Magnetic Flux Expulsion in Superconducting Radio-Frequency Niobium Cavities Made from Cold Worked Niobium

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Outline

- Superconducting Radio Frequency Cavities
- Motivation
- Experimental Set Up
- Flux Expulsion and Trapping Measurements
- Summary

Superconducting Radio Frequency (SRF) Cavity

- SRF cavities are the building block of modern particle accelerators.
- Energy is stored in the form of electric & magnetic fields.

The performance of SRF cavities are measured in terms of quality factor as function of accelerating gradient.

$$Q_0 = \frac{\omega U}{P_c} = \omega \frac{\frac{1}{2}\mu_0 \int |H|^2 dV}{\frac{1}{2}R_s \int |H|^2 dS},$$

$$Q_0 = \frac{G}{R_s}$$

$$G = \frac{\omega \mu_0 \int |H|^2 dV}{\int |H|^2 dS}$$

Geometrical constant depends mainly on the shape of cavities

Higher quality factor can be achieved with lower surface resistance

Surface Resistance

$$R_S = R_{BCS}(T) + \boxed{R_0 + R_{Fl}}$$

R_{BCS} is BCS resistance due to unpaired electrons:

$$R_{BCS} = \left(\frac{1}{T}\right) A(\lambda_L, l, \Delta, \xi_0, f_0, T_c) e^{-\frac{\Delta}{k_B T}}$$

R_0 is the residual resistance depends on the purity, dislocations, imperfections ….

R_{Fl} is the resistance due to the trapped flux during the cooldown (vortex dissipation).

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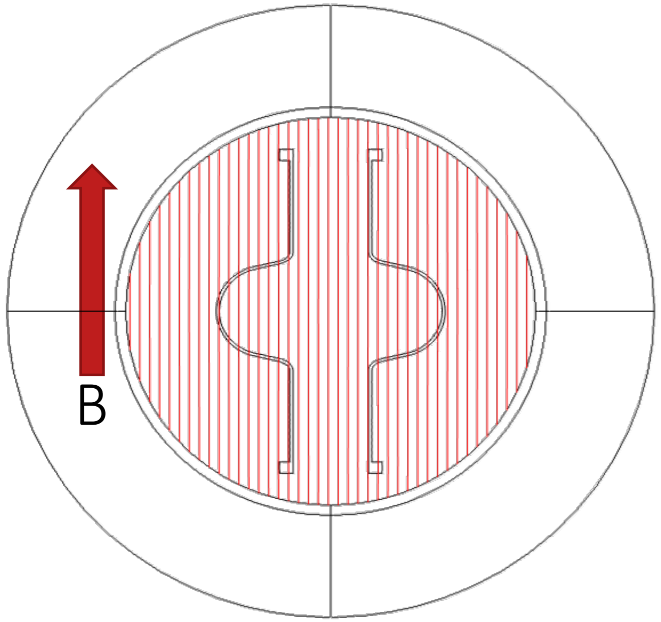
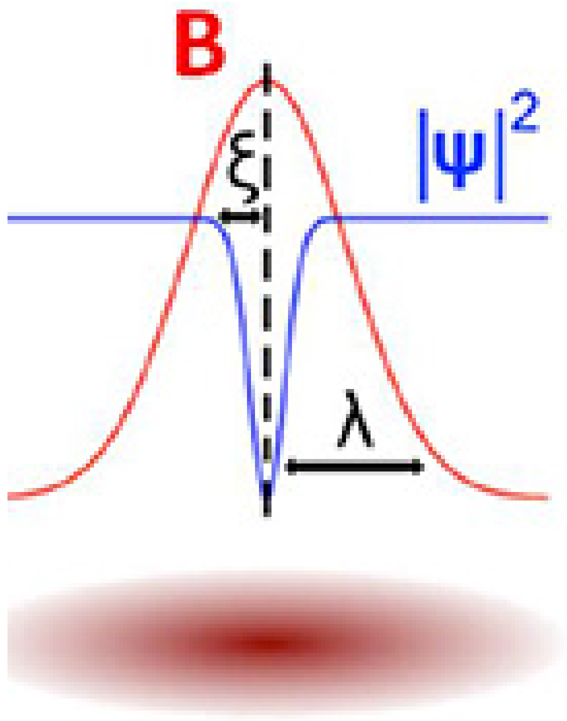
Flux Trapping



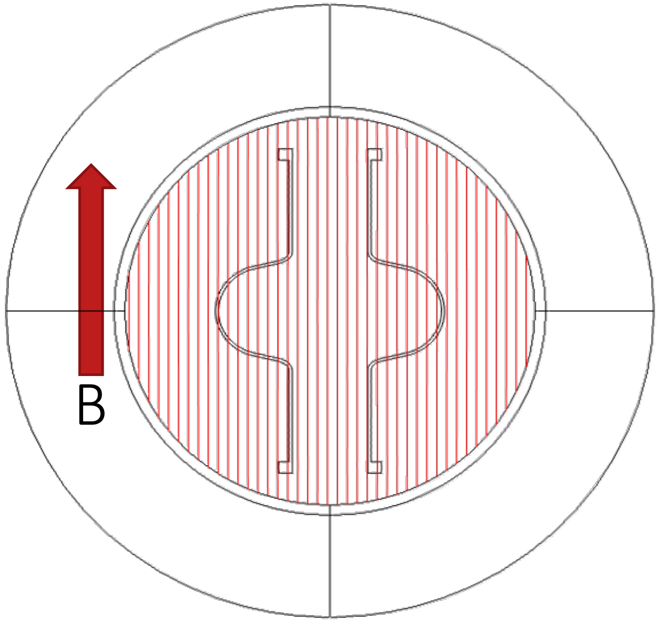


Meissner effect when cavity goes to SC state

Flux trapped in the form of vortices

Jefferson Lab

Flux Trapping



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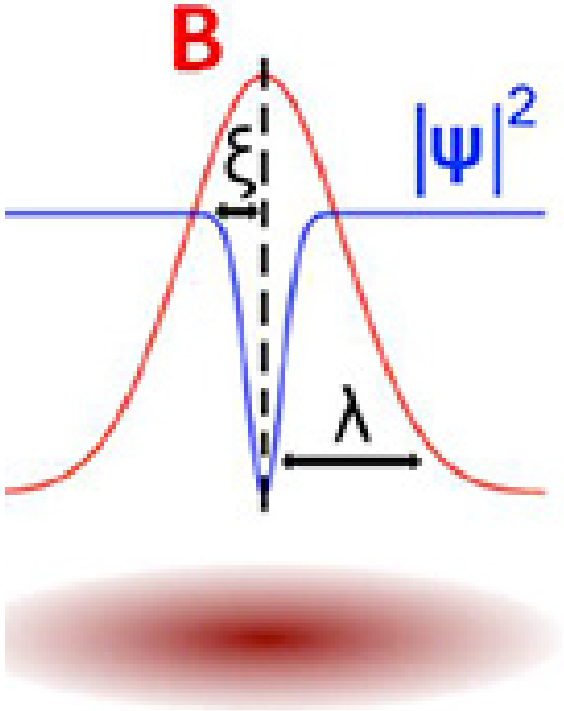

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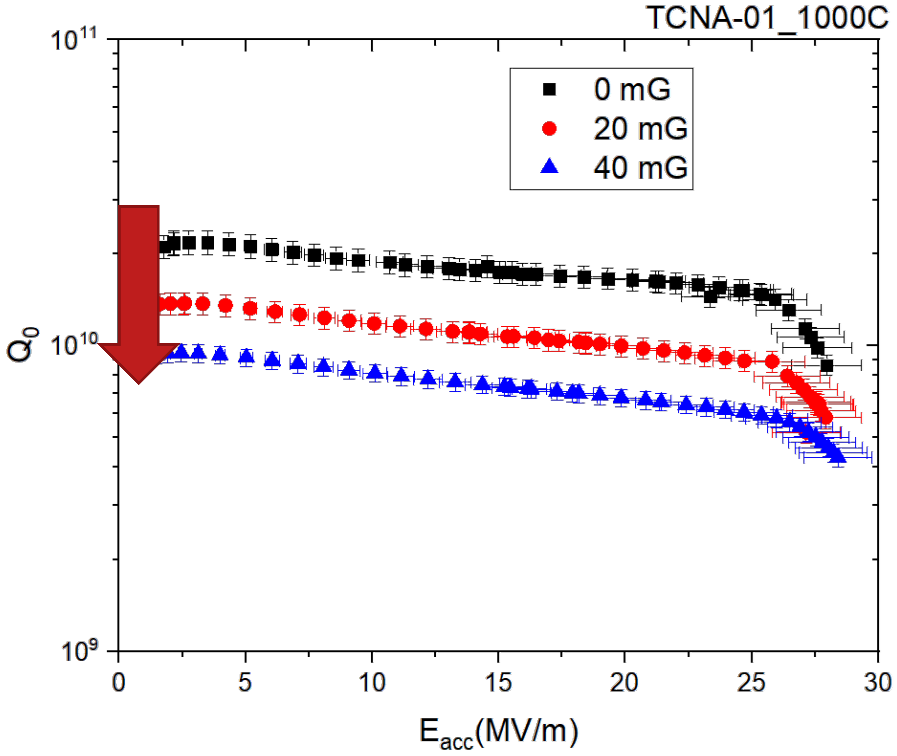

Effect of trapped flux on Q_0

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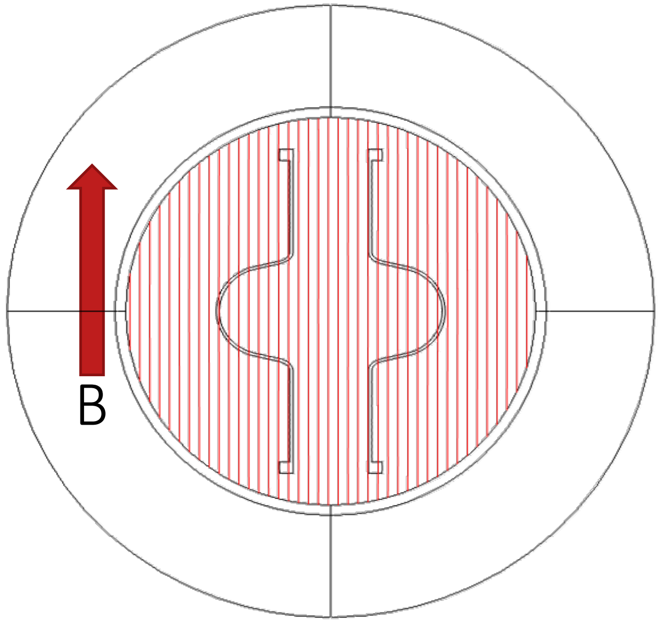
Flux Trapping



