Developments Towards FRIB Upgrade to 400 MeV/u for the Heaviest Uranium Ions

Kellen McGee

Graduate student, FNAL/Michigan State University

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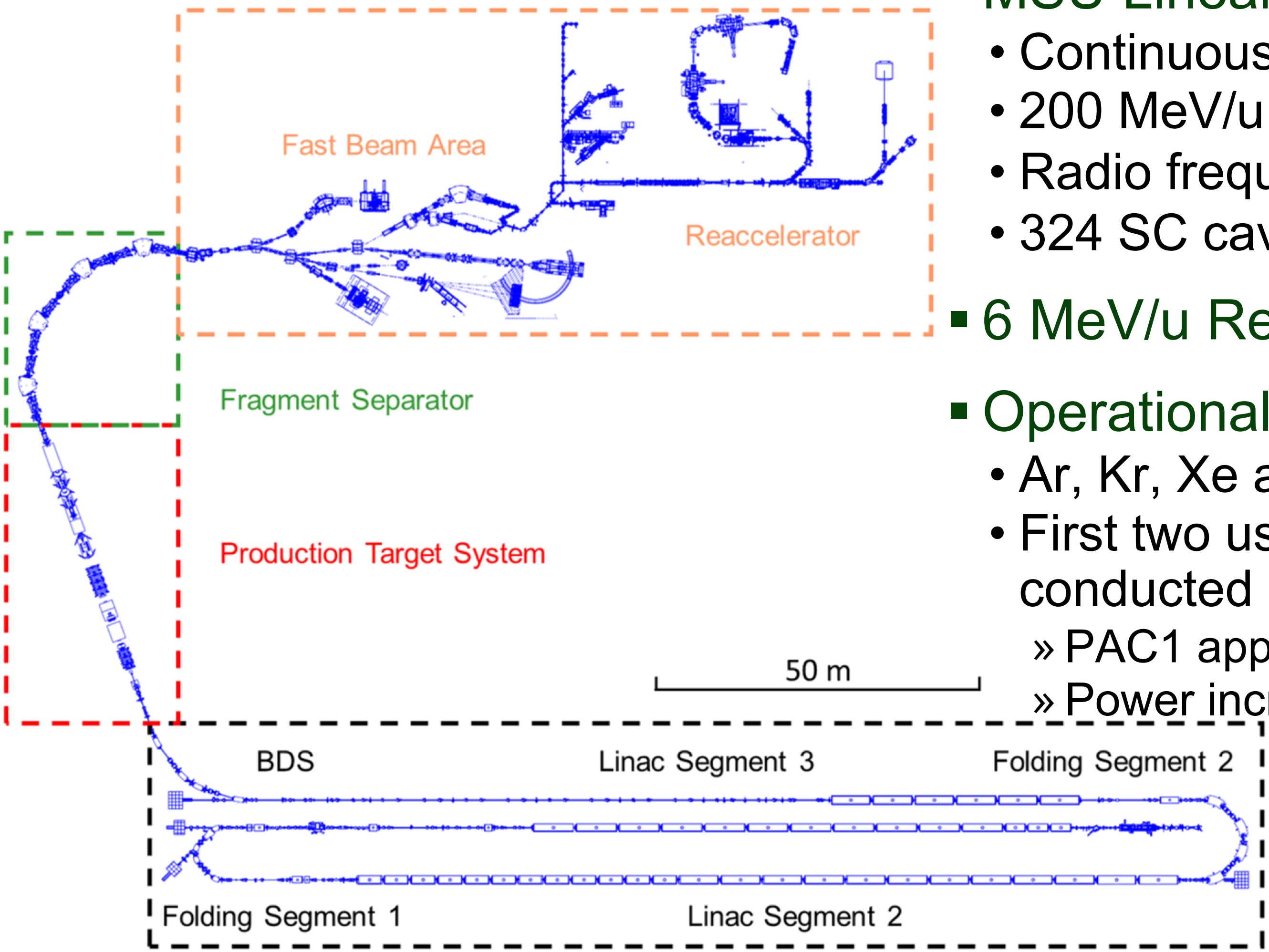
Outline

- Overview of FRIB
- FRIB400 Upgrade Goals
- Cavity Design & RF Testing results
- Understanding and mitigating magnetic field cavity performance degradation

Facility for Rare Isotope Beams (FRIB)



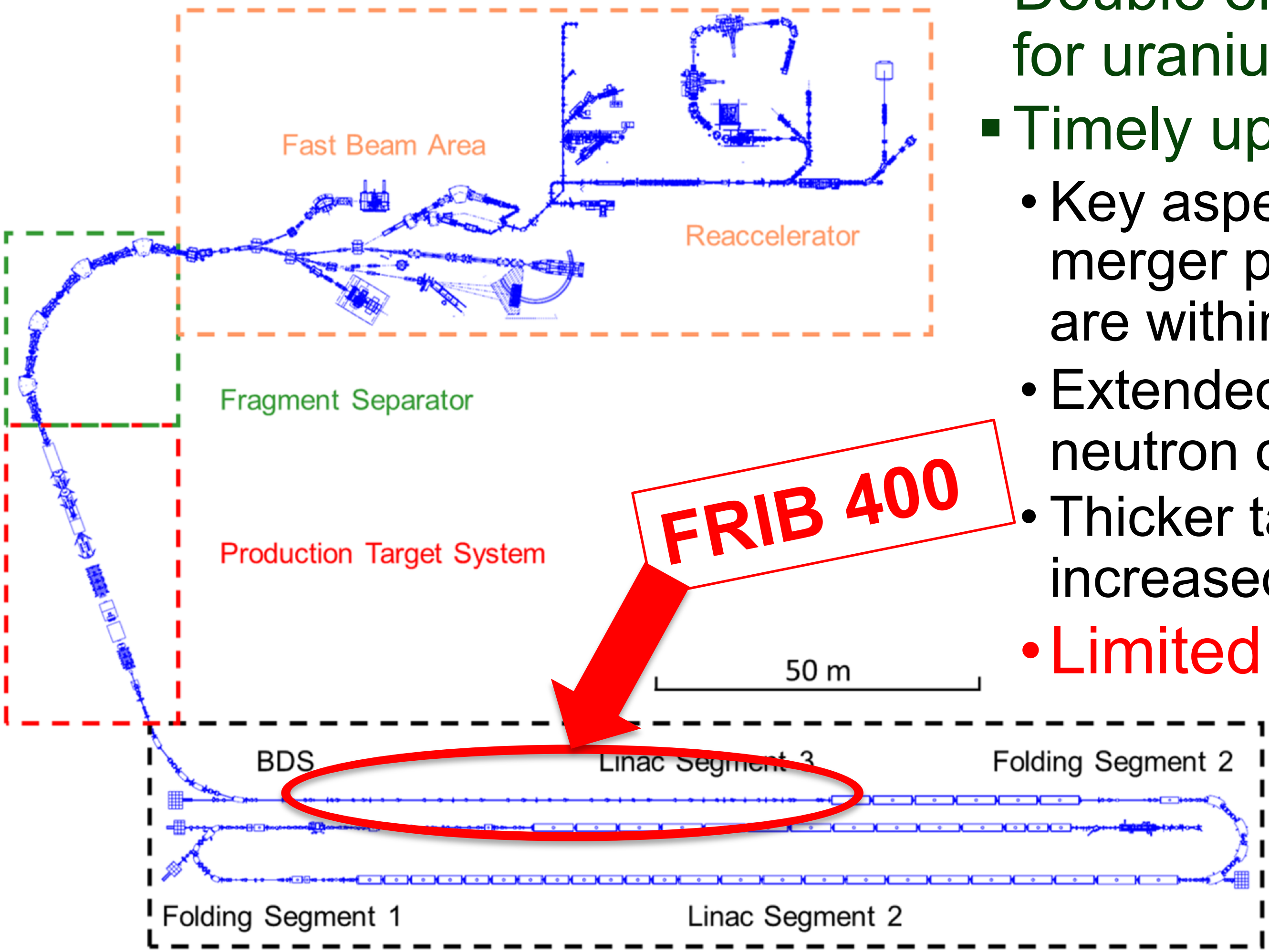
- MSU Linear accelerator*
  - Continuous Wave (CW)!
  - 200 MeV/u for uranium
  - Radio frequency quadrupole
  - 324 SC cavities in 46 cryomodules
- 6 MeV/u Re-accelerator (ReA)
- Operational since 4/2022
  - Ar, Kr, Xe accelerated to 212 MeV/u
  - First two user experiments conducted May-June 2022
    - » PAC1 approved 34 experiments
    - » Power increase phased (1 kW)

*Ostroumov, P. et. al., HIAT'22, 29 June 2022

FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

Fermilab

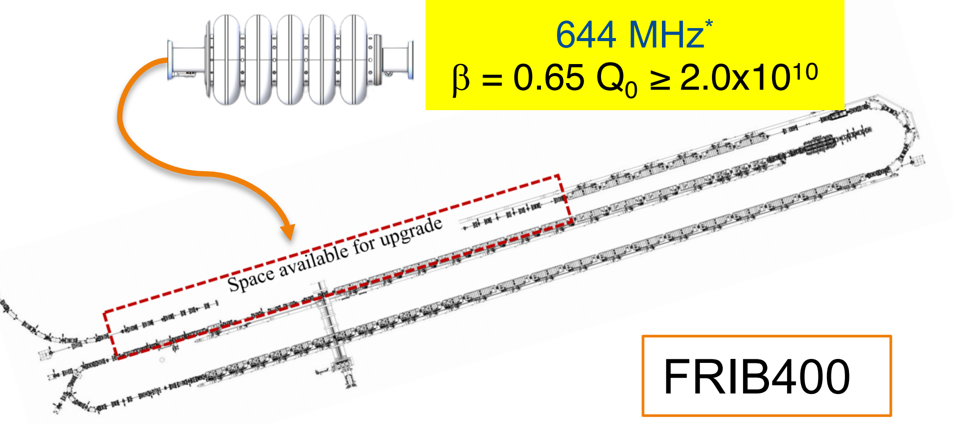
FRIB Energy Upgrade (FRIB400)



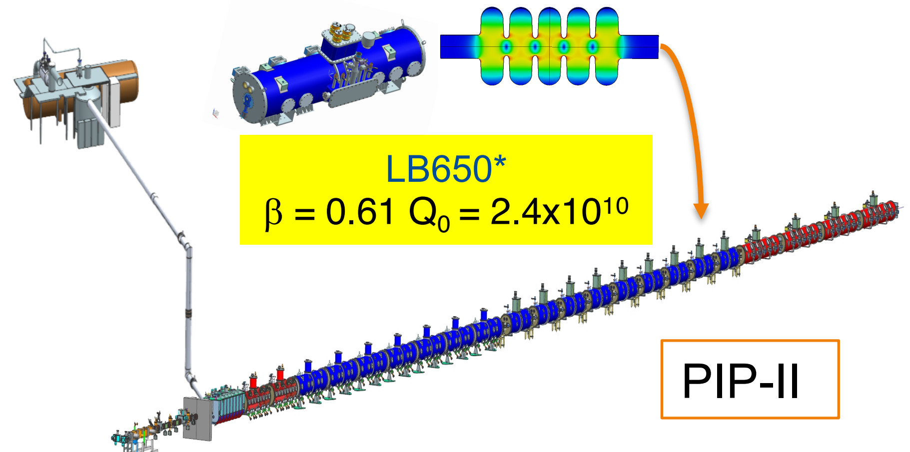
- Double energy to 400 MeV/u for uranium (1 GeV for H^+)
- Timely upgrade!
  - Key aspects of neutron star merger physics, nuclear EoS, are within reach of FRIB400!
  - Extended reach along the neutron drip-line
  - Thicker targets, significantly increased rare isotope yield,
  - Limited to 80 m of space

