SRF R&D for FRIB Energy Upgrade with Medium-beta Elliptical Cavity CW Cryomodules

June 30, 2023

SRF 2023

Sang-hoon Kim on behalf of FRIB Energy Upgrade SRF R&D and collaboration team

MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

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Acknowledgement

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  - **ANL**: B.M. Guilfoyle, M.P. Kelly, T.C. Reid

- Also appreciate useful discussion on EP with G. Wu and V. Chouhan at FNAL

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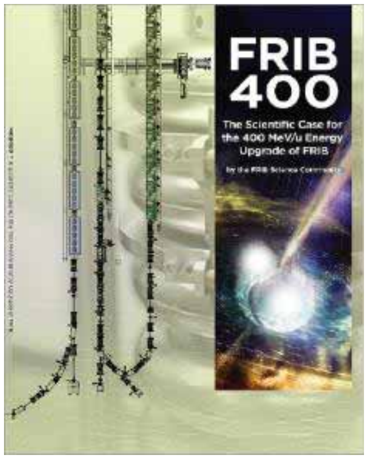
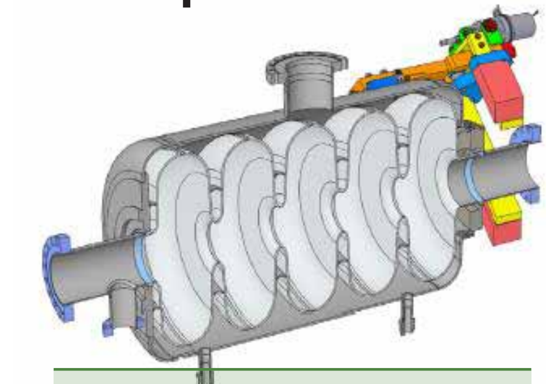
FRIB400: FRIB Energy Upgrade

Doubling the beam energy, accelerate uranium beam up to 400 MeV/u



FRIB400 White Paper (2018)

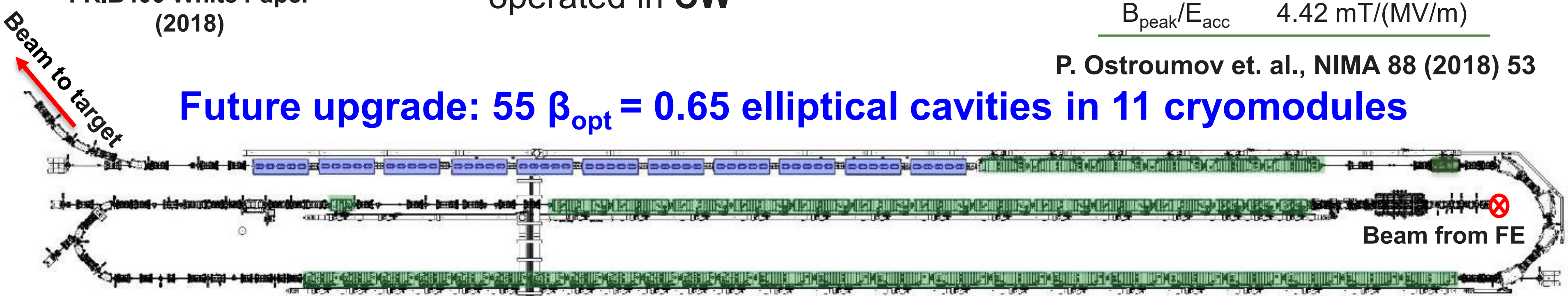
- Demand for scientific cases
  - **Luminosity gain over 50** for rarest isotopes
  - Energy well-matched to exploring **physics of neutron-star merger**
- Cavity and design goal
  - **644 MHz β_{opt} = 0.65 5-cell elliptical cavity** running at **17.5 MV/m** with **Q0 > 2e10,** operated in **CW**



R/Q	368 Ohm
$G=Q*R_s$	188 Ohm
E_{peak}/E_{acc}	2.28
B_{peak}/E_{acc}	4.42 mT/(MV/m)

