Nb_3Sn for SRF Applications

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U.S. DOE award DE-SC0008431: 1.3 GHz coatings + tests
NSF Award 1734189: 2.6 GHz + 3.9 GHz coatings + tests
Center for Bright Beams , NSF Award PHY-1549132: material studies

This works make use of Cornell Center for Materials Research, NSF MRSEC program (DMR-1719875)

Center for BRIGHT BEAMS
A National Science Foundation Science & Technology Center

Outline

- Introduce Nb_3Sn + standard Nb_3Sn cavity performance
- High frequency Nb_3Sn cavities
- Progress in increasing Q
- Progress in increasing E_{acc}
- Outlook: gradients, 9-cells
- Conclusion

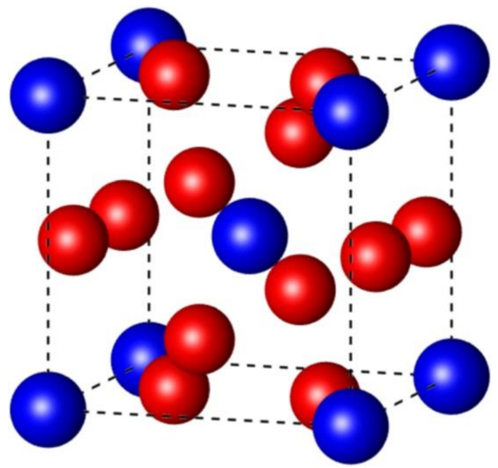
