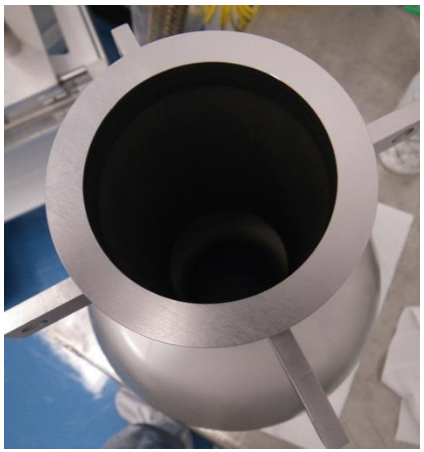
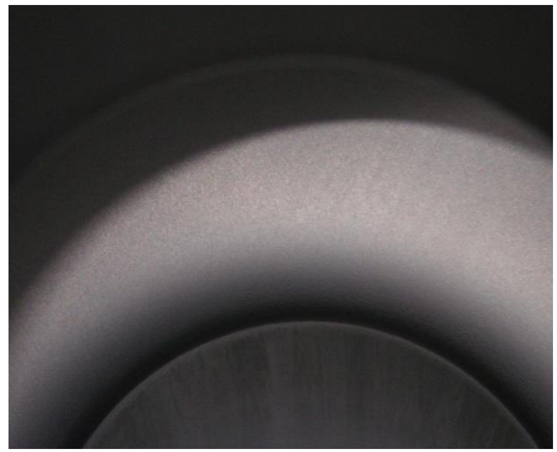
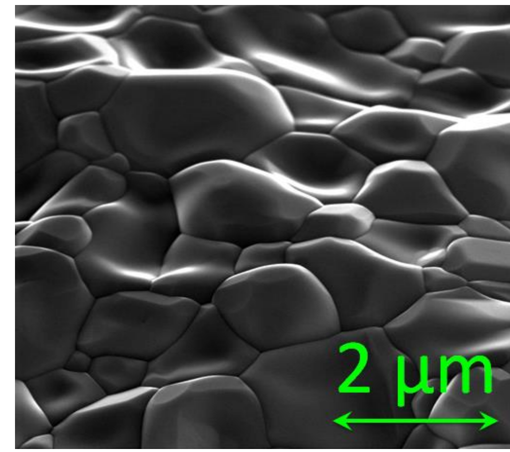
Advances in Development of Diffused Nb_3Sn Cavities at Cornell

Matthias Liepe, Cornell University







FCC Week 2015

IEEE International Future Circular Collider Conference

March 23 - 27, 2015 | Washington DC, USA

Outline

- Why Nb_3Sn?
- Challenges
- Cornell Nb_3Sn Program
- Recent Advances
- Potential for the FCC
- Conclusions

Why Nb_3Sn?

Increase in Q_0 via N-doping

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

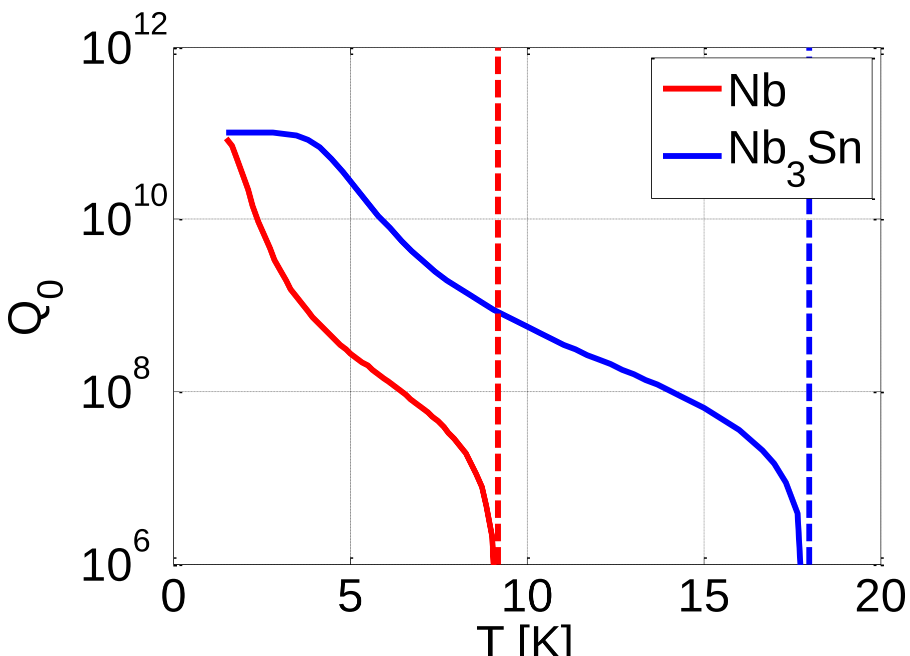
	Niobium	Nb_3Sn
Critical Temperature T_c	9 K	18 K
Q_0 at 4.2 K	6×10^8	6×10^{10}
Q_0 at 2.0 K	5x 10^{10} ~~2.5×10^{10}~~	$>10^{11}$
Max. gradient E_{acc} (theory)	50 MV/m	100 MV/m

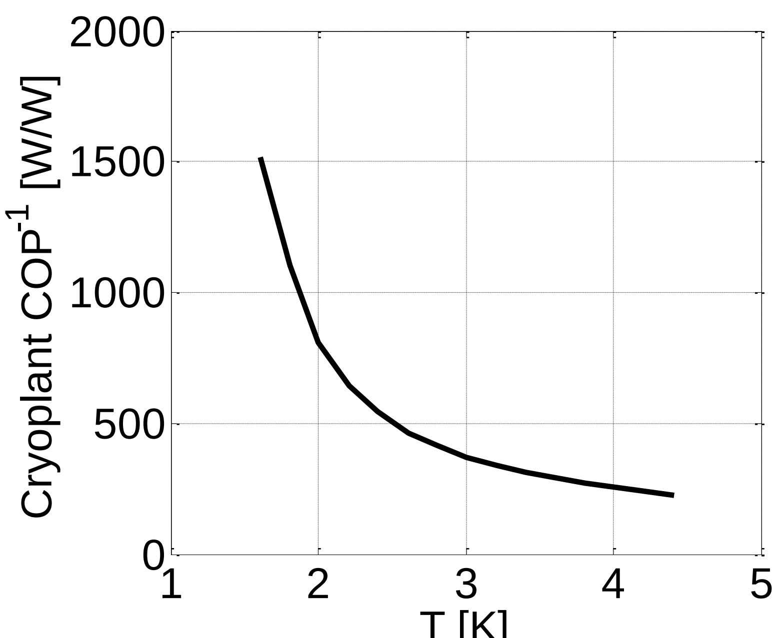
Approximate E_{acc} and Q_0 given for 1.3 GHz TeSLA cavities with R_{res} small

Halve # of cavities to reach energy?

Why Nb_3Sn?

- Nb_3Sn has large Δ and large T_c
  - Very small $R_{BCS}(T)$
  - Can have high Q_0 even at relatively high T
- R_{res} dominates even near 4.5 K





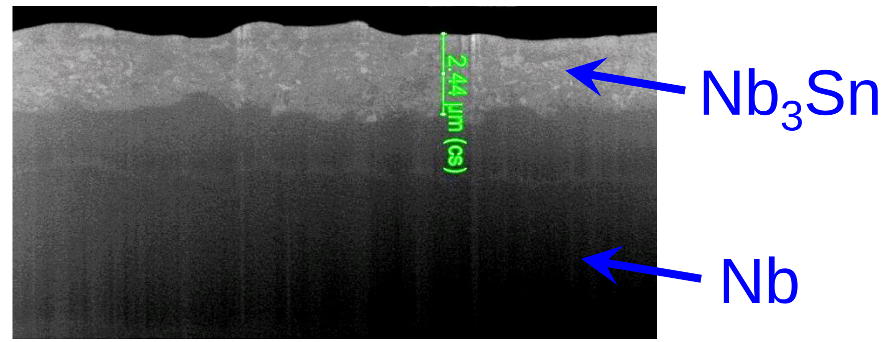
Nb_3Sn: Challenges

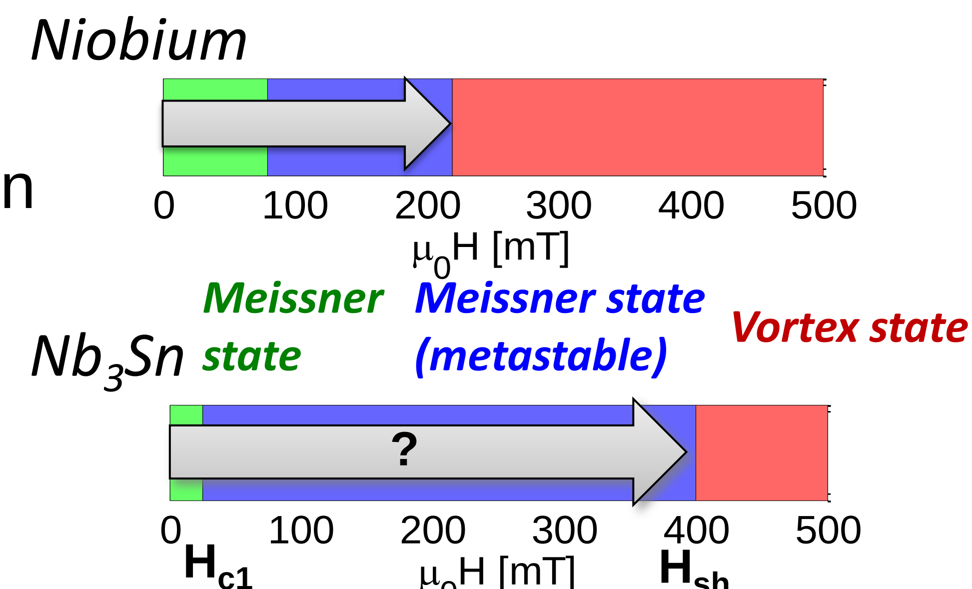
- Material is brittle
- Low thermal conductivity

Films avoid these

- **Small coherence length ξ ~ 3 - 4 nm**
  - More sensitive to small defects
  - Low first critical field H_{c1}=> need to operate in the flux free metastable Meissner state

