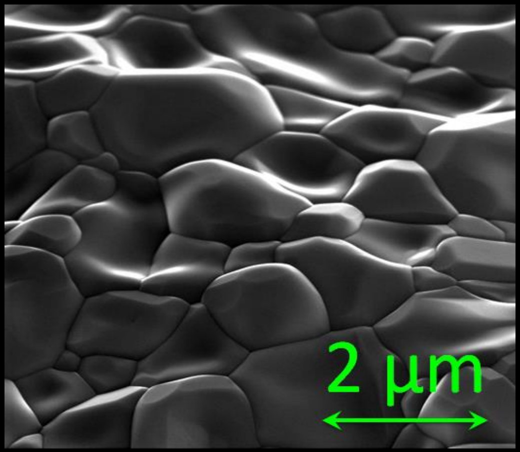
Developing the Next Generation of SRF Cavities with Nb_3Sn



Sam Posen, Cornell University

Fermilab - June 26, 2014

Outline of the Talk

Why Nb_3Sn?

Material development

Lessons from history

My Nb_3Sn cavity research

Material removal studies

Quench fields

Outlook

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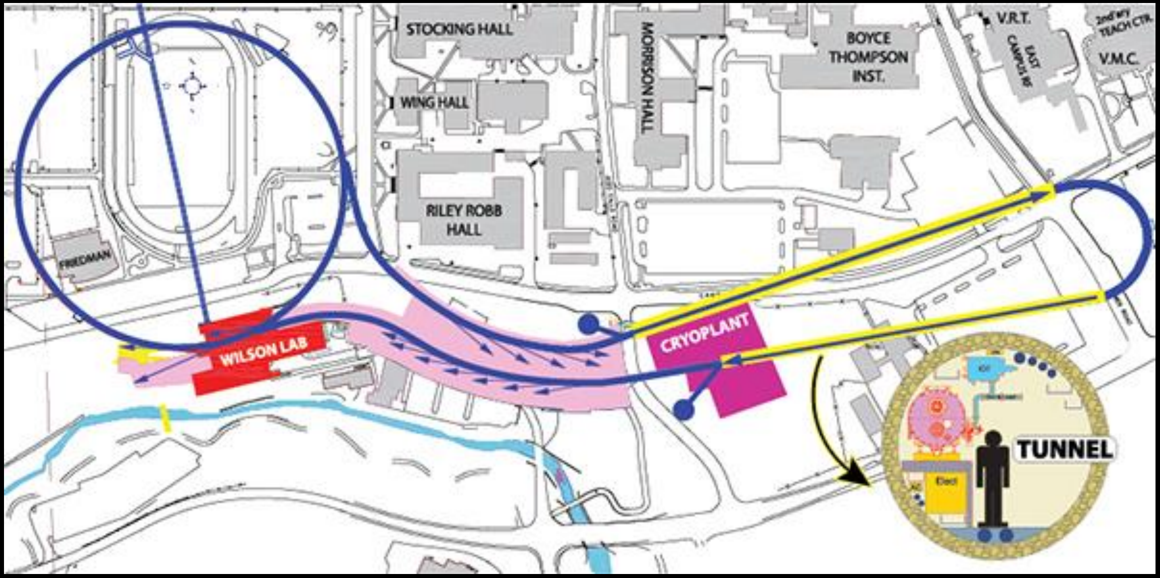
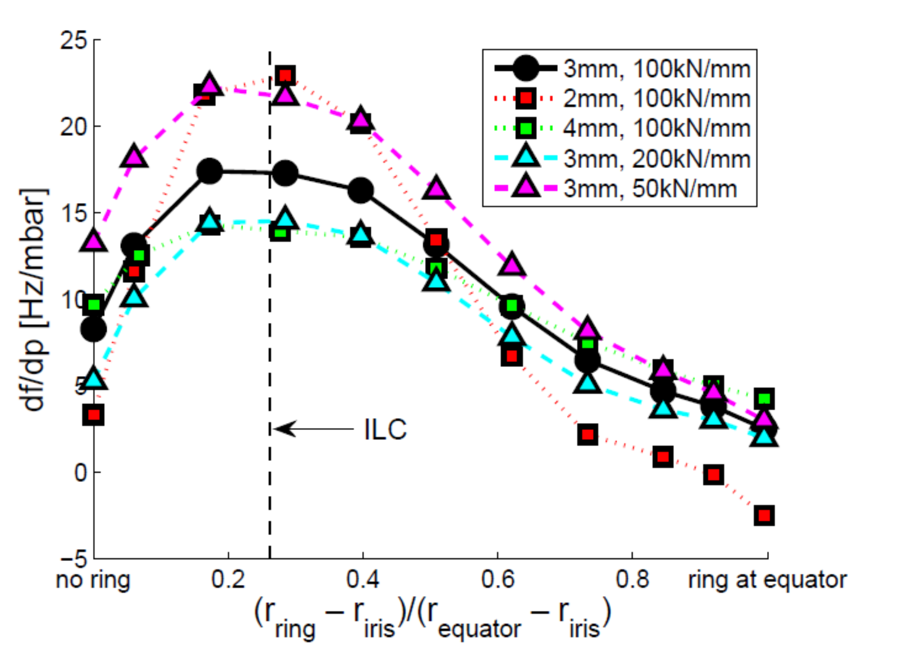
Motivation

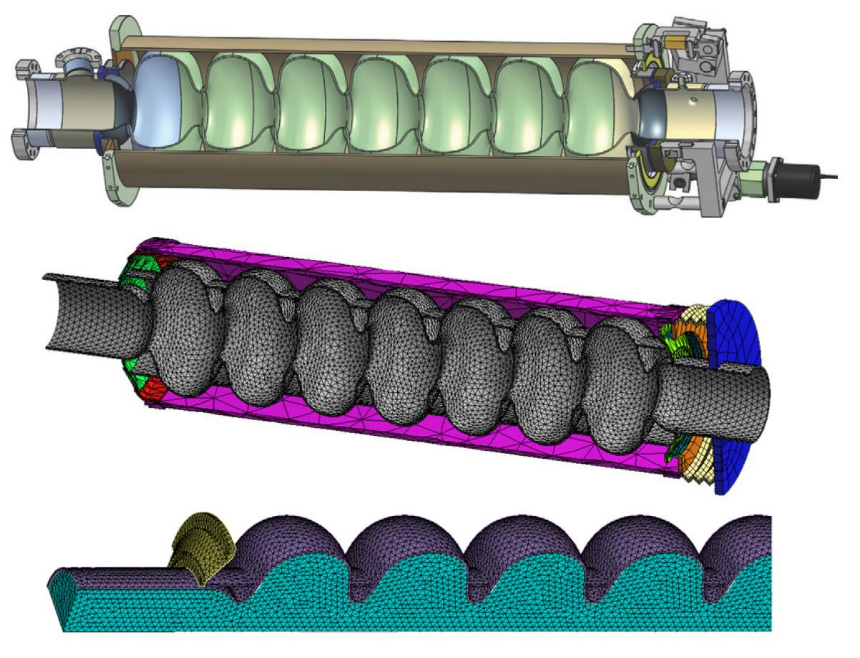
- Cornell has been interested in SRF R&D to make an ERL affordable
  - Minimize df/dp for smaller RF amplifiers
  - Reduce Q_0 degradation in cryomodules
  - Increase Q_0 beyond standard EP/120 C bake Nb



Minimize df/dp

- I used ANSYS simulations to optimize the pressure sensitivity of the main linac cavity
- I found df/dp is minimized for no stiffening rings or large radius stiffening rings, and end tuner with small endwall area (PRST-AB 15, 022002, 2012)





Minimize df/dp

the
cavity
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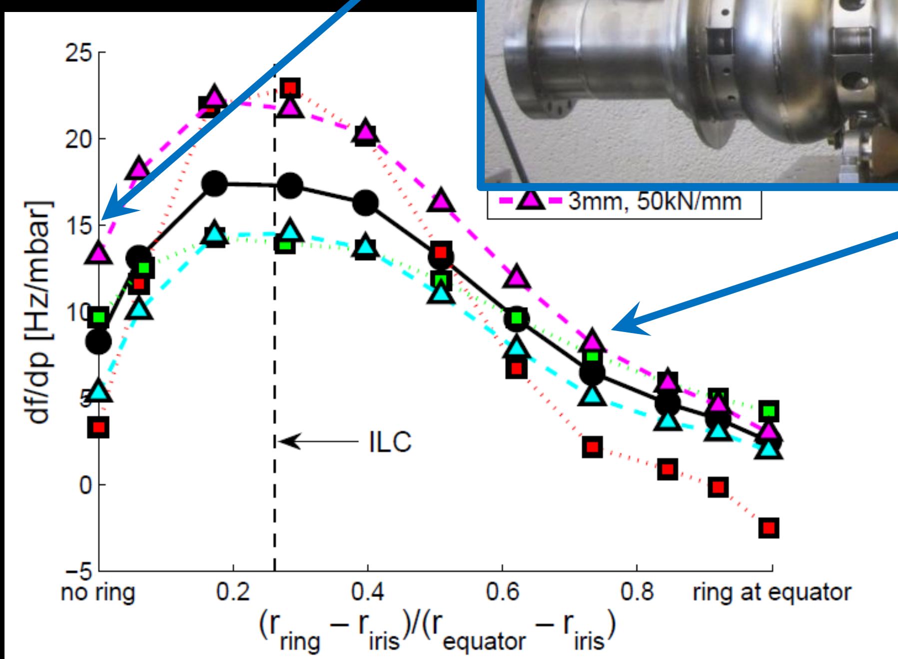
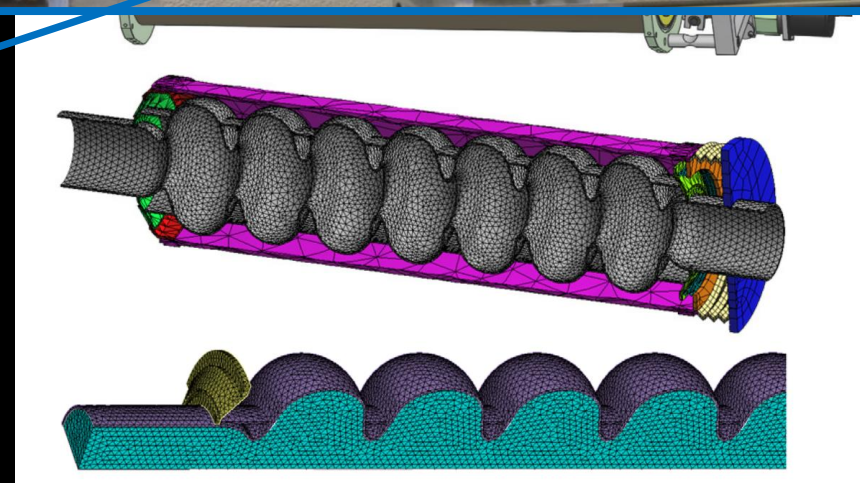
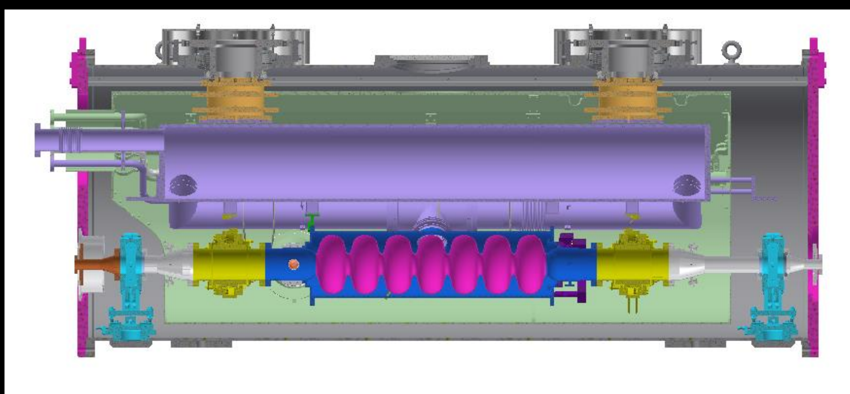
with small

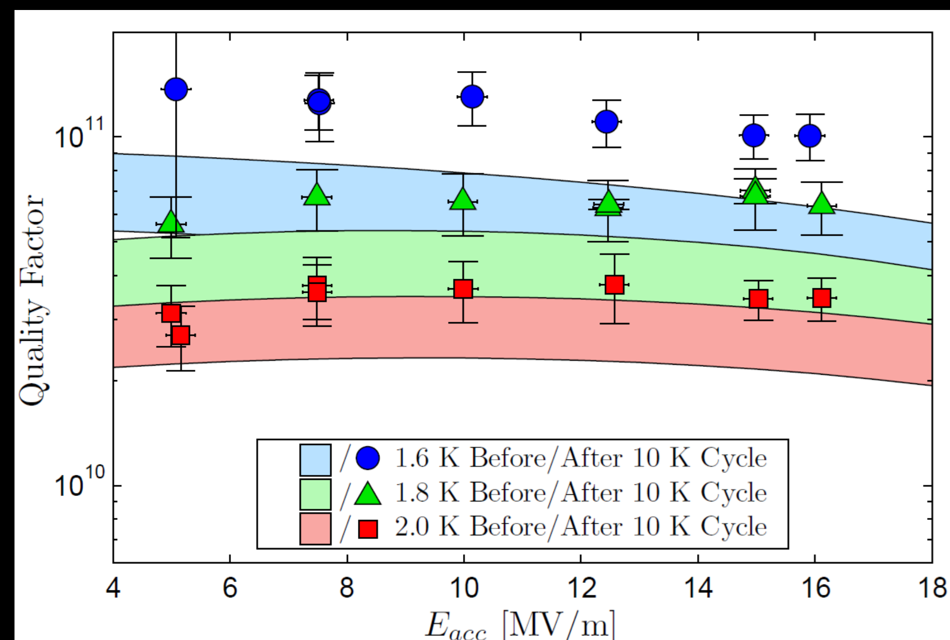




Reduce Q_0 Degradation in Cryomodules

- Previous experience: can achieve high Q_0 in vertical test—often degrades in horizontal test
- Cornell HTC: record Q_0 in a cryomodule





Increase Q_0 Beyond State of the Art

- Available now: Nb with HF rinse, N-doping
- R&D project for future: **Nb_3Sn**
- **T_c = 18 K** vs 9 K for niobium

Preparation	Max Q_0* at 4.2 K	Max Q_0* at 2.0 K
Nb, EP/120 C bake	6×10^8	2×10^{10}
Nb, EP/120 C +HF rinse	6×10^8	3×10^{10}
Nb, N-doped	6×10^8	$4 \times 10^{10} – 8 \times 10^{10}$
Nb_3Sn, vapor diffusion	**6×10^{10}**	**$>10^{11}$**

**Approximate Q_0 for 1.3 GHz TeSLA or 1.5 GHz CEBAF cavities if R_{res} is small*

Cornell University

Importance of High Q_0

- Cryogenic plants for large SRF linacs (LCLS II, Project X, XFEL, ERL) cost ~$100 million and require MW of power
- Higher Q_0 → less heat to remove → smaller cryoplant, less power
- Higher T_c → higher helium temperature → simpler cryoplant, higher efficiency

Images from D. Delikaris, Cryogenics at CERN, 2010

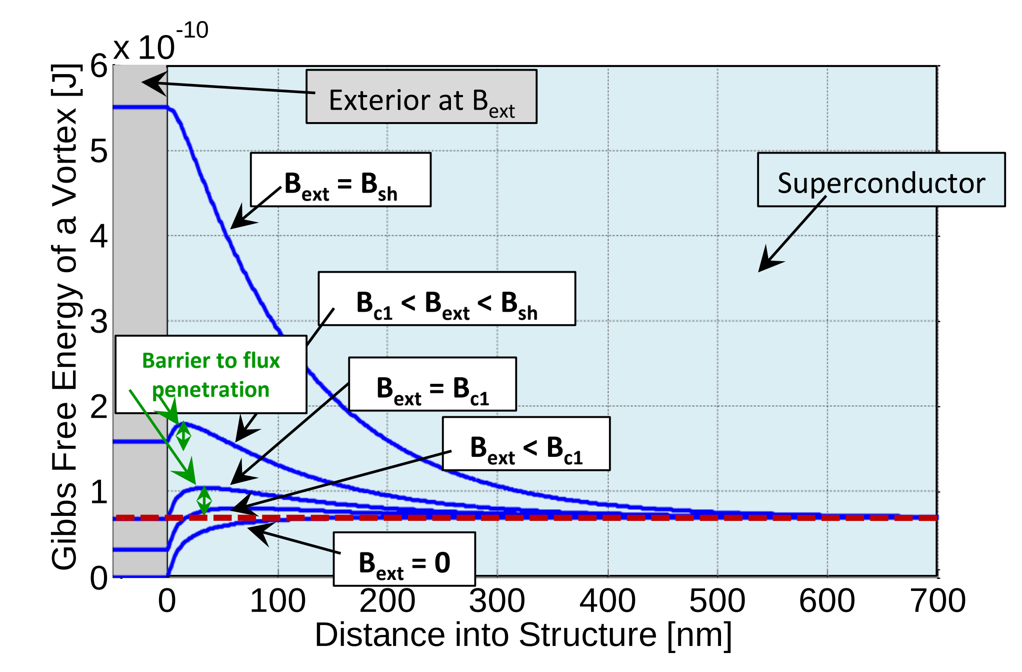
Importance of High Q_0

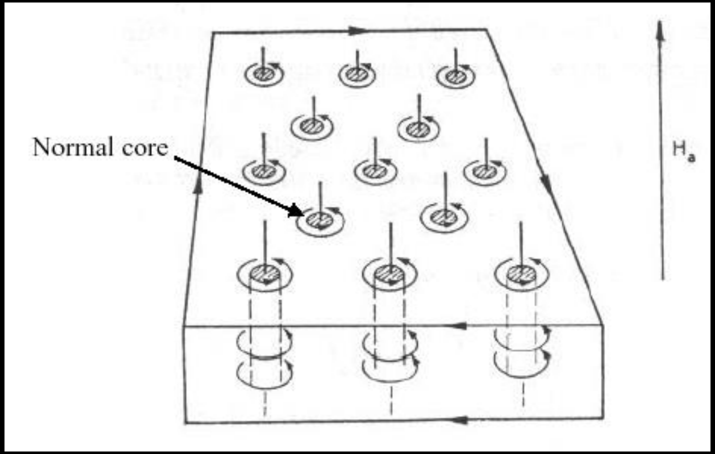
- For lower-energy industrial applications, it may not be cost-effective to have a supply of 2 K LHe
- Higher T_c of Nb_3Sn allows high-Q_0 operation with atmospheric 4.2 K LHe, or even gas/supercritical He
- Flue gas, waste water treatment, isotope production, security

Images from S. Sabharwal, NA-PAC13

Challenge of Strongly Type II SC

- Nb_3Sn is a strongly type II superconductor
  - Small H_{c1}: onset of metastability is low
  - Small ξ: metastable state sensitive to defects
- Unclear if metastable state is reliable
  - Is H_{sh} limit (2x max Nb field) or H_{c1} (1/10th max Nb field)?





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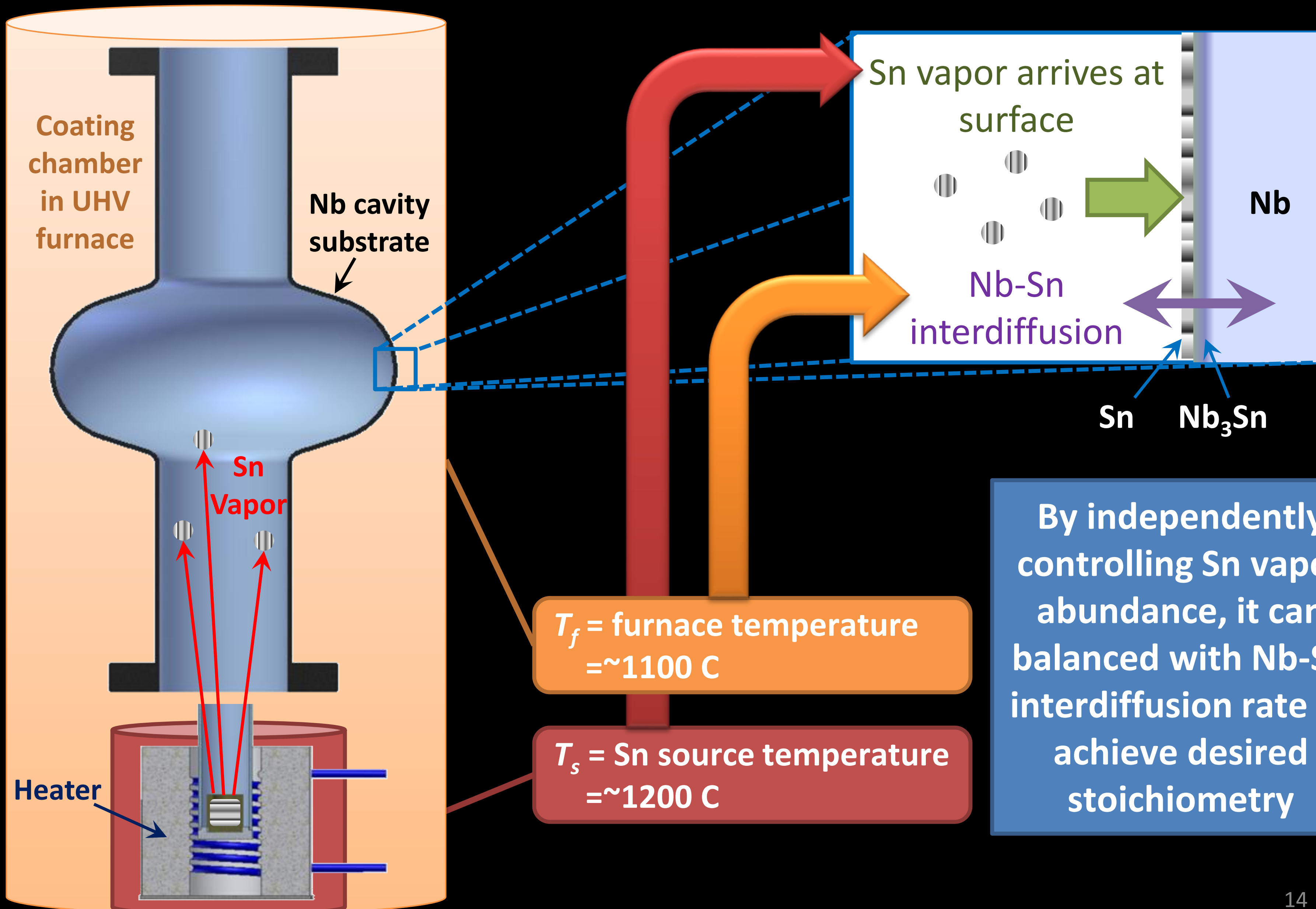
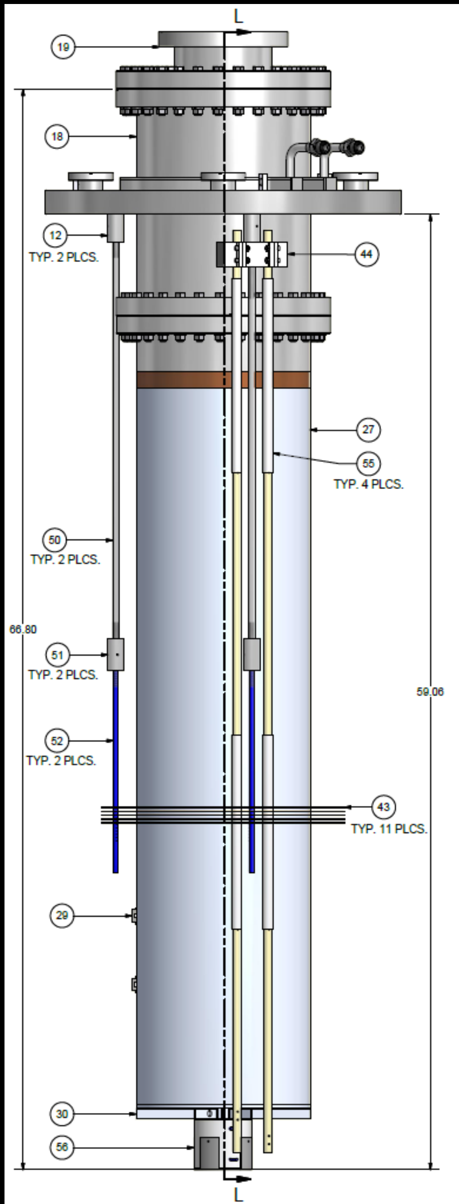
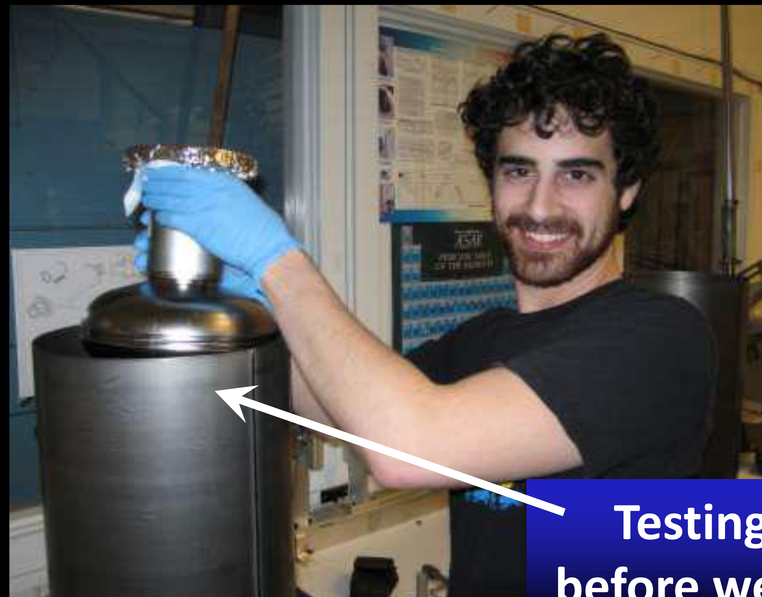
Coating Mechanism: Vapor Diffusion



