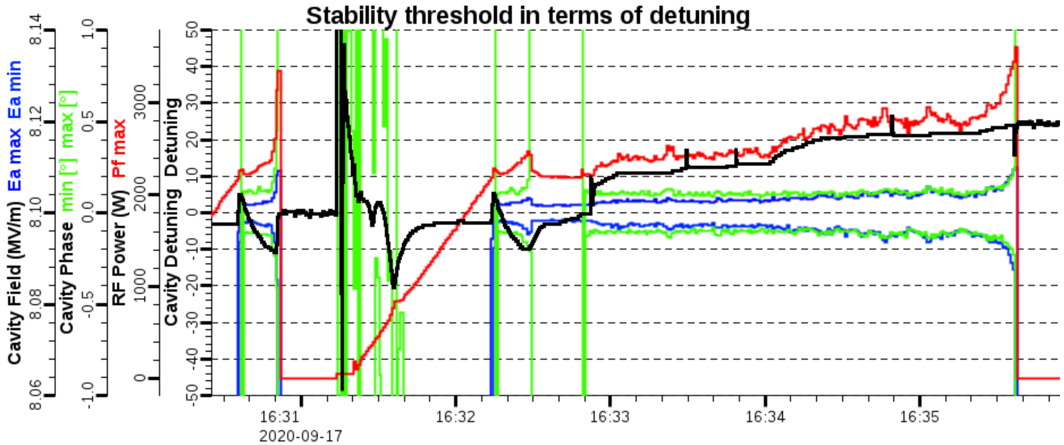
Suppression of Ponderomotive Instability

- Pondermotive-instability, not microphonics, could be suppressed with high-amplitude-loop-gain control

A β=0.53 HWR @ 8.1 MV/m (+10% higher than the design gradient)

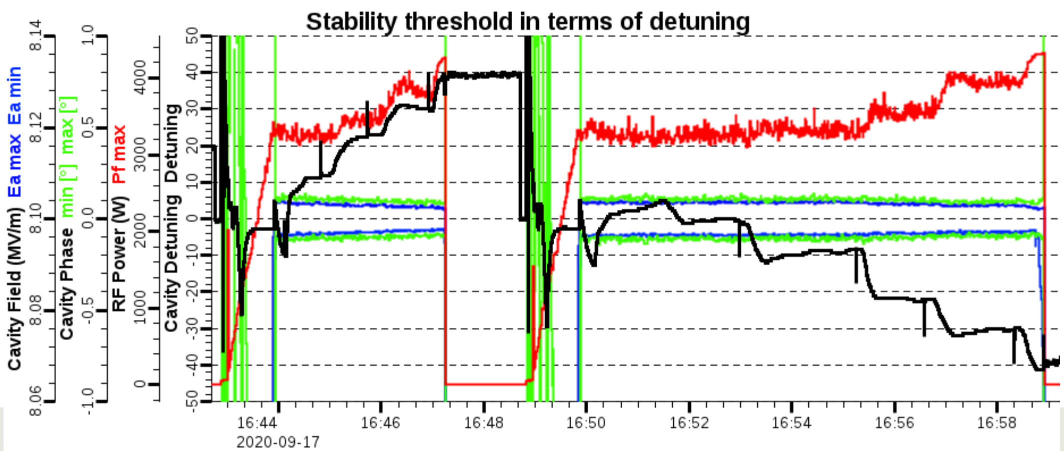
Original control

Controller BW (BWc) = 96 Hz
(cavity bandwidth = 34 Hz)
Stability window: -10º < ψ < +22º,
ψ: detuning angle