Properties of Nb_3Sn

Higher critical temperature

→ Operation at 4.2 K

Higher superheating field

→ Double the limit of niobium



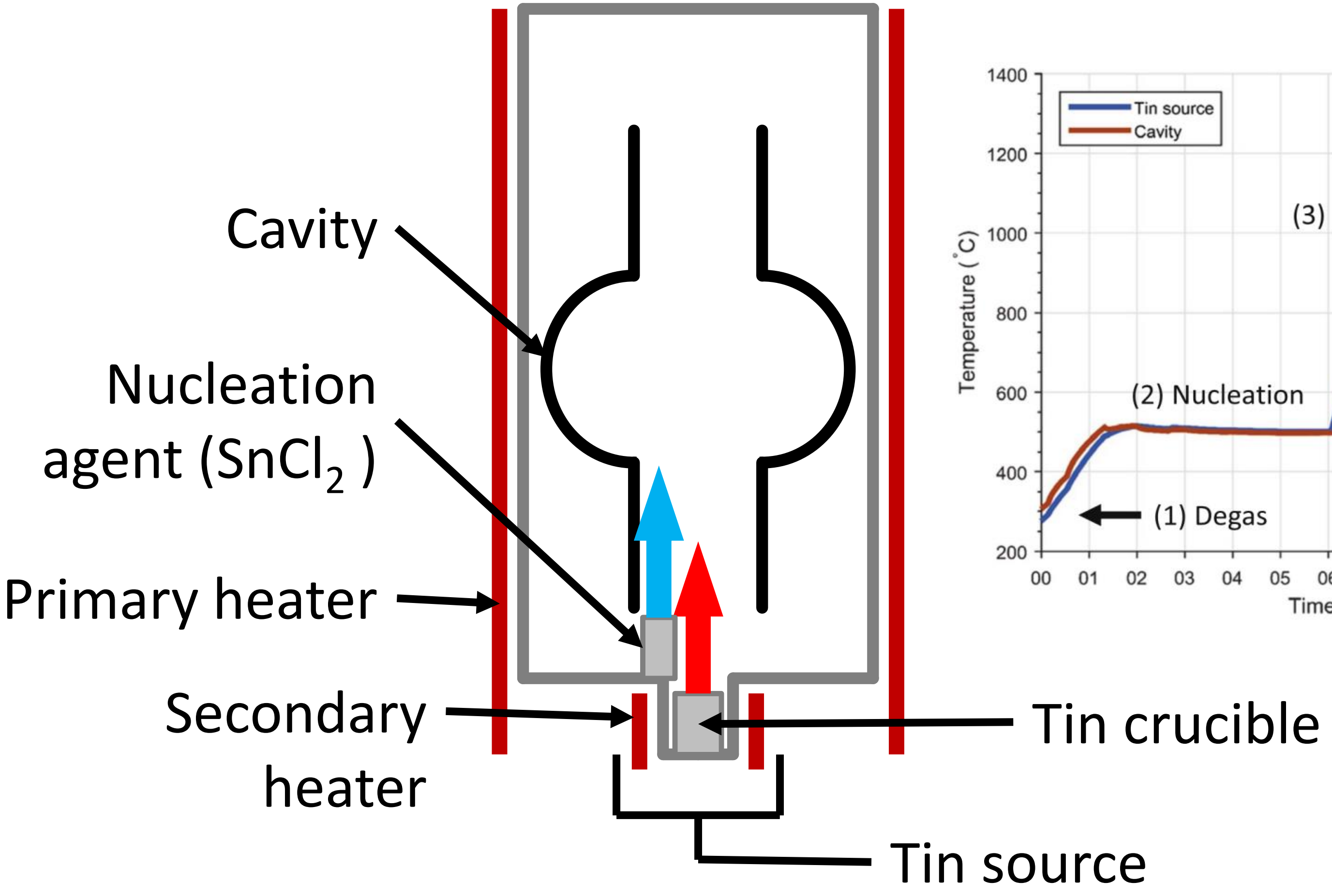
Blue: tin
Red: niobium

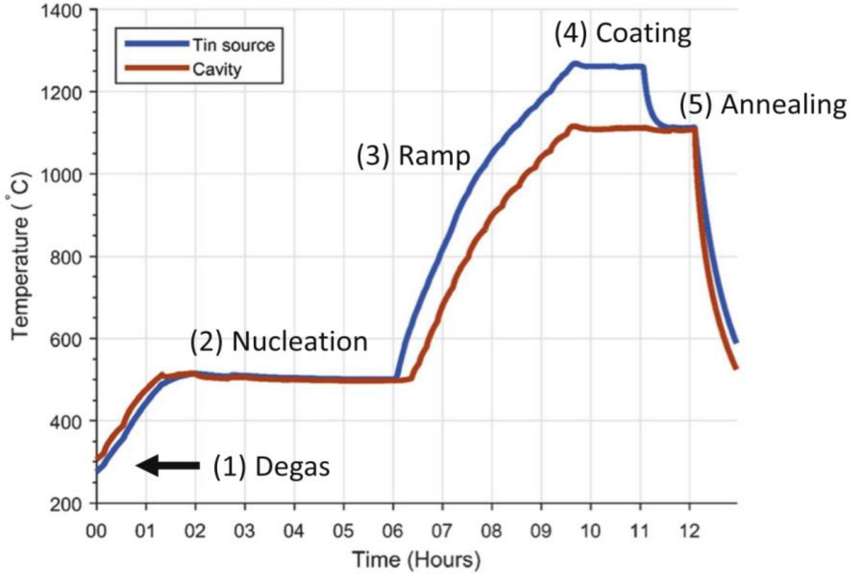
Parameter	Niobium	Nb_3Sn
Transition temperature	**9.2 K**	**18 K**
Superheating field	**219 mT**	**425 mT**
Energy gap Δ/k_bT_c	1.8	2.2
λ at T = 0 K	50 nm	111 nm
ξ at T = 0 K	22 nm	4.2 nm
GL parameter κ	2.3	26

1. Lower losses

2. Higher gradients ~90 MV/m

Cornell Nb_3Sn Vapor Diffusion Furnace





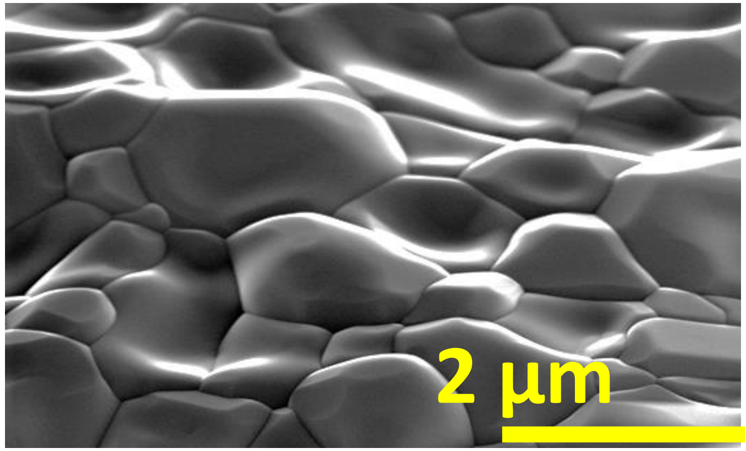
"Wuppertal" configuration, i.e., with secondary heater for the tin source