P. Ostroumov et. al., NIMA 88 (2018) 53

Future upgrade: 55 β_{opt} = 0.65 elliptical cavities in 11 cryomodules

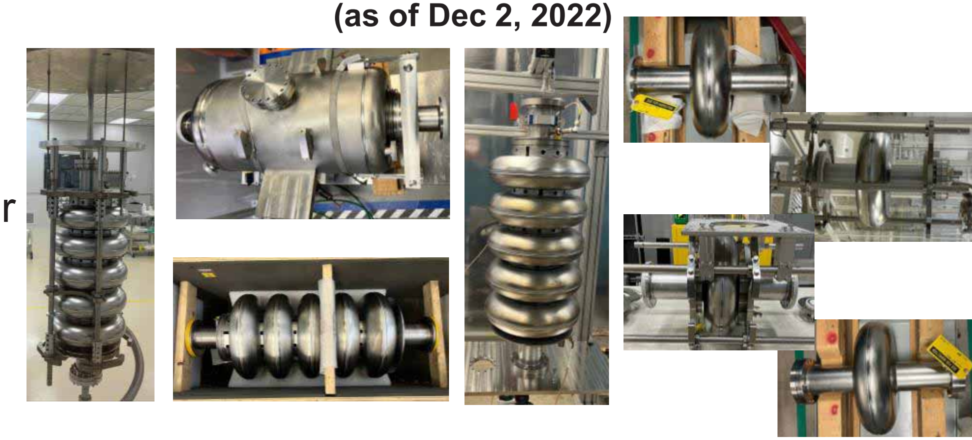


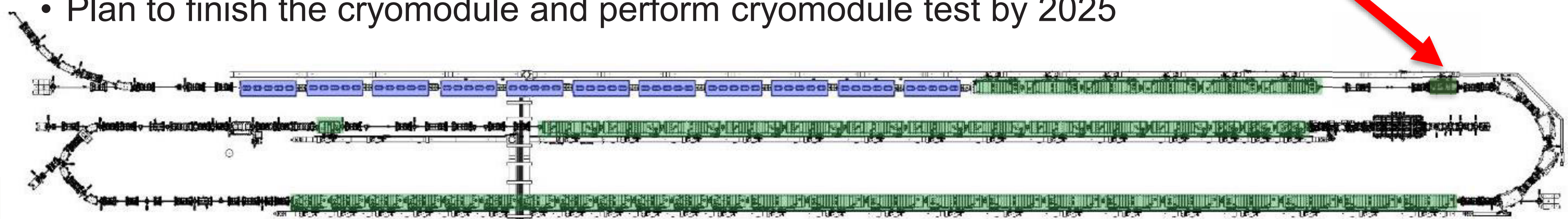
Current: 324 QWRs and HWRs (β: 0.041 – 0.53) in 46 cryomodules

SRF R&D for FRIB Energy Upgrade

- R&D supported by MSU and partially by US-DOE
- Cavity R&D
  - Started with 2x 5-cell cavities
  - Now 4x 5-cell + 5x 1-cell cavities
- Subsystem design and development
  - Frequency tuner, fundamental power coupler
  - Cryomodule
  - LLRF controller
- Facility upgrade
  - EP facility
  - N-doping capability
  - Rotational HPR
- Building a 2-cavity cryomodule in the scope of FRIB Operations: funded
  - As a spare high-β bunching cryomodule, currently used by a 4-HWR (β=0.53) cryomodule
  - Plan to finish the cryomodule and perform cryomodule test by 2025

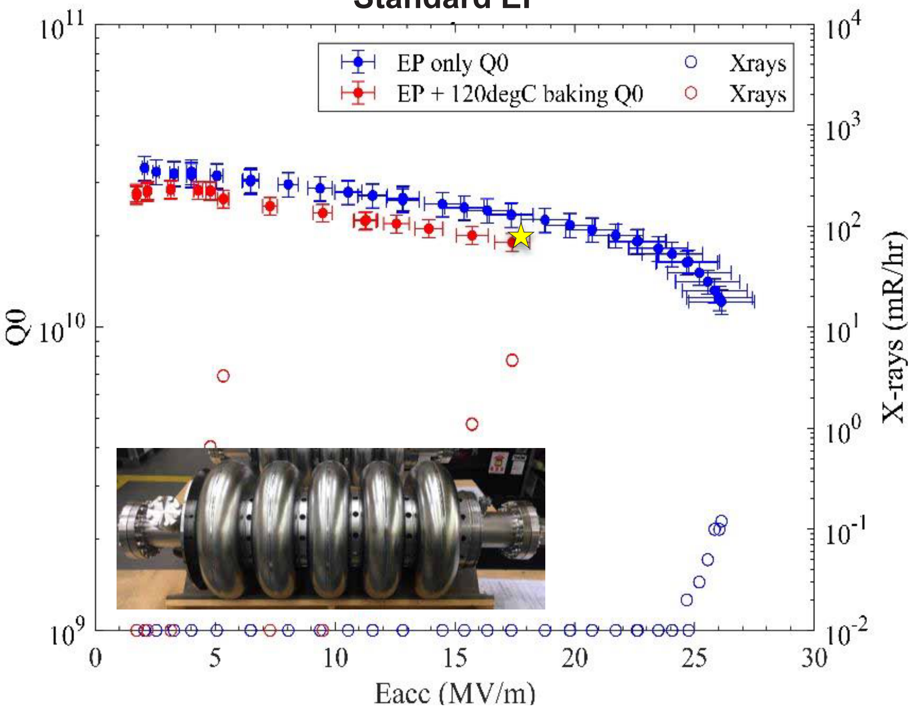
Energy Upgrade cavities in FRIB SRF Highbay (as of Dec 2, 2022)





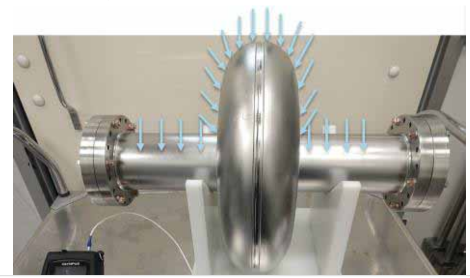
Surface Treatment Study: EP

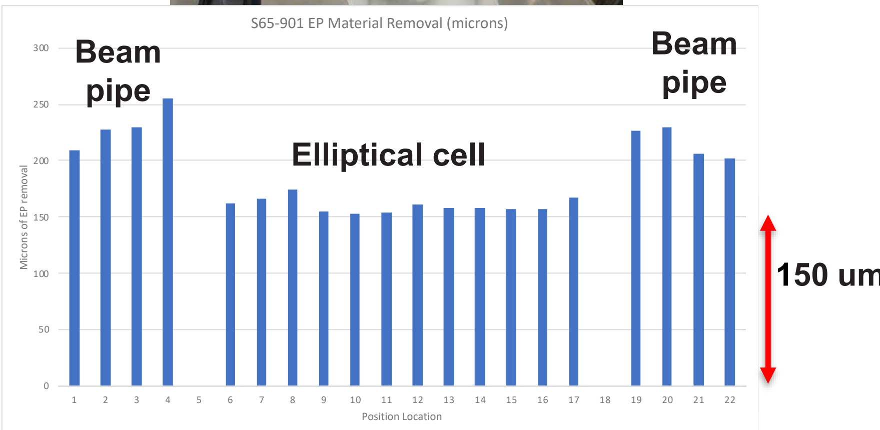
Standard EP



Presented at TTC 2020, also
K. McGee et al., PRAB 24, 112003 (2021)

