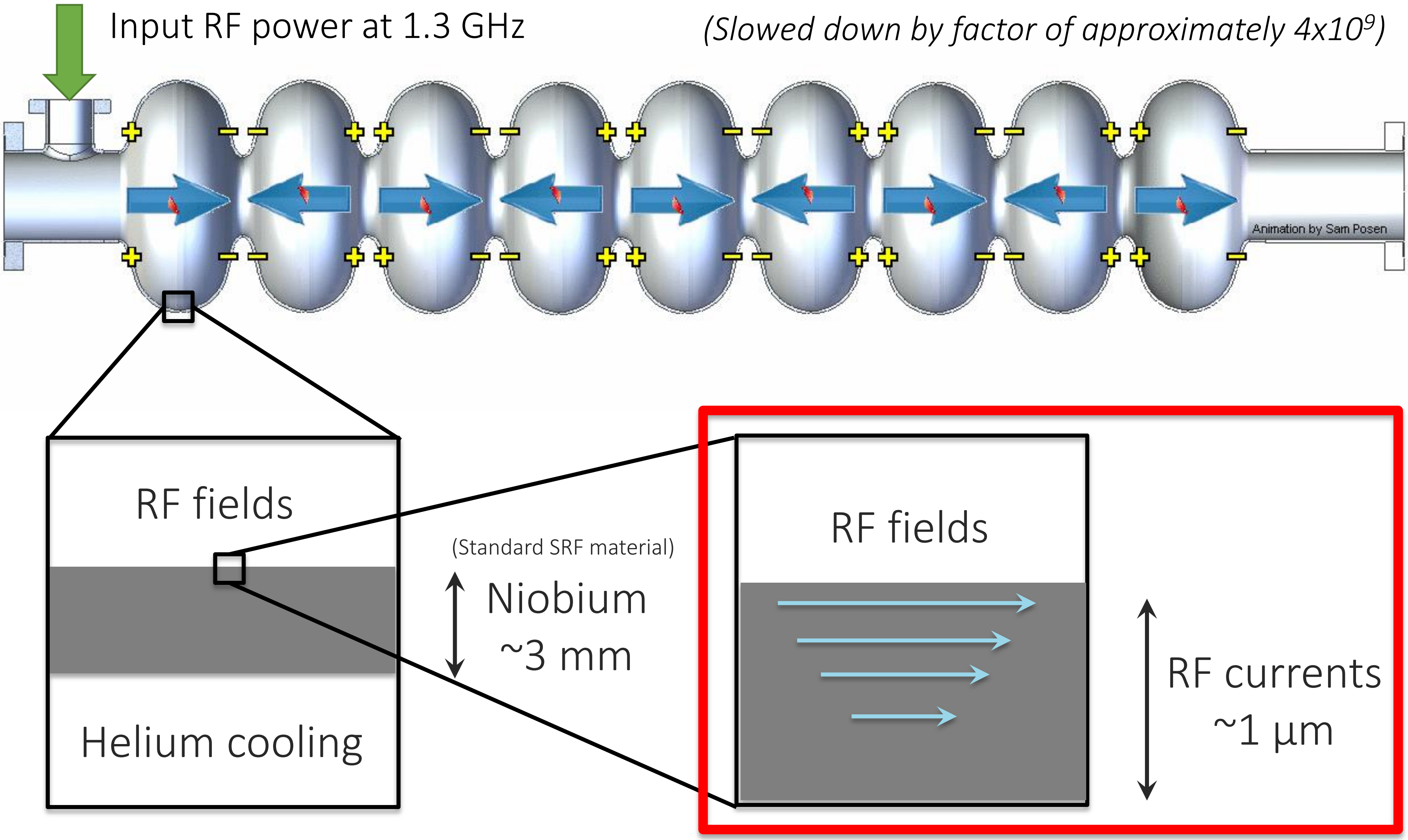
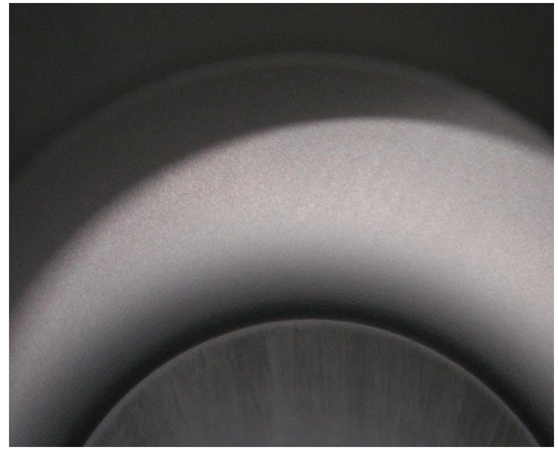
Developing the Next Generation of SRF Cavities with Nb_3Sn

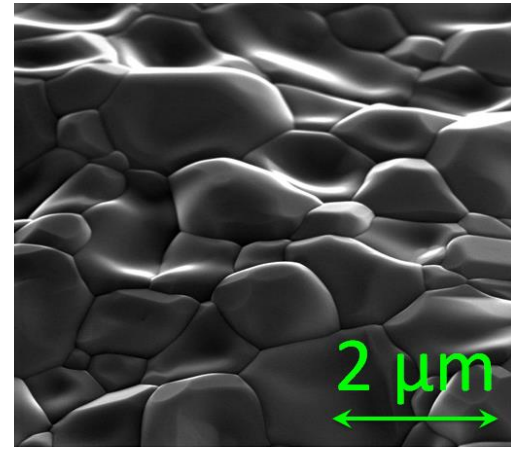
Sam Posen
Associate Scientist, Fermilab
ACFA/IPAC'16 Hogil Kim Prize Presentation
13 May 2016

Superconducting RF Cavities

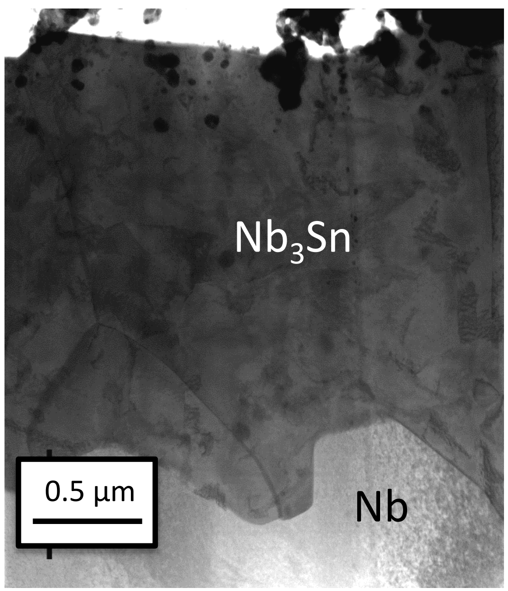


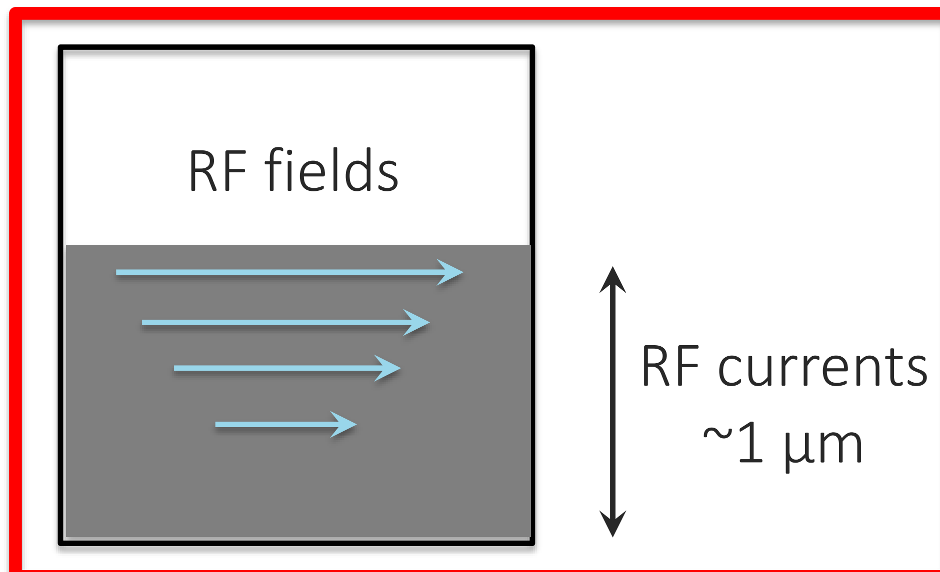
Nb_3Sn Coating on Niobium Cavity





C. Becker et al., *App. Phys. Lett.*, 106, 082602 (2015).

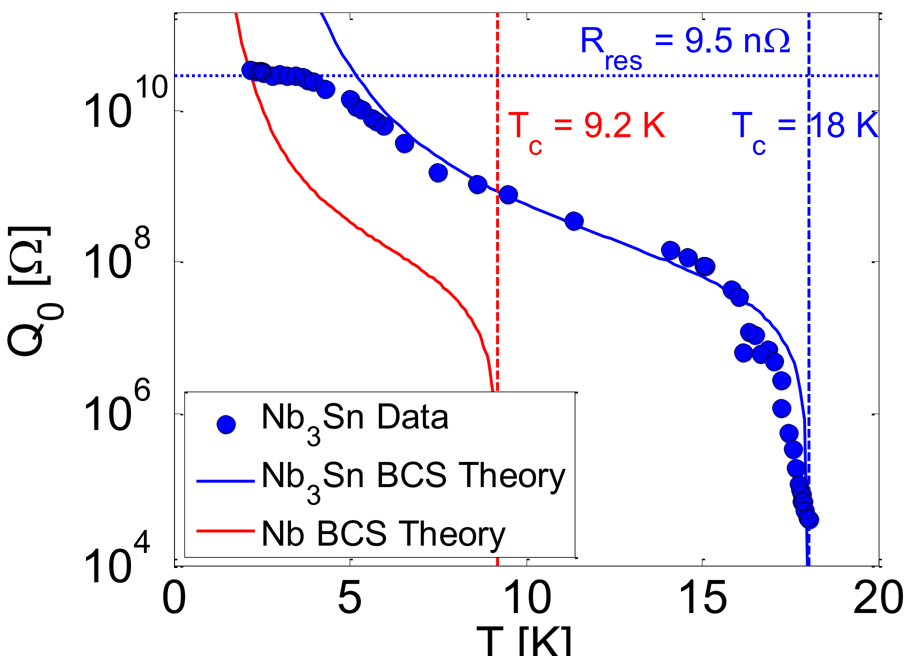


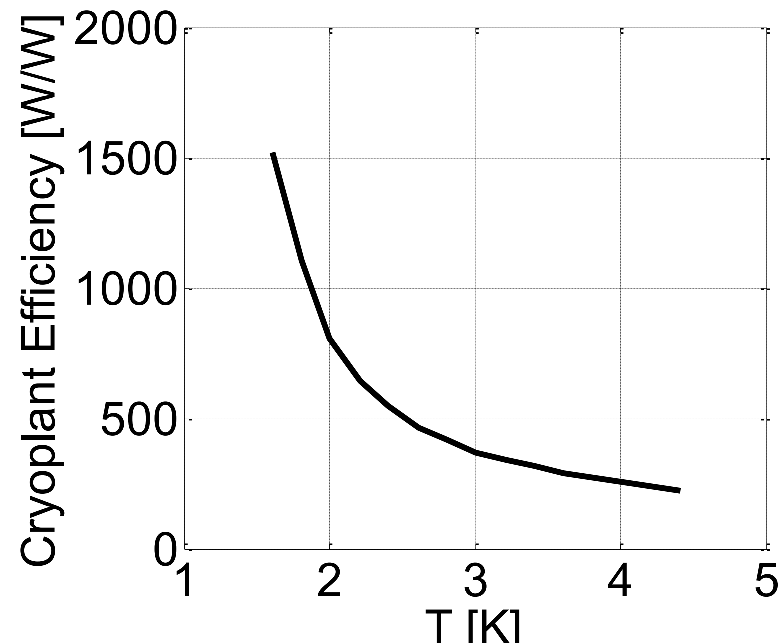


Nb_3Sn $Q_0(T)$

- Large T_c ~ 18 K
  - Very small $R_{BCS}(T)$ – $R_{BCS}(T) \sim e^{-1.76T_c/T}$
  - High Q_0 even at relatively high T
- Higher temperature operation
  - Simpler cryogenic plant
  - Higher efficiency

Big effect! Cryoplants for large installations cost ~$100 million and require MW of power



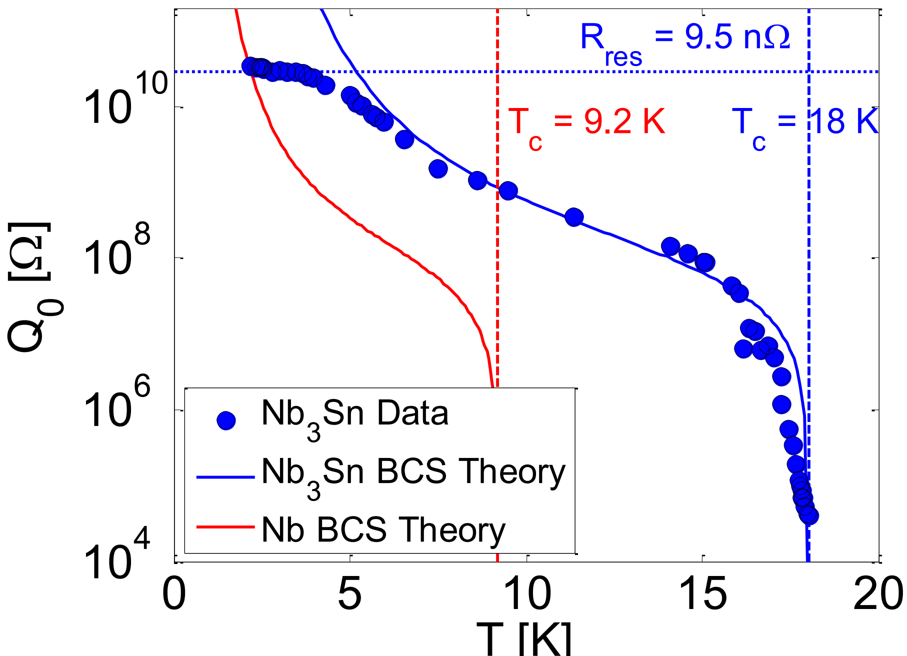


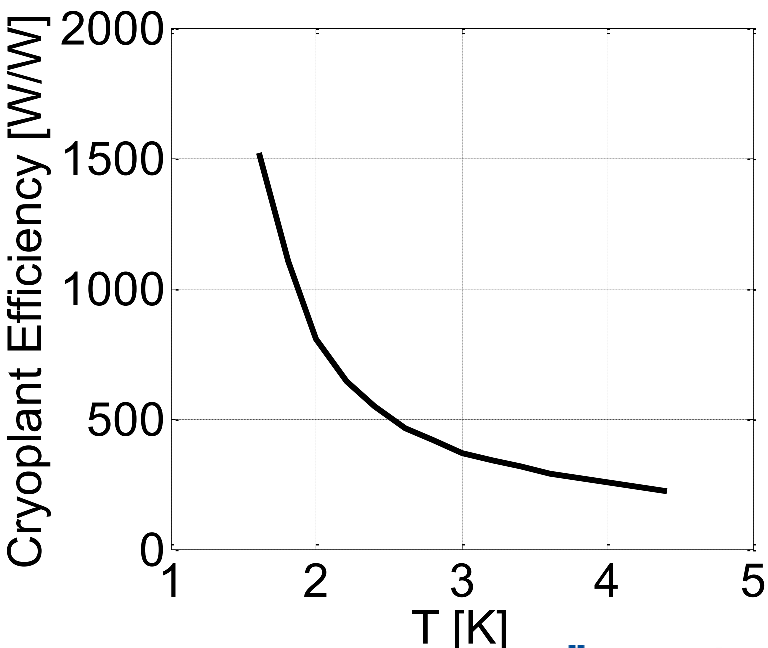
Higher $Q_0(T)$ with Nb_3Sn

- Large T_c ~ 18 K
  - Very small $R_{BCS}(T)$ – $R_{BCS}(T) \sim e^{-1.76T_c/T}$
  - High Q_0 even at relatively high T
- Higher temperature operation
  - Simpler cryogenic plant
  - Higher efficiency

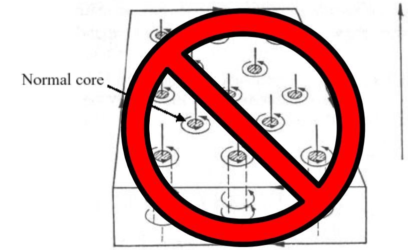
Possibility of cryocooler operation!