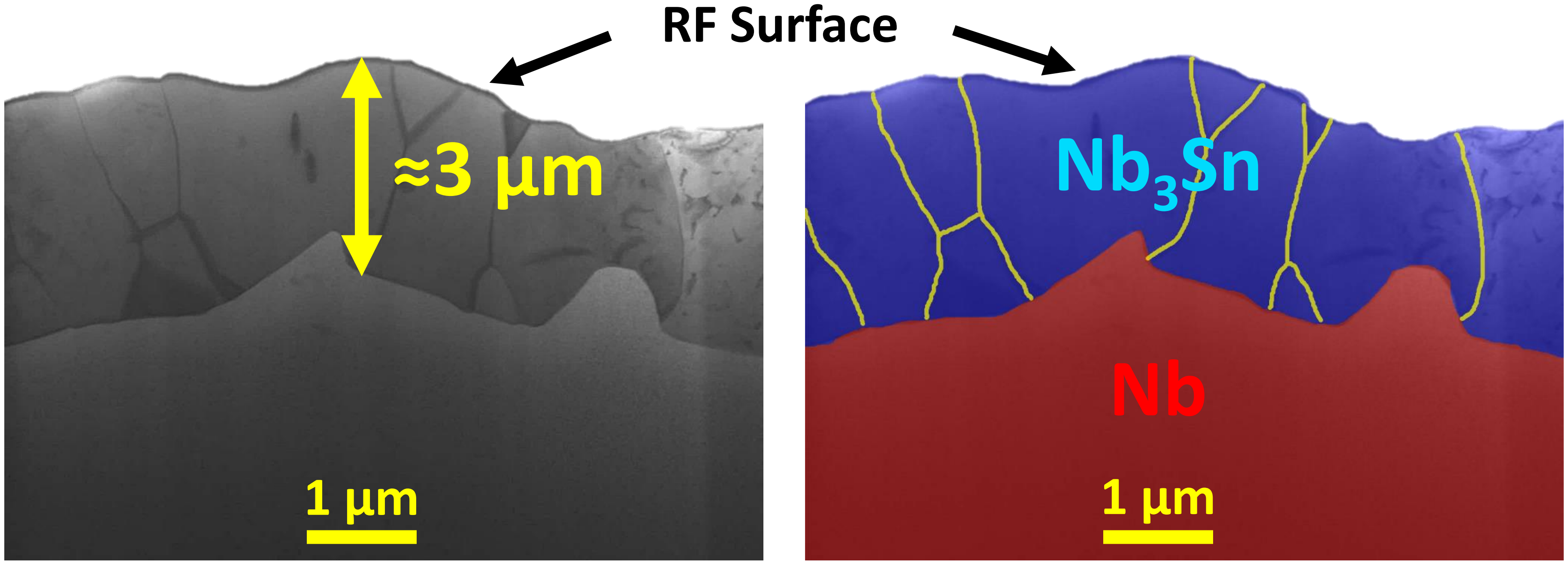
Optimized nucleation and temperature profile

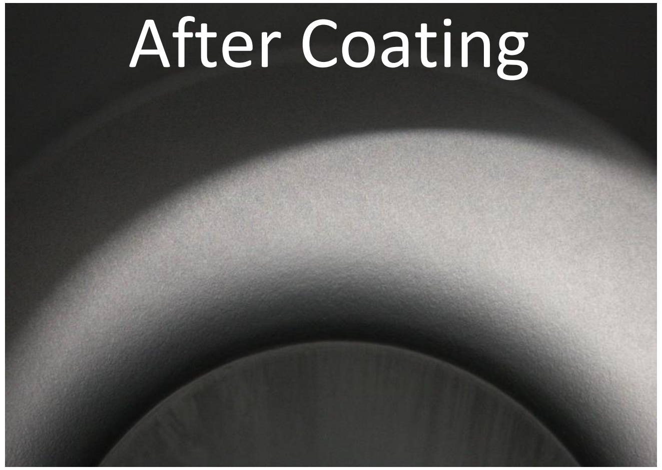
S. Posen and M. Liepe, Phys. Rev. ST Accel. Beams 15, 112001 (2014).