Cavity Design

- Need to meet 400 MeV/u (U) within 80 m of space available
- Need for medium-β, mid-frequency (sub-GHz), high-gradient cavities to cover range between TEM-type cavities and β = 1 cavities.
- No comparable technology exists for CW machines (FRIB400)
- 650 MHz β = 0.65 5-cell elliptical cavities developed concurrently for FNAL PIP-II penultimate stage (pulsed/CW-compatible)
- 5-cell β =0.65 644 MHz had largest beam energy gain of studied options



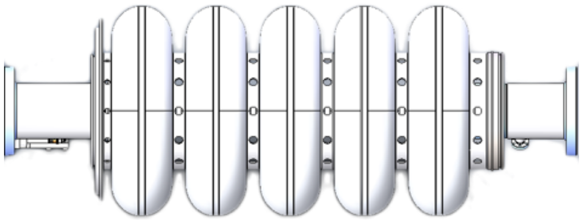
*Ostroumov, P. et. al., Nuclear Inst., A **888** (2018)



*Lia Merminga, PIP-II Workshop, 1-4Dec 2020

FRIB400 Cavity Parameters

- Borrowed FNAL LB 650 MHz design elements, modified for 644 MHz, CW operation
  - Large longitudinal acceptance
  - Admits multi-charge state acceleration
  - Large aperture, long focusing period
- Achieves maximum gradient with minimal additional heat load, minimum number of cryomodules
  - 55 cavities, 11 cryomodules
  - CW, $Q_0 \geq 2.0 \times 10^{10}$



Parameter	Value	Units
Frequency	**644**	MHz
Geometrical β	**0.61**	
Optimal β	**0.65**	
Aperture diameter	**83**	mm
Effective length, L_{eff}	**71.0**	cm
Number of cells	**5**	
Geometric shunt impedance, R/Q	**368**	Ω
Geometry factor, G	**188**	Ω
E_{peak}	**40**	MV/m
B_{peak}	**77.5**	mT
Acc. gradient E_{acc}	**17.5**	MV/m
E_{peak}/E_{acc}	**2.28**	
B_{peak}/E_{acc}	**4.42**	mT/(MV/m)

*Ostroumov, P. et. al., Nuclear Inst., A **888** (2018)

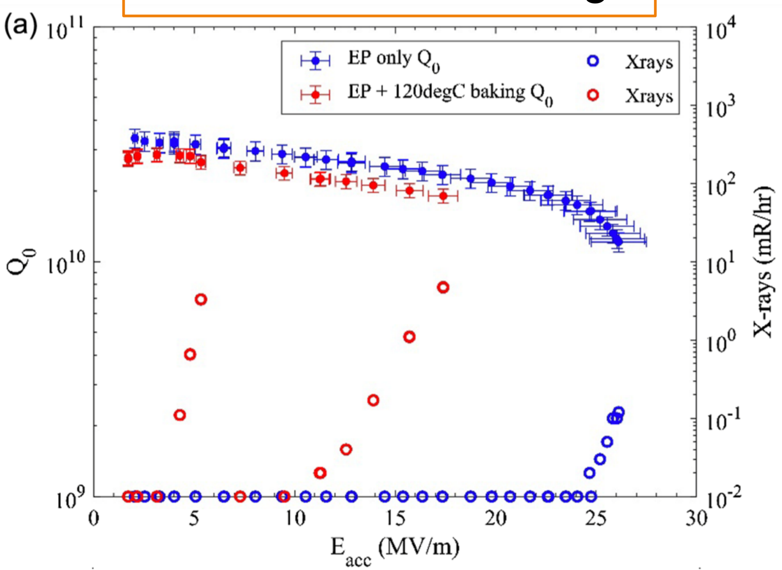
RF Processing R&D

- Goals
  - Fit FRIB400 upgrade within modest upgrade to FRIB cryoplant
  - Seeking *unprecedented* $Q_0 \geq 2.0 \times 10^{10}$ at 17.5 MV/m
  - High-Q recipes for medium-β mid-frequency cavities so far unexplored, but stand to deliver huge benefit current/future machines (FRIB400, PIP-II, etc).
- Previously…
  - SNS/ESS cavities (sub-GHz, pulsed) used BCP, achieved $Q_0 \approx 5 \times 10^9$
  - Novel treatments must be explored
- R&D at MSU
  - Two prototype 5-cell cavities fabricated by RI (2018)
    - » 1 fabricated by Roark, not yet tested
  - Three single-cell cavities available (2021)
  - Explore and optimize High-Q RF recipe potential @ 17.5 MV/m
    - » Electropolishing (large format)
    - » N-doping
    - » Furnace/medium-temperature baking (300C, 3h)

Early Studies[1]

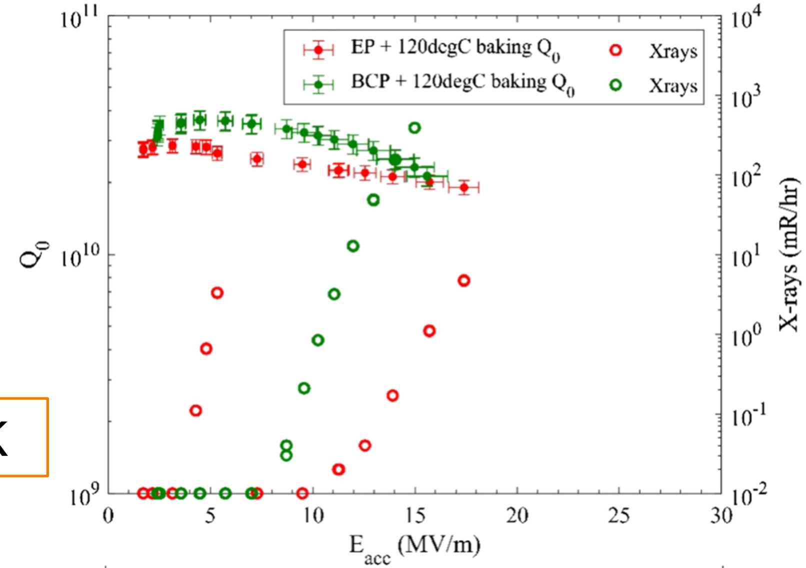
- Conventional recipes: Buffered Chemical Polishing, Electropolishing, 120℃ baking.

Effect of 120℃ baking



@2K

EP vs. BCP



- EP-only had best $Q_0 = 2.3\times10^{10}$@17.5 MV/m, R_s = 8.17 nΩ
- 120℃ baking increased R_0, BCP increased Medium-Field Q-Slope
- Multipacting completely conditioned in ~30min.

[1]K. McGee et al. PRAB **24** 112003 (2021)

Advanced RF Treatments

- N-doping[1]
  - Discovered 2012-13 FNAL: doubled Q, reversed R_{BCS} dependence on E_{acc}
  - Industrialized at 1.3 GHz and used to deliver LCLS-II
  - Thermal diffusion of N_2 into Nb bulk (interstitial)

"2/0" N-doping: Bulk EP, High T (degassing+stress release) bake, light EP, N-Doping (2min doping/0min annealing), Post-doping+cold EP, HPR+VT assembly, RF test.

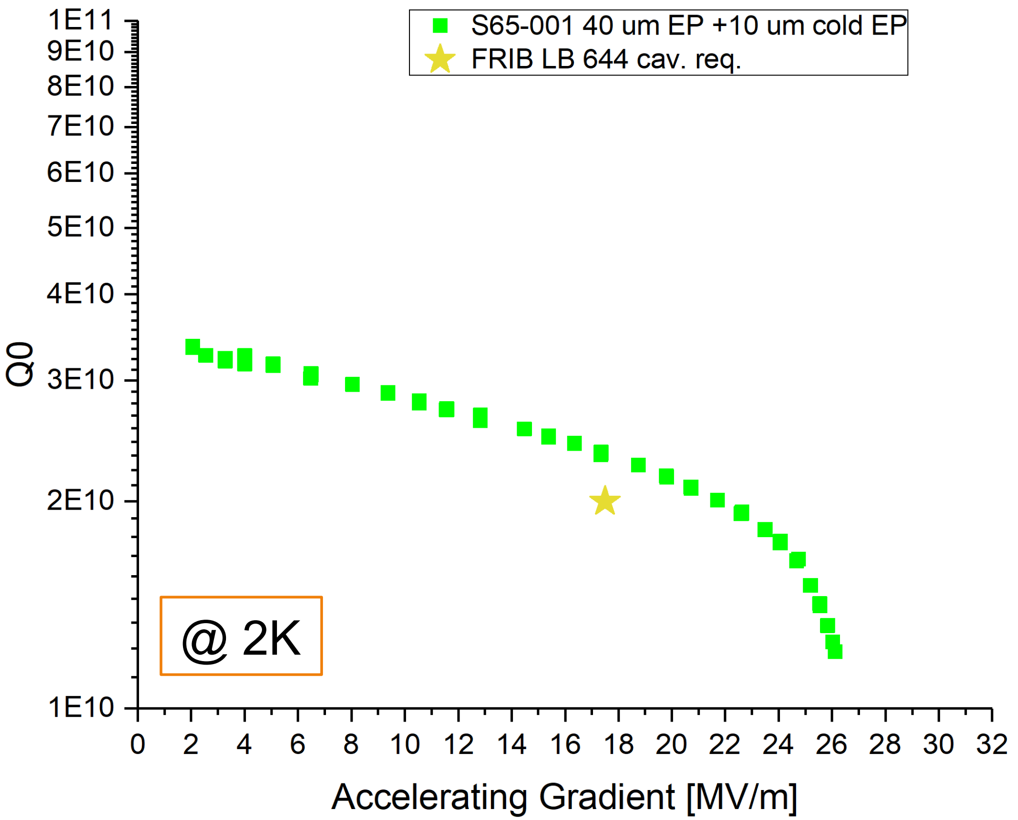
- Furnace/medium temperature bake[2,3,4]
  - Simpler method: no N-profusion, no post-EP
  - Oxygen diffusion can reproduce some effects of N-doping at 1.3 GHz

Bulk EP, High T (degassing+stress release) 800-950C 3h, light EP, mid-T furnace bake 300C 3h, HPR, VT assembly

[1] A. Grassellino et al, *Supercond. Sci. Technol*. **26**, 102001 (2013).
[2] H. Ito, et al., *Prog of Theor. and Exp. Phys.*, Volume 2021, Issue 7, July 2021
[3] E.M. Lechner, et al., *Appl. Phys. Lett.* **119,** 082601 (2021). [4] D. Bafia, TU1A, LINAC'22