Uniformity of EP surface removal

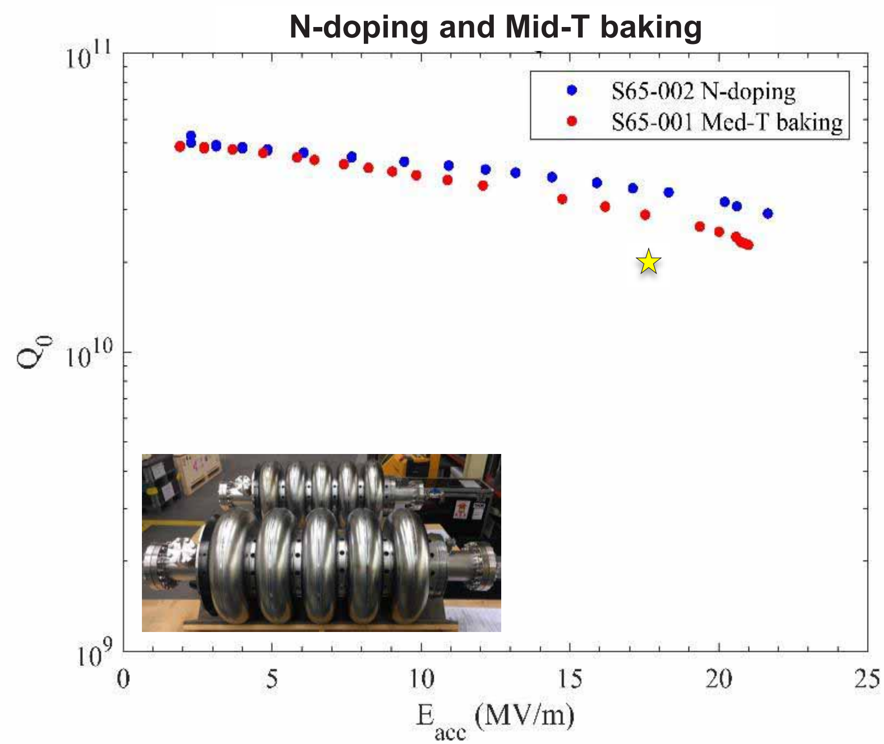




K. McGee et al., SRF 2021

EP is proven to be effective for this medium-beta cavity while the aspect ratio, the equator diameter to the cell length, is higher than the other cavities

Surface Treatment Study: N-doping and Mid-T baking

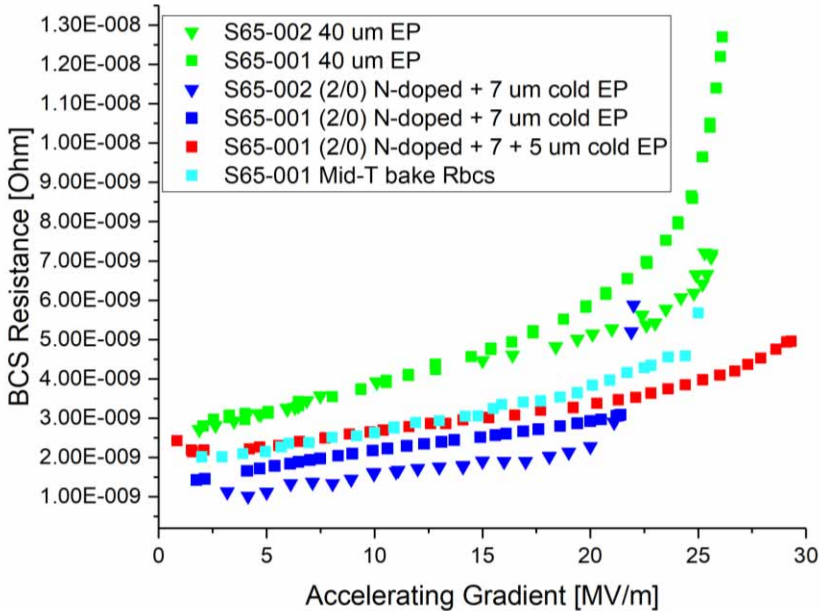


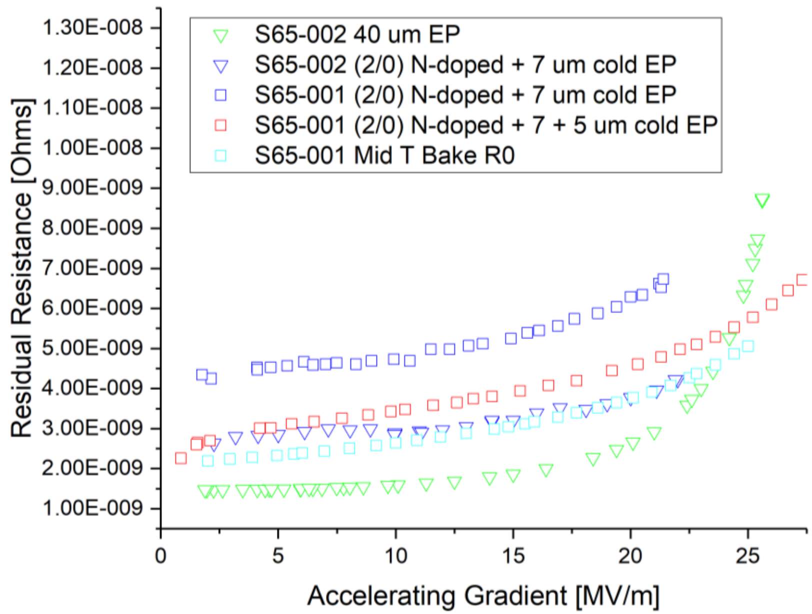
N-doping:
2N0 doping + 7 um post EP,
Annealing history: Max 800ºC

