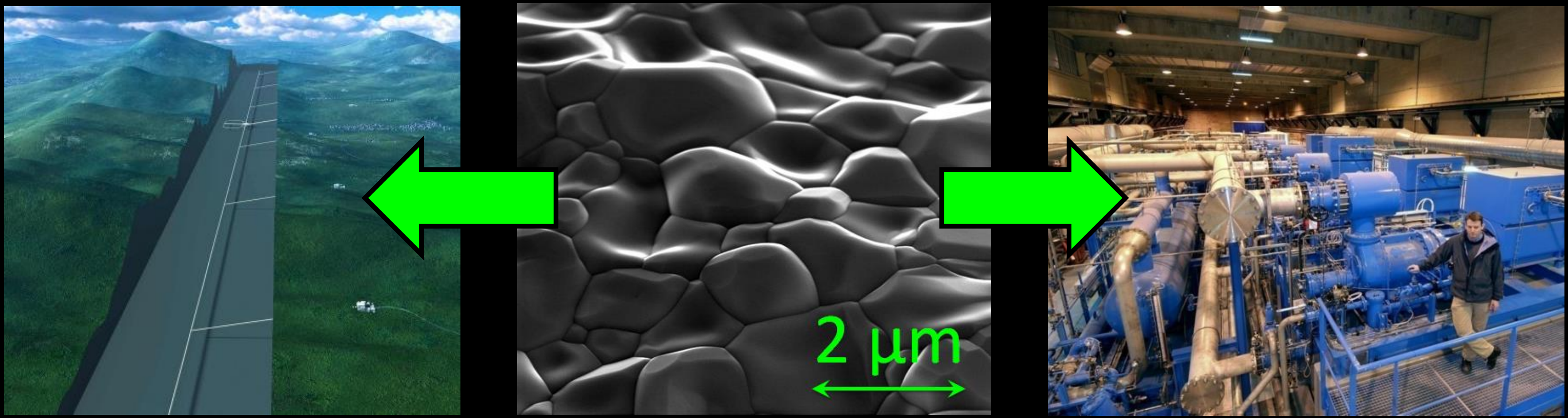
Nb$_3$Sn – Present Status and Potential as an Alternative SRF Material



S. Posen and M. Liepe, Cornell University

LINAC 2014 – Geneva, Switzerland – September 2, 2014

Limits of Modern SRF Technology

Low DF, high energy

- Energy gradient in state of the art Nb cavities limited by B_{sh} (ultimate limit)

Limit: B_{sh}

ILC: 16,000 cavities in 31 km linac

Image from Rei Hori, linearcollider.org

High DF / CW

- Large dynamic load
- Cost optimum gradient relatively low: $P_{diss} \sim E_{acc}^2/Q_0$

Limit: Q_0

Cryoplants for large linacs cost ~$100 million and require MW of power

Image from D. Delikaris, Cryogenics at CERN, 2010

Potential of Nb_3Sn

	Niobium
Critical Temperature T_c	9 K
Q_0 at 4.2 K	6×10^8
Q_0 at 2.0 K	3×10^{10}
Max. gradient E_{acc} (theory)	50 MV/m

Approximate E_{acc} and Q_0 given for 1.3 GHz TeSLA or 1.5 GHz CEBAF cavities with R_{res} small

Potential of Nb_3Sn

Increase in Q_0
via N-doping

	Niobium
Critical Temperature T_c	9 K
Q_0 at 4.2 K	6×10^8
Q_0 at 2.0 K	$4\text{-}8 \times 10^{10}$ ~~3×10^{10}~~
Max. gradient E_{acc} (theory)	50 MV/m

Approximate E_{acc} and Q_0 given for 1.3 GHz TeSLA or 1.5 GHz CEBAF cavities with R_{res} small

Potential of Nb_3Sn

Increase in Q_0 via N-doping

$\eta_{4.2\,K} / \eta_{2.0\,K} \approx 3.6$, simpler cryoplant

	Niobium	**Nb_3Sn**
Critical Temperature T_c	9 K	18 K
Q_0 at 4.2 K	6 x 10^8	**6 x 10^{10}**
Q_0 at 2.0 K	4-8 x 10^{10} ~~3 x 10^{10}~~	>10^{11}
Max. gradient E_{acc} (theory)	50 MV/m	**100 MV/m**

Approximate E_{acc} and Q_0 given for 1.3 GHz TeSLA or 1.5 GHz CEBAF cavities with R_{res} small

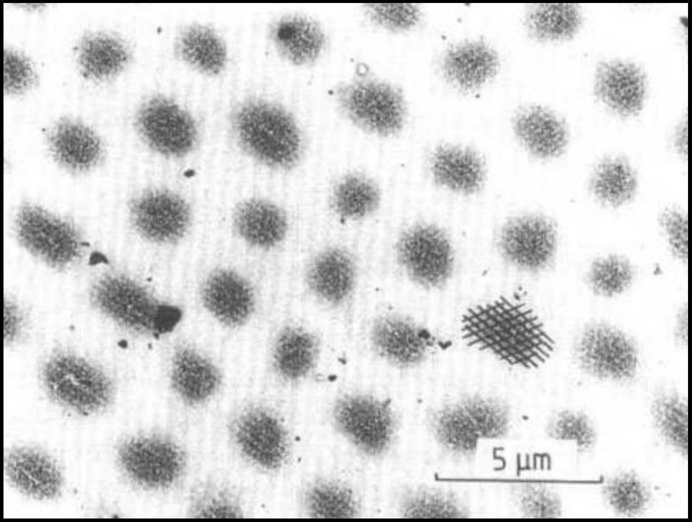
Halve # of cavities to reach energy?

Potential for Small-Scale Accelerators

- 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 low-loss operation with atmospheric 4.2 K LHe, or even gas/supercritical He
- Flue gas, waste water treatment, isotope production, security

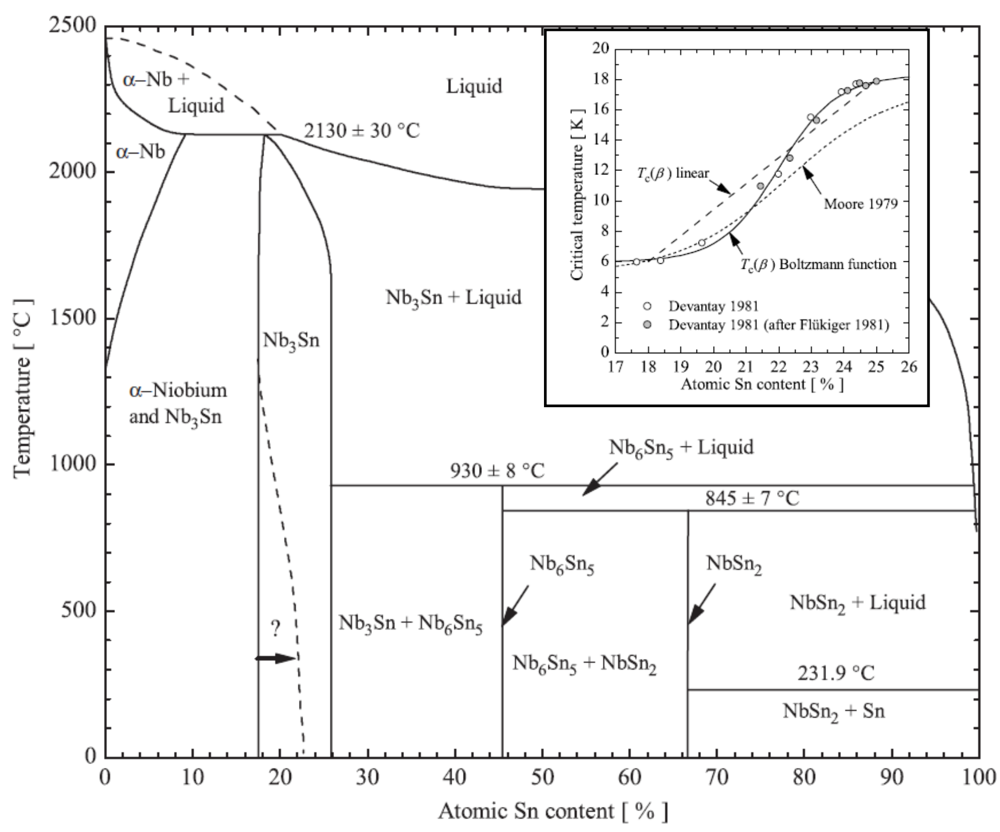
Images from S. Sabharwal, NA-PAC13

Nb$_3$Sn Challenges



Flux lattice in a Type II Superconductor

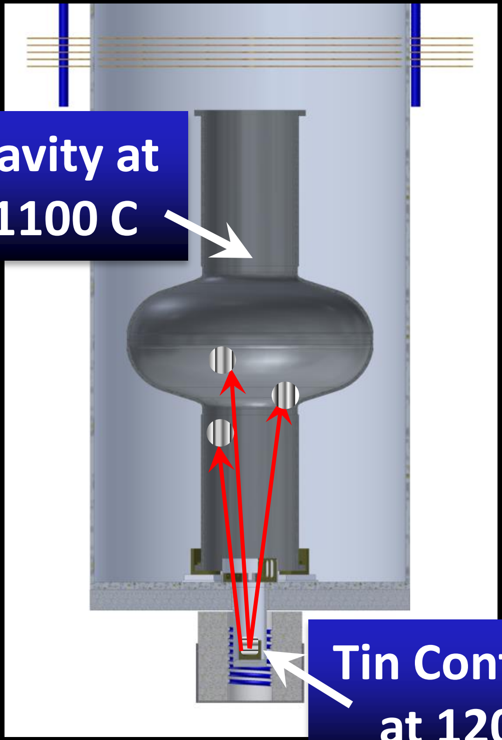
E.H. Brandt, Rep. Prog. Phys. 58 (1995)