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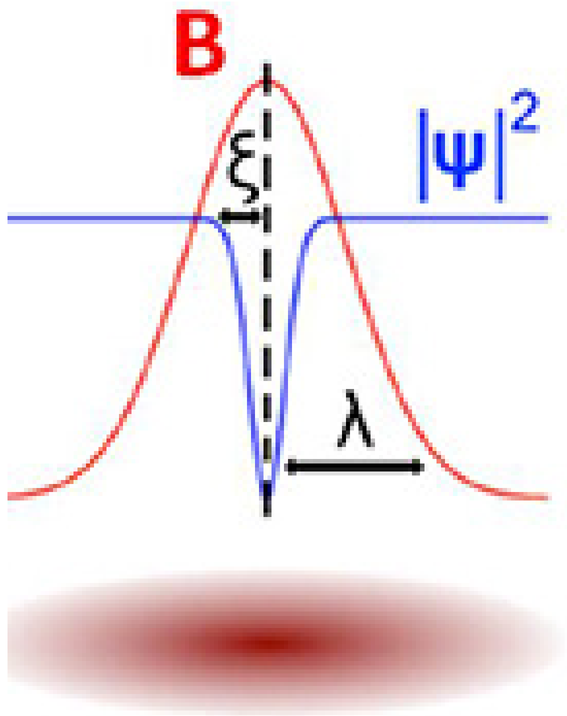

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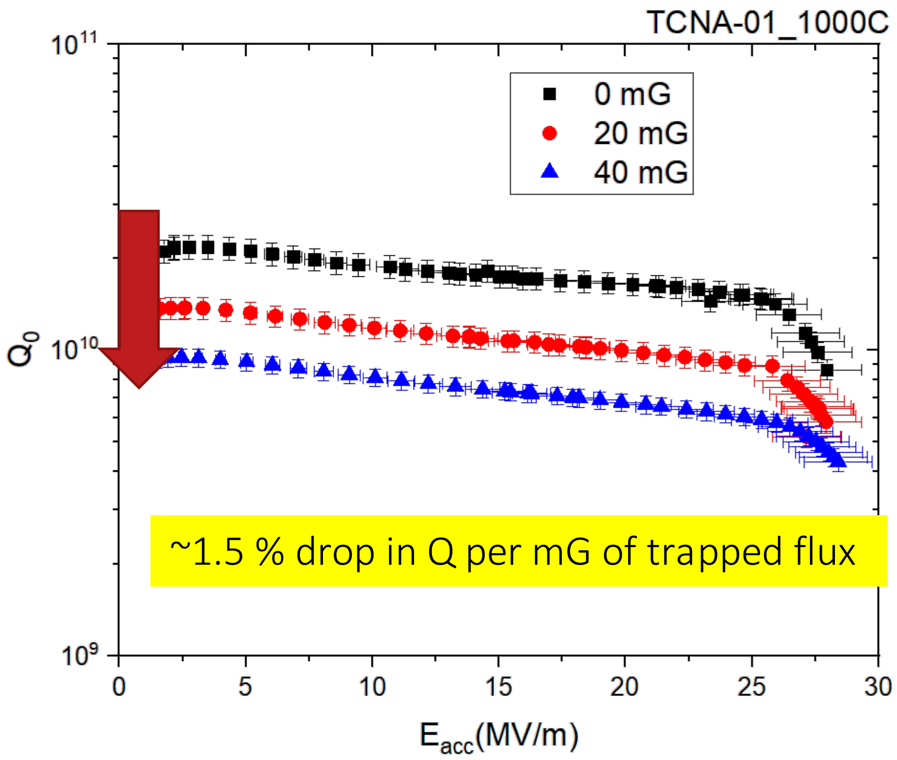

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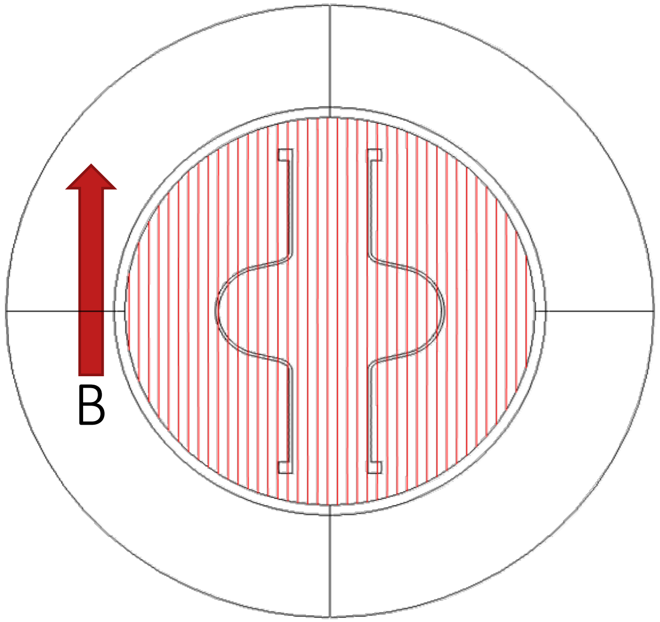

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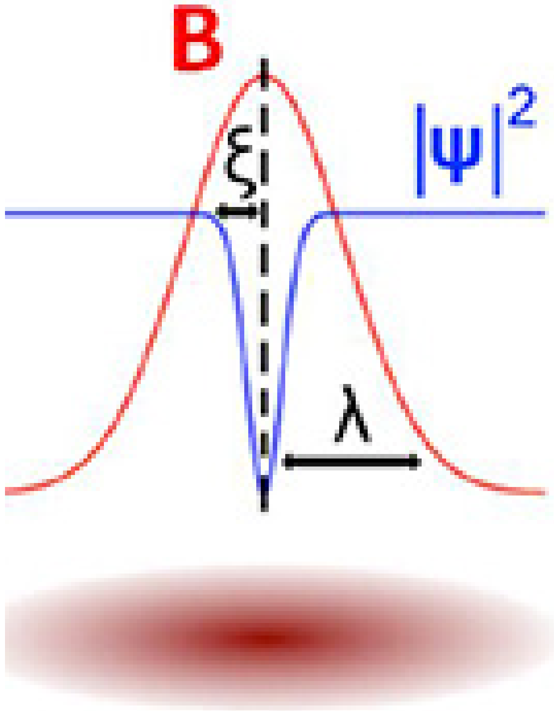

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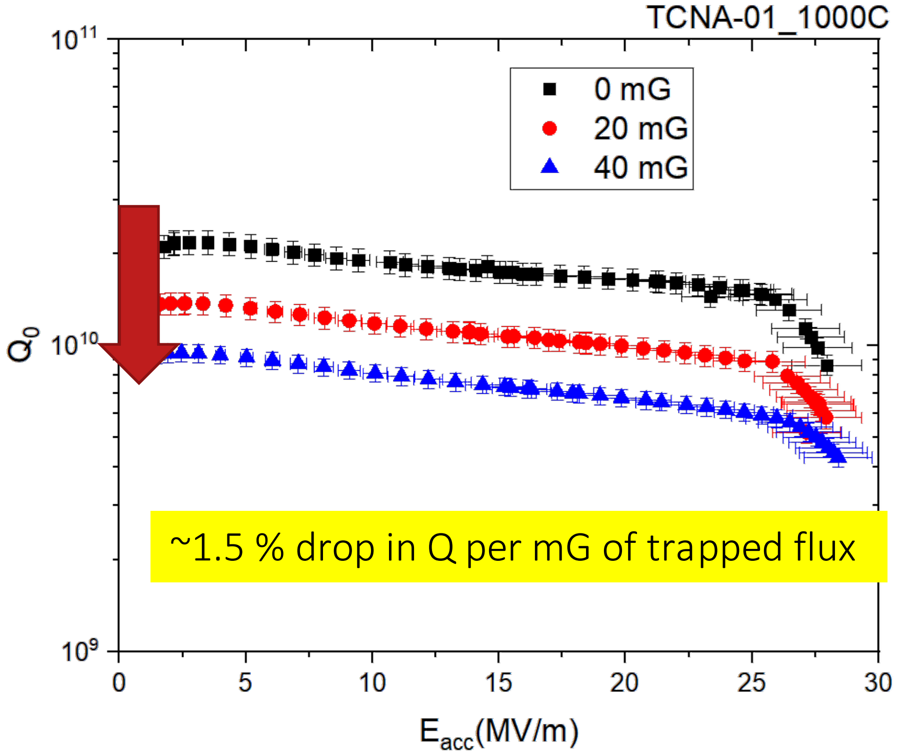
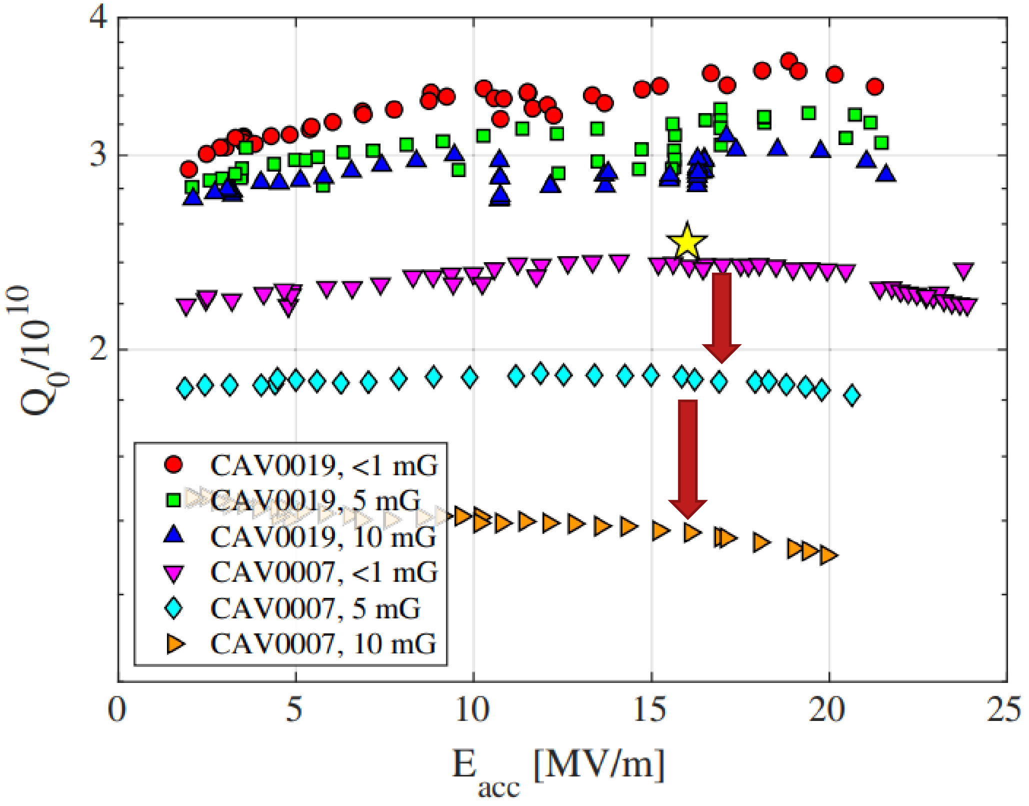


Effect of trapped flux on Q_0

Dislocations, defects, normal conducting precipitates are the primary host sites of flux trapping

Motivation (LCLS-II production)

The effect of flux trapping is even more problematic for nitrogen doped cavities



Posen et al., Phys. Rev. Accel. Beams 22, 032001 (2019)

