High-Q development for medium-velocity 5-cell elliptical ~650 MHz superconducting cavities for hadron linacs

Kellen E. McGee, FNAL/MSU

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Outline

- Motivation for 650 MHz
- High-β 650 MHz ($\beta \approx 0.9$)*
- Low-β 650 MHz ($\beta \approx 0.6$)**
- Flux expulsion studies
- Materials studies

*M. Martinello et al.:

Journal of Applied Physics ARTICLE scitation.org/journal/jap

Q-factor optimization for high-beta 650 MHz cavities for PIP-II

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M. Martinello,[1,a)] D. J. Bice,[1] C. Boffo,[1] S. K. Chandrasekeran,[1] G. V. Eremeev,[1] F. Furuta,[1] A. Grassellino,[1] O. Melnychuk,[1] D. A. Sergatskov,[1] G. Wu,[1] and T. C. Reid[2]

AFFILIATIONS

[1]Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
[2]Argonne National Laboratory, Argonne, Illinois 60439, USA

[a)]Author to whom correspondence should be addressed: mmartine@fnal.gov

**K. McGee et al.:

PHYSICAL REVIEW ACCELERATORS AND BEAMS **24,** 112003 (2021)

Medium-velocity superconducting cavity for high accelerating gradient continuous-wave hadron linear accelerators

K. McGee,[1] S. Kim,[1] K. Elliott,[1] A. Ganshyn,[1] W. Hartung,[1] E. Metzgar,[1] P. Ostroumov,[1] L. Popielarski,[1] J. Popielarski,[1] A. Taylor,[1] T. Xu,[1] M. P. Kelly,[2] B. Guilfoyle,[2] and T. Reid[2]
[1]*Michigan State University, East Lansing, Michigan 48824, USA*
[2]*Argonne National Laboratory, Argonne, Illinois 60439, USA*

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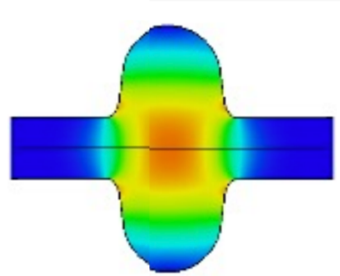
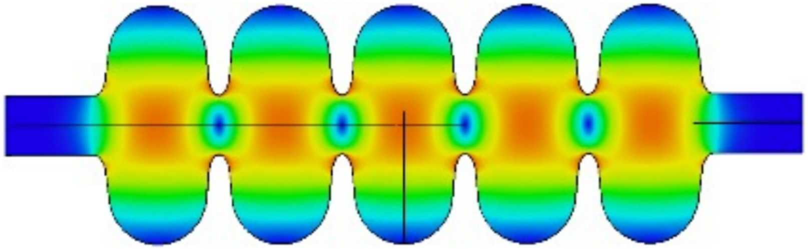
We present the first rf studies of the medium-β superconducting radio frequency (SRF) elliptical cavities designed for Michigan State University's Facility for Rare Isotope Beams (FRIB) energy upgrade linac. The proposed energy upgrade for this continuous-wave (CW) superconducting linac will double the final beam energy from 200 to 400 MeV/u for the heaviest uranium ions within the 80 m of space available in the FRIB tunnel. Two prototype $\beta_{opt} = 0.65$ 644 MHz five-cell elliptical SRF cavities were fabricated and tested to validate the novel cavity design with three conventional rf recipes: (1) Electropolishing (EP-only), (2) EP + 48 h 120 °C bake (EP + baking), and (3) Buffered chemical Polishing + 48 h 120 °C bake (BCP + baking). The EP-only recipe achieved a 2 K quality factor (Q_0) of 2.3×10^{10} at the FRIB energy upgrade design accelerating gradient (E_{acc}) of 17.5 MV/m, and Q_0 of 1.2×10^{10} at a maximum gradient of 26 MV/m, where the gradient was ultimately limited by the available rf amplifier power available for this

Introduction: Focus on ~650 MHz

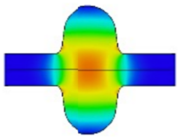
- Motivations
  - To provide the required 800 MeV protons, PIP-II design incorporates "low-β" ($\beta \sim 0.6$) and high-β ($\beta \sim 0.9$) 650 MHz 5-cell elliptical SRF cavities operating at 18.8 MV/m.
    - high-β : $Q_0 \geq 3\times10^{10}$
    - high-β : $\frac{B_{pk}}{E_{acc}} = 3.888$ [mT/(MV/m)]
  - To provide 1 GeV protons (400 MeV U), MSU's Facility for Rare Isotope Beams Energy Upgrade design incorporates "low-β" ($\beta = 0.65$) 644 MHz 5-cell elliptical SRF cavities operating at 17.5 MV/m
    - low-β: $Q_0 \geq 2\times10^{10}$
    - low-β : $\frac{B_{pk}}{E_{acc}} = 4.42$ [mT/(MV/m)]
  - Both applications require unprecedented Q_0 for ~ 650 MHz!



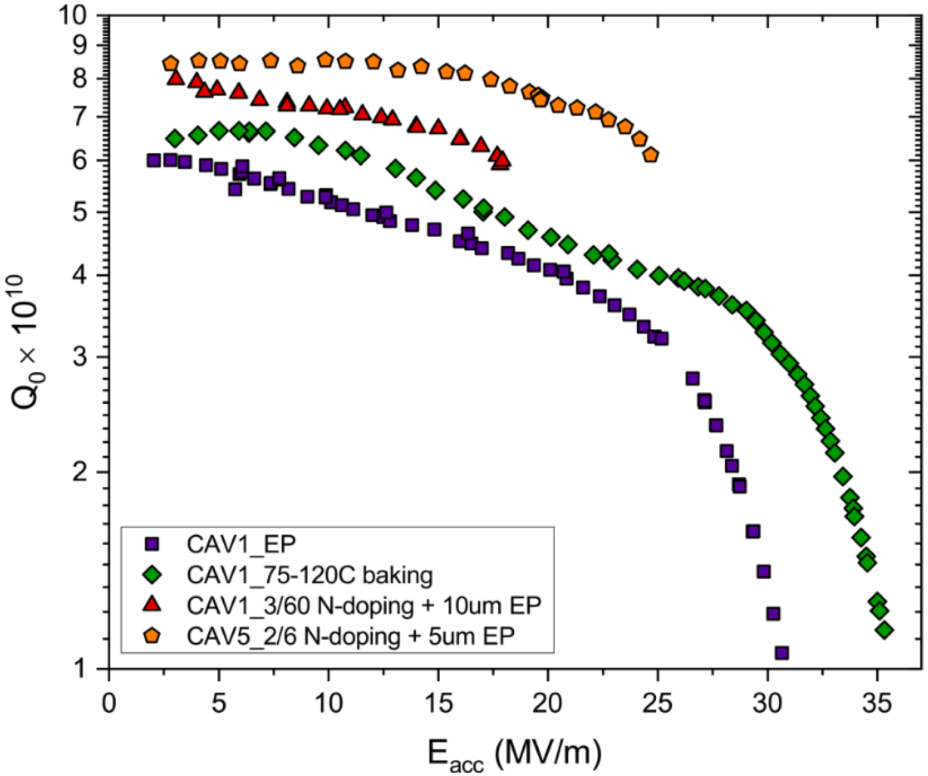
Single & Multi-cell high-β 650 MHz RF studies