Nb$_3$Sn Phase Diagram

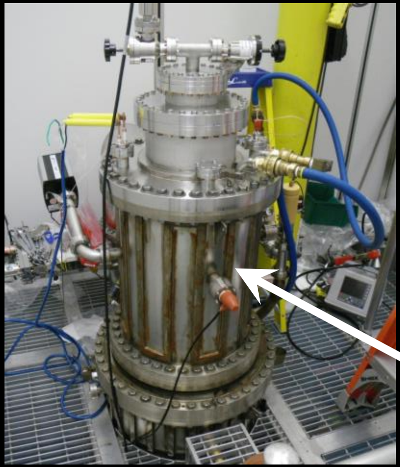
A. Godeke, Supercond. Sci. Tech, 2006

Cornell Coating Chamber



Cavity at 1100 C

Tin Container at 1200 C

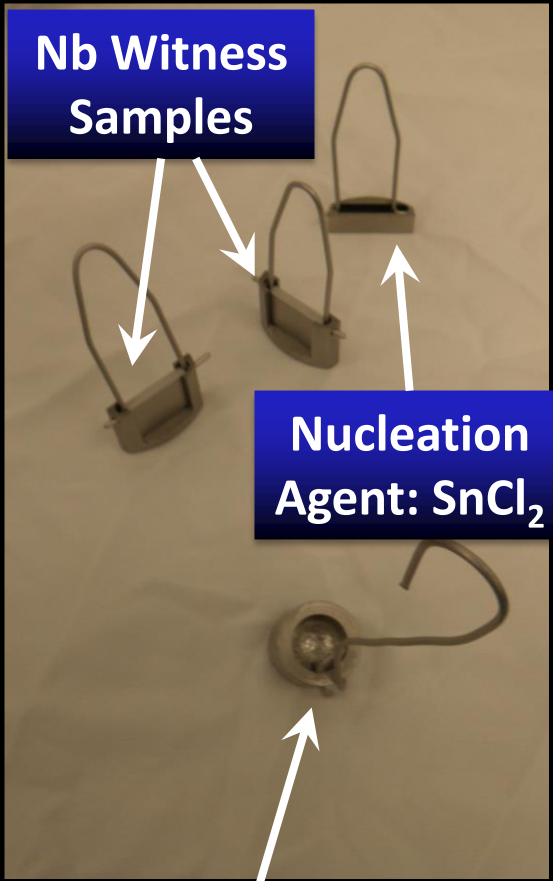


Flange to UHV furnace

Copper transition weld from stainless to Nb

Heat Shields

UHV Furnace

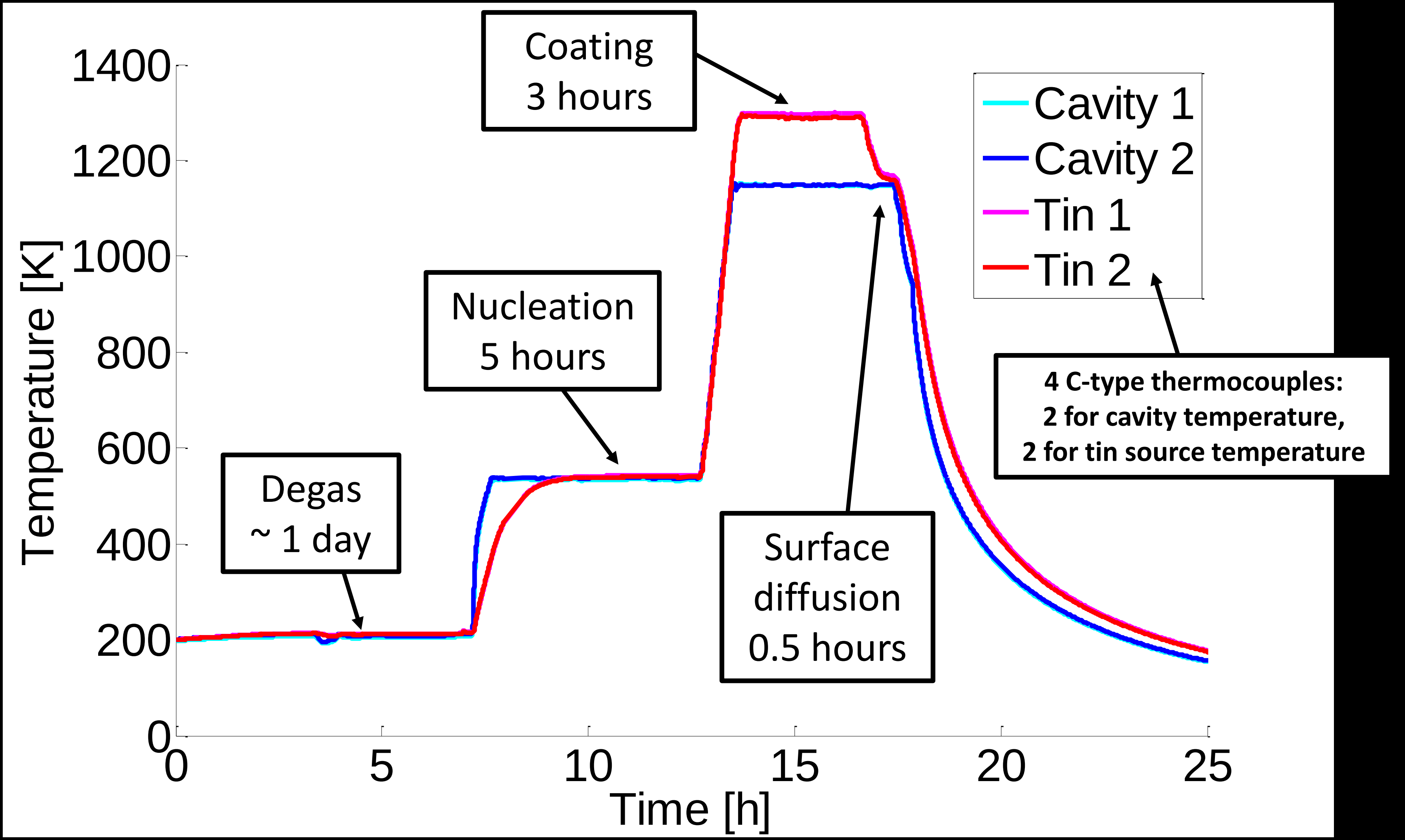


Nb Witness Samples

Nucleation Agent: $SnCl_2$

Sn, High Purity

Coating Procedure



Coating
3 hours

Nucleation
5 hours

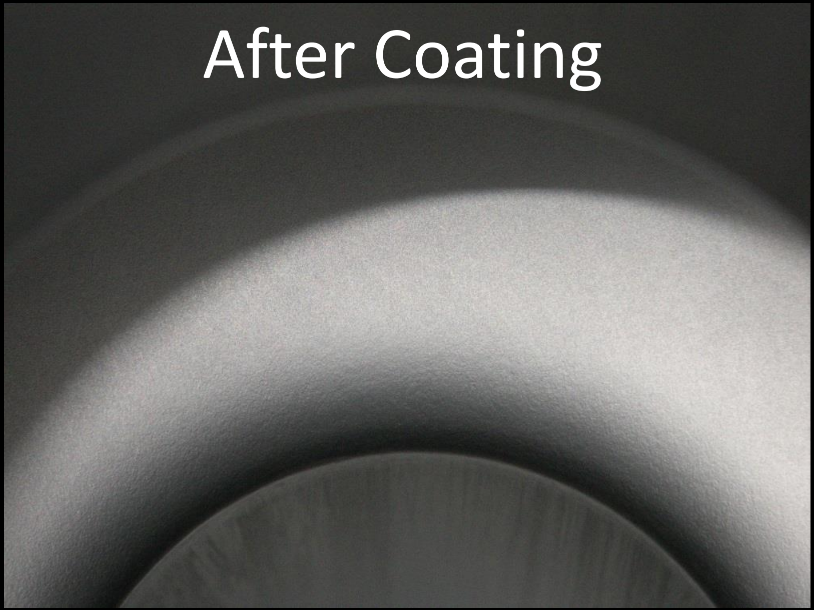
Degas
~ 1 day

Surface
diffusion
0.5 hours

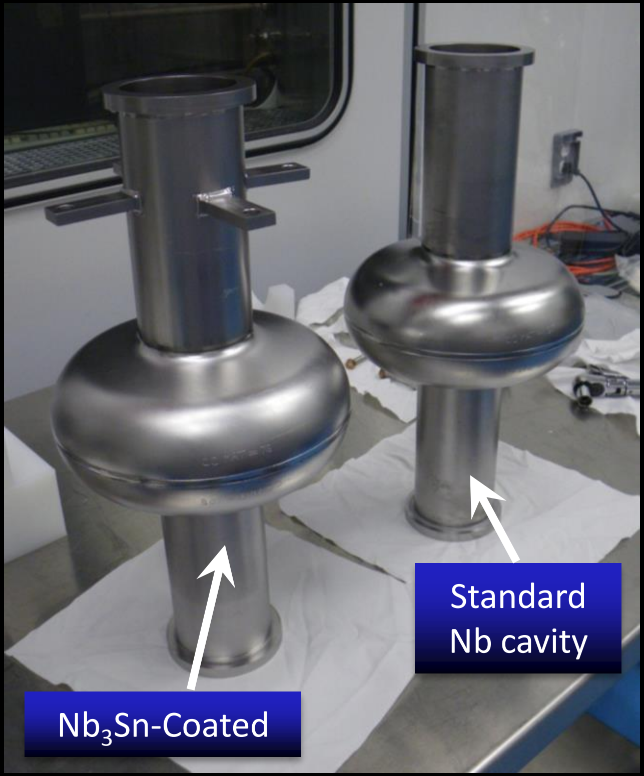
4 C-type thermocouples:
2 for cavity temperature,
2 for tin source temperature