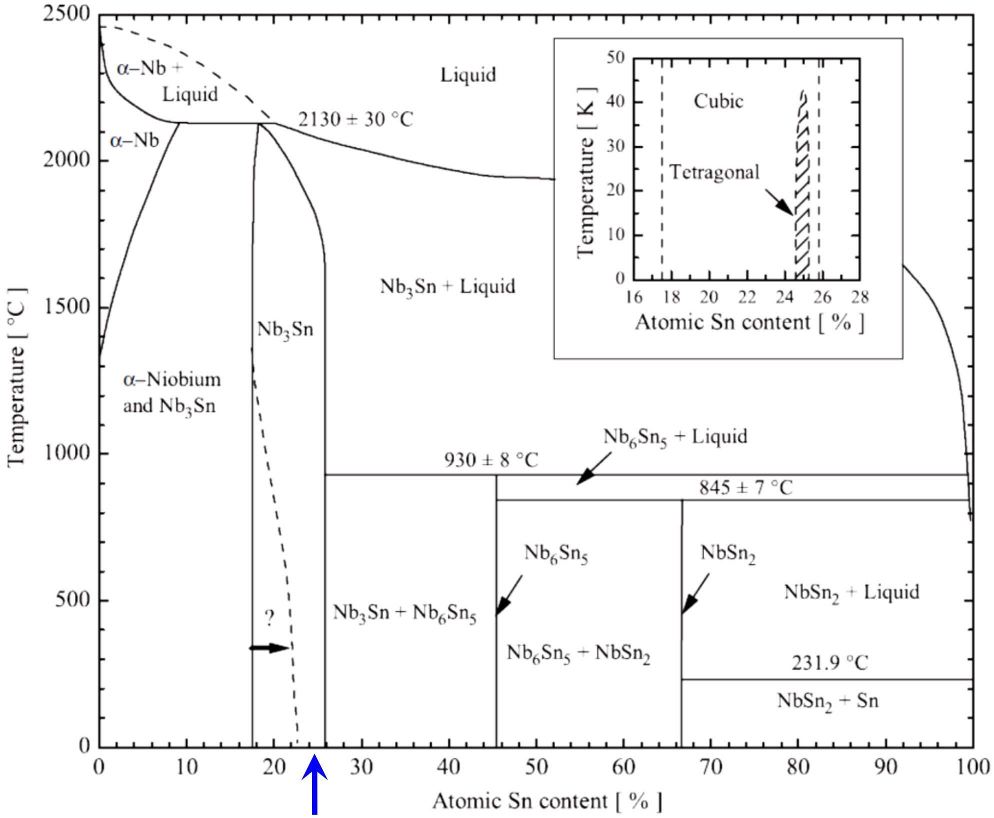
=> Need high quality Nb_3Sn film





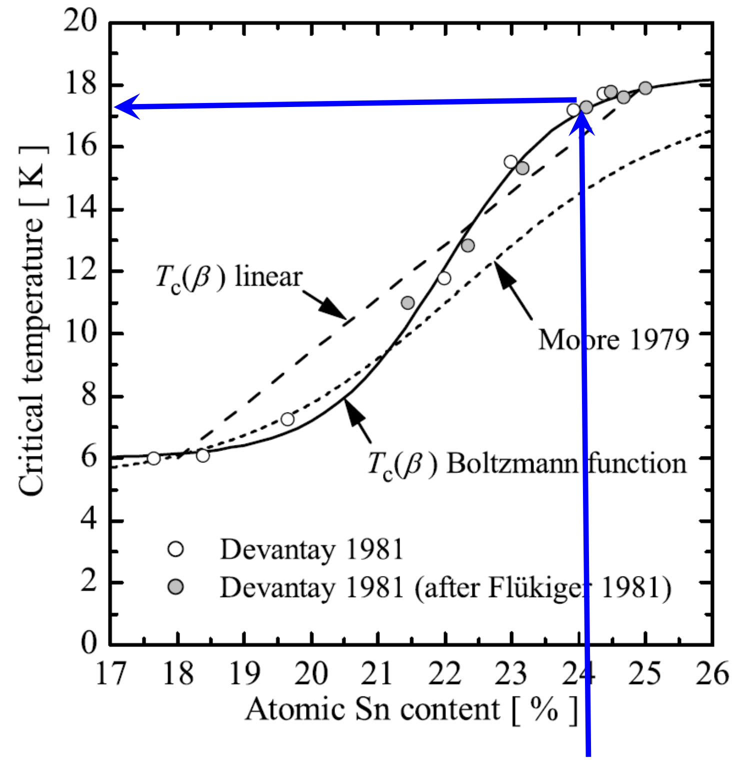
Stoichiometry

Nb_3Sn Phase Diagram



24% target

T_c vs. Tin Content

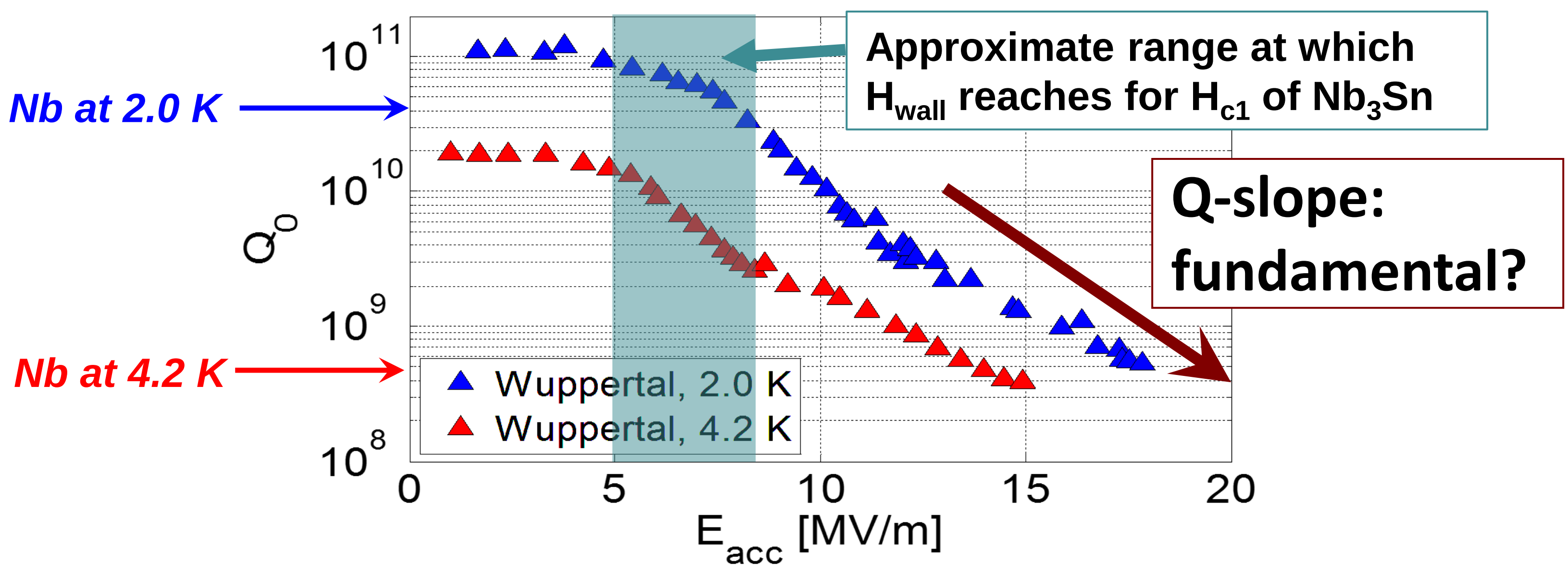


24% target

A. Godeke, Supercond. Sci. Tech, 2006

Nb_3Sn SRF History

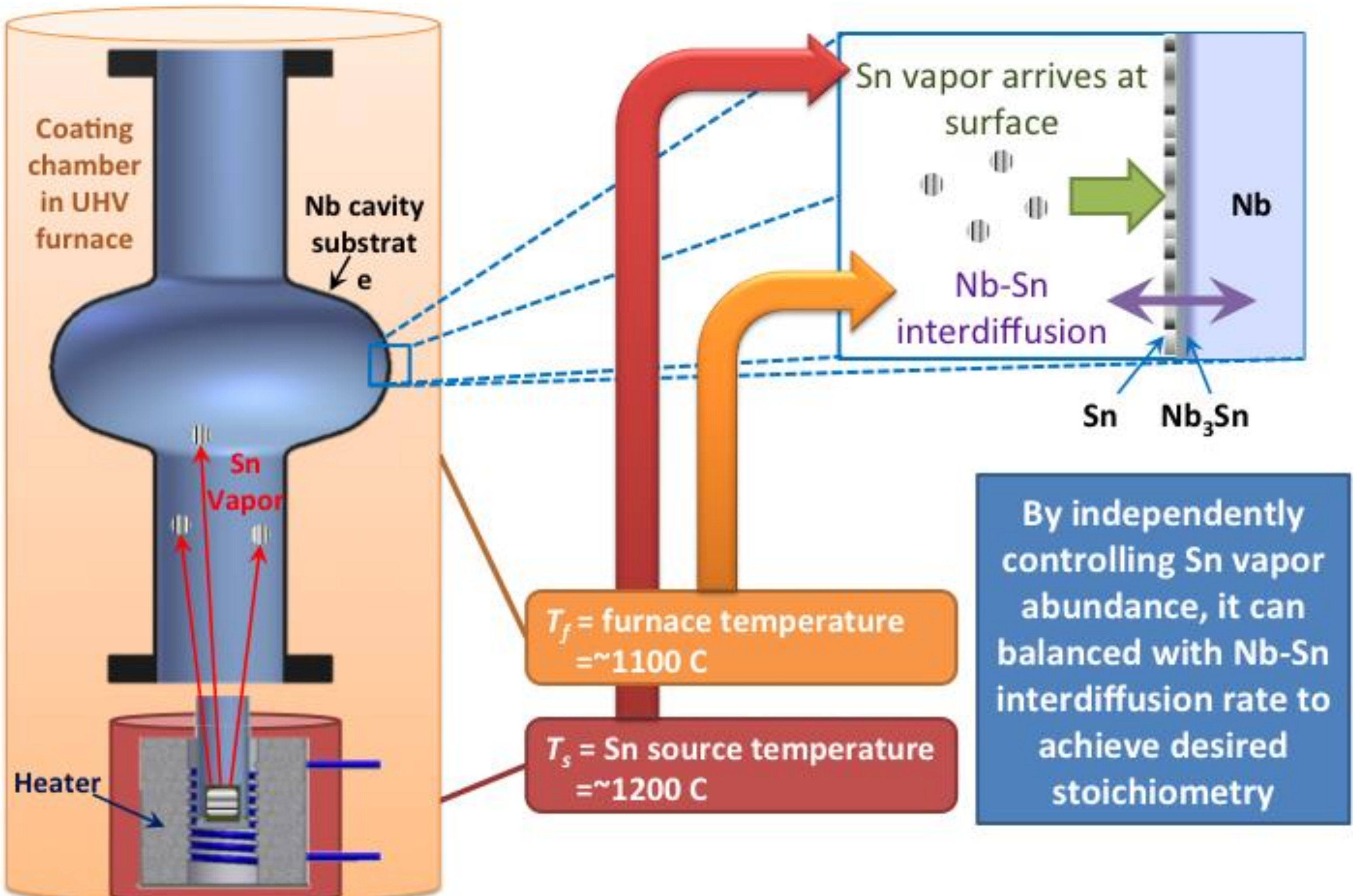
- Pioneering work at Siemens AG, U. Wuppertal, K.F. Karlsruhe, SLAC, Cornell, JLab, and CERN
- U. Wuppertal:
  - Very high Q_0 values in Nb_3Sn cavities
  - **Strong Q-slope, cause uncertain**