Nb_3Sn Coatings

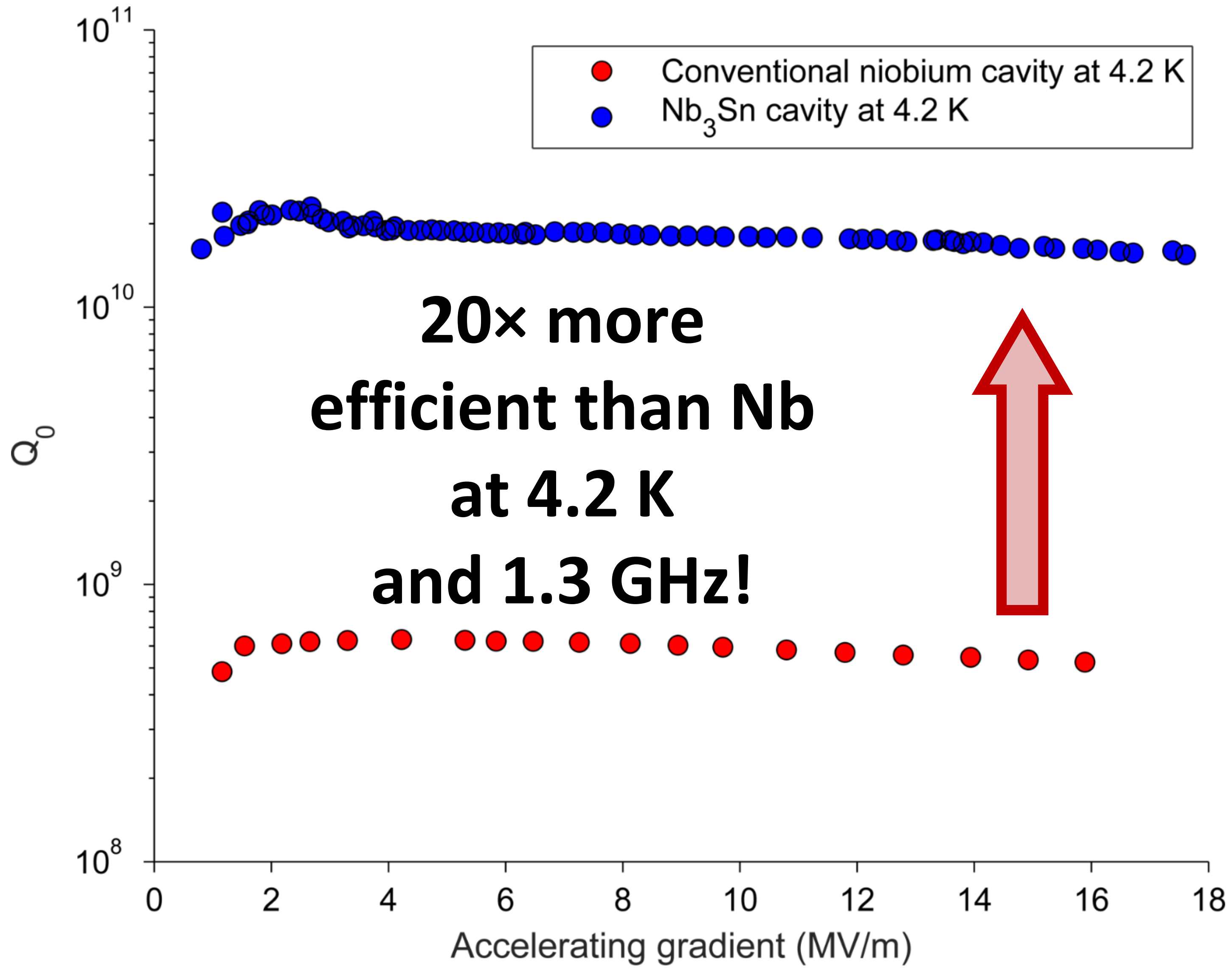
Nb_3Sn forms a polycrystalline layer on the surface of the niobium







Comparison to Niobium

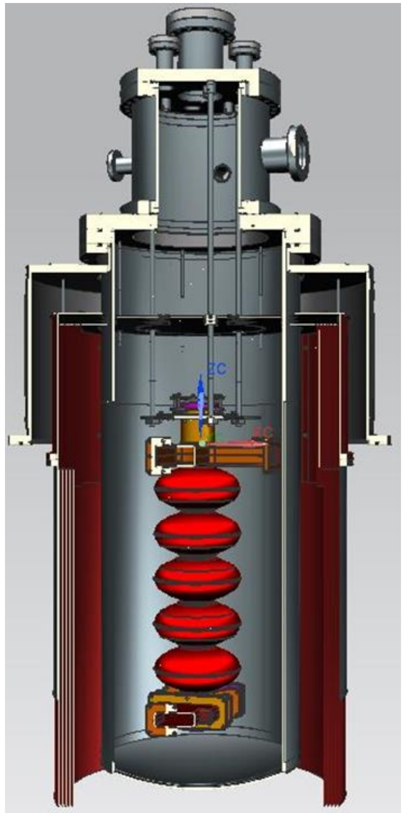


- <u>High Q at **4.2 K**</u>
  - More efficient
    - <u>**Lower dynamic load**</u>
  - Longer pulsed operation
- <u>Could run at **4.2 K**</u>
  - Simplify cryomodule
    - <u>**Lower static load**</u>
  - <u>**Simplify cryogenic**</u> system