Coated Cavity

Before Coating

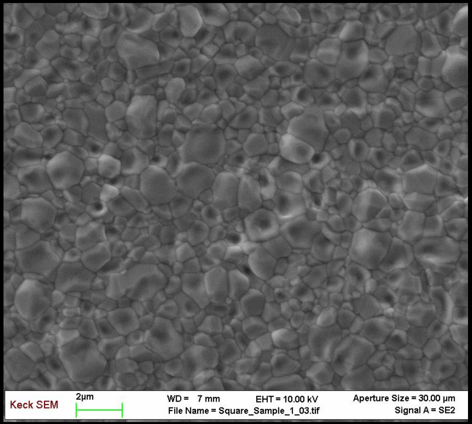


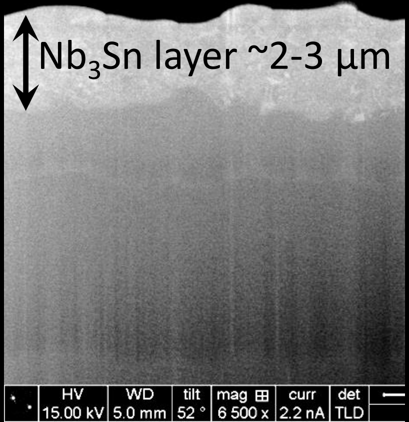
After Coating



Standard Nb cavity

Nb_3Sn-Coated

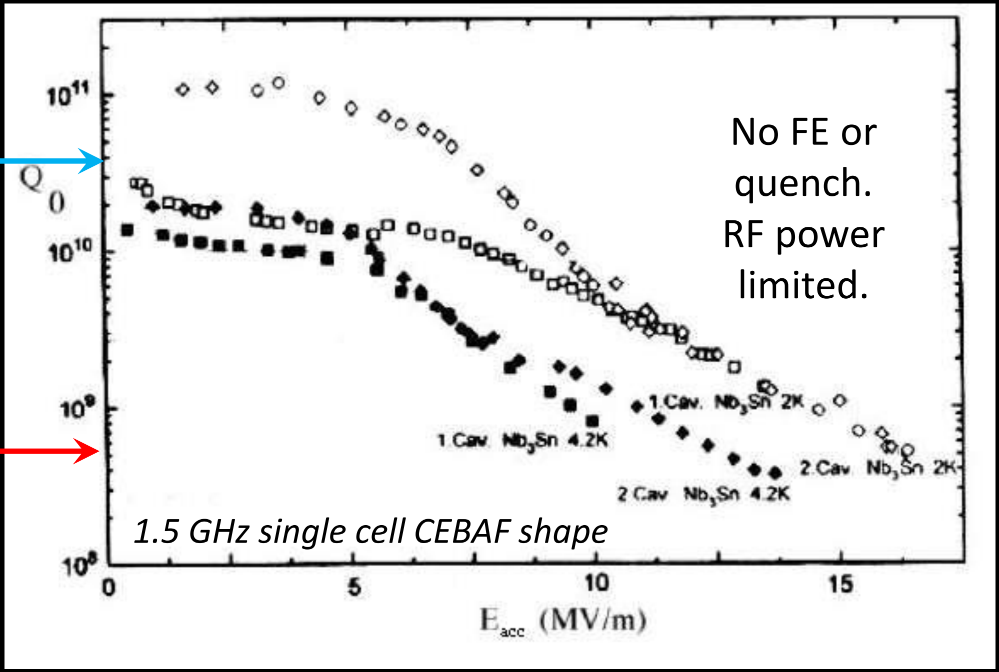




Nb_3Sn layer ~2-3 µm

Nb_3Sn SRF History

- Pioneering work at Siemens AG, U. Wuppertal, K.F. Karlsruhe, SLAC, Cornell U., Jefferson Lab , and CERN
- U. Wuppertal:
  - Very small R_s values in Nb_3Sn cavities
  - Strong Q-slope, cause uncertain



Nb at 2.0 K

Nb at 4.2 K

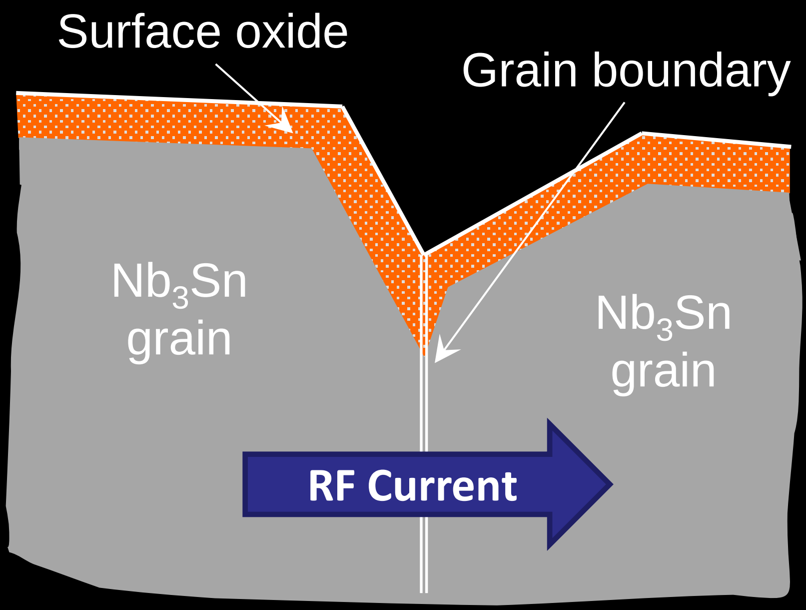
No FE or quench. RF power limited.

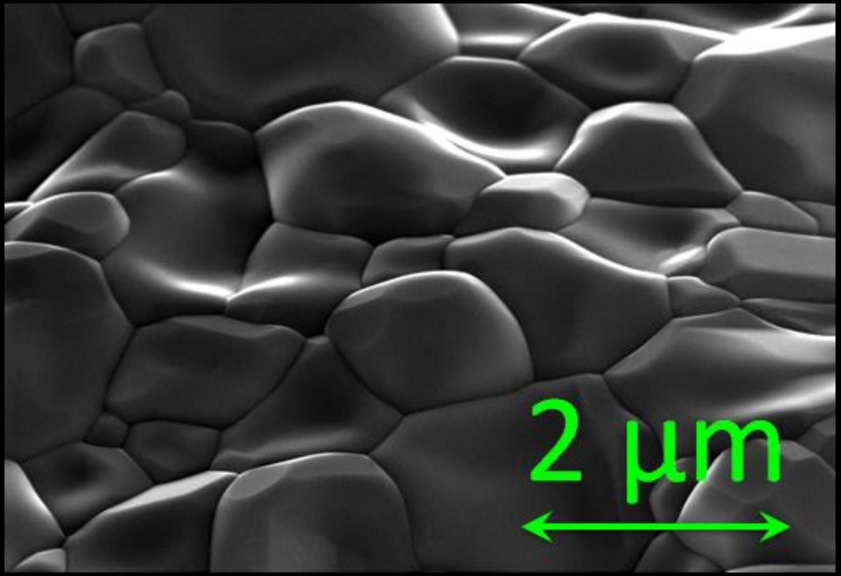
1.5 GHz single cell CEBAF shape

Adapted from G. Müller et al, U. Wuppertal, TESLA Report 2000-15, 2000

“Weak Link” Grain Boundaries

- Losses in material between crystal grains
- Performance similar in appearance to Nb/Cu
- Systematic study on small samples: strong effect from grain size
- Preliminary annealing attempts on cavities gave poor results

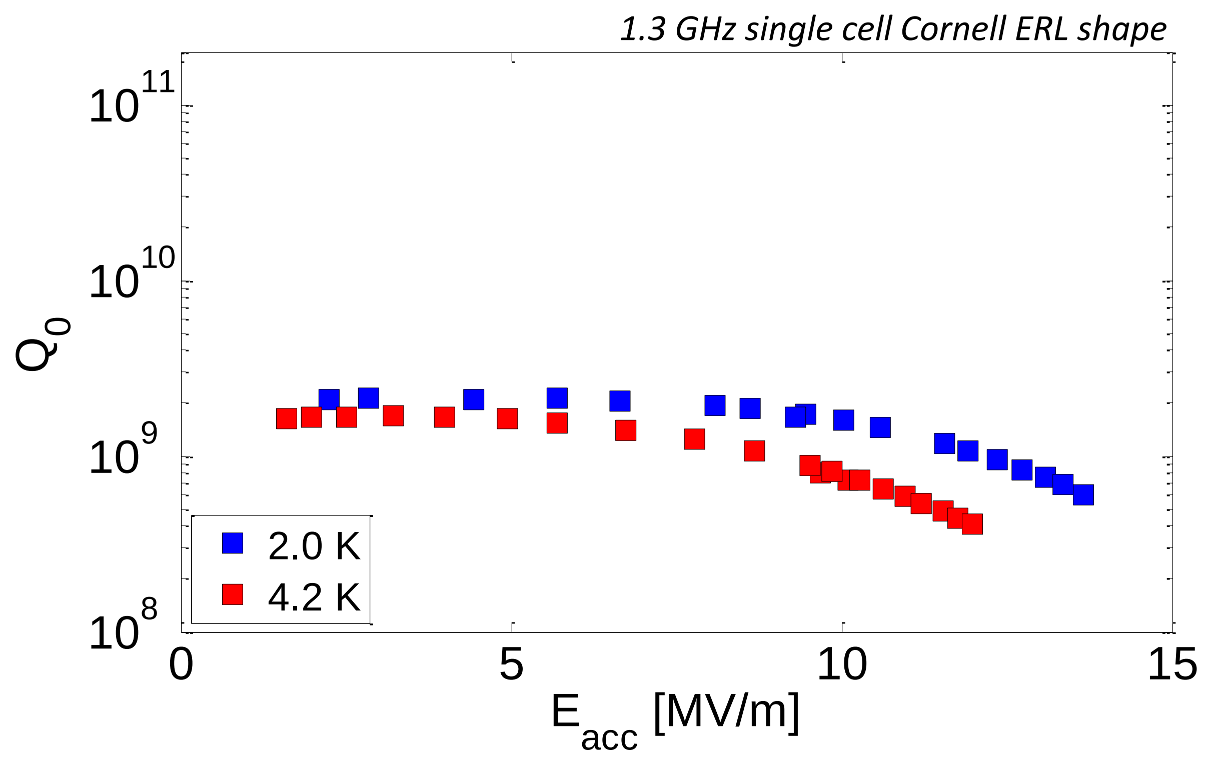




Images adapted from T. Proslier et al., NuFact09 and M. Hein et al., IEEE Trans. Supercond., 2001