Industrial accelerators for treatment of wastewater & flue gas, border security…

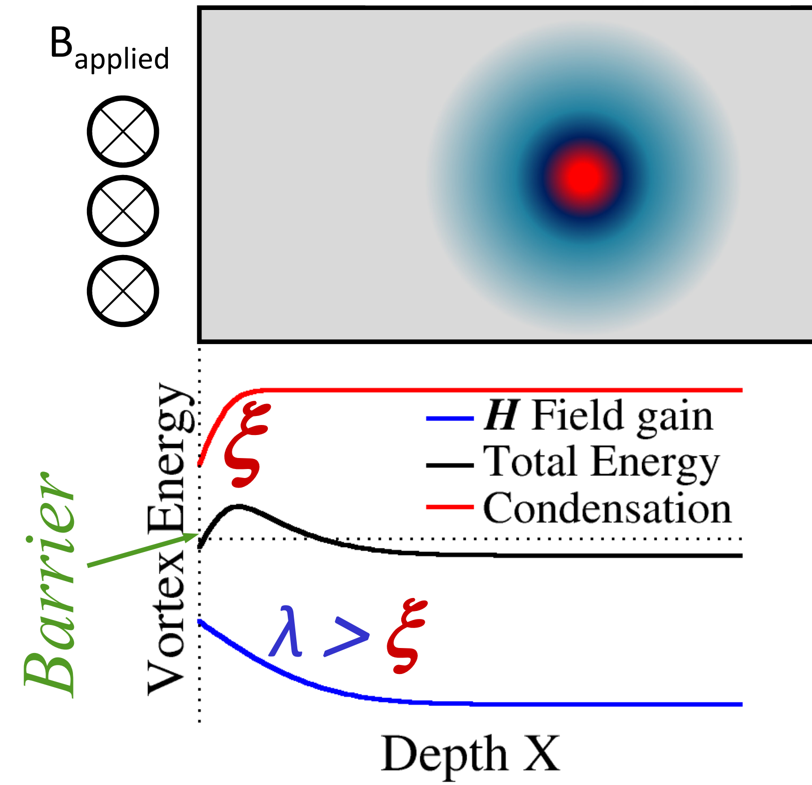




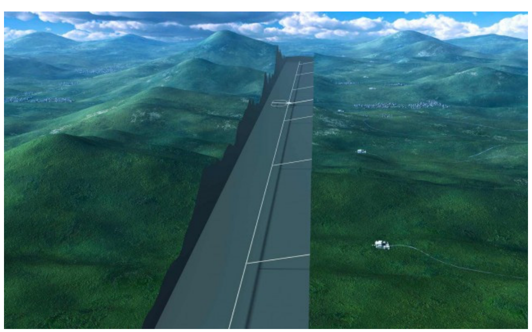
Increased Metastable Limit in Nb_3Sn



- Superconductors can remain flux-free even above H_{c1}
- Ultimate metastable limit is "superheating field" H_{sh}
- H_{sh} of Nb: ~200 mT (~50 MV/m)
- Predicted H_{sh} of Nb_3Sn: ~400 mT
- Achieving H_{sh} would have huge impact on high energy colliders



Energy cost from core (ξ) first;
Energy gain from field (λ) later



ILC: 16,000 cavities in 31 km linac

Fermilab

Slide adapted from J. P. Sethna

Pioneering Nb_3Sn Cavity Research

a lower Δ /1/. These potential advantages are

1. a higher working temperature (for $R_{res}(Nb) \approx R_{res}(Nb_3Sn)$)
2. a better thermal stability "
3. a higher superconducting limit ($B_c \sim T_c$)
4. a lower surface resistance R_S (if $R_{res}(Nb_3Sn)$ can be reduced)

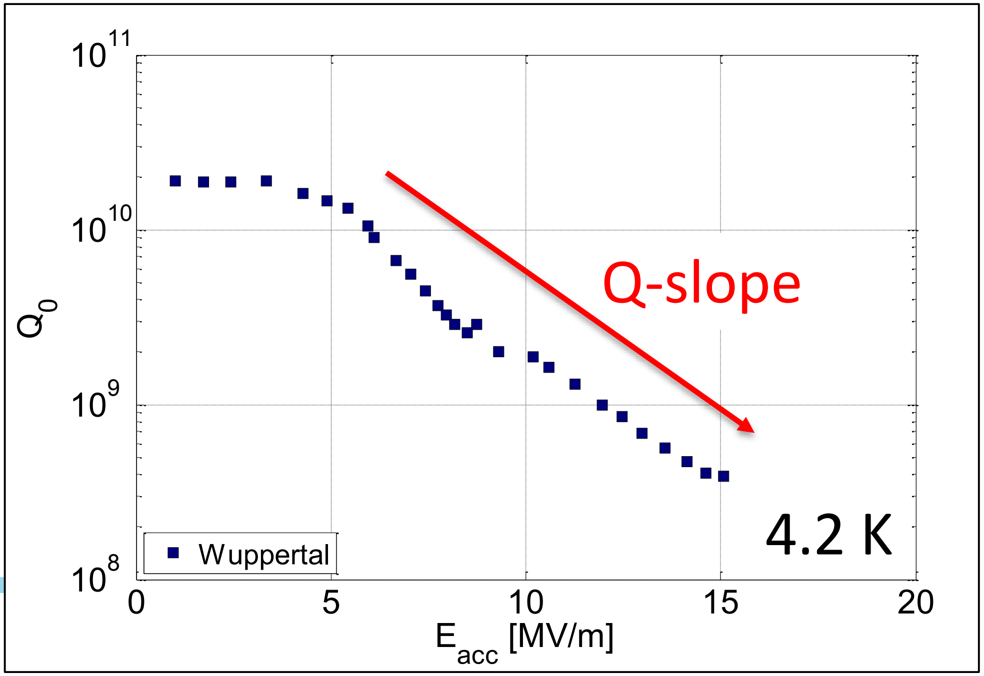
At the moment niobium - the element with the highest T_c (9.2 K) - is nearly always used in superconducting HF-applications. Any

B. Hillenbrand, Siemens (1980)

Because of its high critical temperature (T_c = 18,3 K [3]) Nb_3Sn has to be considered as an alternative matérial. This choice is supported by the high thermodynamic critical field (B_c = 0.535 T [4]) of this alloy. It has to be shown, however, that rf structures of complex shape, like disc loaded waveguides for accelerator application can be coated with a Nb_3Sn layer of good quality and that high accelerating fields can be reached. It also must be shown, that the reduced energy gap Δ/kT_c is comparable to the one measured for niobium. A has to be determined and it

G. Arnolds and D. Proch, Wuppertal, 1977

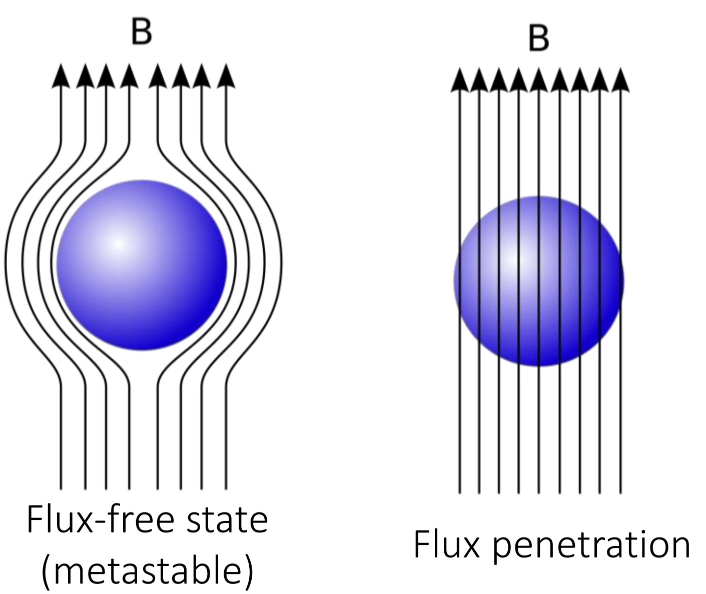
G. Müller et al., U. Wuppertal (2000)

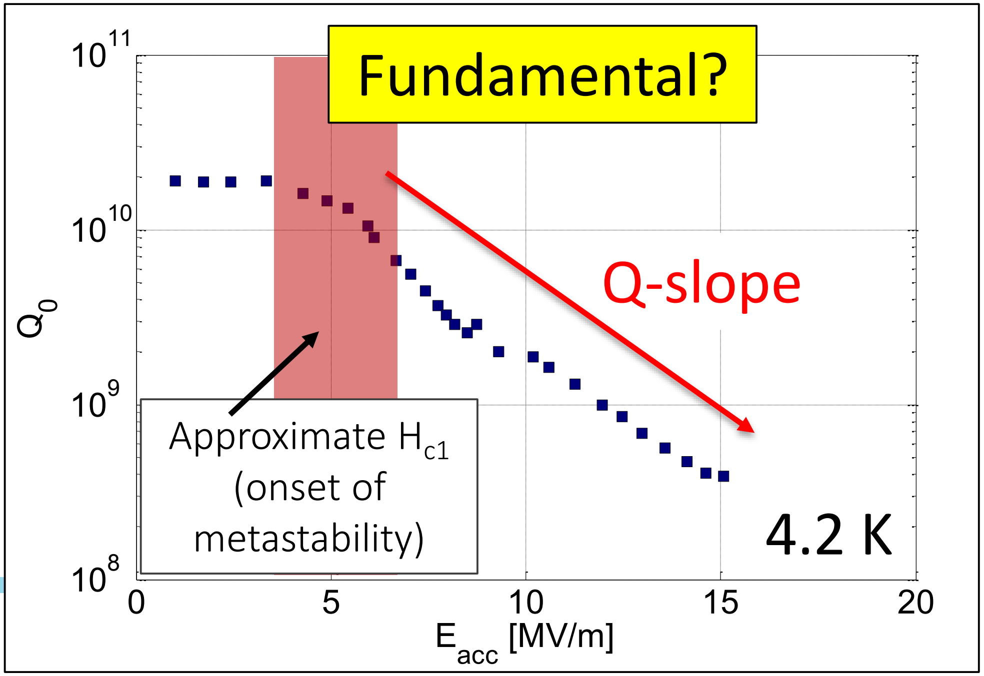


Superconductor Coherence Length

- Coherence length **ξ** ~ Cooper pair interaction distance
- Gives size of disorder that superconductor is sensitive to
- Nb: ξ ~ 20 nm – Nb_3Sn: ξ ~ 3-4 nm
- Can small-ξ superconductors remain in a metastable flux-free state in RF magnetic fields?

G. Müller et al., U. Wuppertal (2000)





Superconductor Coherence Length

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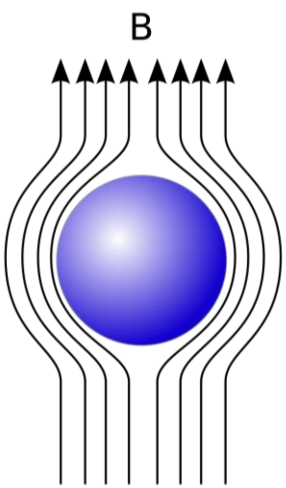
- Gives size of disorder that superconductor is sensitive to

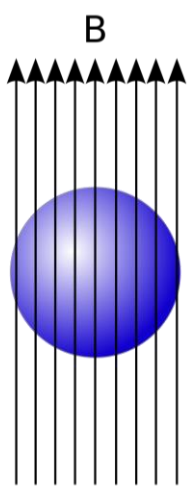
Critical question:

Is ξ of Nb_3Sn so small that H_{c1} is the limit?