Cornell Nb_3Sn Program

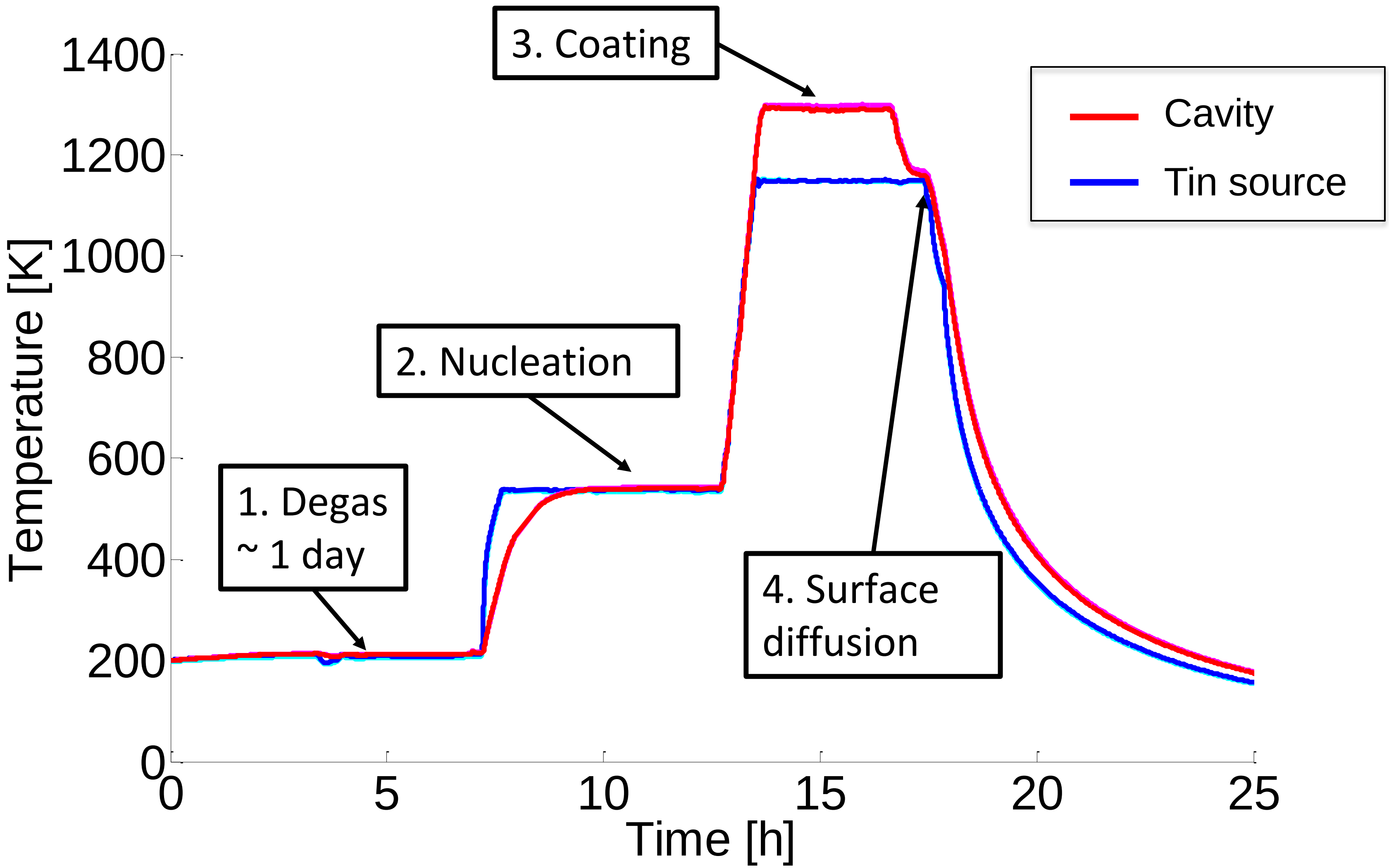
- Where we started:
  - Limited R&D effort in the past did not result in a usable high performance cavity
  - Central question: Is H_{c1} a limit for the flux free state of small-ξ superconductors in RF magnetic fields?
    - **YES**: No hope for Nb_3Sn (or any other strongly type II superconductor for SRF)
    - **No**: Great potential for Nb_3Sn to transform SRF cavities to much higher performance
- Boldly gave Nb_3Sn another chance…

Coating Mechanism: Vapor Diffusion



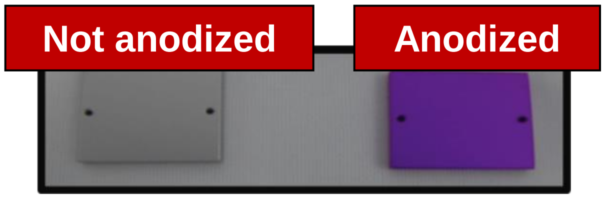
Cornell Nb_3Sn Cavity Coating Chamber

Nb_3Sn Coating Procedure



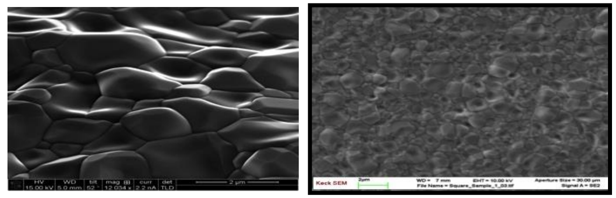
Nb_3Sn Sample Coatings and Studies

Anodization



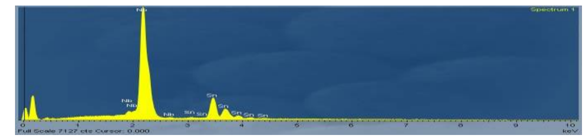
Pink -> Nb3Sn

SEM



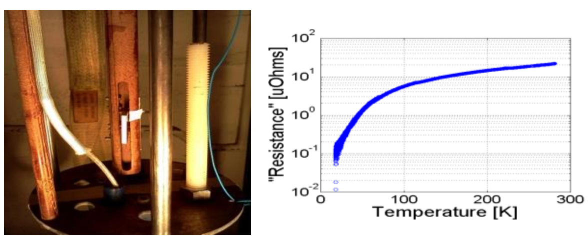
Grains ~1 µm.
Appearance similar to Nb_3Sn from other studies

EDX / XPS



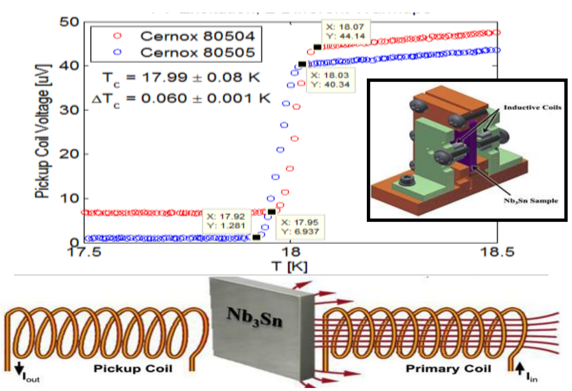
24.2 ± 0.5 atomic % Sn, uniform over surface; 2 µm deep

RRR Measurement



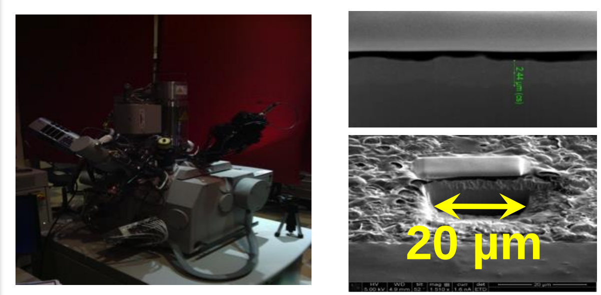
Minimal degradation of thermal conductivity from coating process