JLAB and Fermilab Nb_3Sn Vapor Diffusion Furnaces

JLAB Nb_3Sn Coating System

Jefferson Lab

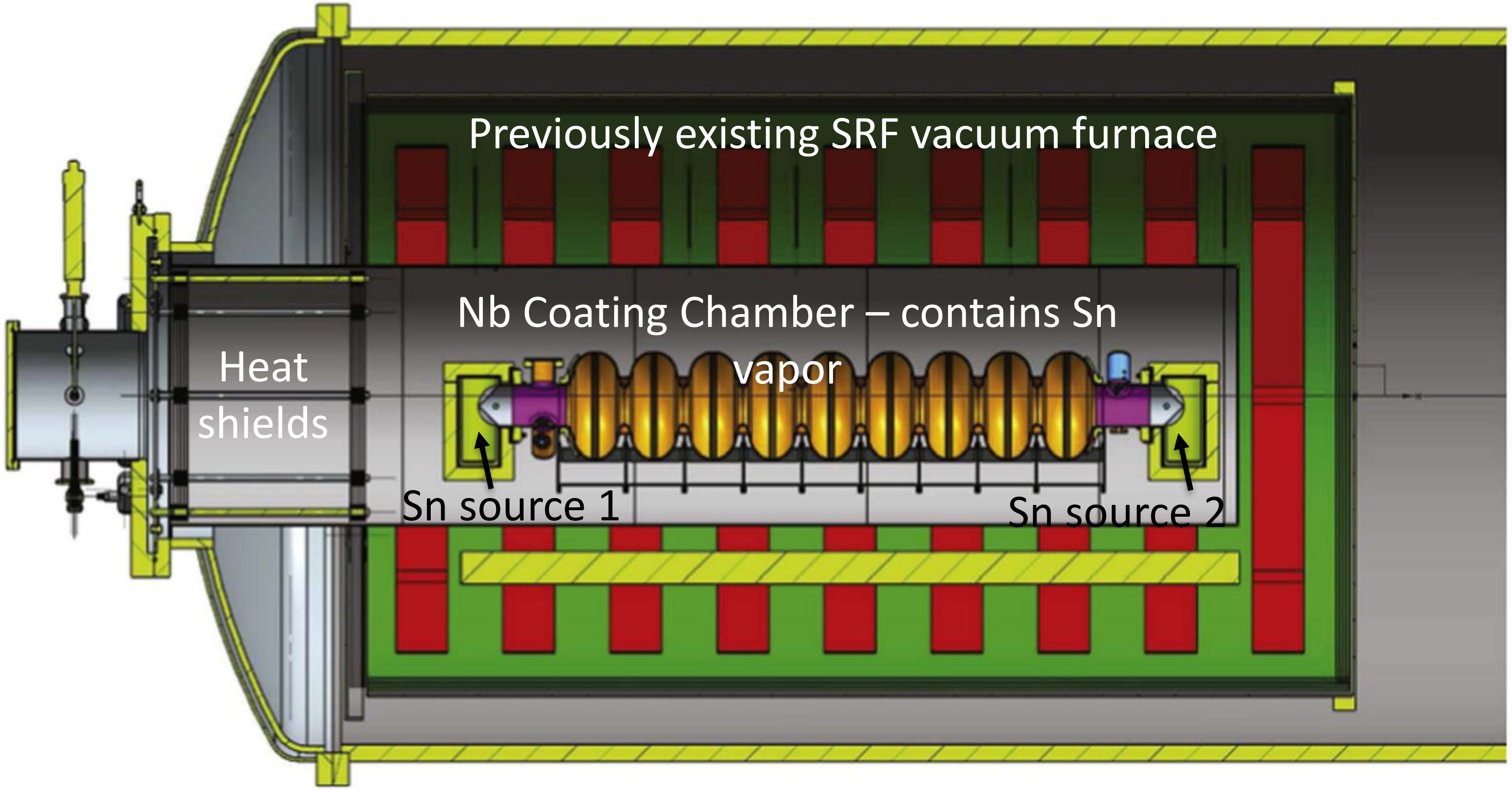


"Siemens" configuration, i.e., no secondary heater for the tin source