Mid-T baking:
300ºC 3 hour in vacuum furnace,
Annealing history: Max 800ºC

Advanced surface treatments such as N-doping, Mid-T baking showed promising results, ~twice of the design Q0.
It also suggested 1-cell R&D for further recipe optimization

BCS and Residual Resistances (R_{BCS}, R_{res})





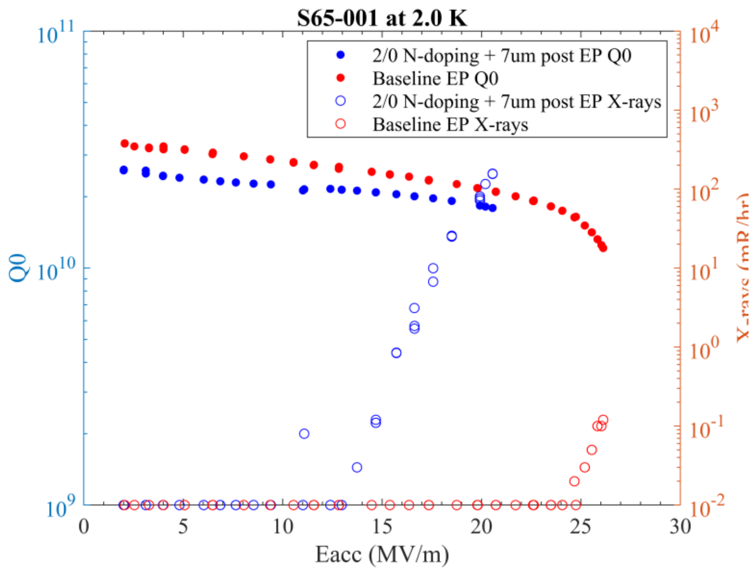
Relative comparison

K. McGee, TTC 2022

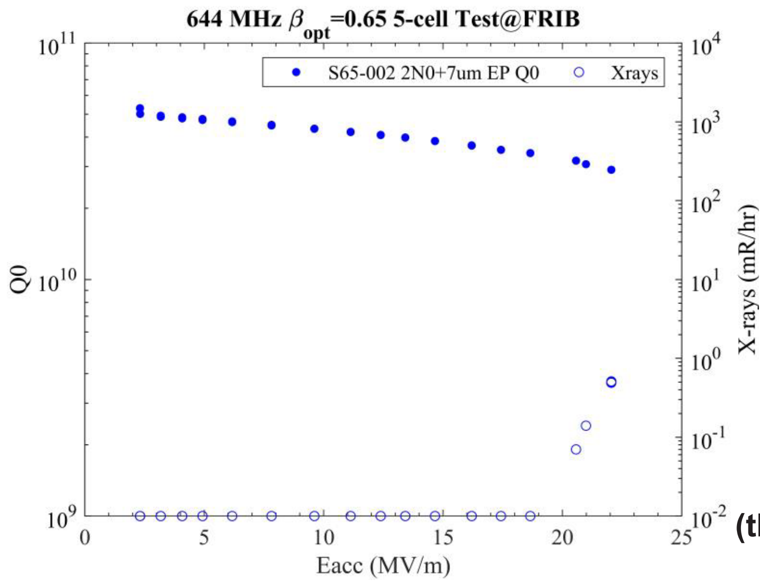
	EP	Mid-T baking	N-doping
R_{BCS}	High	Middle	Low
R_{res}	Low	Middle	High

Challenges with N-doping/Mid-T baking:
Mitigation of R_{res} increase due to trapped magnetic flux

The first attempt of N-doping cavity test: ~3 mG background B-field, no electrical insulation



The best N-doping cavity test: ~1 mG background B-field, electrical insulation



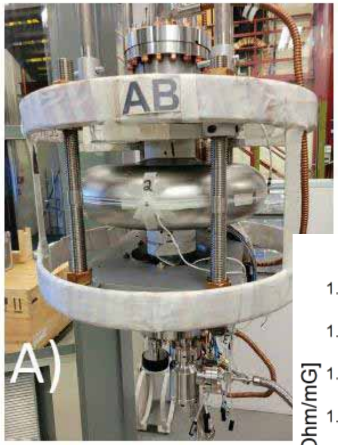
Electrical Insulation (the other 4 on the back)

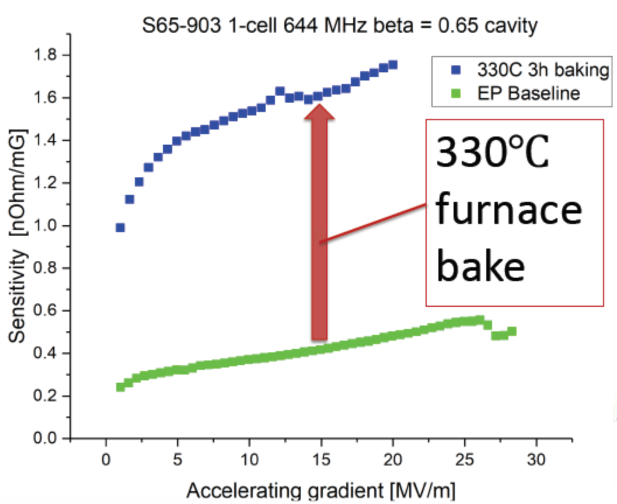
Needed to electrically insulate the support frame bars from the cavity to eliminate B-field induced by thermoelectric current effect, which turned out to be critical to achieve such high Q0 in N-doped/Mid-T baked cavity vertical tests