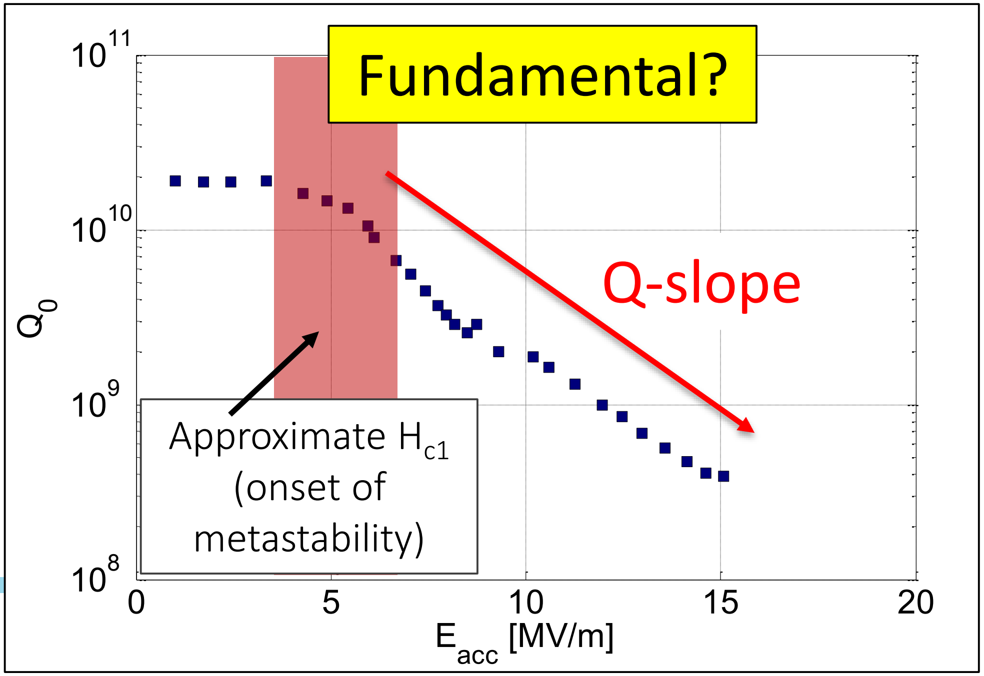
G. Müller et al., U. Wuppertal (2000)



Flux-free state (metastable)

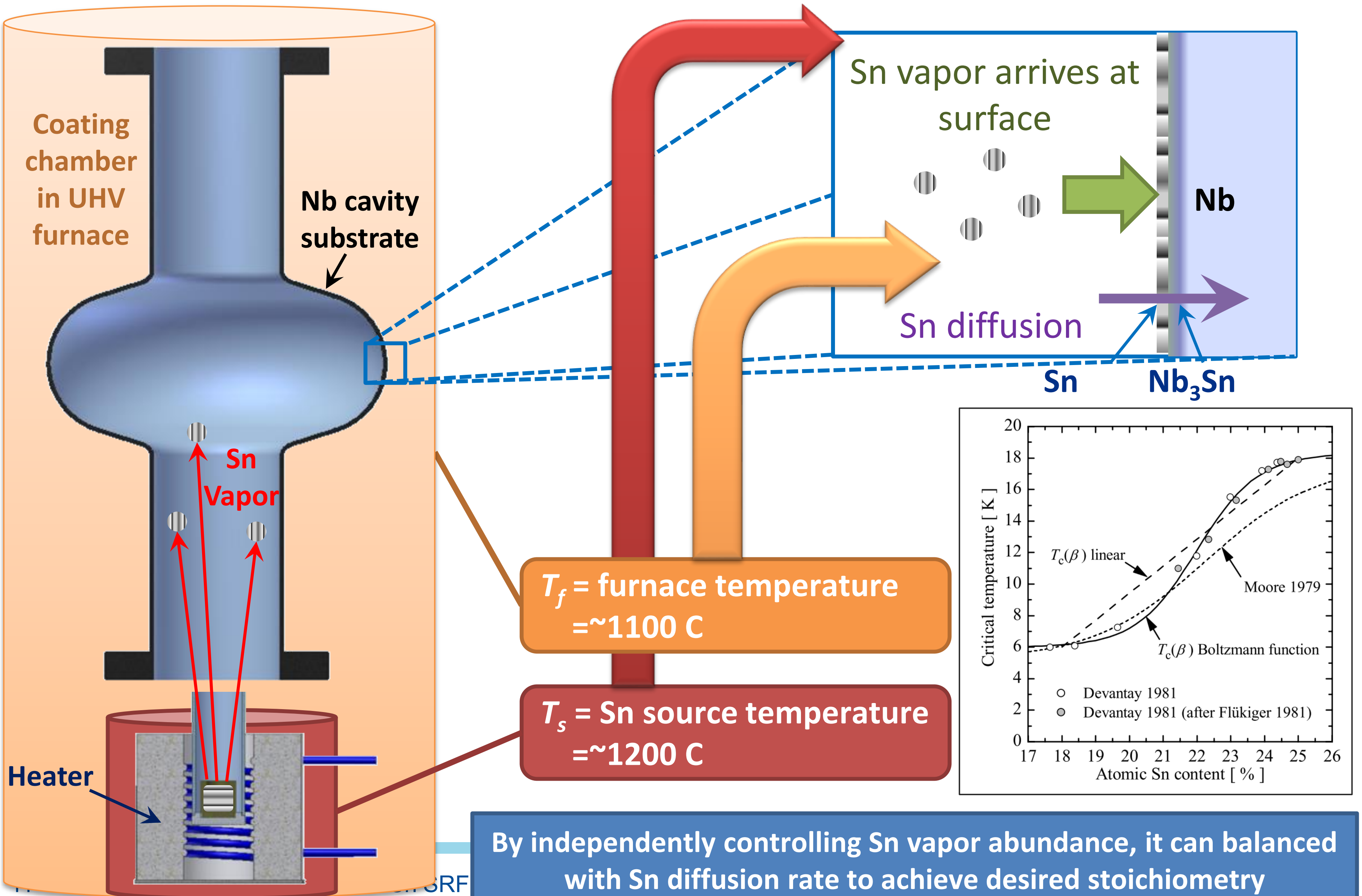


Flux penetration



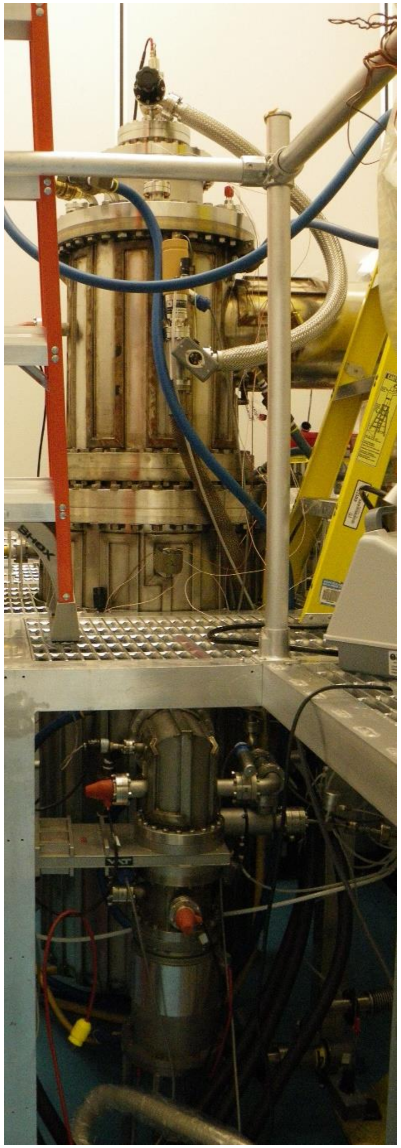
Cornell R&D

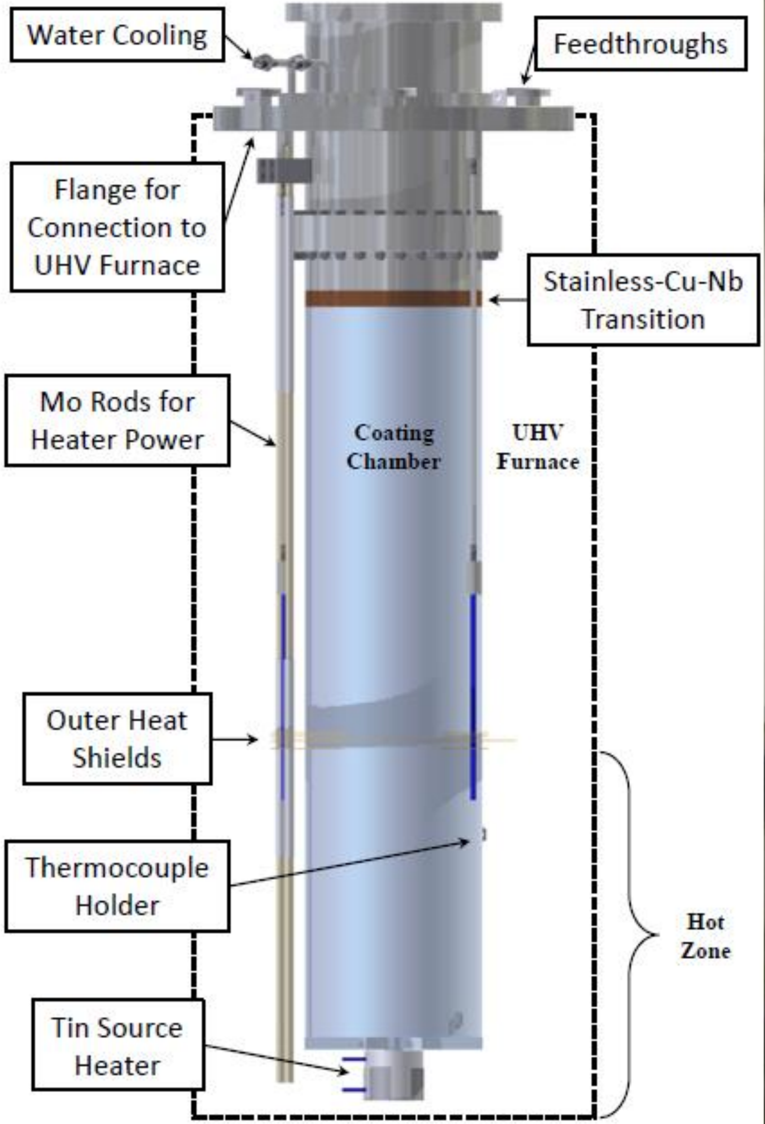
Coating Mechanism: Vapor Diffusion



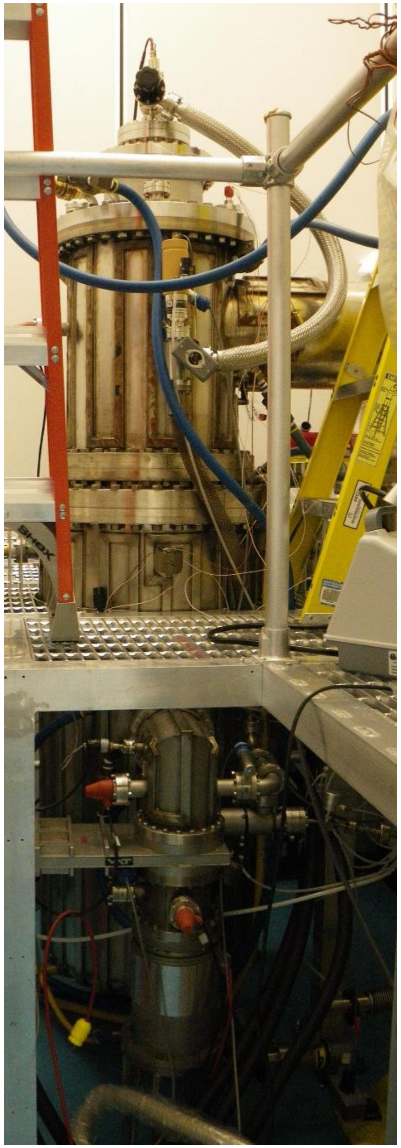
By independently controlling Sn vapor abundance, it can balanced with Sn diffusion rate to achieve desired stoichiometry