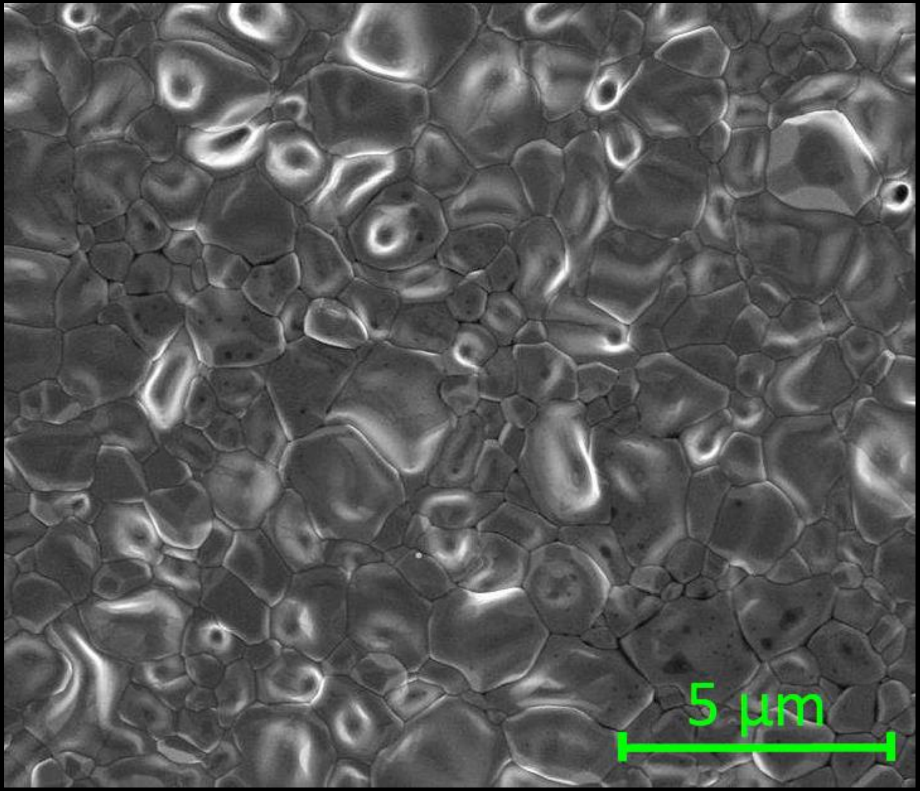
First Cavity: Follow Recipe

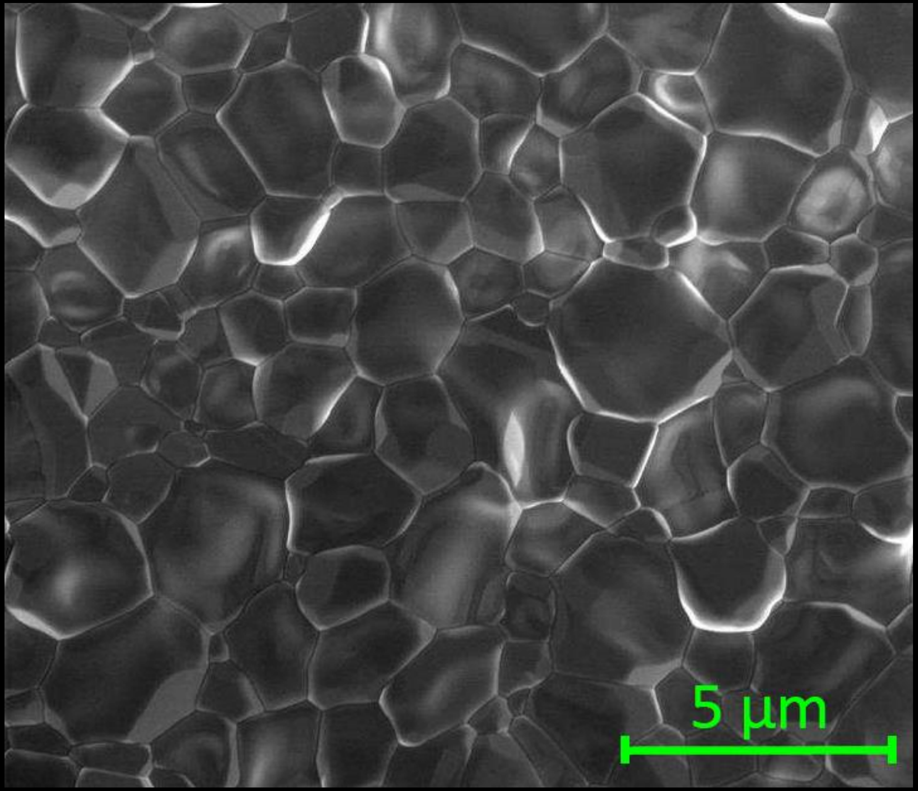
- First cavity: Wuppertal recipe
- Strong Q-slope observed similar to Wuppertal