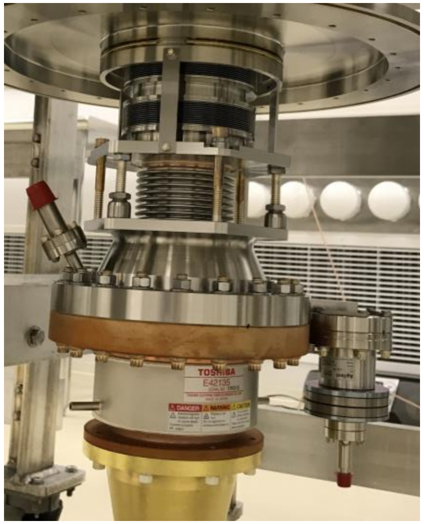
Improved control

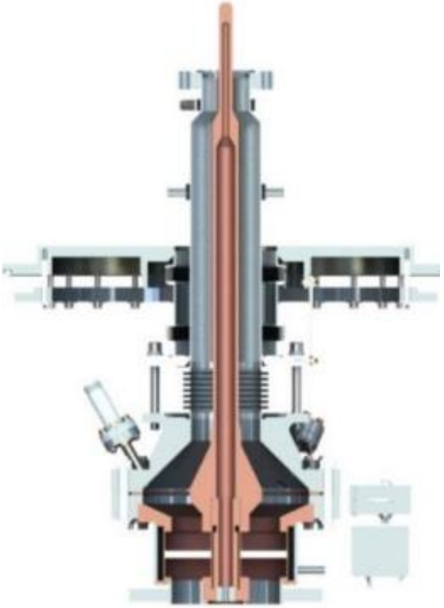
Amplitude-loop BWc = 760 Hz
Phase-loop BWc = 96 Hz
No instability within ~±45º detuning,
i.e. the cavity bandwidth



Availability of Cavities and Cryomodules in Commissioning and Operation

- All 324 cavities were available in the ARR05, 06, 07 beam commissioning
  - ARR05: beam to the linac end (212 MeV/u Ar, Kr, Xe), April 2021
  - ARR06: production of rare isotopes with Kr primary beam, Dec. 2021
  - ARR07: beam to the fragment separator end (210 MeV/u Ar), Jan. 2022
- In user operation May – July 2022, one HWR53 cavity was no use due to FPC cold cathode gauge issue
  - Bad reading instead of real vacuum leaks
  - Plan to replace at the next maintenance opportunity: in-situ replacement after cryomodule warm-up
  - Considering to add a redundant CCG as it is a single point failure on a critical RF interlock