By independently controlling Sn vapor abundance, it can balanced with Nb-Sn interdiffusion rate to achieve desired stoichiometry

Design and Assembly



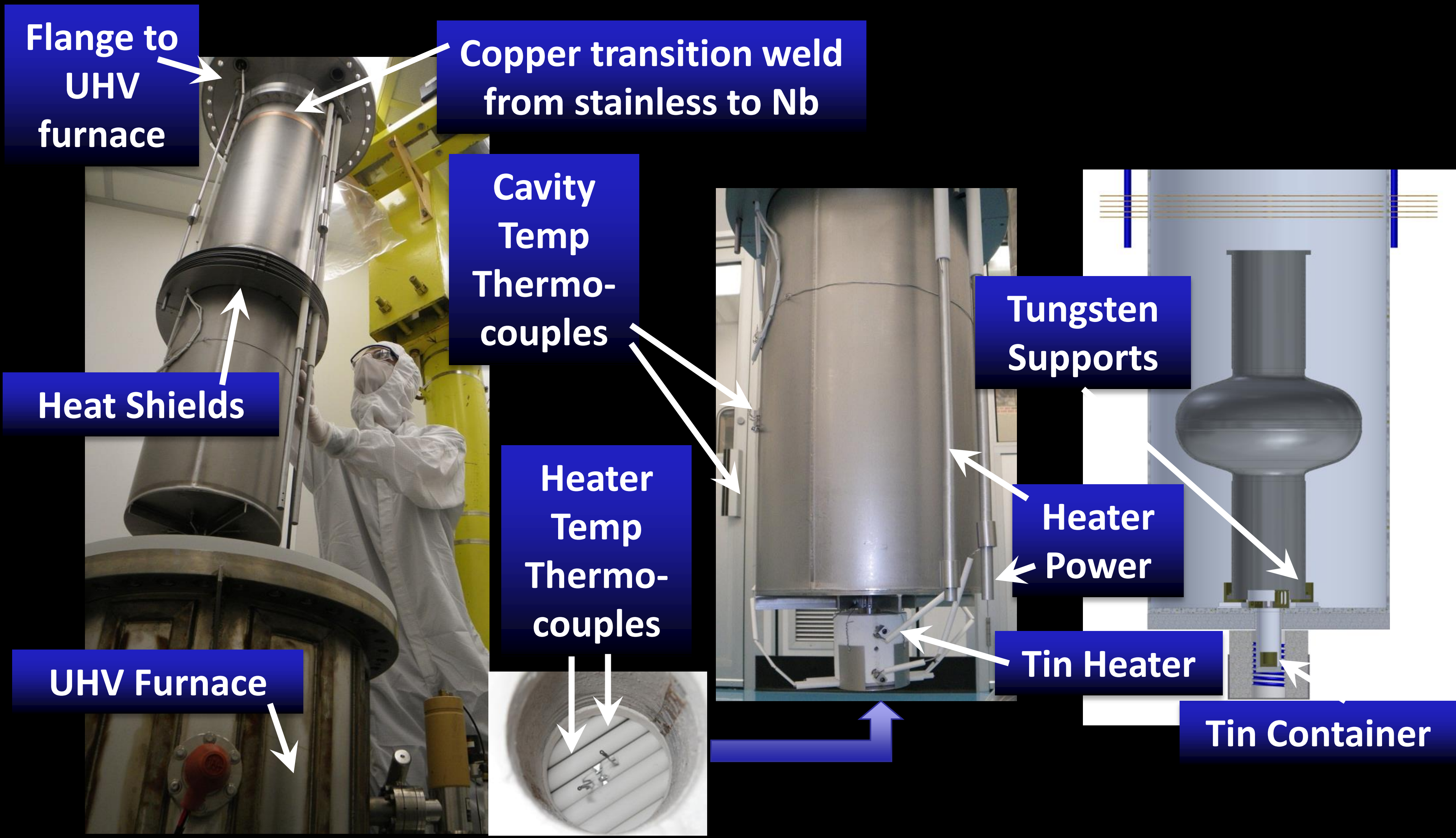


Testing fit before welding

Connection of thermocouples

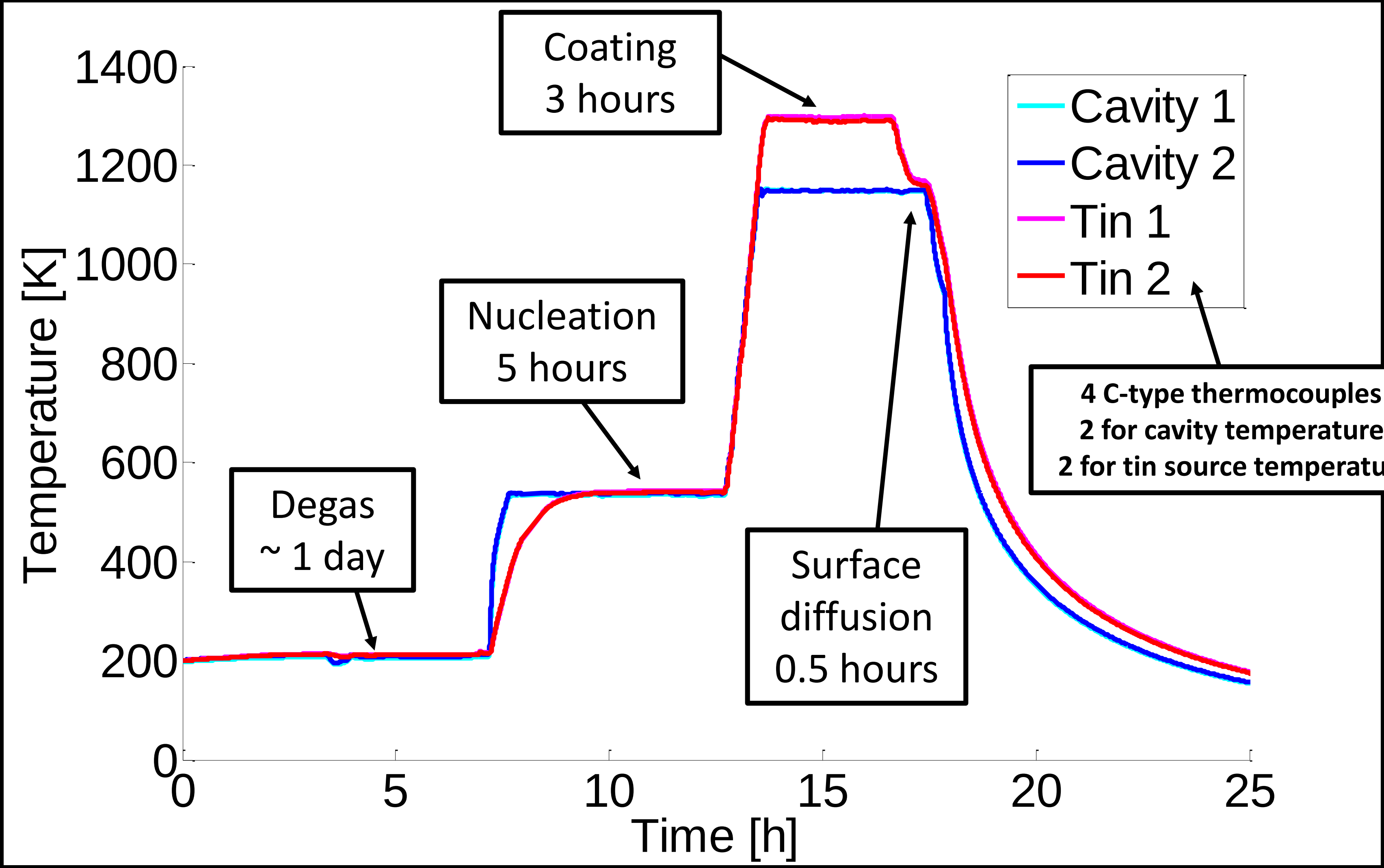
>1200 C heater connection (all Nb, Ta, Mo, ceramic)

Cornell Coating Chamber



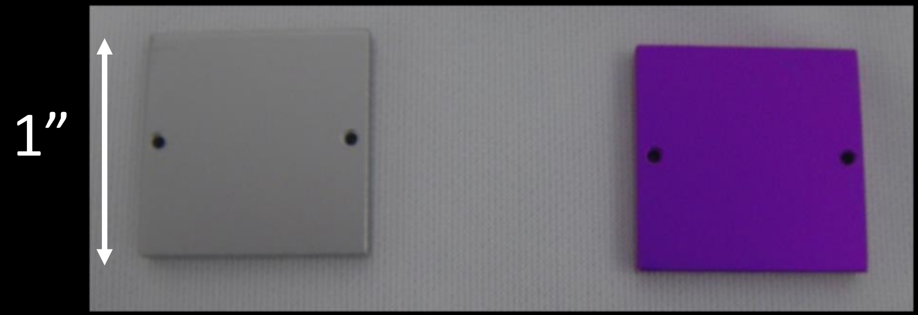
Cornell University

Coating Procedure



Initial Material Development

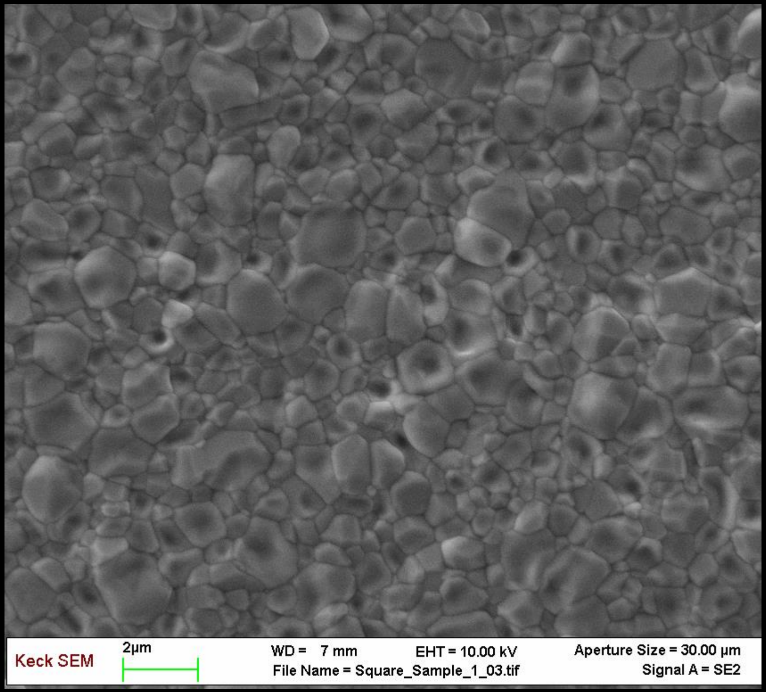
- First coating: 1” square Nb samples
- First test: anodization in NH_4OH at 75 V
- Nb->blue   Sn->yellow Nb_3Sn->Pink/purple
- Color indicates uniform Nb_3Sn, no excess tin

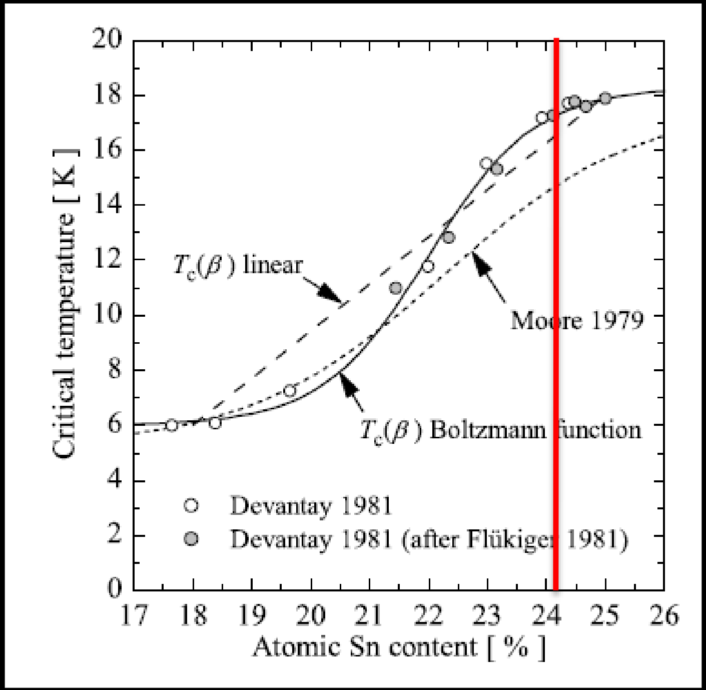


Not anodized   Anodized

SEM/EDX

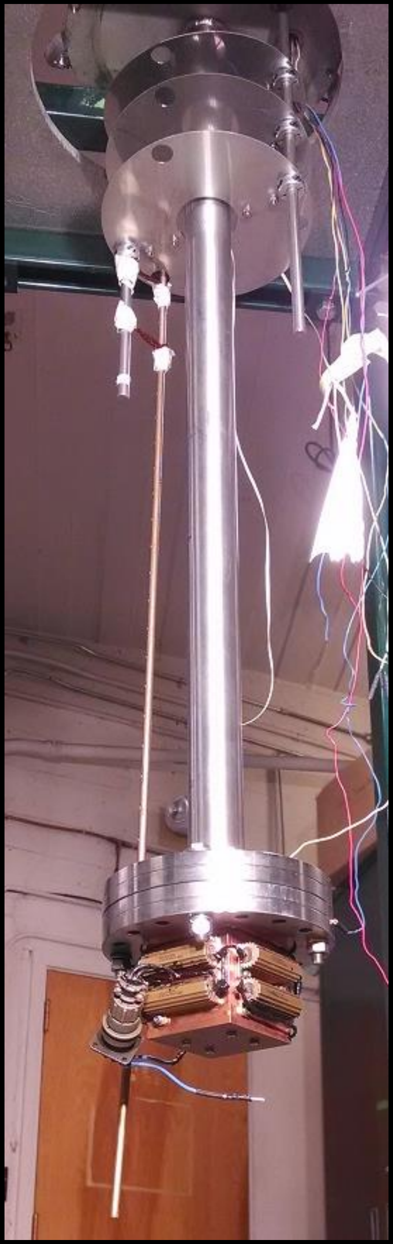
- SEM indicates appropriate grain size and texture
- EDX shows desired tin content for highest T_c
- EDX at various locations confirms uniformity



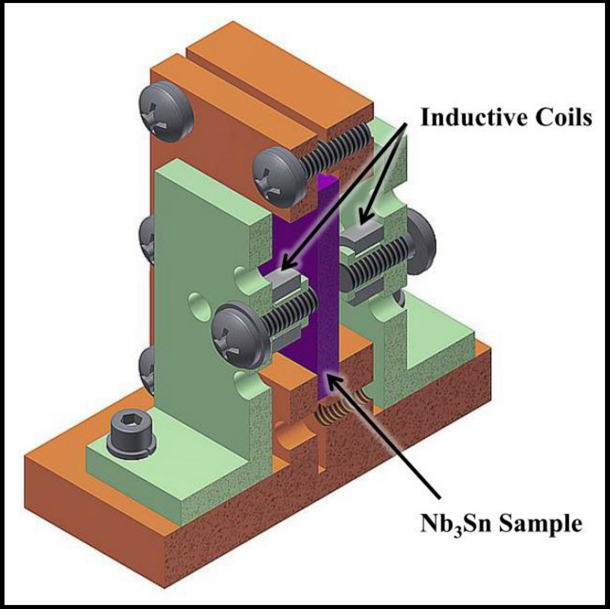


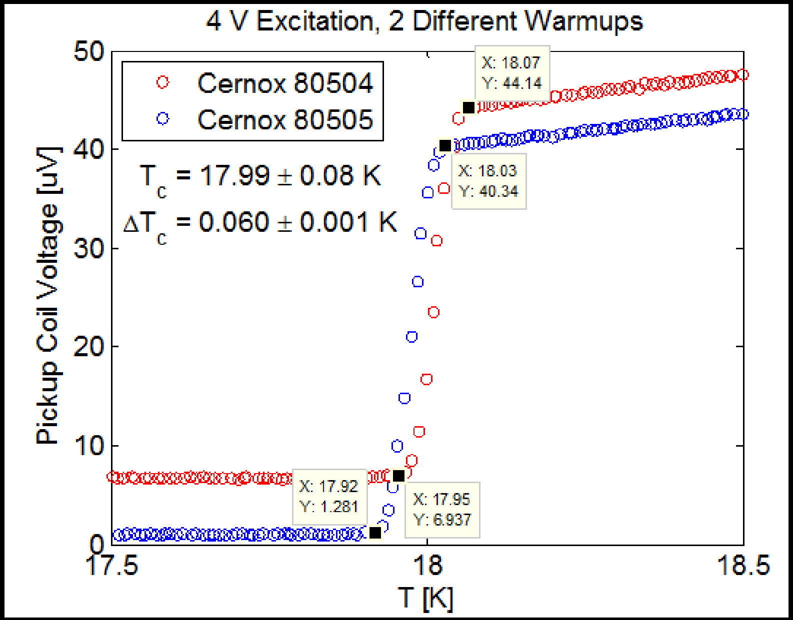
A. Godeke, Supercond. Sci. Tech, 2006

T_c Measurement



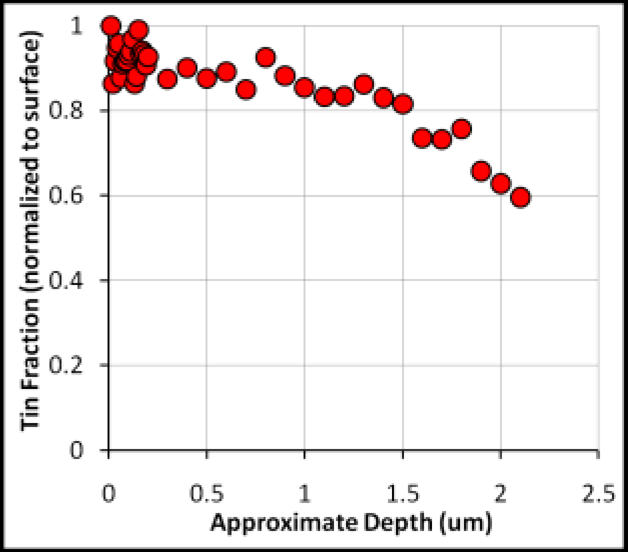
- Inductive T_c measurement system designed and built by community college students working with me
- $T_c = 18.0 \pm 0.1$ K measured inductively is close to highest literature value