Grain Growth via Annealing

- Found 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



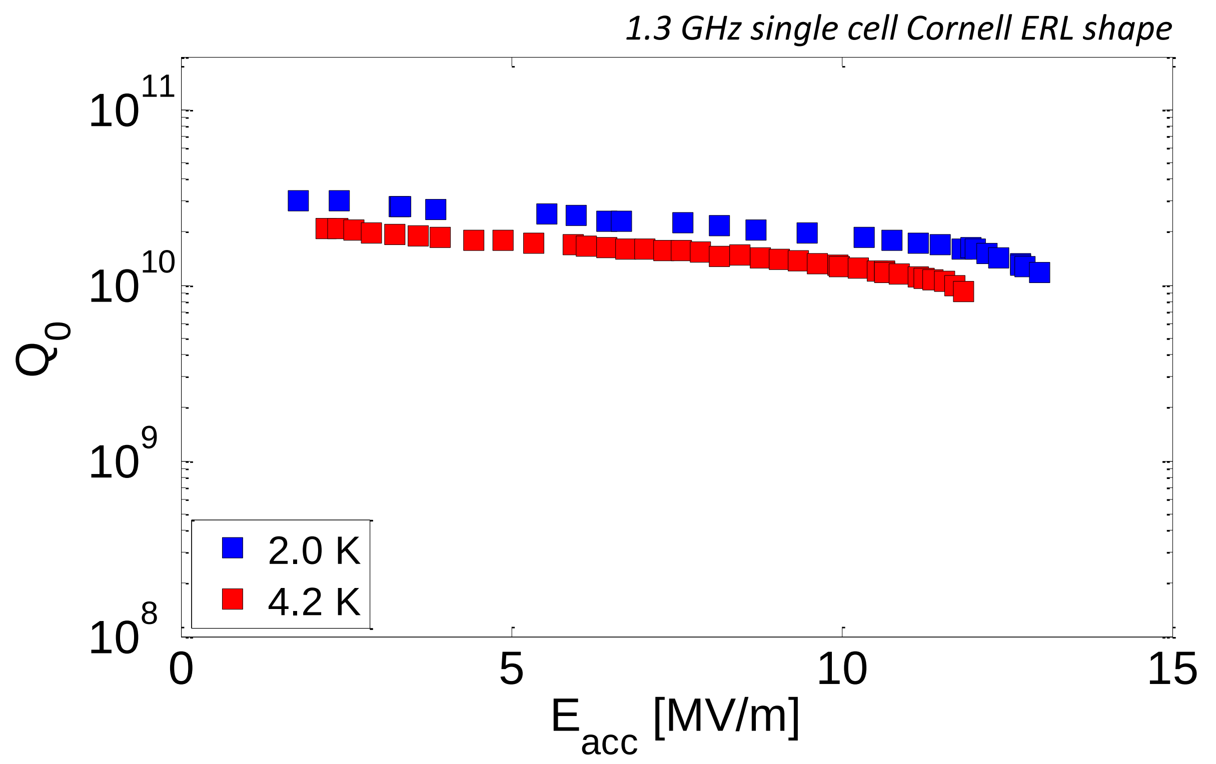


No annealing step, average grain size ~1 µm

Anneal 6 hours, average grain size ~2 µm

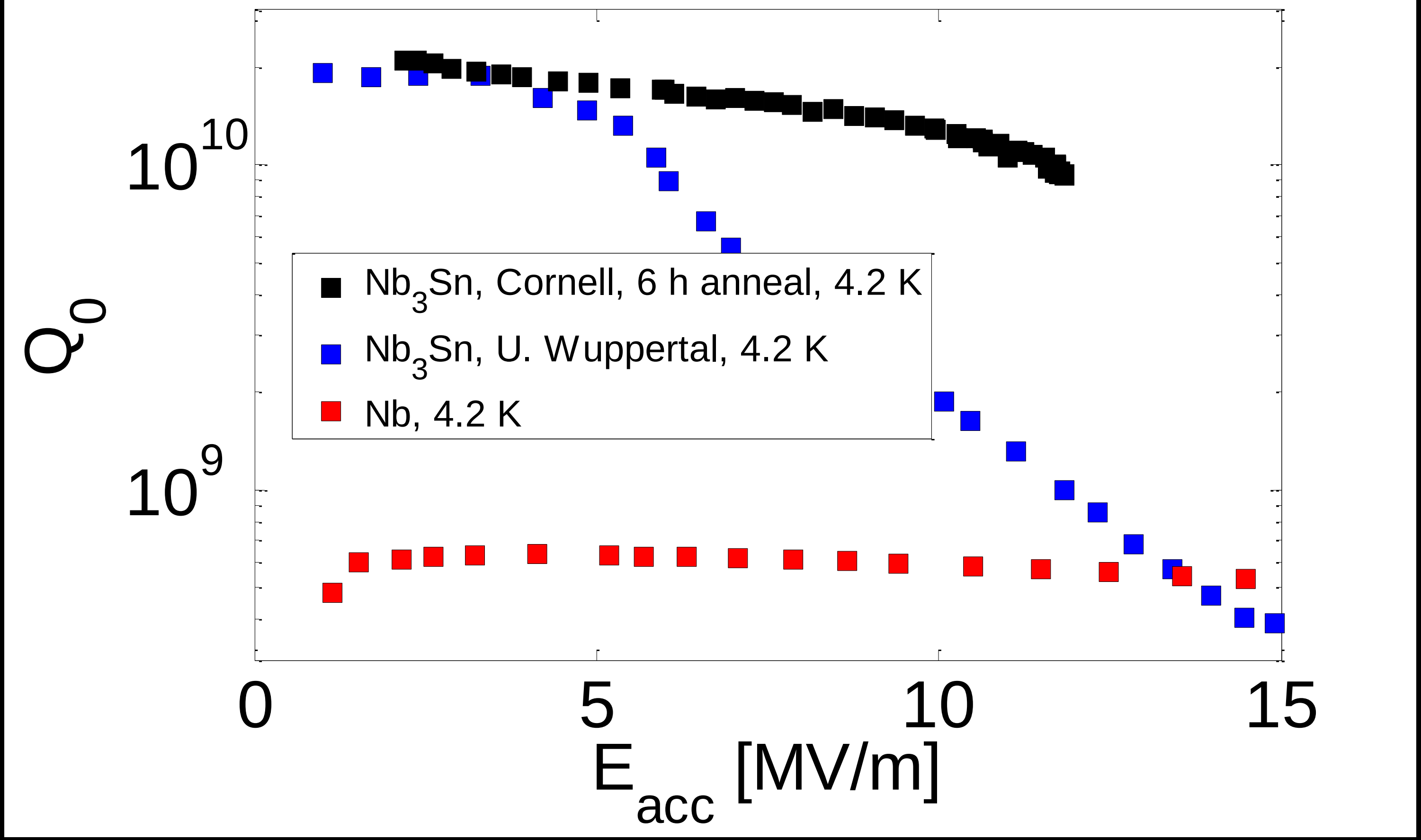
Second Cavity: 6 h Anneal

- 6 hour annealing during coating process
- No strong Q-slope observed

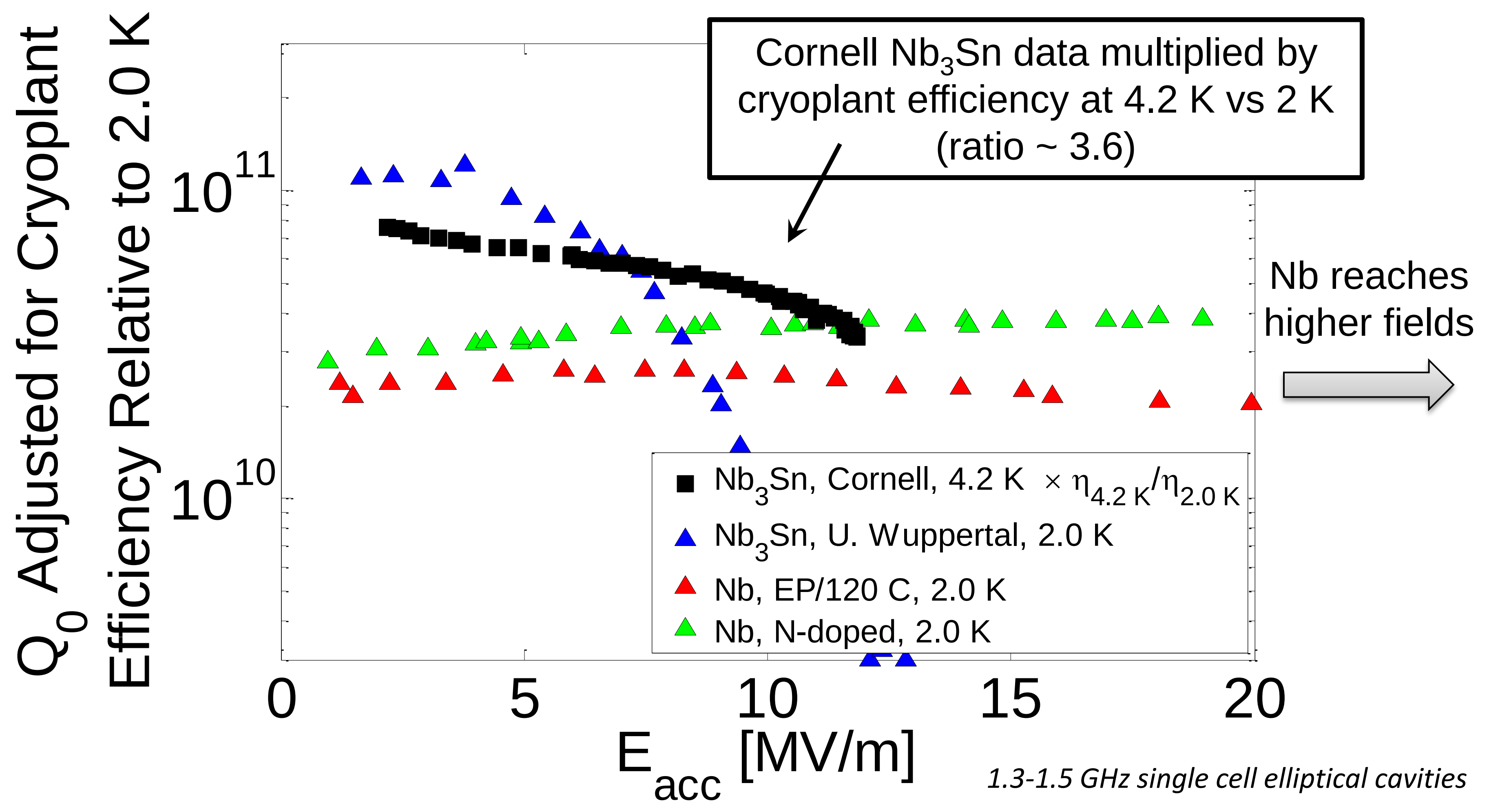


4.2 K Comparison Curves

1.3-1.5 GHz single cell elliptical cavities



2.0 K Comparison Curves



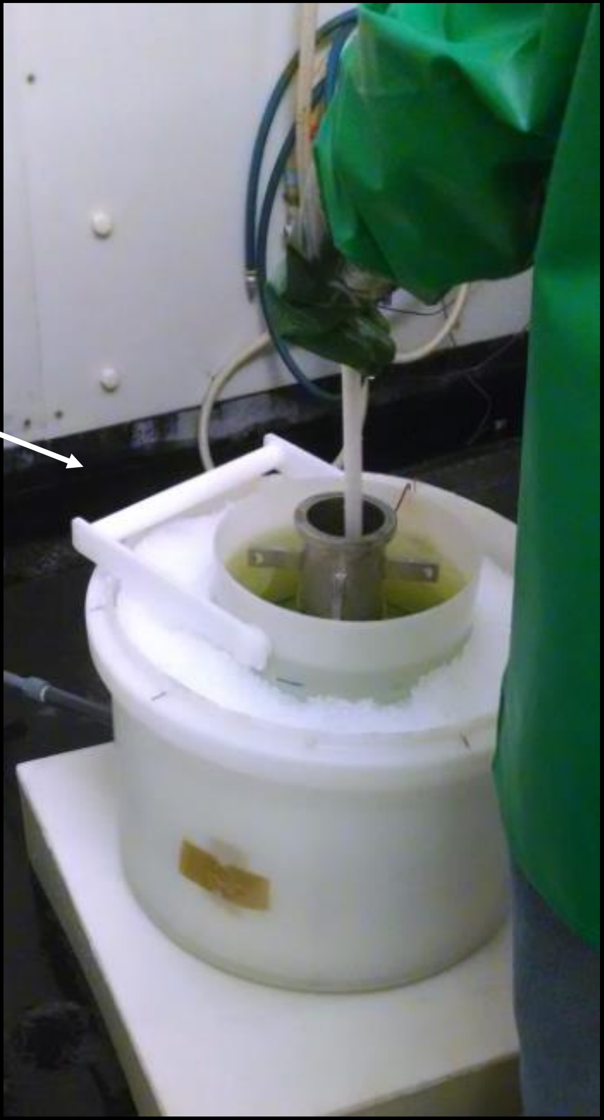
Cornell Nb_3Sn data multiplied by cryoplant efficiency at 4.2 K vs 2 K (ratio ~ 3.6)