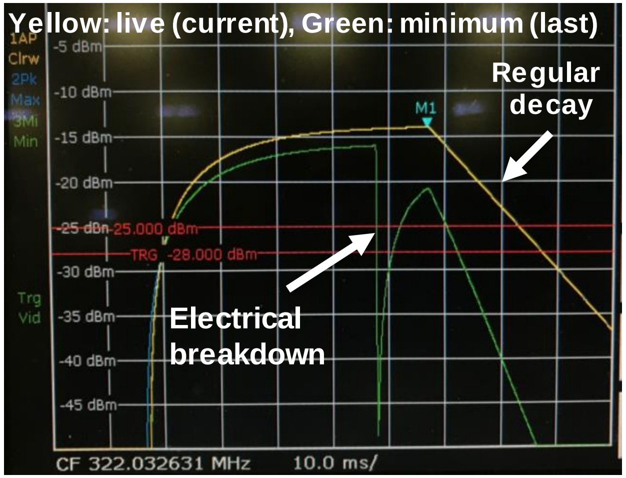


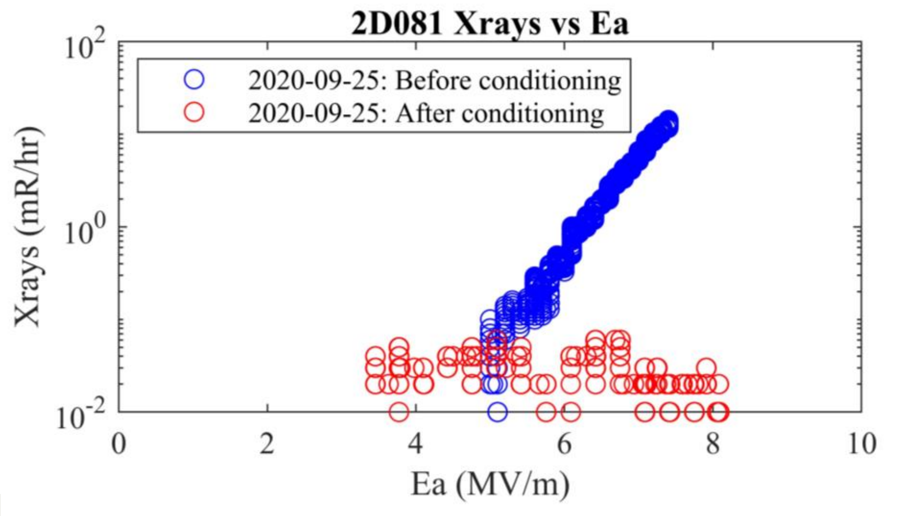


Impacts of Field Emission on Operation

- Issue with field emission
  - Observed conditioning effects such as fast breakdown in a few cavities with relatively high field-emission (FE) X-rays
- Pulsed RF conditioning recovered FE performance in some cavities, particularly if fast (electrical) breakdown happened
  - However, in the other cavities, this technique did not work due to thermal breakdown
- Started plasma processing development as a long-term solution

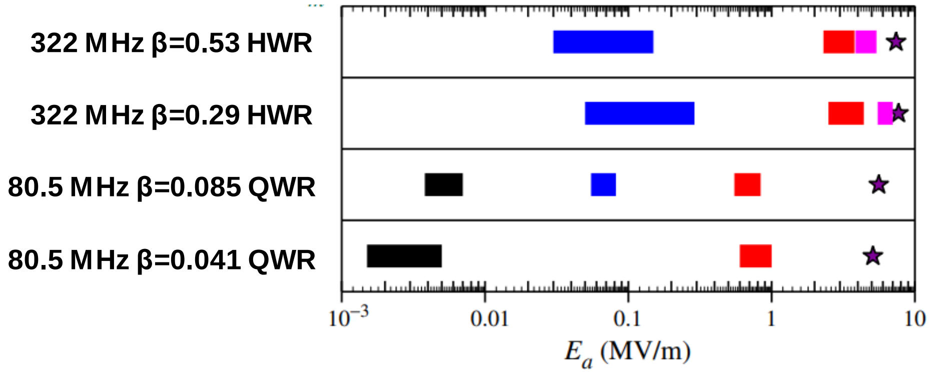
Pt signal





Impacts of Multipacting on Operation

- Multipacting bands in FRIB cavities
  - Low-field MPs in 80.5 MHz QWRs: fast ramp-up passing through the MP bands
  - The other MPs: fully conditioned in the CW mode



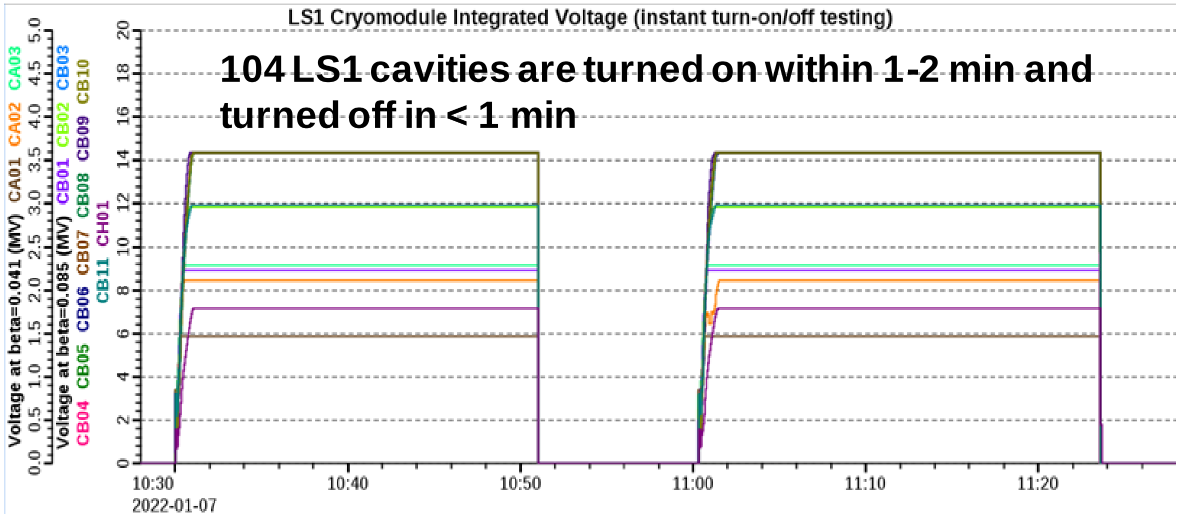
Red: ECR-like MP
Blue, Black: Coaxial MP