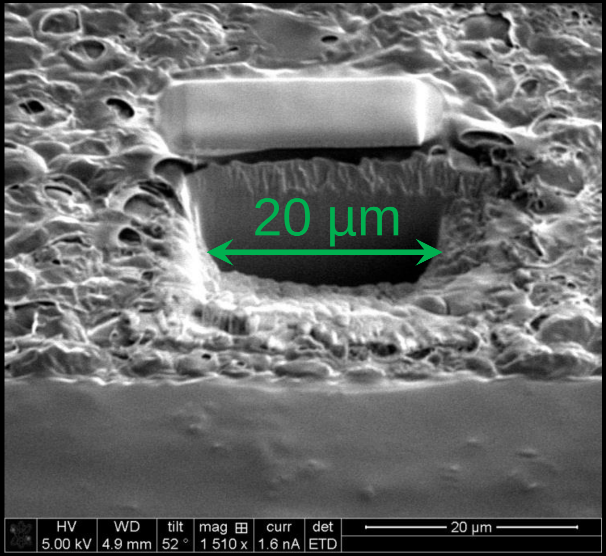


Thickness of Nb_3Sn Layer

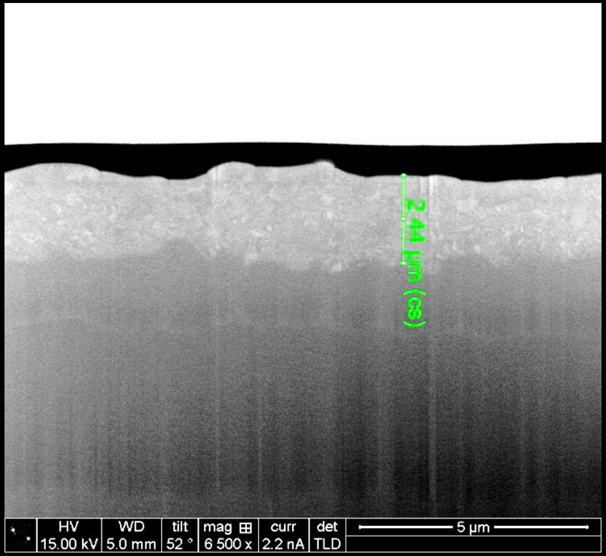
- XPS with incremental sputtering shows uniform composition down to 1.5 µm
- FIB confirms layer is 2-3 microns thick



XPS



FIB



FIB

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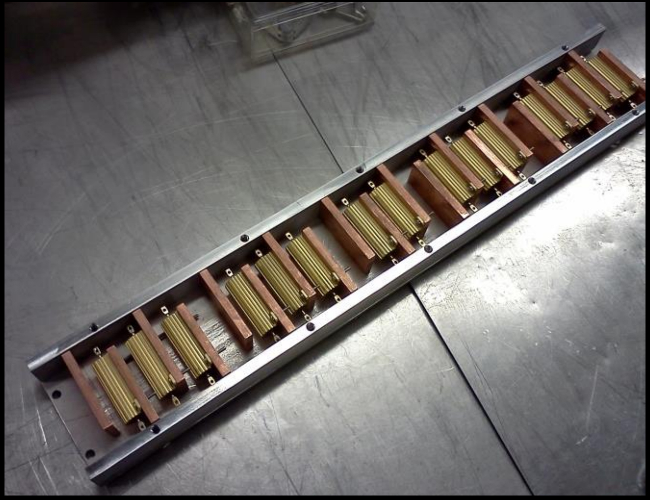
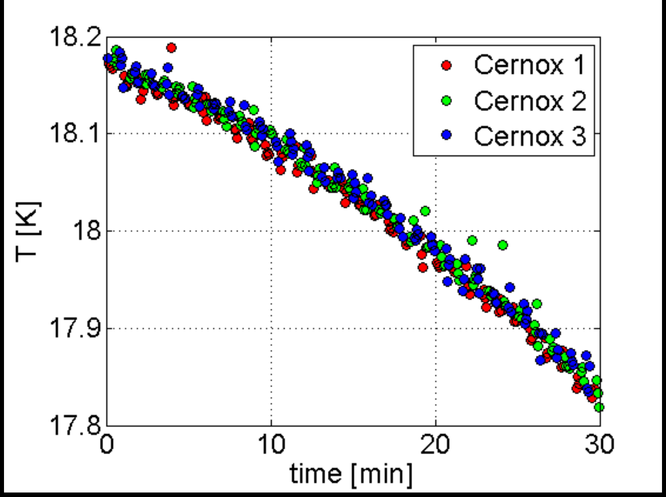
Tool I Developed - Slow Cool System

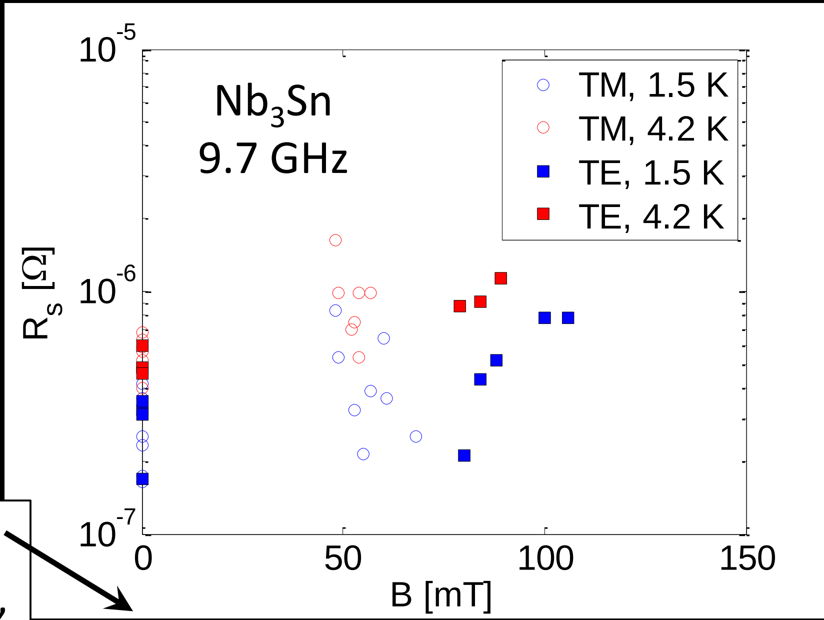
- Nb_3Sn/Nb induces thermocurrents
- To prevent losses, must slowly, uniformly cool through T_c = 18.0 K
- No cold gas: only 4.2 K LHe available
- Designed and made in-line pressure reducer + heater for transfer line





Nb_3Sn SRF History

- Pioneering work at Siemens AG, University of Wuppertal, Kernforschungzentrum Karlsruhe, Cornell University, Jefferson Lab, CERN, and SLAC
- Siemens researchers demonstrated great potential of Nb_3Sn coatings
- High surface magnetic fields in 9.7 GHz cavities, even at 4.2 K

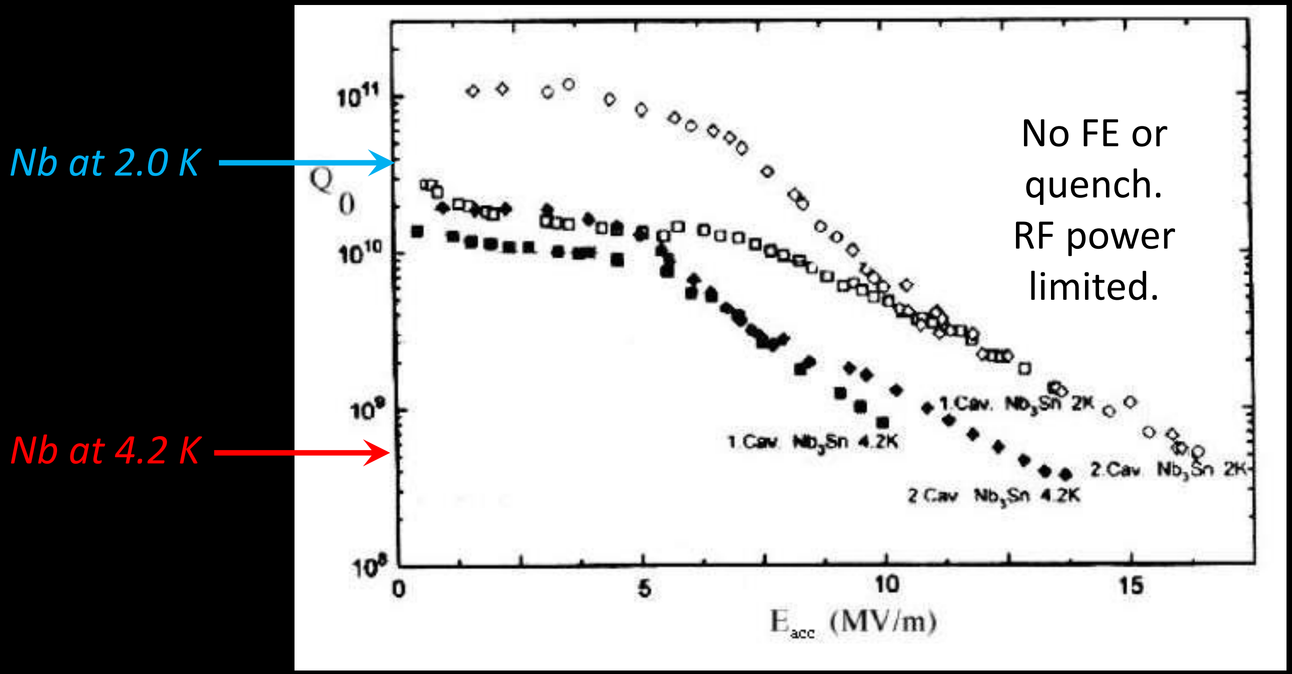


($R_s \sim 10^{-8}\ \Omega$ for Nb at 2K, 1.3 GHz)

B. Hillenbrand et al., Siemens, 1981

Nb_3Sn SRF History

- U. of Wuppertal
  - Small R_s values in Nb_3Sn cavities with shapes and frequencies appropriate for particle accelerators
  - Strong Q-slope, cause uncertain



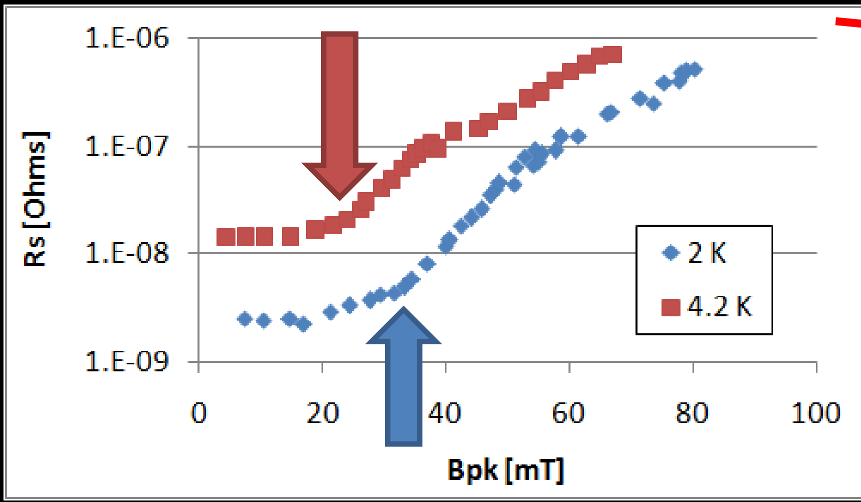
G. Müller et al, U. Wuppertal, 1.5 GHz CEBAF single cell, 2000

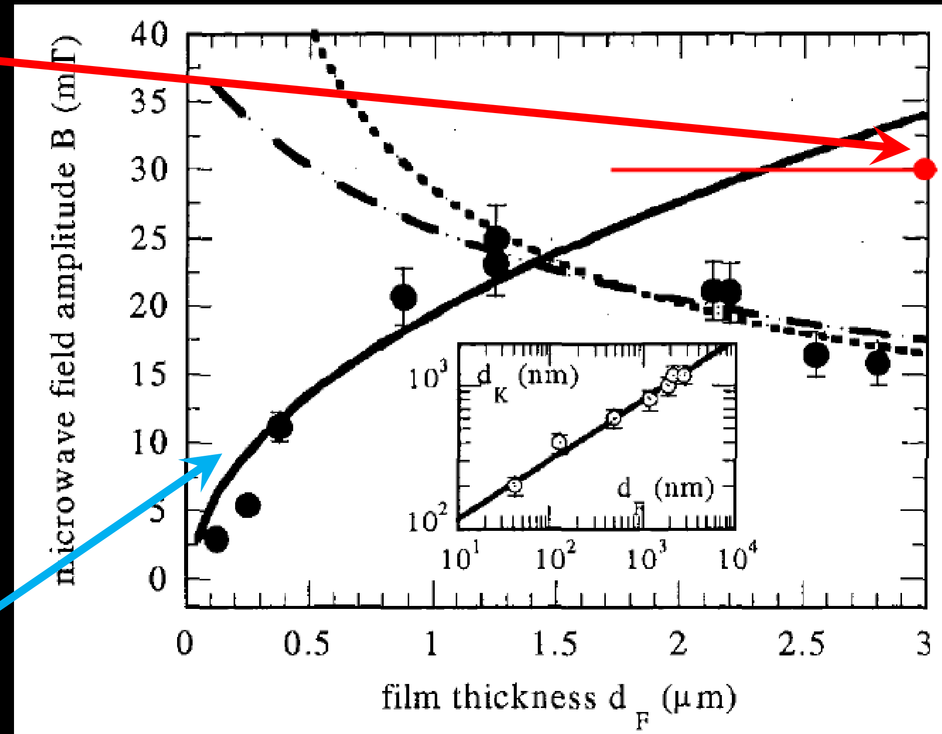
Possible Q-Slope Causes

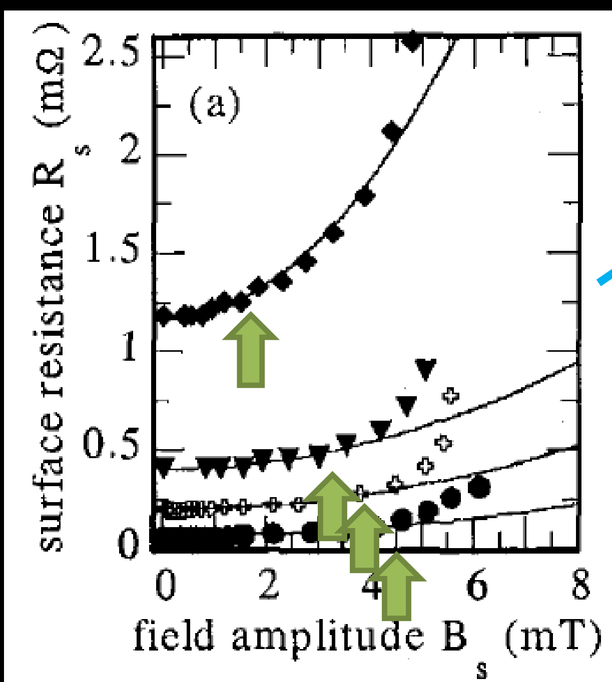
- Exceeding H_{c1}?
  - Nb_3Sn strongly type II: vulnerable metastable state
  - Onset field for increased losses consistently ~ H_{c1}
- Weak links?
  - Losses in material between crystal grains
  - Q vs E similar in appearance to Nb/Cu
  - $R_{res} \sim f^2$ fits some weak-coupling models [1]

[1] Padamsee, Knobloch, and Hays, RF Superconductivity for Accelerators*, 1998.*

Nb_3Sn SRF History



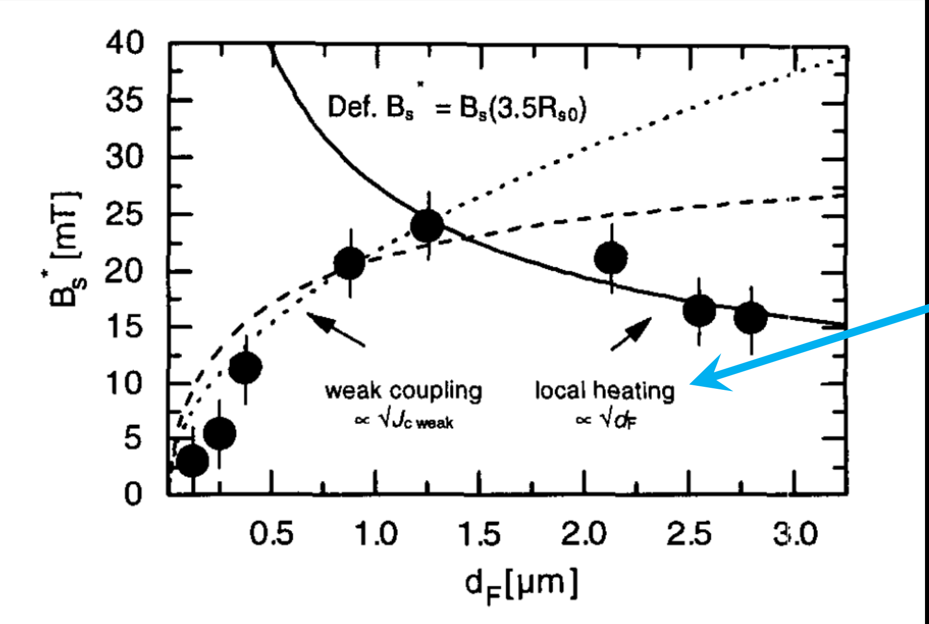




M. Hein et al., U. Wuppertal, 1" dia. samples at 19 GHz, 2001

- U. of Wuppertal
  - Additional studies on samples
  - Found that onset field of RF instability depended on grain size

Ideas from Previous Researchers



M. Perpeet et al., U. Wuppertal, 1999

Overheating less problematic at ~1 GHz vs 19 GHz because R_{BCS} is much smaller

- Wuppertal researchers suggest larger grains leads to larger GB critical currents
- Also fewer GBs (i.e. fewer lossy regions)
- Preliminary 1250 C annealing attempts at Wuppertal had poor results

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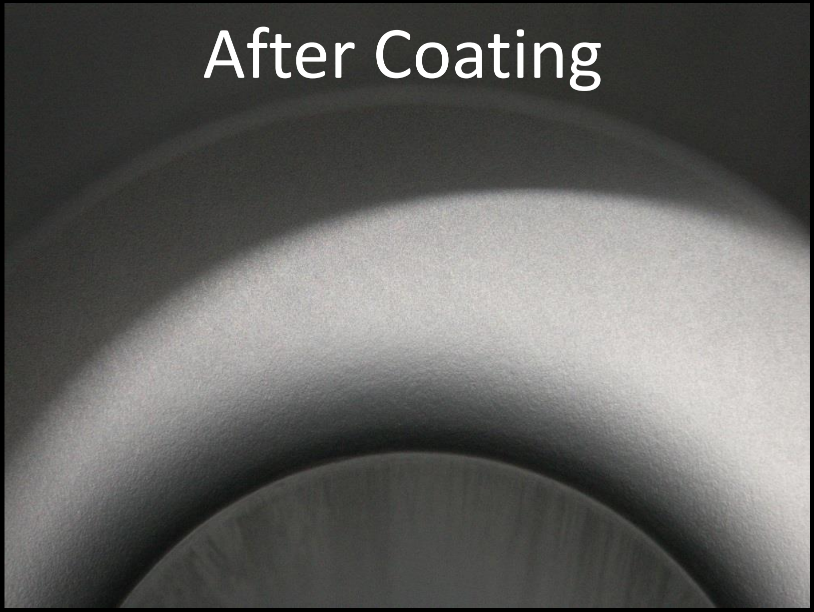
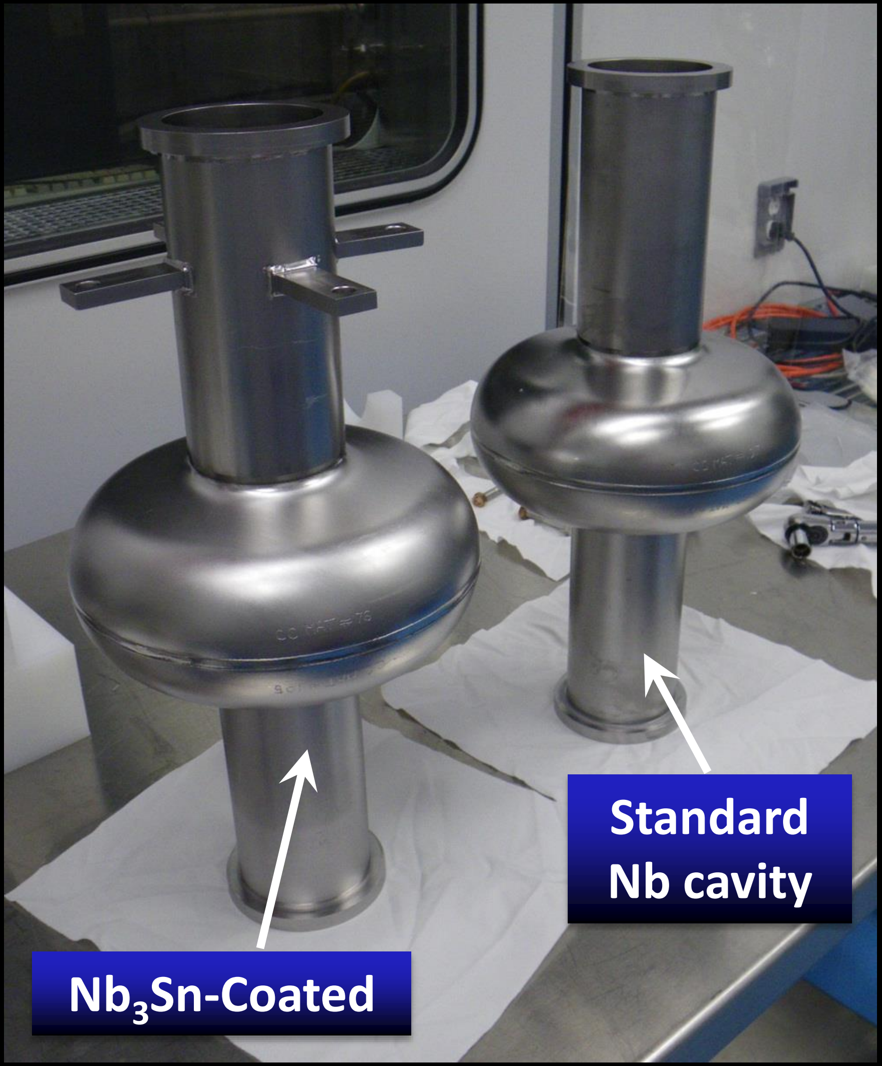
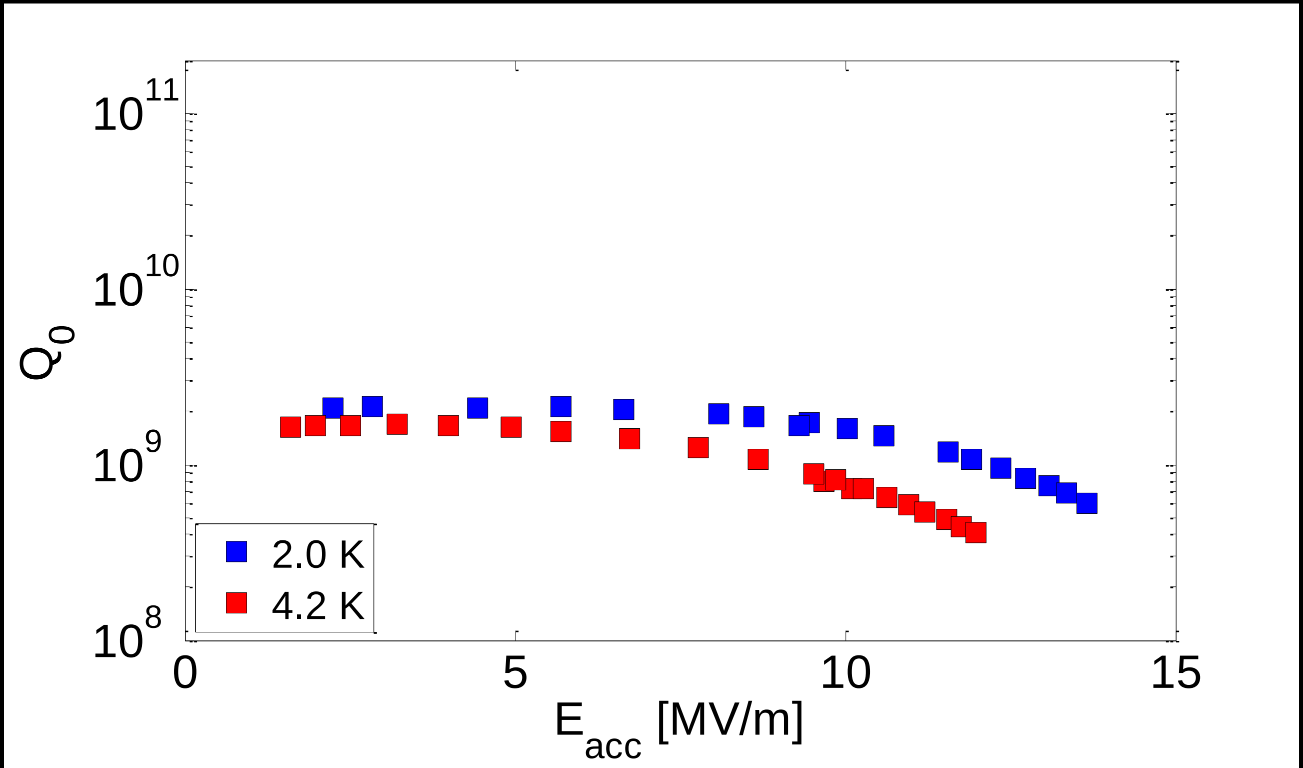
Coated Cavity