Single-cell high-β 650 MHz RF studies*

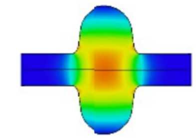


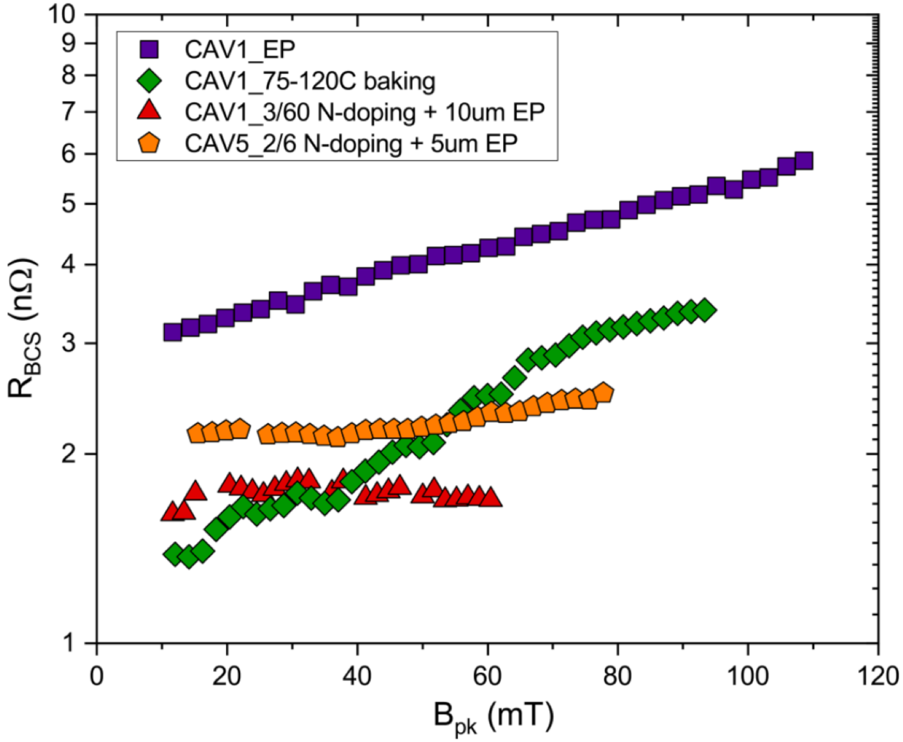
- Single-cell high-β 650 MHz preparations tested
  - Electropolishing
  - Low-T baking
    - 4h/75°C—48h/120°C baking
  - N-doping
    - Minutes doping/minutes annealing: 3/60, 2/6
    - Post-doping cold EP (~15 °C)
- N-doping delivered best performance in high-β 650 MHz single-cell cavities

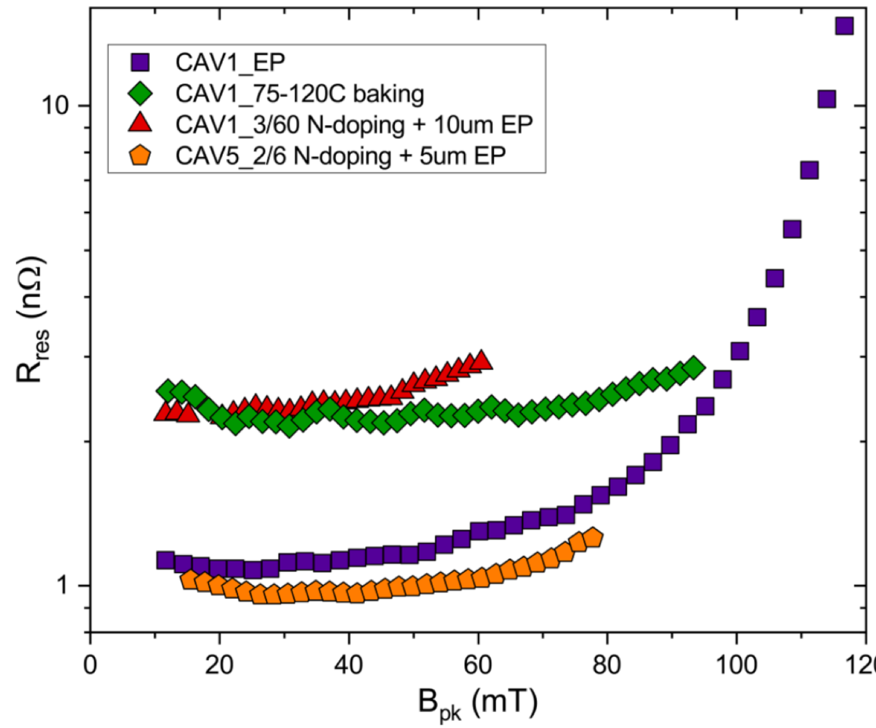


*M. Martinello et al. J. Appl. Phys. **130** 174501 (2021).

Single-cell high-β 650 MHz RF studies*







- 4h/75°C—48h/120°C baking did not mitigate HFQS
- 3/60 N-doping improves R_{BCS} but suffers in R_0
- 2/6 N-doping improves R_{BCS} and R_0

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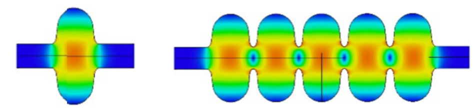
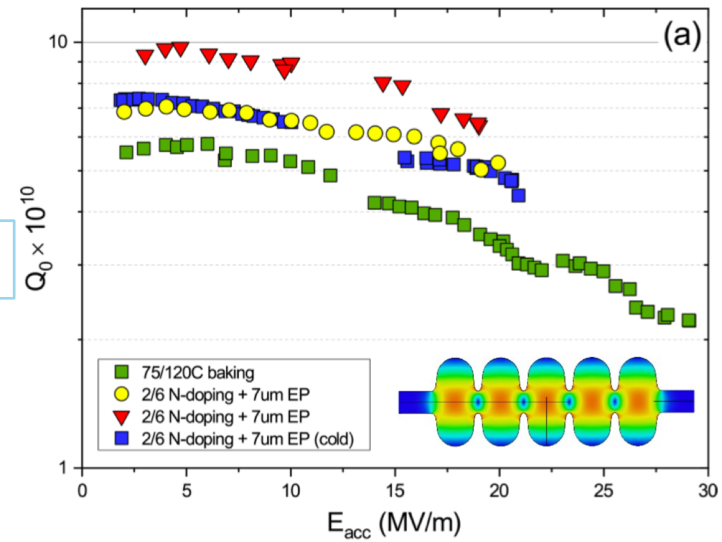
Multi-cell High-β 650 MHz RF studies*

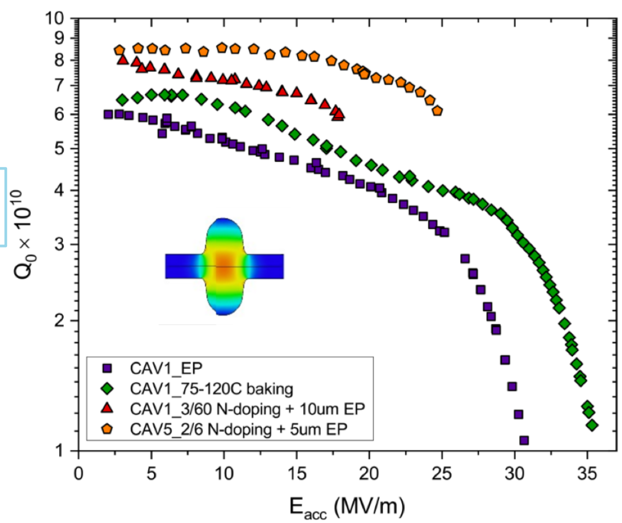


- 2/6 N-doping + cold EP generally delivered best performance in multicell cavities
- $Q_0 \approx 8{\times}10^{10}$ single-cell
- $Q_0 \approx 6{\times}10^{10}$ multicell