- MP performance during operation "so far"
  - Low-field MPs
    - » One case that one cavity was stuck in the MP barrier this year
    - » Developing MP conditioning methods to maximize availability
  - Already conditioned MPs
    - » Not shown up again unless otherwise vacuum events happened

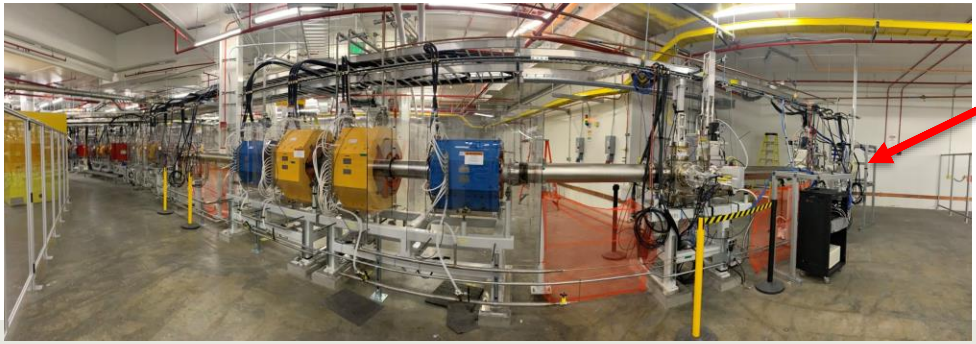
WG2, Kim, "Low-field MP in FRIB QWRs and it mitigation"

Cavity Dynamic Load Compensation by Cryomodule Internal Heaters

- Dynamic load compensation allows fast turn on/off of 104 QWRs in Linac Segment 1 (LS1). This supports efficient user operation particularly for FRIB Single Event Effect (FSEE) experiments



FSEE beamline and user station extended from LS1



user station

Plan for Beam Power Ramp-Up

- Plan to ramp up the beam power to 400 kW for the next 6 years

FRIB power ramp-up plan

Year	FY23	FY24	FY25	FY26	FY27	FY28
Beam list addition	^{48}Ca, ^{82}Se, ^{36}Ar, ^{86}Kr, ^{124}Xe, ^{58}Ni	^{208}Pb, ^{92}Mo, ^{238}U, ^{64}Ni	^{96}Zr, ^{106}Cd, ^{144}Sm, ^{156}Dy, ^{16,18}O	^{162}Er, ^{176}Yb, ^{196}Hg, ^{204}Hg		
Beam power [kW]	10	20	50	100	200	400

- Maintaining cryomodule performance would be a key to success of power ramp up
  - Already capable of refurbishing cryomodule in house
  - Conducting preventive/proactive maintenance: e.g. stepper motor replacement

WG2, Chang/Kim, "Experience with resonance control with slow tuners in low-beta CW linac