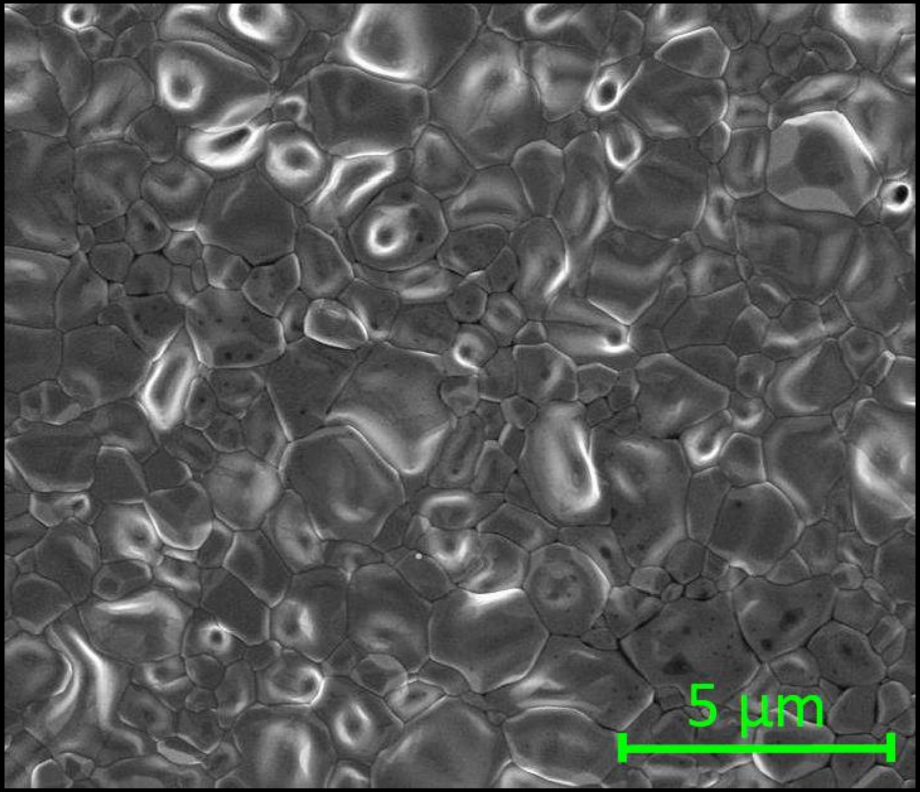
First Cavity: No Anneal

- First cavity: no anneal
- Strong Q-slope observed similar to Wuppertal
- Cause of high R_{res} appears to be coating problems for one half-cell only

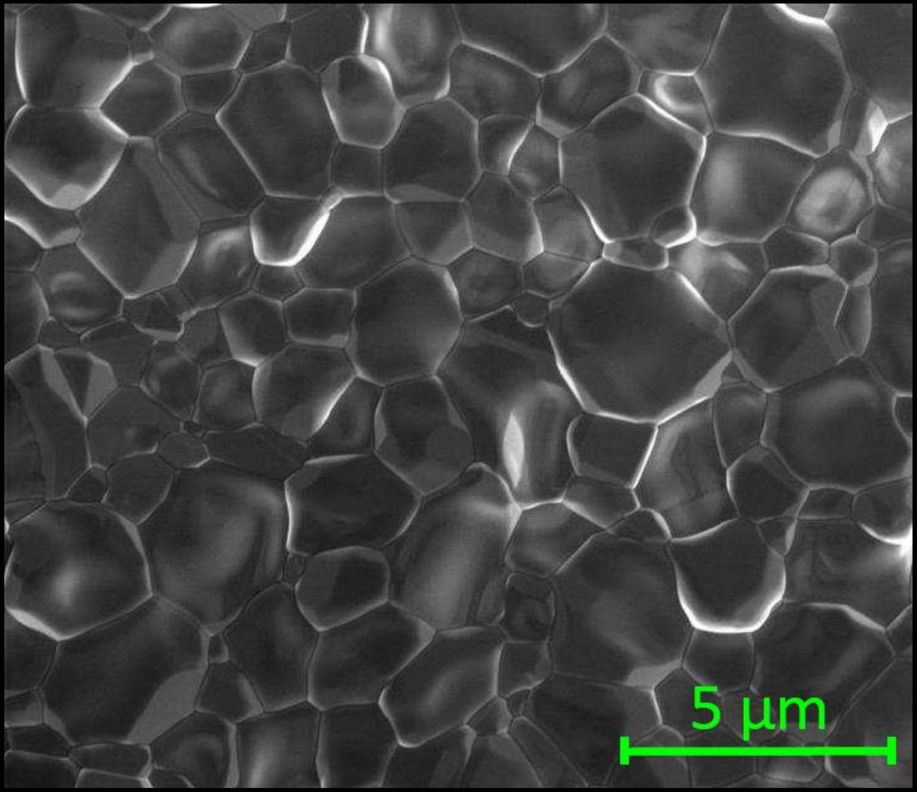


Grain Growth via Annealing

- Found I could grow grains by factor of ~2 while maintaining desired stoichiometry by modifying Wuppertal recipe
  - Extra annealing step: Furnace at 1100 C, but tin heater off



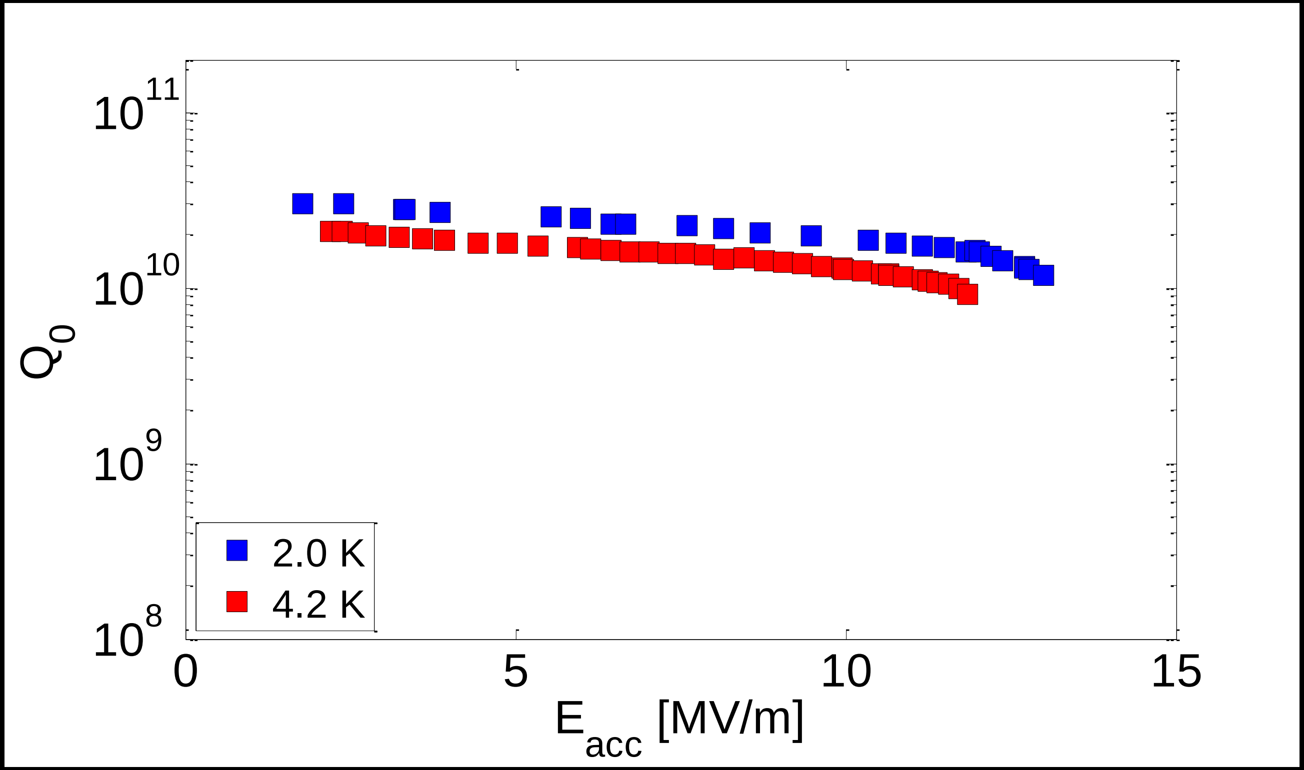
No annealing step, average grain size ~1 µm



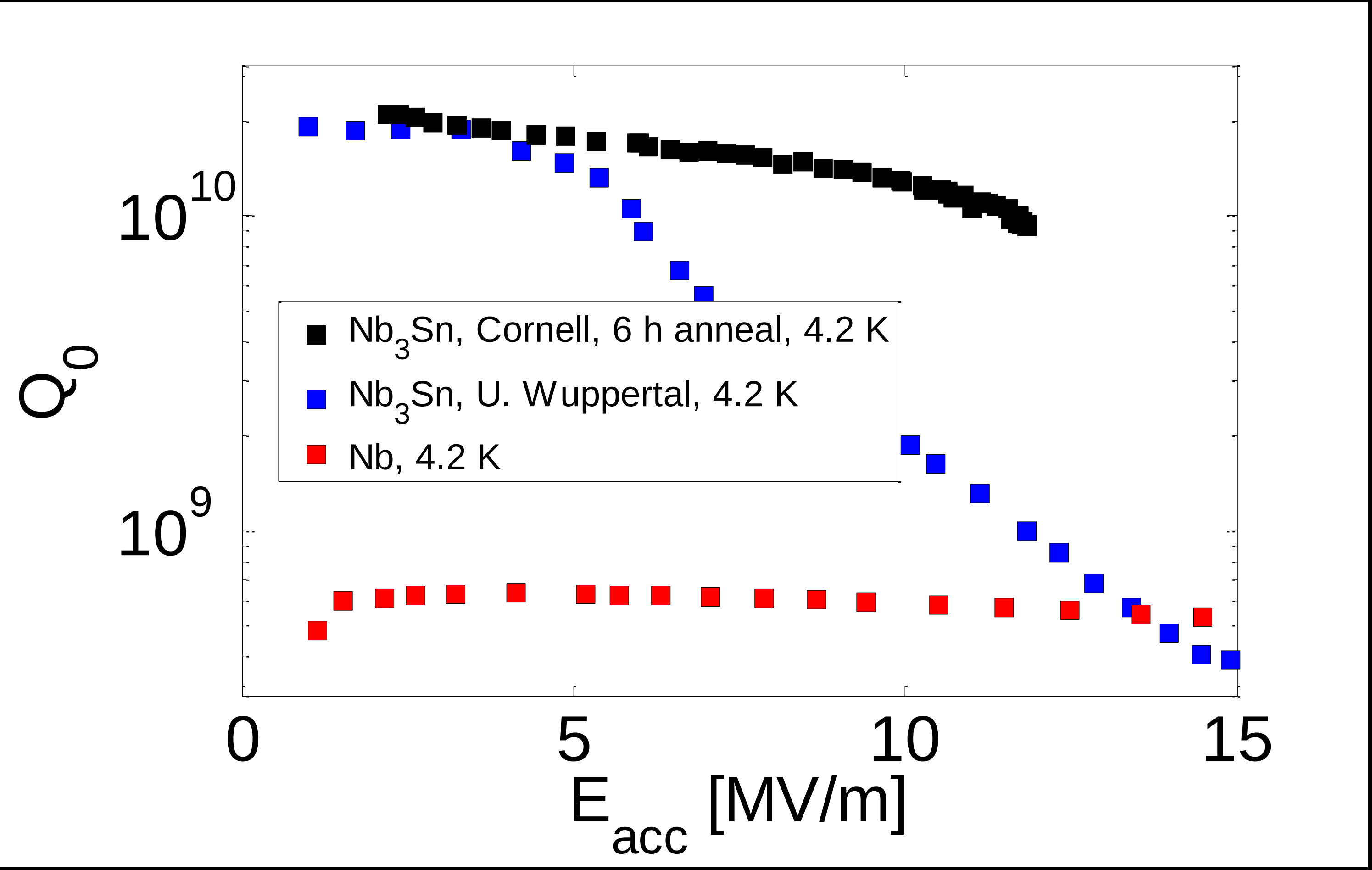
Anneal 6 hours, average grain size ~2 µm

Second Cavity: 6 h Anneal

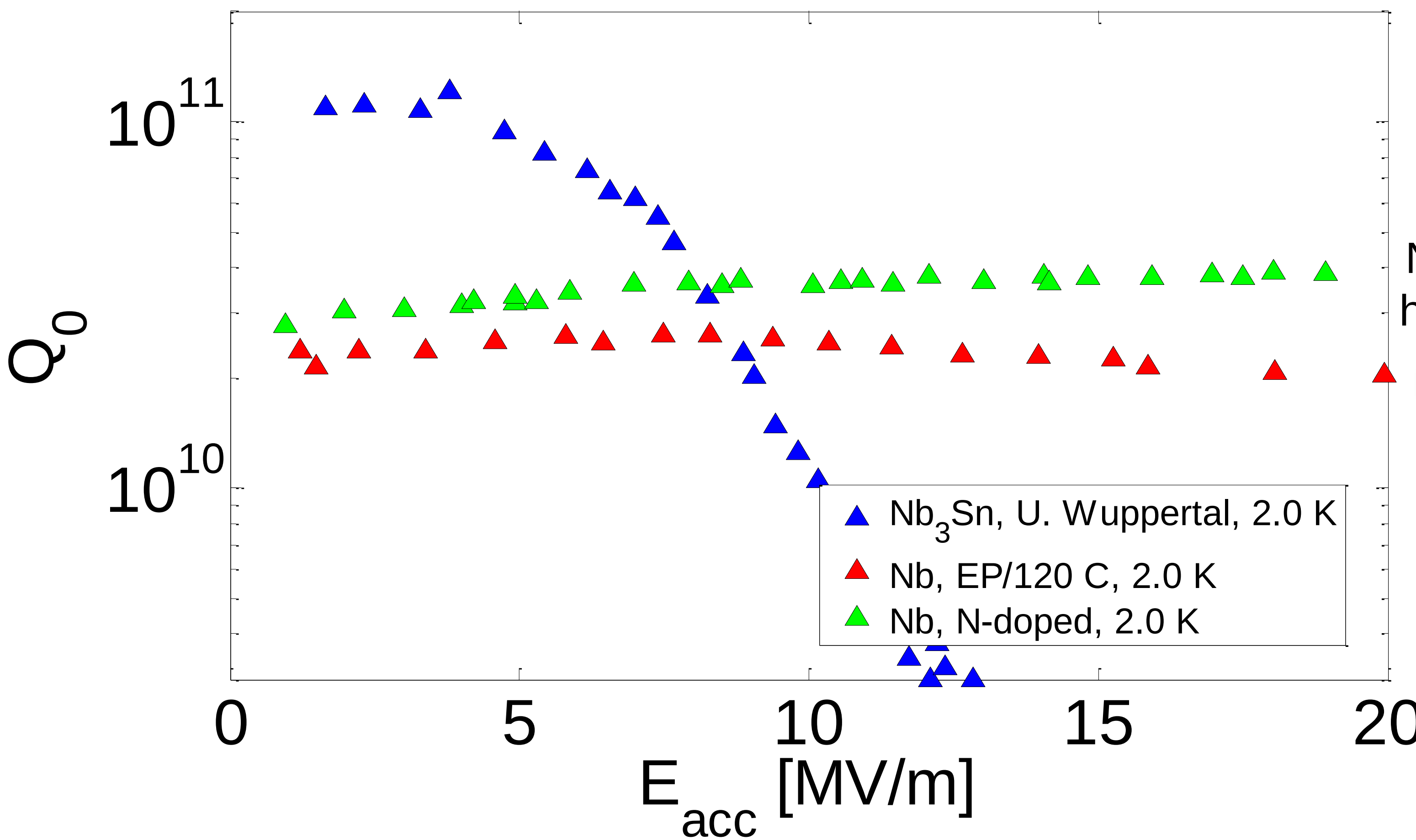
- R_{res} problem seems resolved by new cavity
- 6 hour annealing during coating process
- No strong Q-slope observed