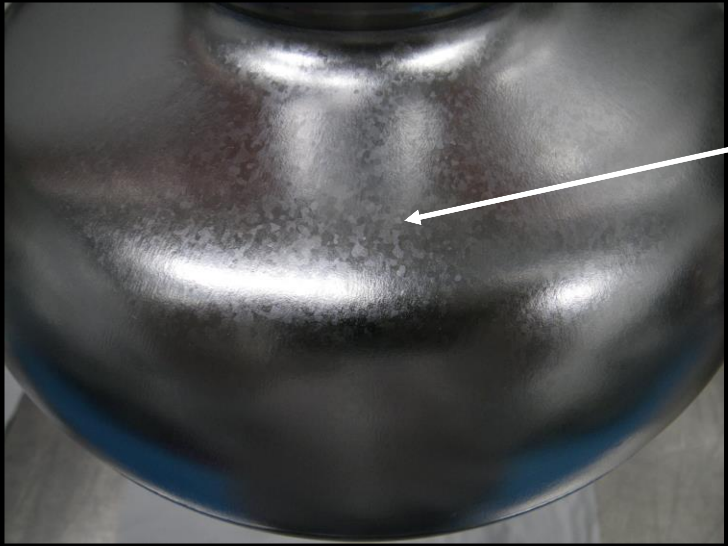
Nb reaches higher fields

1.3-1.5 GHz single cell elliptical cavities

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

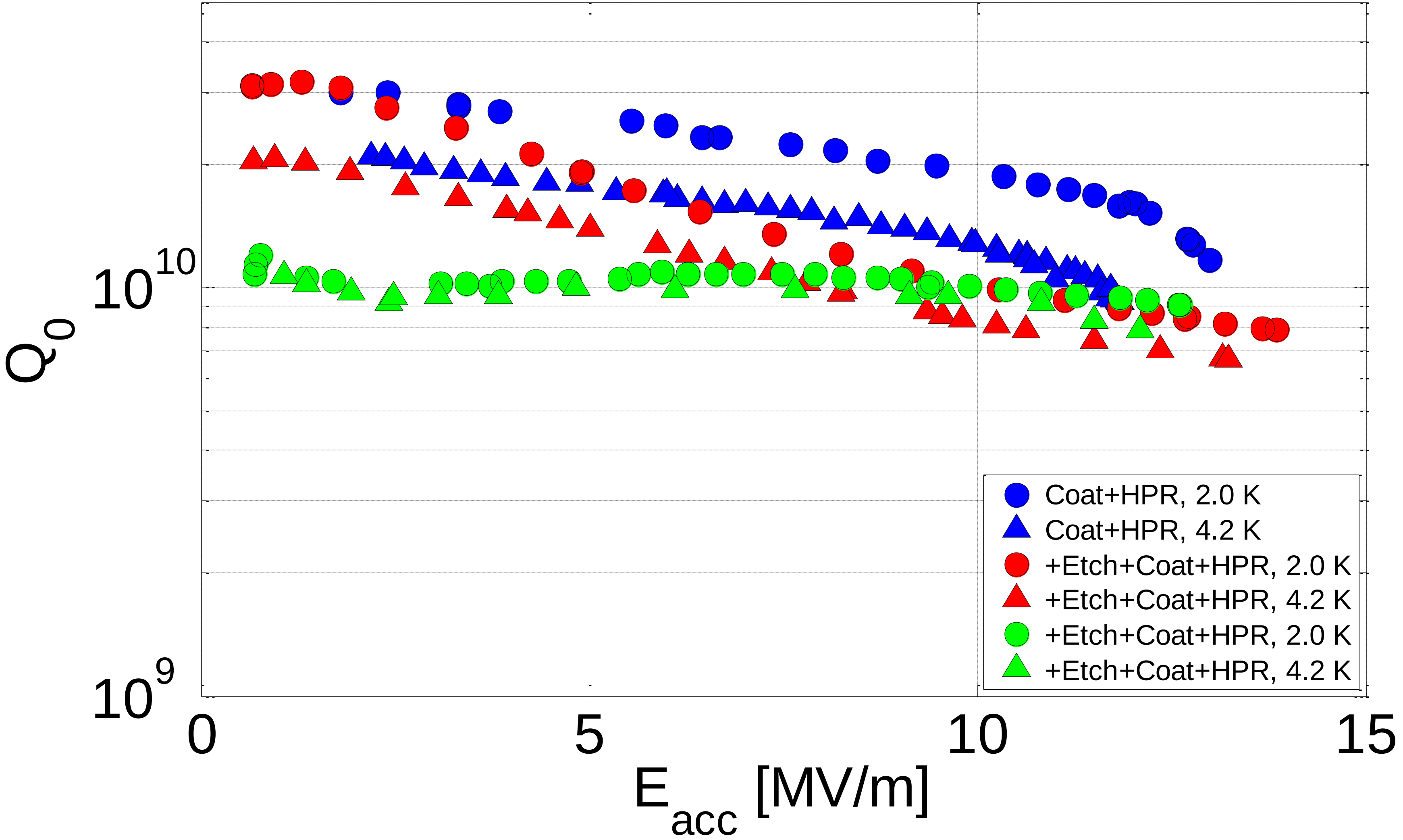




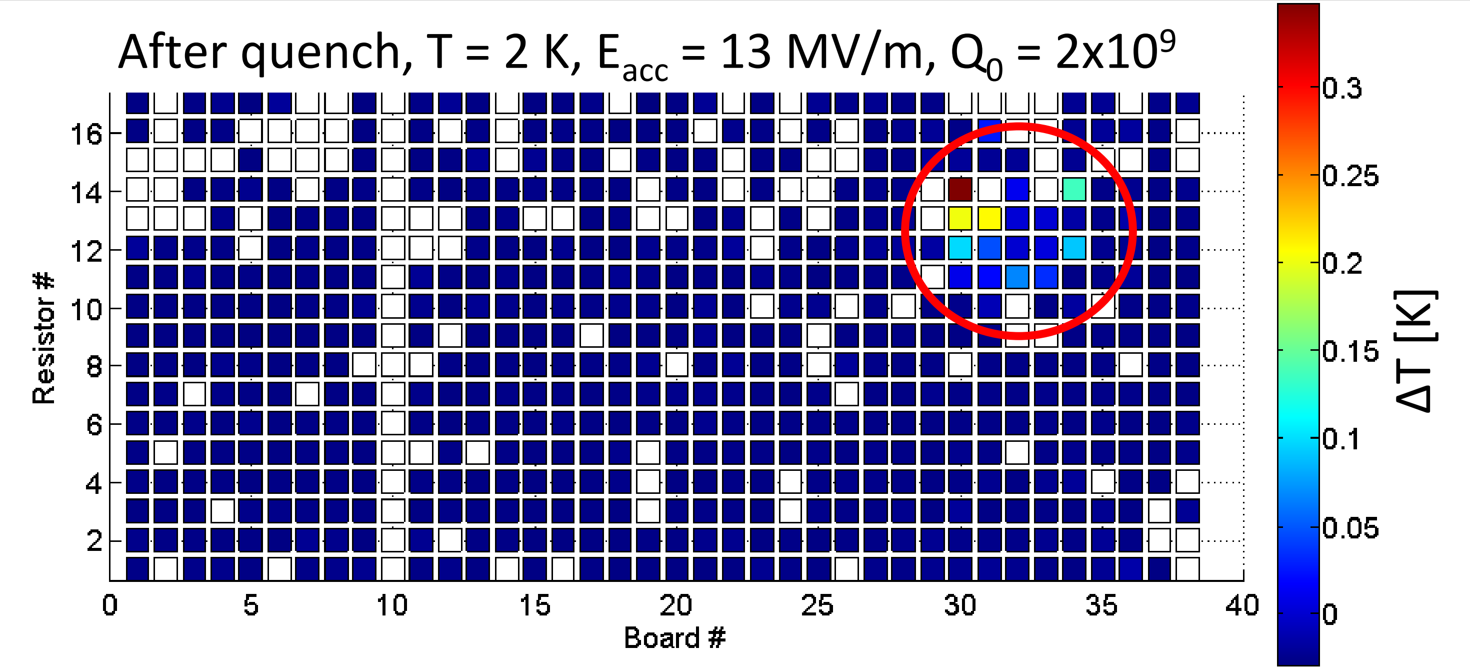
Larger niobium grains after 1100 C heat treatment

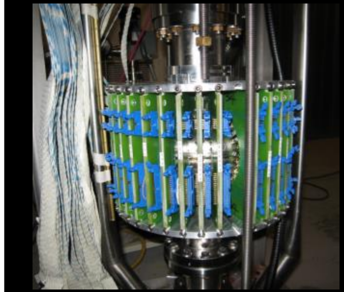
Repeatability

1.3 GHz single cell Cornell ERL shape



Field Limitation – Quench



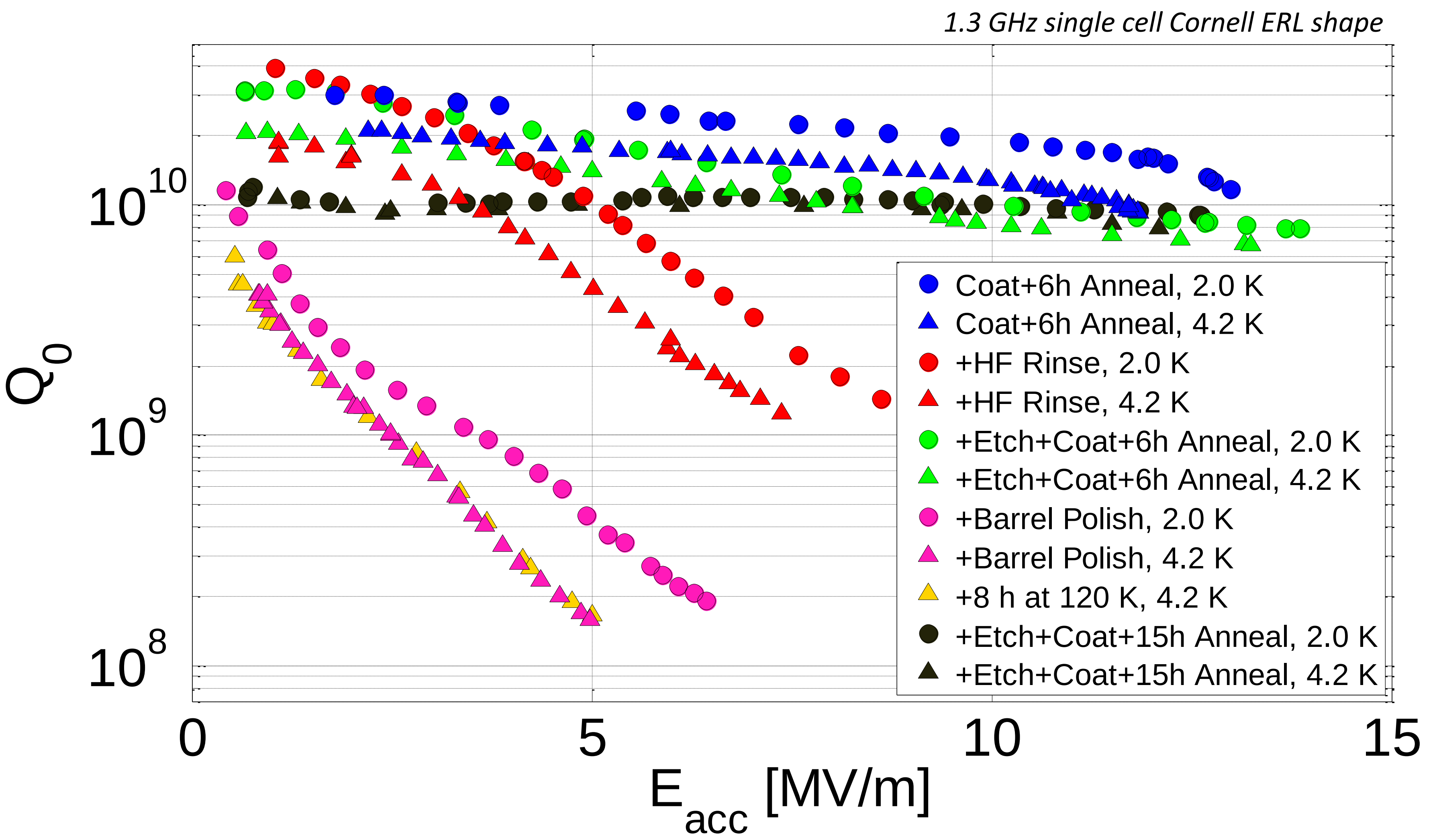


- Temperature maps show excess heating in small area in high magnetic field region – possible defect?