Fermilab Nb_3Sn Coating System

Sam Posen

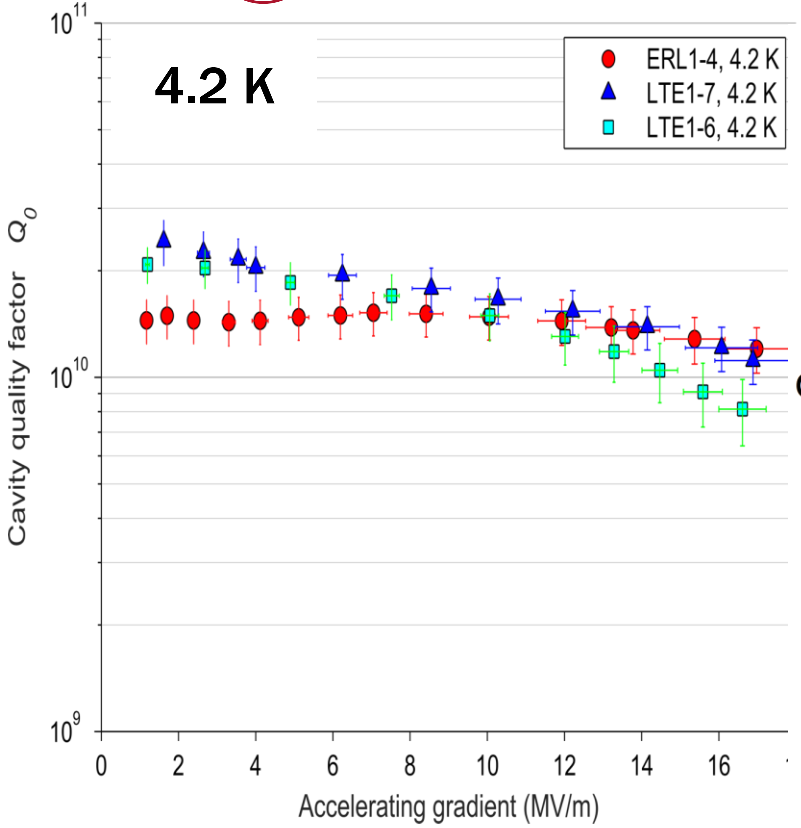
Fermilab



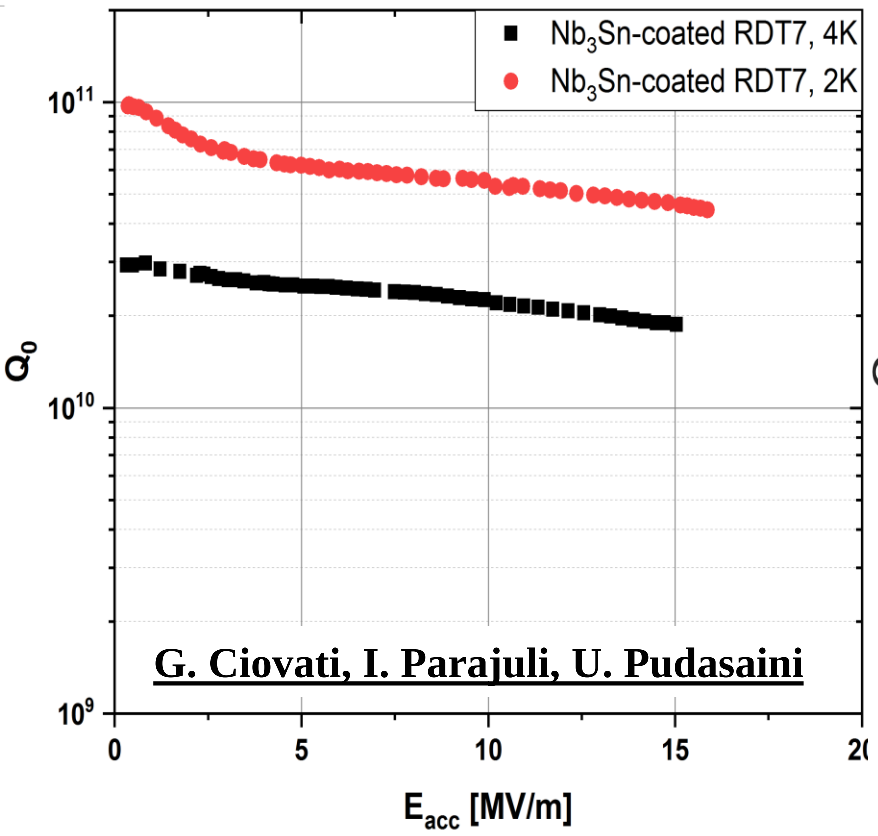
"Wuppertal" configuration, i.e., with secondary heater for the tin source