4.2 K Comparison Curves

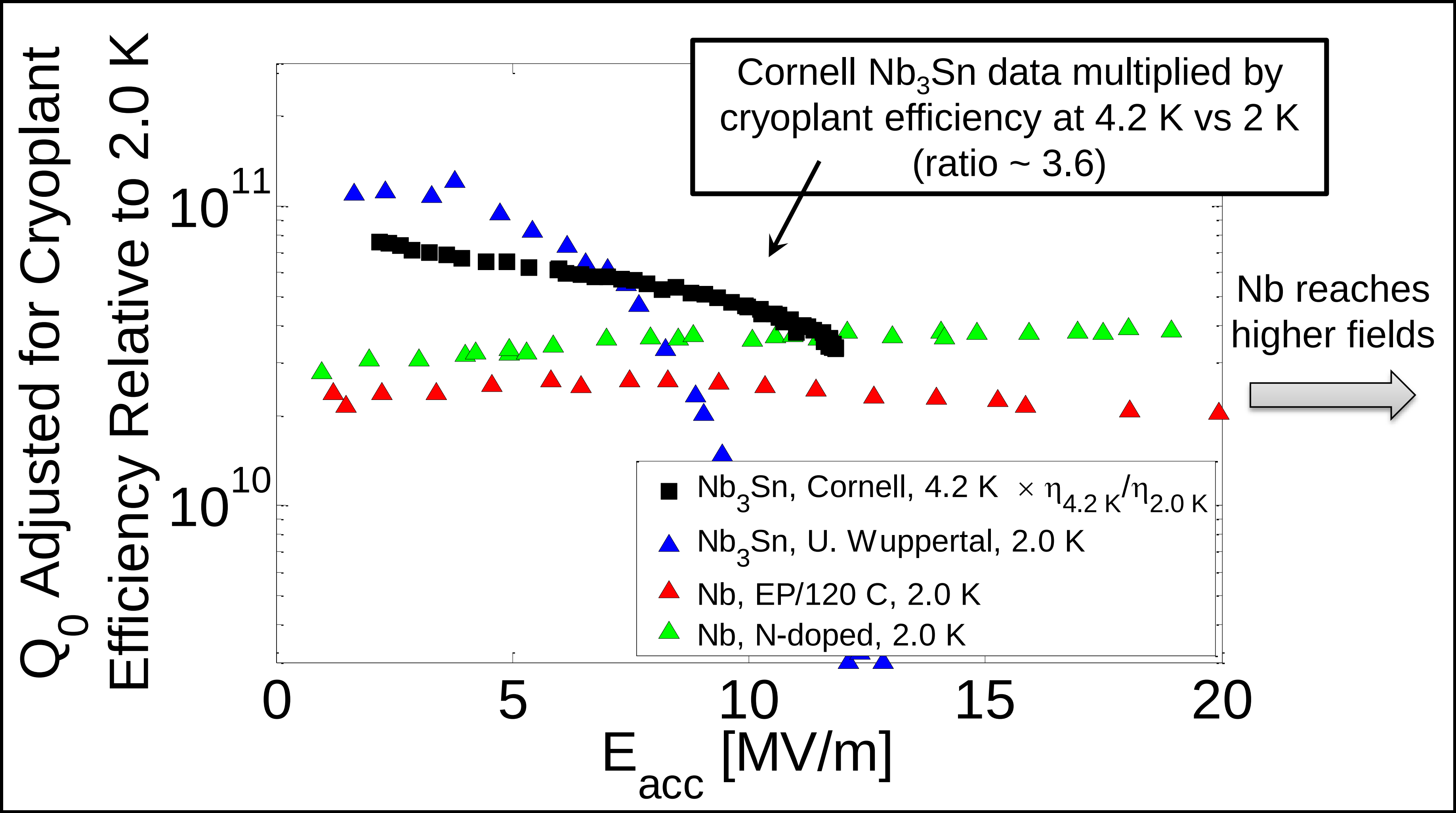


2.0 K Comparison Curves



Nb reaches higher fields

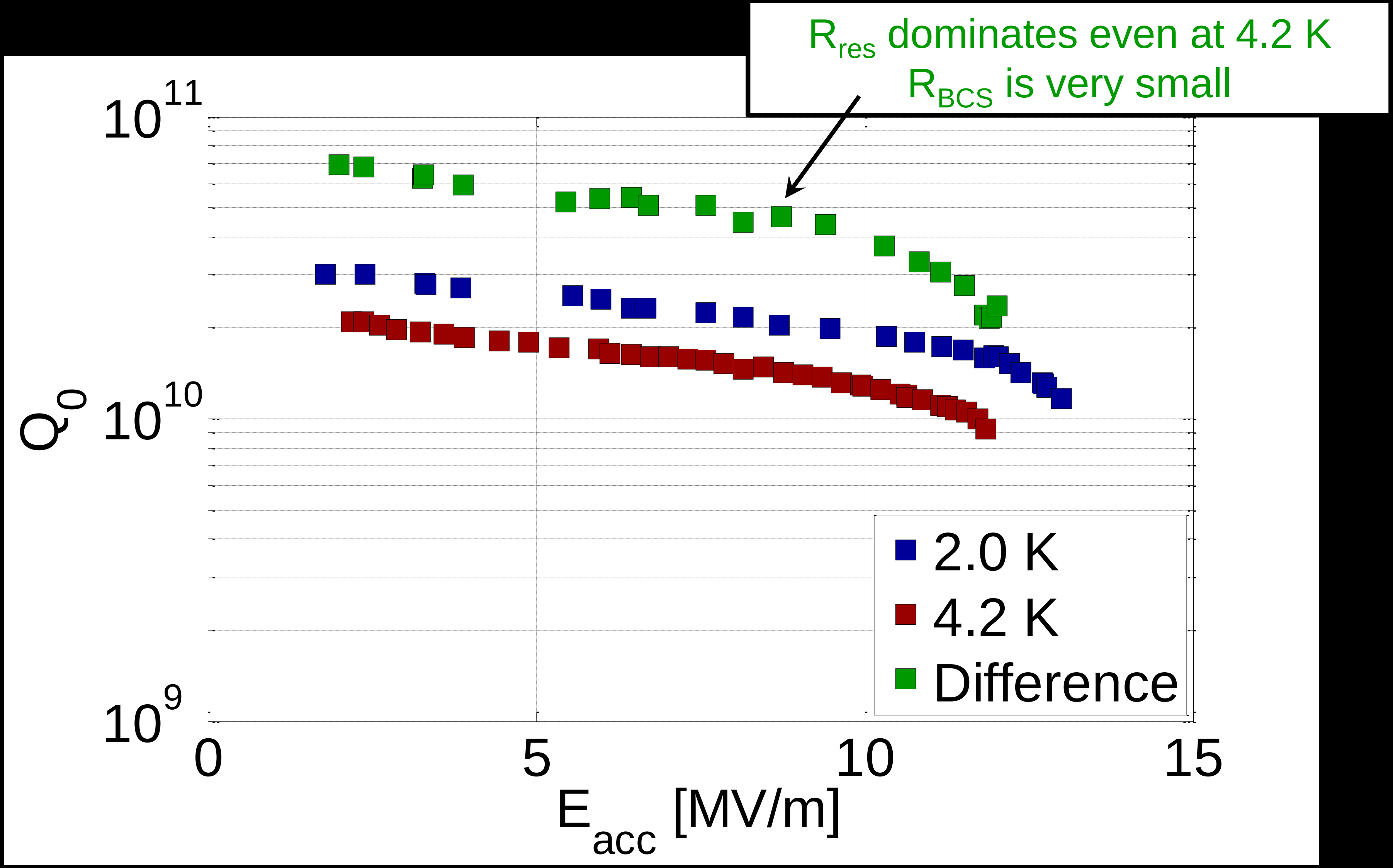
2.0 K Comparison Curves



Q vs E Curve Decomposition

- Generally think of two R_s contributions to overall Q_0:
  - Residual resistance R_{res}: temperature independent
  - BCS resistance R_{BCS}: roughly follows $Ae^{-\Delta/(kT)}$
- For $T << \Delta/k$, R_{BCS} is very small, so residual dominates
- Can subtract low temperature R_s to determine temperature-dependent contribution

Q vs E Curve Decomposition



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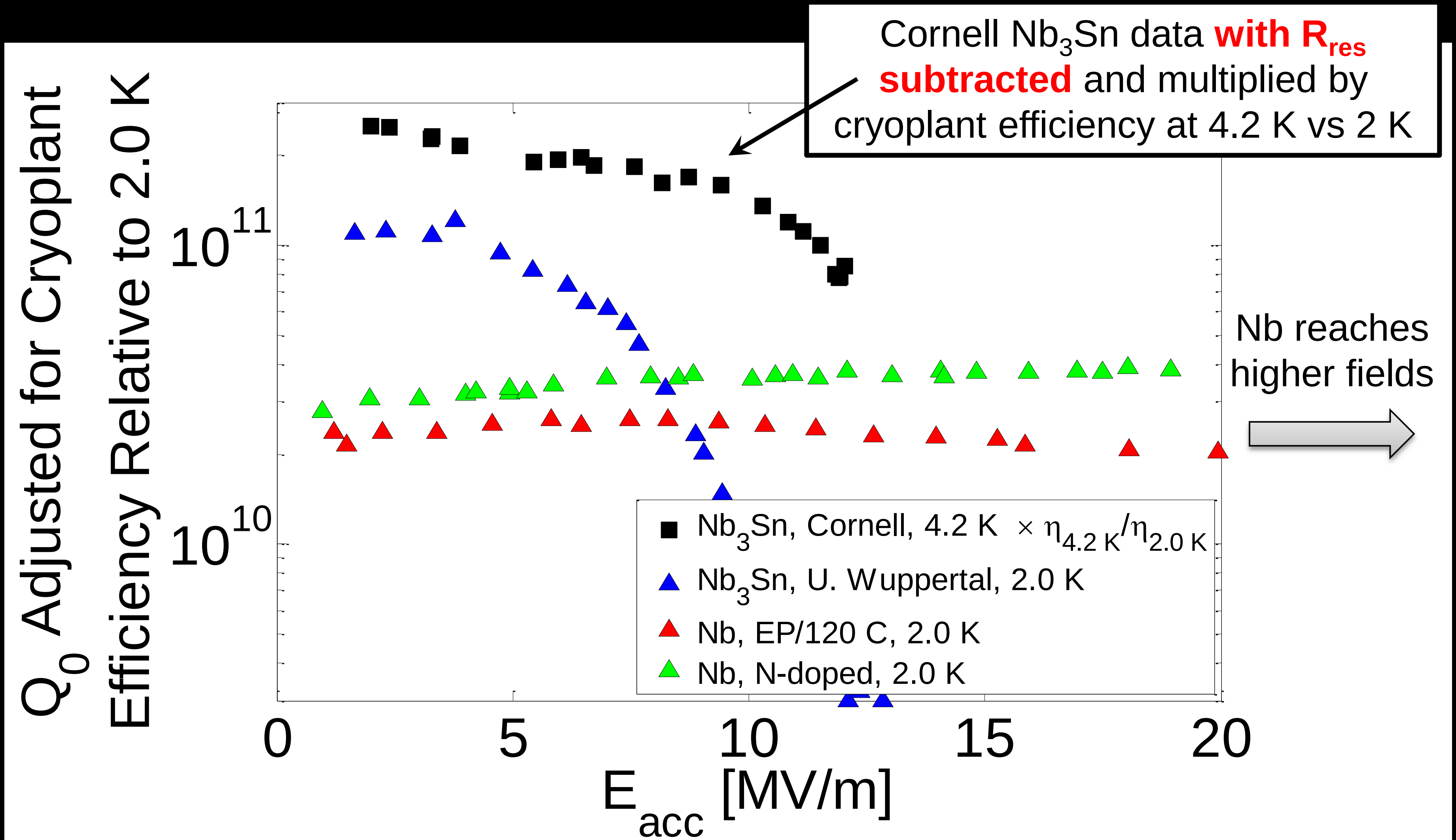
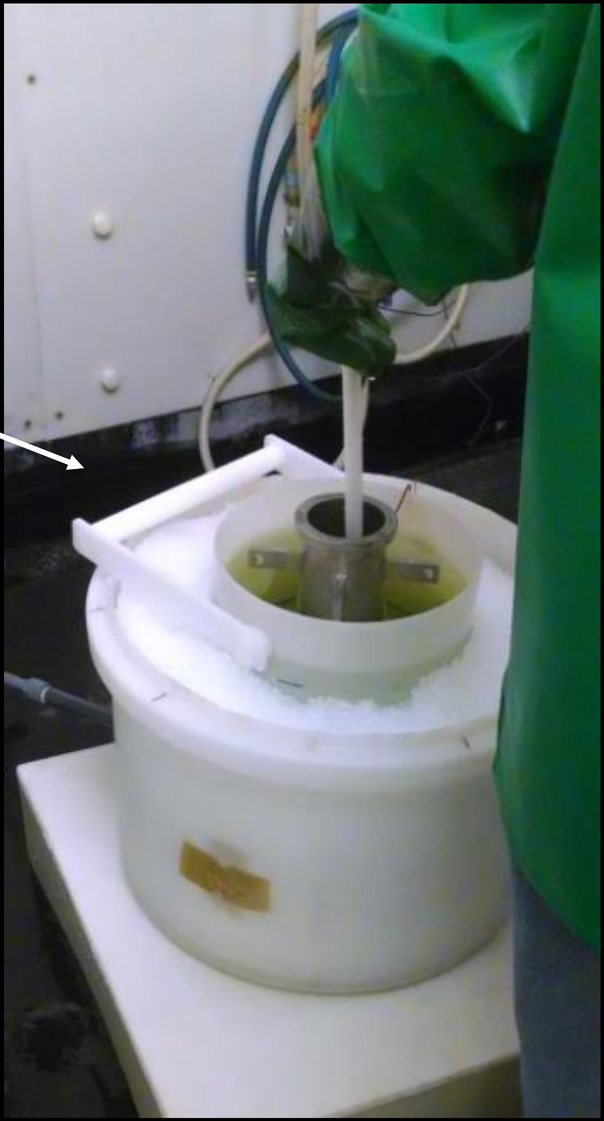
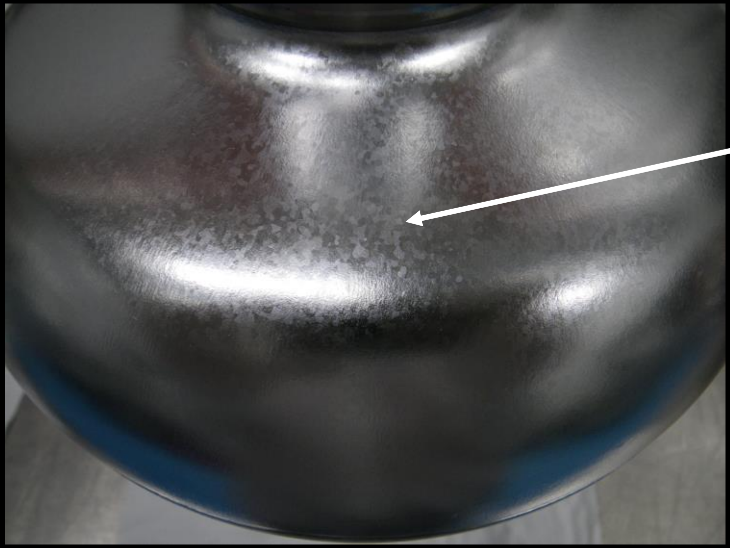


Resetting the Surface

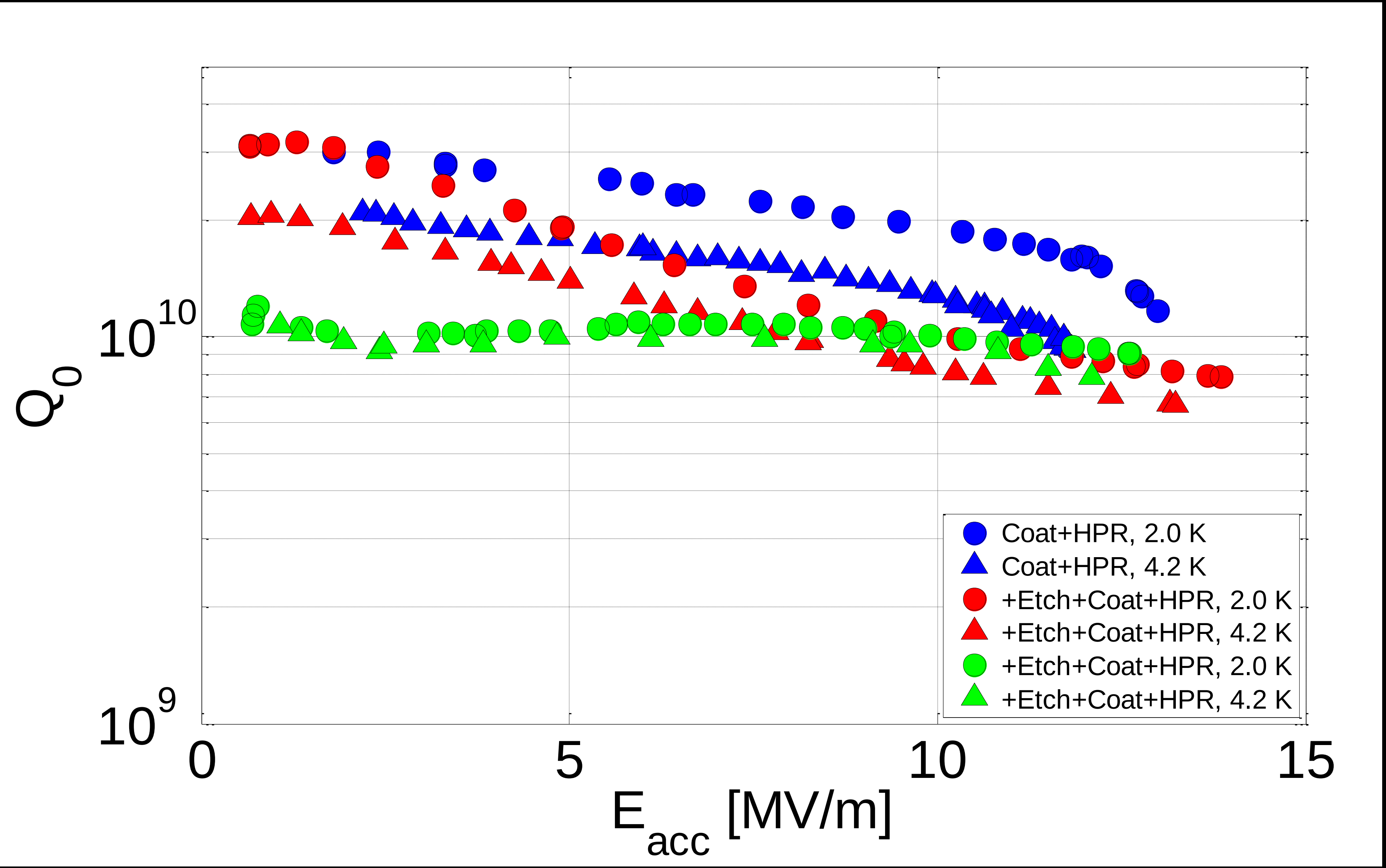
- BCP 10 minutes inside and outside to clean entire surface before putting cavity into clean room furnace
- 10 micron BCP inside to reset RF surface





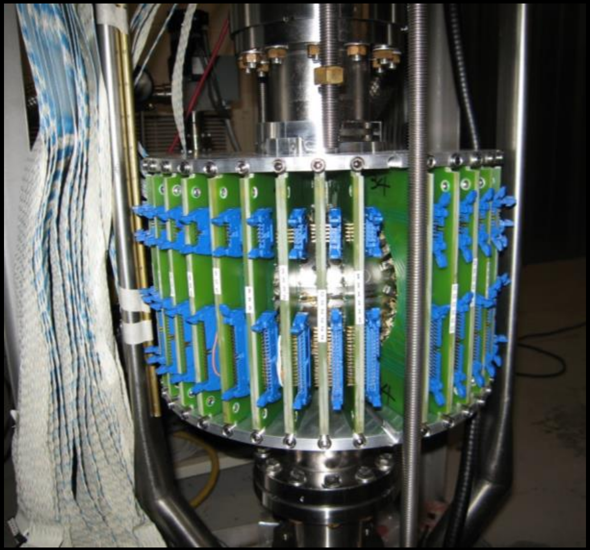
Larger niobium grains after 1100 C heat treatment

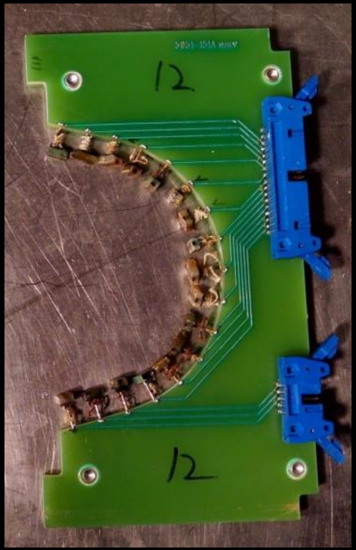
Repeatability

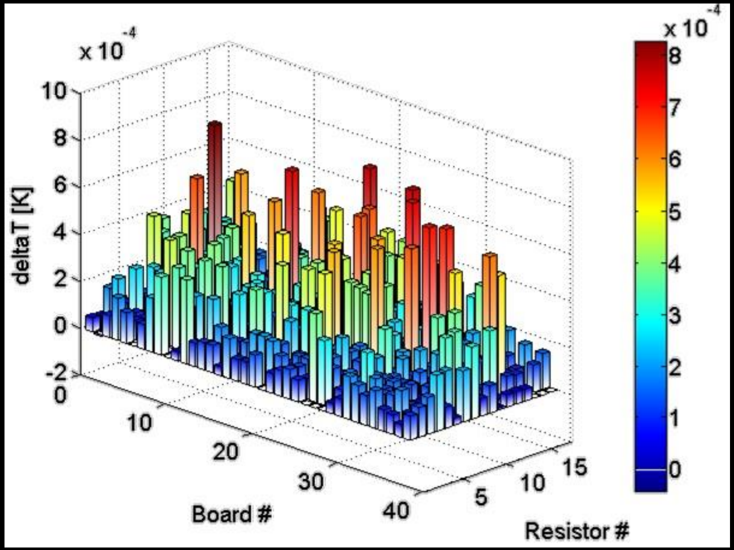


Tool I Developed – 1.3 GHz Temperature Map

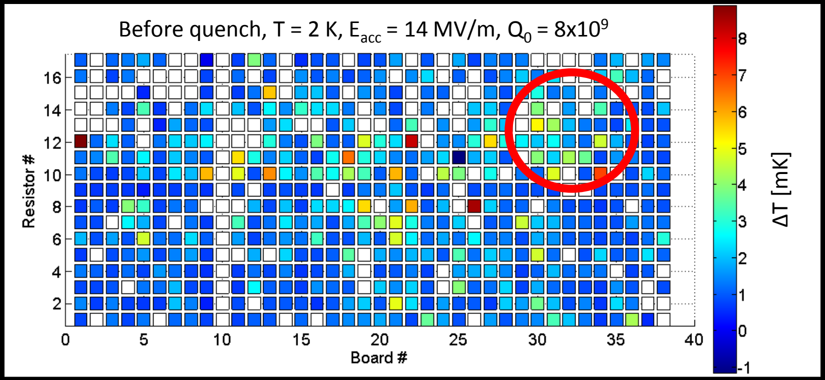
- Converted 1.5 GHz CEBAF-shape T-map to 1.3 GHz TeSLA- and ERL-shapes
- New boards, holders, test insert
- Wrote MATLAB program to take data from multiplexer, convert to temperature, and plot

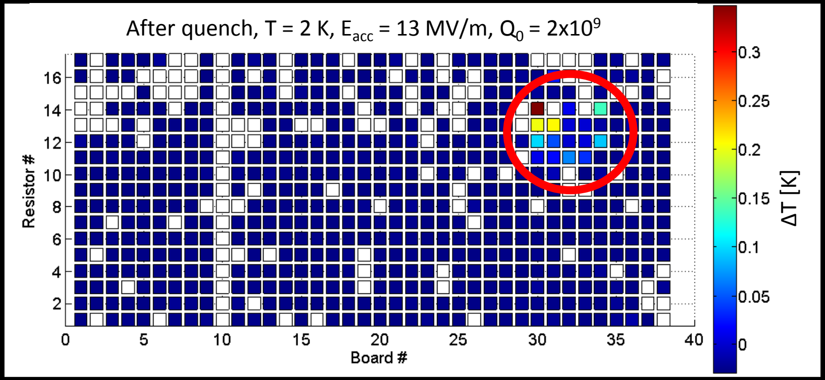


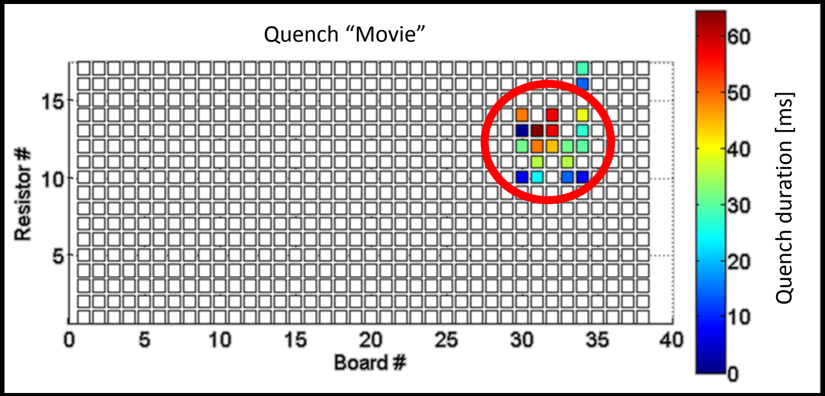




Field Limitation – Quench







- Temperature maps show quench occurs in small area in high magnetic field region (2nd coating shown)
- Defect with size comparable to ξ (~3-4 nm) is suspected cause
- Before resetting surface, I used material removal to try to remove defects

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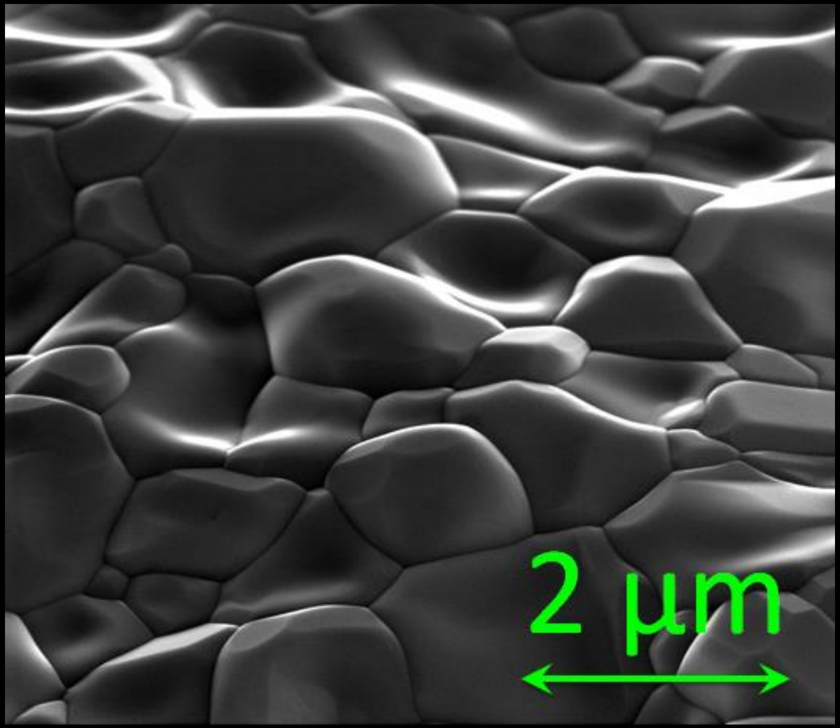
HF Rinse