Flux Expulsion Study

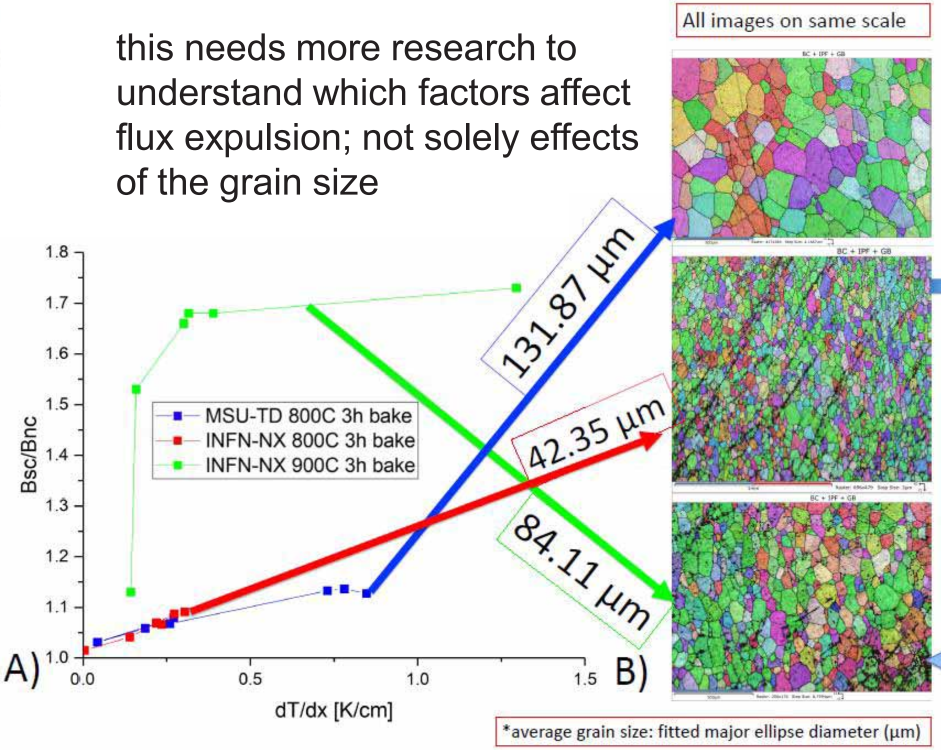
K. McGee, MOPMB025

- Mid-T baking: higher residual resistance sensitivity to trapped magnetic flux
- Almost no flux expulsion in the previously tested FRIB cavities: flux expulsion efficiency as material characteristics rather than cooldown speed issue
- Suggests high T such as 900ºC annealing for efficient flux expulsion





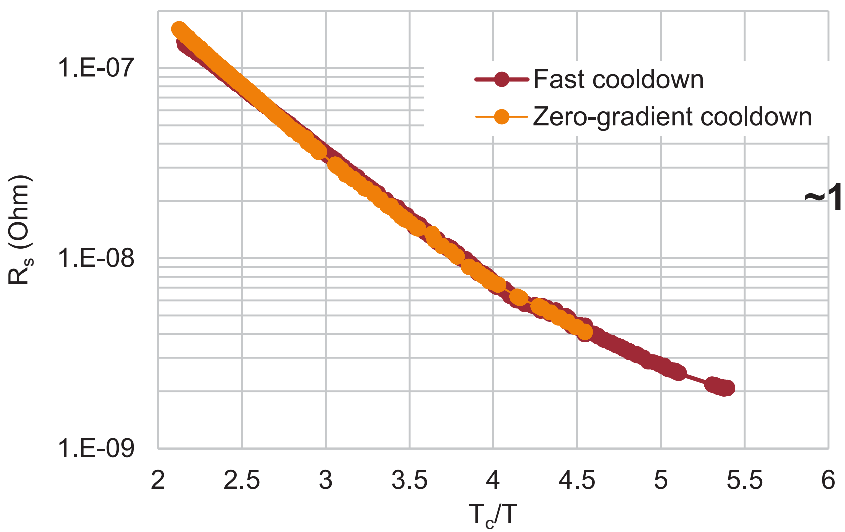
this needs more research to understand which factors affect flux expulsion; not solely effects of the grain size

