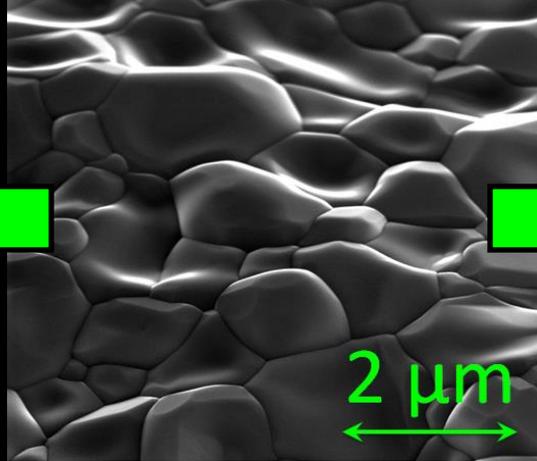
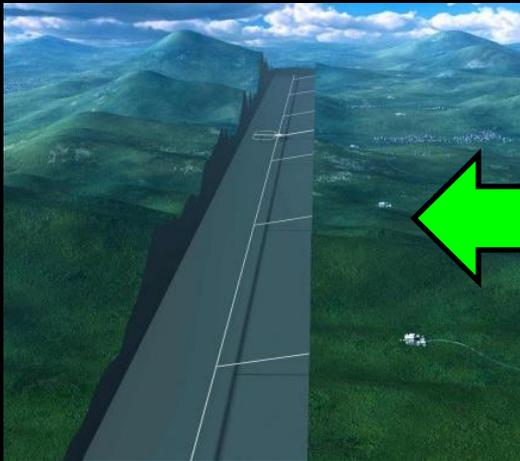




Nb₃Sn – Present Status and Potential as an Alternative SRF Material



S. Posen and M. Liepe, Cornell University

LINAC 2014 – Geneva, Switzerland – September 2, 2014



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



	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



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	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 Nb₃Sn

Increase in Q₀
via N-doping

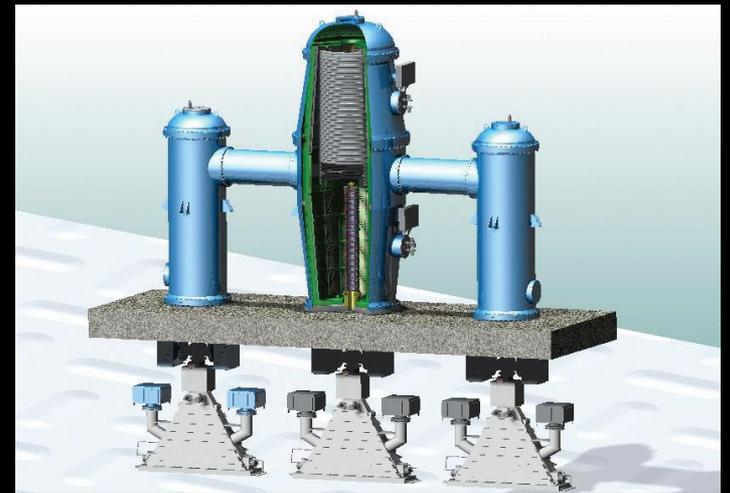
$\eta_{4.2\text{ K}} / \eta_{2.0\text{ K}} \approx 3.6$,
simpler cryoplant

	Niobium	Nb ₃ Sn
Critical Temperature T _c	9 K	18 K
Q ₀ at 4.2 K	6 x 10 ⁸	6 x 10¹⁰
Q ₀ at 2.0 K	3 x 10¹⁰ 4-8 x 10 ¹⁰	>10 ¹¹
Max. gradient E _{acc} (theory)	50 MV/m	100 MV/m

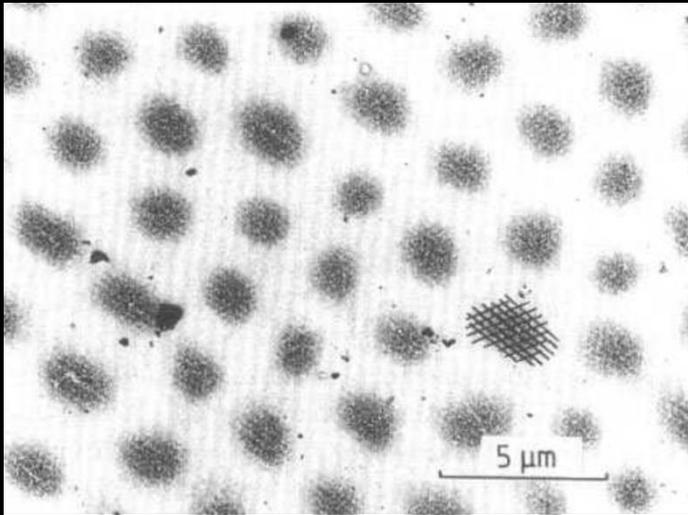
Approximate E_{acc} and Q₀ given for 1.3 GHz TeSLA or 1.5 GHz CEBAF cavities with R_{res} small

Halve # of
cavities to
reach energy?

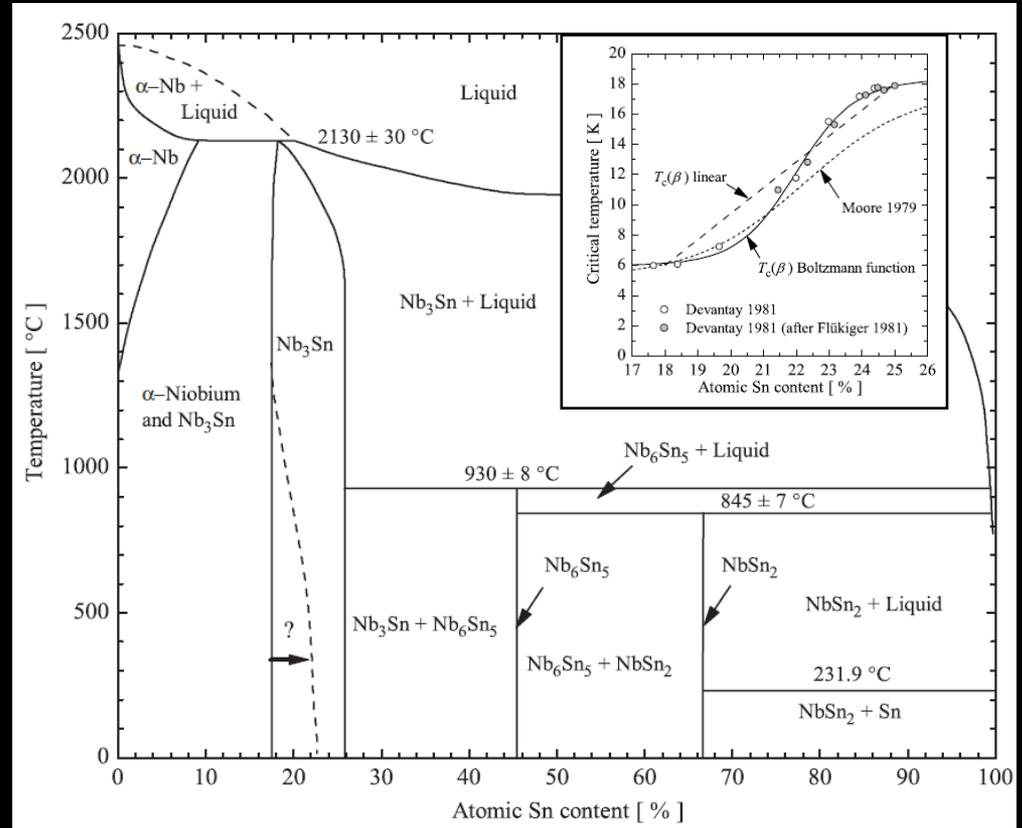
- For lower-energy **industrial applications**, it may not be cost-effective to have a supply of 2 K LHe
- Higher T_c of Nb_3Sn allows low-loss operation with atmospheric 4.2 K LHe, or even gas/supercritical He
- Flue gas, waste water treatment, isotope production, security



Images from S. Sabharwal, NA-PAC13



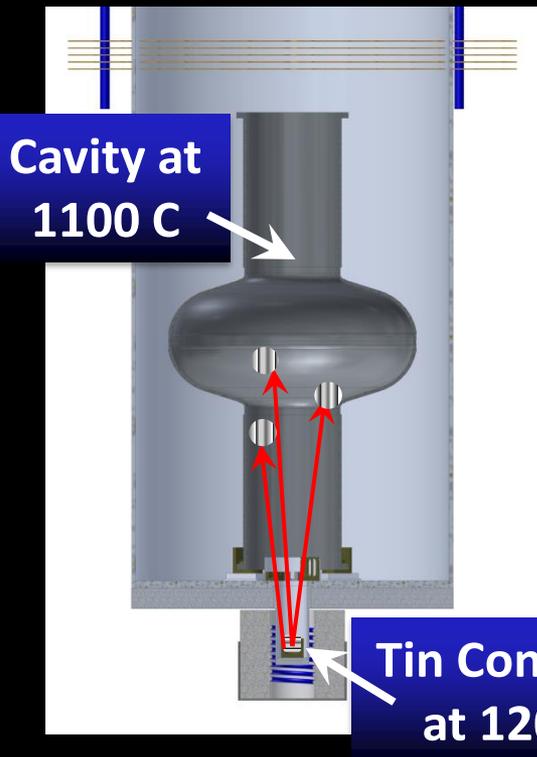
Flux lattice in a Type II Superconductor
E.H. Brandt, Rep. Prog. Phys. 58 (1995)