- Five cycles of:
  - Fill cavity with HF and leave it for 2 minutes to remove oxide layer, then remove acid
  - Fill with DI water and leaving for 5 minutes to regrow the oxide, then remove water
- HPR and mount to test stand

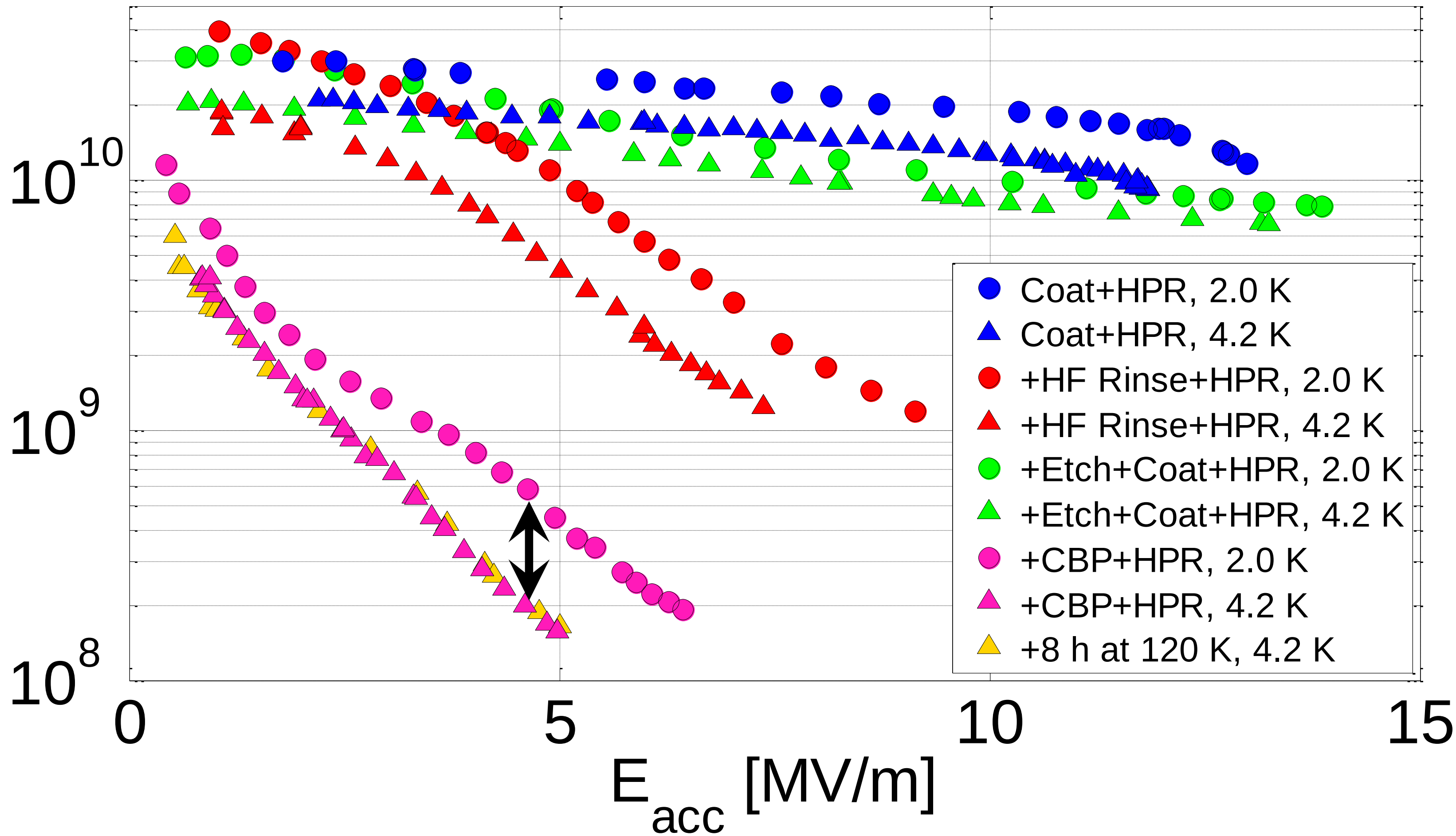


HF rinse: Uniform removal of 30-50 nm to smooth as-coated surface, remove defects

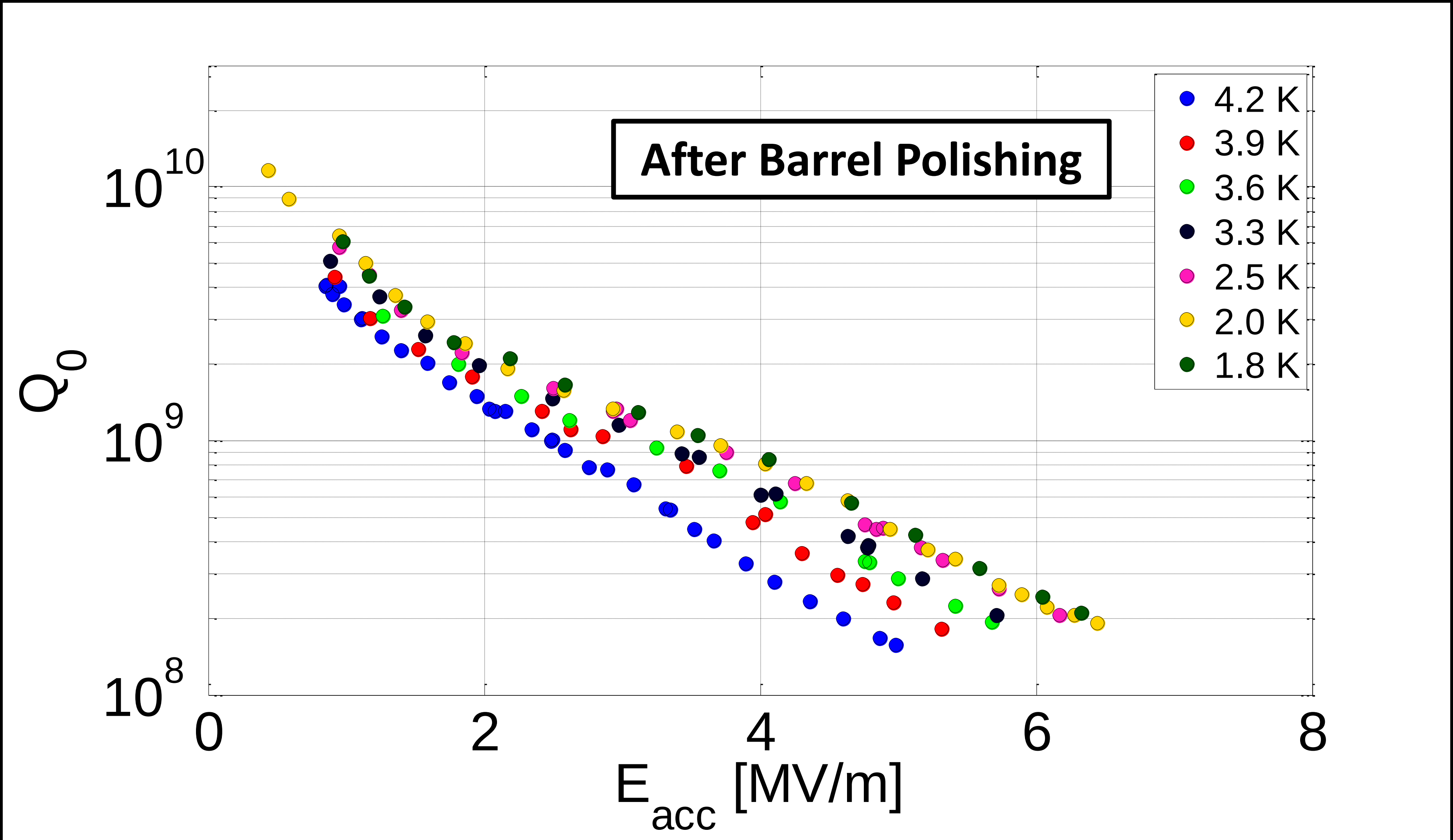
Centrifugal Barrel Polish (CBP)

- Applied only finest polishing step from Charlie Cooper's Nb recipe (coating is only 3 μm thick!)
  - 40 nm colloidal silica with wood blocks
- Short duration: 4.5 hours (minimal removal to see if degradation occurs due to CBP)
  - Nb recipe calls for 40-300 hour duration
- HPR and mount to test stand

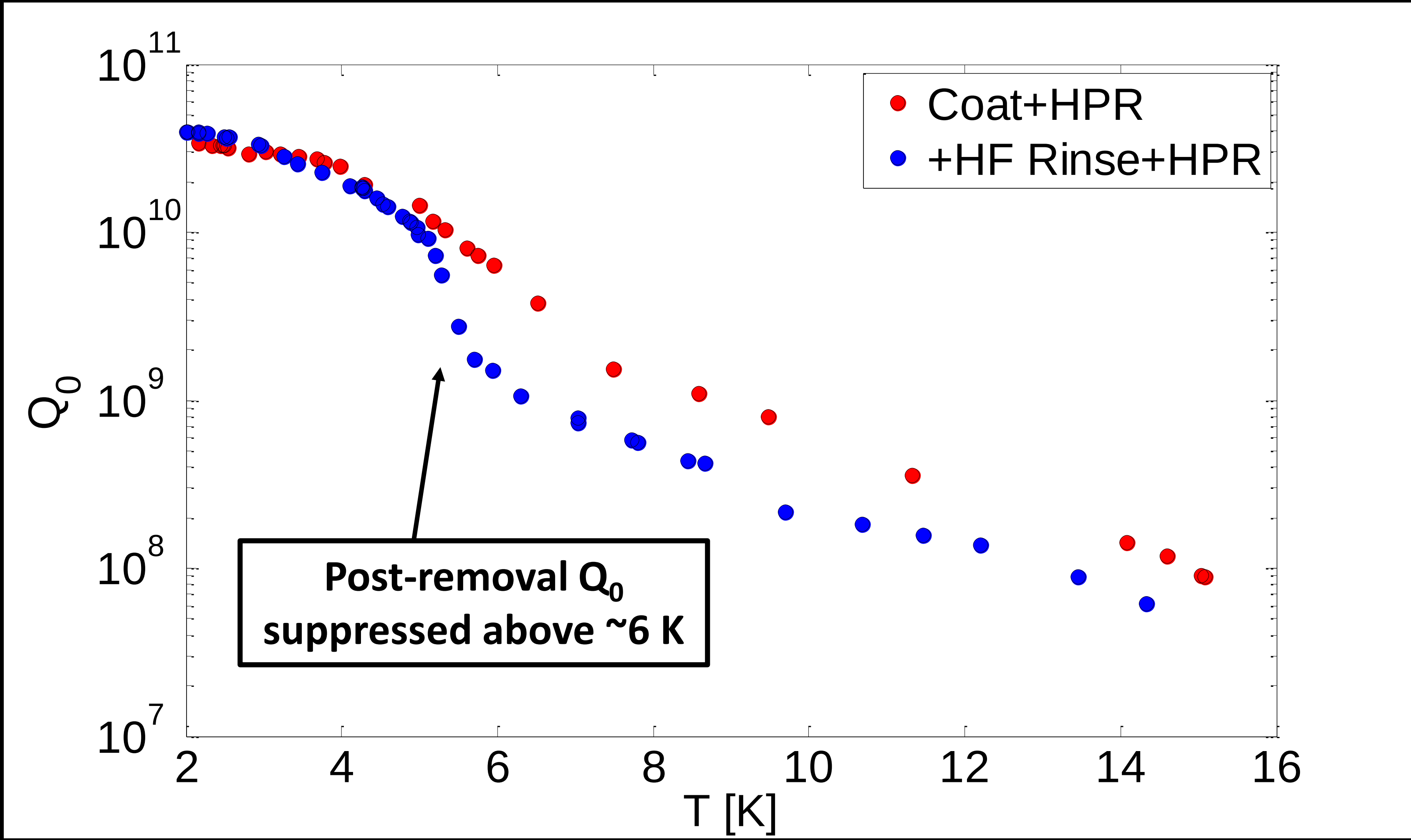
Degradation from Material Removal



Indications of GB Losses?

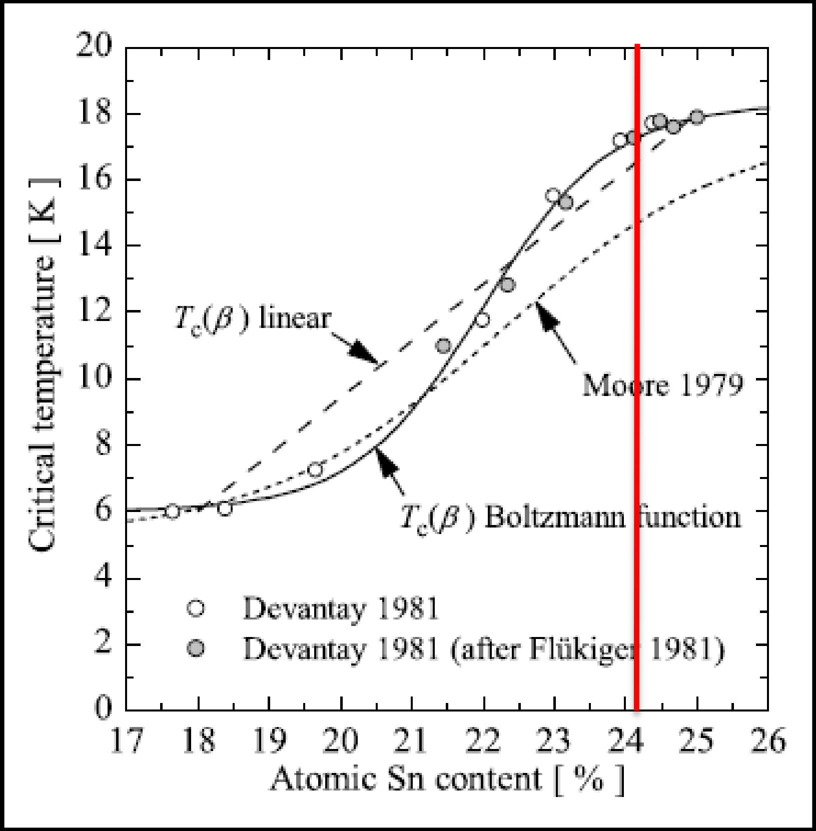


Indications of GB Losses?



Indications of GB Losses?

- Q-slope is strongly temperature dependent
- Post-removal Q_0 suppressed above ~6 K
- Suggests poor quality superconducting material with T_c ~ 6 K



A. Godeke, Supercond. Sci. Tech, 2006

Why Nb_3Sn?

Material development

Lessons from history

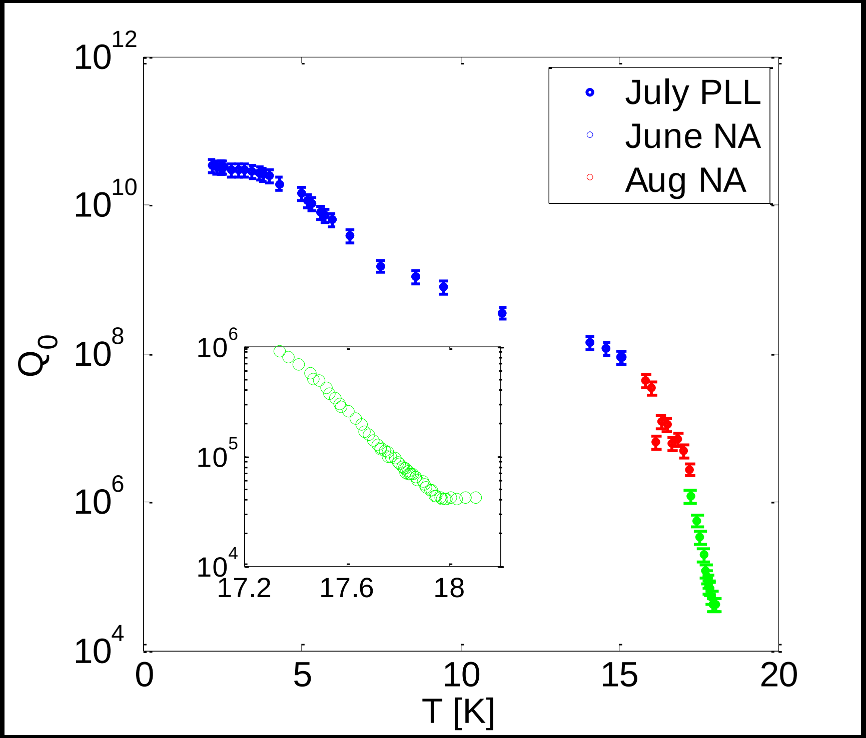
My Nb_3Sn cavity research

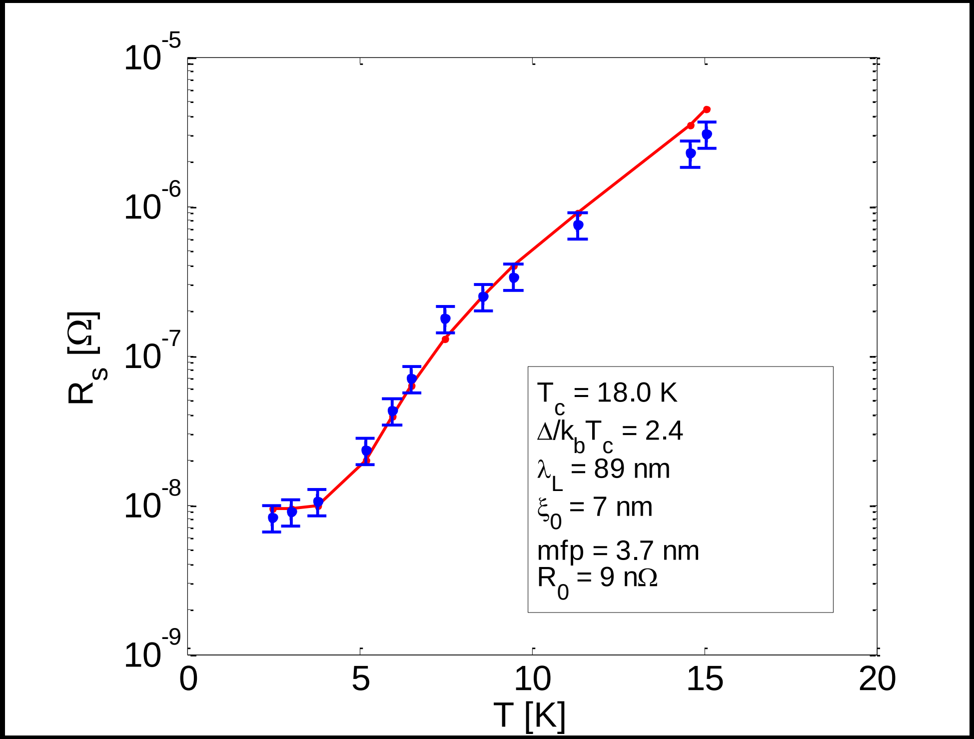
Material removal studies

Quench fields

Outlook

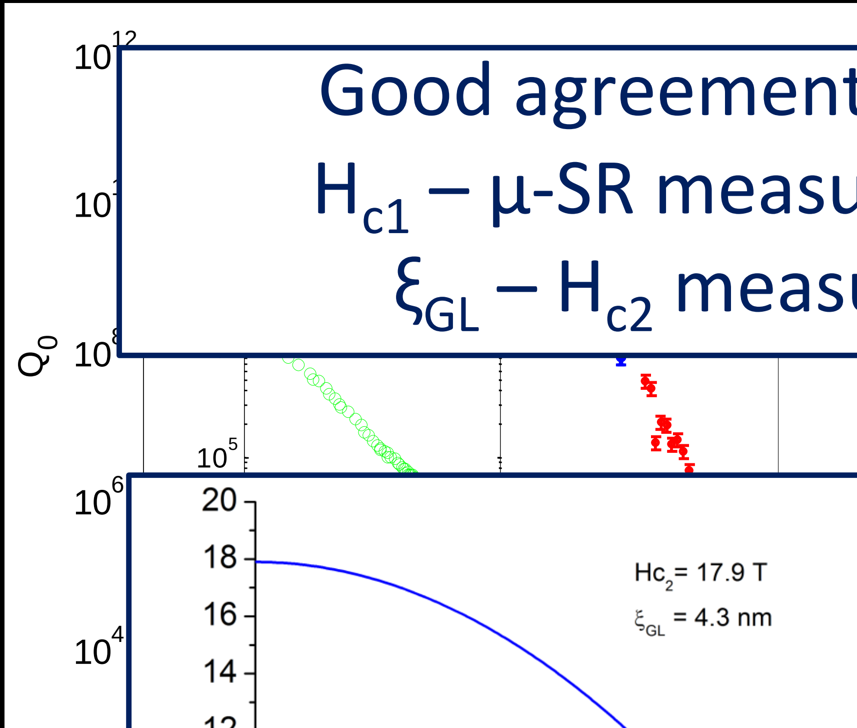
Material Parameters

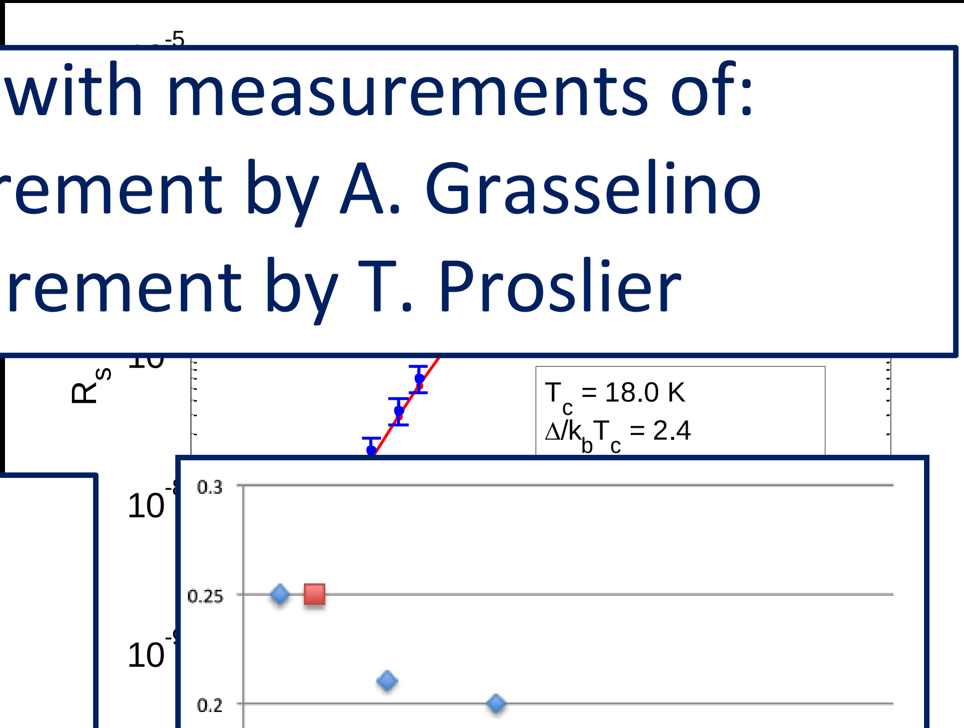




- Extract Nb_3Sn material parameters from fits to R_s vs T data
- Use them to calculate Ginzburg Landau parameters and critical fields