T_c Measurement



FIB

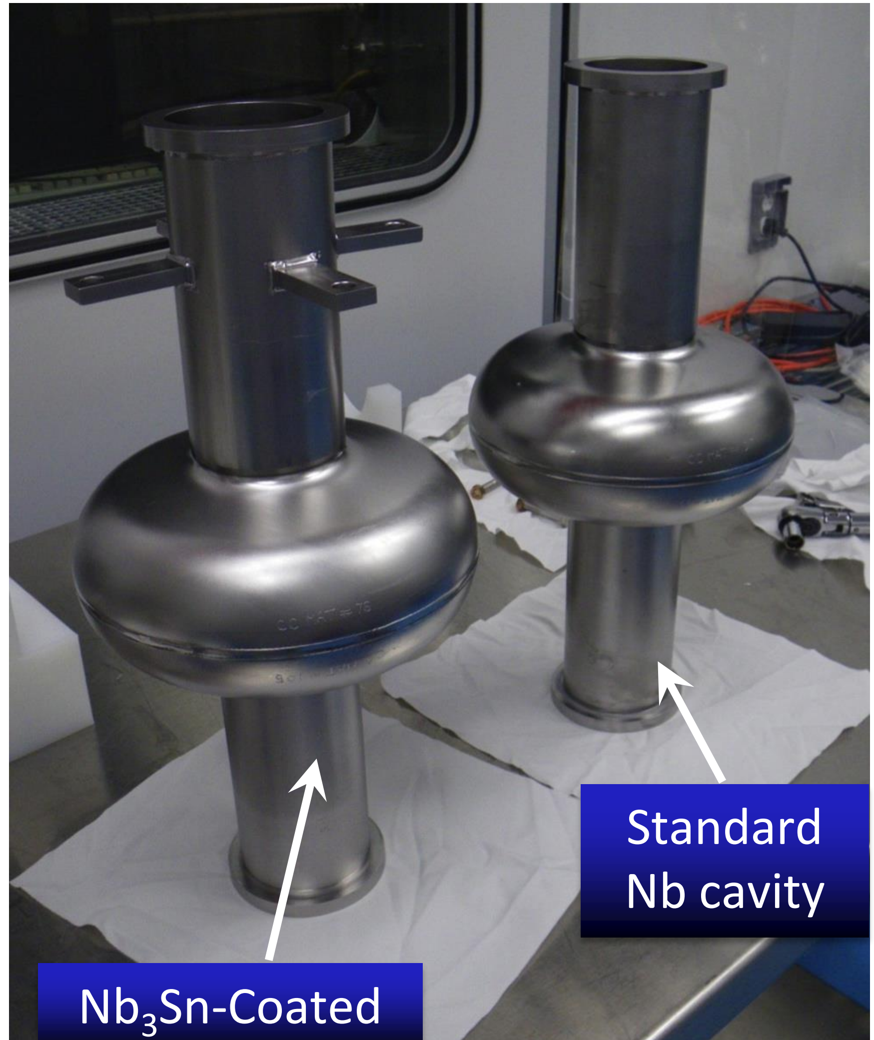
Sample prep for TEM, view of coating cross section



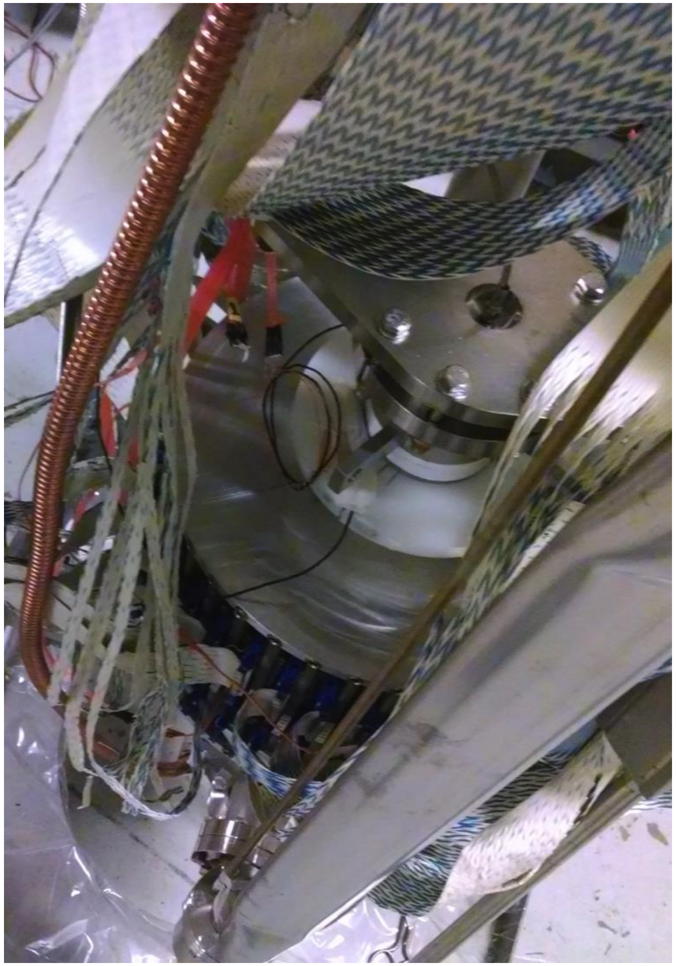
Preparation of Cavity for Coating

Start out with single-cell Niobium 1.3 GHz cavity

Coated Cornell 1.3 GHz Nb_3Sn Cavity



Vertical Performance Testing

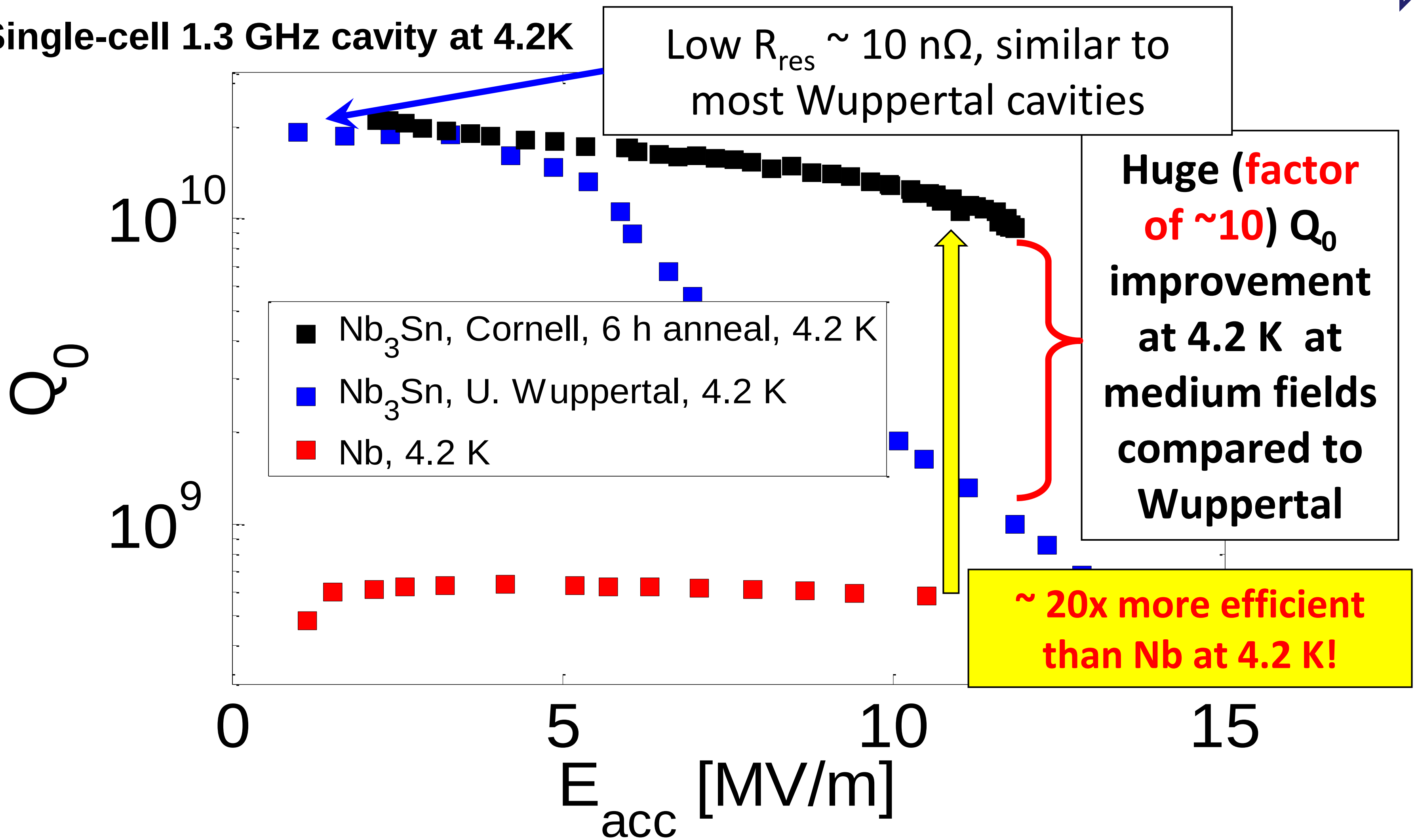


Cornell Nb_3Sn Results

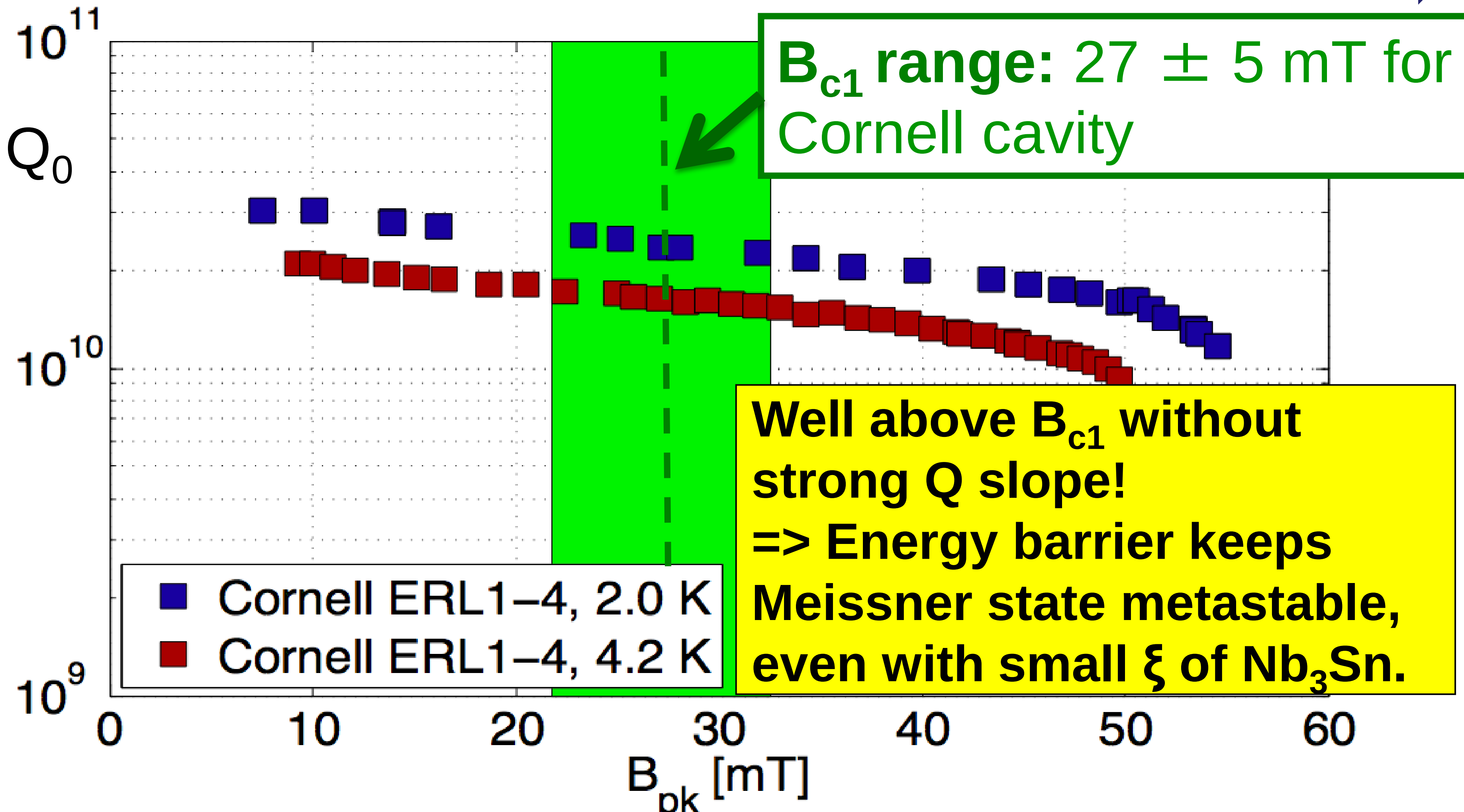
- After improving of the coating process
  - **The first accelerator cavity made with an alternative superconductor that outperforms Nb at usable gradients!**
    - **No strong Q-slope**
    - **Excellent Q_0 at 4.2K at medium fields**
  - **Prove that H_{c1} is not a fundamental limit for SRF**
- Nb_3Sn shows great promise for even higher performance with continued R&D