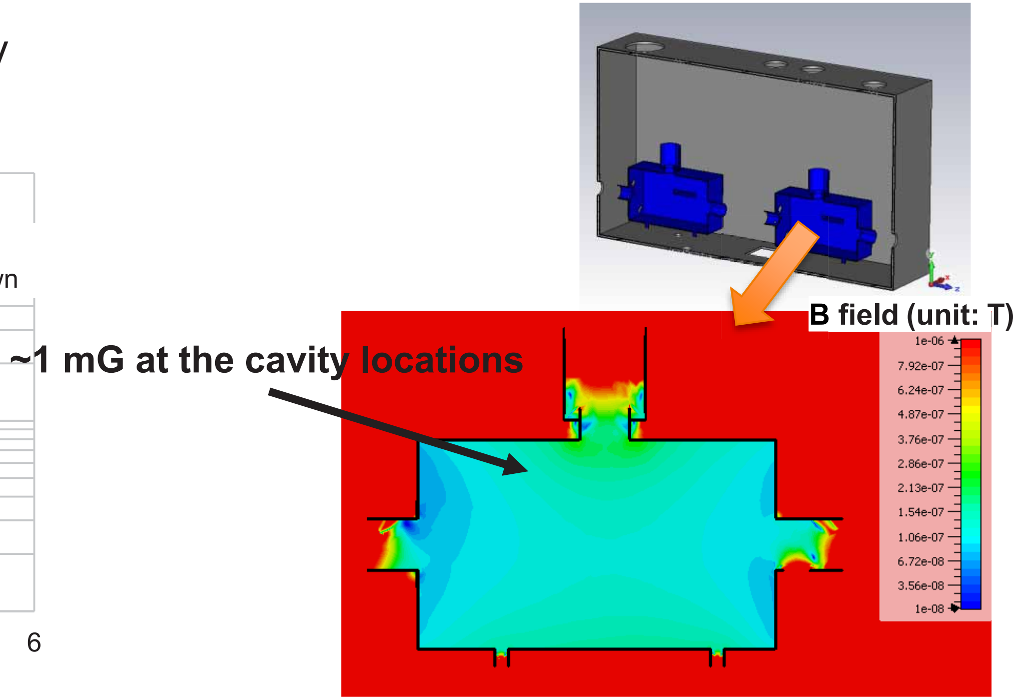


Alternative Approach: Slow Cooldown with Low Background Magnetic Field

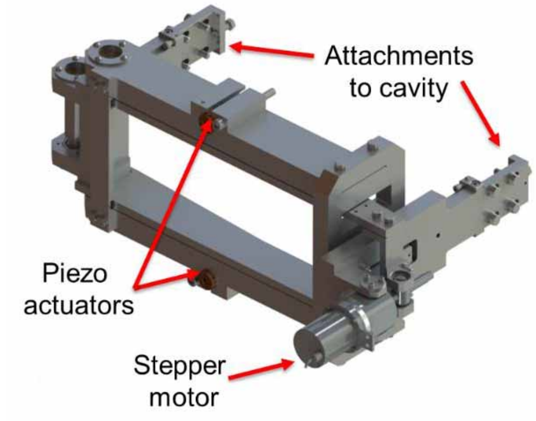
- Zero ∇T cooldown test results showed the same R_{res} as the fast cooldown test results because of no effective flux expulsion in the fast-cooldown case
- However, this suggested that slow cooldown can be an option for cryomodule
  - Ultra low background field such as ~1 mG, slow cooldown to eliminate thermoelectric current effects
  - Thought to be the same condition as unjacketed cavity vertical tests, thus Q0 > 3e10 could be achievable
  - Plan to demonstrate with a jacketed cavity

S65-001 mid-T baking with different cooldown:
Rs vs Tc/T at Eacc = 2 MV/m





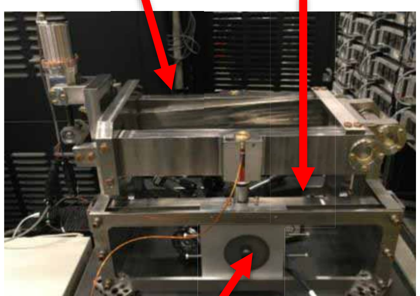
Tuner Development



- Lever tuner with:
  - A stepper motor for coarse tuning (200 kHz)
  - twin piezo actuators for fine tuning
- Room temperature bench tests showed no deadband or noticeable hysteresis

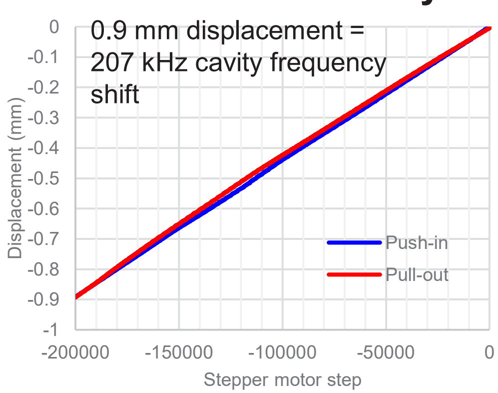
Real tuner assembly: one stepper motor + two piezo actuators