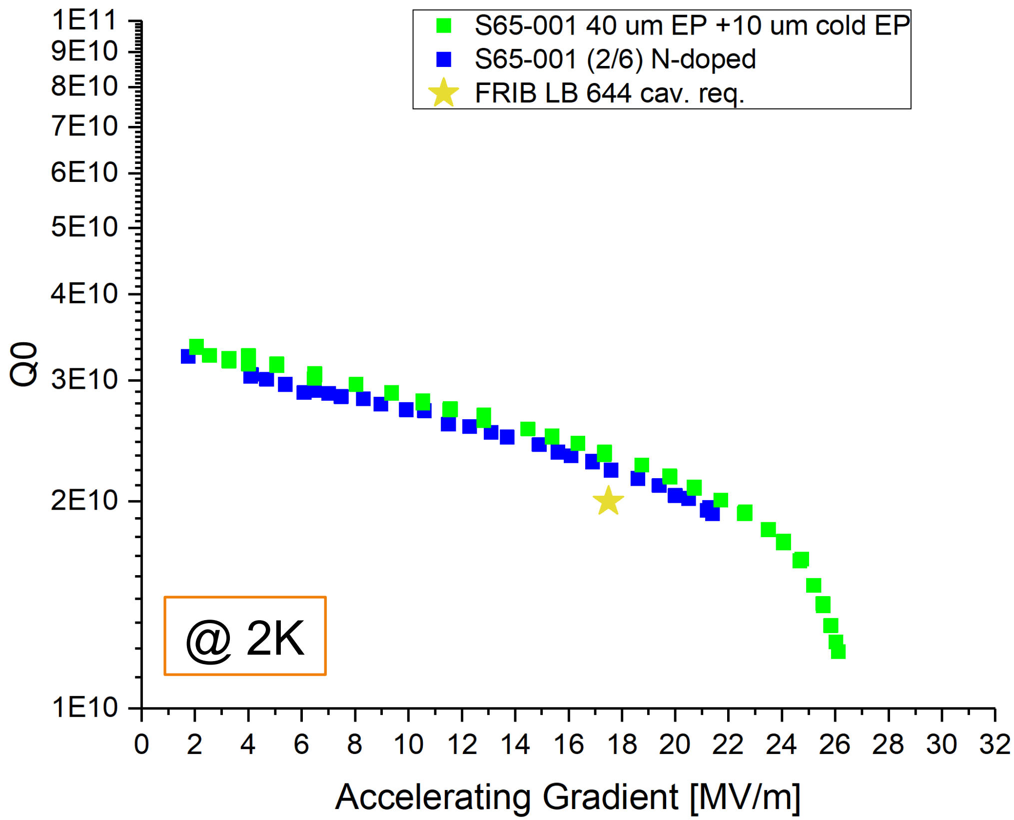
5-cell β=0.65 644 MHz RF Studies

- EP baseline
- FRIB400 min spec achieved, but further improvements in Q_0 highly motivated



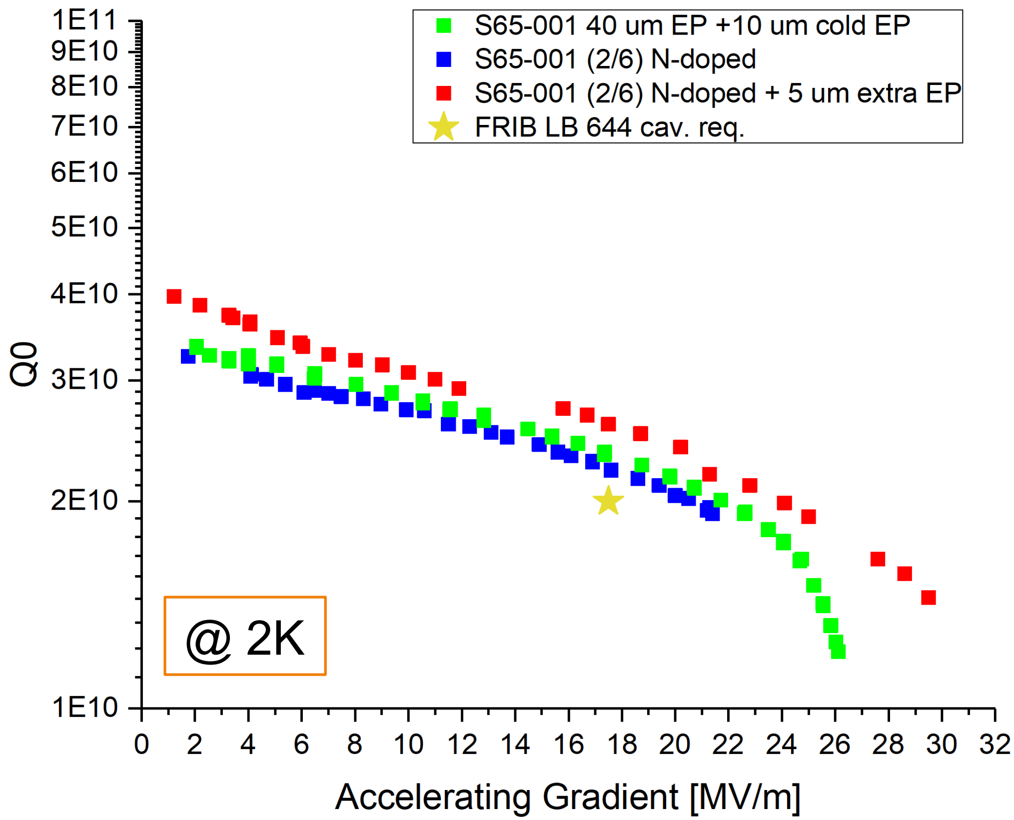
5-cell β=0.65 644 MHz RF Studies

- N-doping
  - 2/6 recipe applied in β = 0.65 644 MHz 5-cell cavity



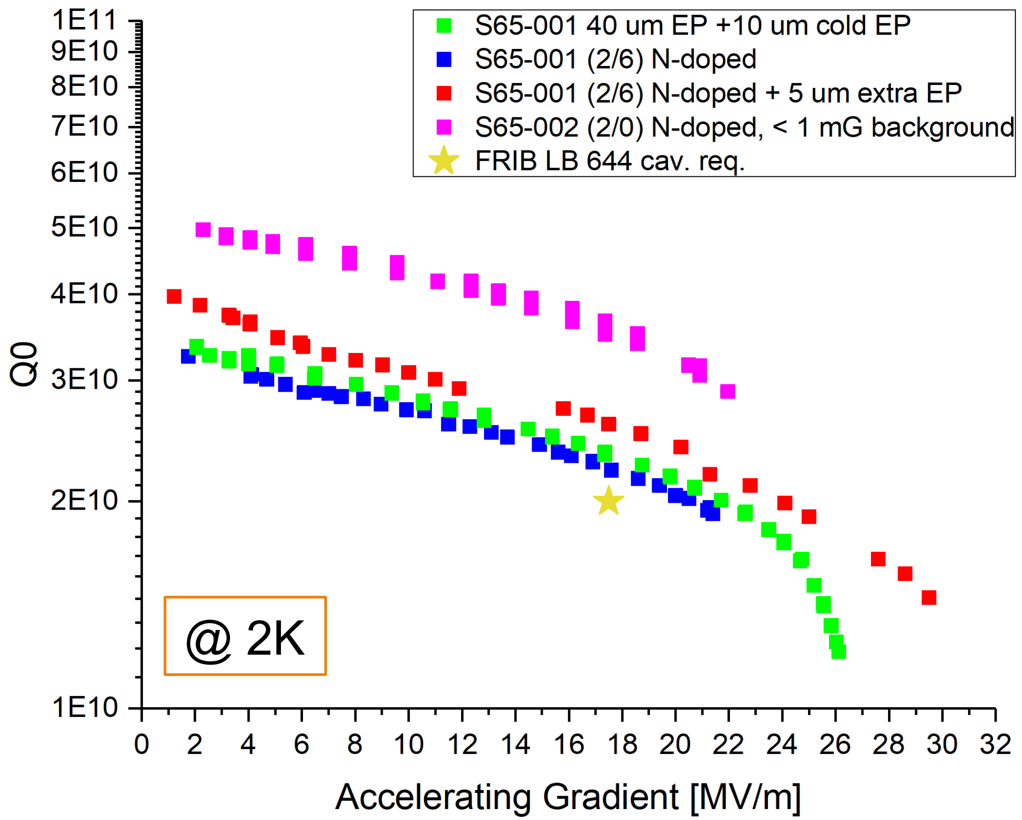
5-cell β=0.65 644 MHz RF Studies

- N-doping
  - 2/6 recipe applied in β = 0.65 644 MHz 5-cell cavity
  - + more post-EP



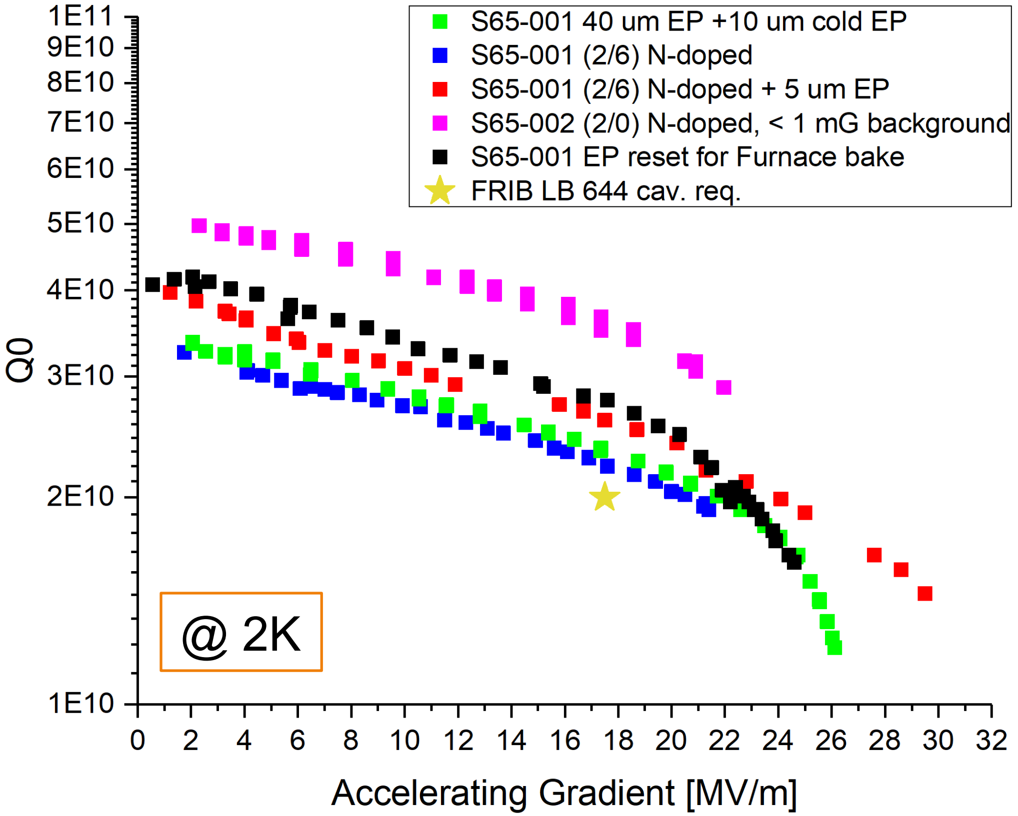
5-cell β=0.65 644 MHz RF Studies

- N-doping
  - 2/0 recipe applied for improved R_{BCS}
  - Background magnetic field cancelled to < 1 mG