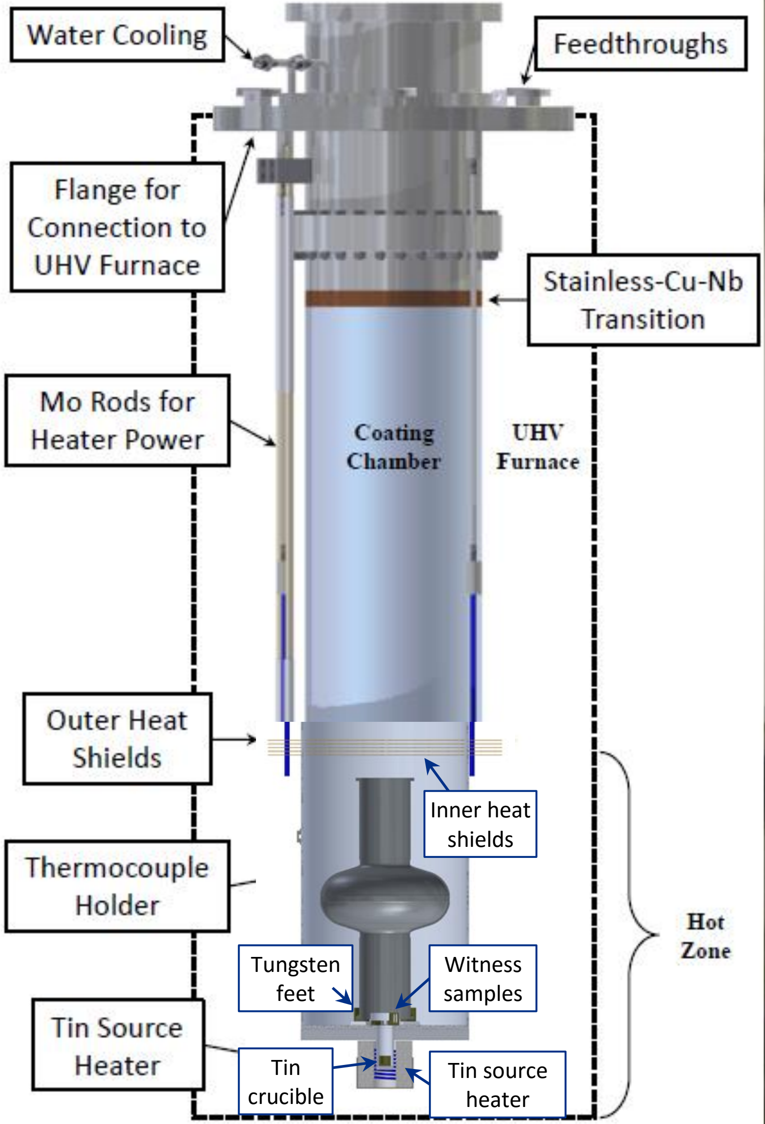
Cornell Nb_3Sn Coating Chamber





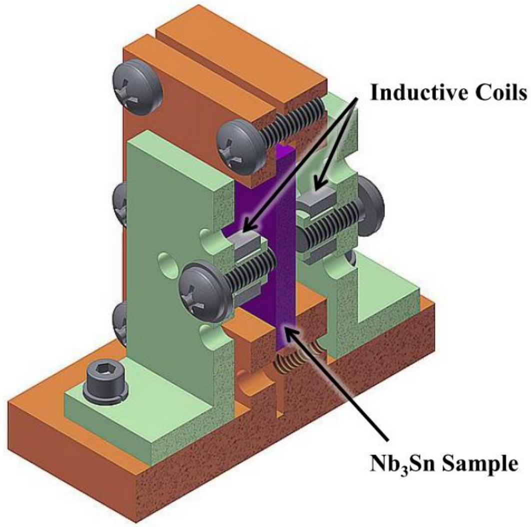
Cornell Nb_3Sn Coating Chamber

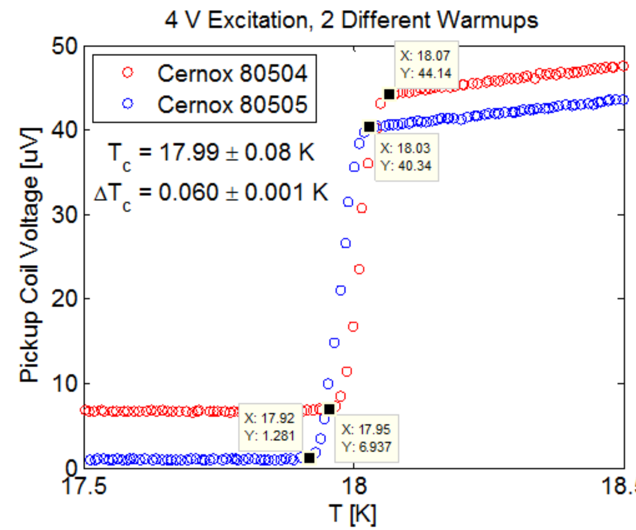


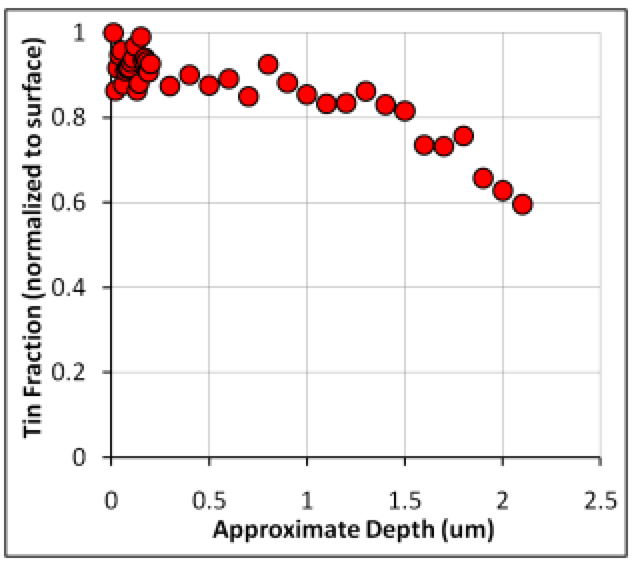


Sample Studies

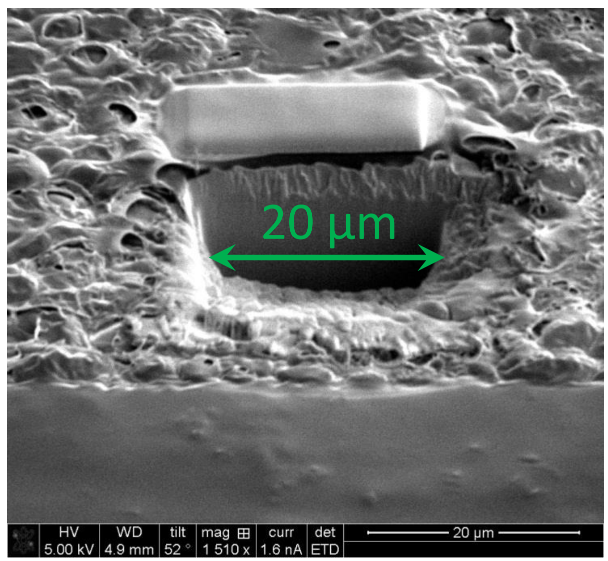
- Composition 25% tin as desired
- Near ideal T_c 18 K, sharp transition
- 2-3 µm thickness to screen RF