Flexible bar: the same stiffness as cavity



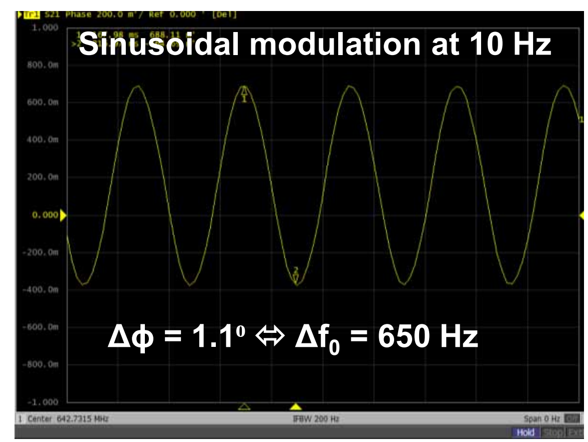
Laser displacement sensor

Stepper motor tuner test with a 'mock' cavity



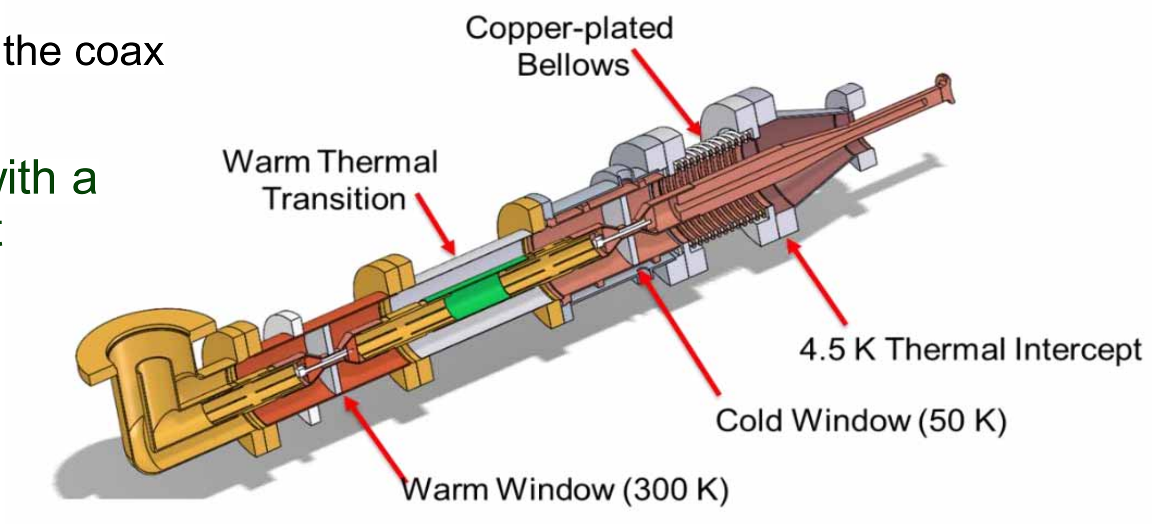
Tuner installed on the jacketed cavity

RT piezo tuner test



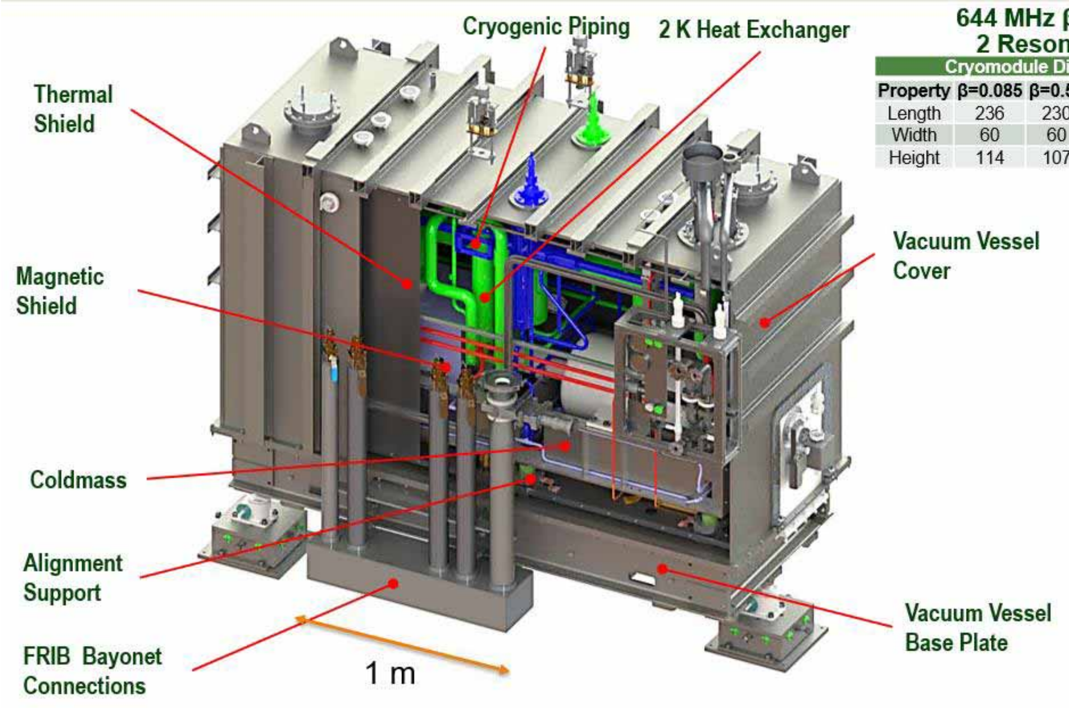
FPC Design

- Requirement: 15 kW CW
- Chose a double-window FPC option with (planar) disk windows:
  - Compact clean assembly parts to minimize impacts on cavity field emission
  - Based on success in ANL's 1.4 GHz 20 kW CW (TW) FPCs
  - Equipped with DC bias, while not in the coax MP band
- Plan to build and test integrated with a jacketed cavity in a horizontal test cryomodule this winter



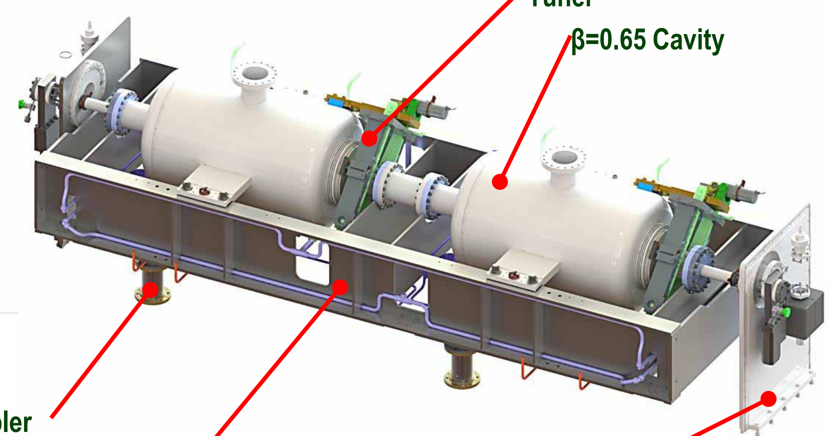
Cryomodule Design: β=0.65 Spare Buncher Cryomodule (under construction)