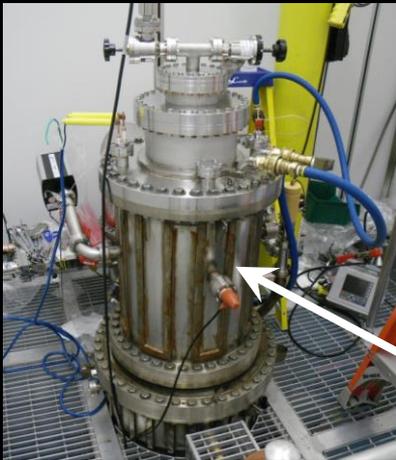
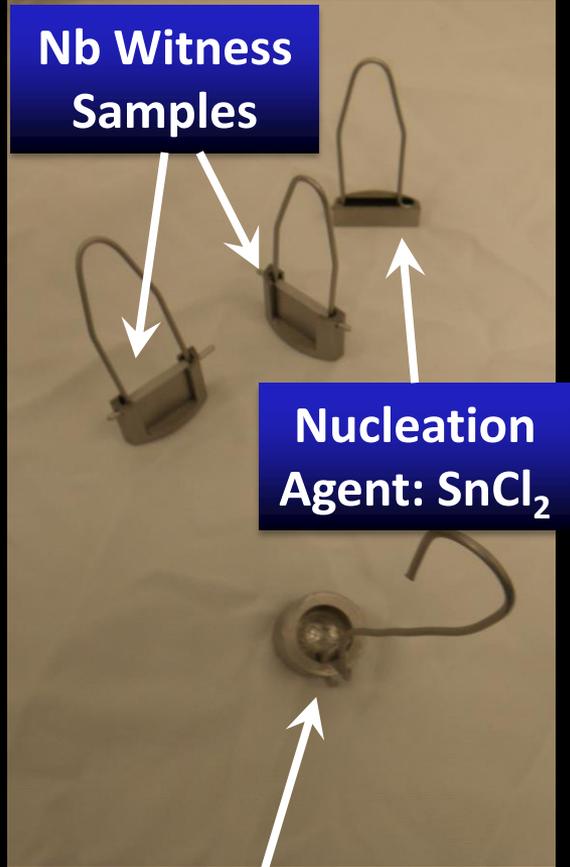
Nb₃Sn Phase Diagram
A. Godeke, Supercond. Sci. Tech, 2006



Cornell Coating Chamber

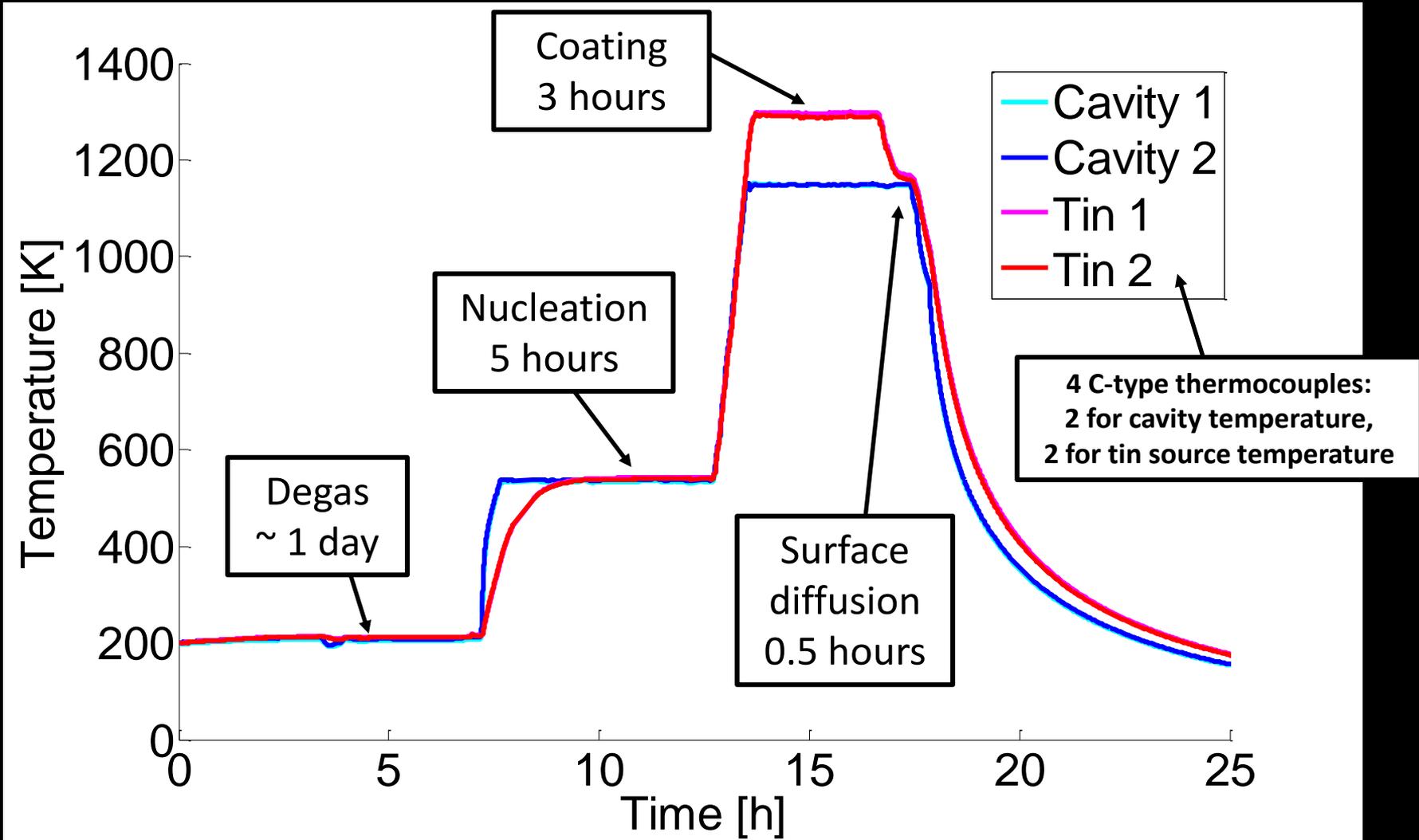


Copper transition weld from stainless to Nb





Coating Procedure



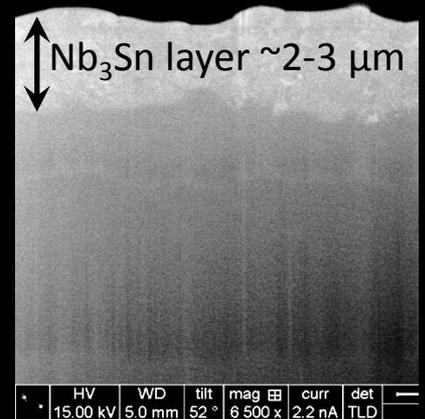
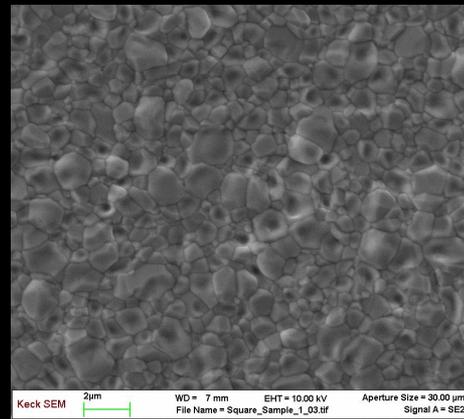
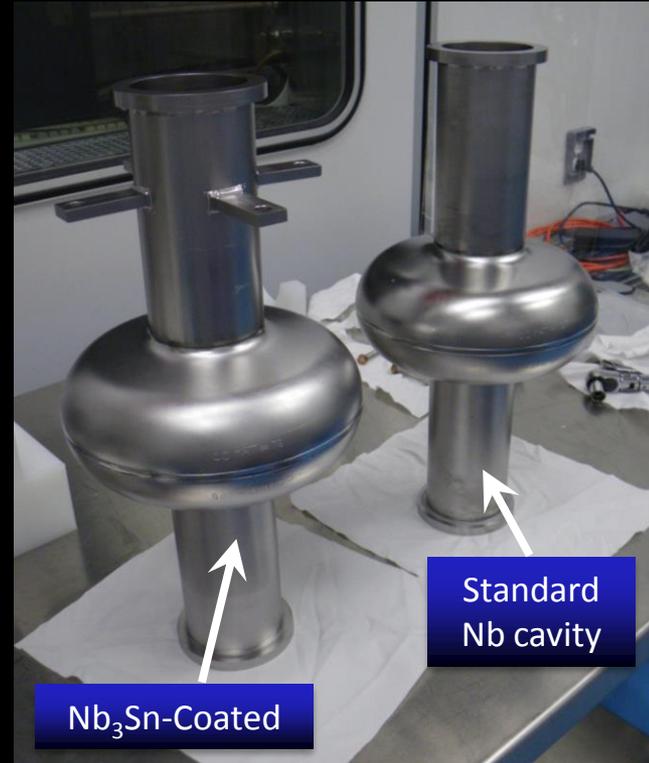
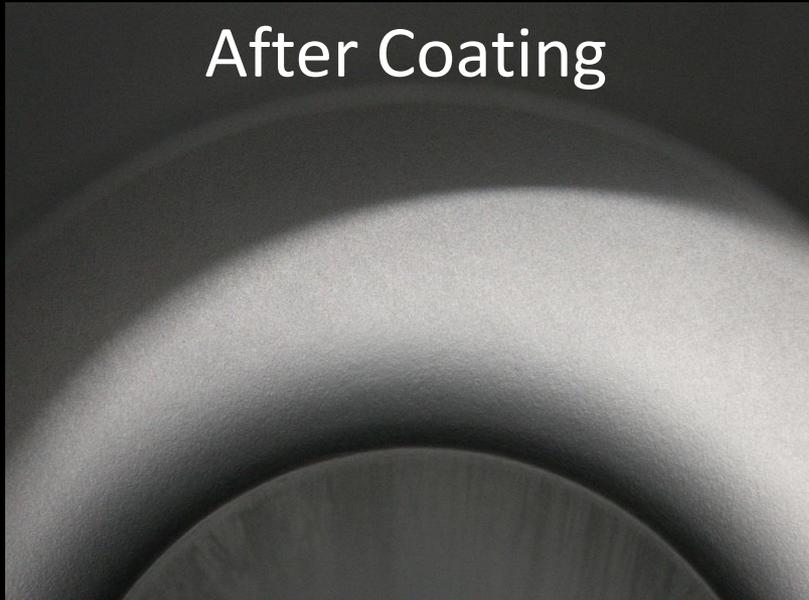