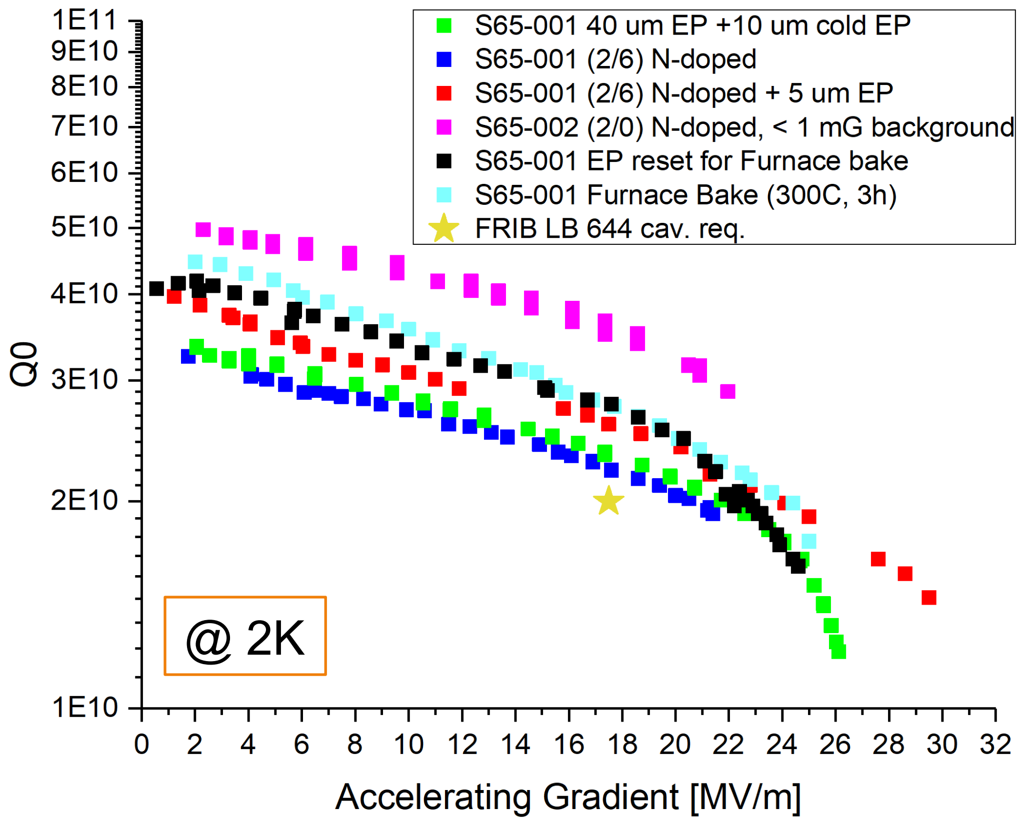
5-cell β=0.65 644 MHz RF Studies

- Re-baseline EP, improved R_{BCS}
  - Baseline for furnace/medium temperature bake



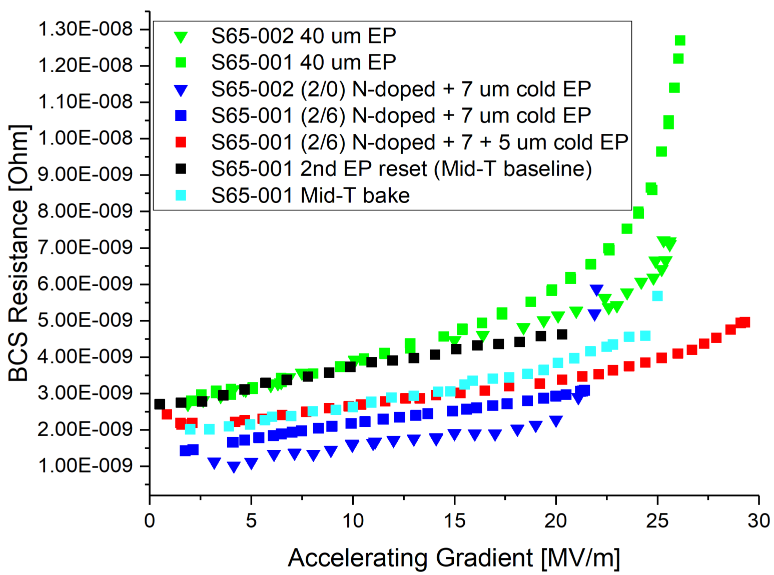
5-cell β=0.65 644 MHz RF Studies

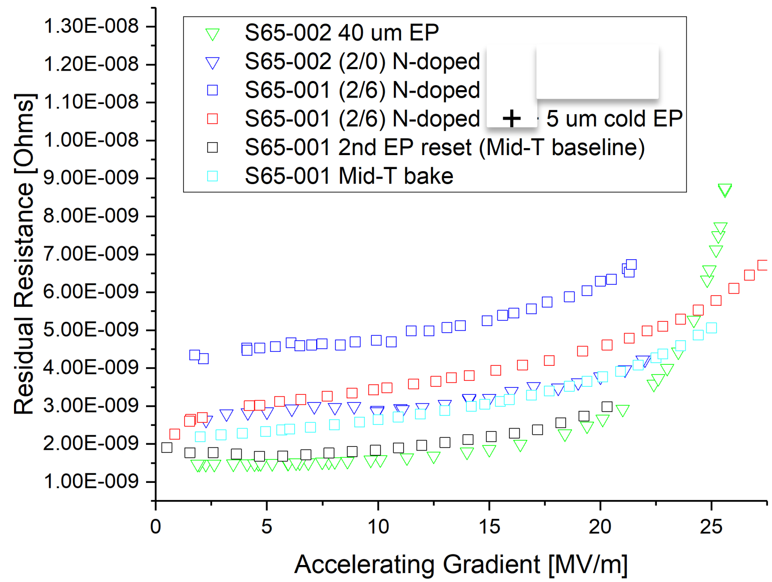
- Furnace bake
  - 300℃, 3h
  - R_{BCS} decreased from baseline EP
  - R_0 increased from baseline EP
  - Overall Q same in this temperature range (2K)



5-cell β=0.65 644 MHz RF Studies

- (2/0) N-doping
  - R_{BCS} **reduced 60%** from EP treatment, R_0 **increased 30%** from EP treatment
- 300C 3h Furnace baking
  - R_{BCS} **increased by 7.5%** from N-doped test, R_0 **decreased by 19%** from N-doped test,





5-cell β=0.65 644 MHz RF Studies

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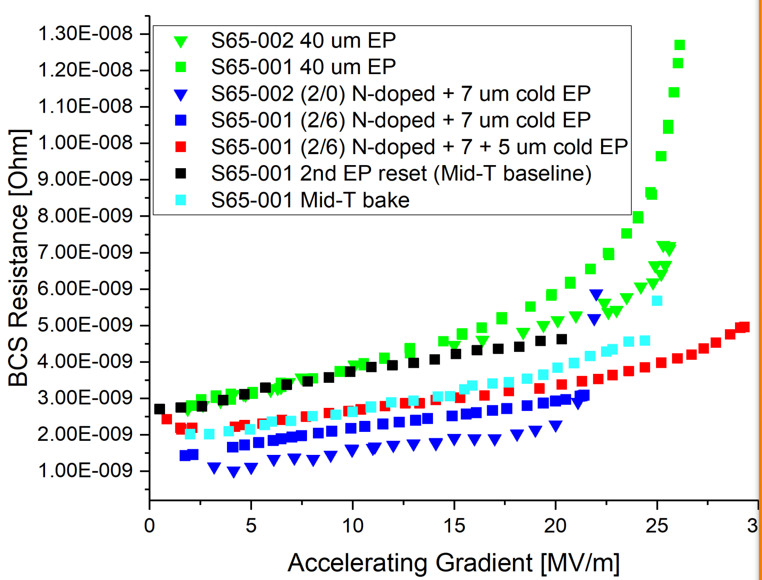
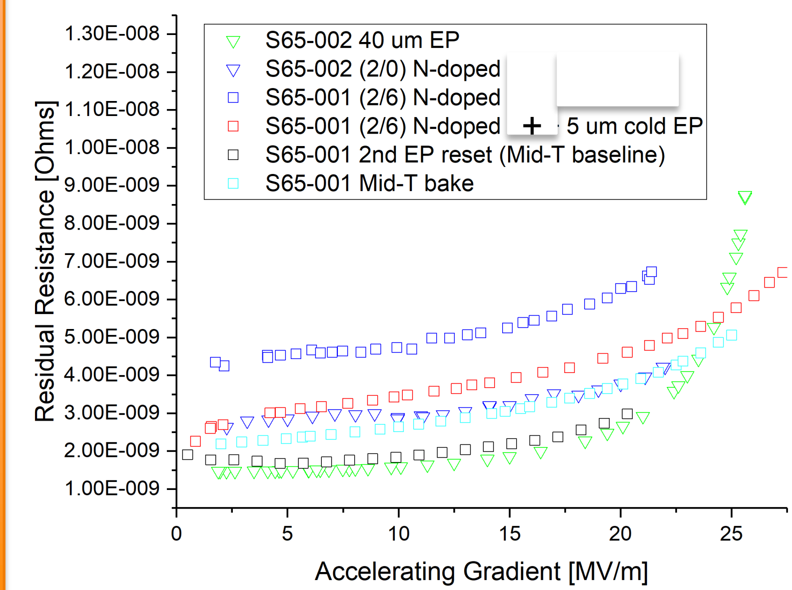
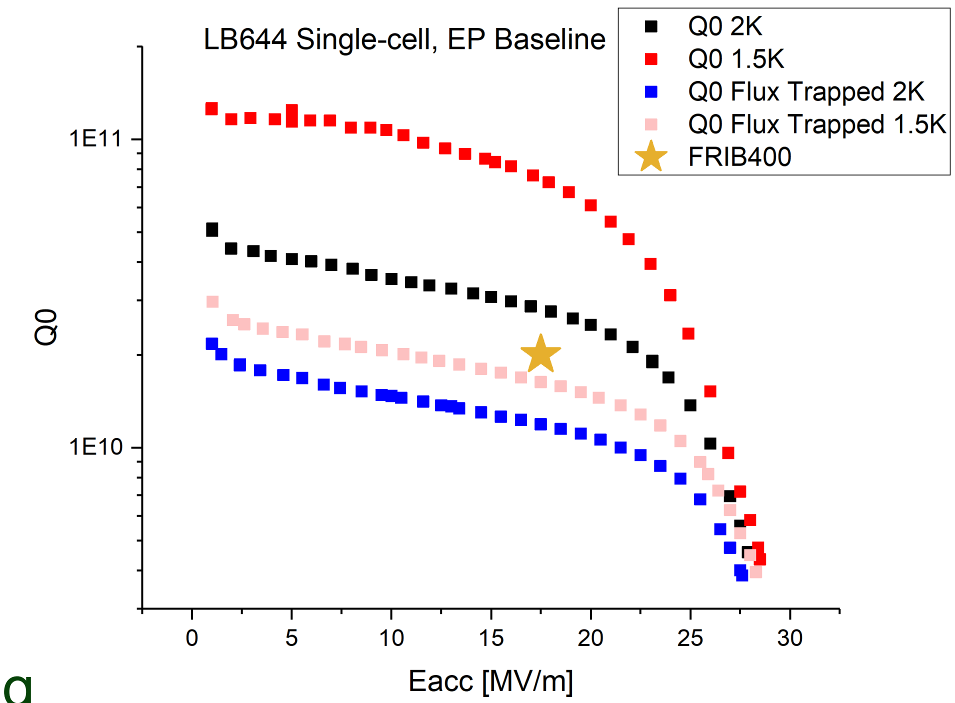
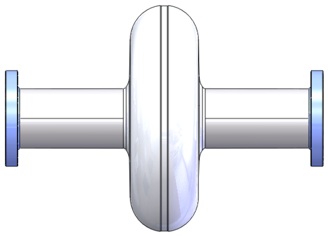


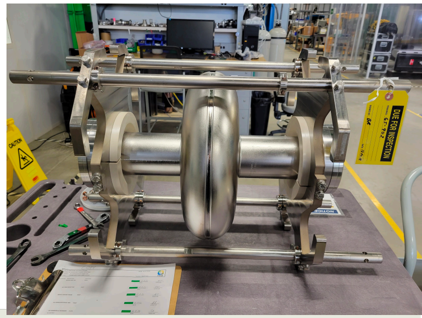


1-cell β=0.65 644 MHz Flux Sensitivity

- Residual resistance (R_0) is most challenging parameter in N–doped cavities
- 1-cell cavities allow direct measurement of trapped flux sensitivity (nΩ/mG)
  - Impose 20 mG, then slow-cool
- Measured 0.45 nΩ/mG @ 17.5 MV/m in EP cavity
- Expected to increase after N-doping
- Inform CM implementation of flux-trapping mitigation techniques