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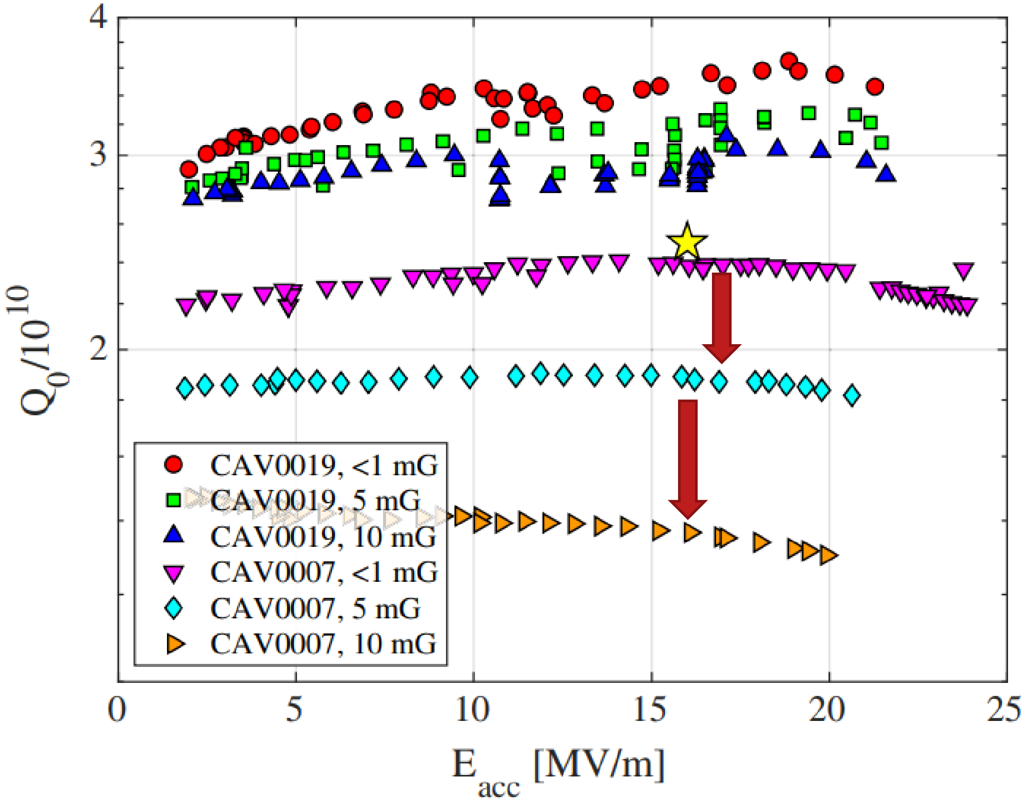

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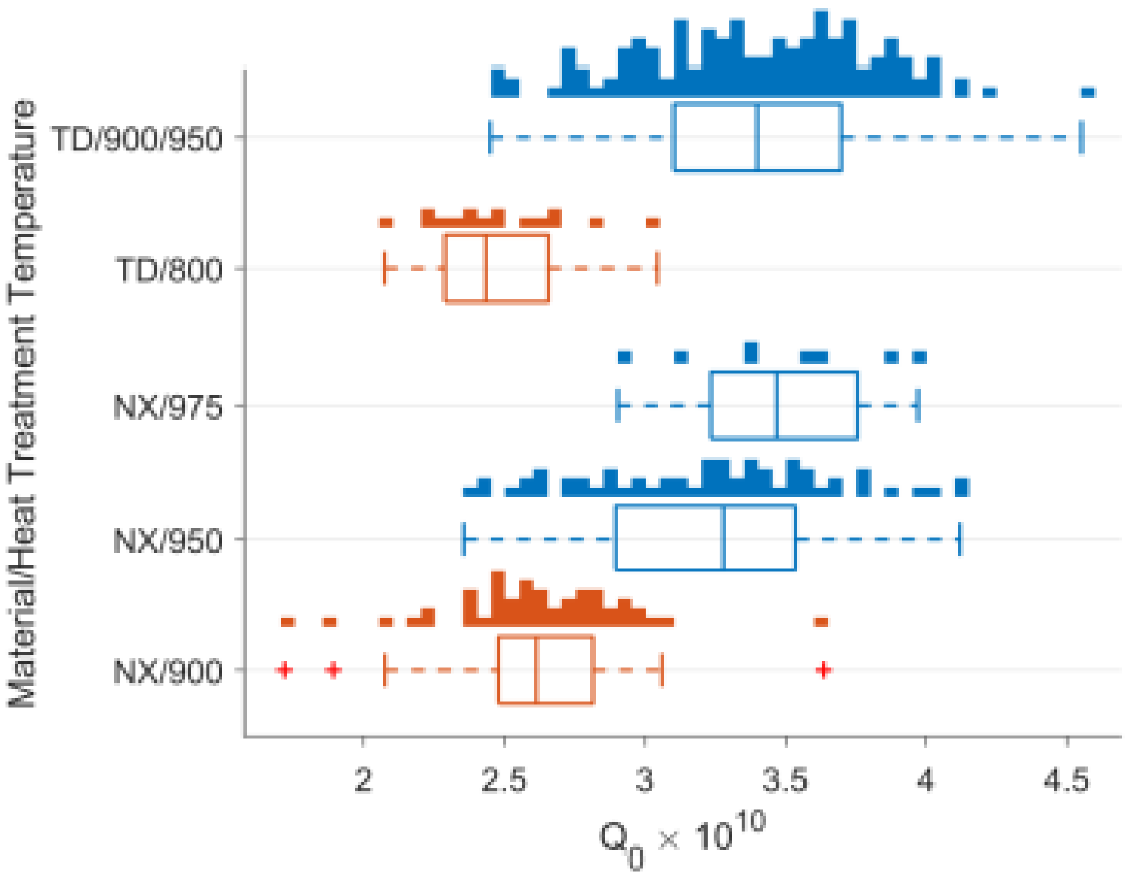
Variability of Q_0, with respect to the vendor and heat treatment temperature



D. Gonnella et al., SRF 2019, Dresden Germany

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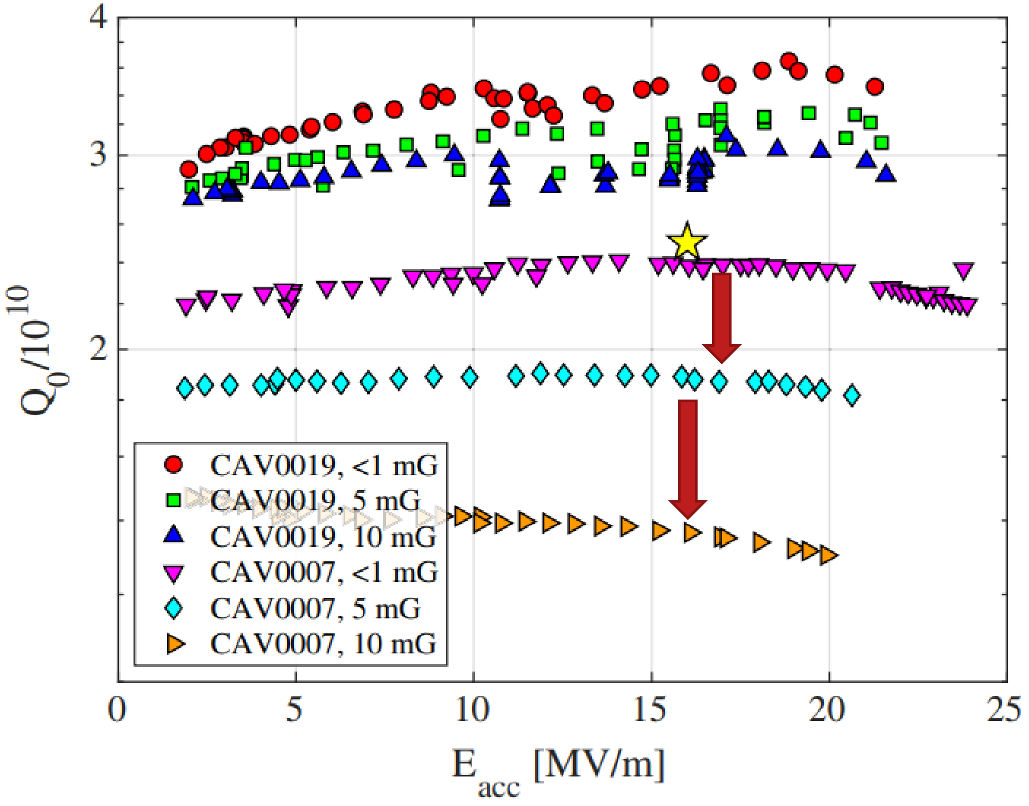

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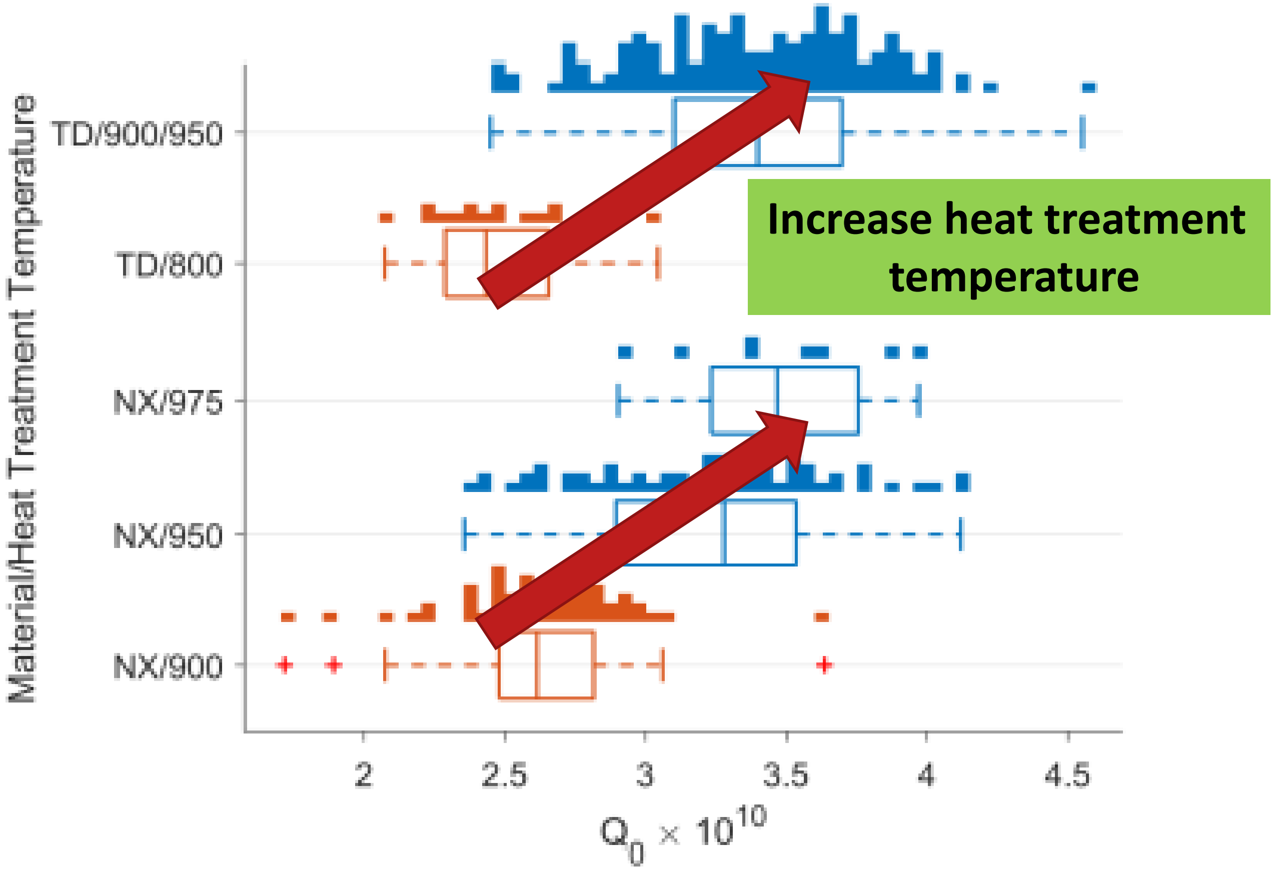