Breakthrough Nb_3Sn Cavity

Single-cell 1.3 GHz cavity at 4.2K



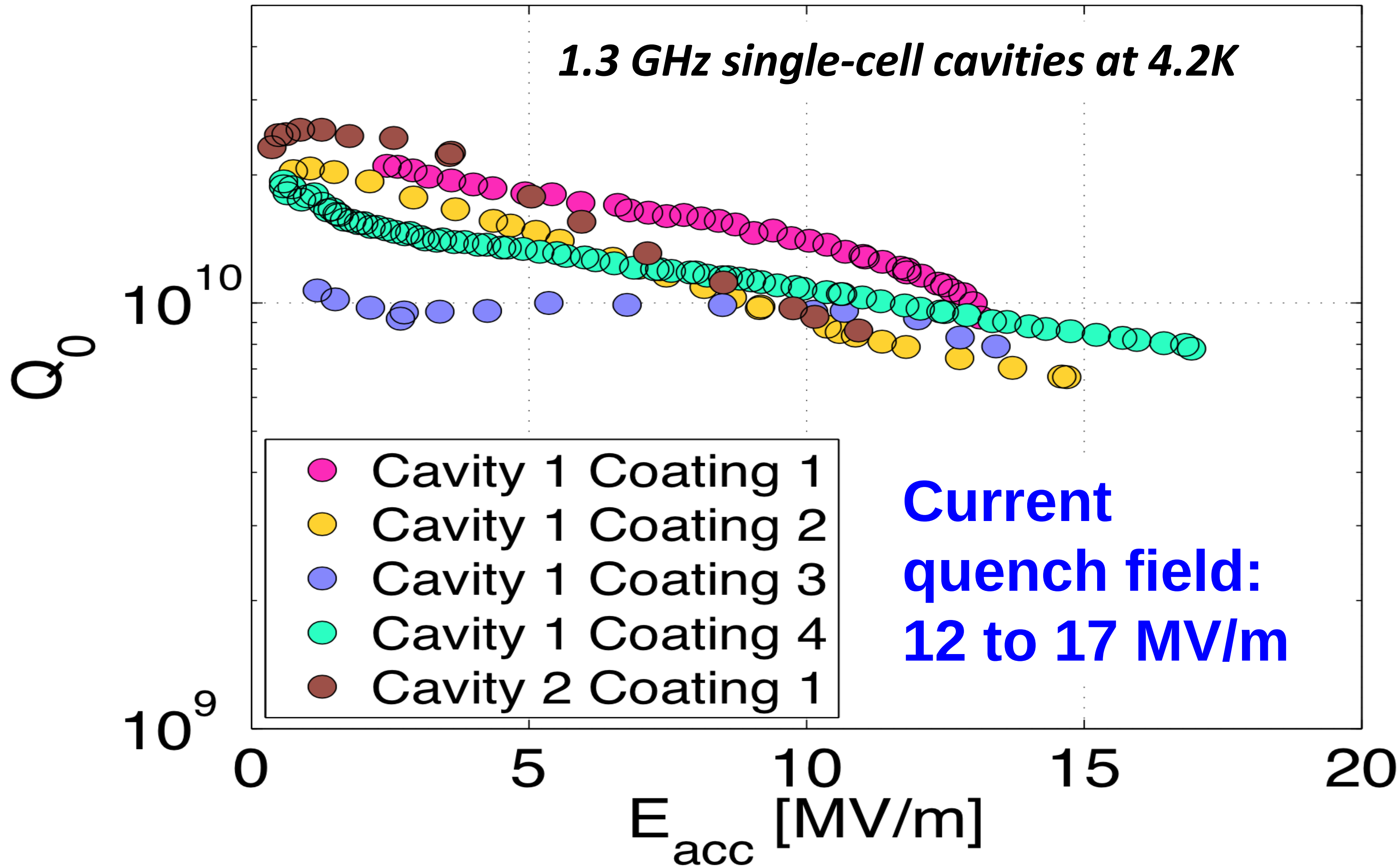
H_{c1} is NOT the Limit for Small-ξ Materials!



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

Well above B_{c1} without strong Q slope!
=> Energy barrier keeps Meissner state metastable, even with small ξ of Nb_3Sn.