Coated Cavity

Before Coating



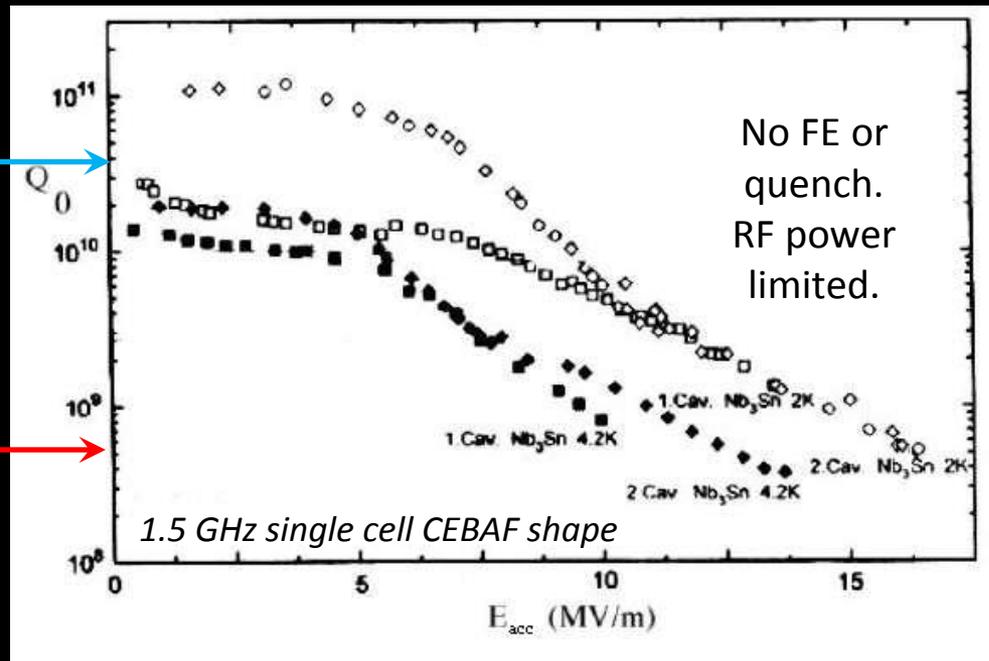
After Coating



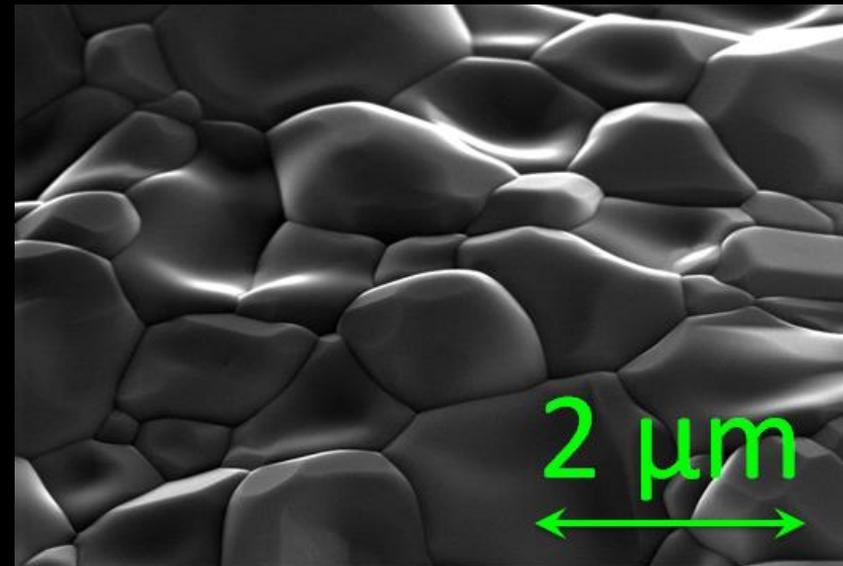
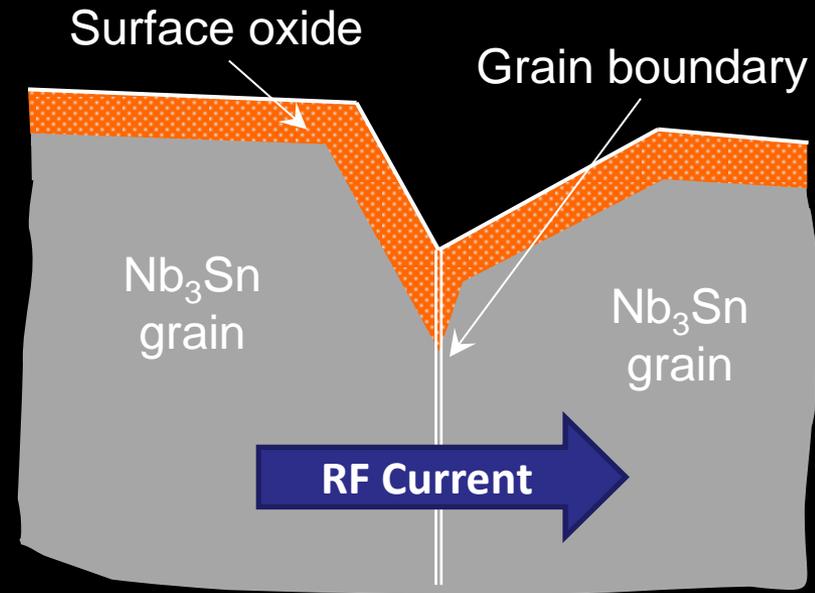
- Pioneering work at Siemens AG, U. Wuppertal, K.F. Karlsruhe, SLAC, Cornell U., Jefferson Lab, and CERN
- U. Wuppertal:
 - Very small R_s values in Nb₃Sn cavities
 - Strong Q-slope, cause uncertain

Nb at 2.0 K

Nb at 4.2 K



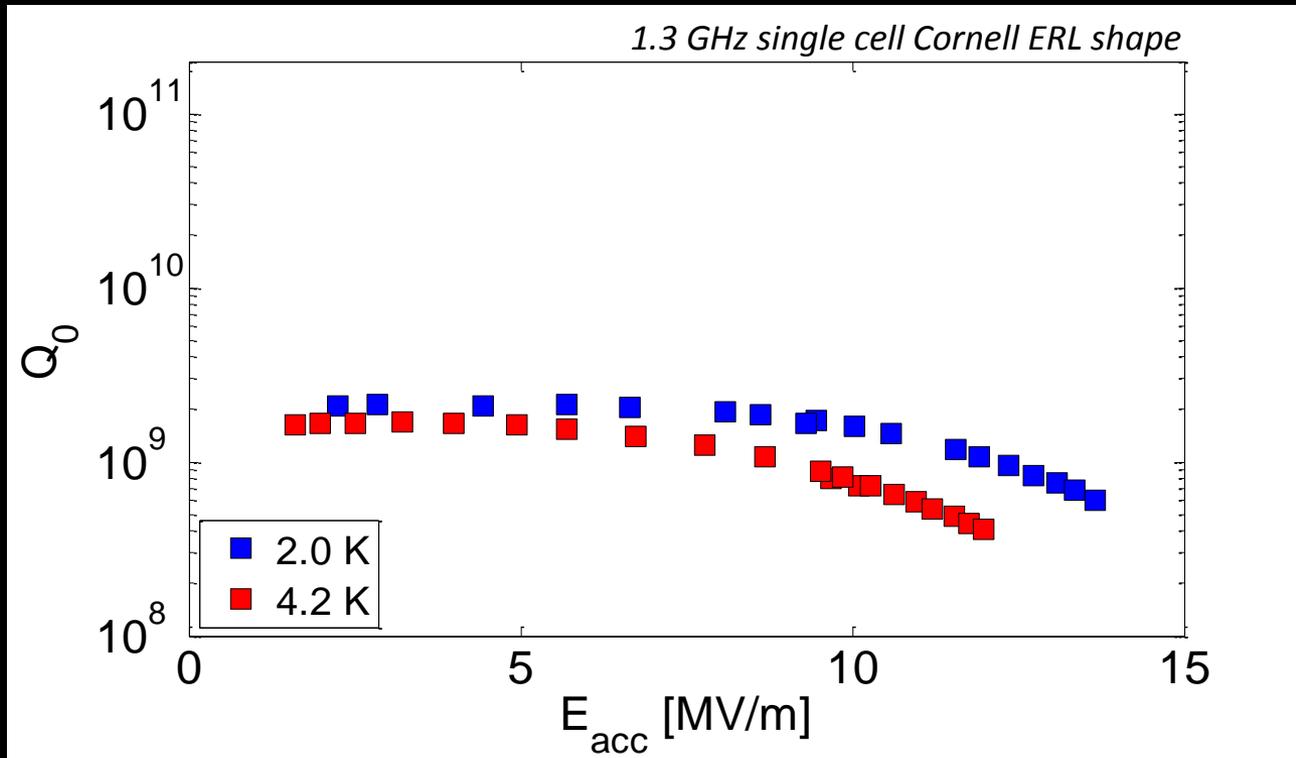
- Losses in material between crystal grains
- Performance similar in appearance to Nb/Cu
- Systematic study on small samples: strong effect from grain size
- Preliminary annealing attempts on cavities gave poor results