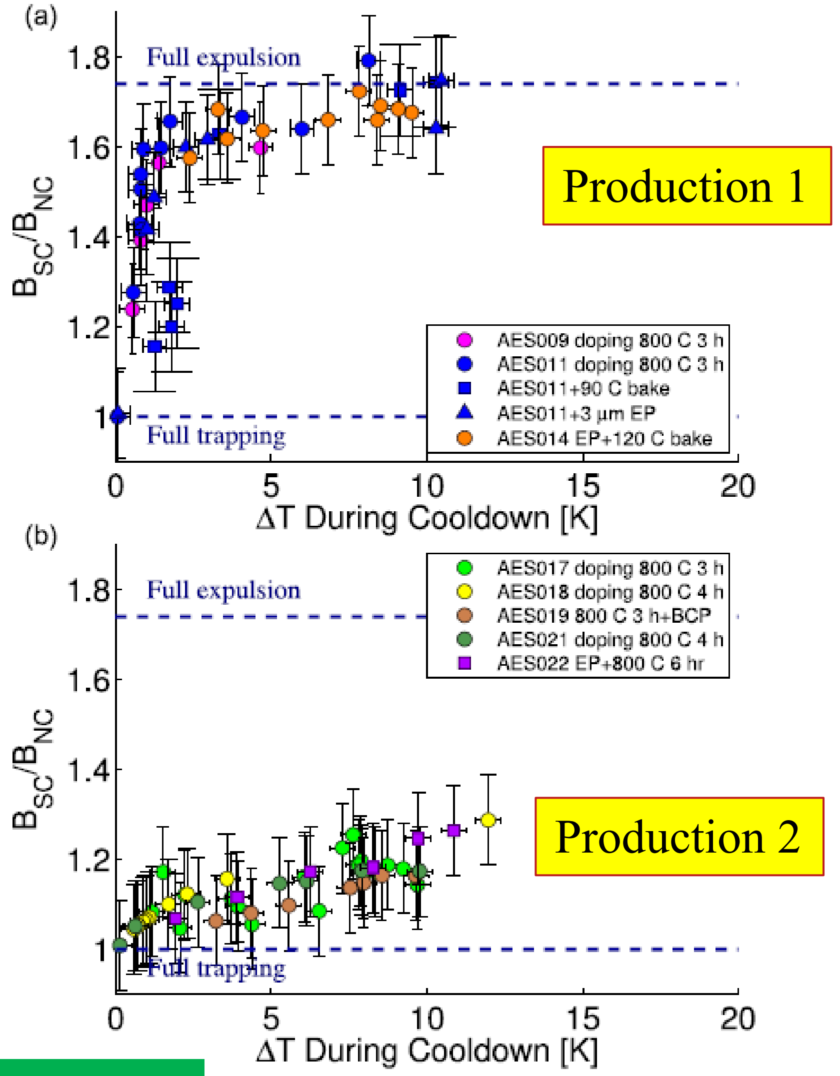
D. Gonnella et al., SRF 2019, Dresden Germany

Motivation

- Production 1(strong expel), made from grain size ~100μm and production 2 (poorly expel), made from smaller grain size (same vendor).

- In each case, flux expulsion nearly the same for the cavities with similar bulk history regardless of surface condition.

- It is demonstrated that substantial improvement in flux expulsion via UHV furnace treatment at 900-1000 ^{0}C.



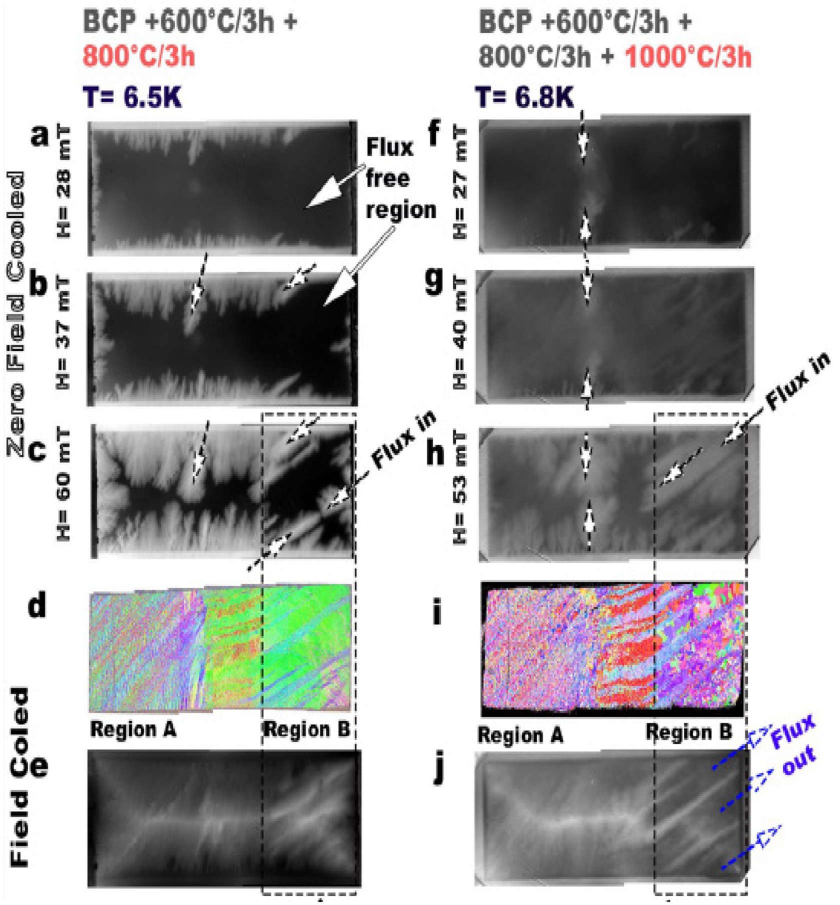
Is microstructure more important for better flux expulsion?

Posen et al., J. Appl. Phys. 119, 213903 (2016)

Motivation

Bi-crystal sample was deformed and successive heat treatments were done to investigate:

- Microstructure
- Flux penetration by magneto optical imaging
- Pinning force measurements



Balachandran et al., Scientific Reports, 11, 5364 (2021)

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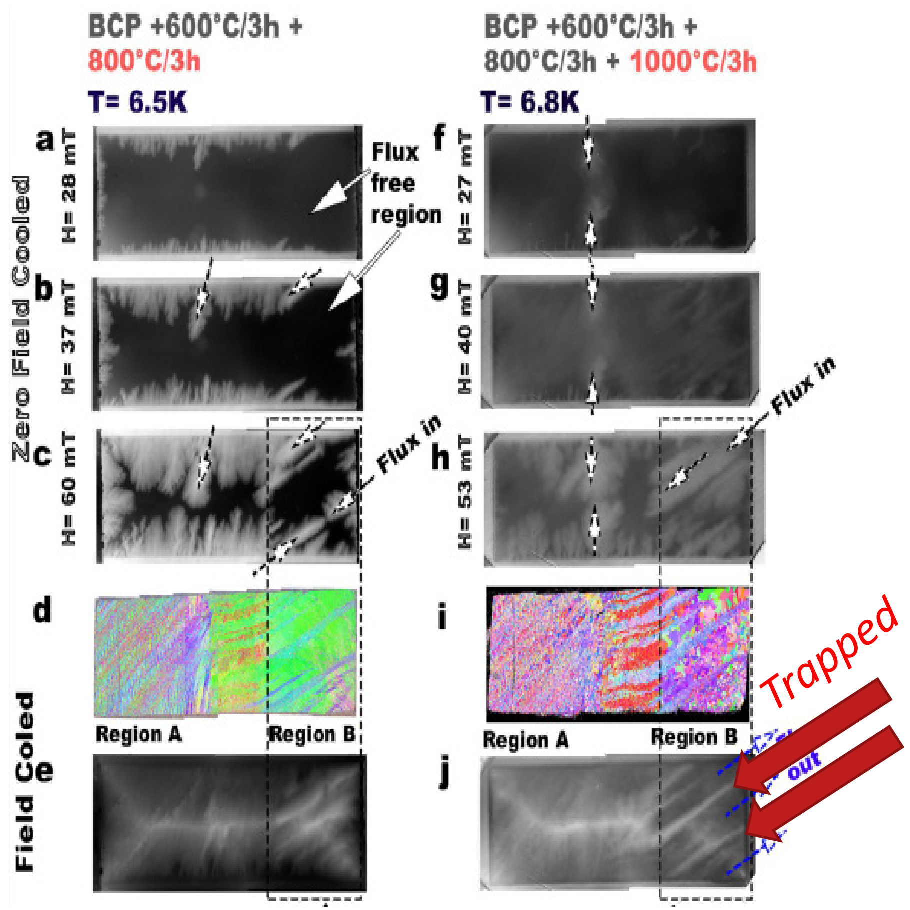

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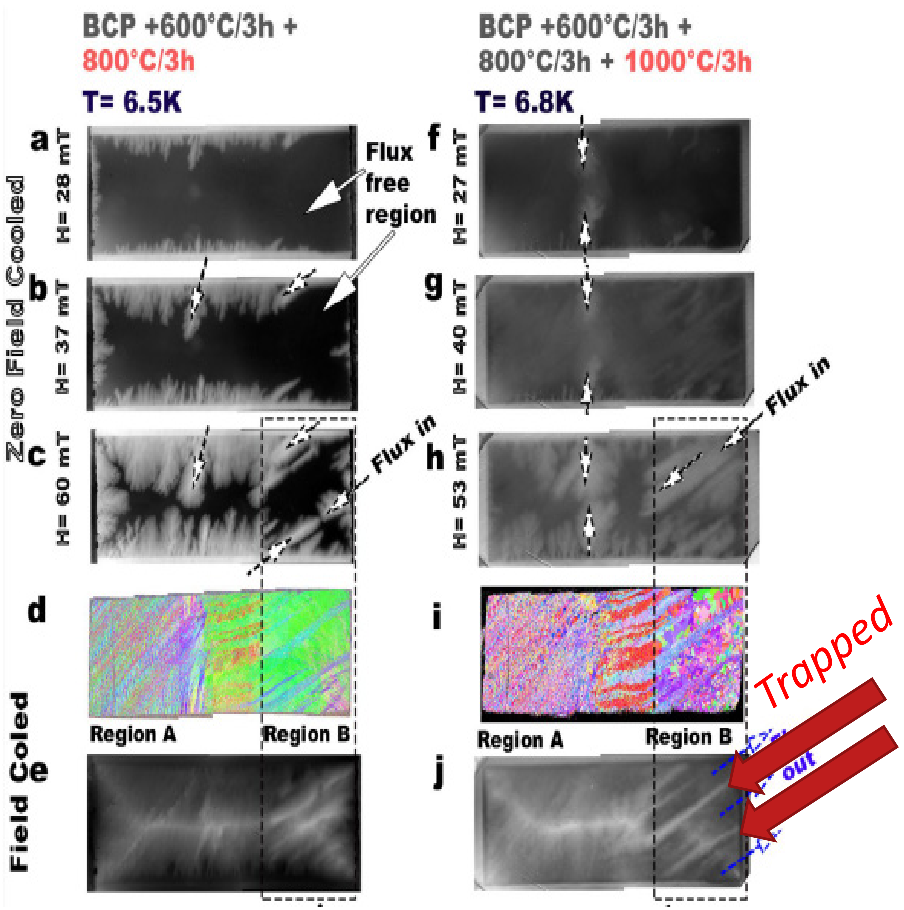
Result suggests that particular attention should be given to the **recovery and recrystallization** of polycrystalline Nb as both dislocation structures and recrystallized grains < 100 µm can contribute to flux trapping.