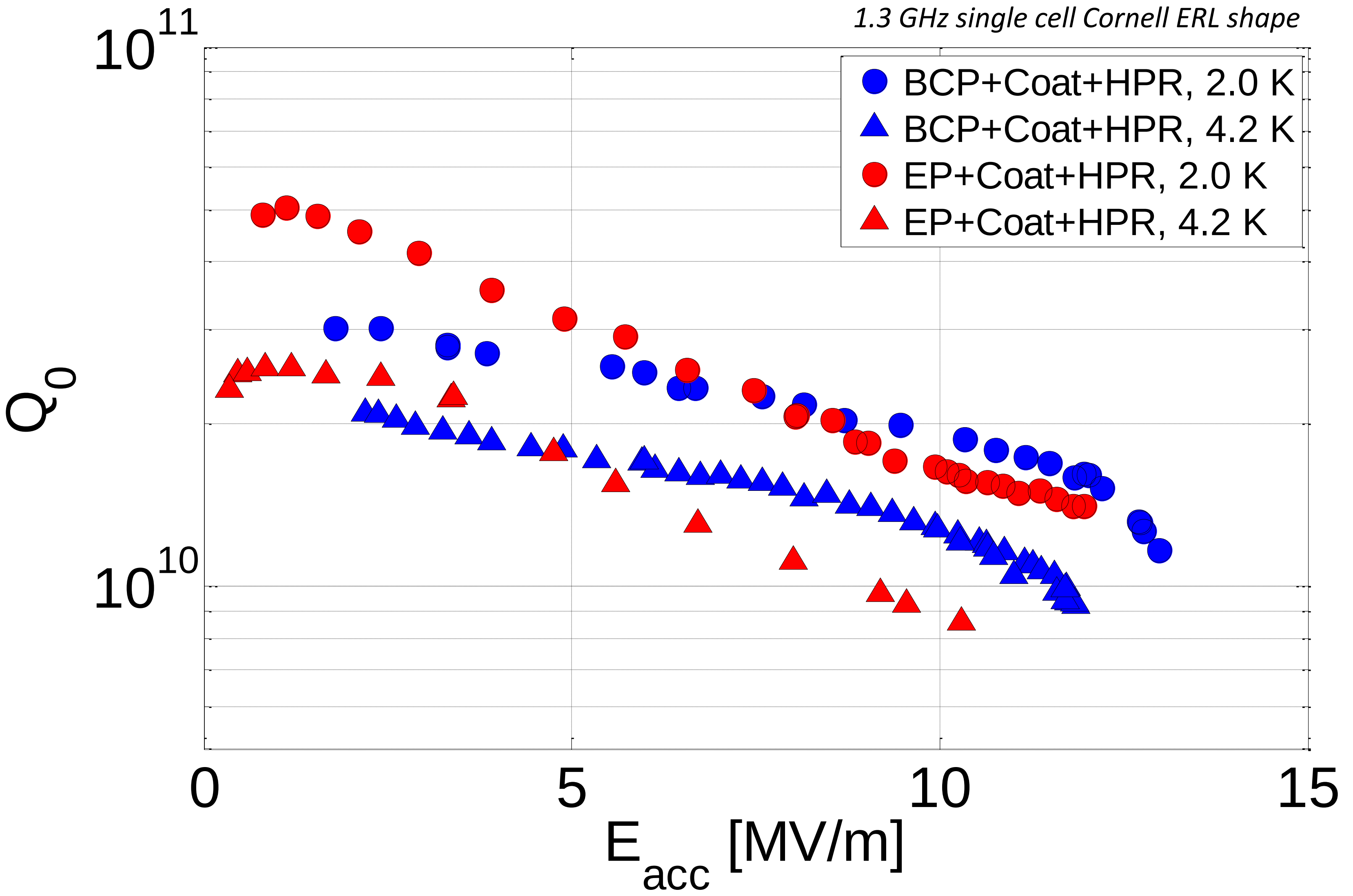
New Treatments

- Try to prevent/remove defects via:
  - – HF rinse (layer is thin, so need very light removal)
  - – Centrifugal barrel polishing (first use on Nb_3Sn)
  - – EP substrates (first use on Nb_3Sn)