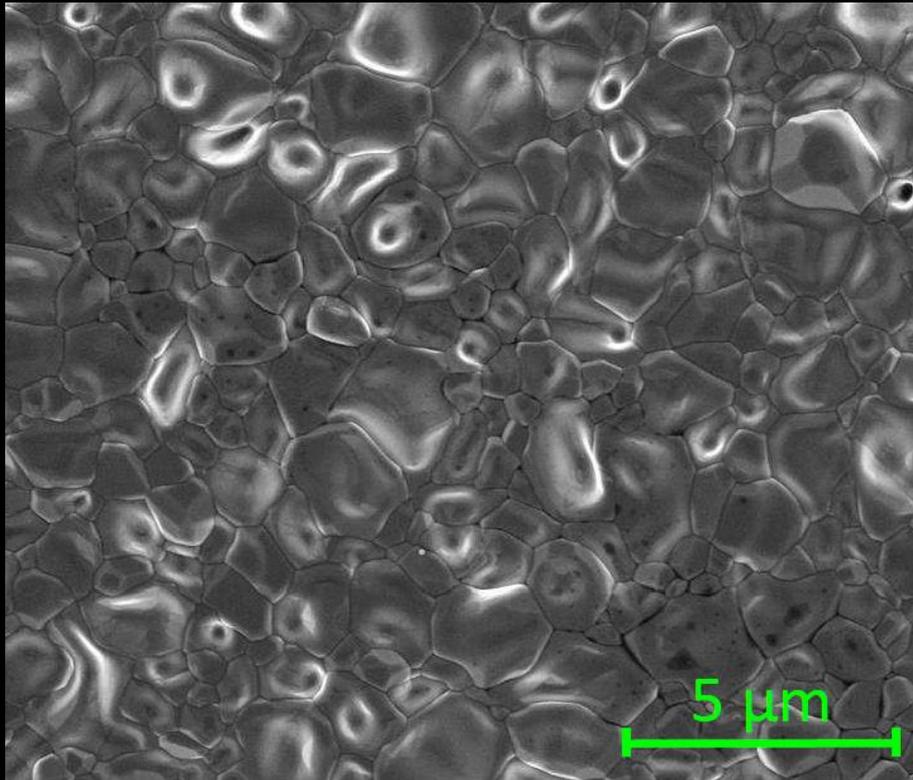
Images adapted from T. Proslie et al., NuFact09 and M. Hein et al., IEEE Trans. Supercond., 2001



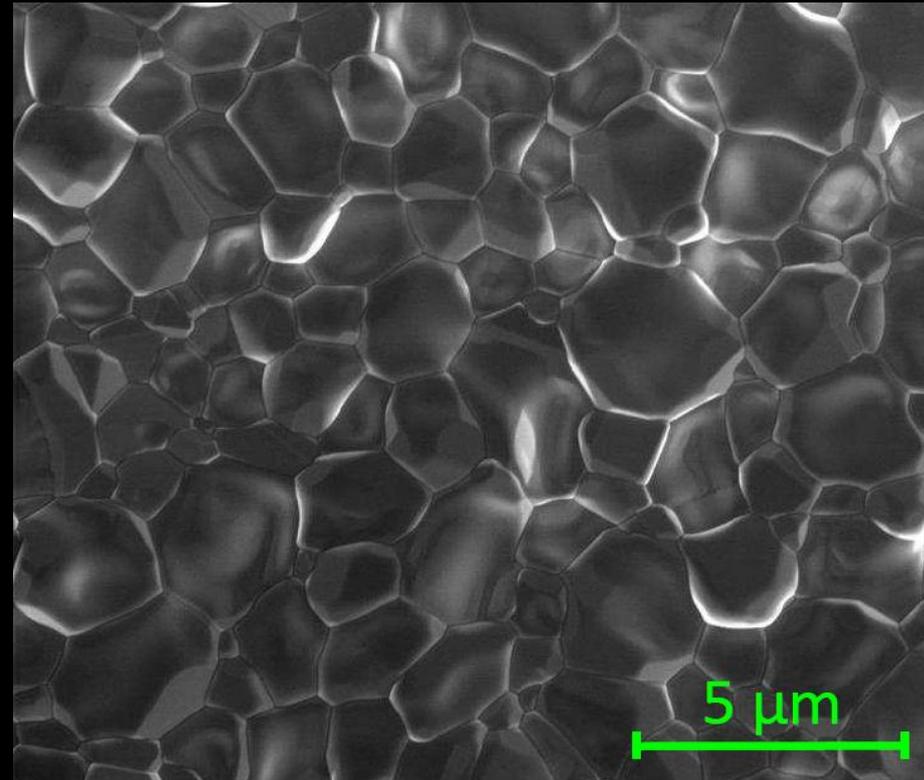
- First cavity: Wuppertal recipe
- Strong Q-slope observed similar to Wuppertal



- 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



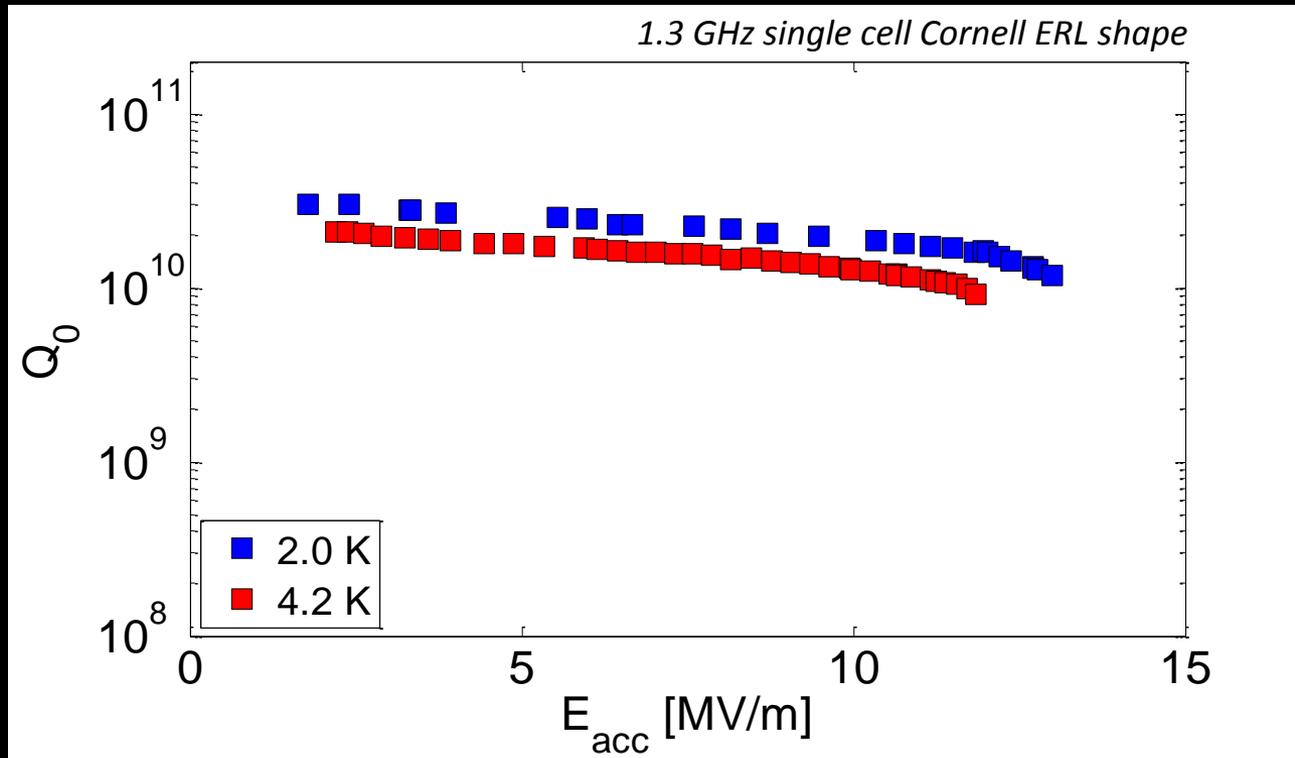
No annealing step, average grain size $\sim 1 \mu\text{m}$