1.3 GHz Nb_3Sn Cavity Performance: JLab and Fermilab

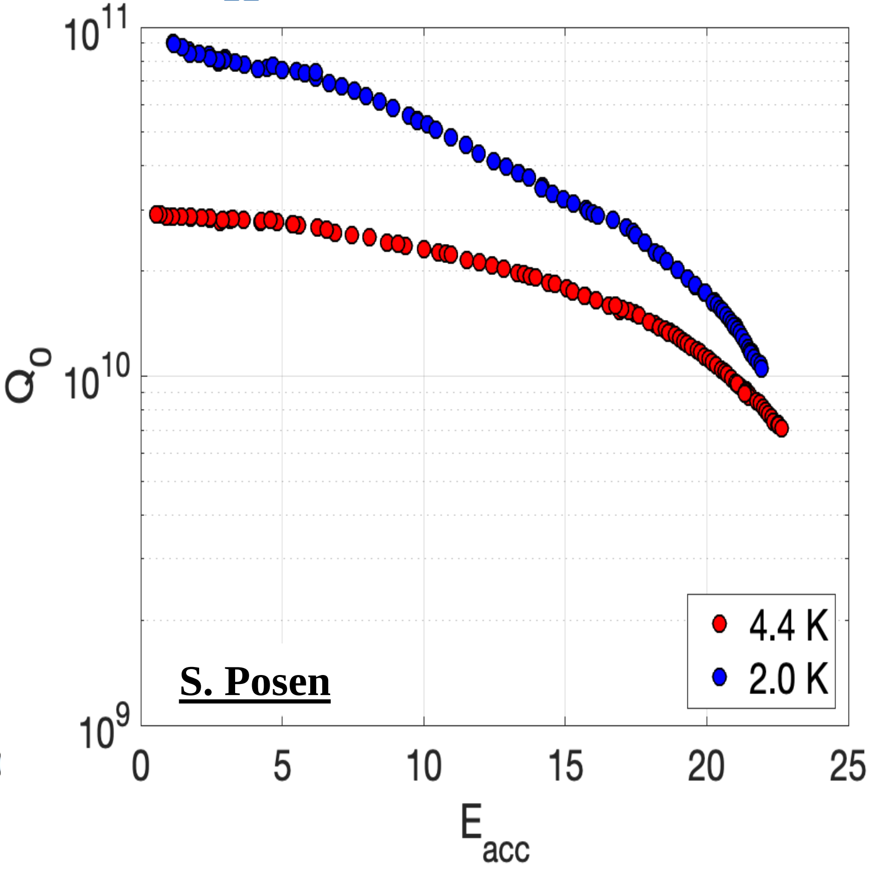
Cornell University



Jefferson Lab

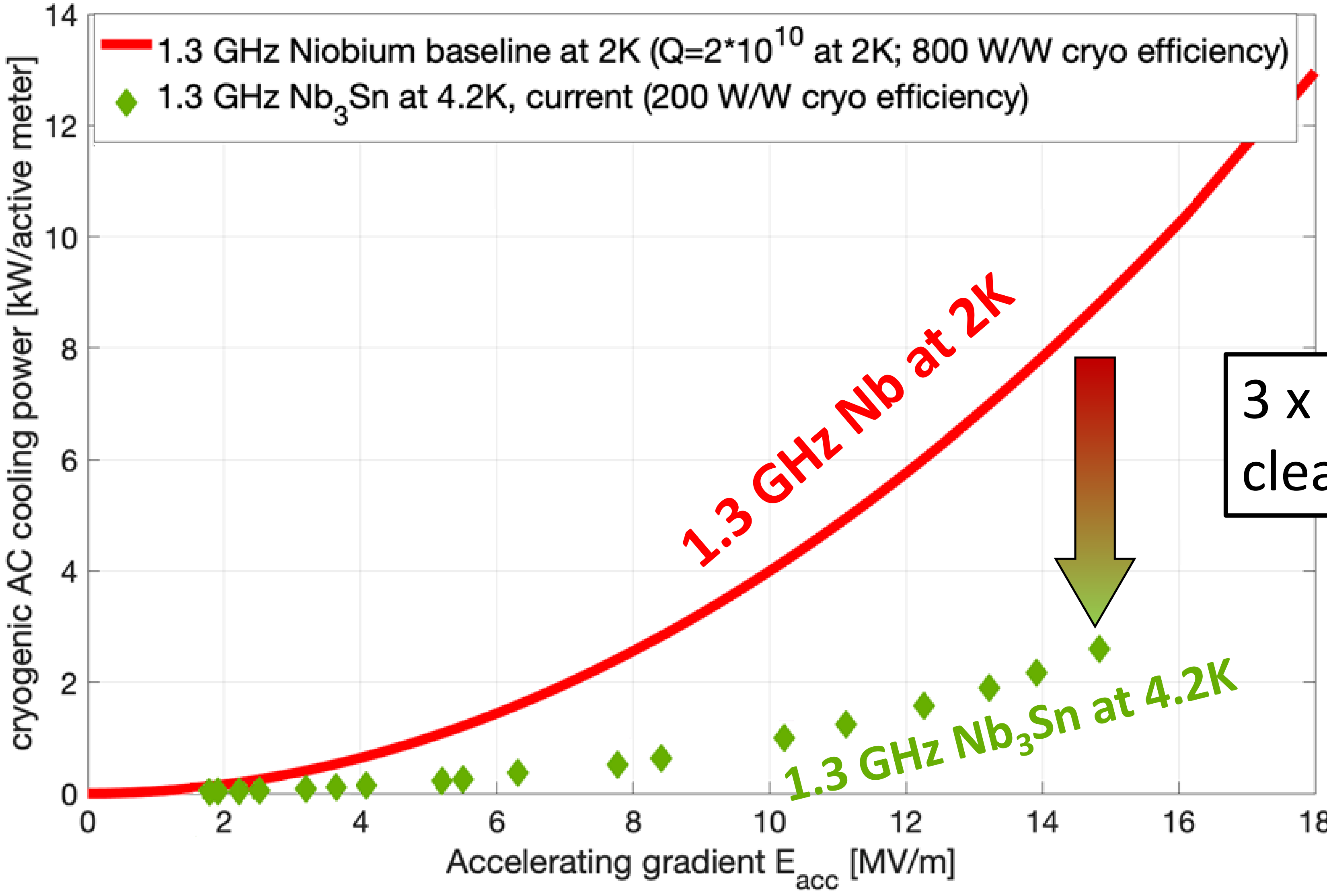


Fermilab