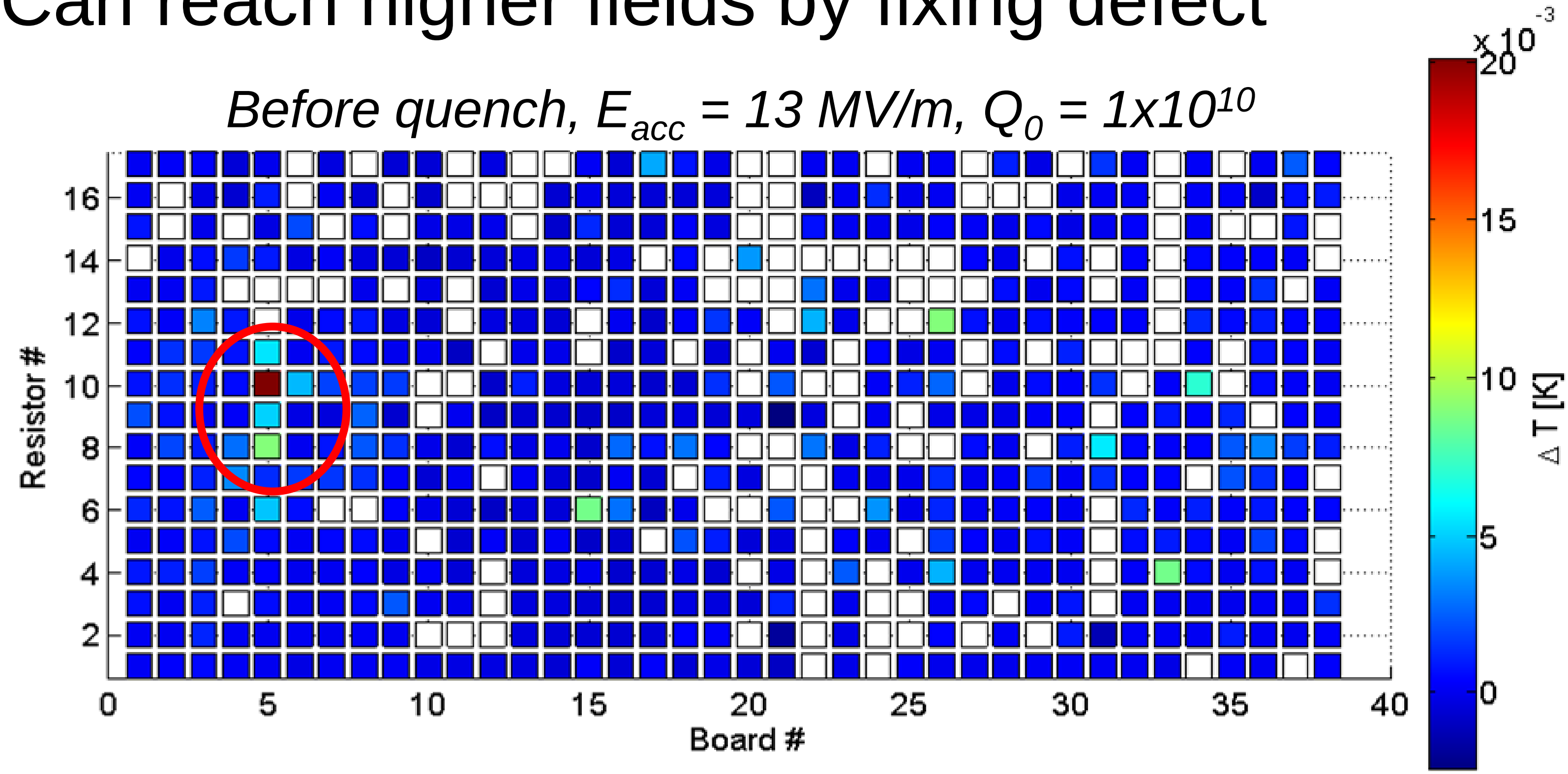
Repeatability



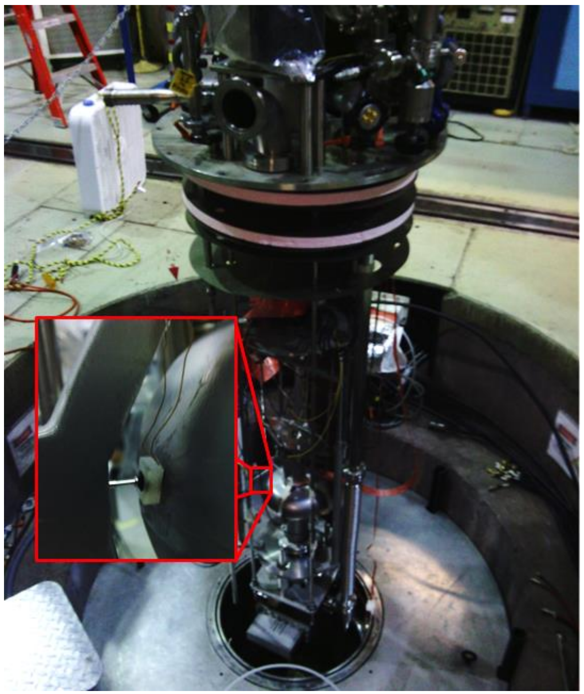
Current quench field: 12 to 17 MV/m

Field Limitation – Quench

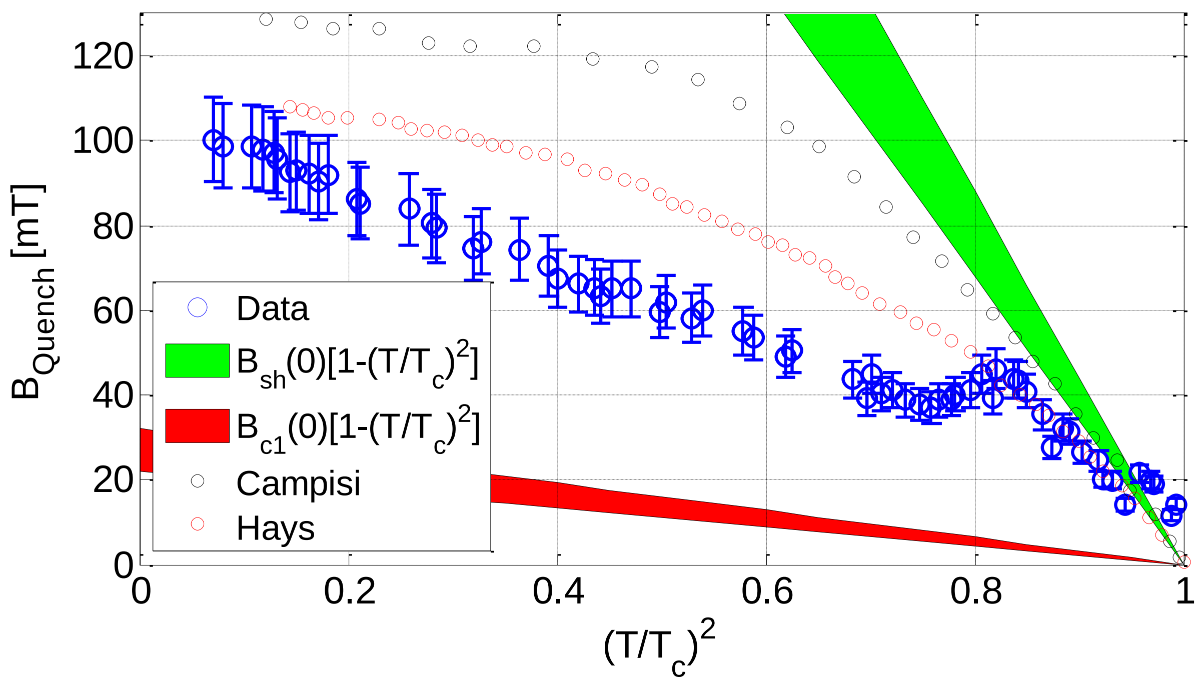
- Localized pre-heating just below first quench
- Defect – not a fundamental limit
- Can reach higher fields by fixing defect



Pulsed Quench Field >20 MV/m



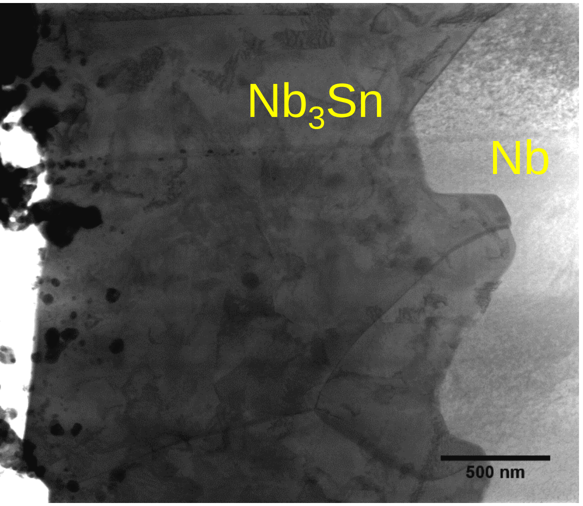
T_c = 18.0 ± 0.1 K , $B_{sh}(0)$ = 0.39 ± 0.05 T,
$B_{c1}(0)$ = 27 ± 5 mT

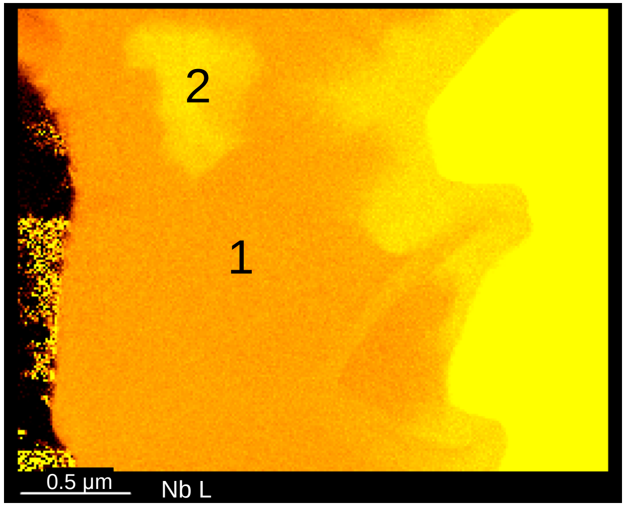


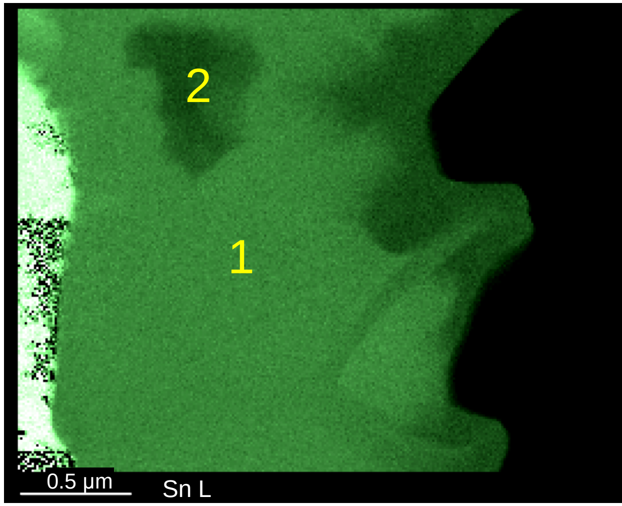
Shorter pulses => higher quench fields => defect limited

Low Tin Content Nb_3Sn Regions (I)

- TEM/EDX and X-ray Diffraction (XRD) revealed tin-depleted regions (~0.5 µm size)





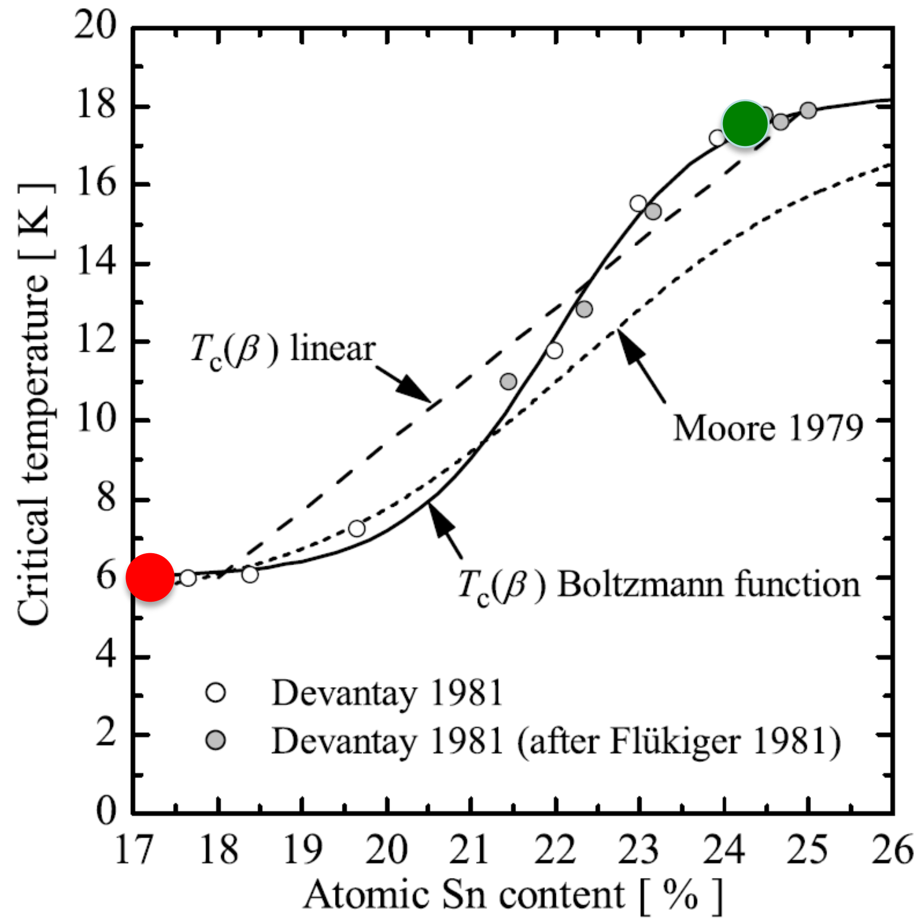


- “1”: 24-25 % Sn – “2”: 16-18 % Sn

Low Tin Content Nb_3Sn Regions (II)