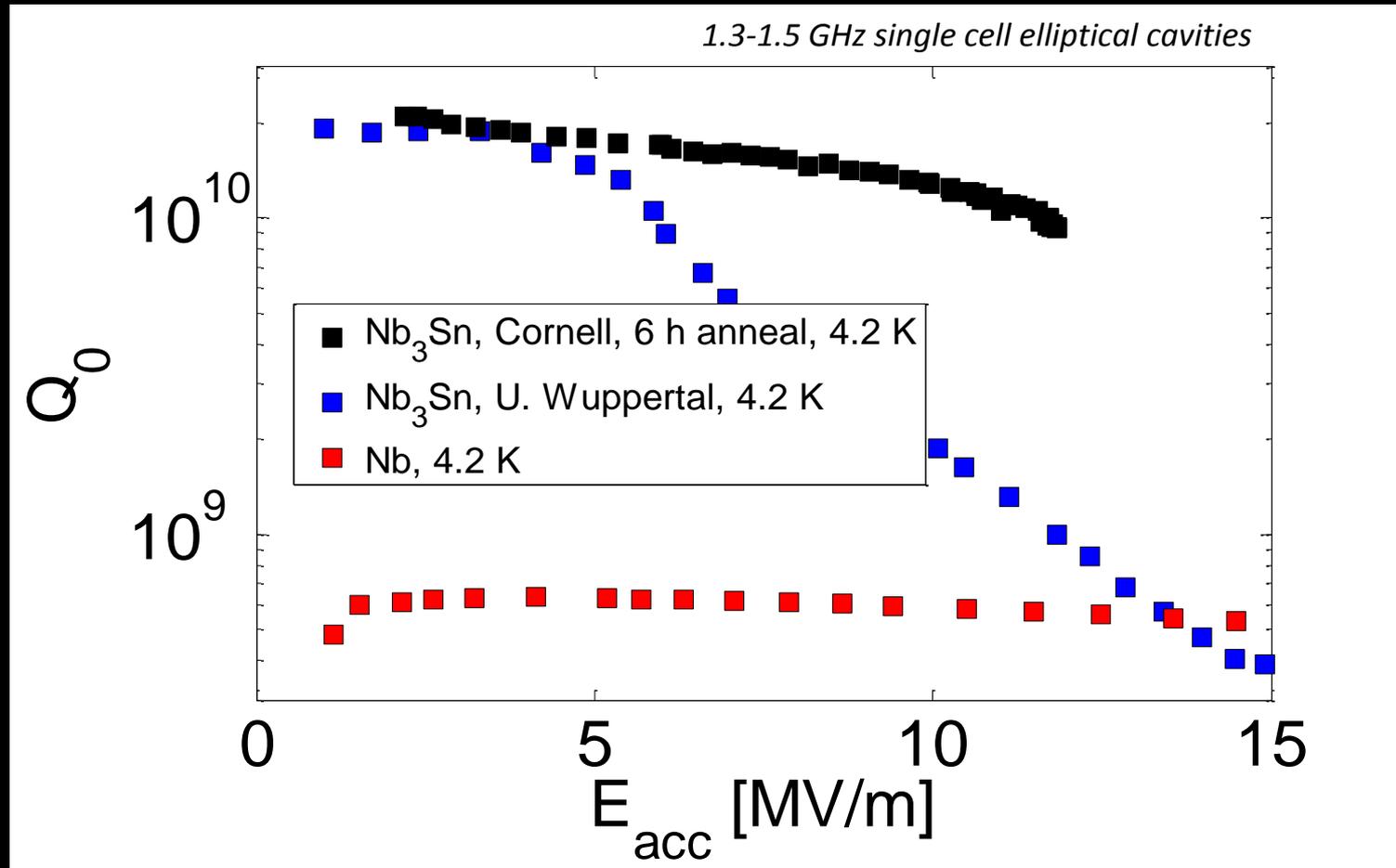


Anneal 6 hours, average grain size $\sim 2 \mu\text{m}$



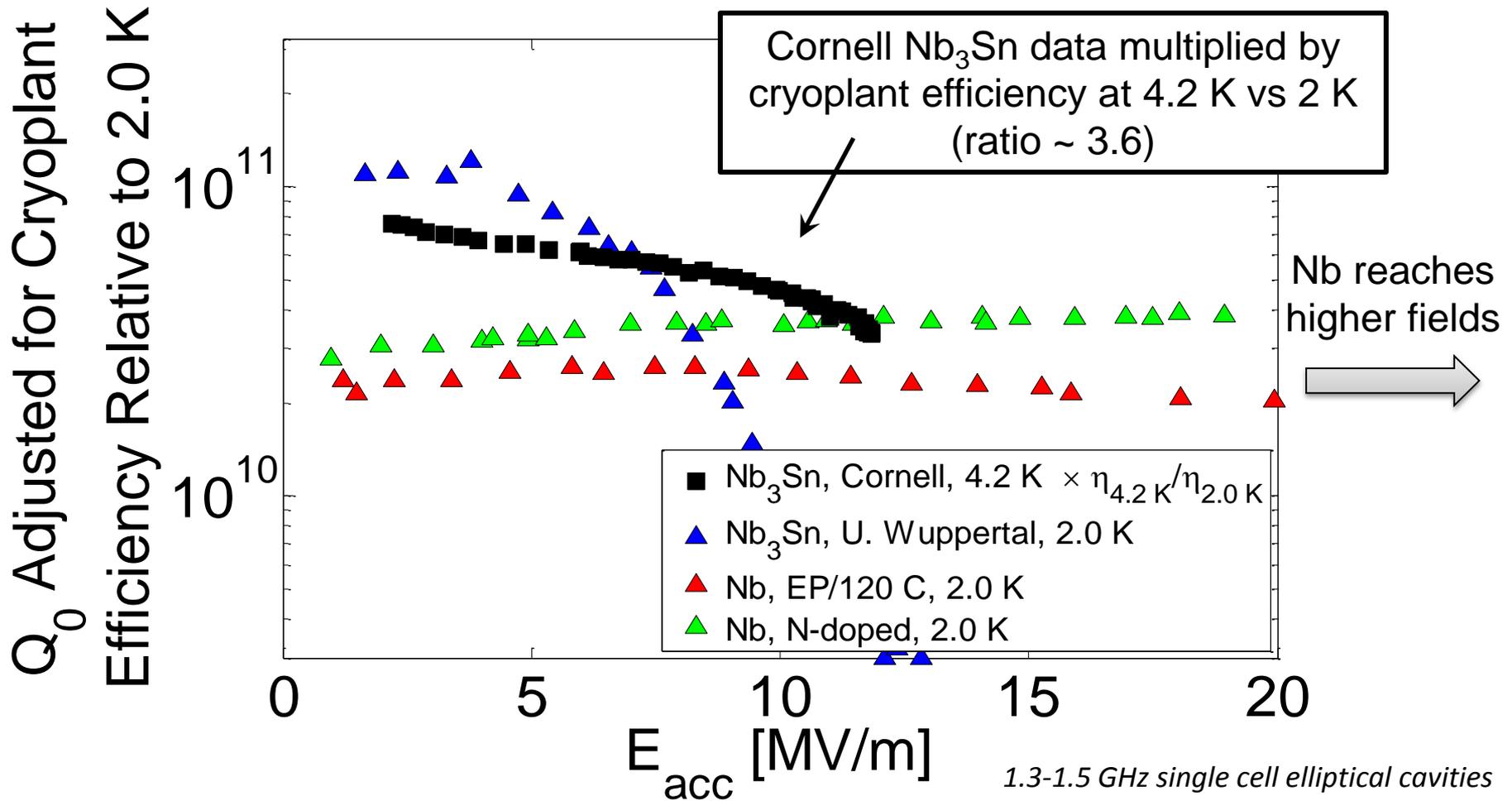
- 6 hour annealing during coating process
- No strong Q-slope observed