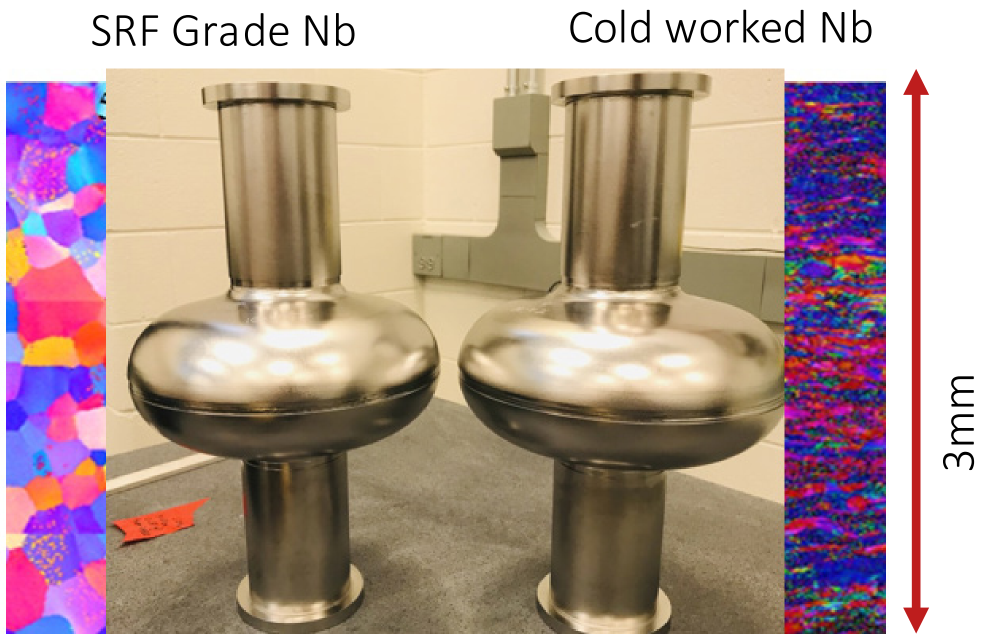
Balachandran et al., Scientific Reports, 11, 5364 (2021)

Our Approach

- We purchased SRF grade Nb and cold worked Nb sheet from two different vendors.

- 1.3 GHz single cell cavities were fabricated and processed together (surface polishing with EP and heat treatments (800 – 1000 ^{o}C).

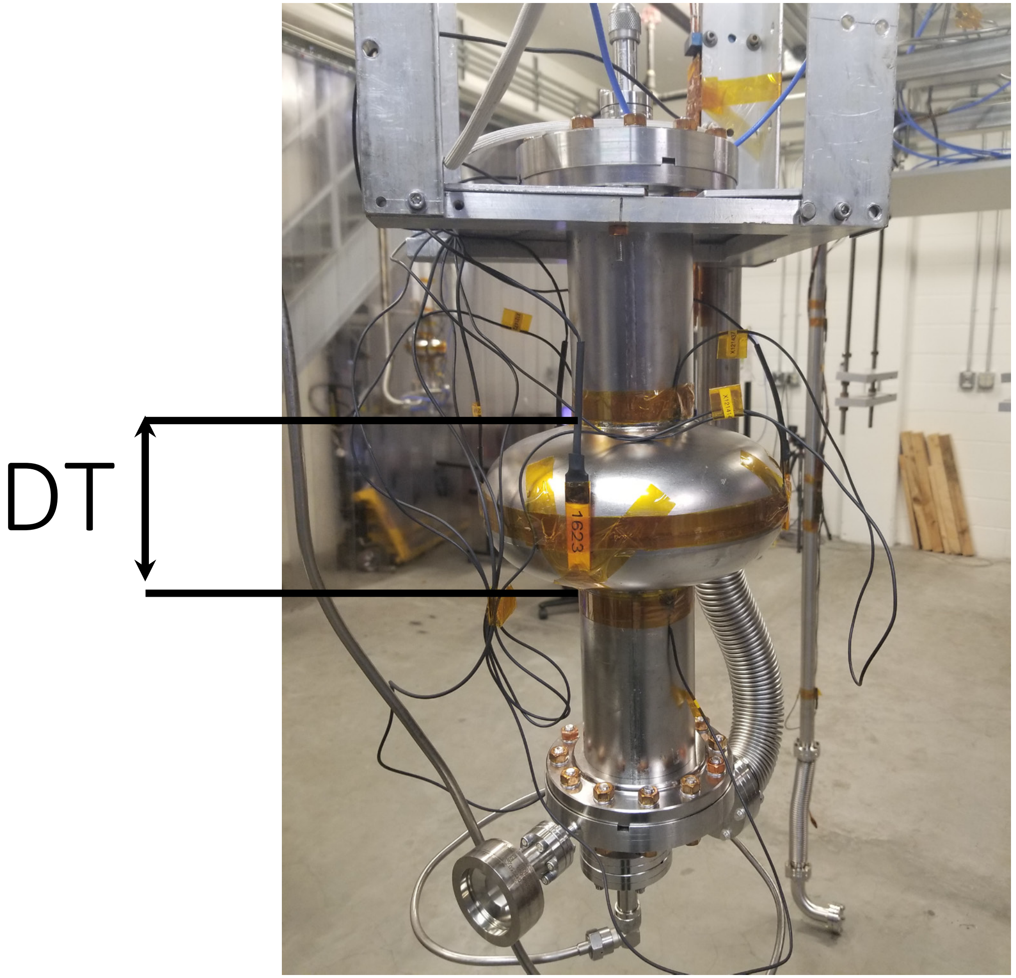
- Flux expulsion and flux trapping sensitivity were measured as a function of heat treatment temperature.



- Several sample coupons from the sheet as well as cut out from half cells were analyzed by EBSD, pinning measurements and thermal conductivity.

Collaboration with FSU and MSU

Flux Expulsion Measurement Set Up



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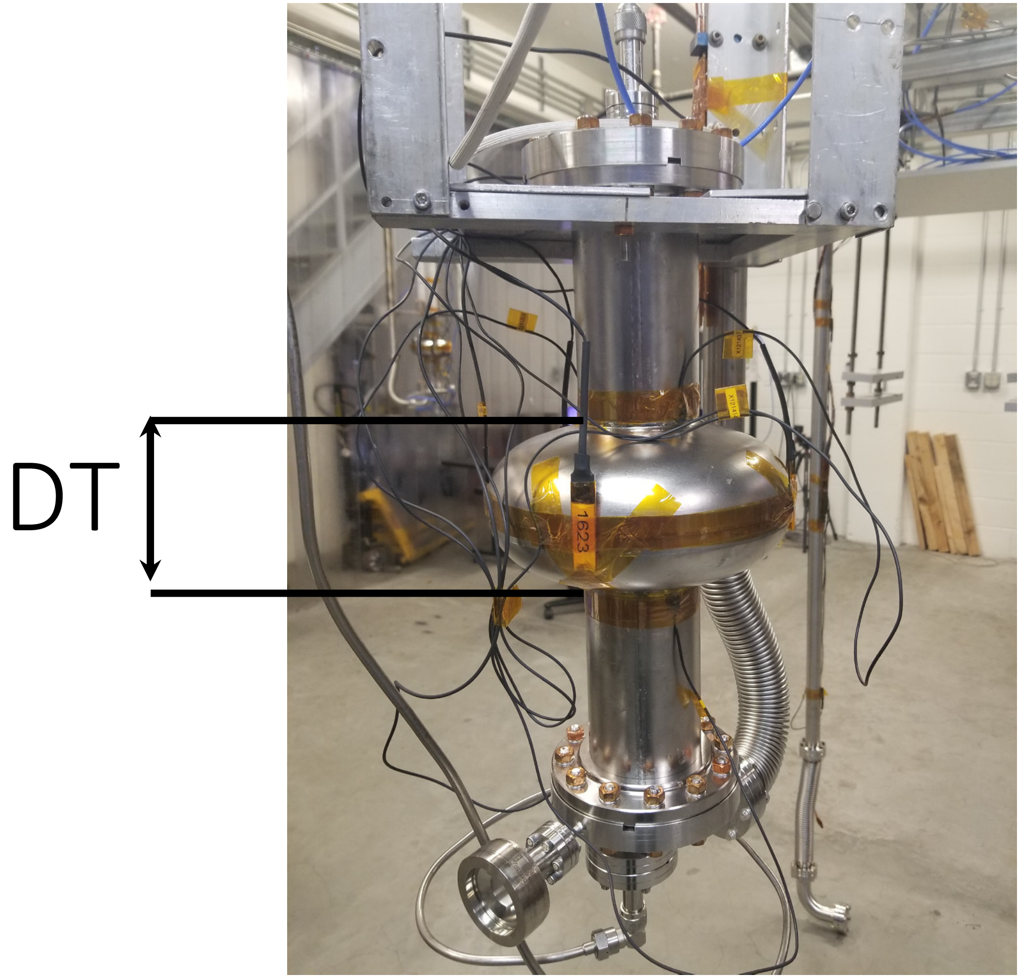