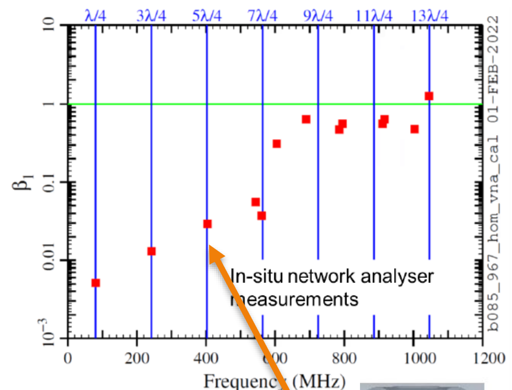
  - Pursuing SRF development for cryomodule maintenance and performance improvement

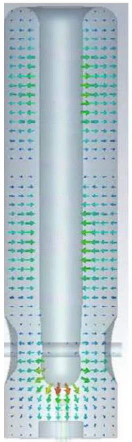
SRF R&D for Maintenance, Improvement, Future Energy Upgrade

New EP Facility at FRIB

Plasma Processing Development

- Plasma processing for low-β coaxial cavities in CW linacs
  - Challenges: high coupler field at room temperature due to high Q_{ext}, no HOM couplers
  - HOMs are still effective in reducing coupler field while driving plasma via FPC
- Progress in development of plasma processing at FRIB
  - Developed the processing setup, performed processing in β = 0.085 QWRs equipped with FPCs
  - Use 5λ/4-TEM mode, neon plasma with a few % of oxygen, pressure at 100 mtorr
  - Promising results so far: FE improved in 2 out of 3 cases