Low tin content regions near surface are likely candidate for source of quench

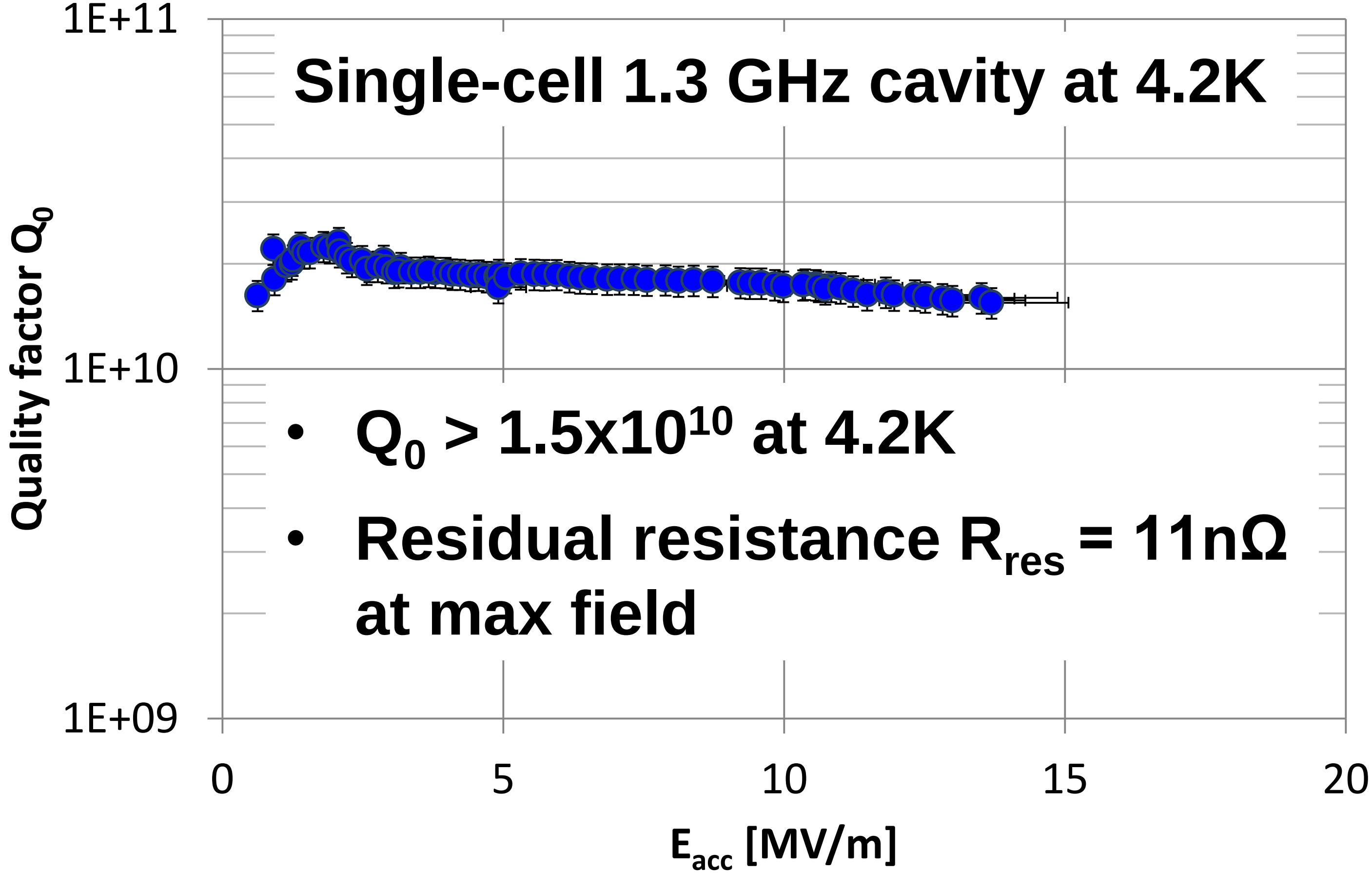
– Have much lower T_c, lower critical fields



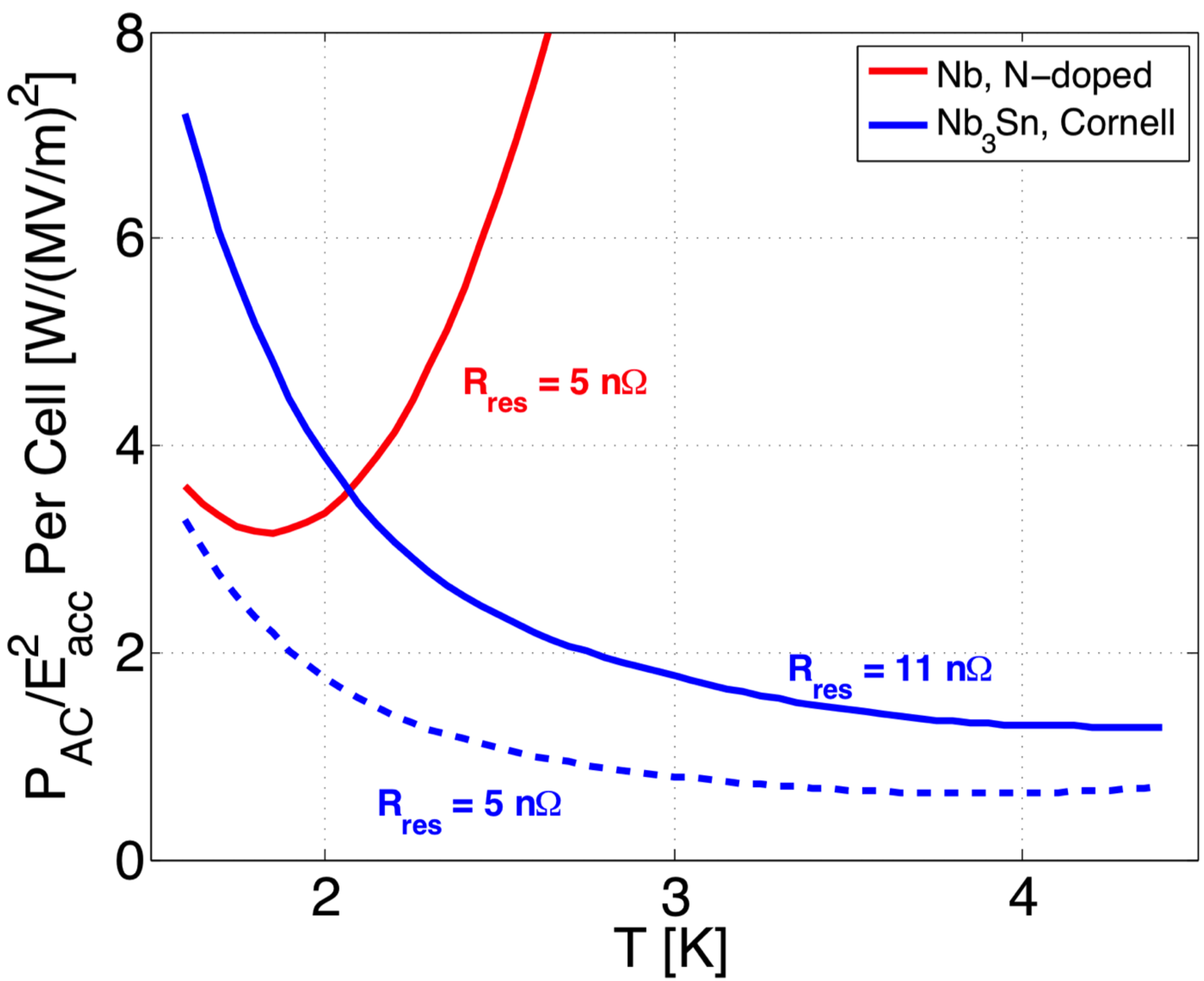
A. Godeke, Supercond. Sci. Tech, 2006

Nb_3Sn: State of the Art

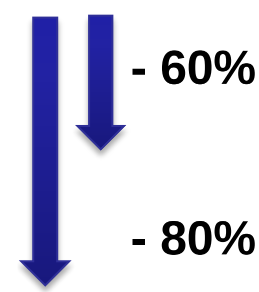
- With improved slow cool-down procedure:



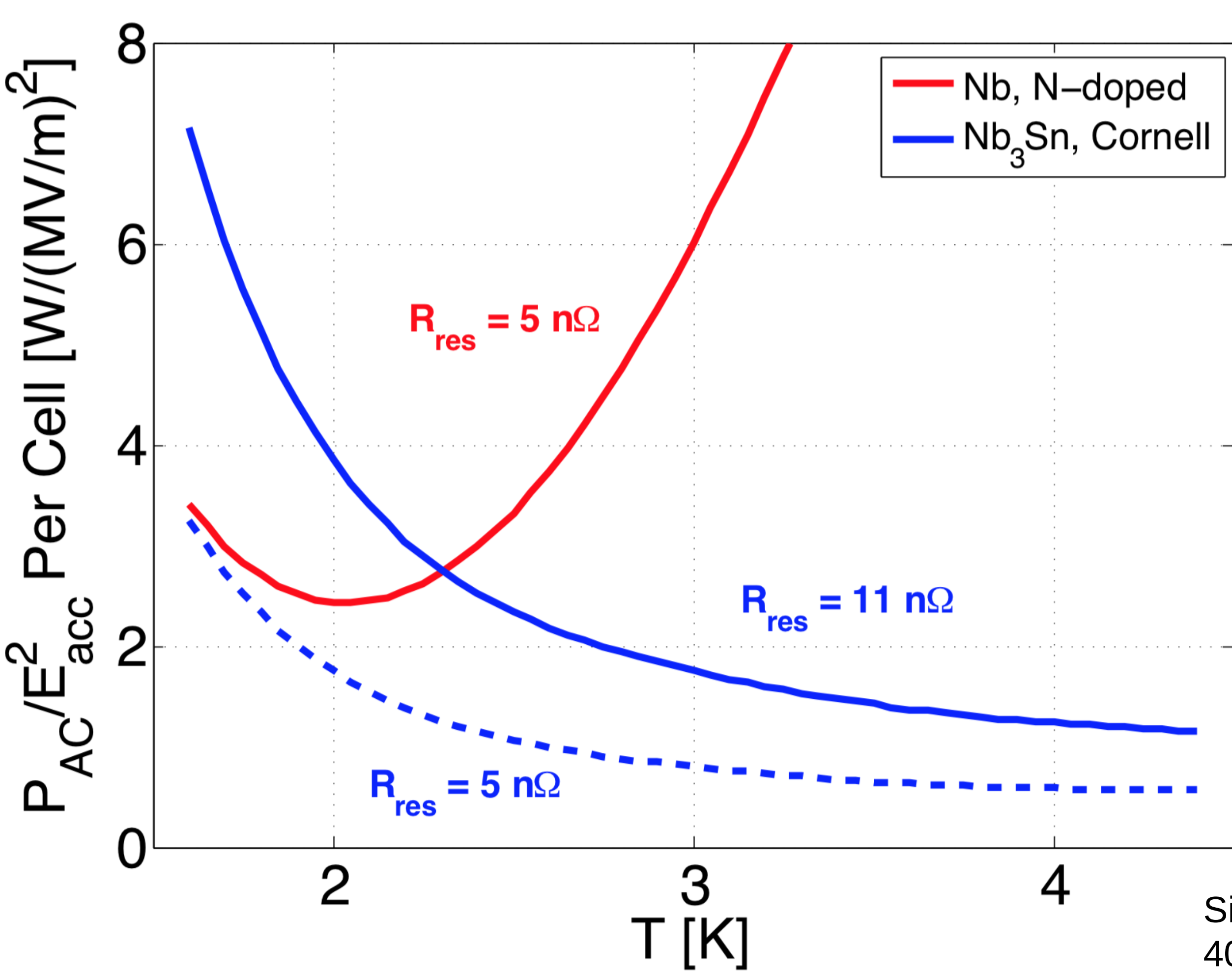
Cooling-Power Impact for 1.3 GHz SRF



- **SRF operation at ~4K instead of 2K!**
- **Greatly simplified cryo-system**
- **Greatly reduced cryo AC power**



Cooling-Power Impact for 800 MHz SRF



- **SRF operation at ~4K instead of 2K!**
- **Greatly simplified cryo-system**
- **Greatly reduced cryo AC power**

- 50%

- 75%

Similar cryo load reductions for 400 MHz to 800 MHz range.