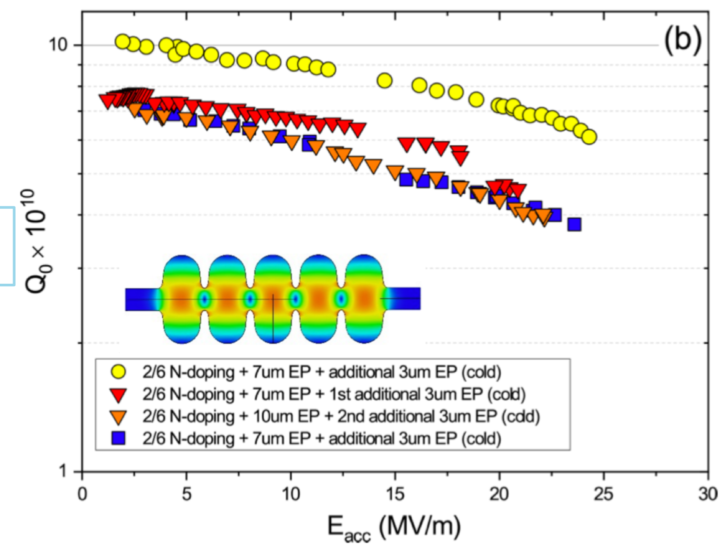
Multicell



Single-cell



Multicell



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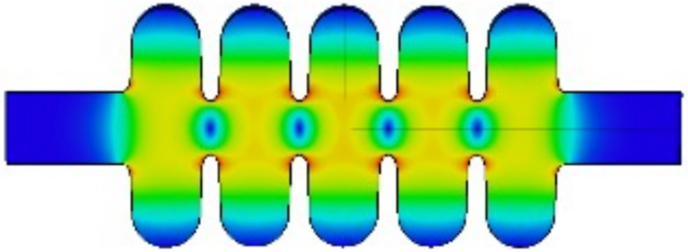
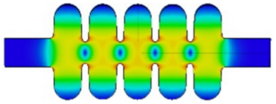
Multi-cell low-β 644 MHz RF studies

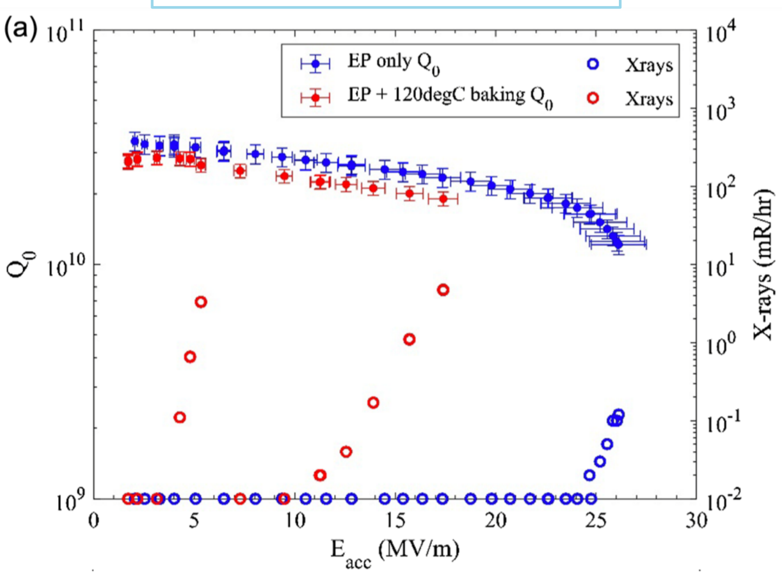


Multi-cell low-β 644 MHz RF studies*

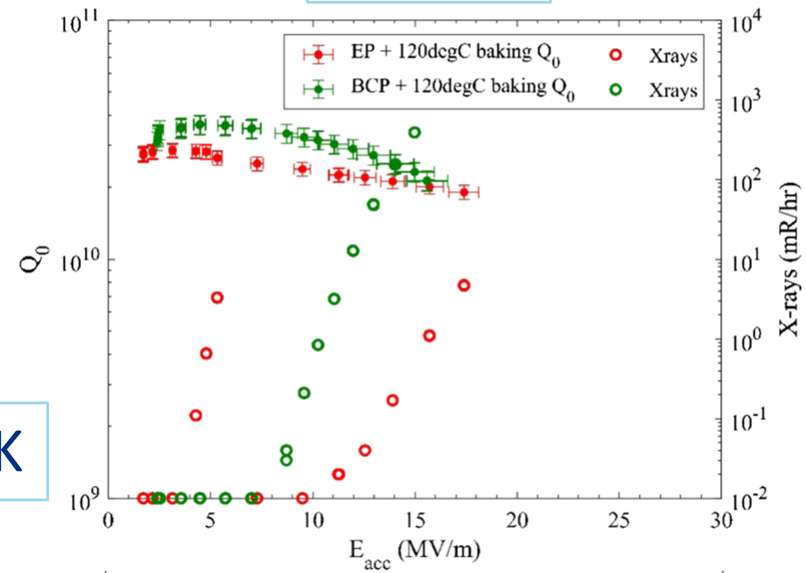


- Preliminary studies: conventional preparations

Effect of 120℃ baking



EP vs. BCP



@2K

  - EP-only had best performance at $Q_0 = 2.3{\times}10^{10}$@17.5 MV/m
  - 120℃ baking increased R_0 and MFQS
  - BCP increased MFQS

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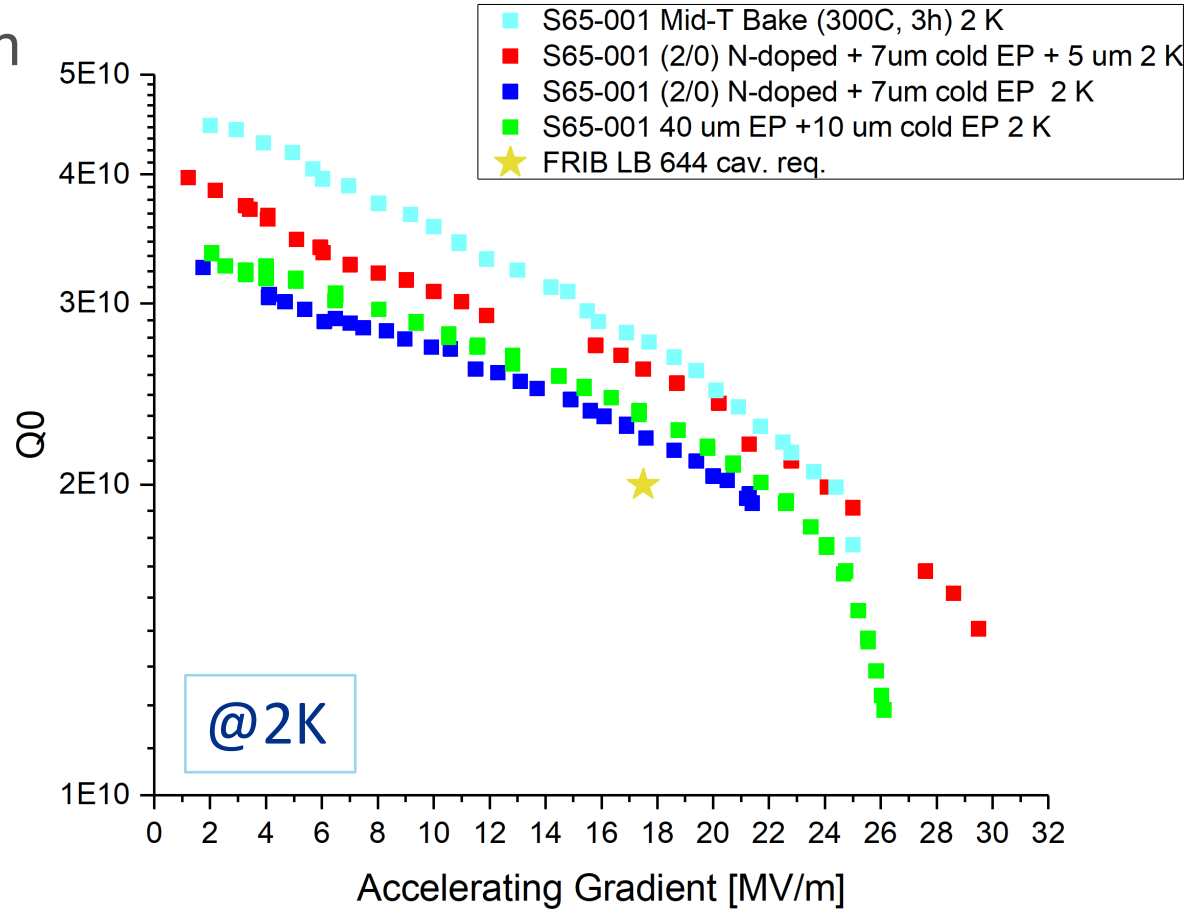
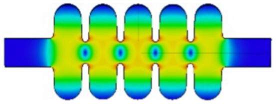
Multi-cell low-β 644 MHz RF studies