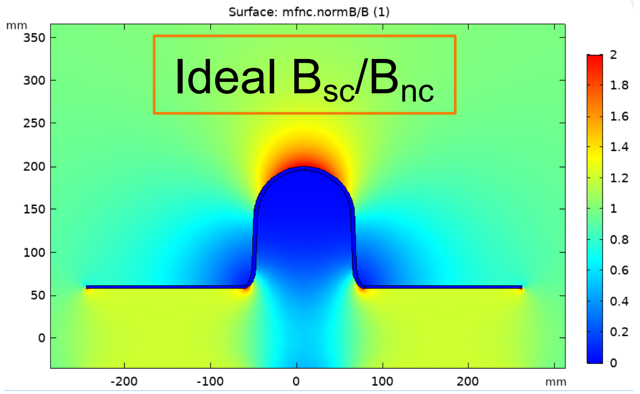




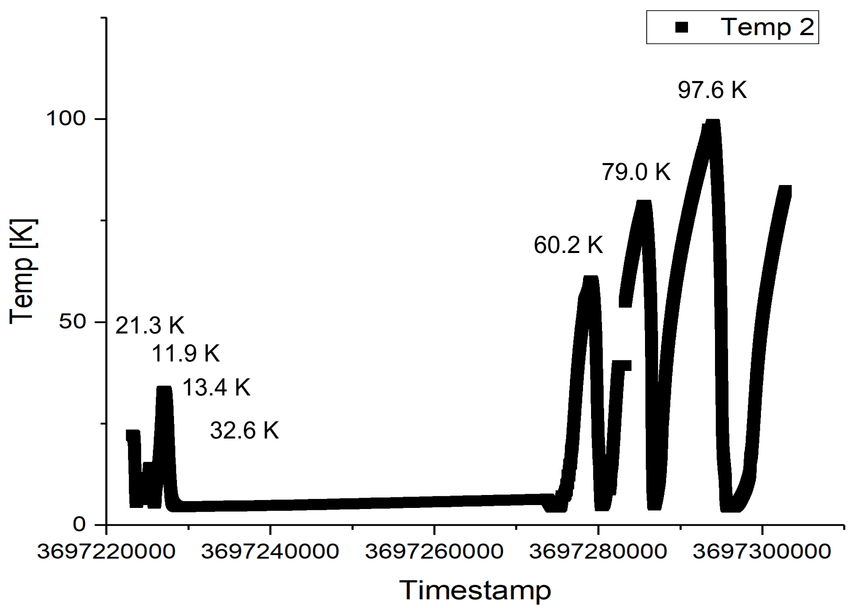


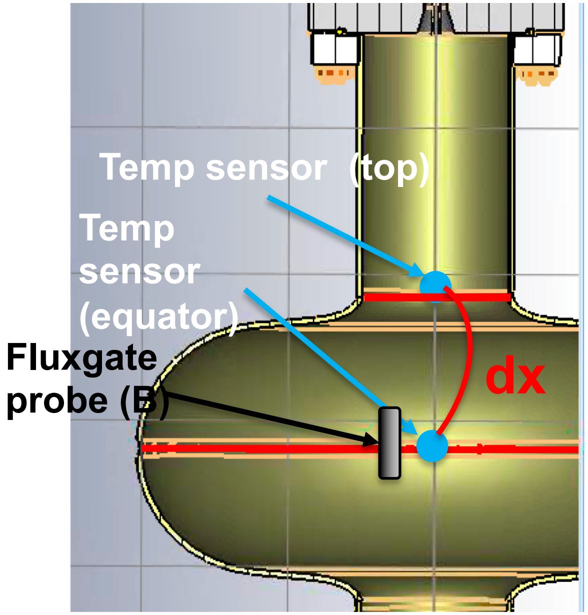
Cavity Flux Expulsion

- Reduce R_0 by improving flux expulsion!
- At cavity equator, measure $\frac{B_{superconducting\ state}}{B_{normal\ conducting\ state}}$
- Plot as a function of $\frac{\Delta T}{dx} = \frac{T(top)-T(equator=9.2K)}{x(top)-x(equator)}$



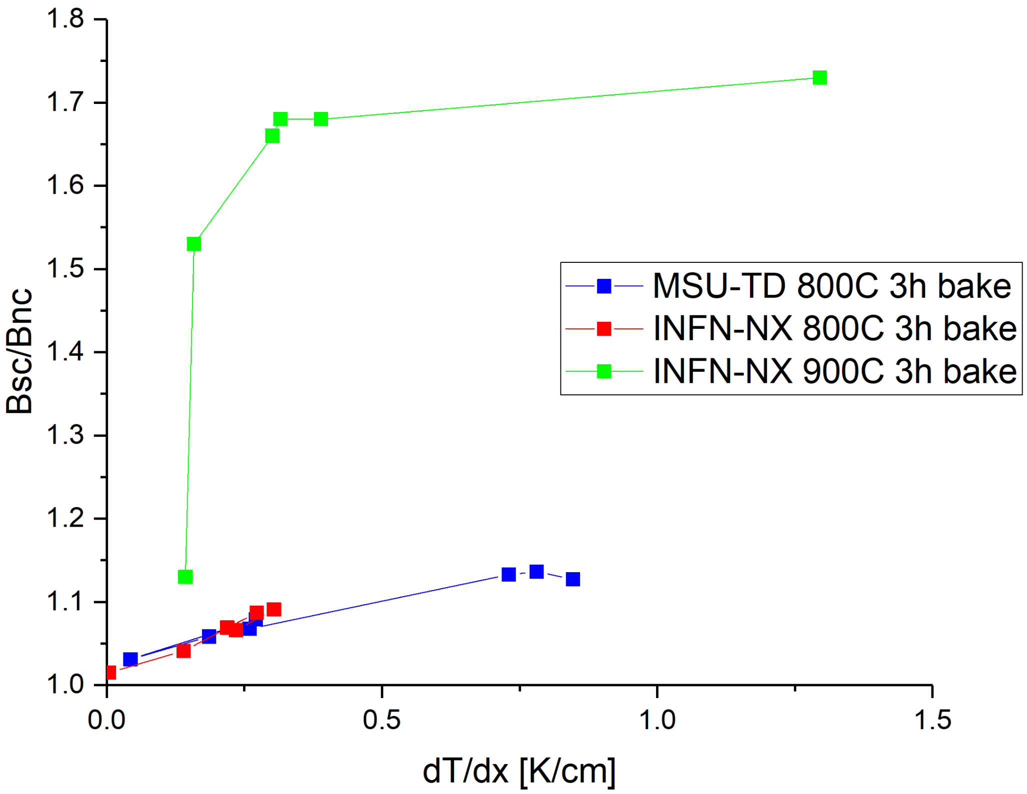
Example profile of thermocycle test:





Flux Expulsion: ~650 MHz

- 2 single-cell cavities tested
- β=0.61 650 MHz (NX material)
  - Bsc/Bnc significantly improved after 900℃ bake
- β=0.65 644 MHz (TD material)
  - 900℃ bake completed, awaiting EP, RF + flux expulsion test
- HT baking seems good for FE, but structural concerns apply in 5-cell

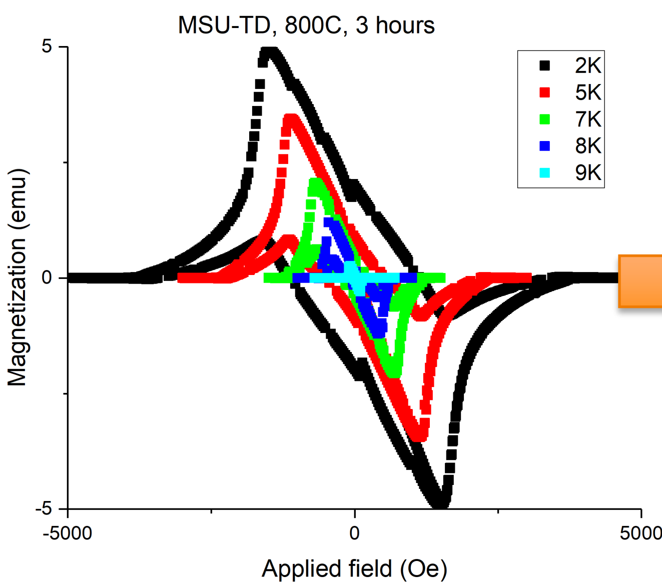


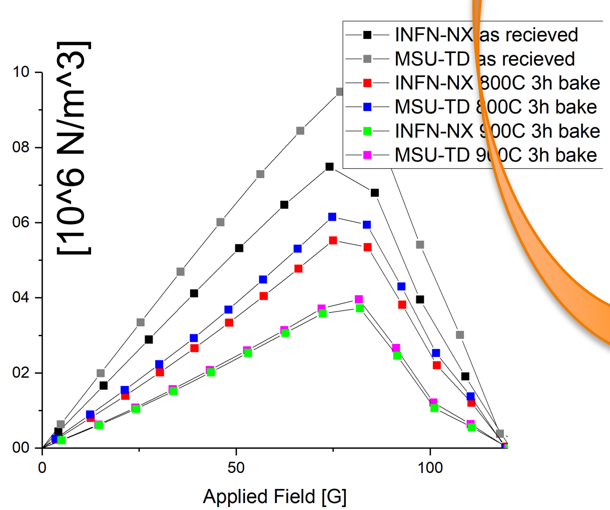
Flux Expulsion & Sample Studies

- Motivation
  - N-doping has clear advantages in Q_0, but flux sensitivity is also increased
  - Understanding mechanisms affecting trapped flux in cavities key to extracting best performance
  - If easily measurable physical properties of raw Nb material can be correlated with the cavity flux performance, we may write material specifications for Nb vendors!
- Method
  - PPMS (Physical Property Measurement System) instrument allows measurement of flux pinning force (Fp) on a small Nb sample

Physical Property Measurement System [PPMS]

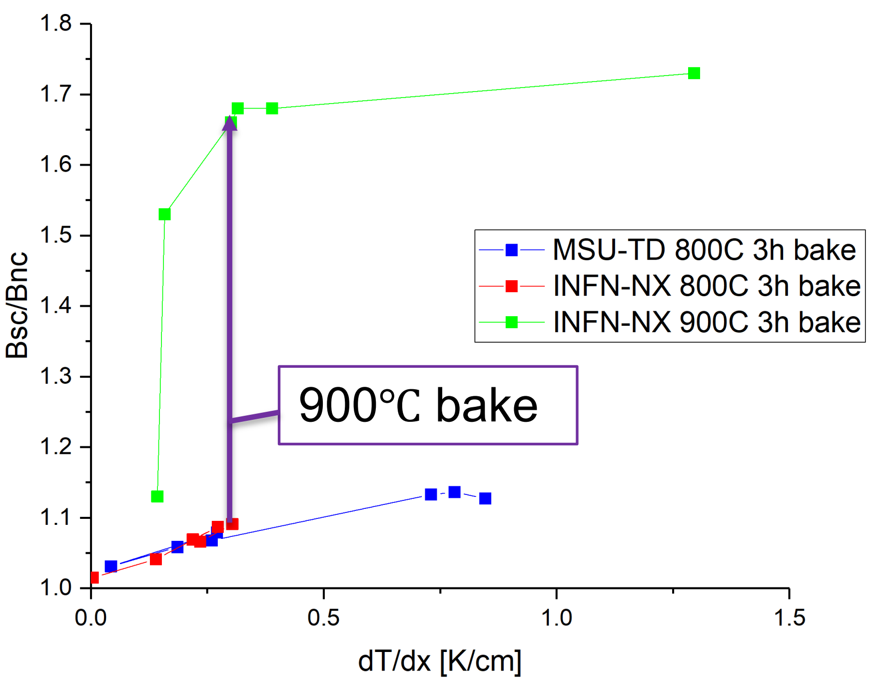
- Small sample size (2 x 2 x 8 mm)
- Cool sample to 2-9 K
- Impose DC magnetic field (+/- 150 G)
- Measure irreversible magnetization
- Calculate assoc. current => Flux pinning force