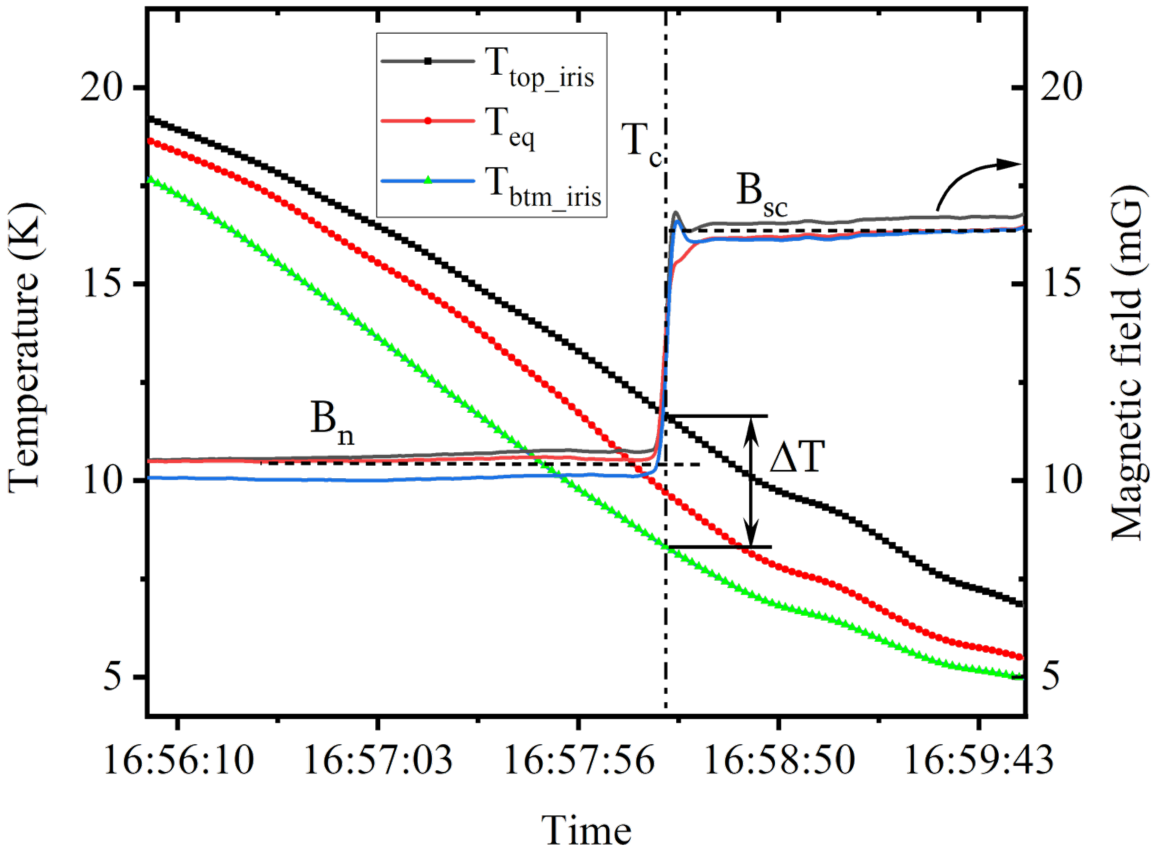

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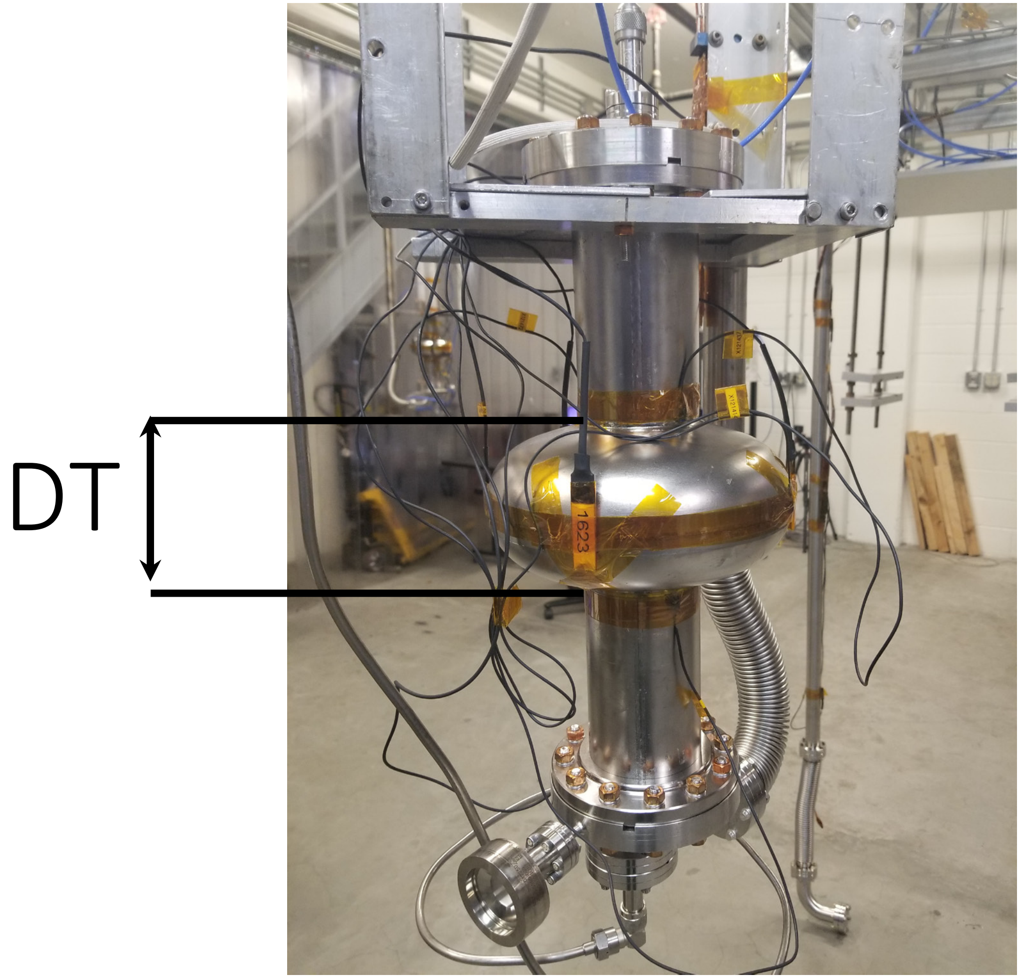