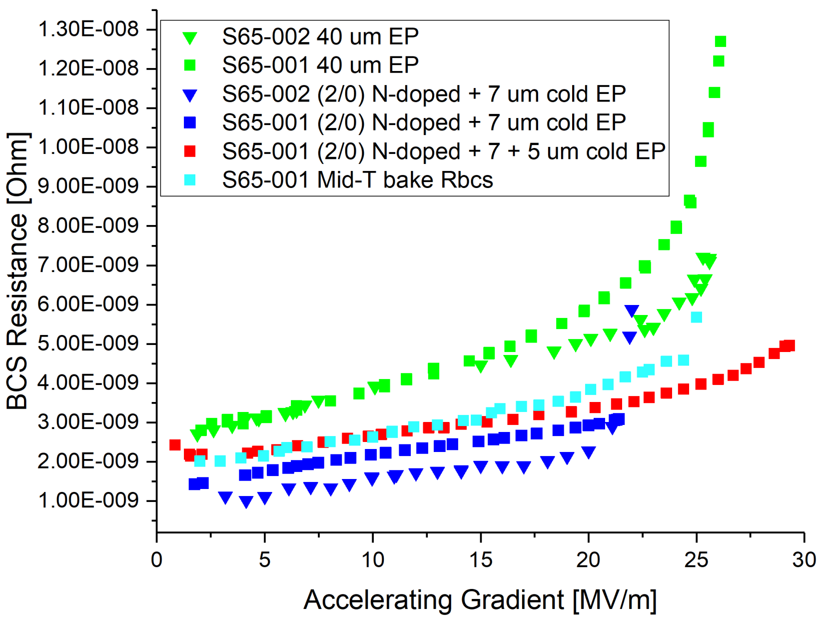
- N-doping
  - 2/0 recipe applied in two $\beta = 0.65$ 644 MHz 5-cell cavities
- Mid-T bake
  - 300℃, 3h
- FRIB400 min spec achieved, but further improvements in Q_0 highly motivated

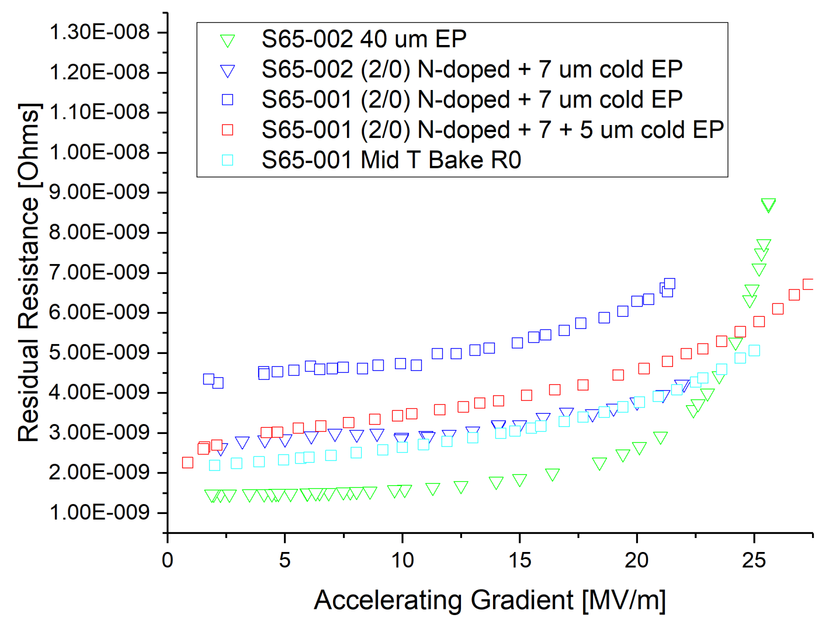


Multi-cell low-β 644 MHz RF studies

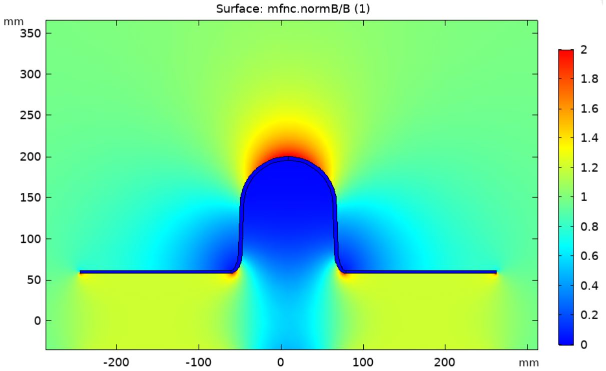


- (2/0) N-doping
  - R_{BCS} **reduced 60%** from EP treatment, R_0 **increased 30%** from EP treatment
- Mid-T baking
  - R_0 **decreased by 19%** from N-doped test, R_{BCS} **increased by 7.5%** from N-doped test.

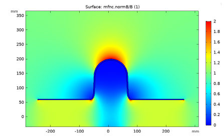




Flux expulsion & sample studies

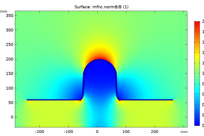


Flux expulsion & sample studies

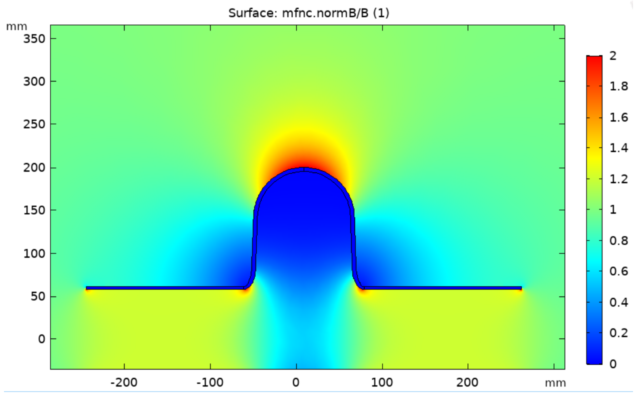


- Motivation
  - While N-doping has clear advantages in Q_0, flux sensitivity is also increased
  - Understanding mechanisms affecting trapped flux in cavities key to extracting best performance
  - If easily measurable physical properties of raw Nb material (i.e., grain boundaries, or flux pinning force) can be correlated with the cavity flux performance, we may write material specifications for Nb vendors!
- Methods
  - PPMS instrument allows measurement of flux pinning force Fp on a small Nb sample
  - Thermocycling RF cavity in imposed magnetic field, measuring magnetic field outside equator before/after SC transition