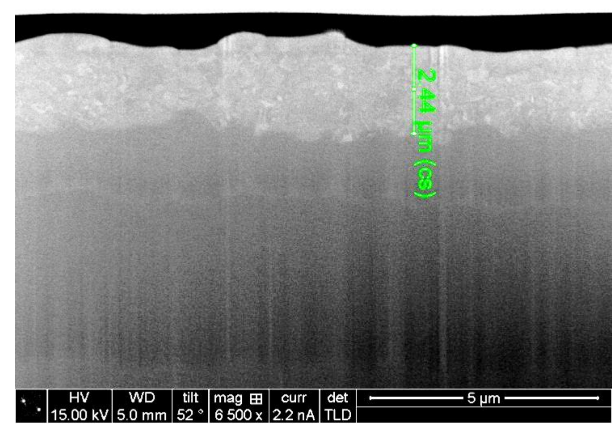




XPS



FIB

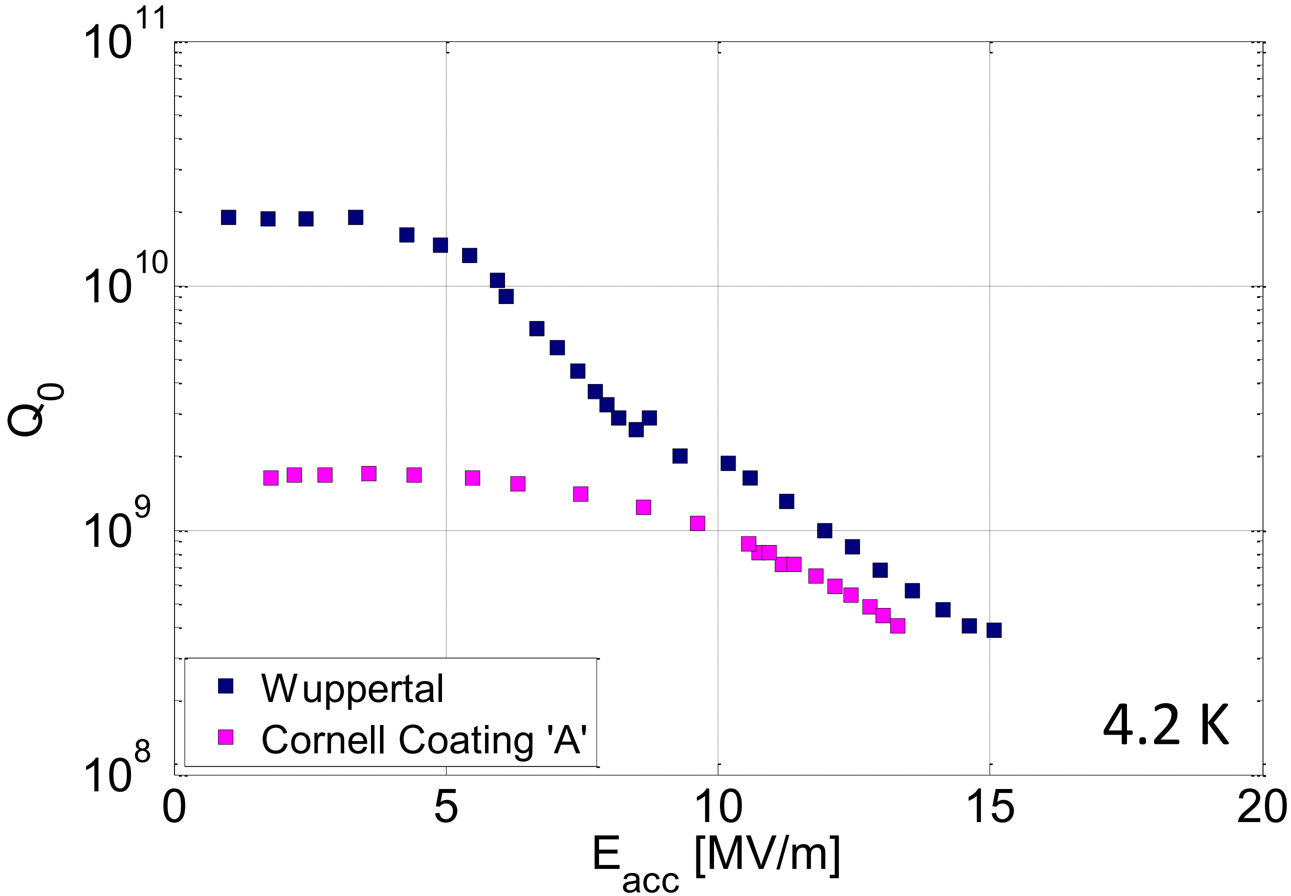


FIB

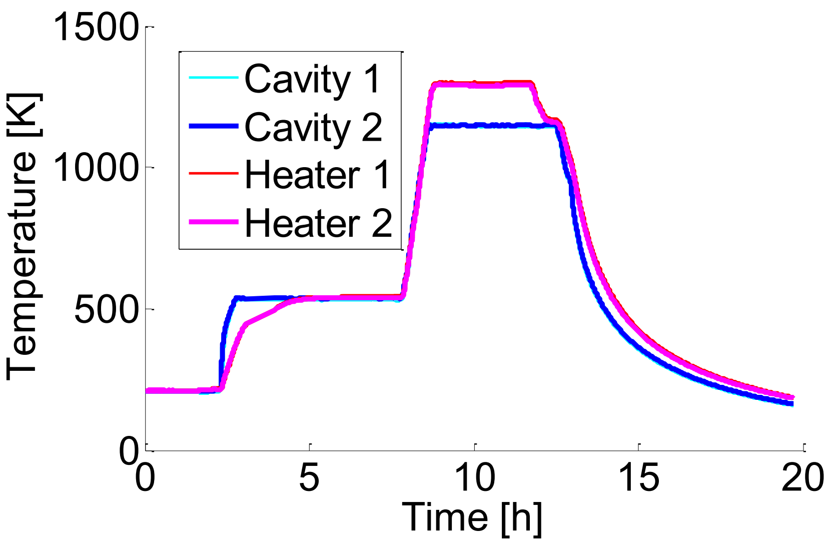
Cavity Coating

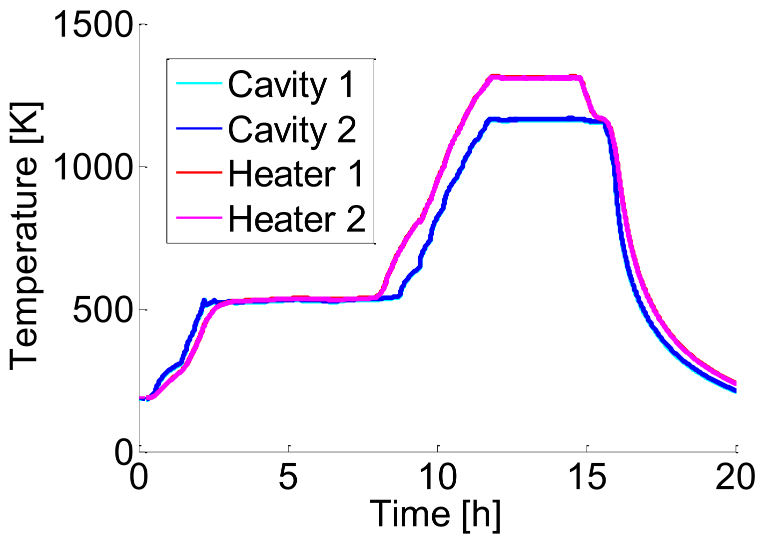
Early Coatings

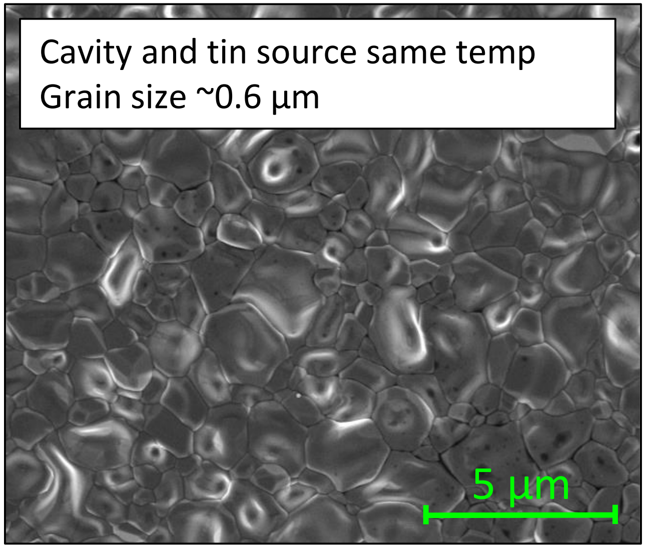
- There were some difficulties early on



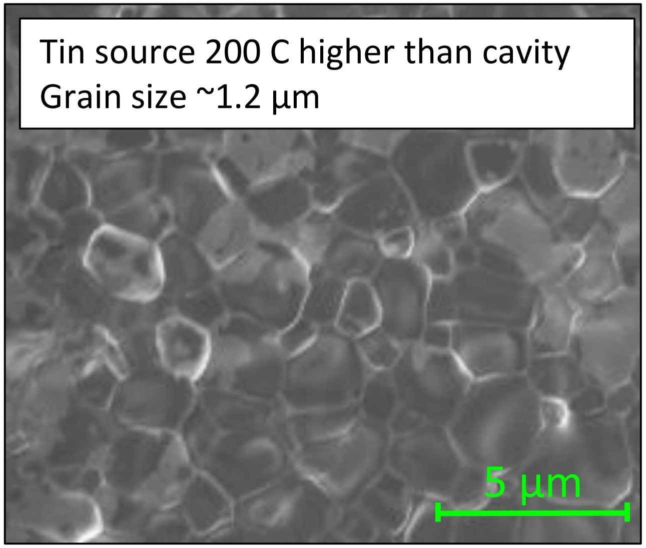
Lessons Learned



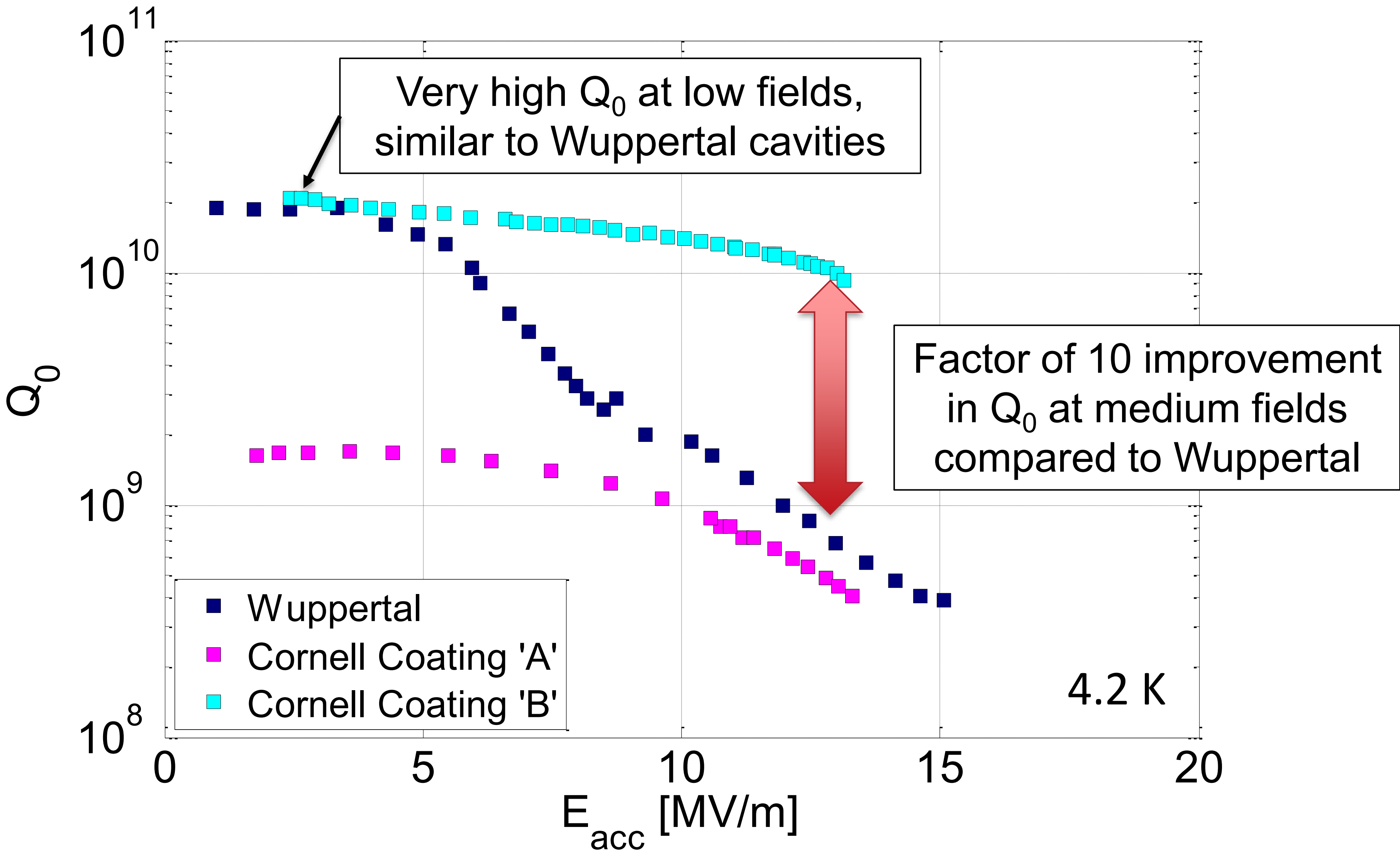




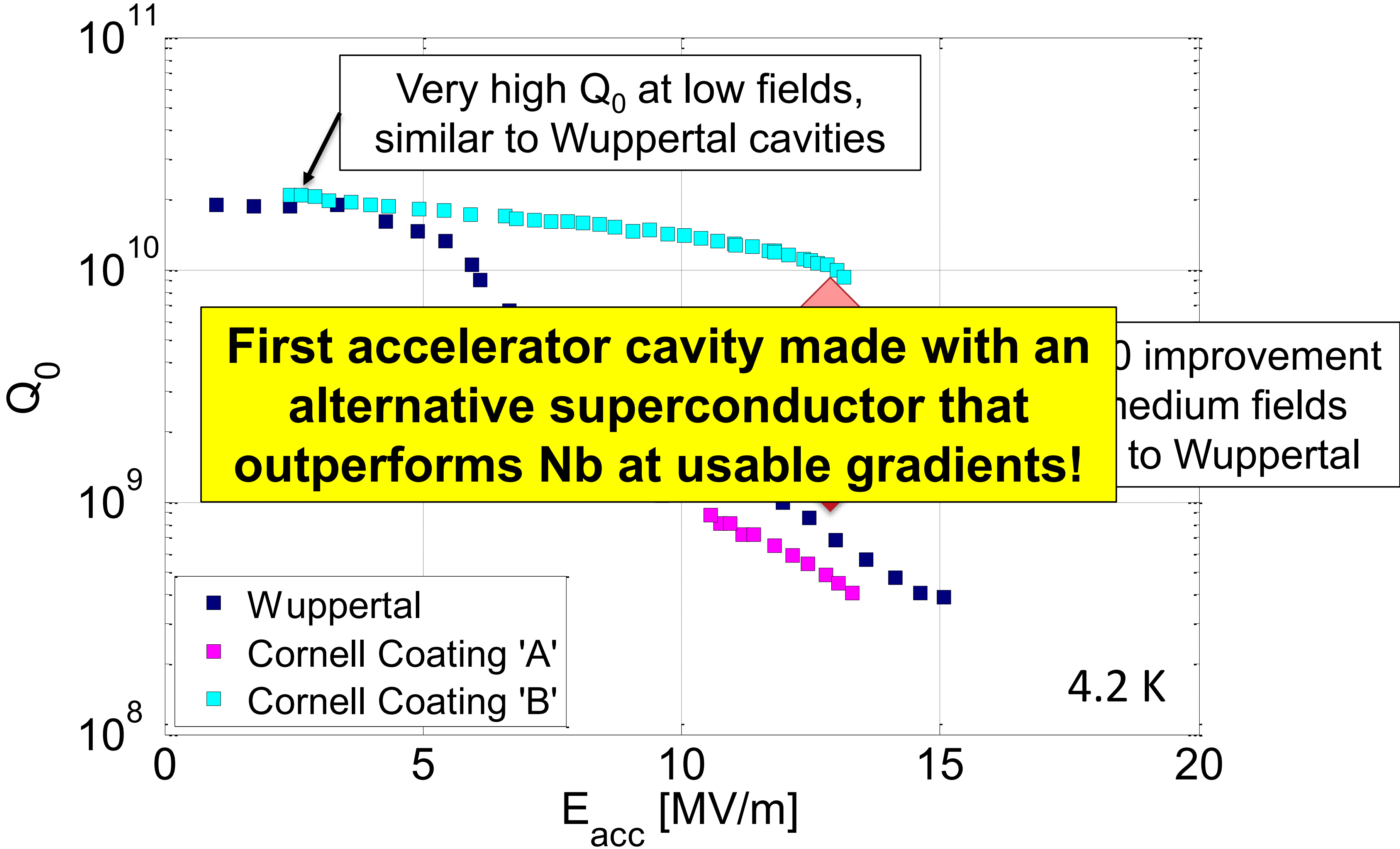
Lesson learned: temperature gradient between tin source and substrate strongly affects grain size



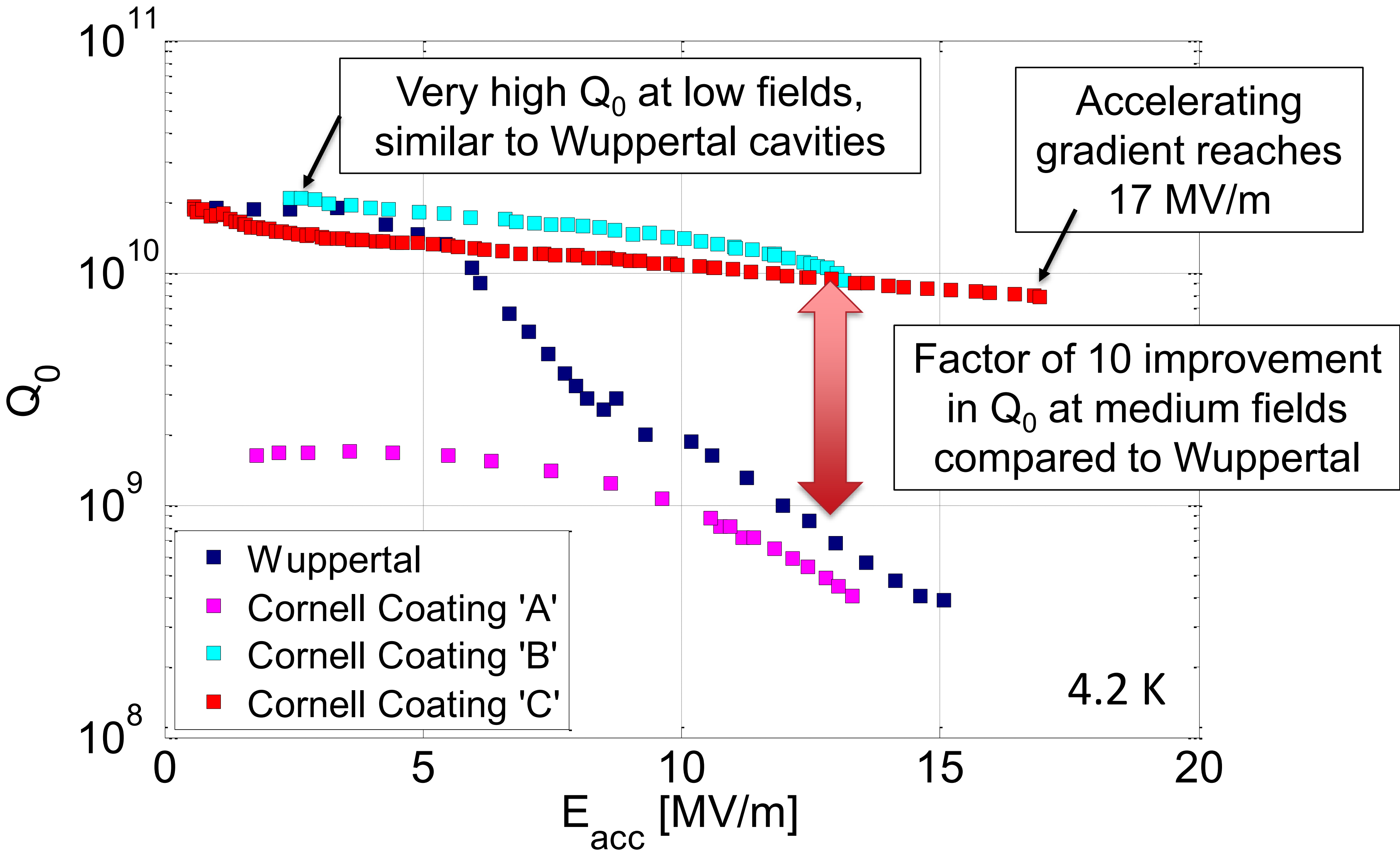
Later Coatings



Later Coatings

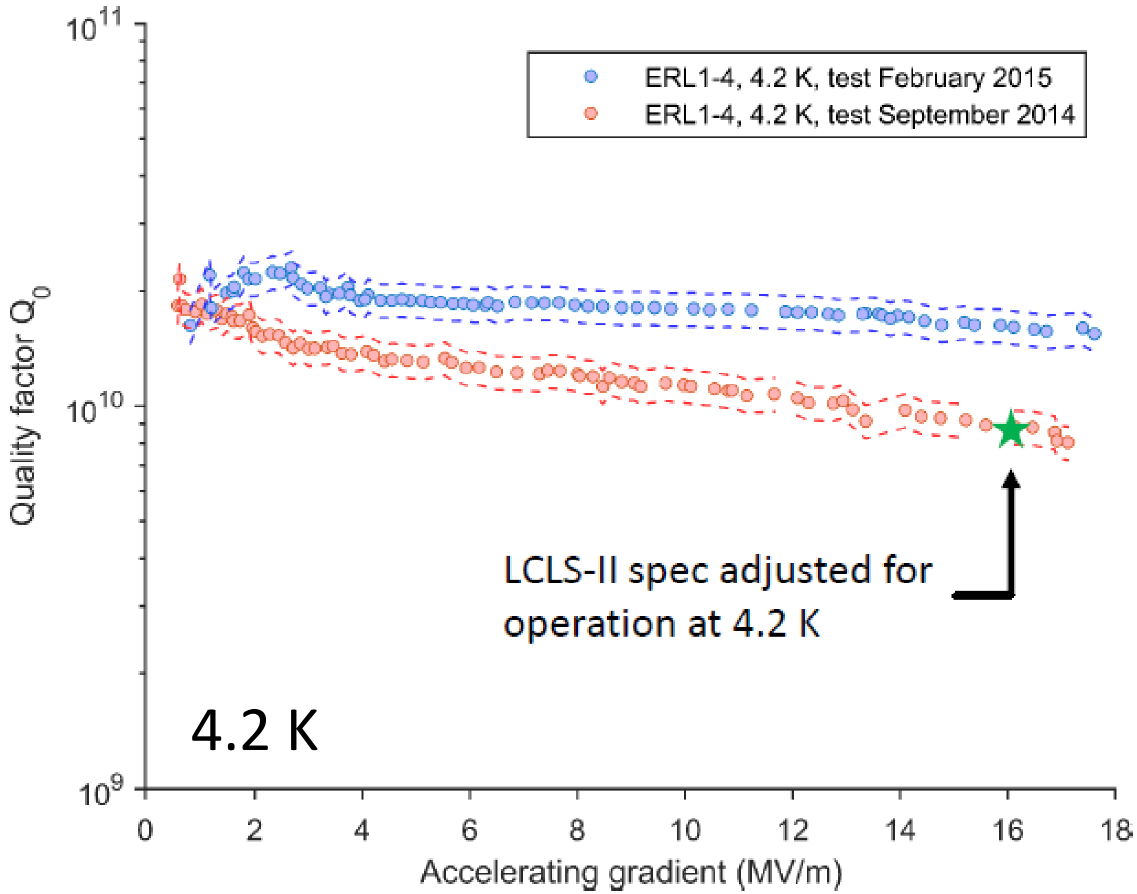


Later Coatings



Improved Cooldown

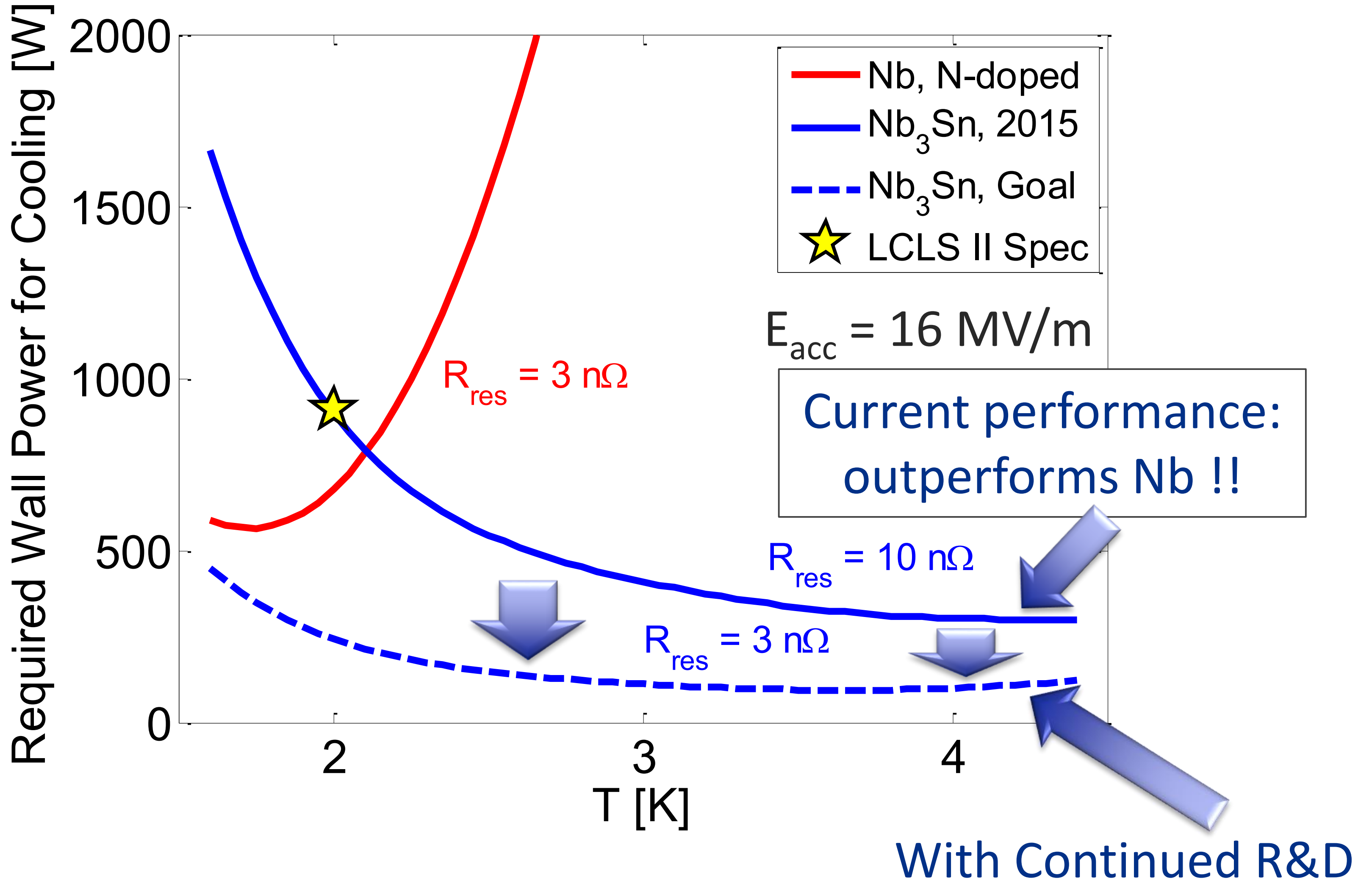
- Same cavity, but with improved cooldown procedure by Daniel Hall, Cornell (slide courtesy Daniel)