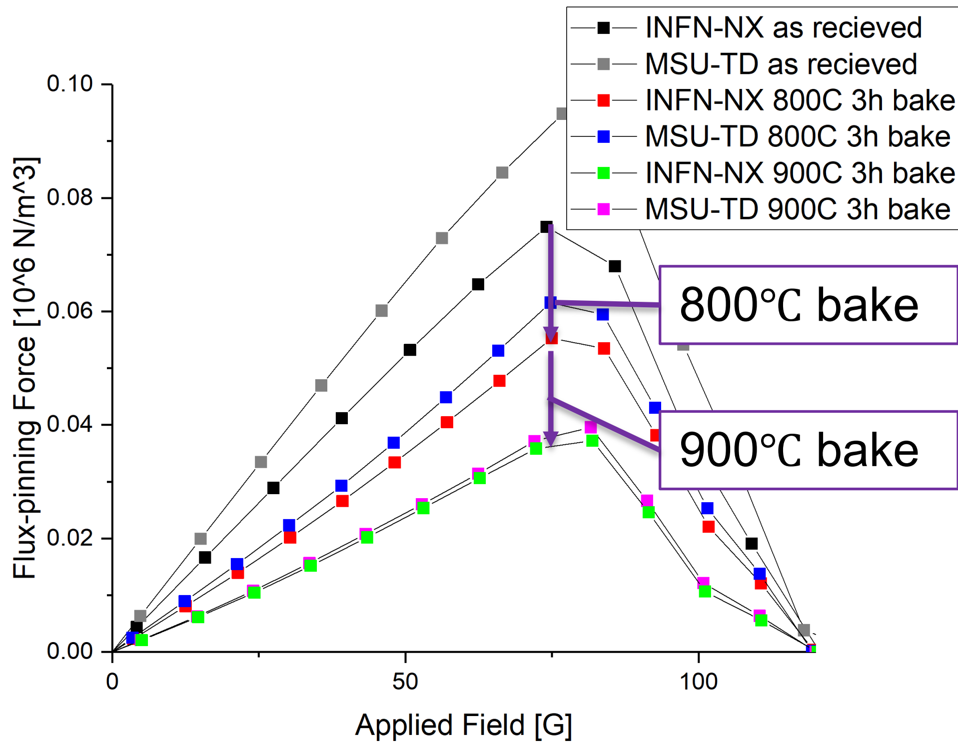




Flux Pinning Correlates With B_{sc}/B_{nc}

- Better flux expulsion corresponds to lowered Fp after 900℃ baking
- Confirmed with multiple Nb sources (NX, TD)
- Next: measure B_{sc}/B_{nc} of MSU-TD 900℃ cavity
  - Flux pinning force measurement appears to be a good candidate for baking study





Summary

- (2/0) N-doping was successful at achieving FRIB and PIP-II Q requirements in both low-β and high-β ~650 MHz cavities
- Furnace/medium-T baking is a simplified treatment that also achieves these requirements
- Relation between Fp measurements and flux expulsion performance may provide new & more economical way to screen Nb material & baking treatments for expulsion
- Further studies focused on furnace baking and flux expulsion underway in single-cell, and multicell 644 MHz and 650 MHz cavities.
- 900℃ baking appears advantageous for flux expulsion, mechanical/yield strength studies underway
- We expect significant progress in improving cavity performance and extending it to a fully dressed cavity by the time we receive the project funding for the FRIB400

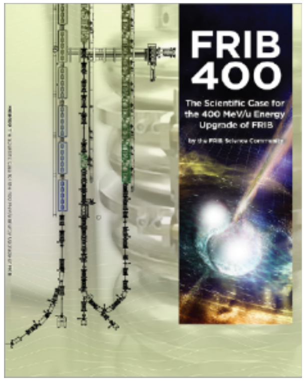
Thank You

Questions?

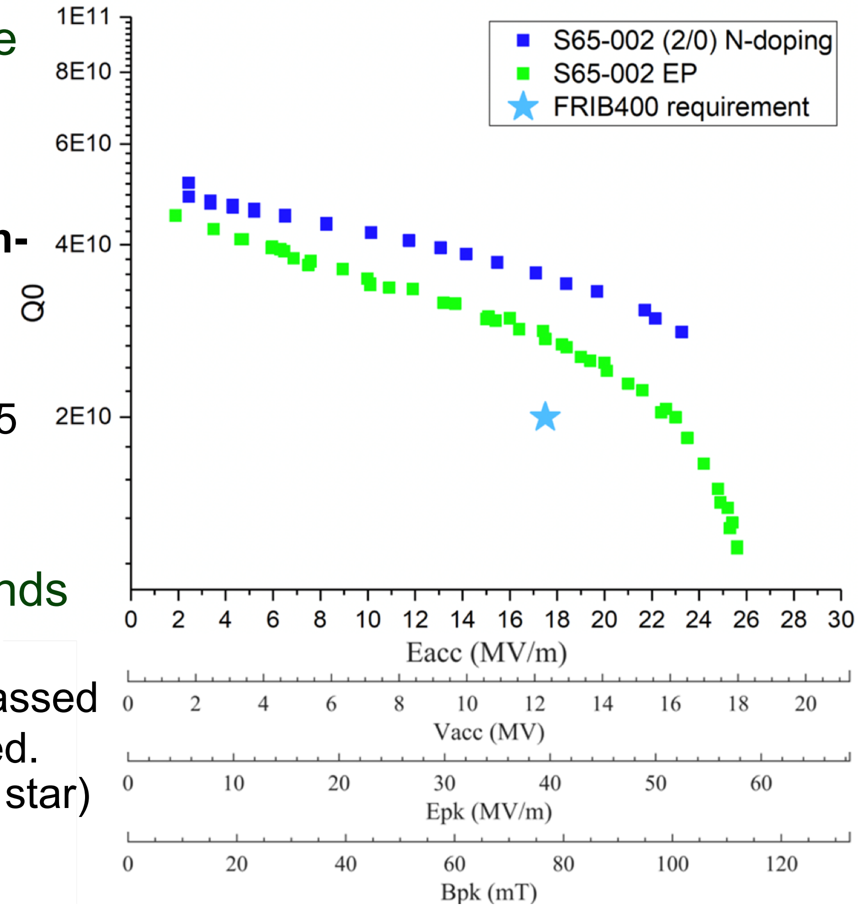
LINAC2022
LIVERPOOL

Backup

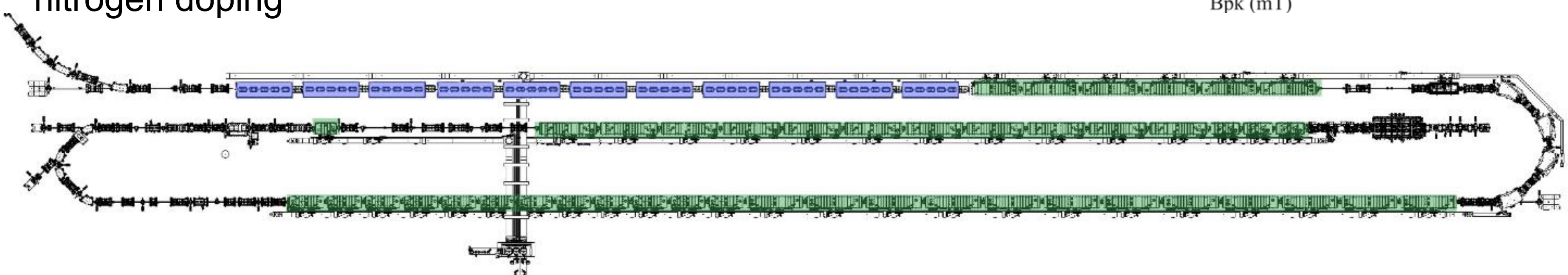
FRIB Energy Upgrade to 400 MeV/nucleon
Science Case Made, Technology Being Demonstrated



- Community made science case
  - **Luminosity gain over 50** for rarest isotopes
  - Energy well-matched to exploring **physics of neutron-star merger**
- Approach
  - Add 11 cryomodules, each with 5 elliptical β=0.65 resonators operating at 644 MHz

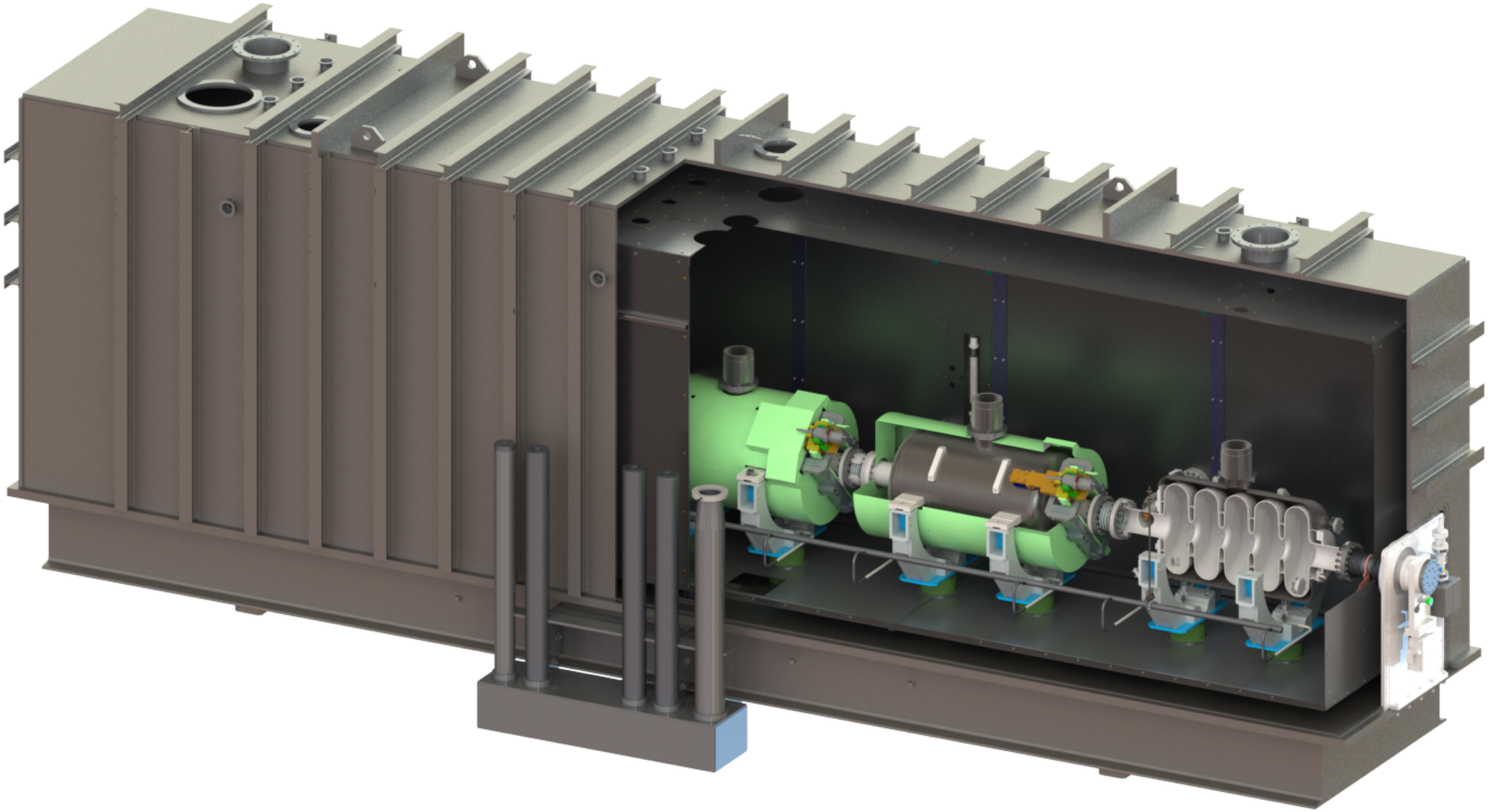


- Technology being demonstrated with MSU funds and DOE/HEP Grant
  - Received 2 resonators, electropolished (EP), degassed
  - R&D of the RF surface processing is being pursued. Dewar-tests at 2 K demonstrate design goal (blue star) can be met with “standard” EP and exceeded with nitrogen doping