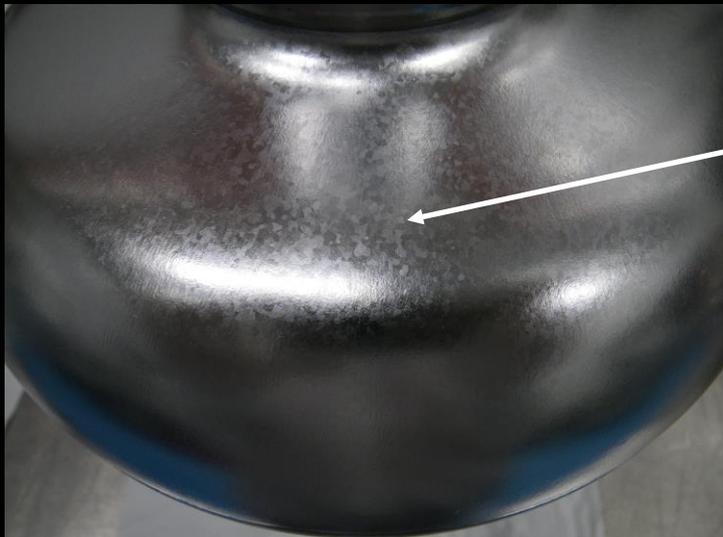




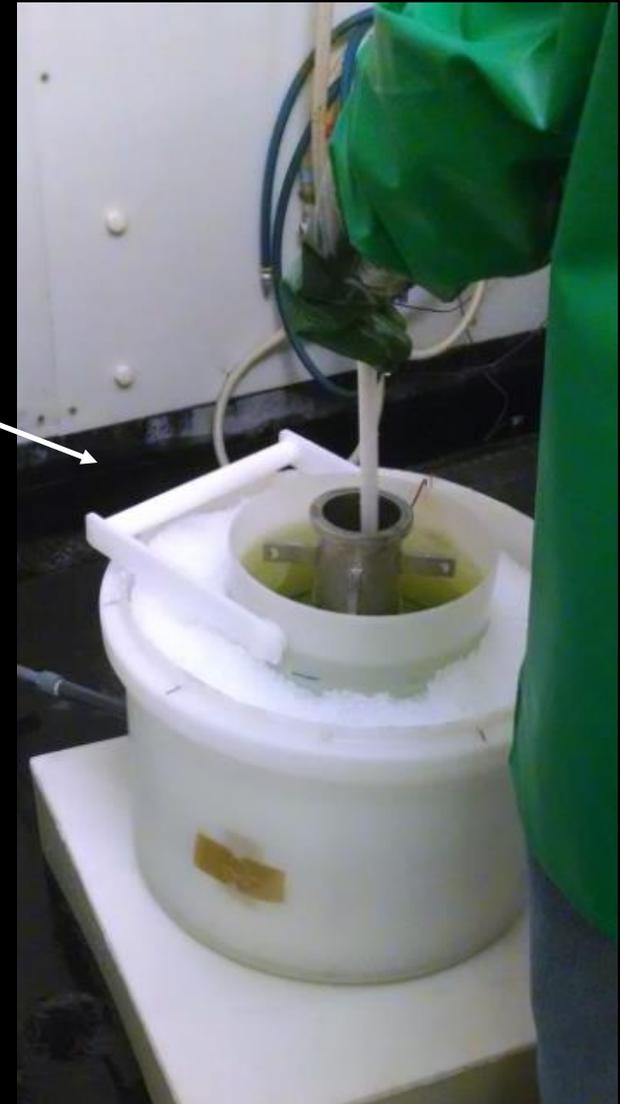
2.0 K Comparison Curves



- 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



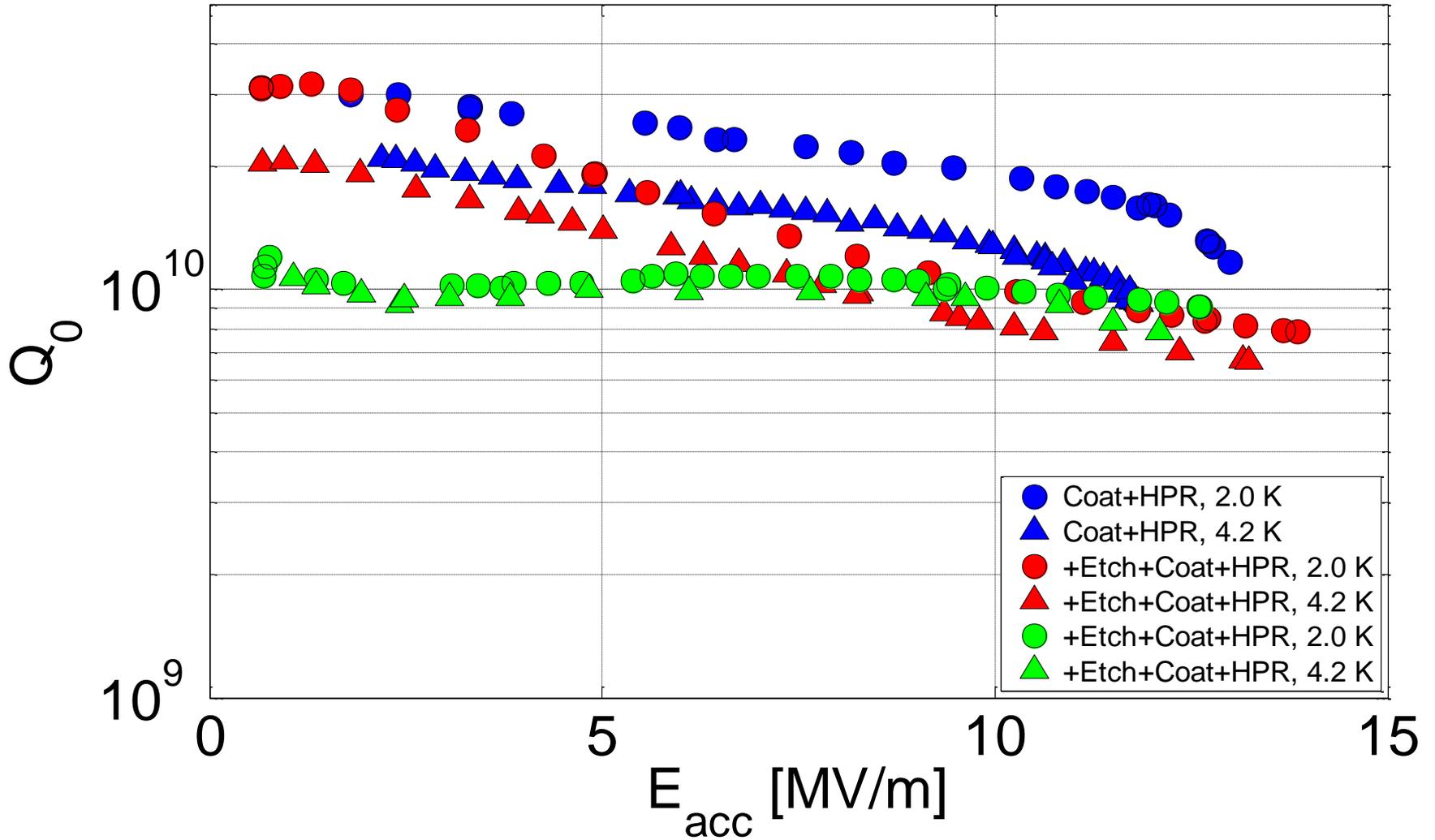
Larger niobium grains after 1100 C heat treatment

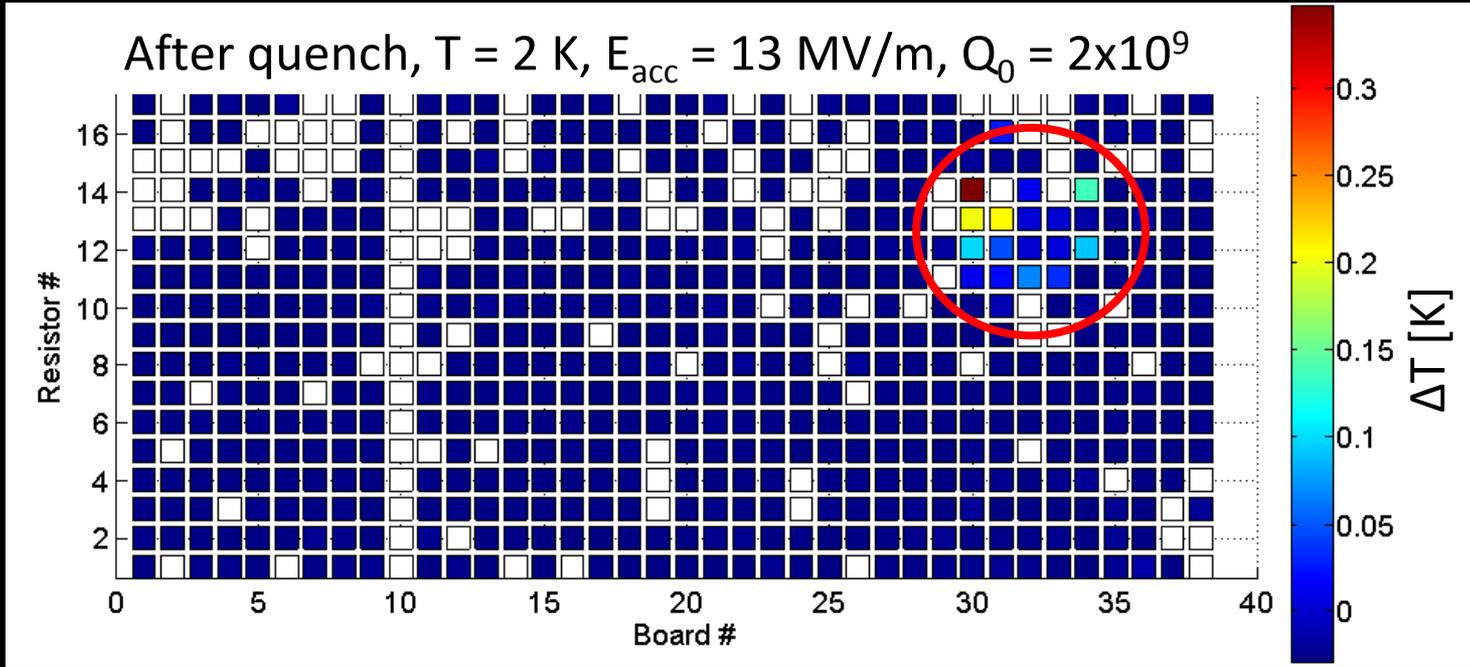




Repeatability

1.3 GHz single cell Cornell ERL shape





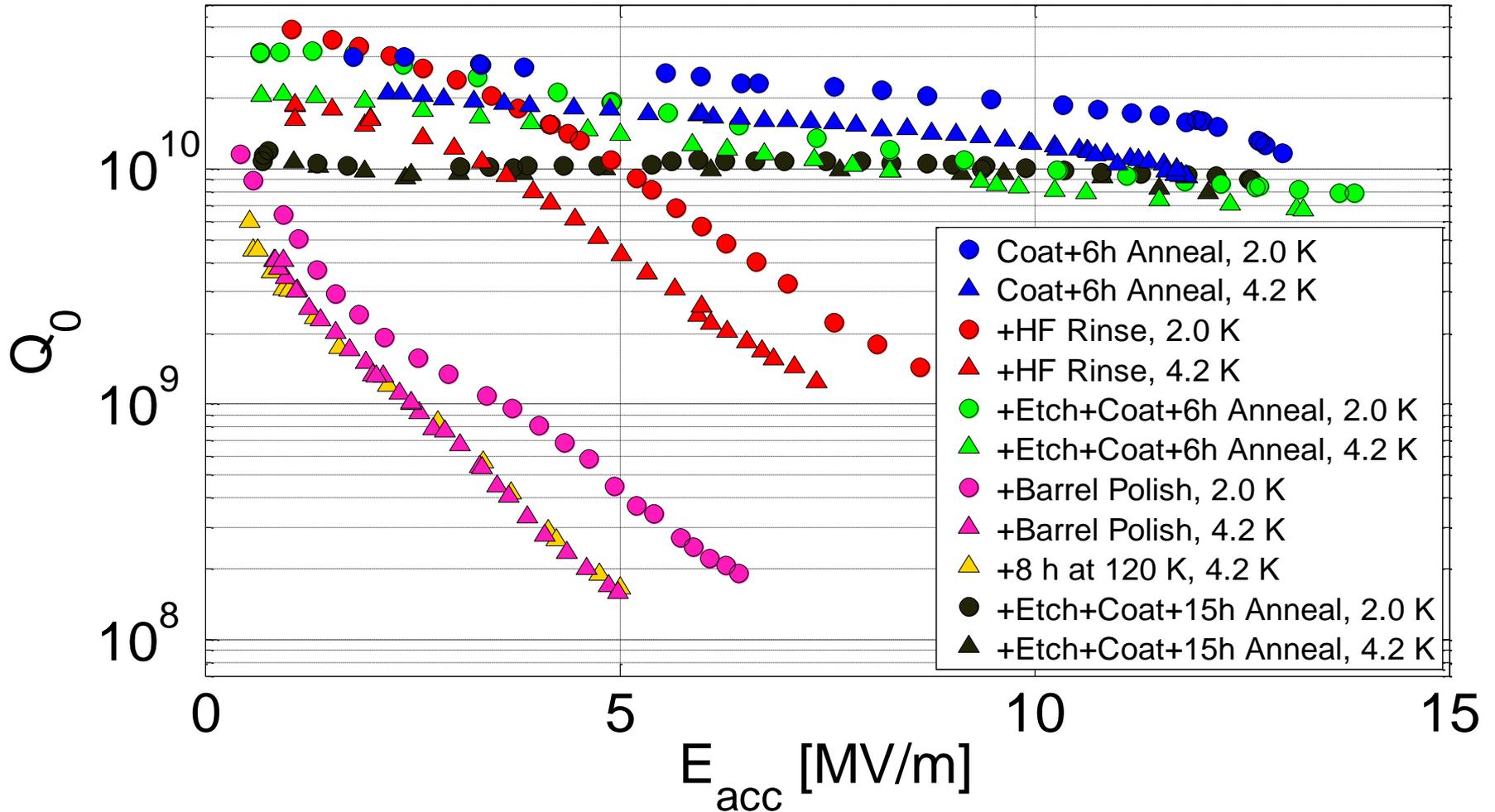
- Temperature maps show excess heating in small area in high magnetic field region – possible defect?