Material Parameters

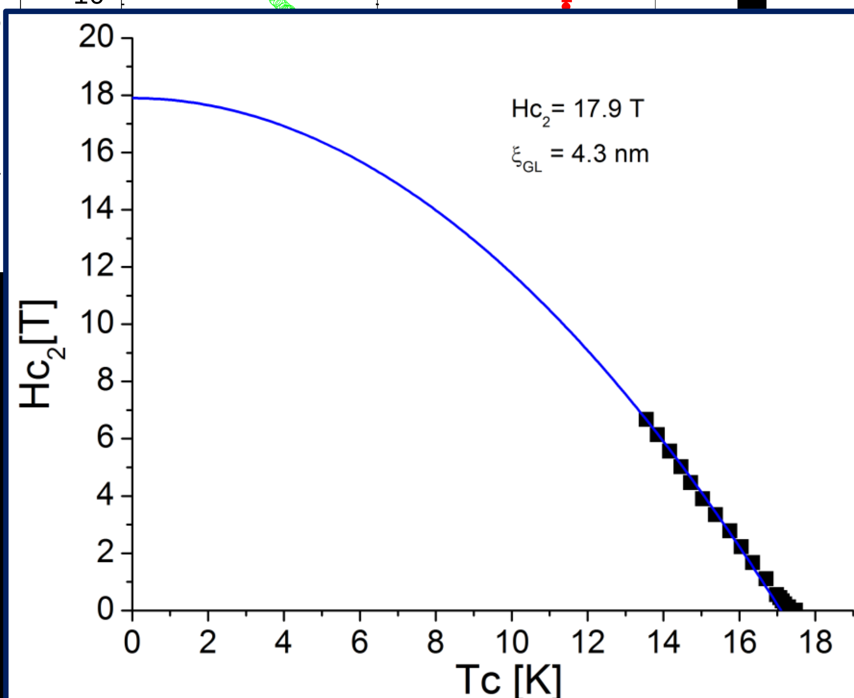


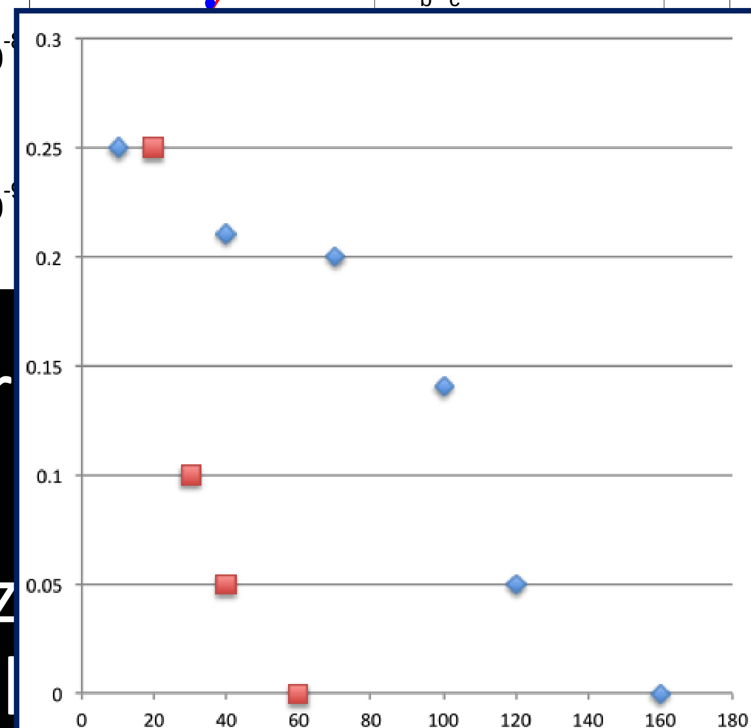


Good agreement with measurements of:

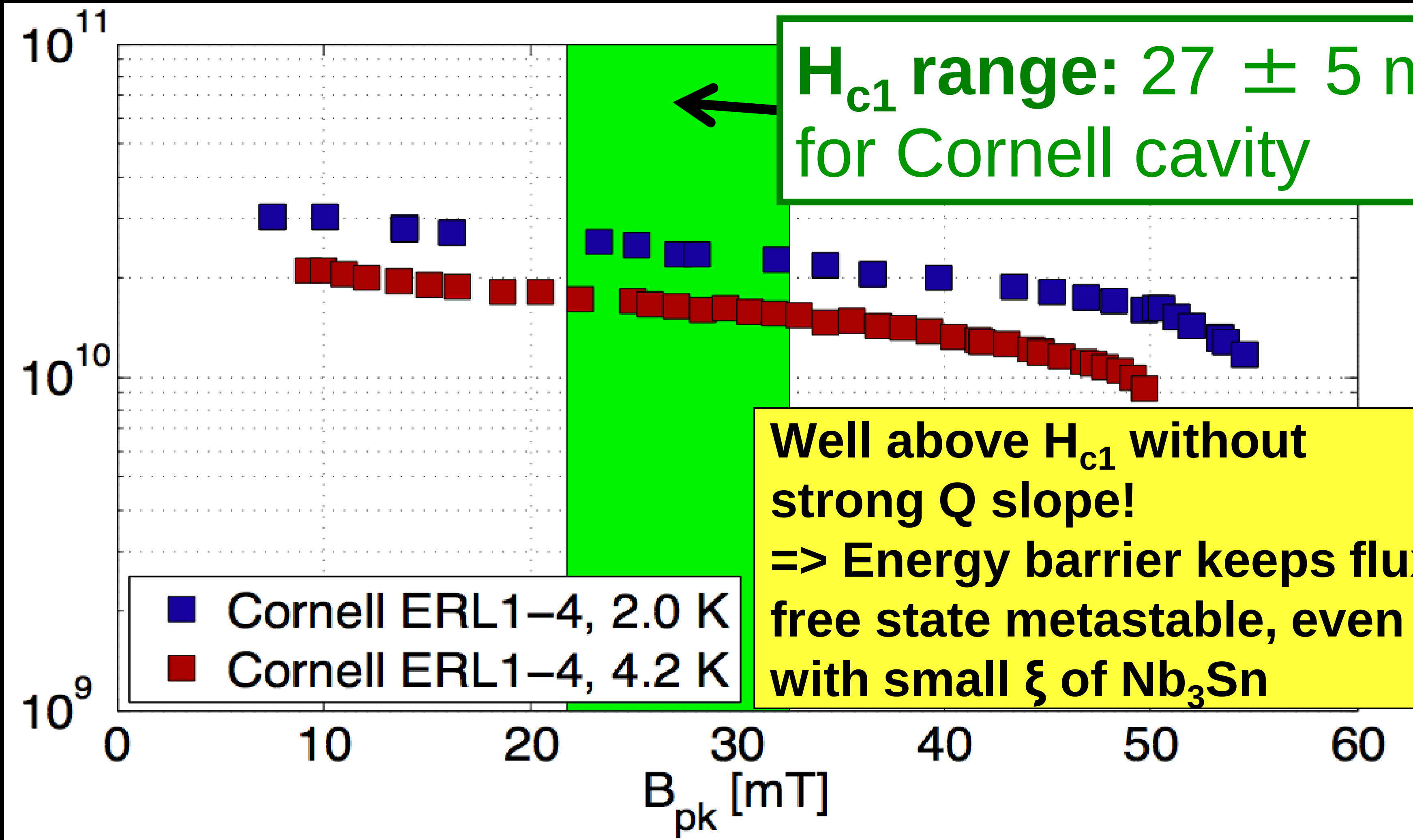
H_{c1} – μ-SR measurement by A. Grasselino

ξ_{GL} – H_{c2} measurement by T. Proslier





H_{c1} NOT a Fundamental Limit for low-ξ Materials

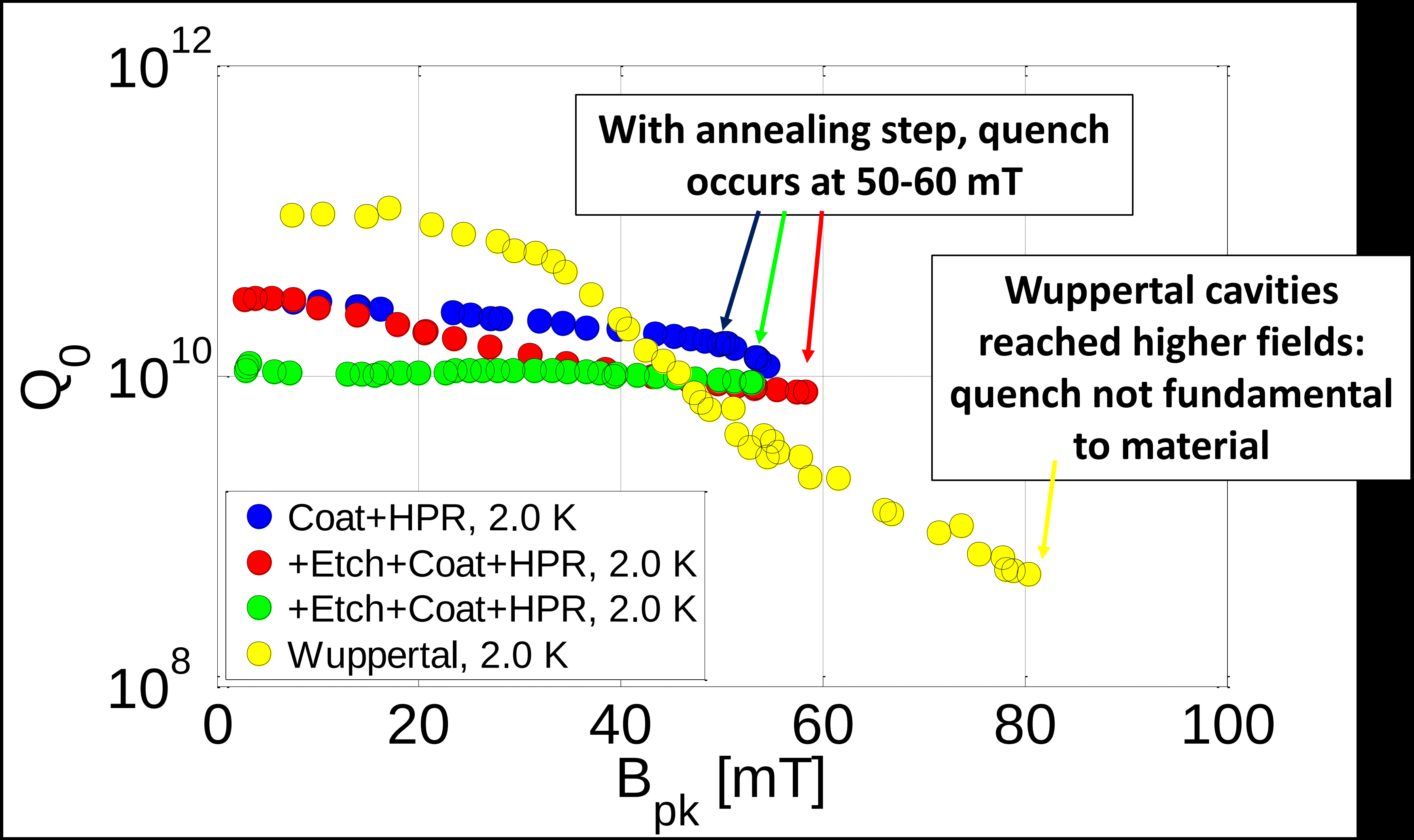


H_{c1} range: 27 ± 5 mT for Cornell cavity

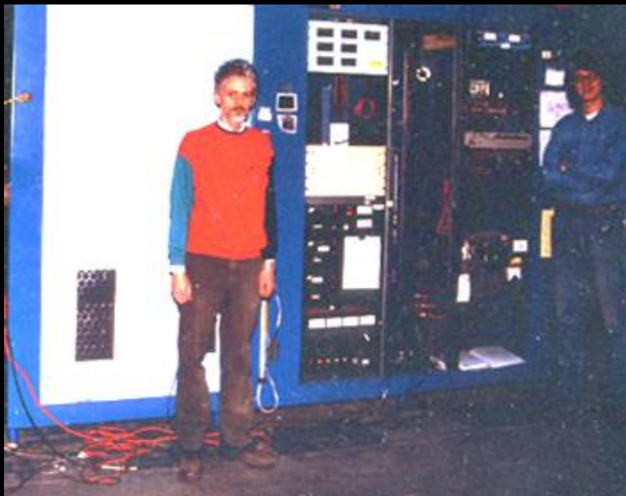
Well above H_{c1} without strong Q slope!
=> Energy barrier keeps flux-free state metastable, even with small ξ of Nb_3Sn

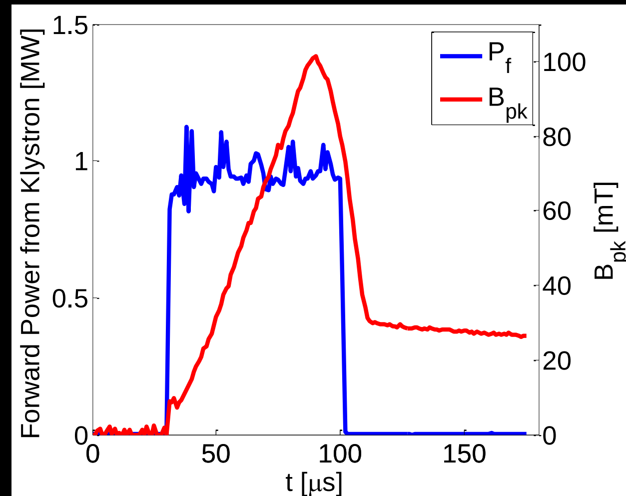
H_{c1} is NOT a fundamental limitation!