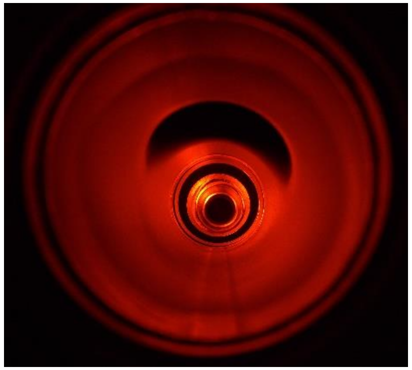


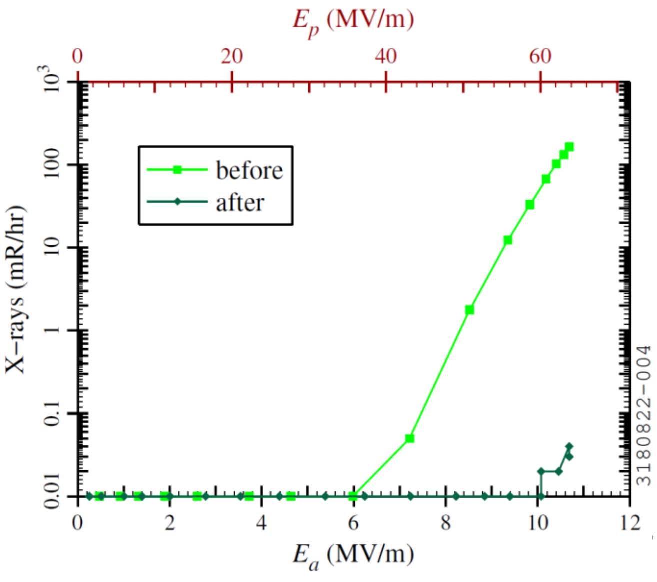


5λ/4 mode E-field

Plasma processing setup: β = 0.085 QWR with FPC

Plasma generated in the cavity

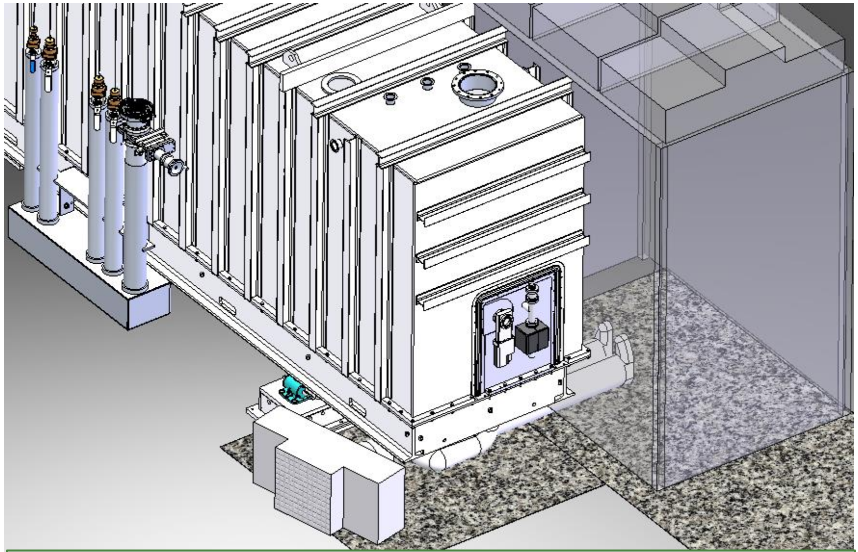




FE X-rays before and after plasma processing

Fundamental Power Coupler (FPC): Developing In-situ Replacement

- FPC windows may need to be replaced due to vacuum leaks or other failures according to SNS experience [M. Howell et al., Linac 2014]
- Developing in-situ replacement of the 322 MHz FPC window
- First practice trial was done under conditions simulating a real cryomodule
  - FPC assembled to the cavity with spacer for nearly critical coupling in vertical test
  - Temporary clean room setup equivalent to a real cryomodule: cavity height, clean room space
  - Achieved a promising preliminary result: no FE changes up to E_{acc} ~10 MV/m (E_{peak} ~35 MV/m)



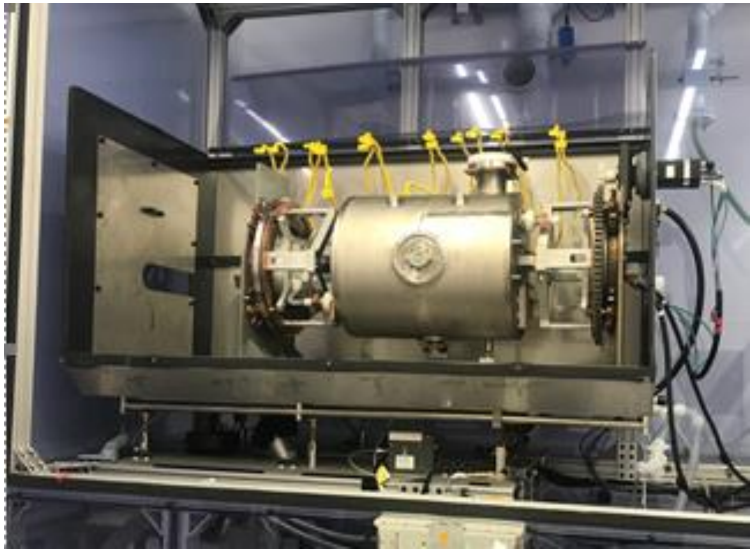
Model of set-up for in-situ FPC swap

Practice FPC swap with temporary clean room

High Q/G β=0.53 HWR Cavity R&D Program

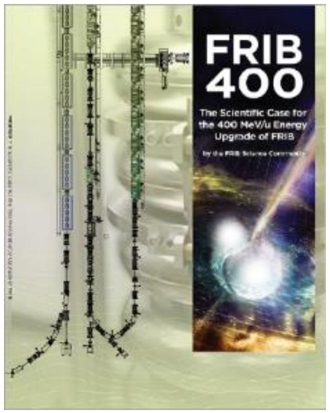
- Develop transformative processing technology for High Q/G performance, for a FRIB β=0.53 HWR spare cryomodule
- EP or EP+LTB will applied to realize the high Q/G performance
- Local magnetic shield will be added around cavity jacket to reduce remnant magnetic field in VT Dewar
- Two challenging R&D on cavity surface processing:
  - Development of HFQS-free BCP
  - New doping method without high temperature annealing.