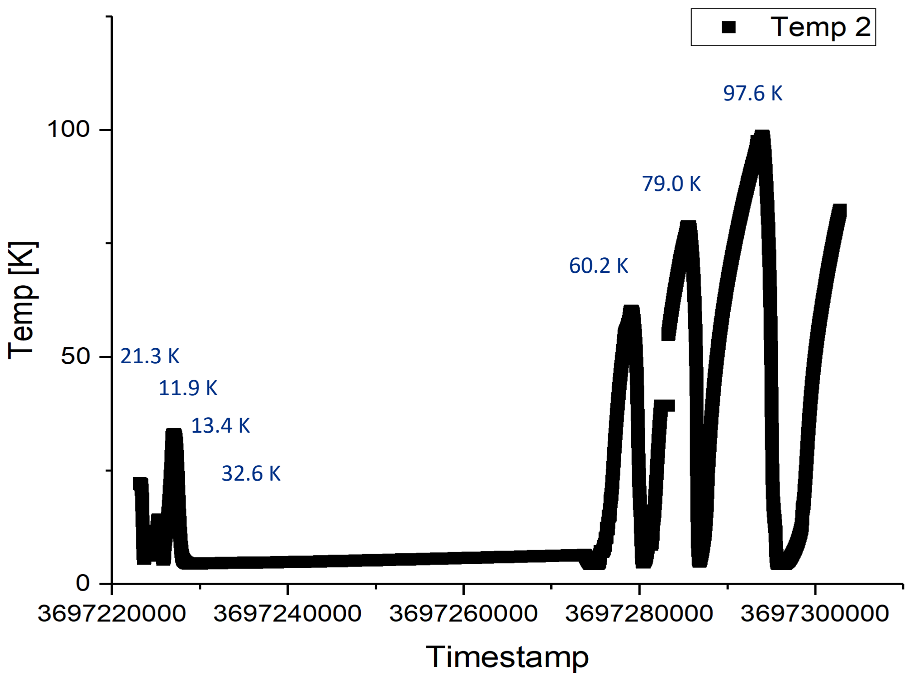
Flux expulsion measurements



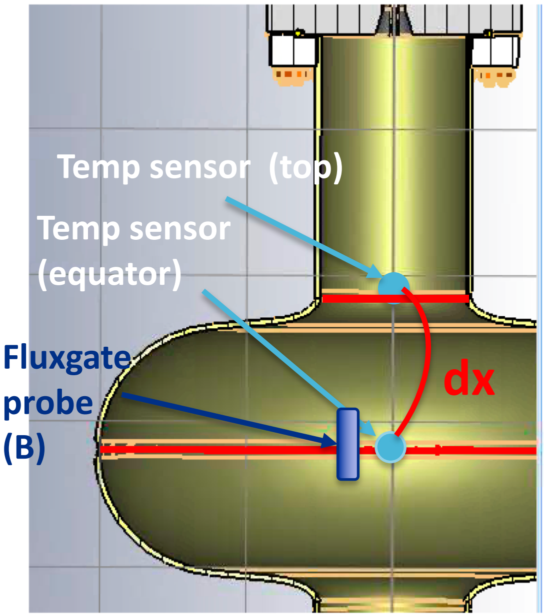
- Expulsion: Measured as B_{sc}/B_{nc} vs. $\Delta T/dx$
- $\frac{\Delta T}{dx} = \frac{T(top) - T(equator=9.2K)}{x(top) - x(equator)}$



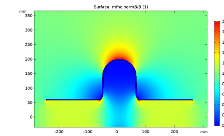
Example profile of thermocycles conducted in B61S-EZ-001 test:



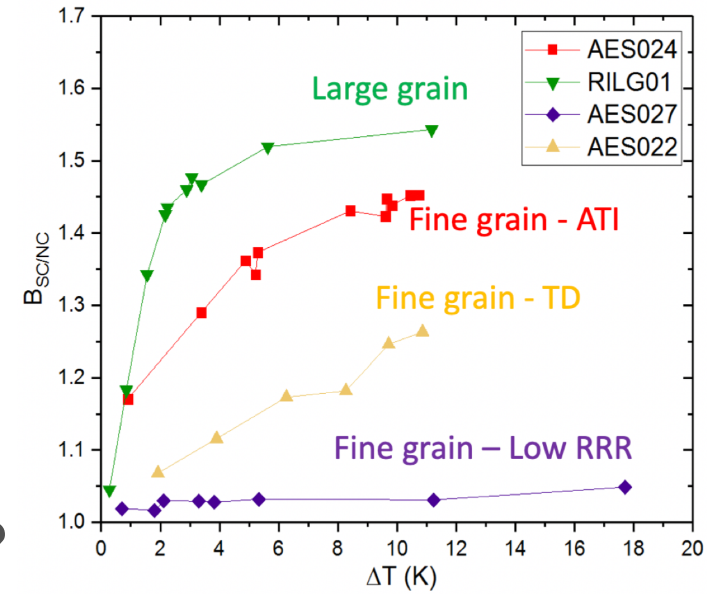
Experimental setup

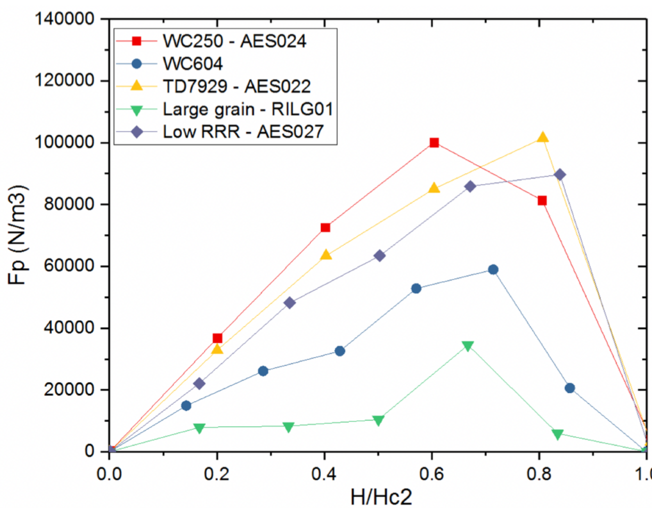


Flux pinning force (Fp): Introduction*

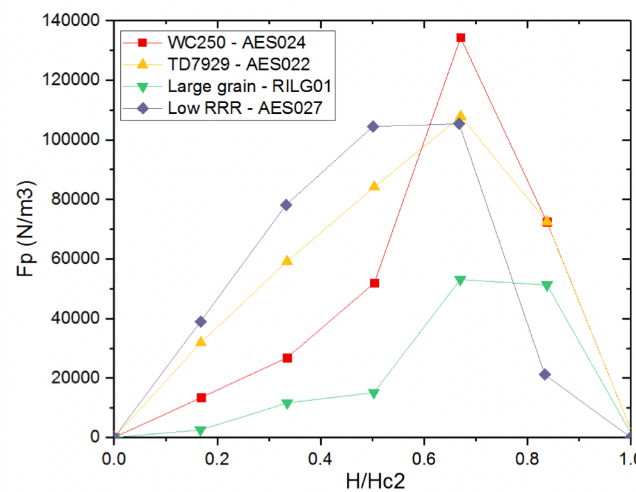


- Cavities made from Nb from various vendors (ATI and TD) show different pinning properties
- 800°C baking suggested lower Fp correlated with better flux expulsion properties
- Can Fp be used to pick T treatments?





800°C bake



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

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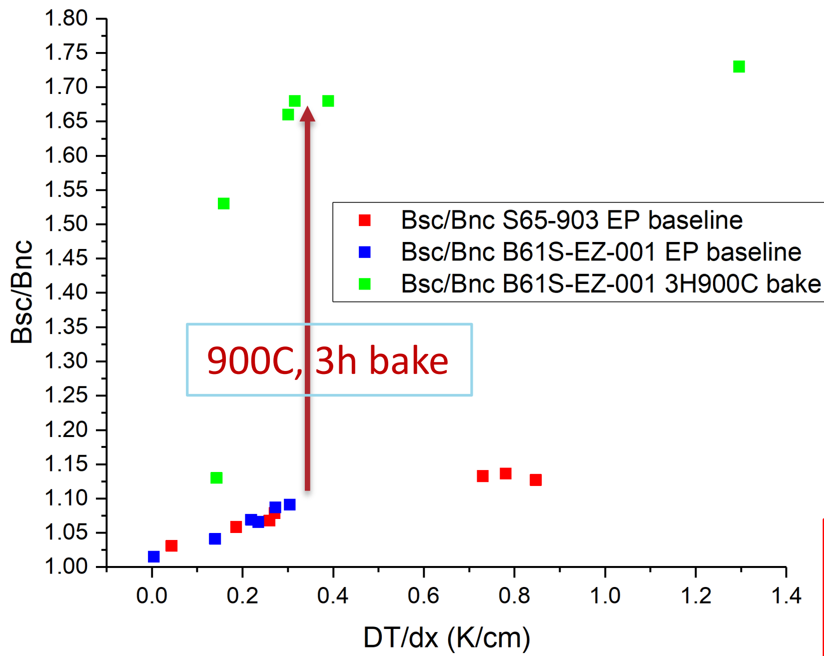
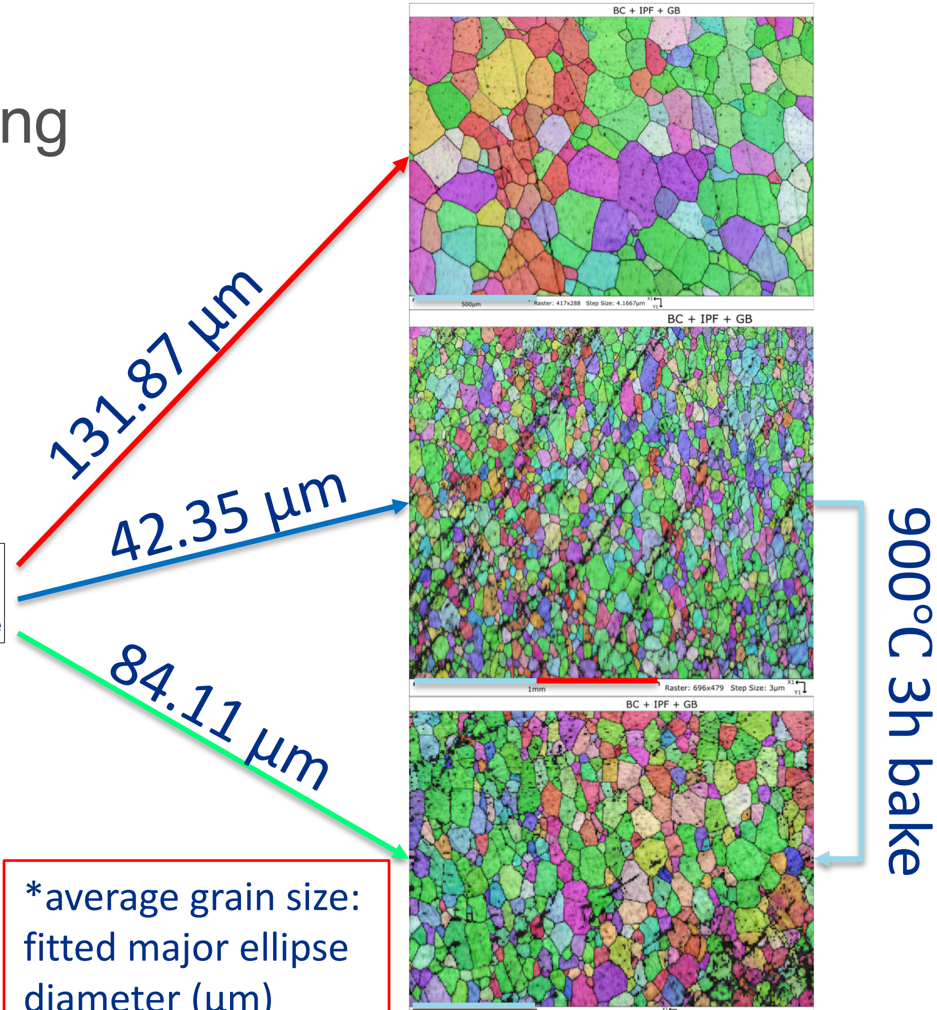
Low-β 644 & 650 MHz single-cell