Small thermal gradients give better performance

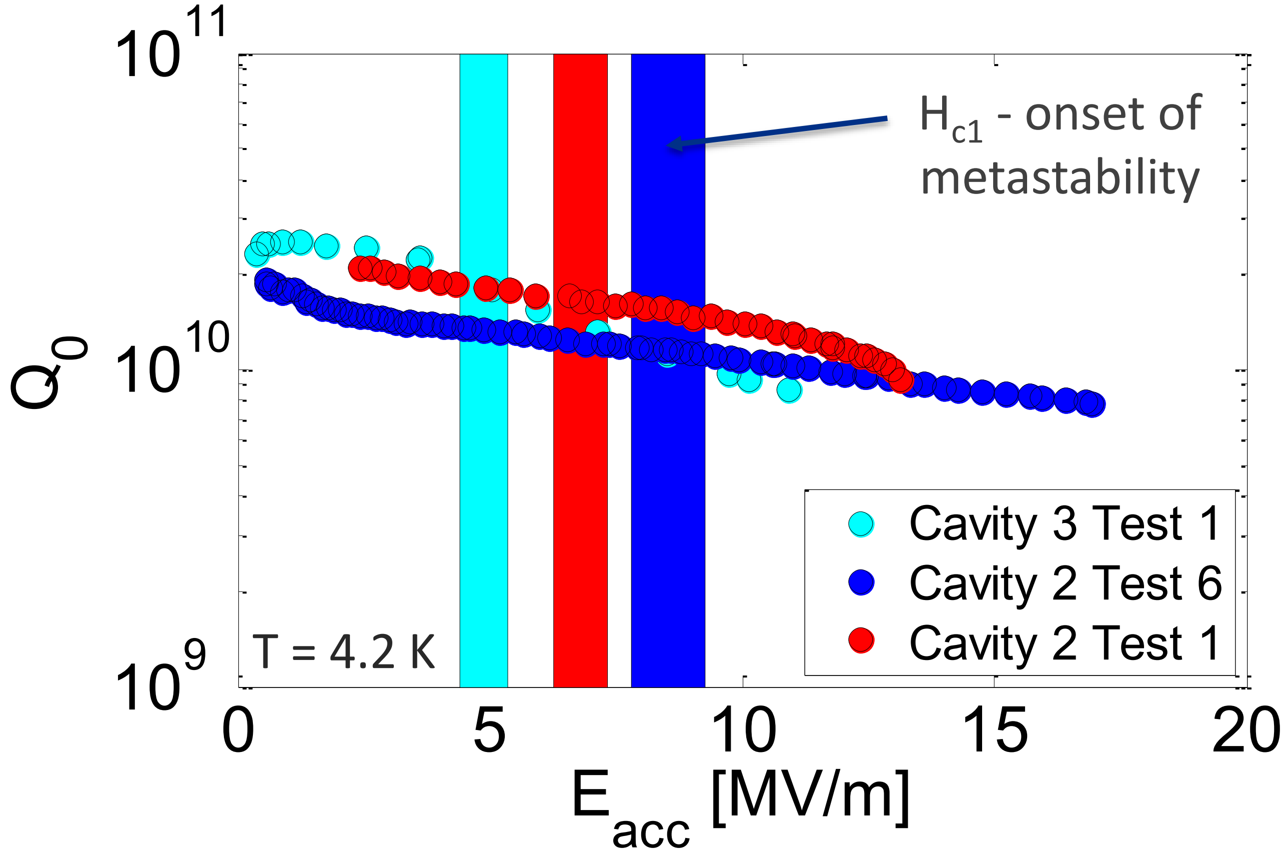
This cavity exceeds LCLS-II spec by a factor of 2

Cryogenic Power Requirements, 1 cell at 1.3 GHz



Metastability

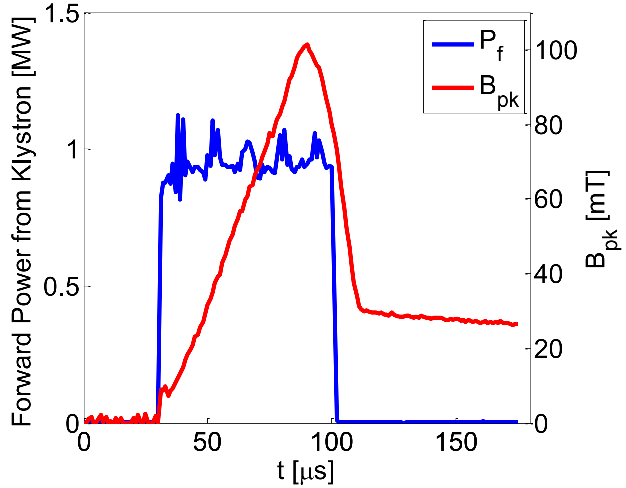
S. Posen, M. Liepe and D. Hall, Appl. Phys. Lett. 106, 082601 (2015)

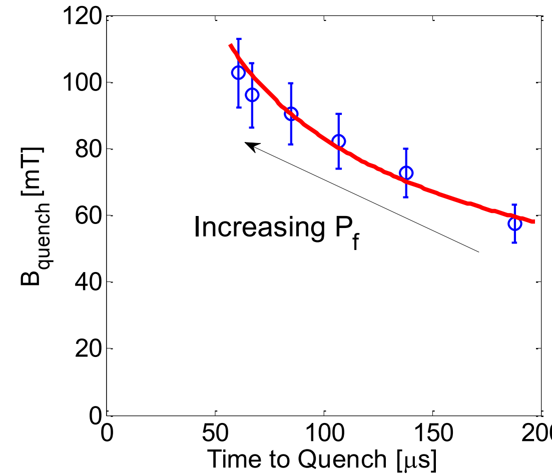


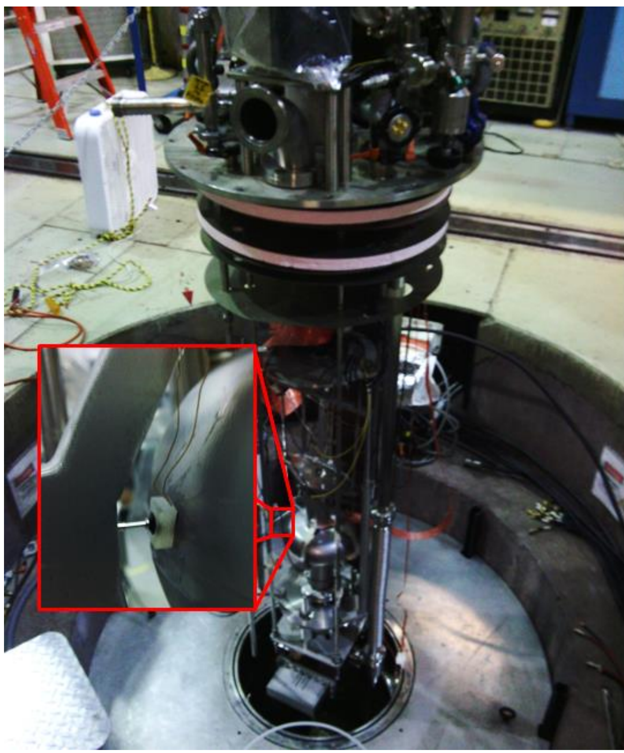
Direct measurement: R. Laxdal et al. SRF2015 TUPB041

- Can small-ξ superconductors remain in a metastable flux-free state above H_{c1}?
  - Yes! H_{c1} is NOT a fundamental limit

Pulsed Quench Field

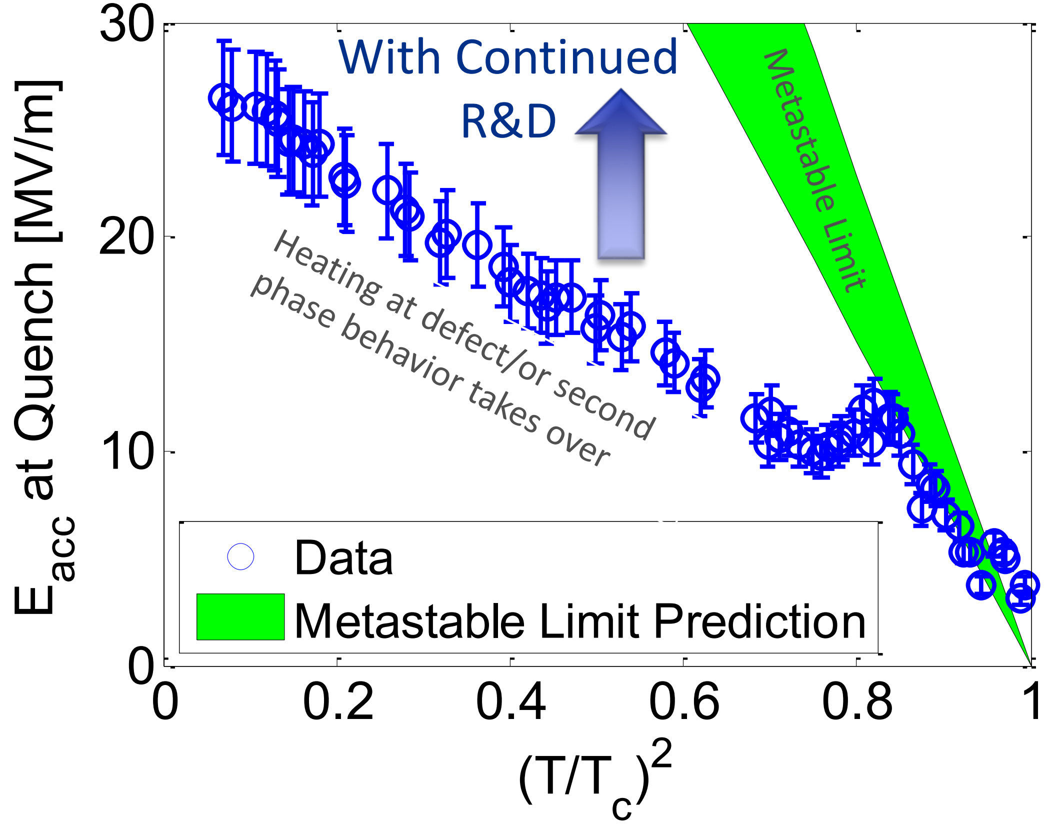






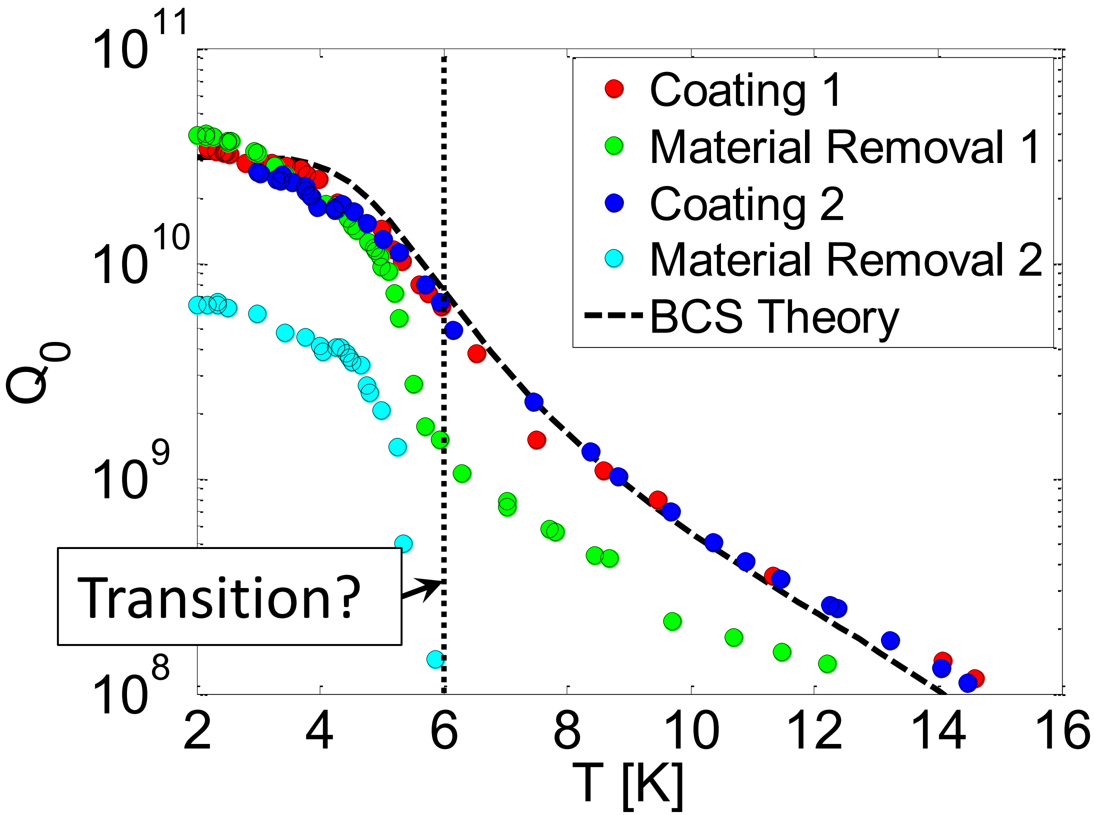
- Used high power RF (MW) from klystron with short pulses
- Pulse length ~100 μs to try to outpace thermal effects
- Measure quench field as a function of temperature
- Compare to predicted limit of metastable state

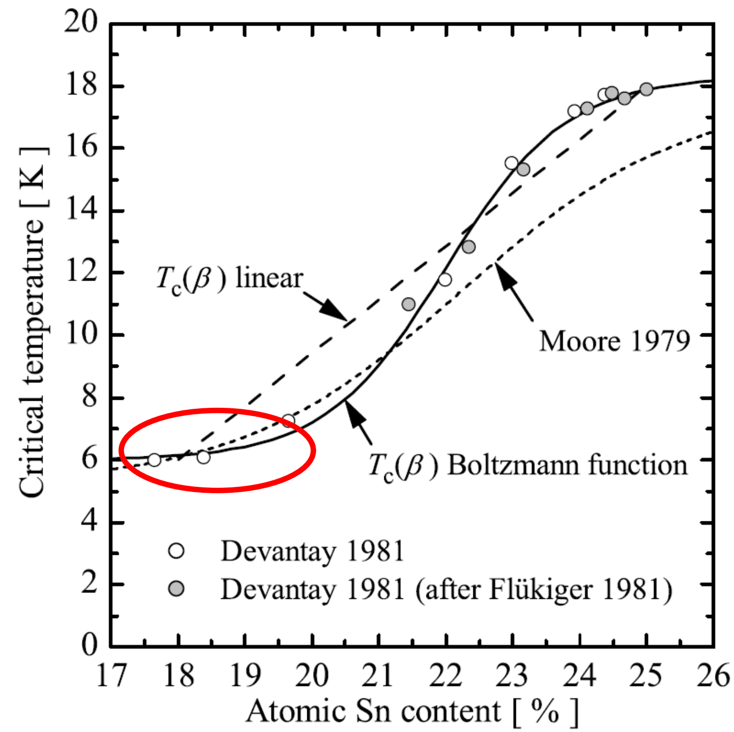
High Gradients – Klystron Measurements



Posen, Valles, Liepe, **Phys. Rev. Lett.** 115, 047001 (2015)