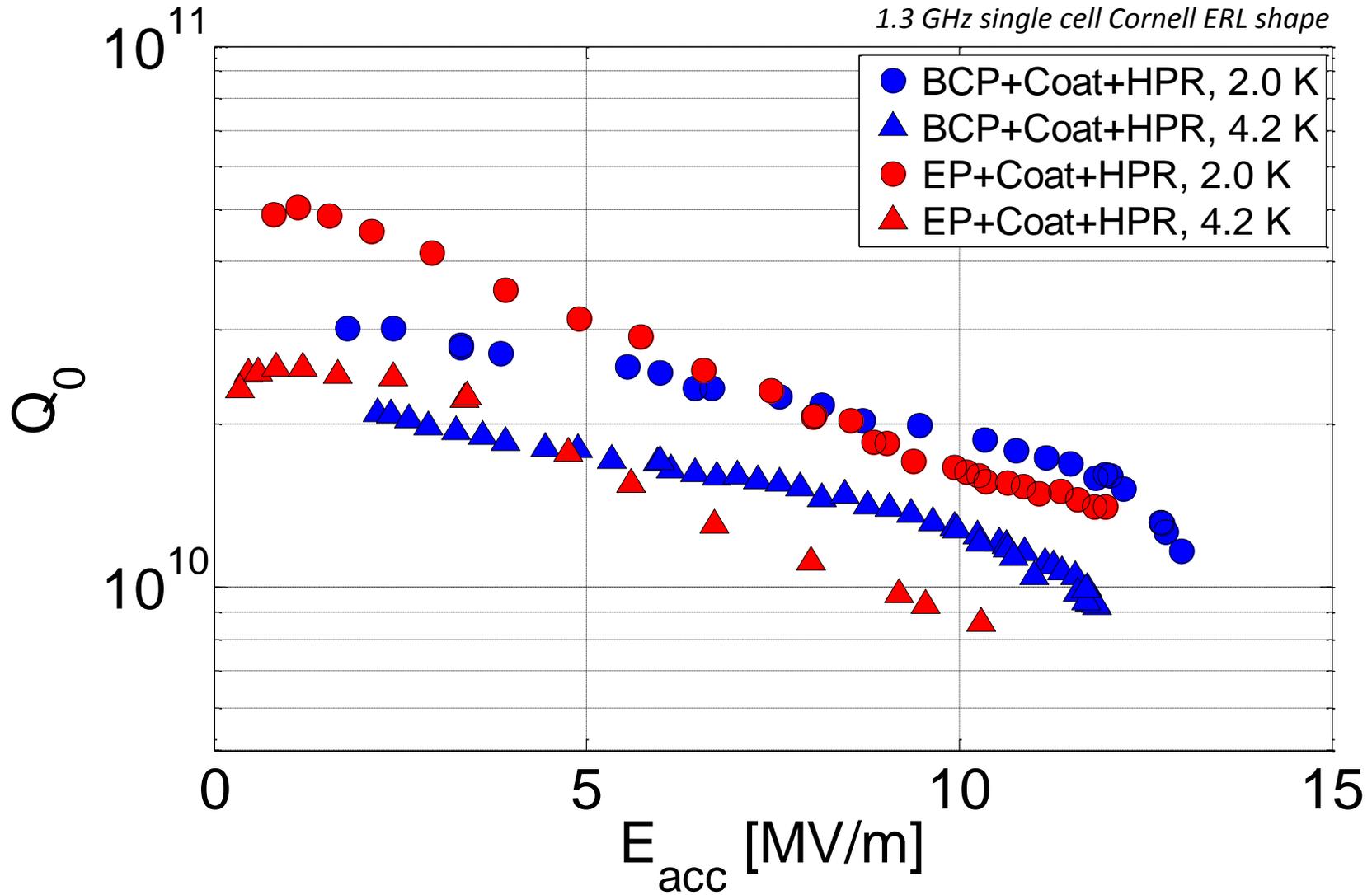
- Try to prevent/remove defects via:
 - HF rinse (layer is thin, so need very light removal)
 - Centrifugal barrel polishing (first use on Nb_3Sn)
 - EP substrates (first use on Nb_3Sn)

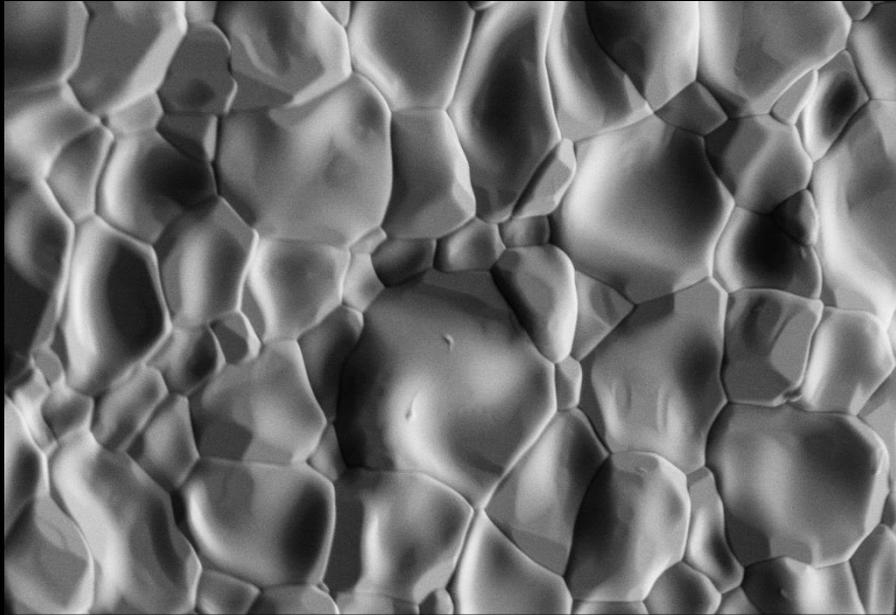




1.3 GHz single cell Cornell ERL shape

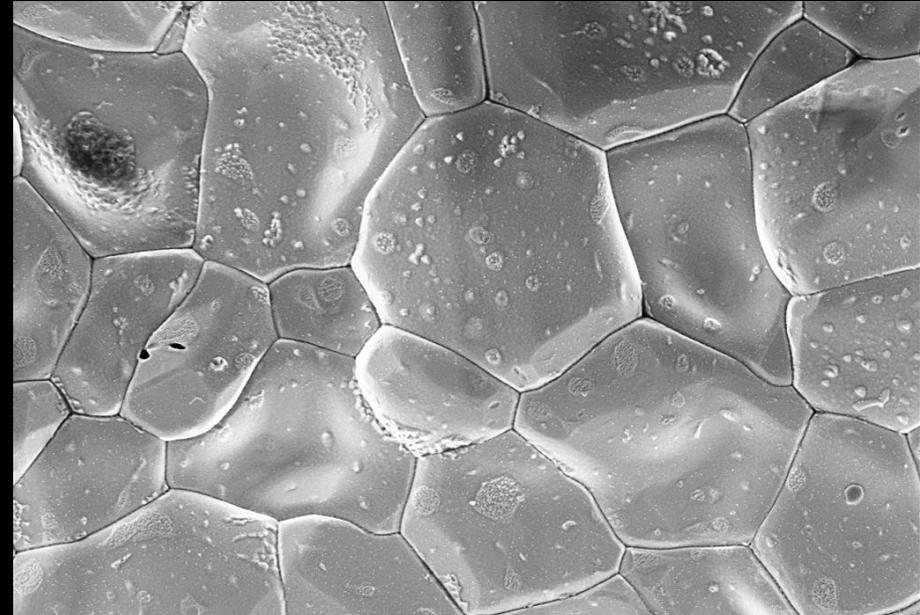






Keck SEM 1 μ m WD = 5.3 mm EHT = 3.00 kV Aperture Size = 30.00 μ m Date : 1 Aug 2014
File Name = tilt_ep1_02.tif Signal A = SE2 Time : 10:15:30