*all images on same scale

- 900C 3h bake significantly improved Bsc/Bnc
- But, GBs not only flux trapping sites, impurities/dislocations important**

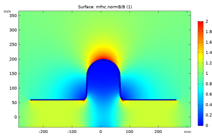




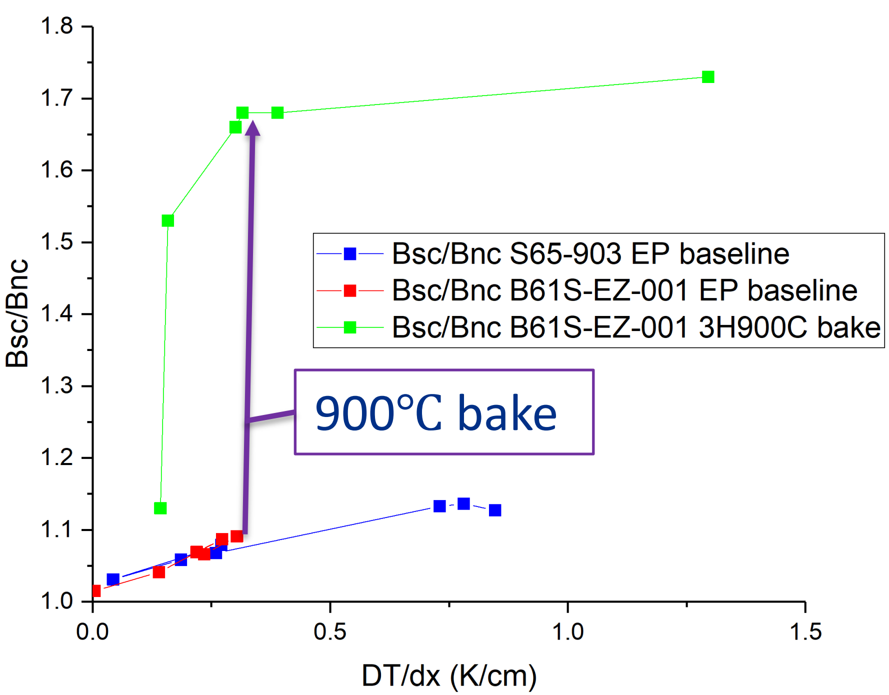
*average grain size: fitted major ellipse diameter (µm)

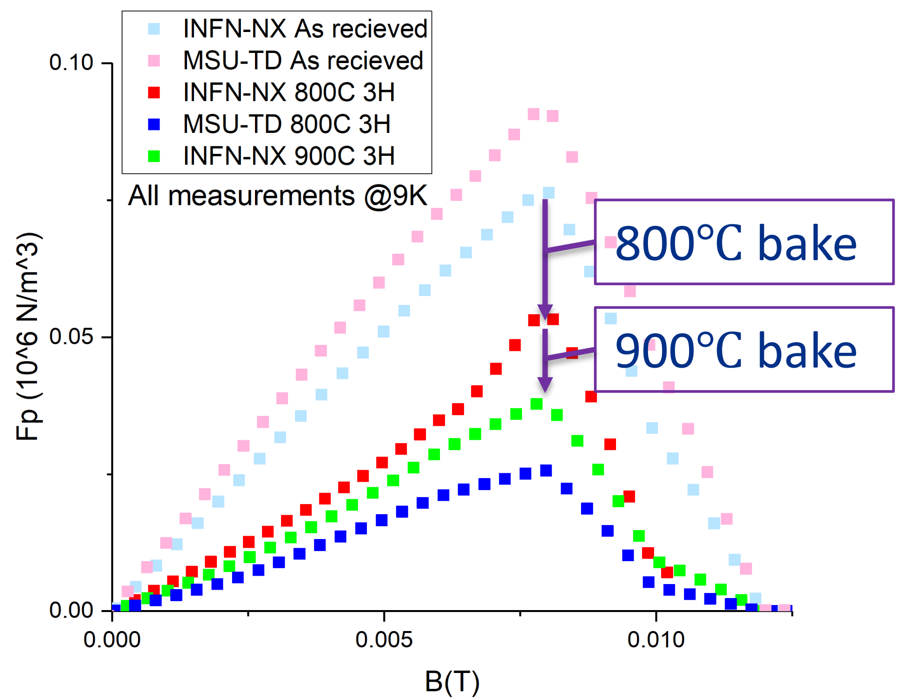
**More: M. Martinello, et al., SRF (2019)

Flux Pinning



- Cavities with similar flux expulsion performance have similar Fp curve
- Better flux expulsion corresponds to lower Fp due to baking
- Relate Fp to Bsc/Bnc with more data?