Nb_3Sn: Next Steps

- Reduce residual resistance further to fully utilize the very high 4.5K Q_0 performance of Nb_3Sn
- Increase quench fields by improving fabrication parameters to eliminate tin-depleted regions
- Extend coating to multicell cavities

$\Rightarrow$ Nb_3Sn R&D

- Strong, DOE supported Nb_3Sn program at Cornell
- Coating facility and R&D program at JLAB
- Nb_3Sn R&D starting up at FNAL
- …

Nb_3Sn: Conclusions

- **Nb_3Sn very promising for SRF**
  - **Potential for factor ~4 higher efficiency, twice energy gain per length**
- **Cornell's leading Nb_3Sn program has resulted in significant Nb_3Sn performance improvements**
  - **Strong Q-slope seen previously suppressed**
  - **H_{c1} NOT a fundamental limit**
  - **High Q_0 at useful fields, T = 4.2 K**
  - **First Nb_3Sn cavities to outperform niobium**
  - **Low-T_c Nb-Sn alloys are likely cause of quench**
- **Very promising for FCC-ee and many other future accelerators with continued R&D**

Thank you for your attention!

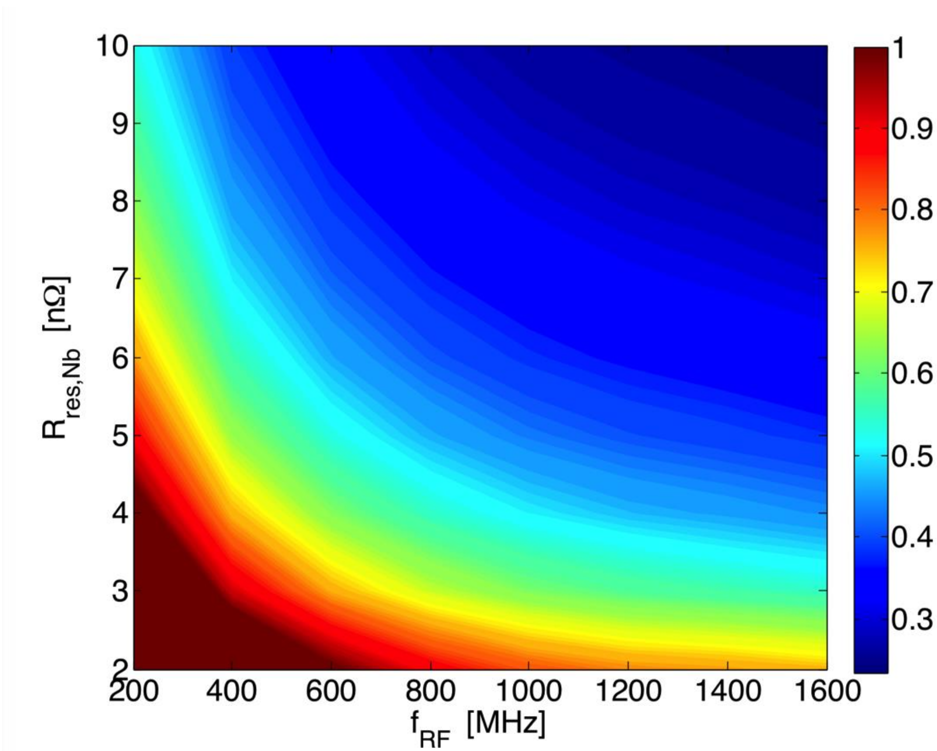
The end of this talk…
…just the beginning of Nb_3Sn for SRF

Recent Publications:

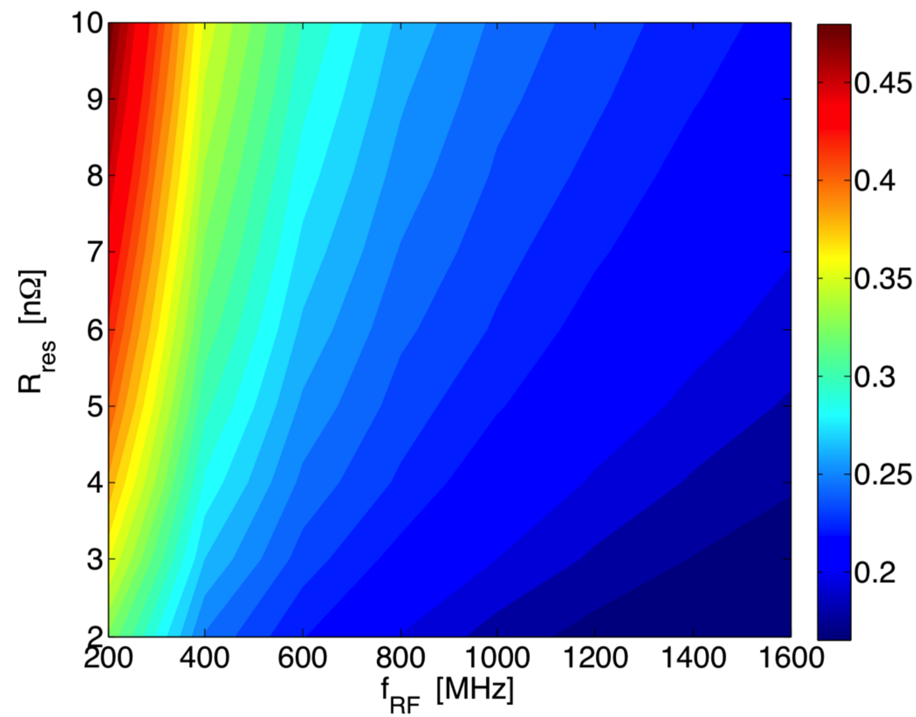
1. *Proof-of-principle demonstration of Nb3Sn superconducting RF cavities for high Q0 applications*, S. Posen, M. Liepe. D. Hall, Applied Physics Letters 106, Issue 8 (2015). http://dx.doi.org/10.1063/1.4913247
2. *Analysis of Nb3Sn surface layers for superconducting RF cavity applications,* C. Becker, S. Posen, N. Groll, R. Cook, C. M. Schlepuetz, D. Hall, M. Liepe, M. Pellin, J. Zasadzsinski, and T. Proslier, Applied Physics Letters 106, Issue 8 (2015). http://dx.doi.org/10.1063/1.4913617
3. *Advances in development of Nb3Sn superconducting radio-frequency cavities,* S. Posen and M. Liepe, Phys. Rev. ST Accel. Beams 15, 112001 (2014). http://dx.doi.org/10.1103/PhysRevSTAB.17.112001

Backup slide: $P_{cryo,Nb3Sn}/P_{cryo,Nb}$

For $R_{res,Nb3Sn}$ = 11 nΩ



For $R_{res,Nb3Sn} = R_{res,Nb}$



Material Parameters

Property	Cavity 2 Test 1	Cavity 2 Test 3	Cavity 2 Test 5	Cavity 2 Test 6	Cavity 3 Test 1
T_c [K]	18.0 ± 0.1	18.0 ± 0.1	18.0 ± 0.1	18.0 ± 0.1	18.0 ± 0.1
$\Delta/k_B T_c$	2.5 ± 0.2	2.5 ± 0.2	2.6 ± 0.2	2.25 ± 0.12	2.5 ± 0.2
l [nm]	3.0 ± 1.0	1.7 ± 1.0	2.4 ± 1.0	4.8 ± 2.0	1.7 ± 1.0
R_{res} [nΩ]	9.5 ± 1.5	10.3 ± 1.2	21 ± 2	8.5 ± 1.2	7.2 ± 1.0
$\lambda_{\mathrm{eff}}(0)$ [nm]	161 ± 25	198 ± 50	174 ± 32	139 ± 23	198 ± 50
$\xi_{GL}(0)$ [nm]	3.0 ± 0.4	2.4 ± 0.6	2.8 ± 0.4	3.4 ± 0.5	2.4 ± 0.6
$\kappa(0)$	54 ± 11	82 ± 28	63 ± 16	41 ± 9	82 ± 28
$\mu_0 H_c(0)$ [T]	0.49 ± 0.10	0.48 ± 0.17	0.49 ± 0.12	0.49 ± 0.10	0.48 ± 0.17
$\mu_0 H_{c1}(0)$ [mT]	29 ± 2	21 ± 2	25 ± 2	36 ± 3	21 ± 2
$E_{acc}\|_{B_{pk}=\mu_0 H_{c1}(0)}$ [MV/m]	6.8 ± 0.5	4.9 ± 0.5	6.0 ± 0.5	8.5 ± 0.7	4.9 ± 0.5
$\mu_0 H_{c2}(0)$ [T]	37 ± 11	56 ± 27	43 ± 15	28 ± 9	56 ± 27
$\mu_0 H_{sh}(0)$ [T]	0.40 ± 0.08	0.39 ± 0.13	0.40 ± 0.10	0.41 ± 0.09	0.39 ± 0.13
$E_{acc}\|_{B_{pk}=\mu_0 H_{sh}(0)}$ [MV/m]	95 ± 19	93 ± 32	94 ± 23	97 ± 21	93 ± 32