Modular Design Utilized as on All FRIB Cryomodule Types



644 MHz β = 0.65
2 Resonators

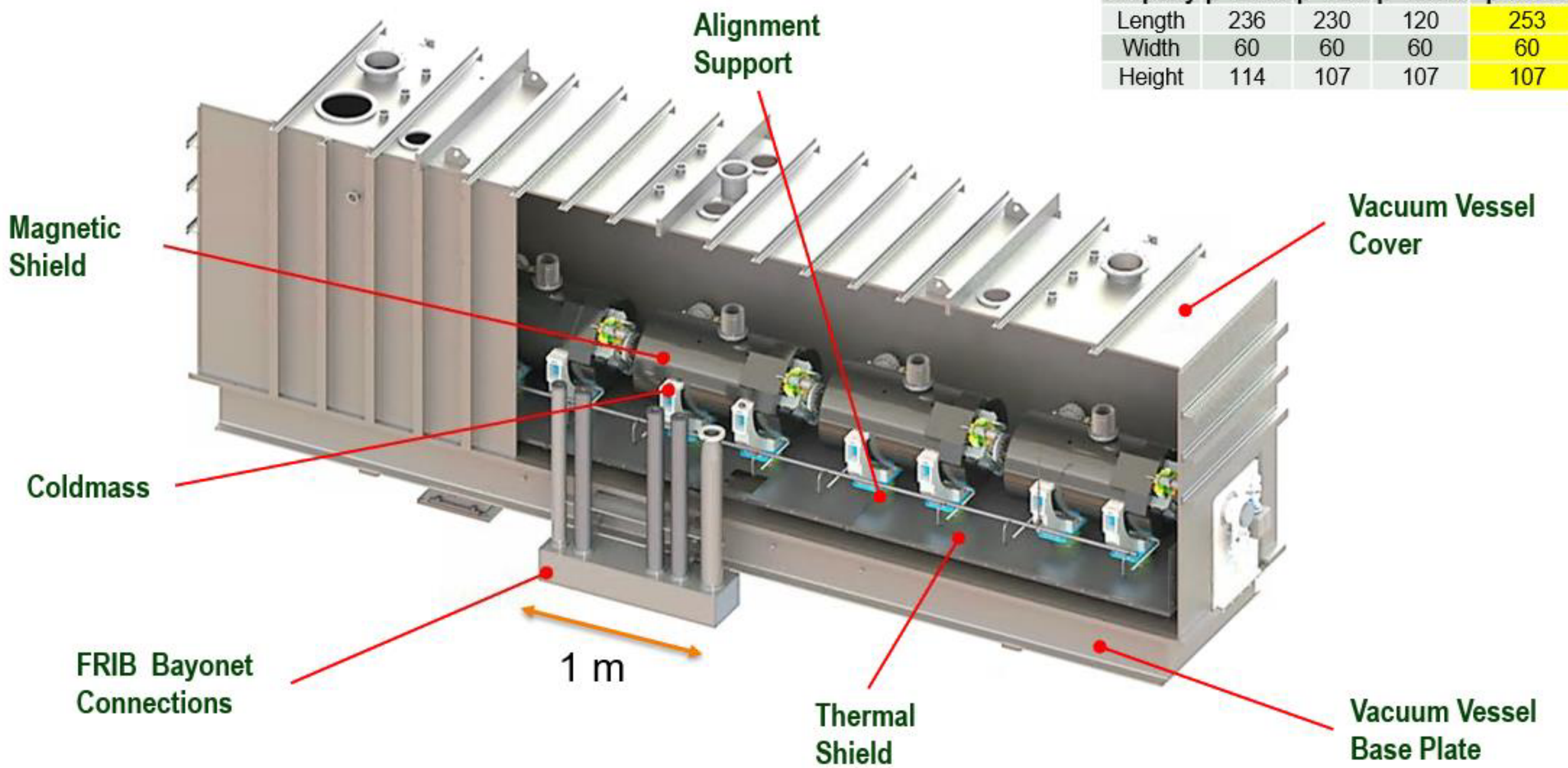
Cryomodule Dimensions (in)				
Property	β=0.085	β=0.53	β=0.53R	β=0.065R
Length	236	230	120	120
Width	60	60	60	60
Height	114	107	107	107



Cryomodule Design: Energy Upgrade Cryomodule (future)

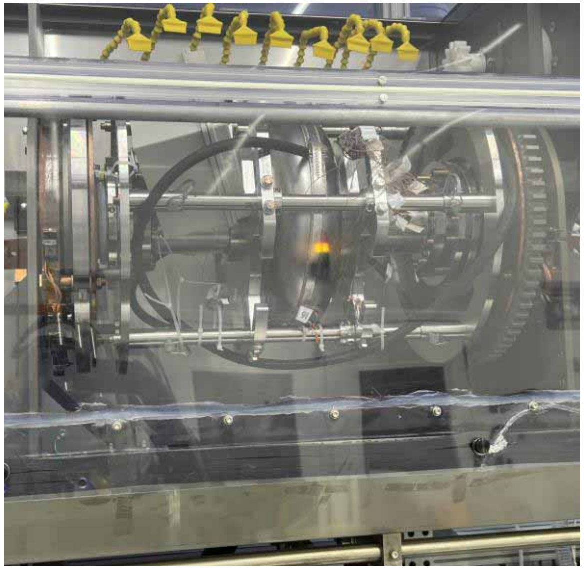
644 MHz β = 0.65
5 Resonators

Cryomodule Dimensions (in)				
Property	β=0.085	β=0.53	β=0.53R	β=0.065
Length	236	230	120	253
Width	60	60	60	60
Height	114	107	107	107



FRIB SRF Facility Upgrade for In-house Processing of N-doping Cavities

EP facility supporting cold EP



E. Metzgar, TUPTB016

N-doping in vacuum furnace

Rotational HPR with minimum numbers of water jets

Concluding Remarks

- As achieved high Q0 such as 3.5e10 @ 17.5 MV/m in a unjacketed cavity, we are moving forwards
  - Jacketed cavities and cryomodule test: to demonstrate such high Q0 in the cryomodule
  - Single-cell cavities: for further recipe study including flux expulsion
- Developing subsystems and cryomodule. A 2-cavity cryomodule will be built as a spare bunching cryomodule of the existing FRIB linac, planned to complete by 2025
- FRIB SRF surface processing facility has been upgraded to support in-house processing of N-doping cavities