Performing EP of β=0.53 322 MHz HWR at FRIB EP facility



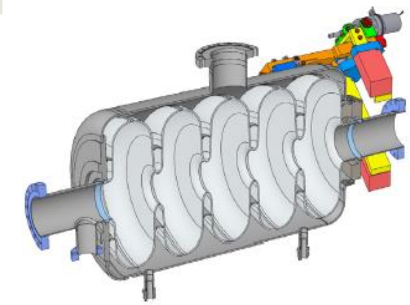
WG1, Saito, "High Q/G beta 0.53 HWR Cavity R&D program for high gradient cryomodule to enhance the operational gradient"

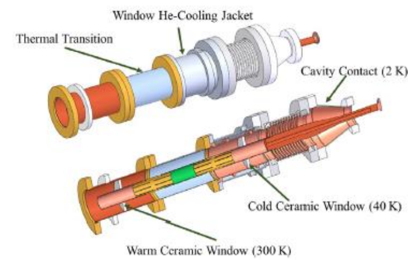
FRIB400: Linac Energy Upgrade to 400 MeV/u

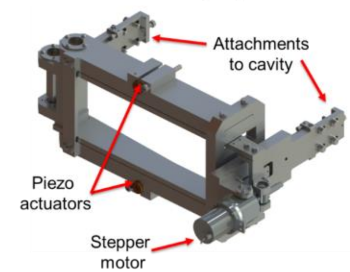


FRIB400 White Paper (2018)

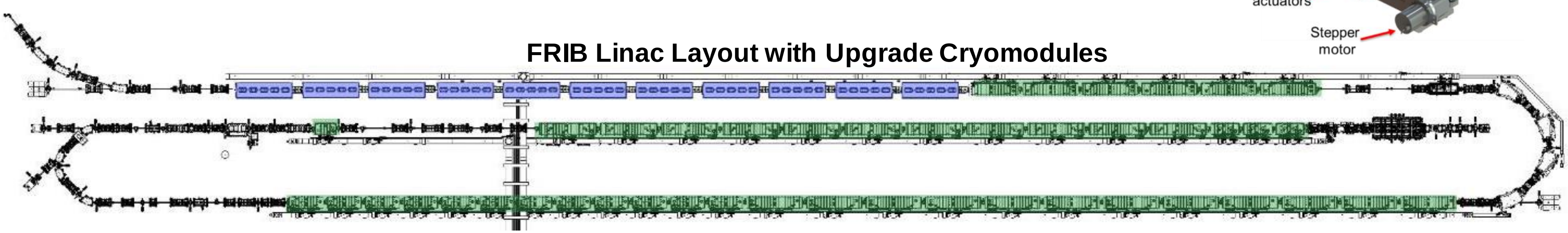
- Low-energy nuclear physics community made science cases
  - Luminosity gain over 50 for rarest isotopes
  - Energy well-matched to exploring physics of neutron-star merger
- Technical approaches
  - Add 11 cryomodules to the space reserved for energy upgrade
  - β=0.65 644 MHz elliptical cavity, design goal: Q0 = 2e10 @ Eacc of 17.5 MV/m
  - Lever frequency tuner combined with stepper motor and piezos
  - Double window FPC