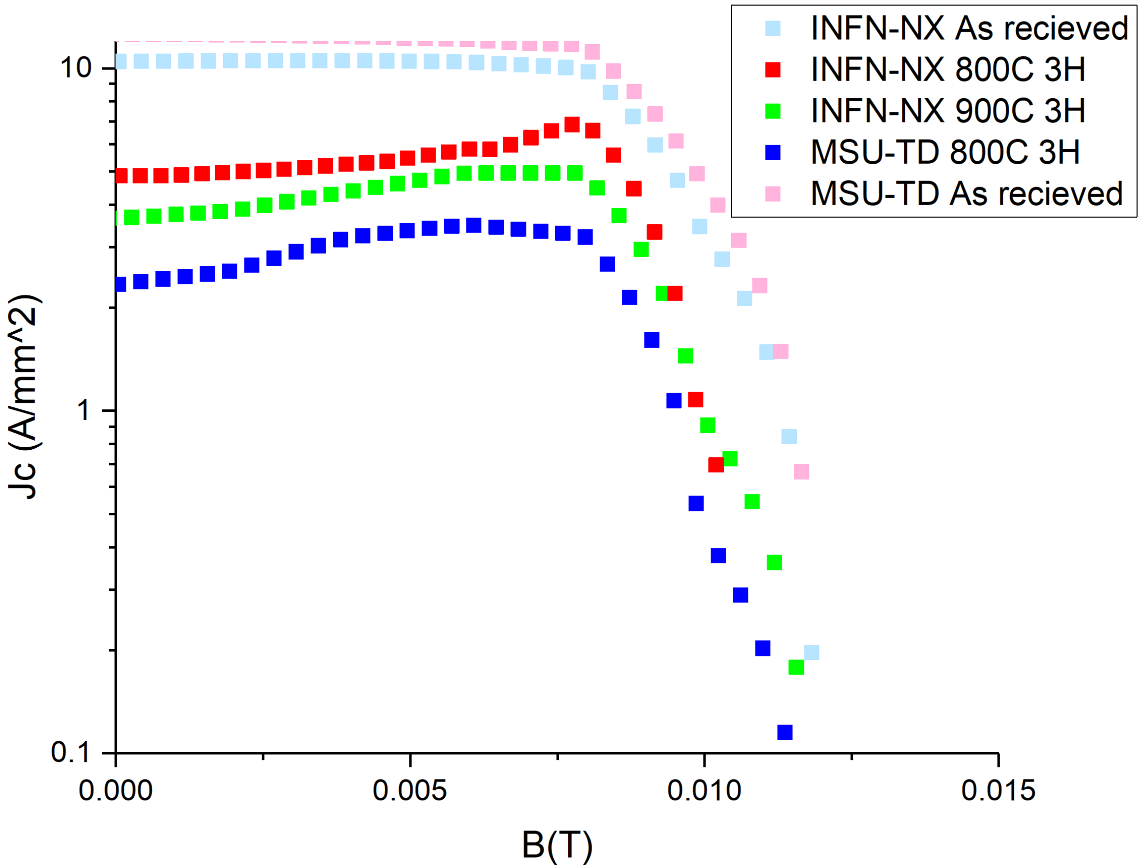


Summary of results

- N-doping was successful at achieving FRIB and PIP-II Q requirements in both low-β and high-β ~650 MHz cavities
- Mid-T baking is promising as 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
- Further studies focused on Mid-T baking and flux expulsion underway in single-cell, and multicell 644 MHz and 650 MHz cavities.