Just After Coating

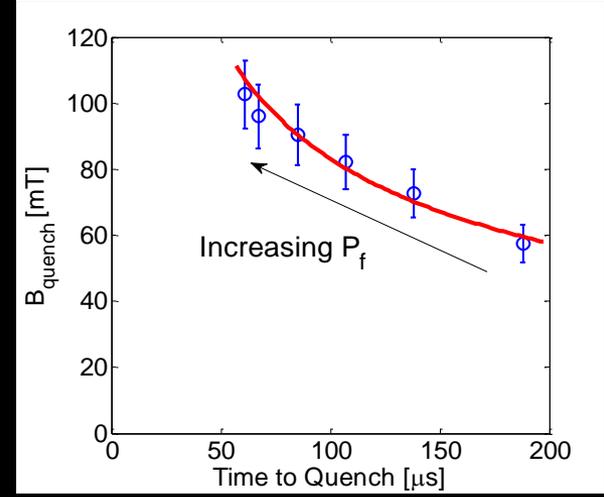
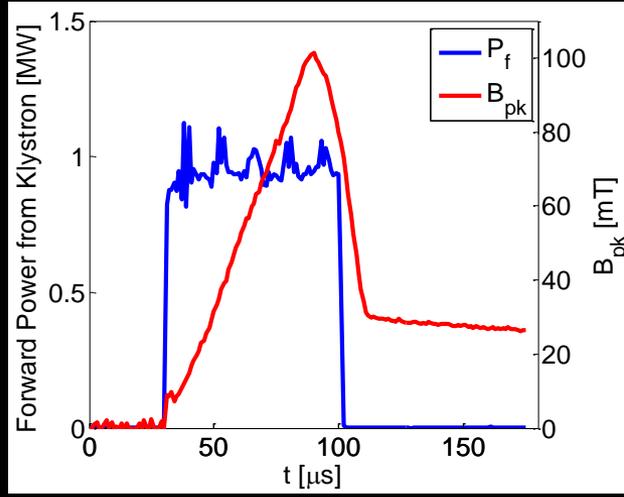
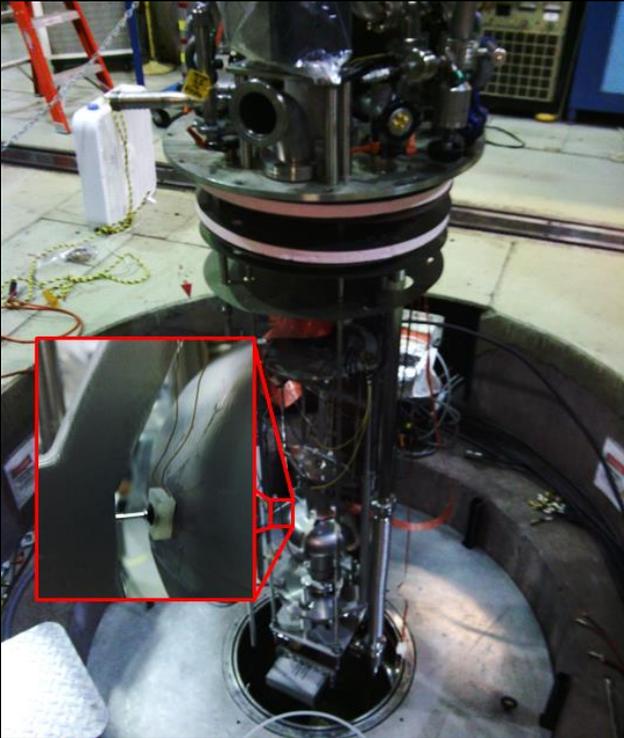


Keck SEM 1 μ m WD = 2.8 mm EHT = 2.00 kV Aperture Size = 30.00 μ m Date : 18 Aug 2014
File Name = HF04.tif Signal A = InLens Time : 9:49:59

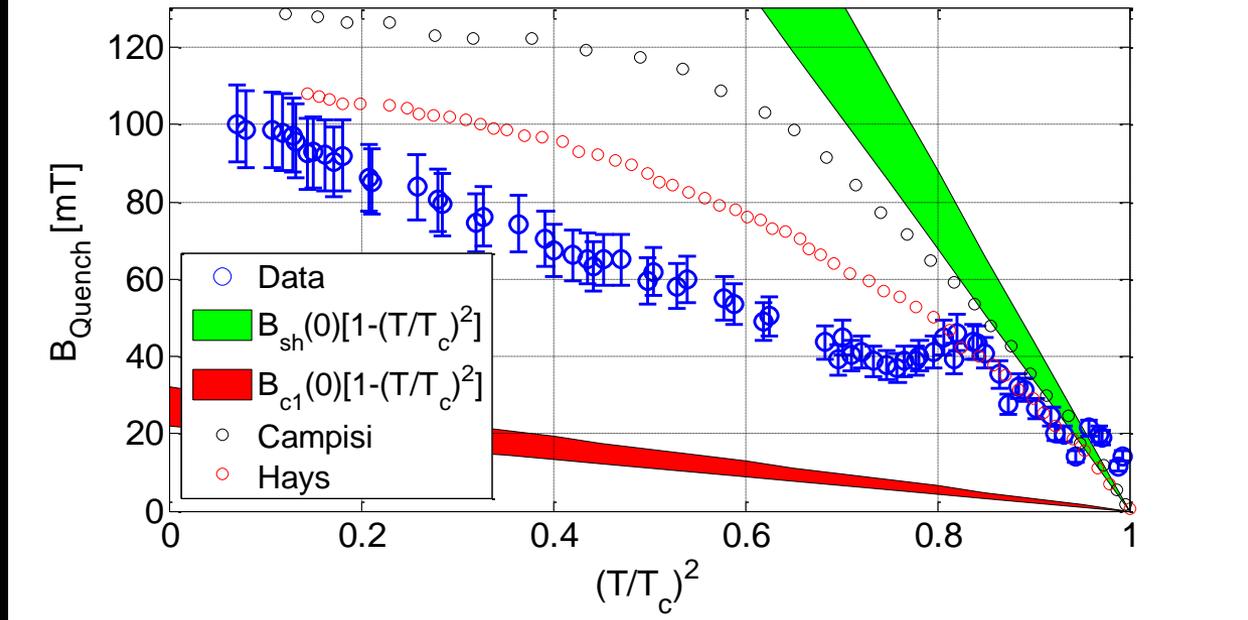
After HF Rinse



Pulsed Quench Field



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

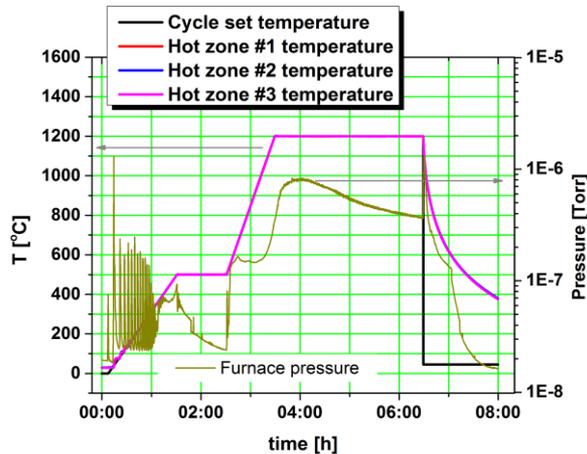


Nb₃Sn progress

Slides courtesy G. Ereemeev, JLab



The coating system during the commissioning run.

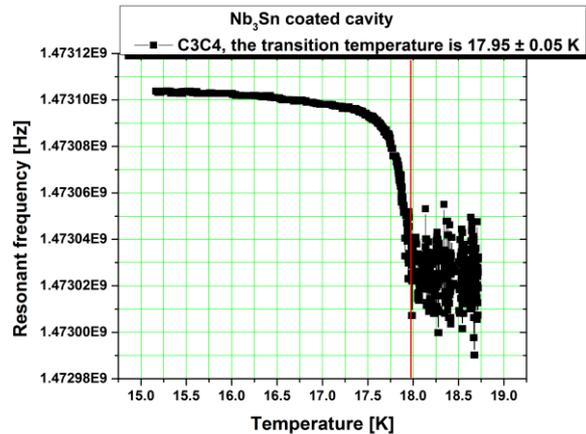


Temperature and pressure profile during coating system commissioning run. The furnace pressure is in 1E-7 Torr range and the temperature deviation is <1 °C at 1200 °C.

- The R&D furnace for Nb₃Sn development has been delivered and commissioned empty in November 2013.
- The Nb₃Sn insert has been converted from horizontal to vertical orientation, loaded with a CEBAF-shape 1-cell cavity (C3C4), Sn, and SnCl₂, 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.

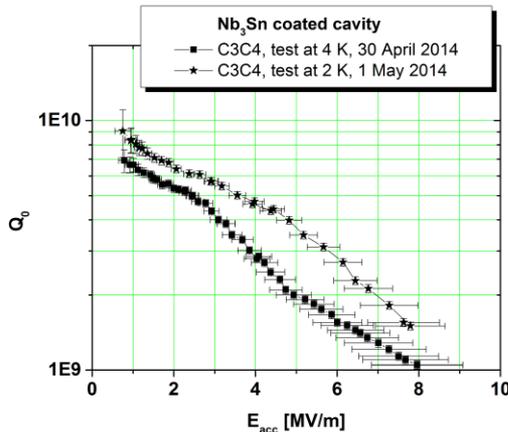
Nb₃Sn progress

Slides courtesy G. Ereemeev, JLab

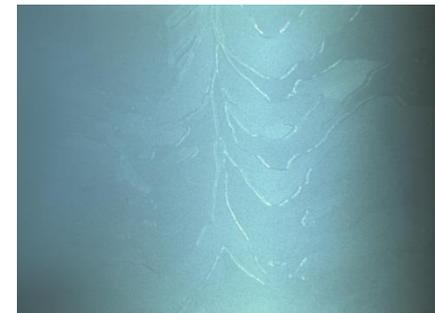


The resonant frequency as a function of temperature during cooldown. Data indicate the transition temperature of about 18 K.

- 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.



Quality factor of the Nb₃Sn coated C3C4 as a function of field at 4 K and 2 K.





- Alternative materials can benefit future SRF linacs
 - Nb easy to work with, but reaching fundamental limits
 - Nb₃Sn very promising – order of magnitude more efficient, twice energy gain per length
- New research: significant Nb₃Sn performance improvement
 - Strong Q-slope suppressed after extra annealing step
 - High Q₀ 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 Nb₃Sn



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