Low Tin Content Nb_3Sn

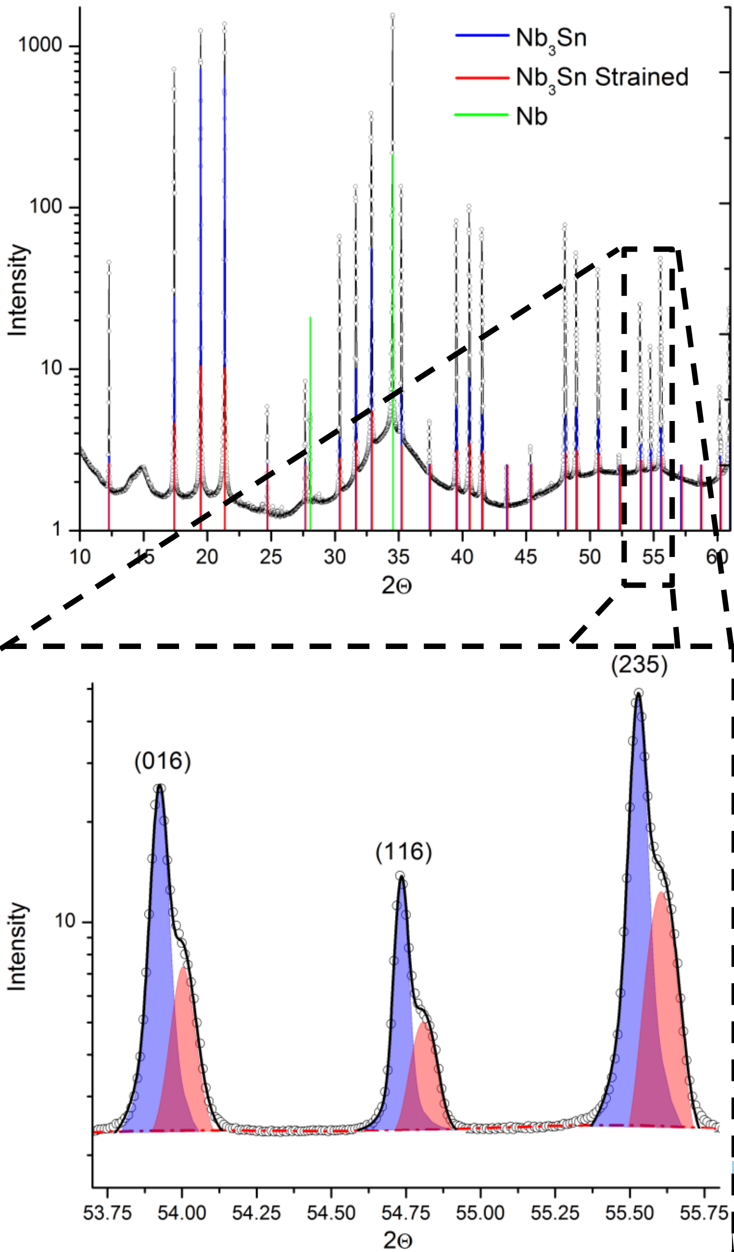




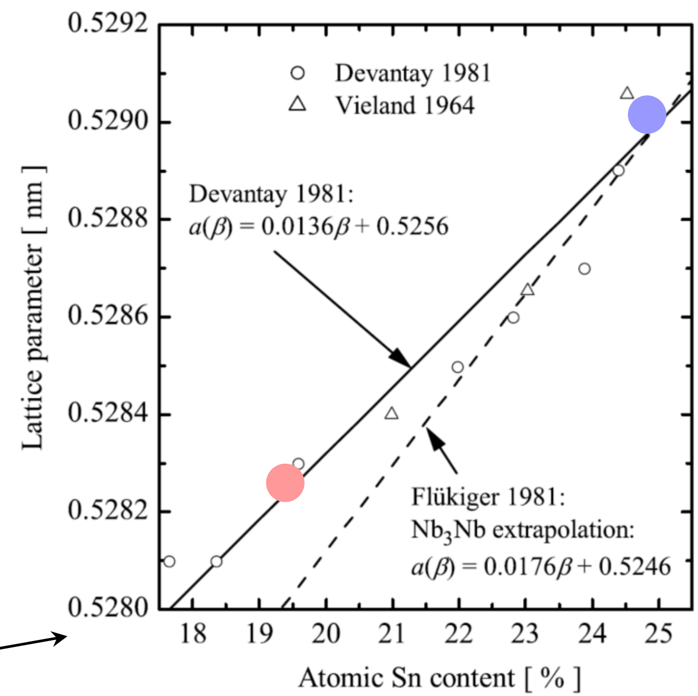
A. Godeke, Supercond. Sci. Tech, 2006

Low Tin Content Nb_3Sn

- XRD by Argonne collaborators at Advanced Photon Source
- Reveals 2 strong peaks corresponding to 24-25% tin and 19-20% tin



XRD studies courtesy T. Proslier, Argonne National Lab



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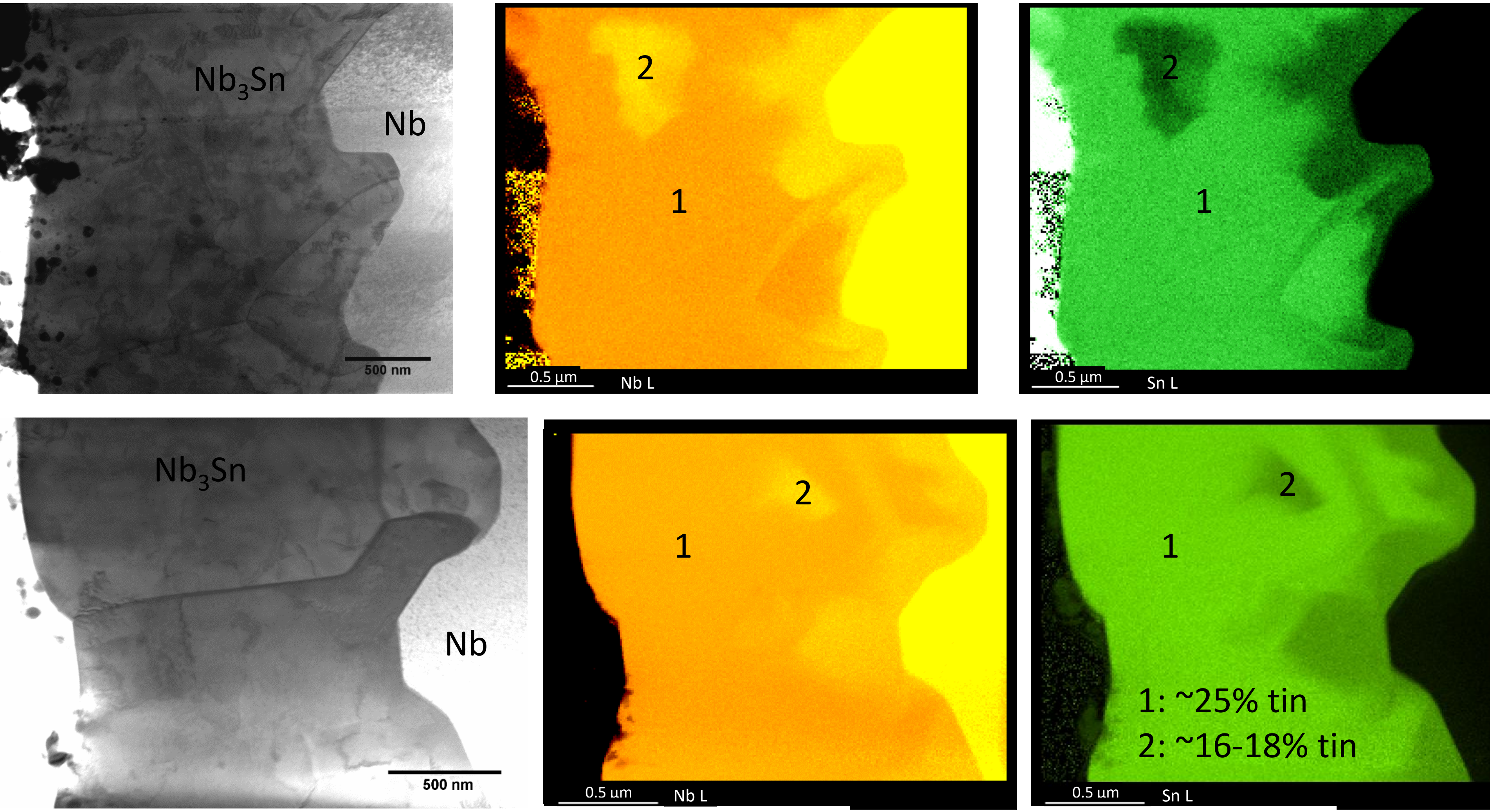
Low Tin Content Nb_3Sn?



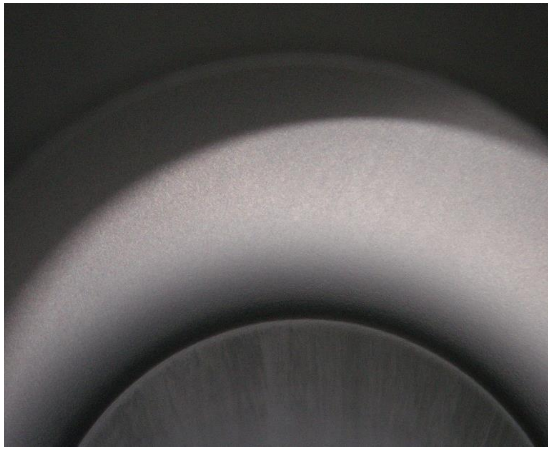
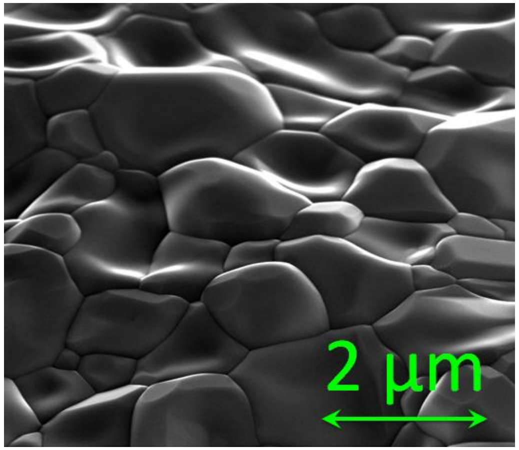
C. Becker et al., *App. Phys. Lett.*, 106, 082602 (2015).

Outlook

Nb_3Sn Outlook

- Proof-of-principle established on small cavities at Cornell
  - Outperforms Nb at useful temperatures and gradients
- R&D initiatives at Fermilab, Cornell, JLab, and CERN for continued progress
- Significant interest:



05.03.16

DOE's Office of Science Selects 49 Scientists to Receive Early Career Research Program Funding

Program provides support to exceptional researchers.

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WASHINGTON, DC – The Department of Energy's (DOE's) Office of Science has selected 49 scientists from across the nation – including 22 from DOE's national laboratories and 27 from U.S. universities – to receive significant funding for research as

Exciting topic: 2 DOE Early Career research grants this year on Nb_3Sn SRF cavities!

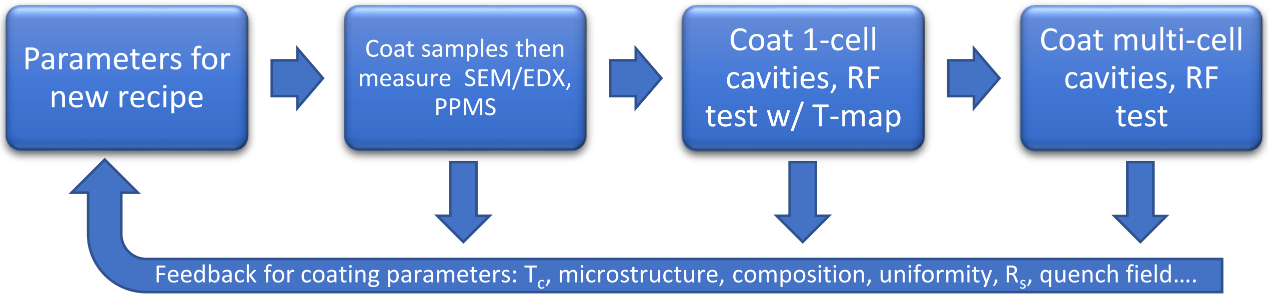
Under the program, university-based researchers will receive at least $150,000 per year to cover summer salary and research expenses. For researchers based at DOE national laboratories, where DOE typically covers full salary and expenses of laboratory employees, grants will be at least $500,000 per year to cover year-round salary plus research expenses. The research grants are planned for five years.

Posen, Sam, Fermi National Accelerator Laboratory, Batavia, IL, "Developing the Next Generation of Superconducting RF Cavities with Nb_3Sn," selected by the Office of High Energy Physics.