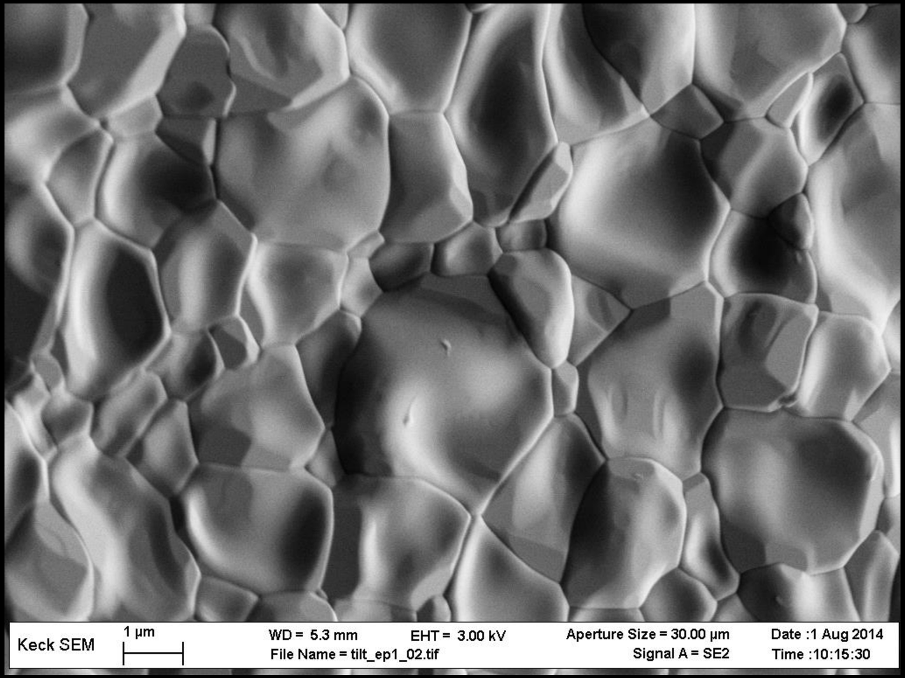
Material Removal



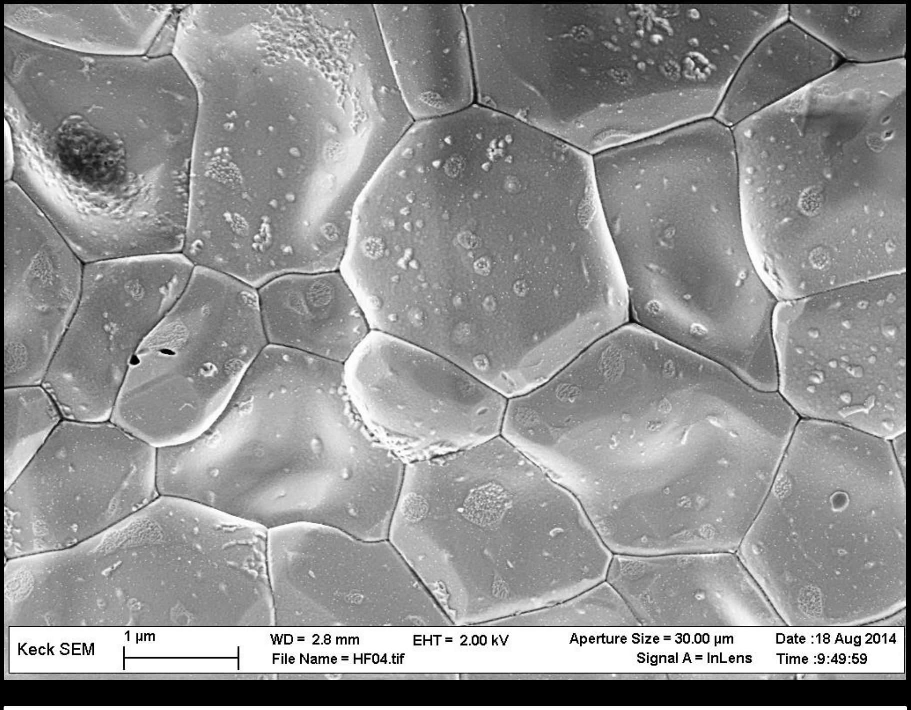
Material Removal



Developing New Understanding

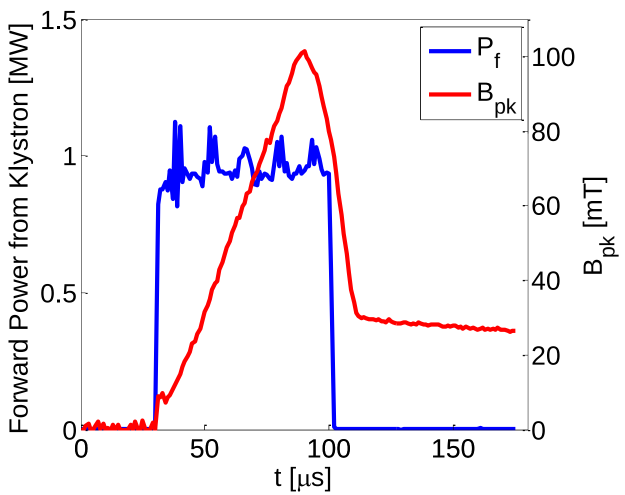


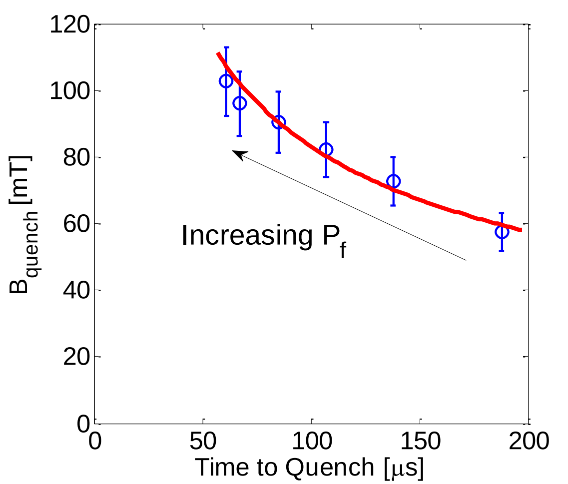
Just After Coating

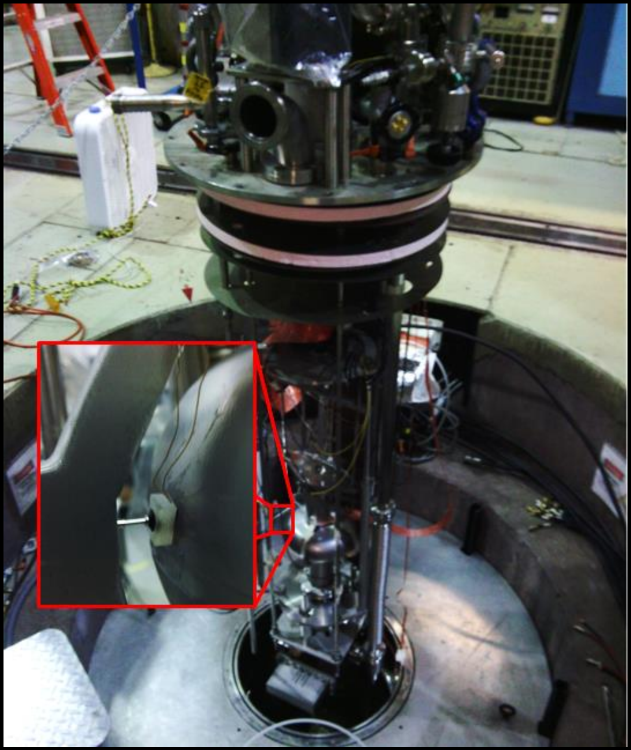


After HF Rinse

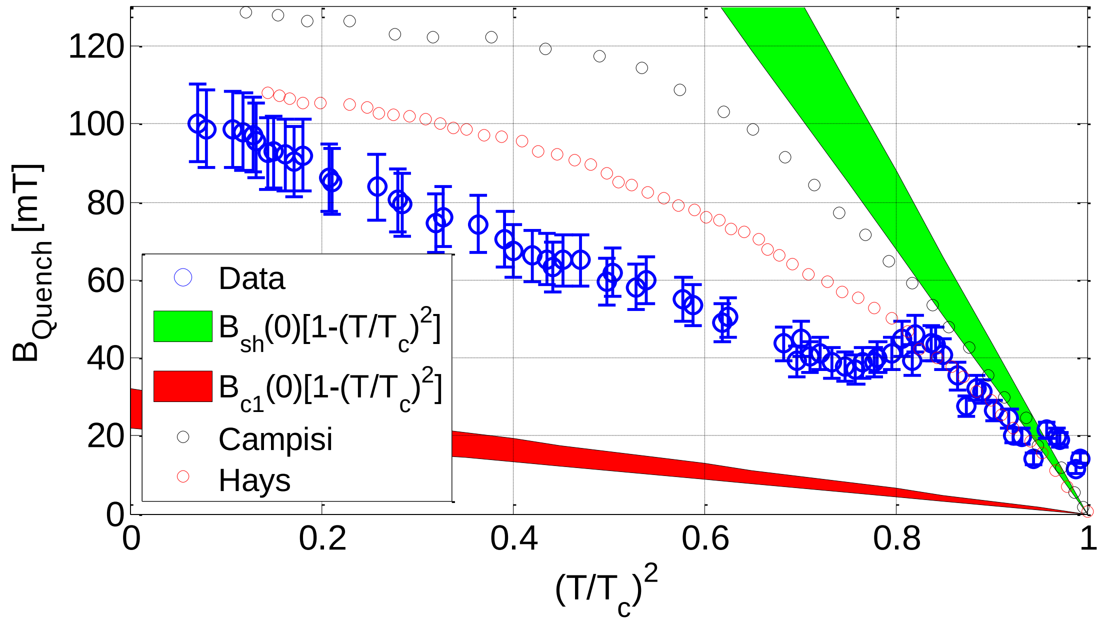
Pulsed Quench Field







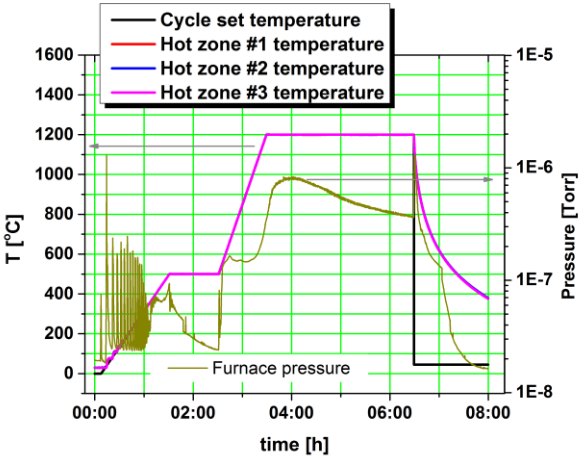
T_c = 18.0 ± 0.1 K , $B_{sh}(0)$ = 0.39 ± 0.05 T,
$B_{c1}(0)$ = 27 ± 5 mT



Nb_3Sn progress

Slides courtesy G. Eremeev, JLab

The coating system during the commissioning run.

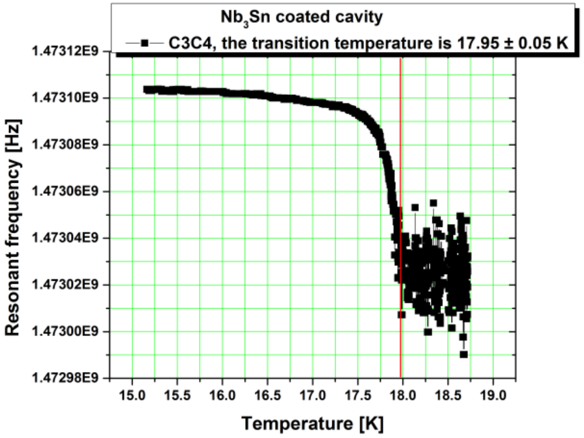


Temperature and pressure profile during coating system commissioning run. The furnace pressure is in 1E-7 Torr range and the temperature deviation is <1 °C at 1200 °C.

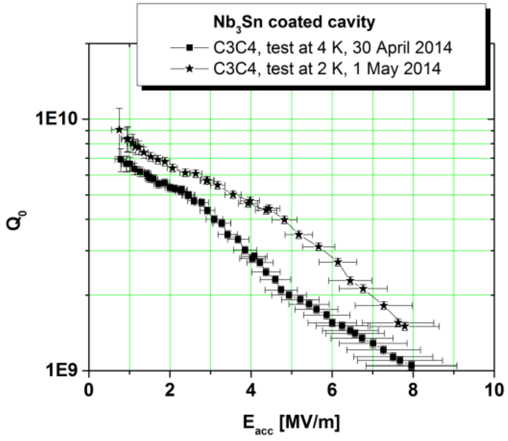
- The R&D furnace for Nb_3Sn development has been delivered and commissioned empty in November 2013.
- The Nb_3Sn insert has been converted from horizontal to vertical orientation, loaded with a CEBAF-shape 1-cell cavity (C3C4), Sn, and $SnCl_2$, and installed into the new furnace. The commissioning run was done in “Siemens” configuration at temperatures of interest in March 2013.
- The coating system is planned to be commissioned with separate heating and cooling of Tin crucible, “Wuppertal” configuration.

Nb_3Sn progress

Slides courtesy G. Eremeev, JLab



The resonant frequency as a function of temperature during cooldown. Data indicate the transition temperature of about 18 K.



Quality factor of the Nb_3Sn coated C3C4 as a function of field at 4 K and 2 K.

- The single cell (C3C4) was found to have complete coating without any droplets on the RF surface.
- The cavity went through the standard preparation procedure for RF testing, i.e., degreasing, HPR, etc., evacuated, and tested at 4 and 2 K.
- The cavity had the transition temperature of about 18 K. The low field Q_0 was 7E9 at 4 K and 9E9 at 2 K. The cavity exhibited strong Q-slope dropping to about 1E9 at 8 MV/m at both temperatures.

Summary and Outlook

- Alternative materials can benefit future SRF linacs
  - Nb easy to work with, but reaching fundamental limits
  - Nb_3Sn very promising – order of magnitude more efficient, twice energy gain per length
- New research: significant Nb_3Sn performance improvement
  - Strong Q-slope suppressed after extra annealing step
  - High Q_0 at useful fields, T = 4.2 K
  - First cavity to outperform niobium
- With continued R&D can surpass limitations
  - Fundamental studies for better understanding
  - Modern cavity treatments never used on Nb_3Sn

Acknowledgements

- My advisor Matthias Liepe
- Fellow Cornell graduate students
- Collaborators