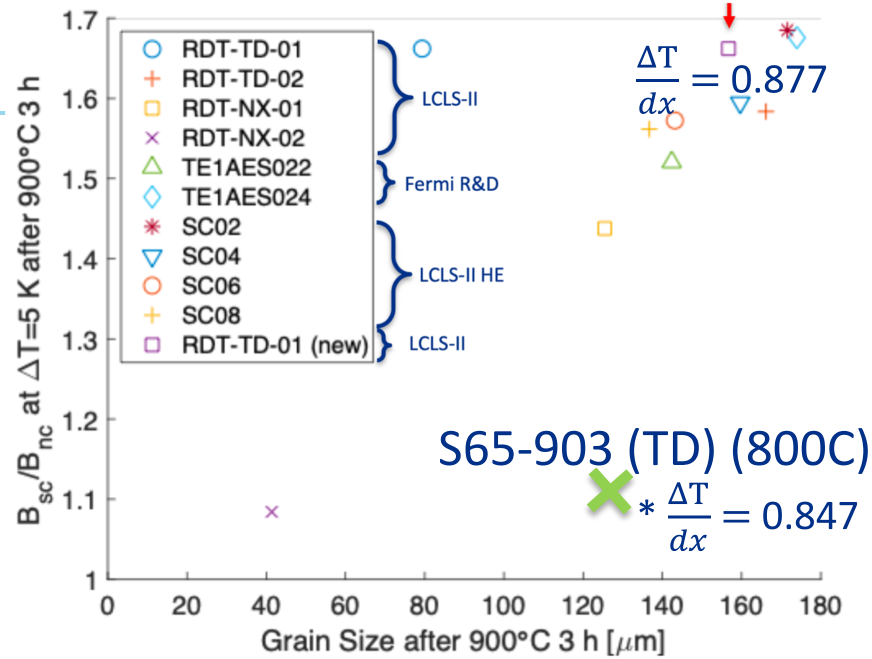
Backup

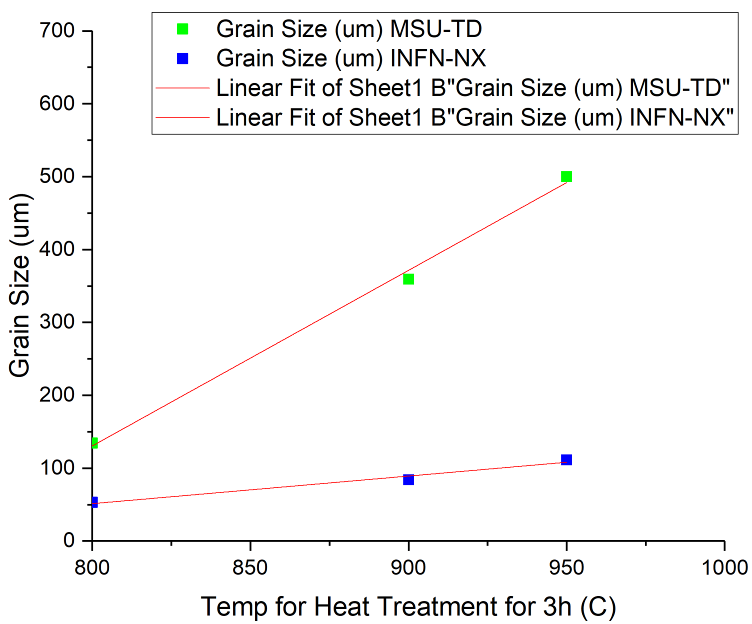
Critical current

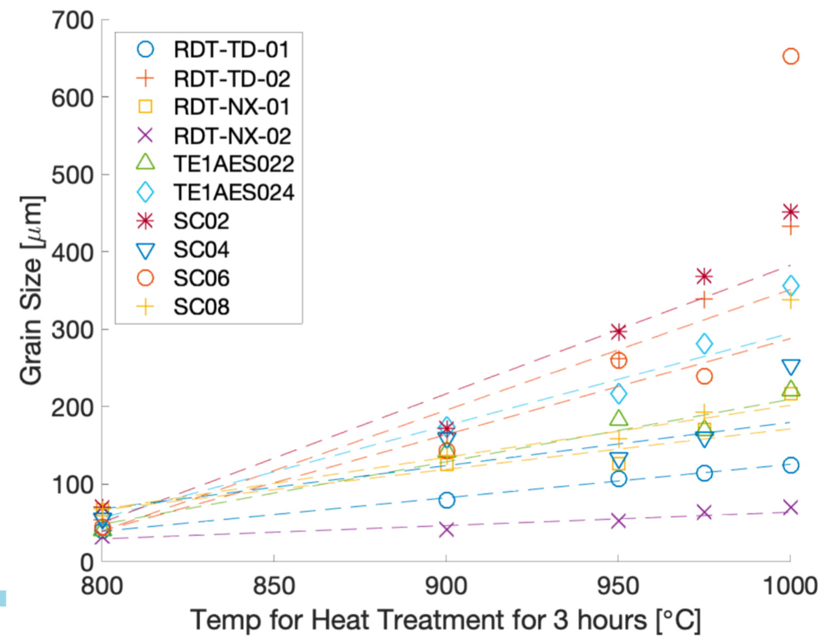


Grain Size

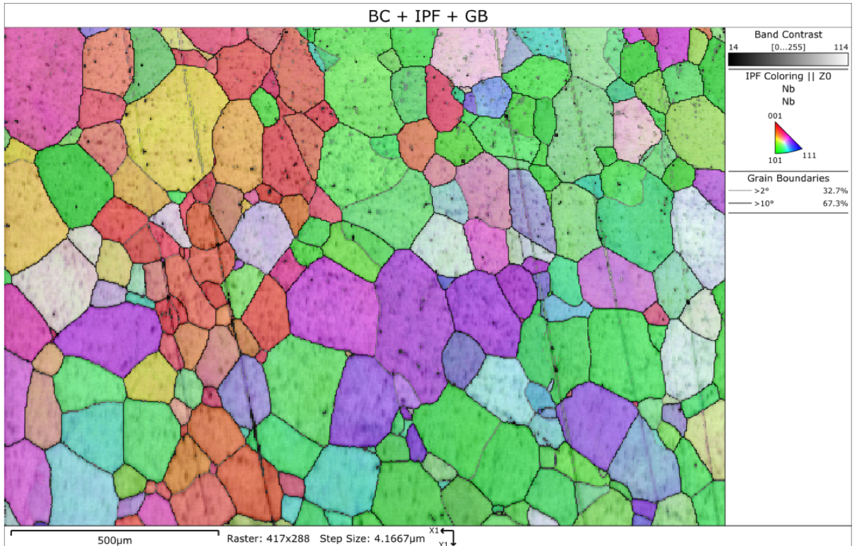
- ΔT = 5K in 1.3 GHz
  - $\frac{\Delta T}{dx} = \frac{5K}{5.7cm} = 0.877\frac{K}{cm}$
  - 0.877 K/cm not achieved in LB cavity tests (6.95 cm, $\frac{\Delta T}{dx} \leq 0.3$)
- Grain size vs Temp for heat treatment for 3h





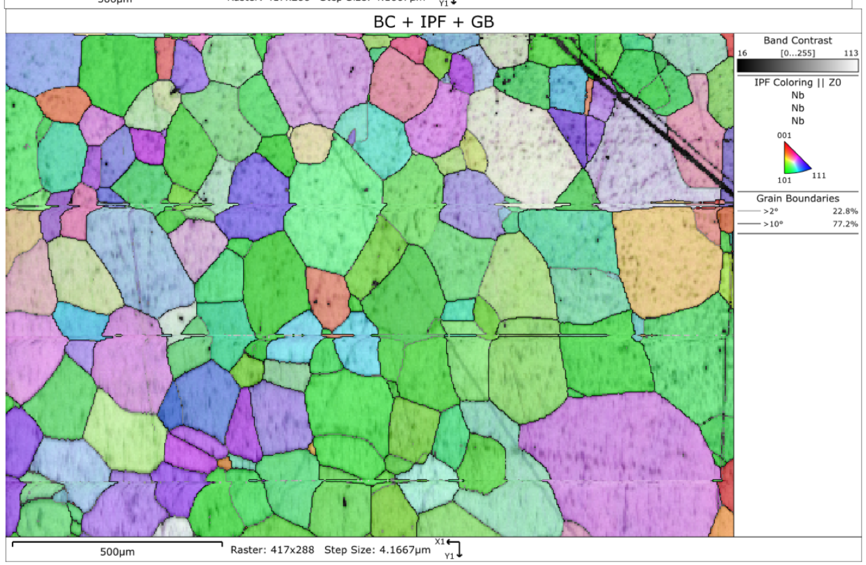


Constant Temp (800C at 3, 6, & 9 hours)



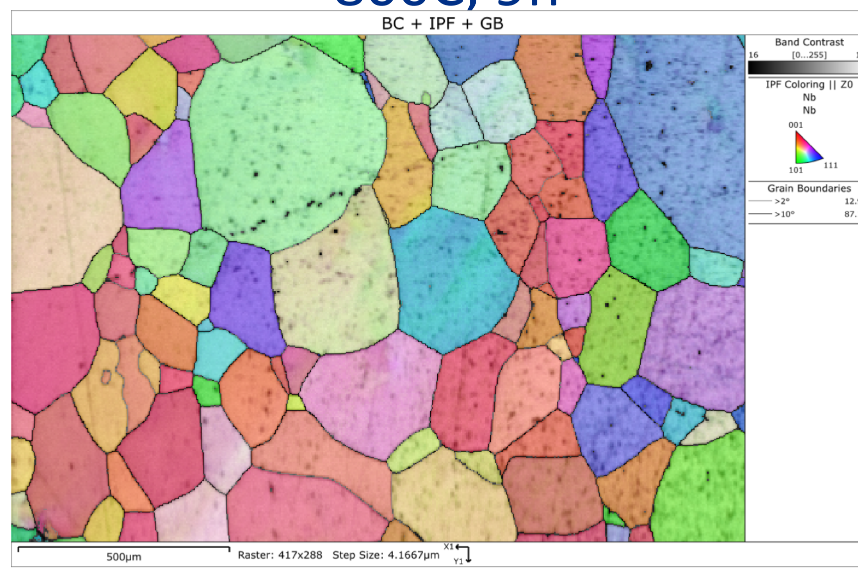
800C, 3h

*all images on same scale



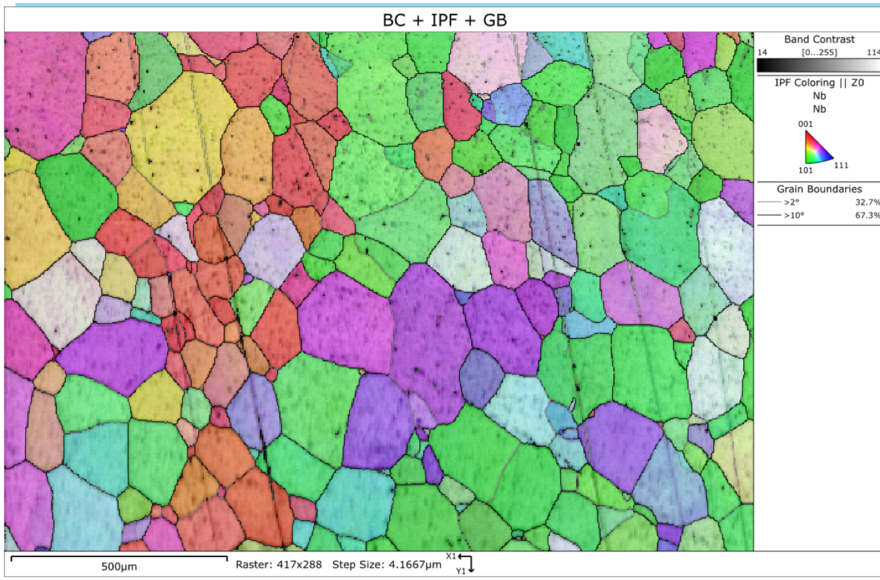
800C, 6h

800C, 9h

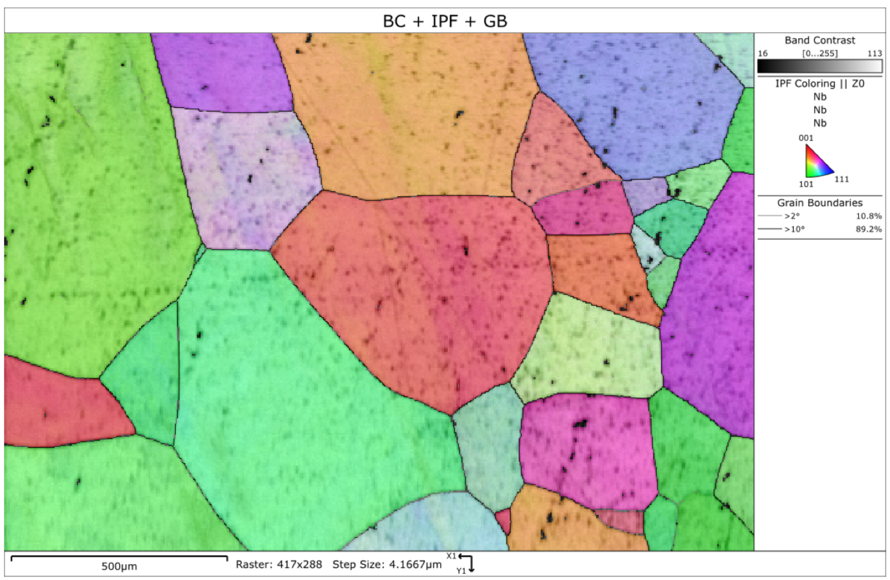


Constant Time (800C, 900C, 950C at 3 hours)

*all images on same scale



800C



900C

950C