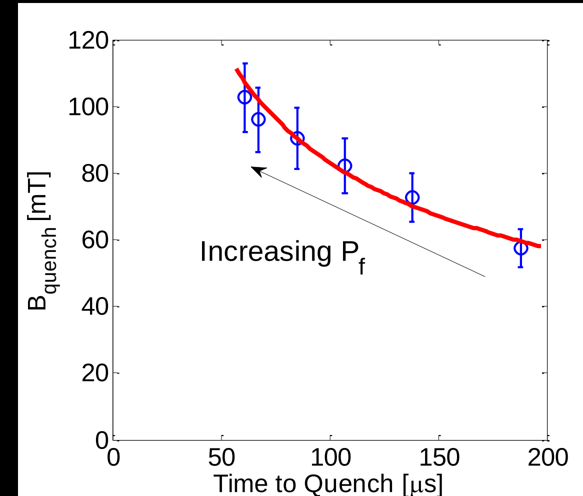
CW Quench Field

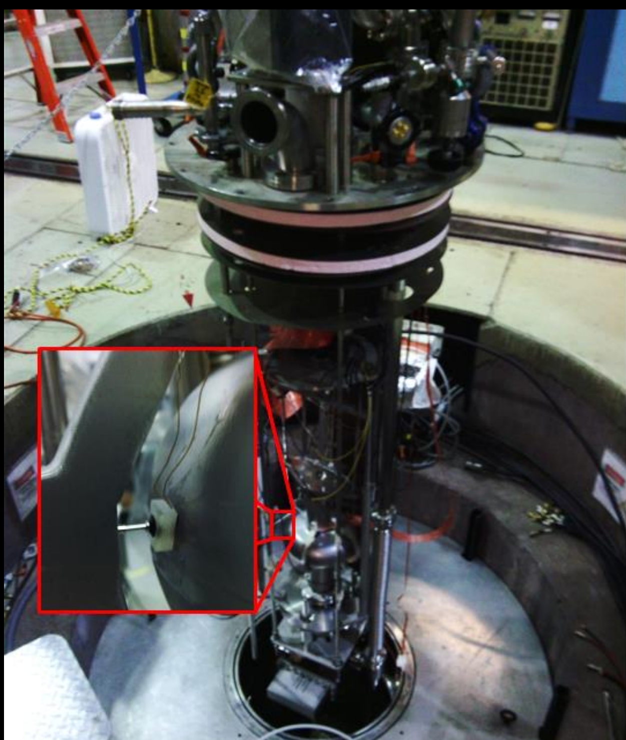


Pulsed Quench Field

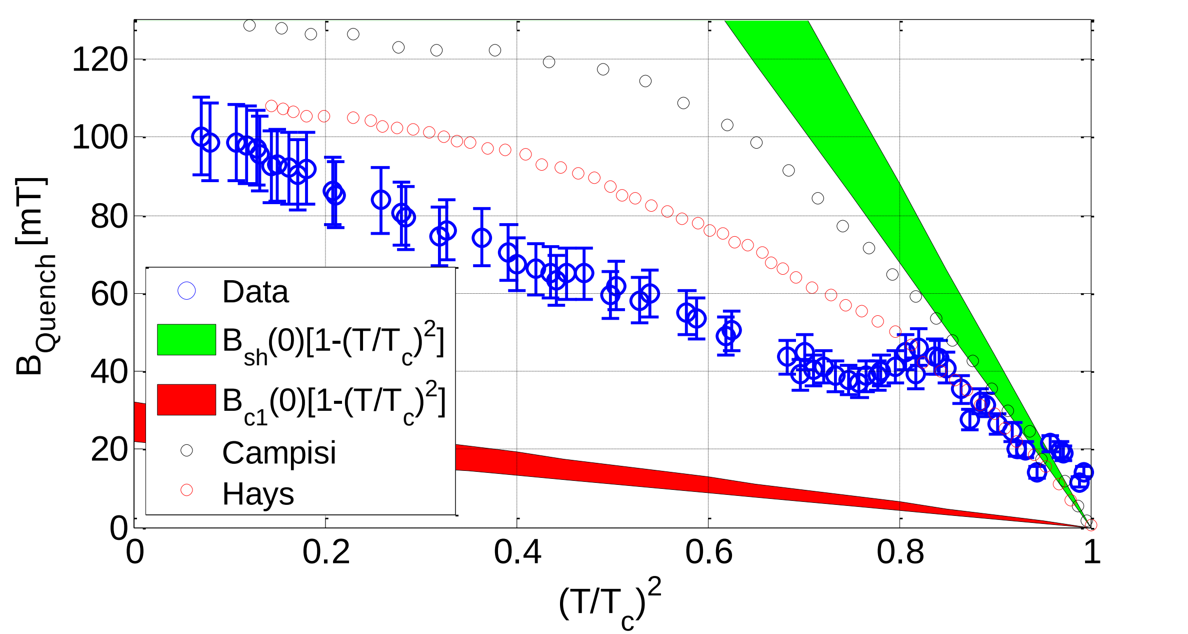




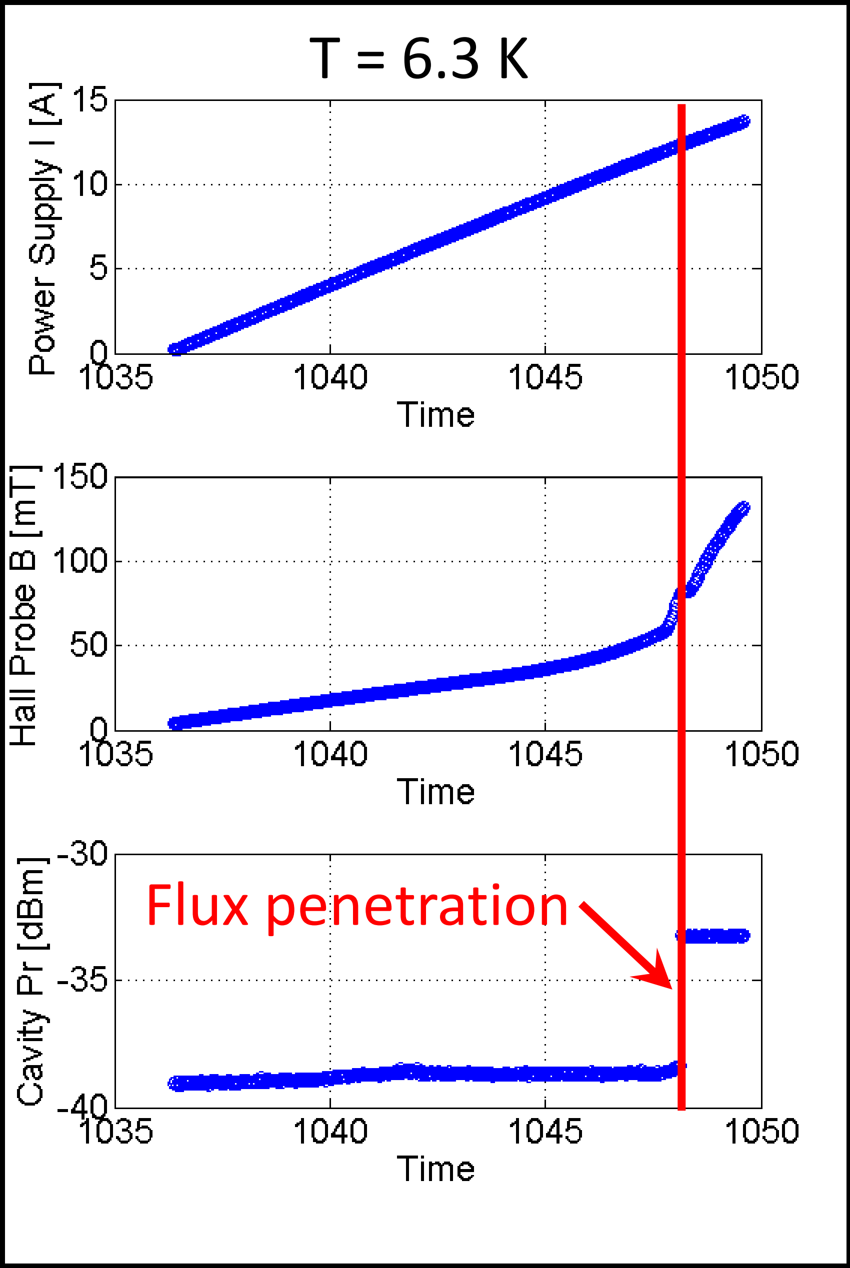


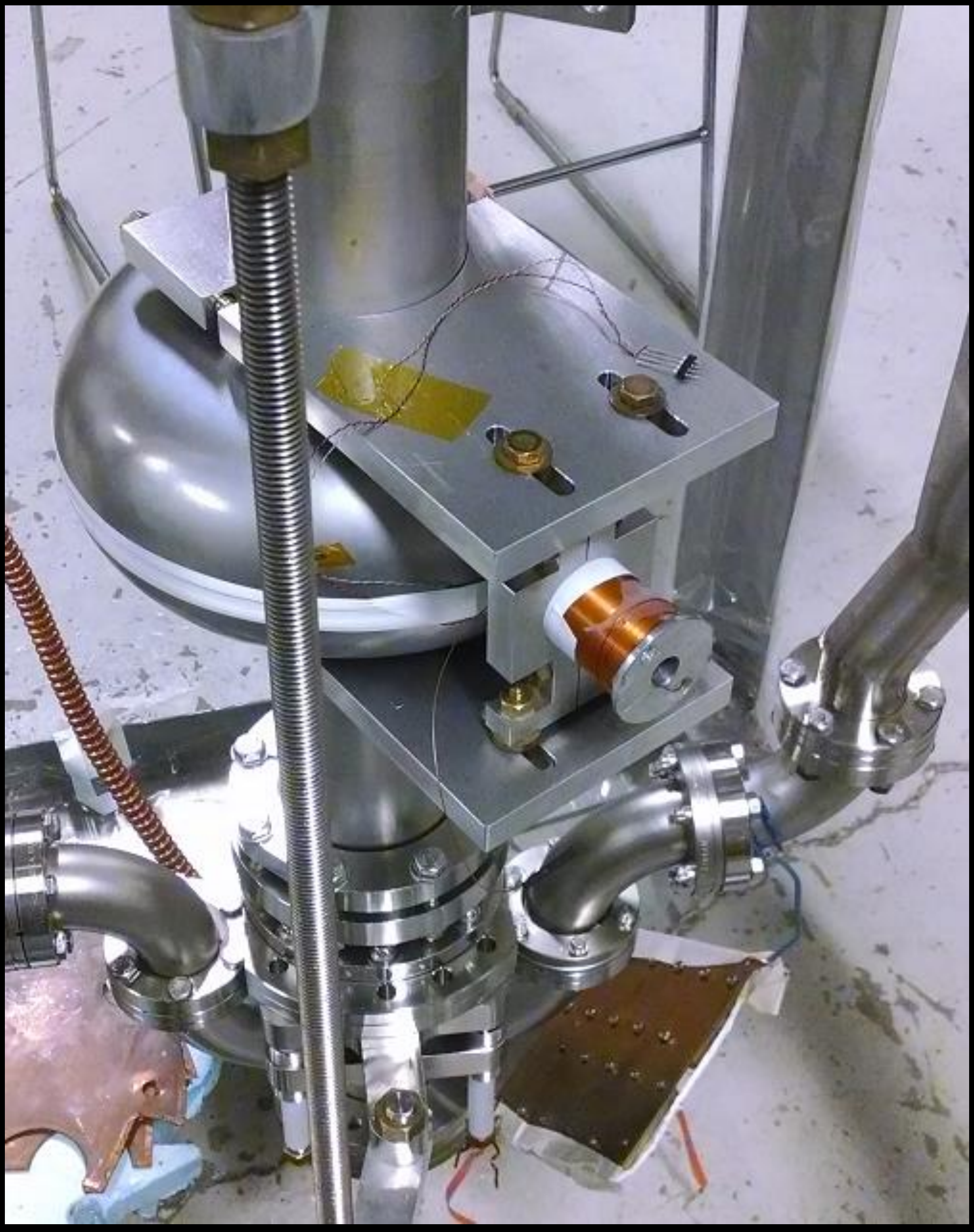


T_c = 18.0 ± 0.1 K , $B_{sh}(0)$ = 0.39 ± 0.05 T,
$B_{c1}(0)$ = 27 ± 5 mT



DC Flux Penetration Field



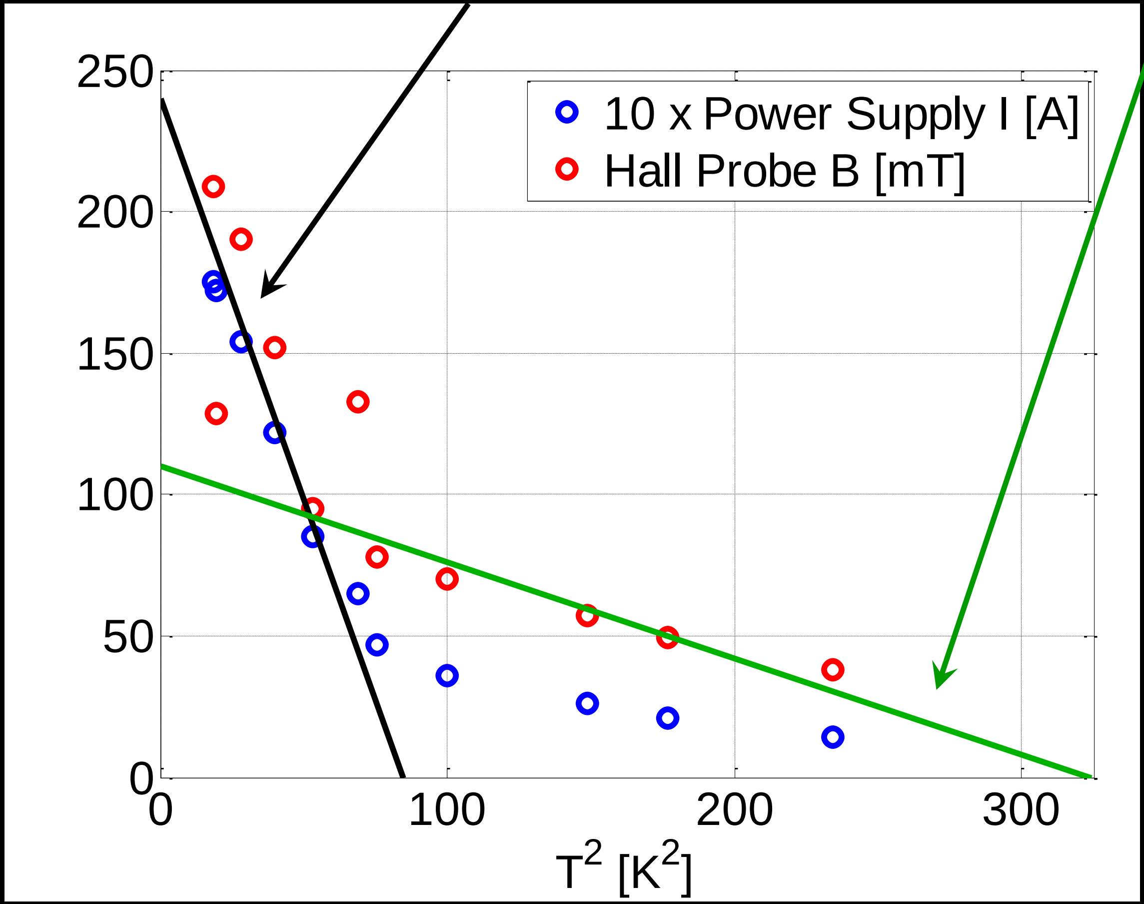


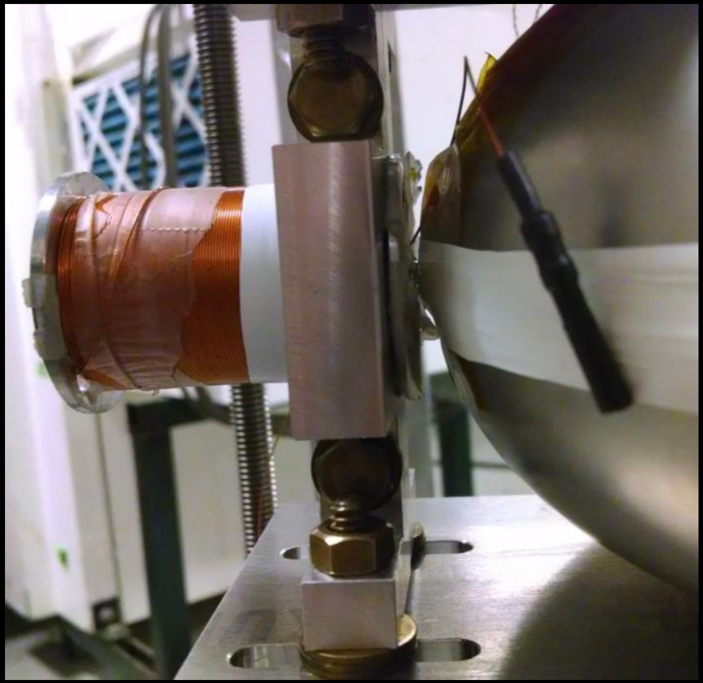
DC Flux Penetration Field

Expected curve for clean Nb from cavity bulk:
B_{sh} ~ 240 mT x $[1-(T/9.2\ K)^2]$

Expected curve for Nb_3Sn:
B_{sh} ~ 390 mT x $[1-(T/18\ K)^2]$

Extrapolated low-T pen. field measured is closer to 110 mT
→ GB penetration?





Cornell University

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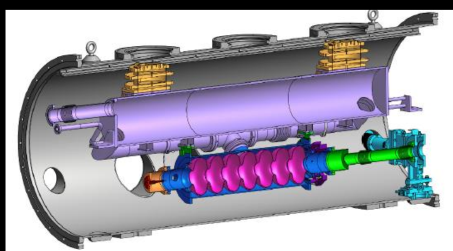
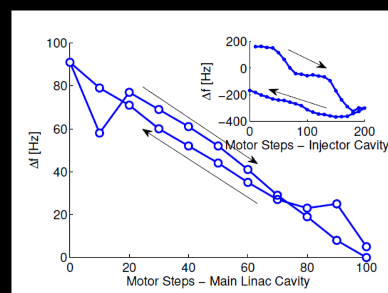
Summary and Outlook

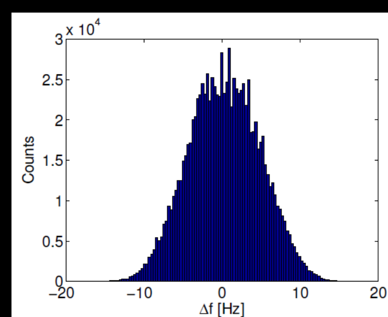
- Significant Nb_3Sn performance improvement
  - Strong Q-slope suppressed after annealing
  - High Q_0 at useful fields, T = 4.2 K
- Important knowledge gained
  - Low-T_c Nb-Sn alloys in grain boundaries are likely cause of Q-slope
  - H_{c1} NOT a fundamental limit
- Exciting ideas for what to do next
  - EP cavity (freshly loaded in furnace)
  - Nb_3Sn cavities for mid-field applications

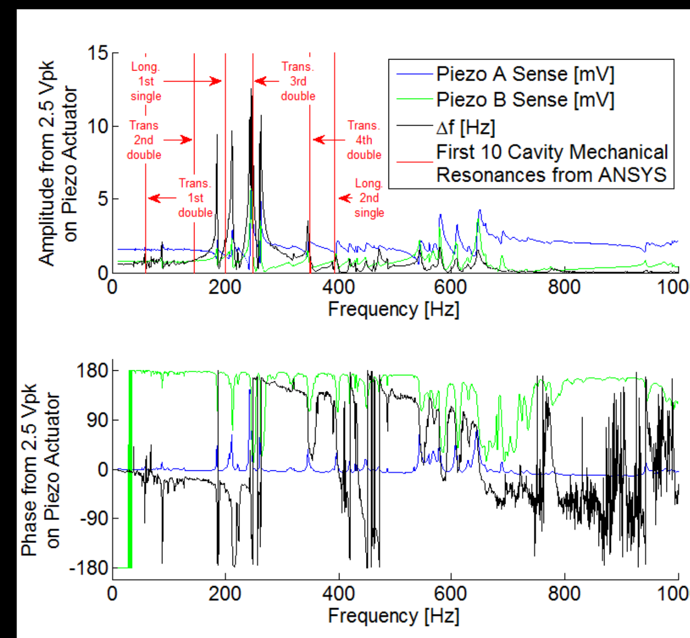
Other SRF Projects – Cryomodule Work

- Helped assemble HTC and MLC prototype
- With HTC, I performed cryogenic Q vs E measurements, tuner studies, microphonics and df/dp measurements, LLRF optimization

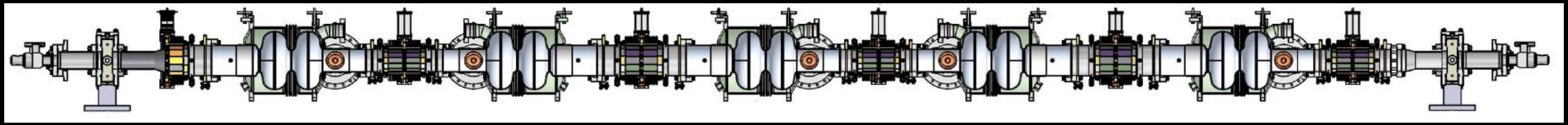




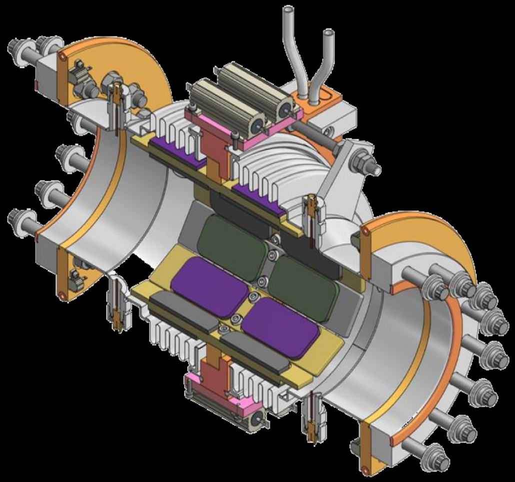


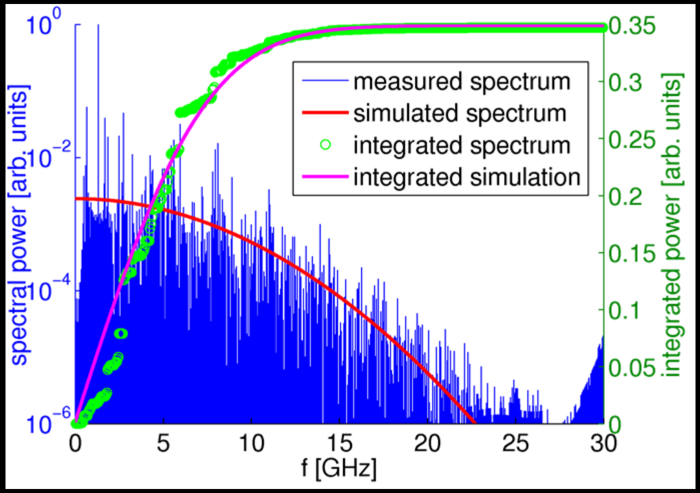


Other SRF Projects – Beam Operation

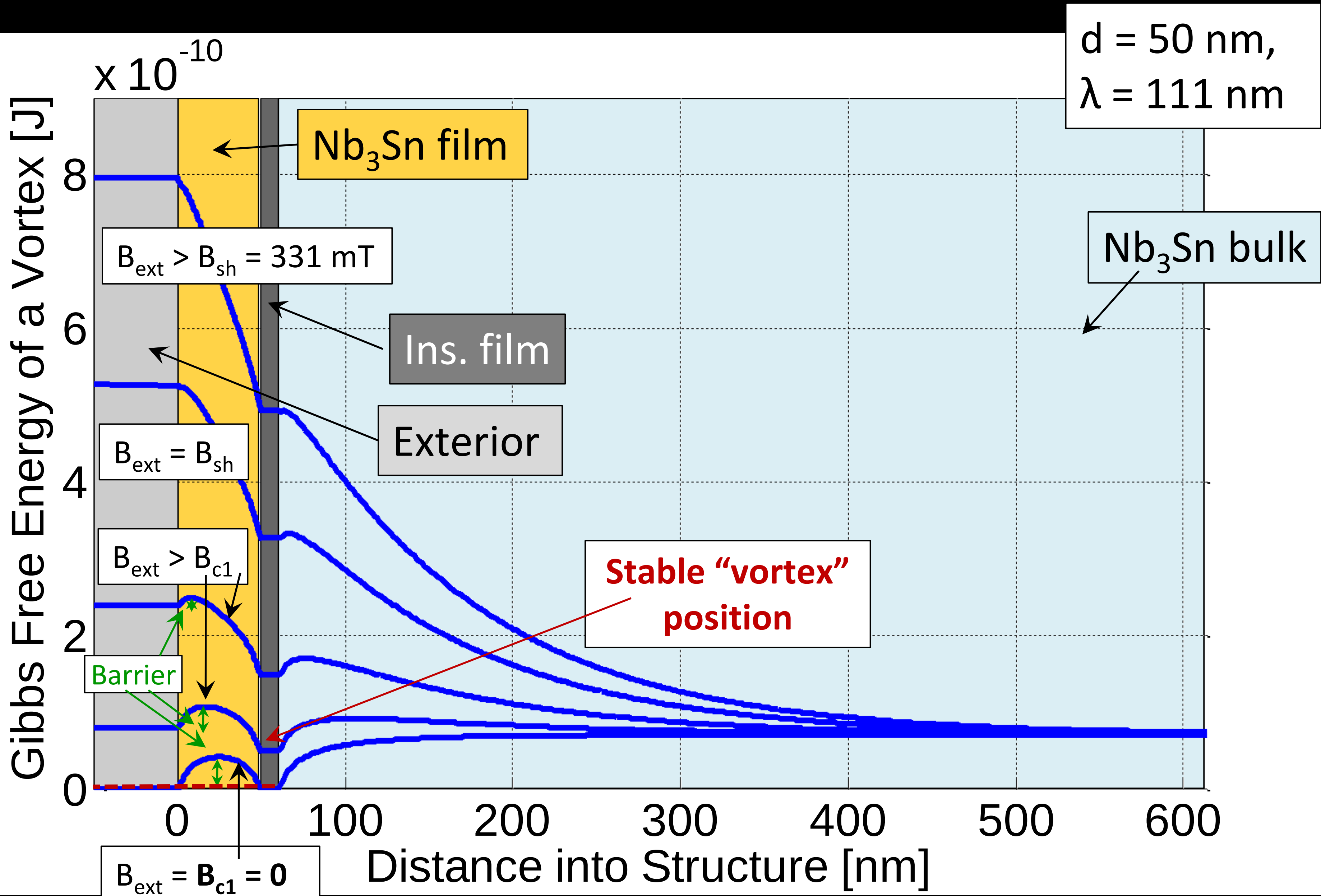


- Measured suppression of HOMs by ferrite absorbers in ERL injector prototype
- Recorded HOM power as a function of freq. while running high current through cavities



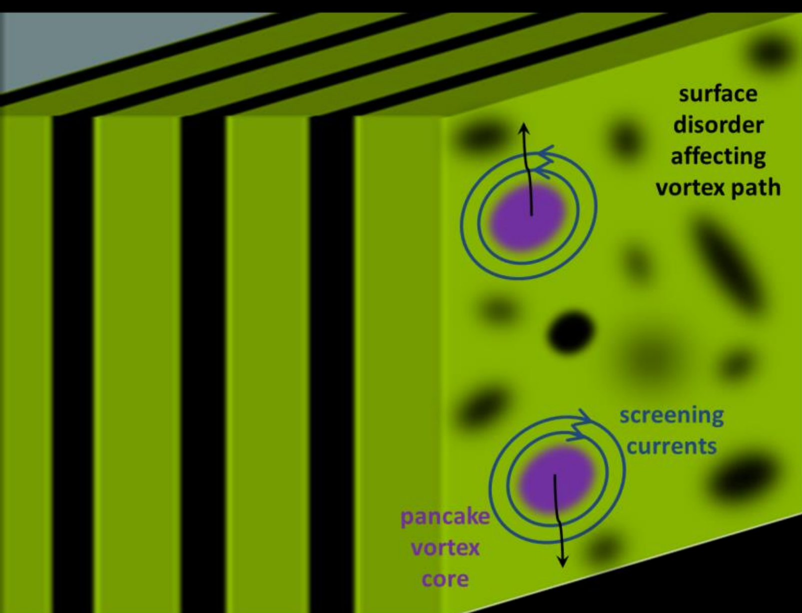


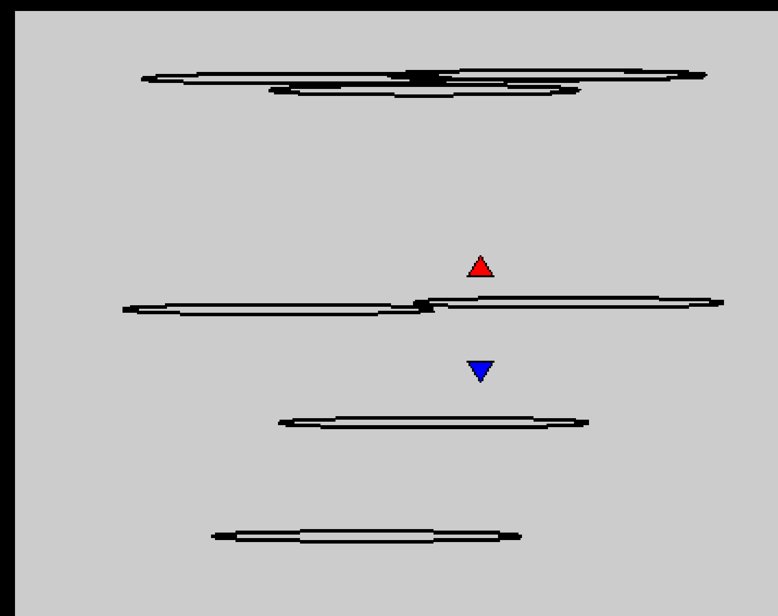
Other SRF Projects – Theory



Other SRF Projects – Theory

- Studies on vortex behavior in SRF films with Cornell theorist James Sethna
- Attempt to determine if SIS structure can be beneficial





Acknowledgements

- My advisor Matthias, whose wisdom and guidance made this research possible
- Fellow Cornell graduate students
- Collaborators
- Hasan Padamsee for fruitful discussions