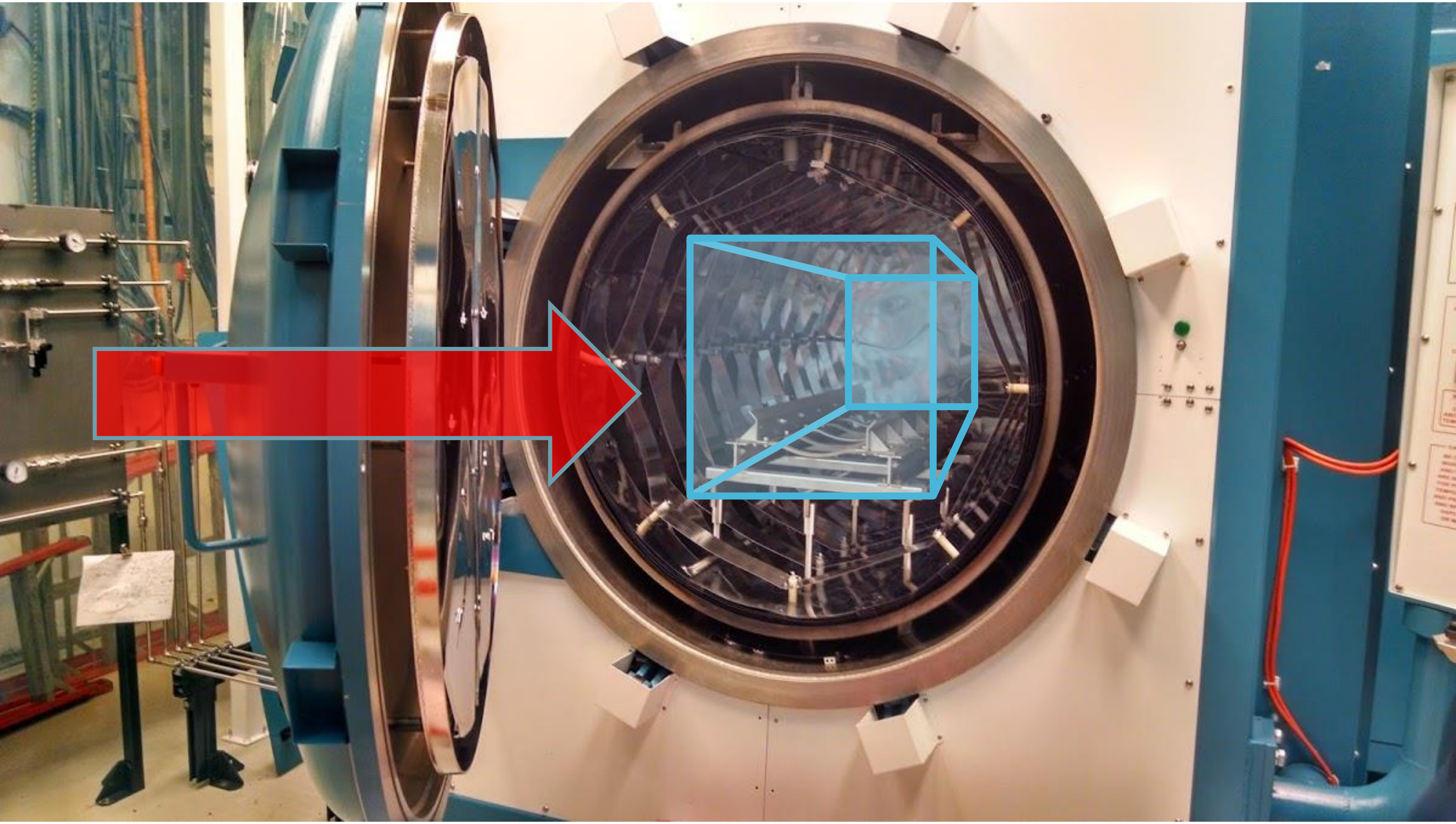
Eremeev, Grigory V., Thomas Jefferson National Accelerator Facility, Newport News, VA, "Formation of Superconducting Nb_3Sn Phase for Superconducting Radio Frequency (SRF) Cavities," selected by the Office of Nuclear Physics.

Nb_3Sn SRF R&D at Fermilab

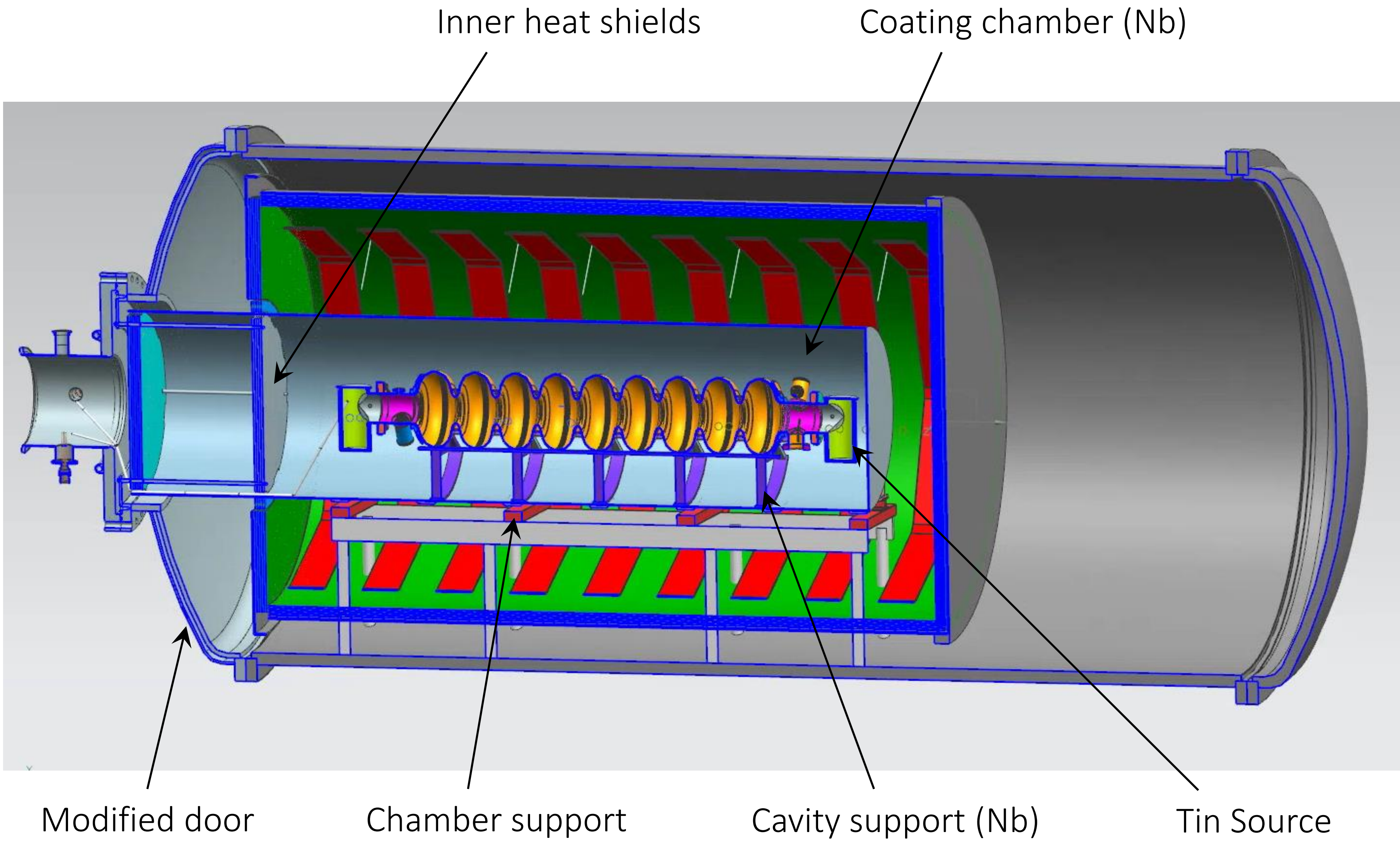
- Increase accelerating gradients E_{acc}
  - Eliminate low tin content regions, study fundamental field limits with high power RF, study influence of disorder
- Increase quality factors Q_0
  - Study origins of residual surface resistance, reduce influence of thermocurrents, retain high Q_0 to high fields
- Scale process up to production-style cavities
  - 9-cell 1.3 GHz, 5-cell 650 MHz: show ready for applications



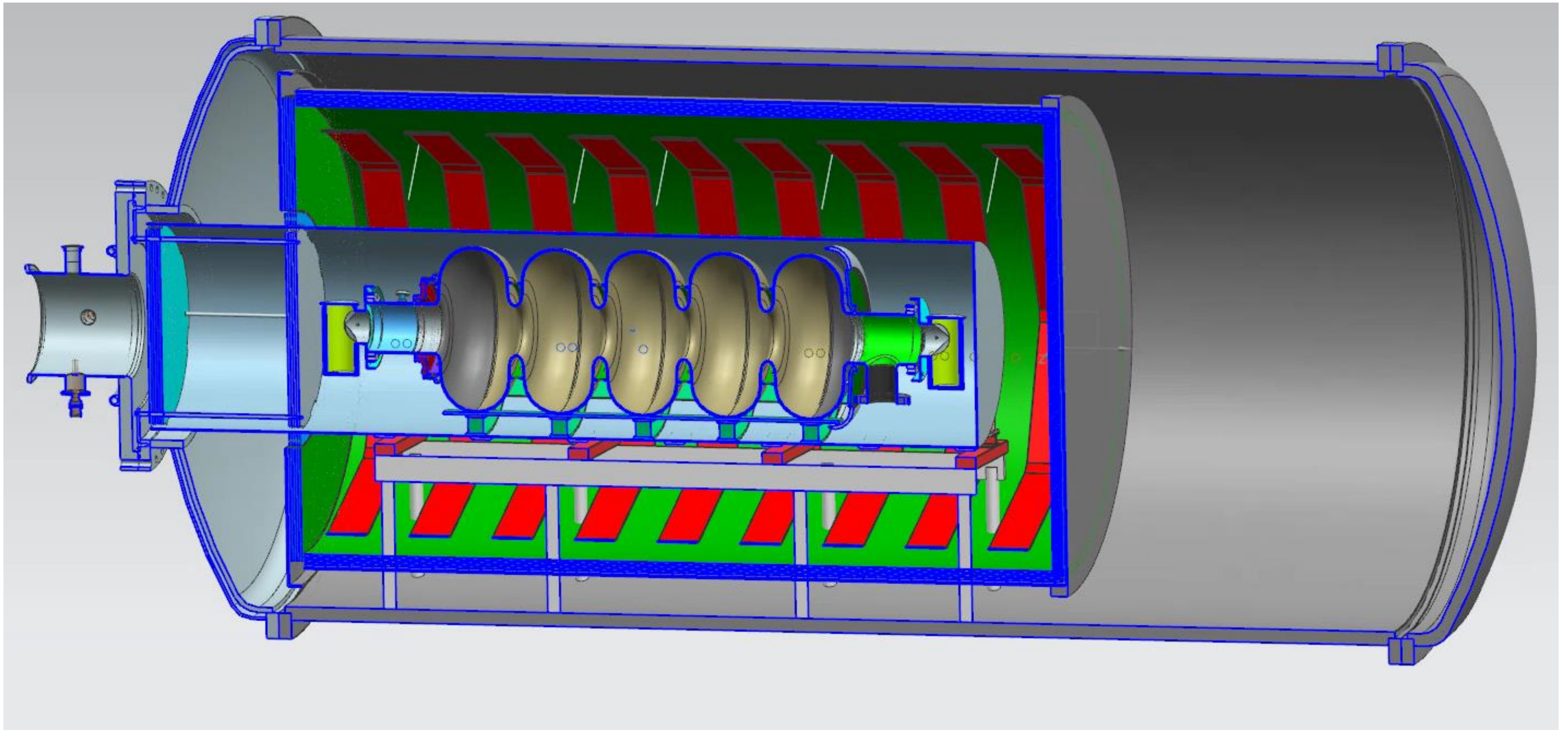
Fermilab Furnace



1.3 GHz 9-cell


Inner heat shields
Coating chamber (Nb)
Modified door
Chamber support
Cavity support (Nb)
Tin Source

650 MHz 5-cell

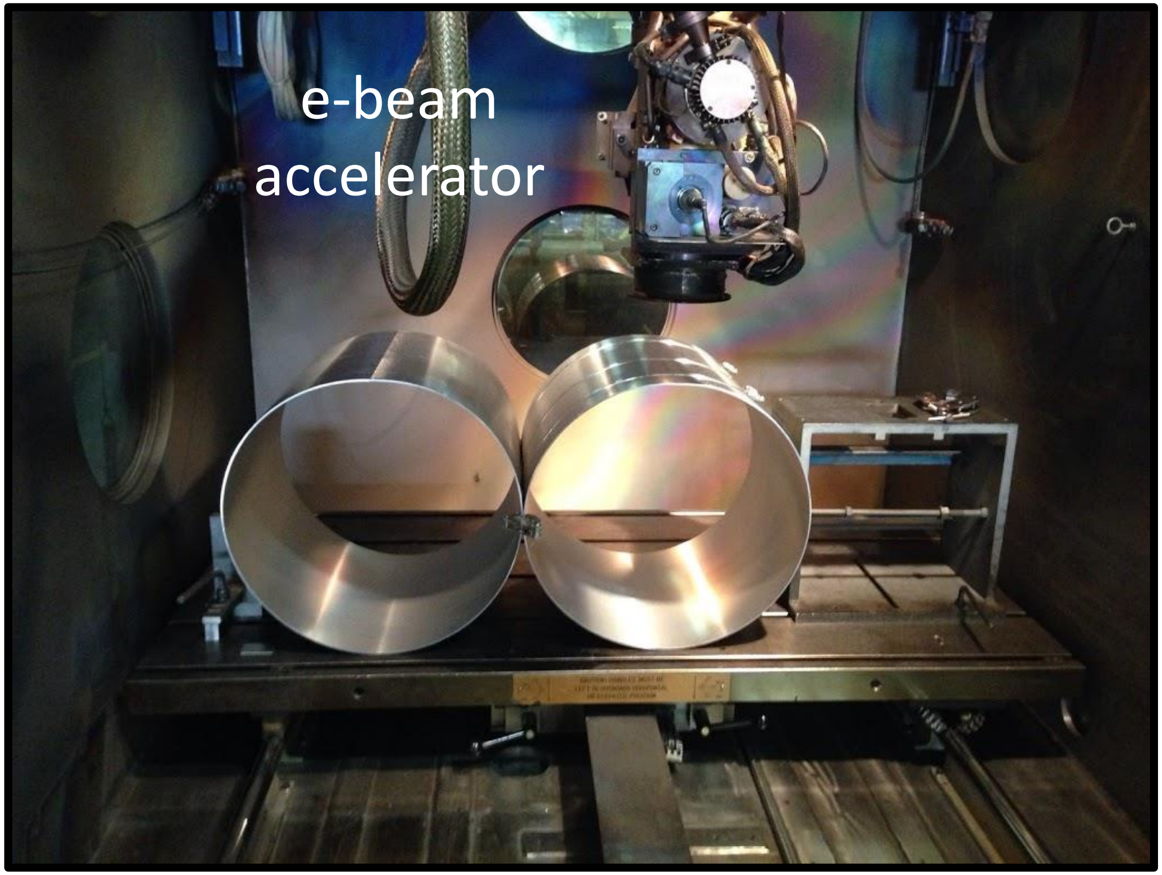


Fermilab

Fermilab Outlook

- Activities towards Nb_3Sn coating capability:
  - Upgrade of Fermilab large UHV furnace and chilled water system for high temperature operation (1300 C)
  - Design and production of niobium coating chamber for furnace to contain tin vapor
  - Modifications of UHV furnace to accommodate chamber
  - New lifting capabilities in UHV furnace area
  - …
- First coatings on samples anticipated in fall 2016
- Single cell cavities to be coated after satisfactory samples are obtained

Final Thought



Special Thanks

- Sincere thank you to my thesis advisor, Matthias Liepe
- Collaborators: Gianluigi Catelani, Grigory Eremeev, Mark Transtrum, Thomas Proslier, Bob Laxdal, Sergey Belomestnykh, and Sarah Aull
- Mentors: Hasan Padamsee, Maury Tigner, Don Hartill, Georg Hoffstaetter
- Fermilab SRF Program
- Cornell graduate student contemporaries
- IPAC organizers, awards committee, and those who nominated me for this prize