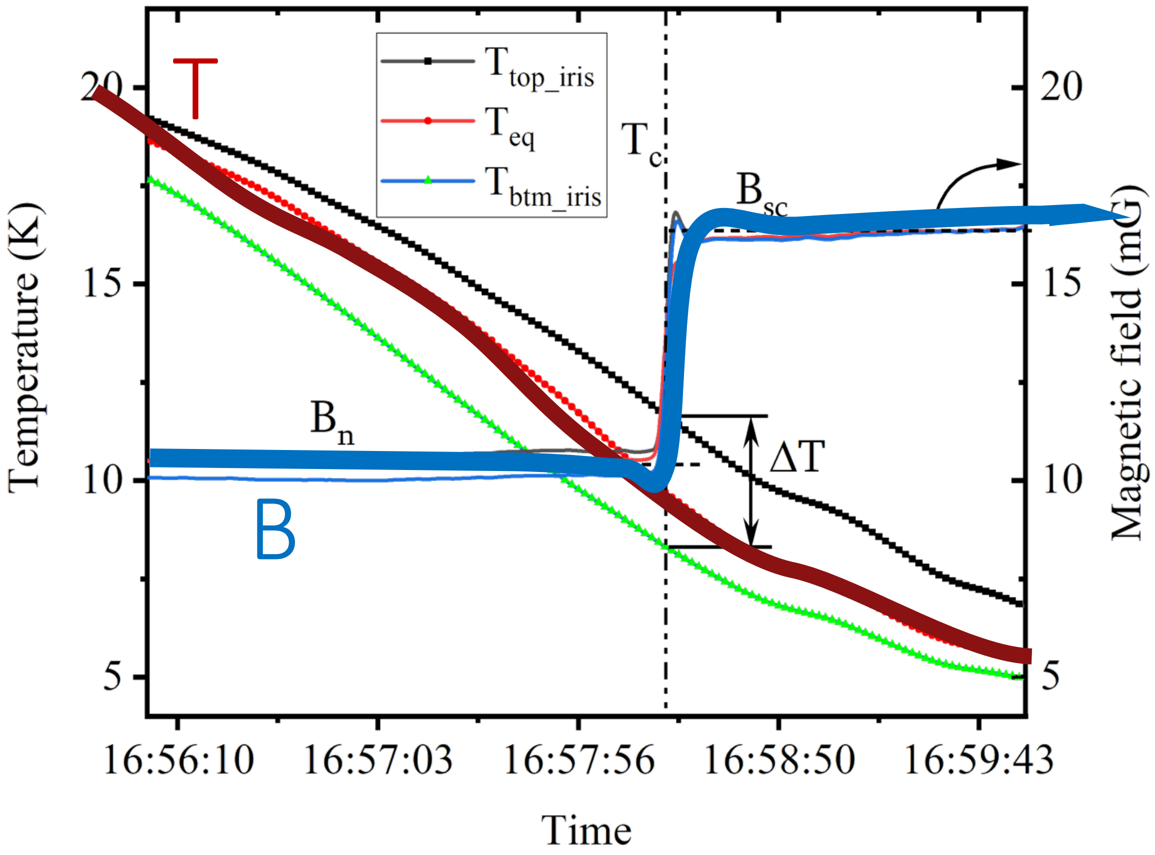

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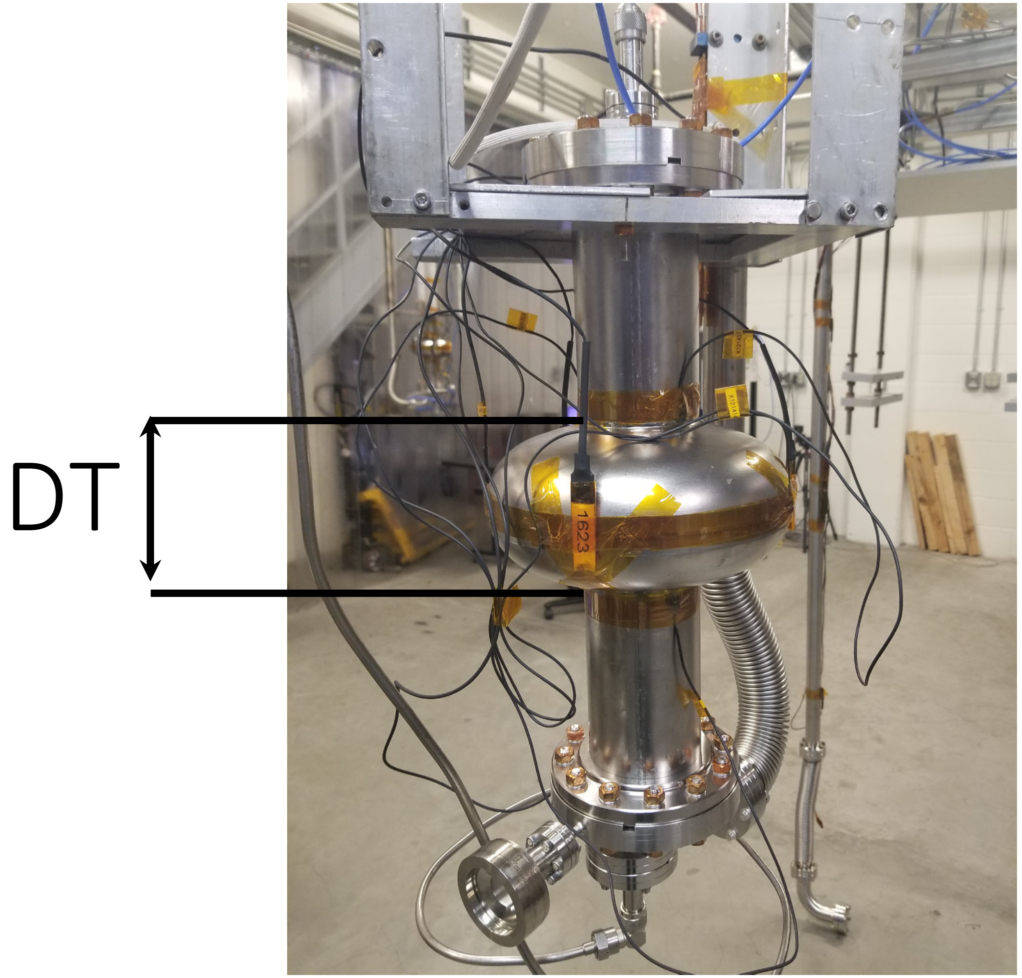
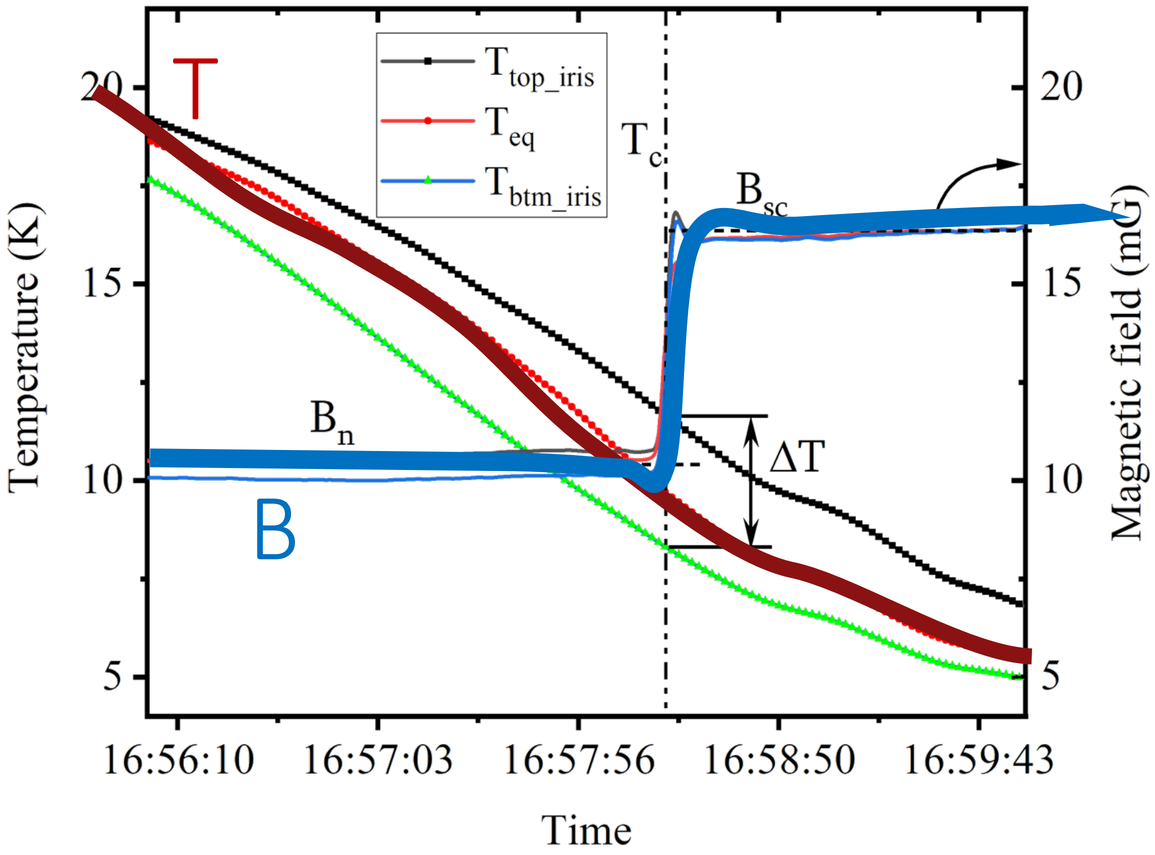
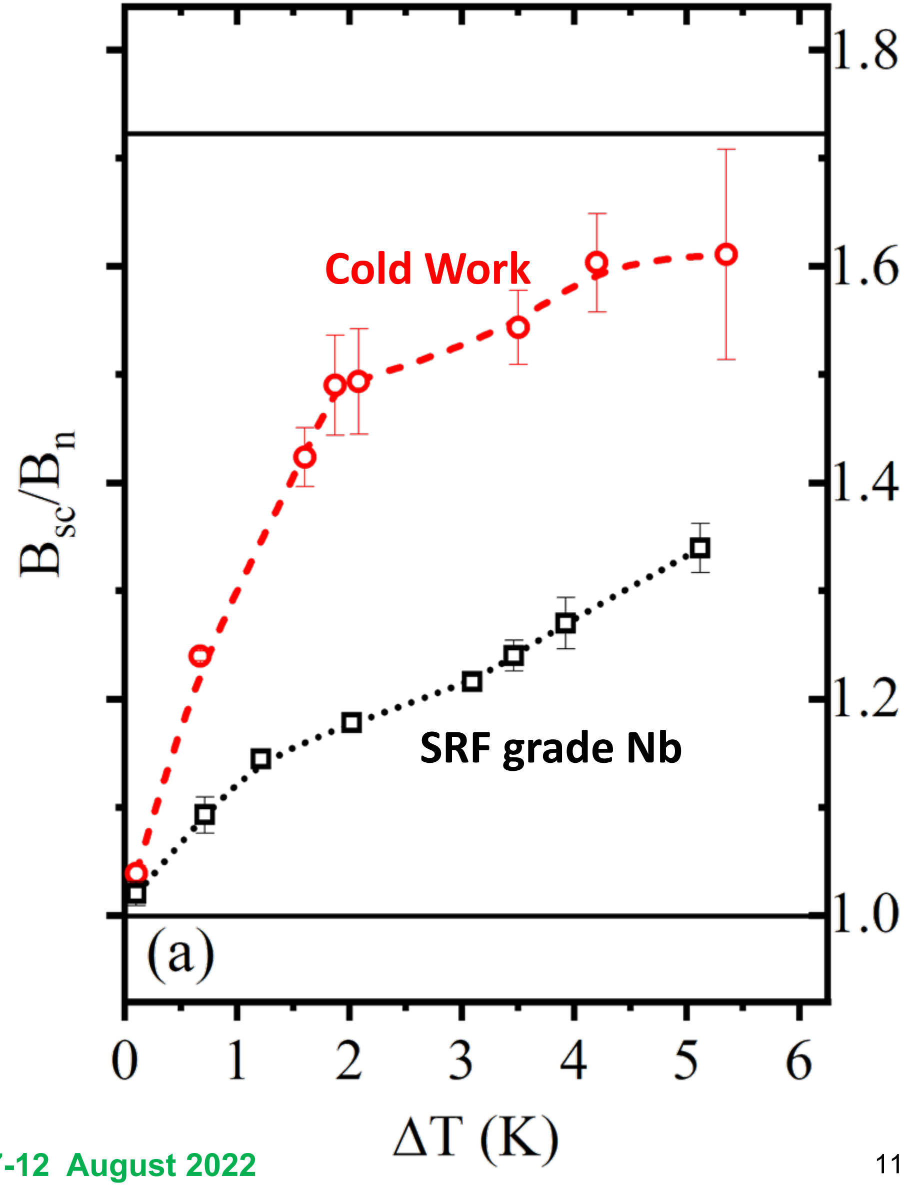


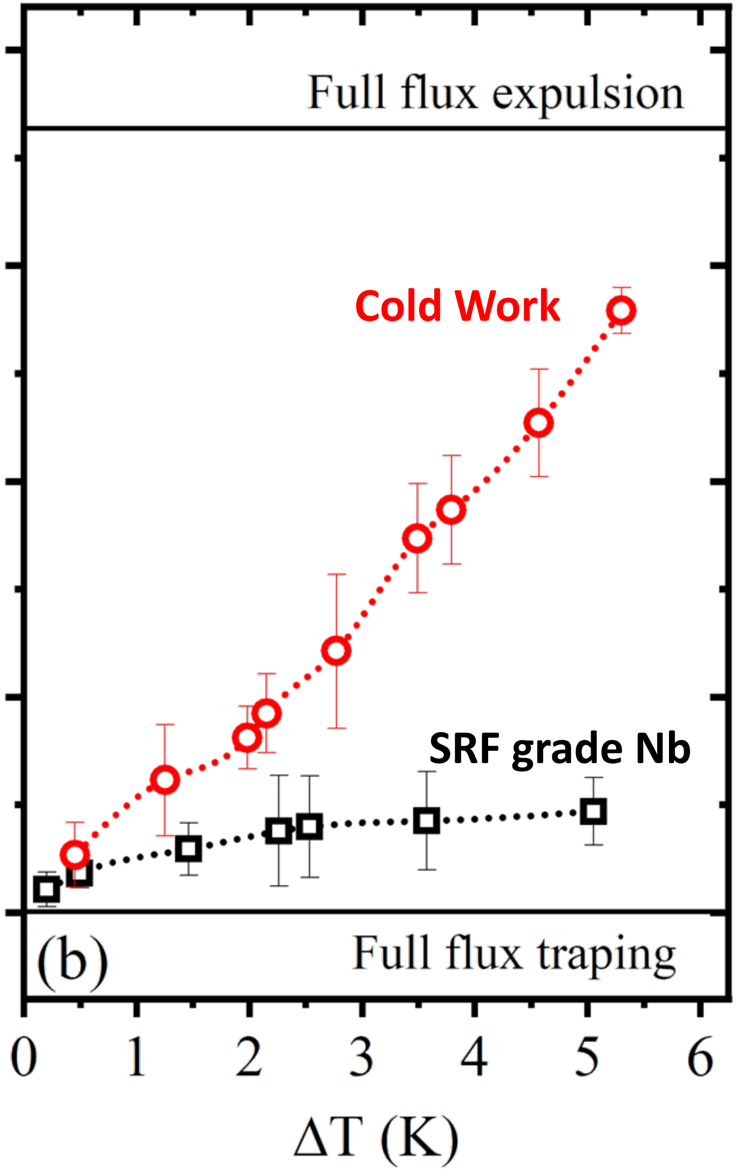


During the cooldown, when the cavity transition from normal state to superconducting state, the jump in flux is measured. The jump changed with ΔT.