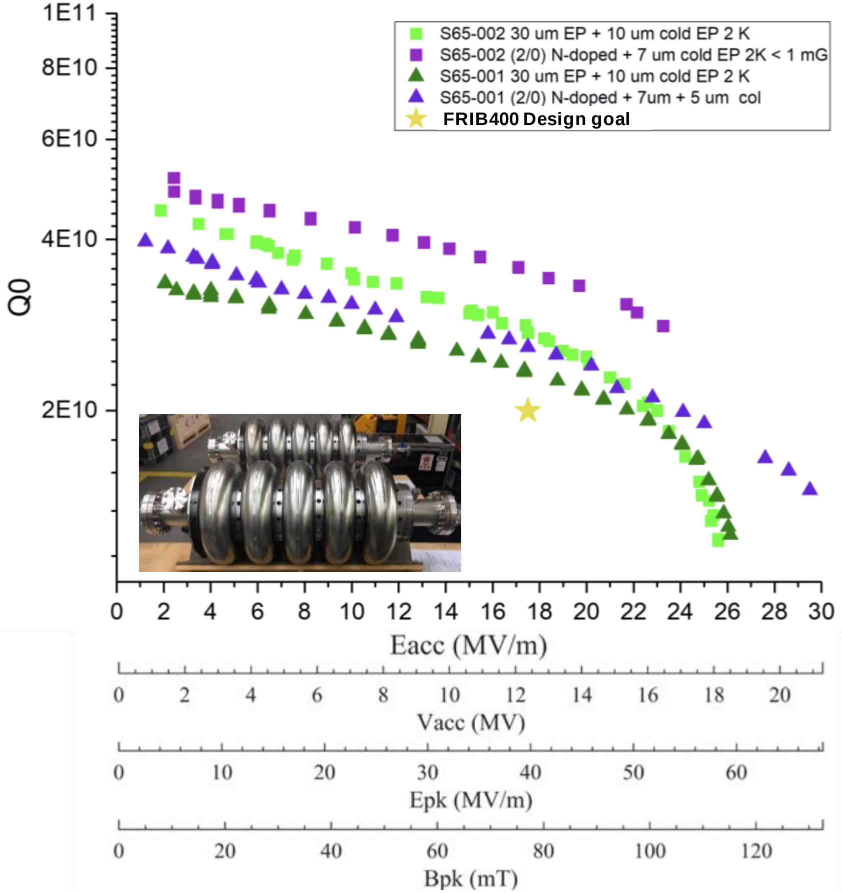


FRIB Linac Layout with Upgrade Cryomodules



FRIB400 SRF R&D Achievements and Plan

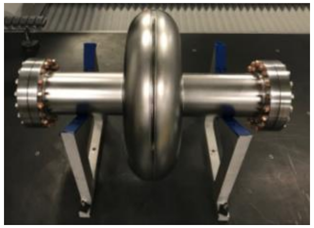
FRIB400 SRF Cavity R&D Progress



Argonne NATIONAL LABORATORY

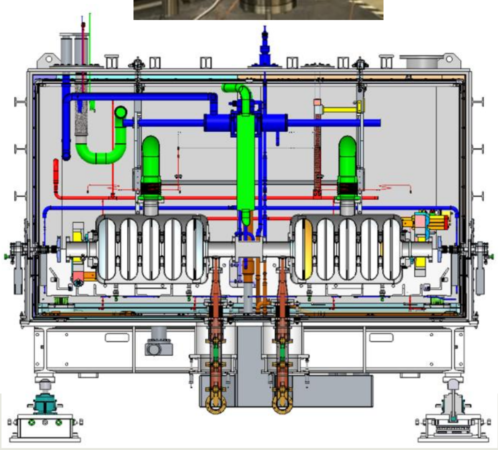
Fermilab

High Q R&D with 1-cell cavity



Development of Jacketed cavity, tuner, FPC

High-β spare buncher with upgrade cavities



Summary

- FRIB begun user operation starting with 1 kW primary beam. Plan to ramp up to 400 kW in the next 6 years
- SRF cryomodules as operated in the linac met the specifications of the FRIB project
- Maintaining cryomodule performance would be a key to success of user operation and power ramp-up. We are performing SRF development for cryomodule maintenance and improvements as well as routine hardware maintenance
- We also pursue SRF R&D for FRIB Energy Upgrade, FRIB400

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  Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA
  [1]also at INFN - Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy
  [2]also at TRIUMF, Vancouver, British Columbia, Canada
  [3]also at Argonne National Laboratory, Argonne, Illinois, USA
  M. Wiseman, Thomas Jefferson National Laboratory, Newport News, Virginia, USA
  M. Kelly, Argonne National Laboratory, Argonne, Illinois, USA
  K. Hosoyama, KEK, Tsukuba, Japan
  S. Prestemon, Lawrence Berkeley National Laboratory, Berkeley, California, USA

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