FRIB Team Developed Conceptual Design of New Cryomodule

- The design is based on successful development of FRIB cryomodules
- The 6.9-meter long cryomodule consists of five 644 MHz elliptical cavities



Review: Meissner effect/Cavity flux expulsion

- Meissner effect: mG flux expelled as cavity cooled through T_C
- Cavity flux trapping[1]
  - Random distribution of defects traps flux inside the cavities when the flux-pinning force (F_p) exceeds the force acting on the fluxons from the thermal gradient
- Power loss mechanisms
  - Vortex pinning force (low mean-free-path)
  - Viscus drag in flux-flow regime (high mfp)
- “Fast cooldown”: increase dT/dx
  - During SC transition, vortices minimize Gibbs free energy by moving in direction of thermal gradient
  - Higher thermal gradient -> more expulsion
- Motive: reduce trapped flux as much as possible

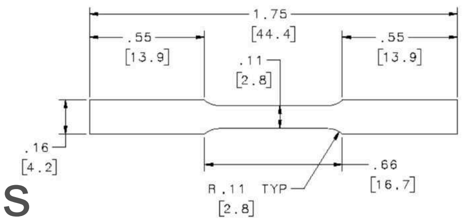
$$f = -\frac{\partial g}{\partial x} = -\frac{\partial g}{\partial T}\frac{\partial T}{\partial x}$$

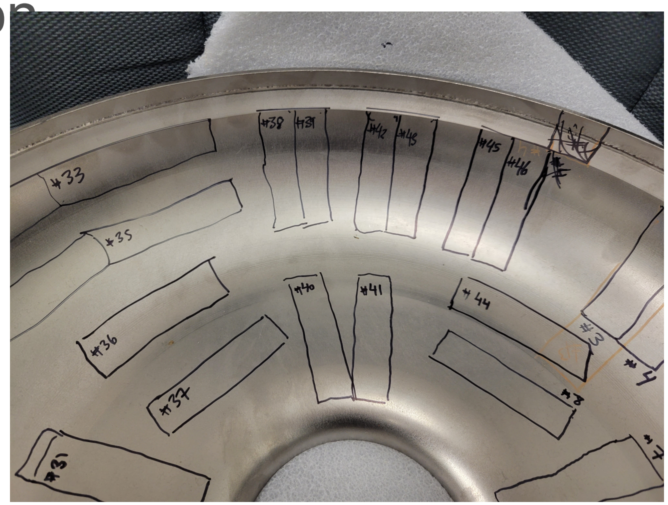
$$f_p = \left|\bar{J}_c \times n\bar{\Phi}_0\right| = J_c B$$

[1]M. Martinello. PhD thesis, 2017.

Dog-bone yield strength study for 900℃ baking

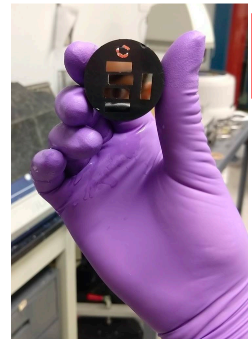
- Is 900 ℃ baking safe for big cavities?
- Flat scrap samples in preparation for 800/900℃ testing
- LB 650 half-cell to cut
  - Longitudinal & axial directions
- Measure YS as a function of baking temp, location
  - As a function of location



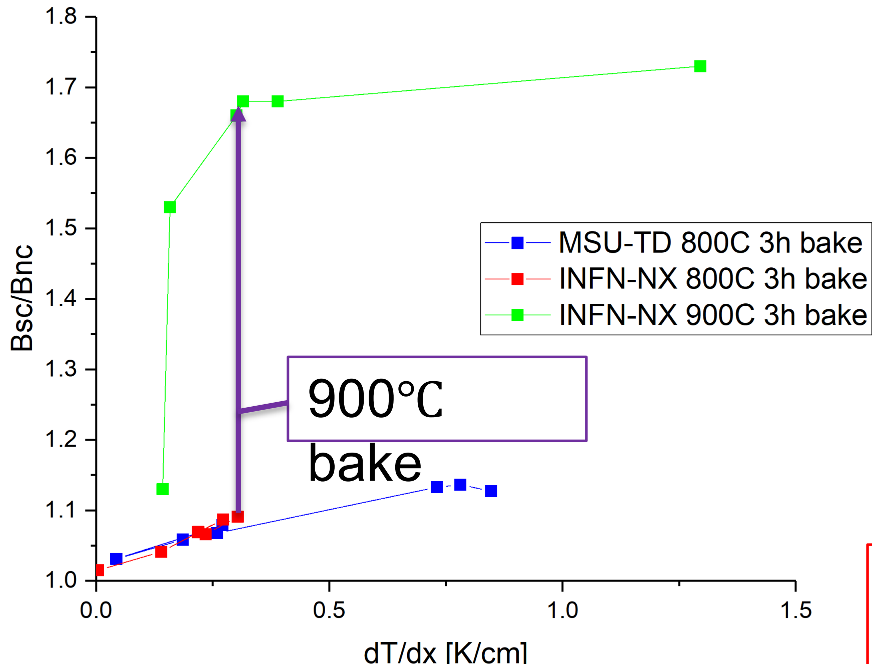


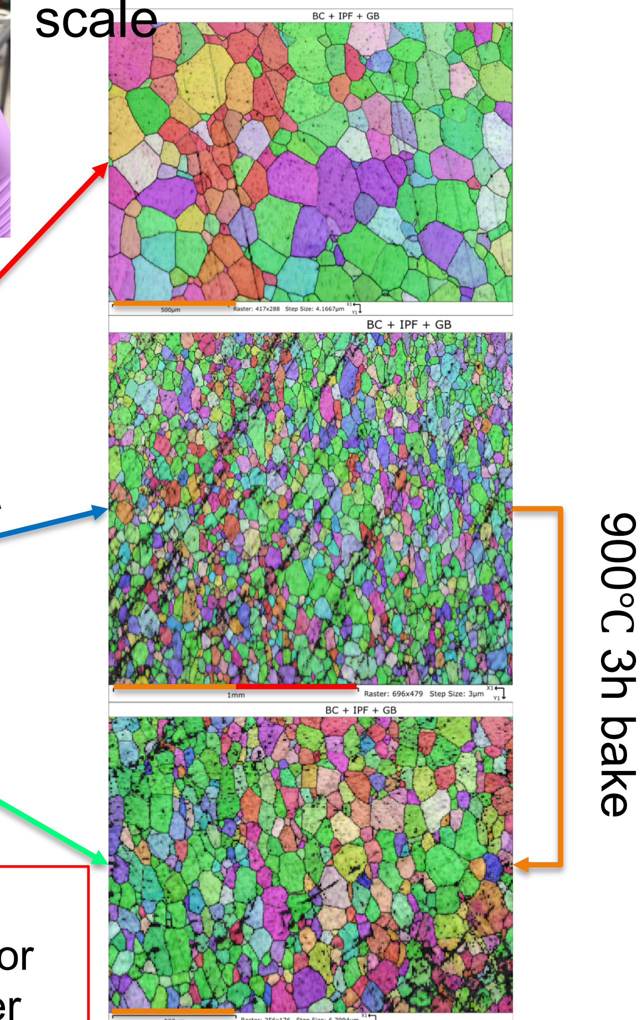
EBSD grain size measurement

- 900℃ 3h bake significantly improved B_{sc}/B_{nc}
- But, GBs not only flux trapping sites, impurities/dislocations complicate the picture**



*all images on same scale

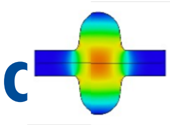


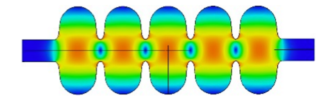


*average grain size: fitted major ellipse diameter (μm)

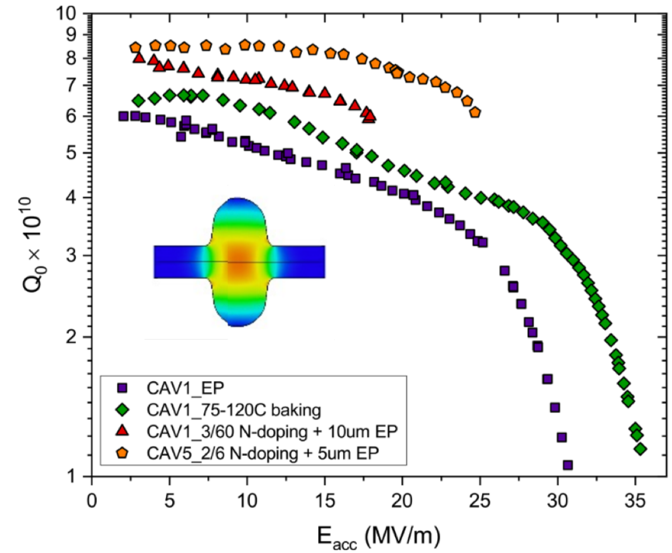
**More: M. Martinello, et al., SRF (2019)

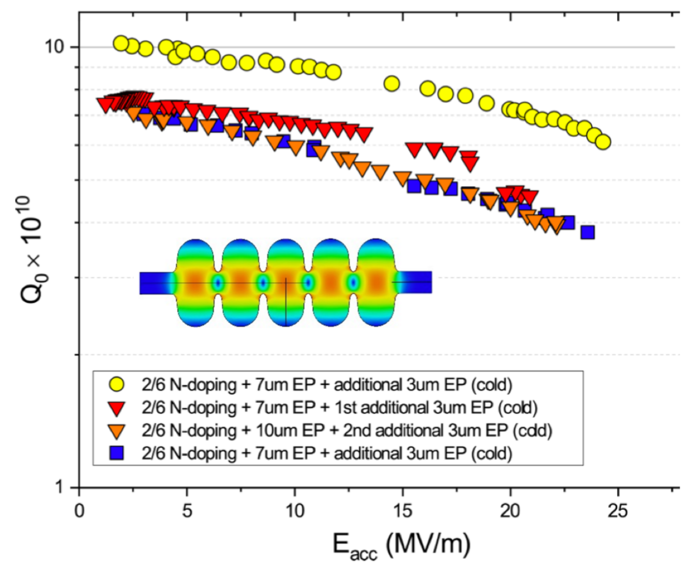
High-β 650 MHz RF stuc





- Single-cell high-β 650 MHz preparations tested
  - N-doping delivered best performance in high-β 650 MHz single-cell cavities
- Multi-cell high-β 650 MHz
  - 2/6 N-doping
  - "cold" EP (12-17 ℃)
  - 900℃ baking: better flux expelling
  - Q_0 = 6-8x10^{10}
    - » G = 260 Ω, $R_s \approx$ 3.7 nΩ