Flux Expulsion Test (800C/3h)

Vendor A

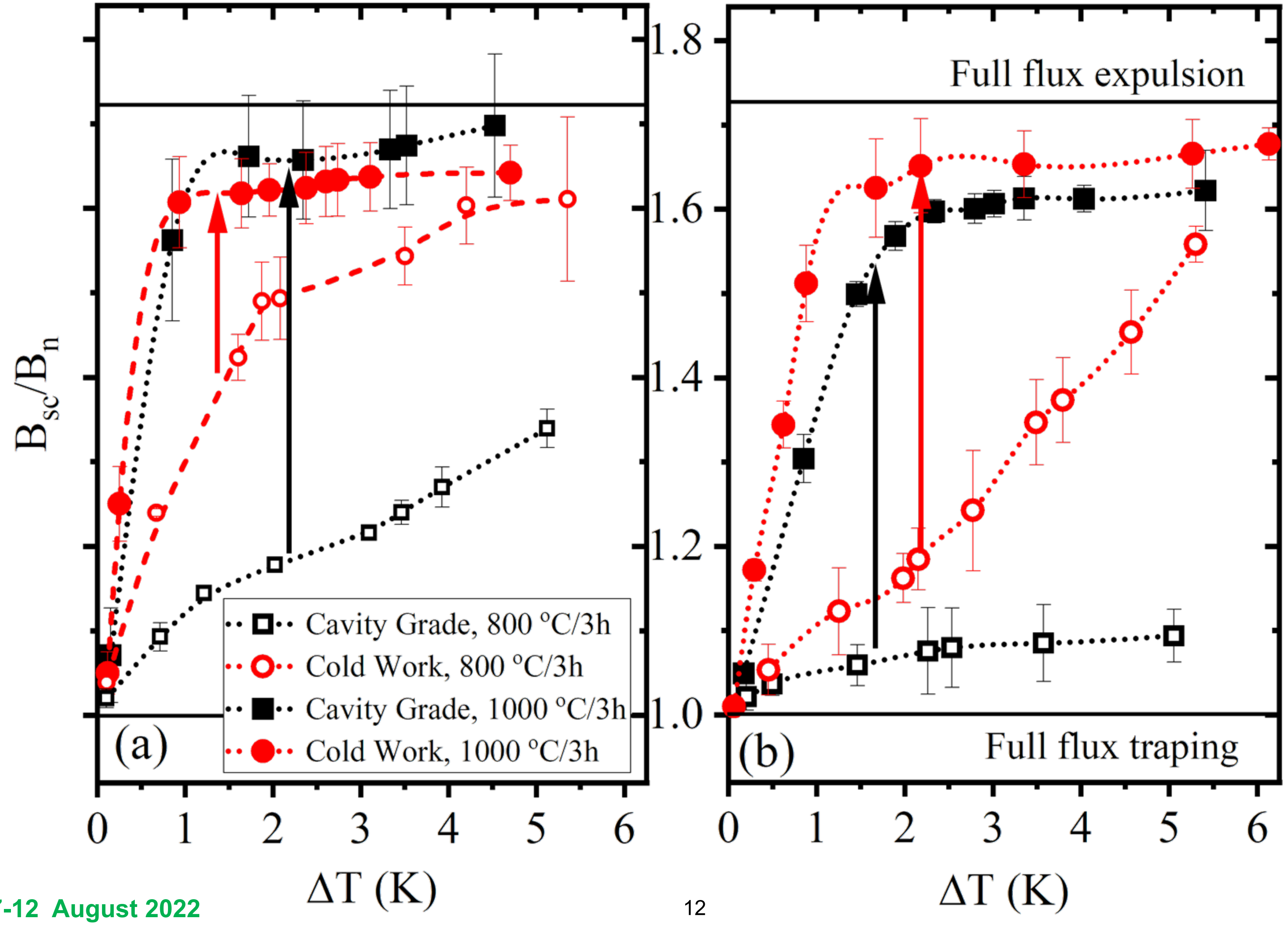




Vendor B

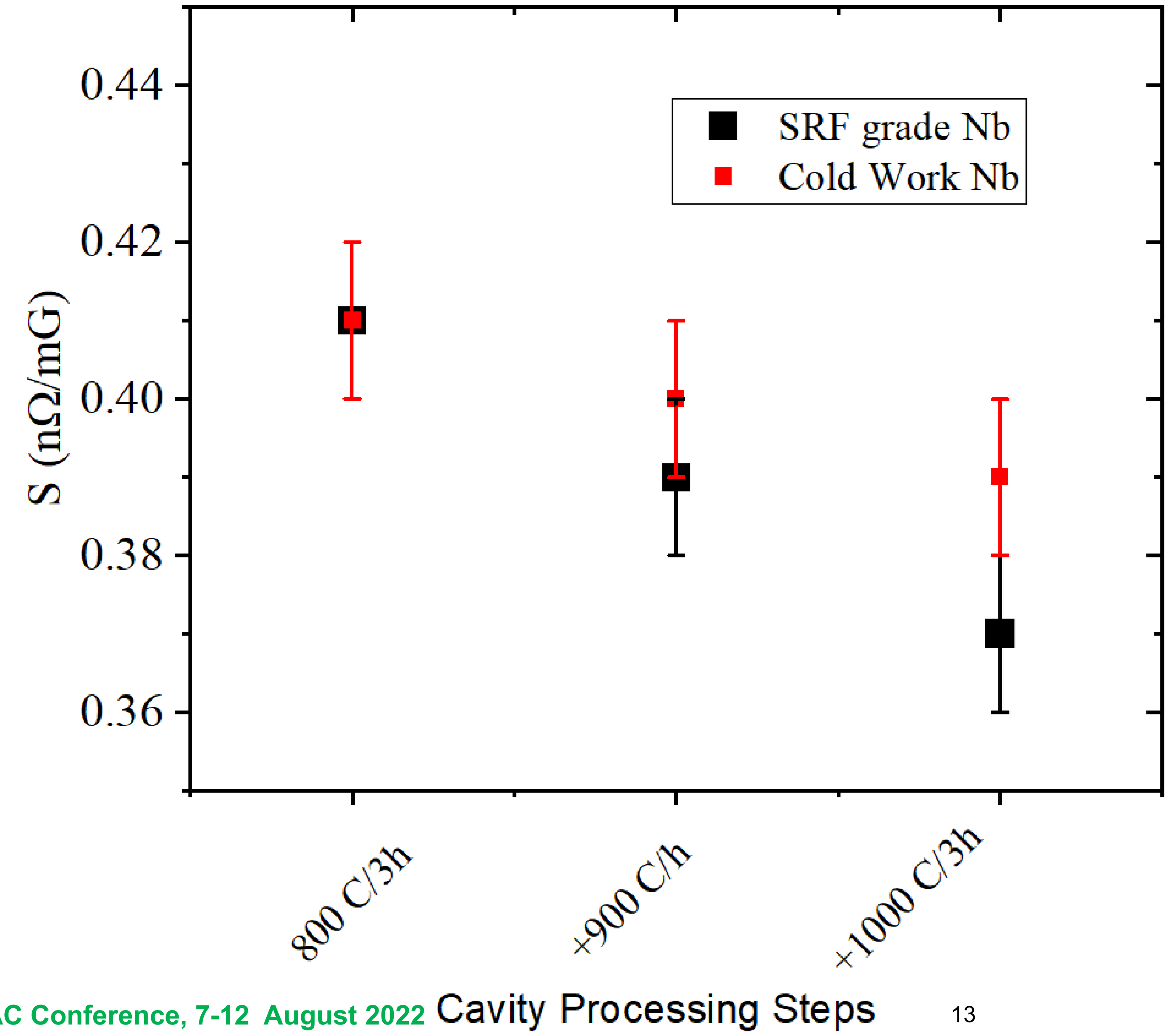
Flux Expulsion Test (1000C/3h)

Vendor A



Vendor B

Flux Trapping Sensitivity (Increase in R per mG trapped flux)



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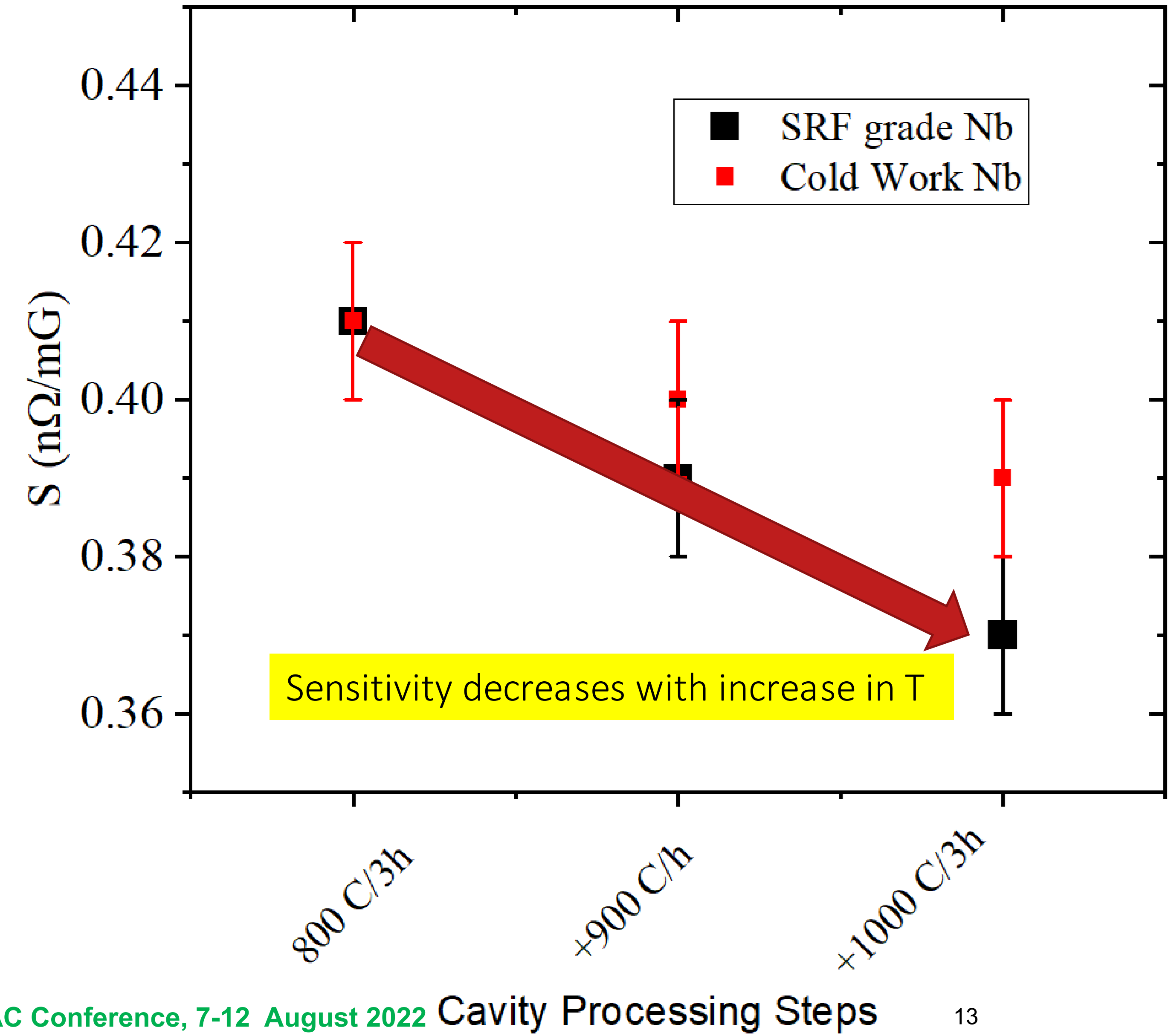

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Summary

- The flux expulsion on SRF cavity increase with increase in heat treatment temperature. The higher temperature heat treatment minimize the pinning centers.
- Cavity made from cold work Nb showed better flux expulsion after 800 ^{o}C heat treatment compared to cavity made from traditional Nb.
- The study showed that the initial metallurgical state influence the recrystallization during heat treatment, which in turn affect flux expulsion.
- Systematic investigation of SRF cavities made from different Nb (different vendor and different microstructure) are under way.

Acknowledgements

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THANKS FOR YOUR ATTENTION