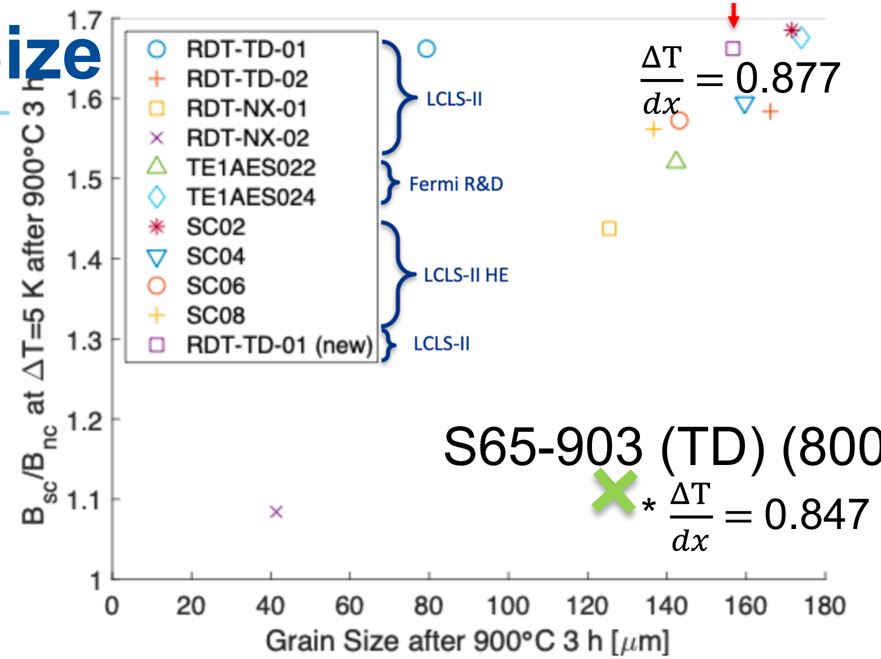


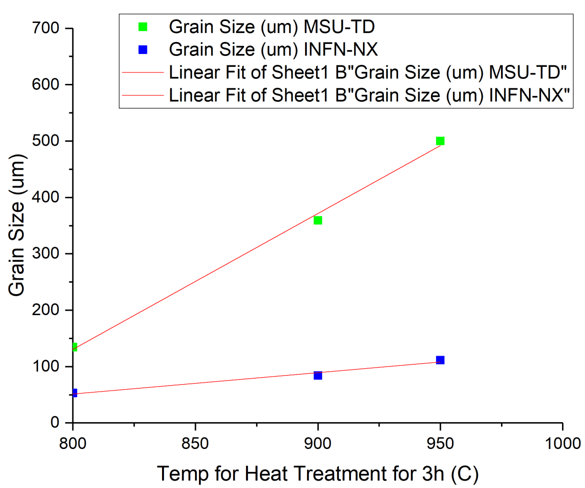


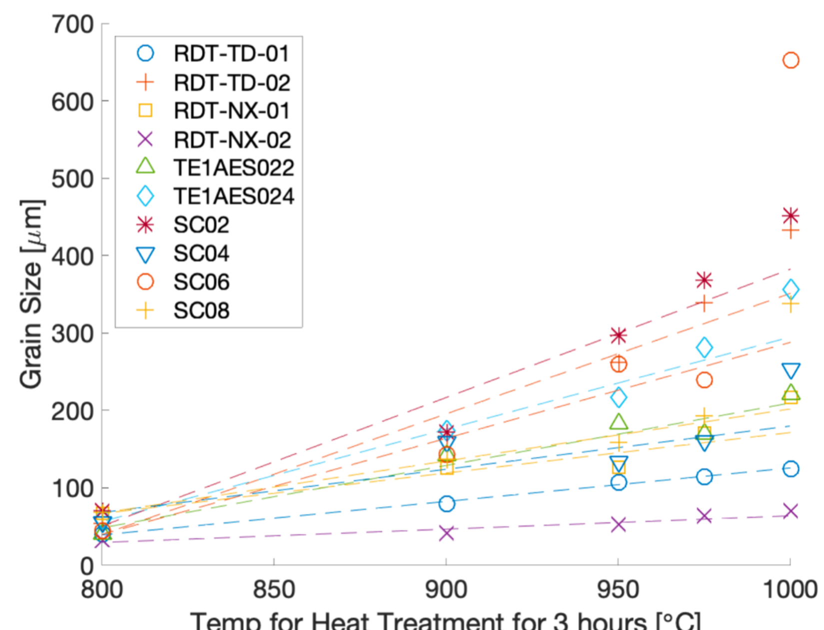
*M. Martinello et al. J. Appl. Phys. **130** 174501 (2021).

Grain Size

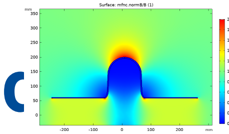
- ΔT = 5K in 1.3 GHz
  - $\frac{\Delta T}{dx} = \frac{5K}{5.7cm} = 0.877\,\frac{K}{cm}$
  - 0.877 K/cm not achieved in LB cavity tests (6.95 cm, $\frac{\Delta T}{dx} \leq 0.3$)
- Grain size vs Temp for heat treatment for 3h



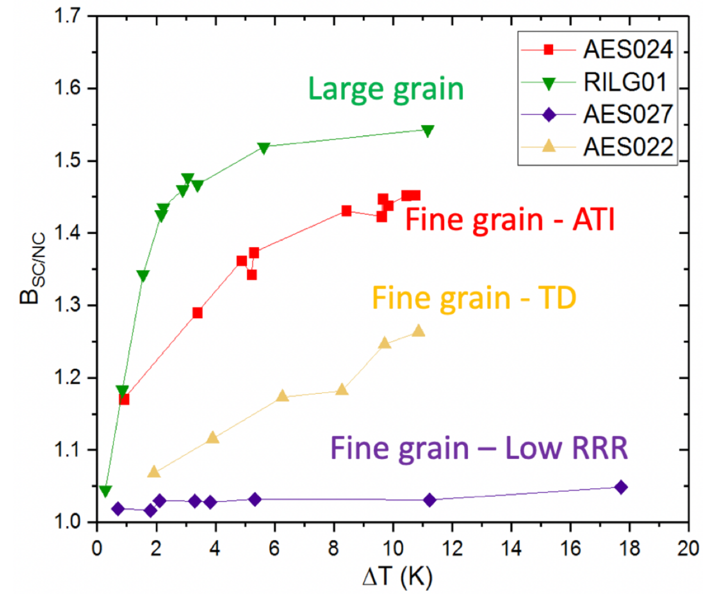


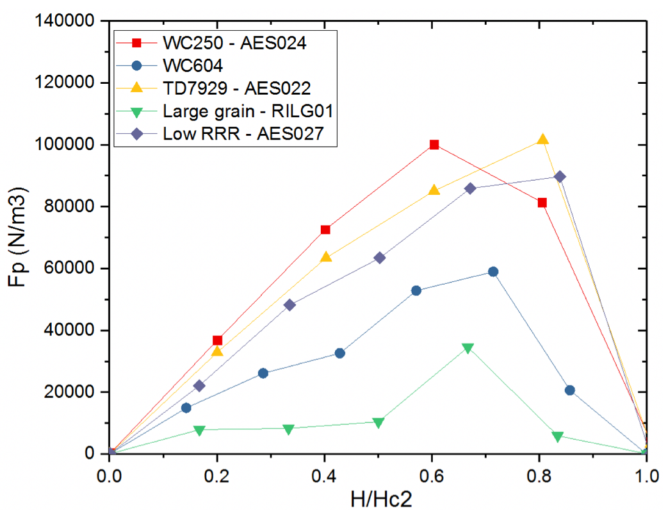


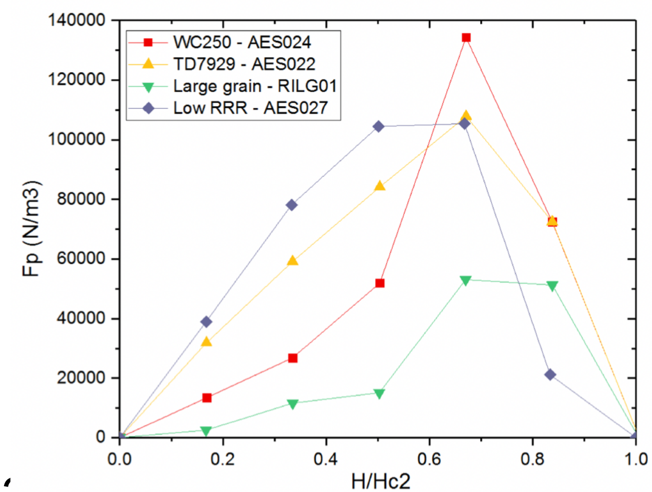
Flux pinning force (Fp): Initial stuc



- Cavities made from Nb from various vendors (ATI and TD) show different pinning properties
- 800℃ baking suggested lower Fp correlated with better flux expulsion properties
- Can Fp be used to pick T treatments?







*M. Martinello, et al., SRF (2019), Dresden, THP013

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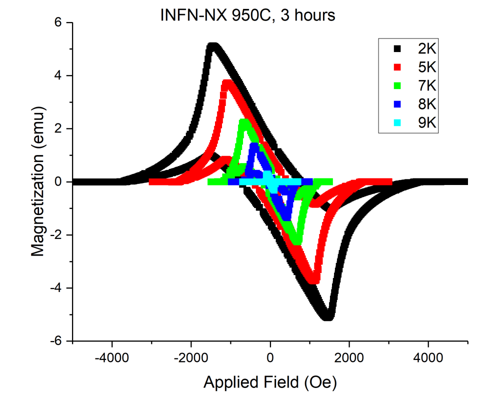
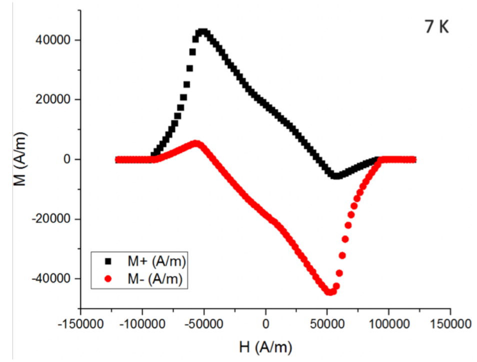
PPMS calculations/process

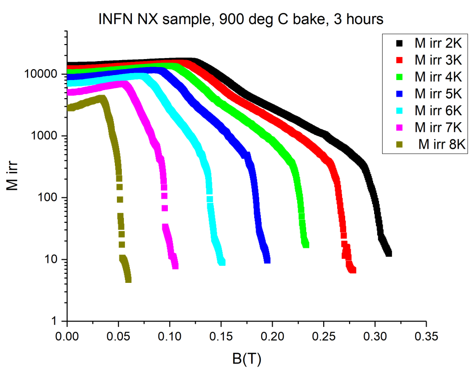


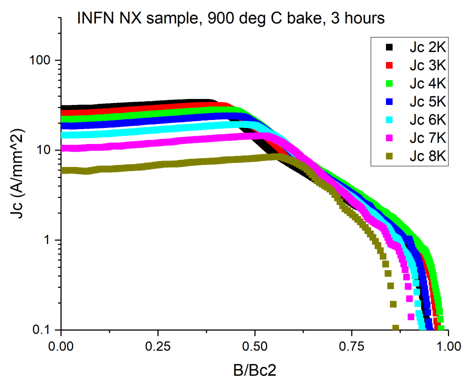


$$M_{irr} = \frac{(M_+ - M_-)}{2} = -\frac{J_c a}{2}$$

$$-4\pi M_{irr} = \frac{a}{3} 4\pi J_c$$

$$J_c = -\frac{3M_{irr}}{a}$$





Multi-cell low-β 644 MHz RF studies

- N-doping
  - 2/0 recipe applied in two $\beta = 0.65$ 644 MHz 5-cell cavities
- Furnace bake
  - 300℃, 3h
- FRIB400 min spec achieved, but further improvements in Q_0 highly motivated