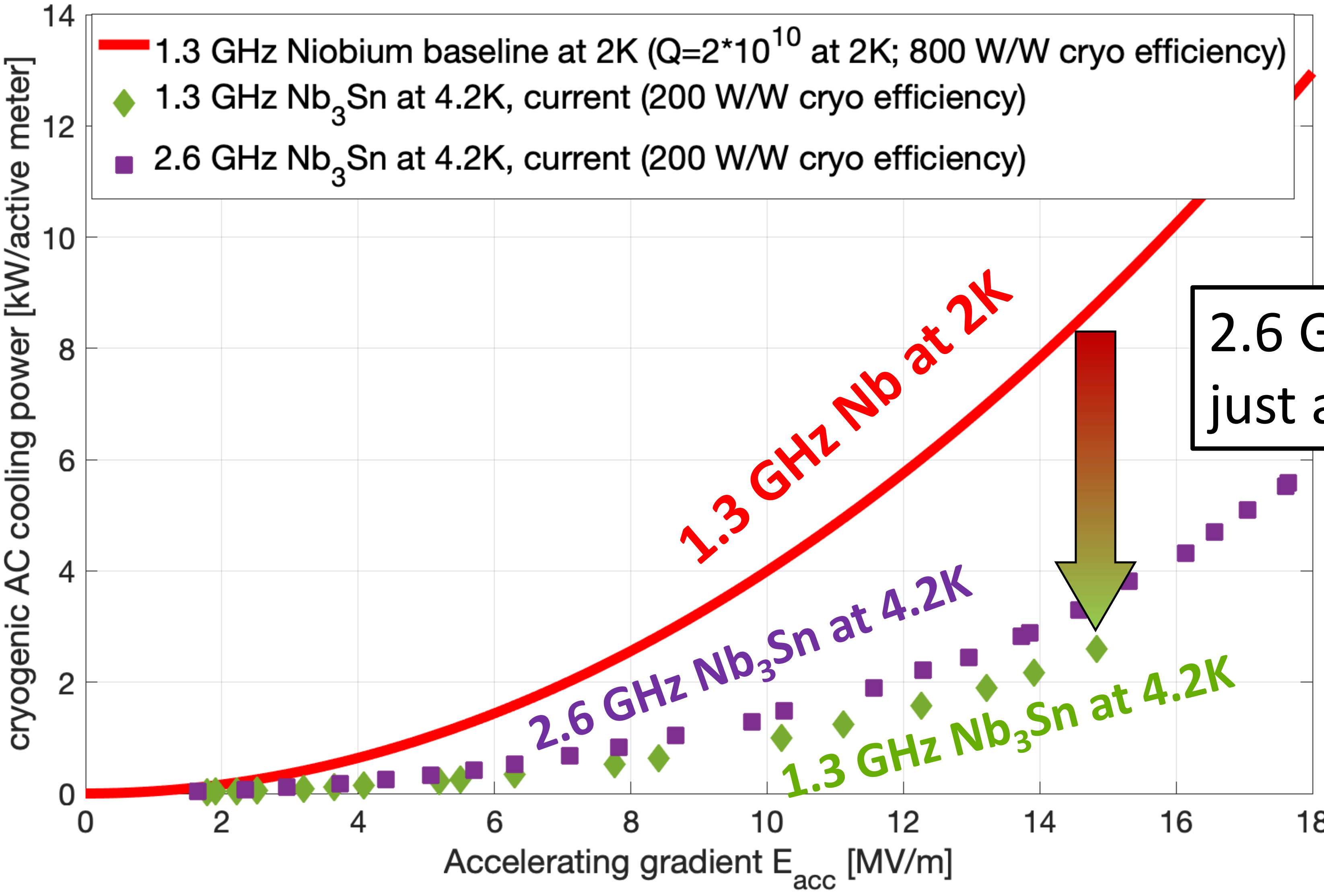
- Very reproducible performance
- ~4K operation with unprecedented Q >10^{10} at typical CW operating fields

Cryo-Efficiency



3 x efficient than clean niobium!

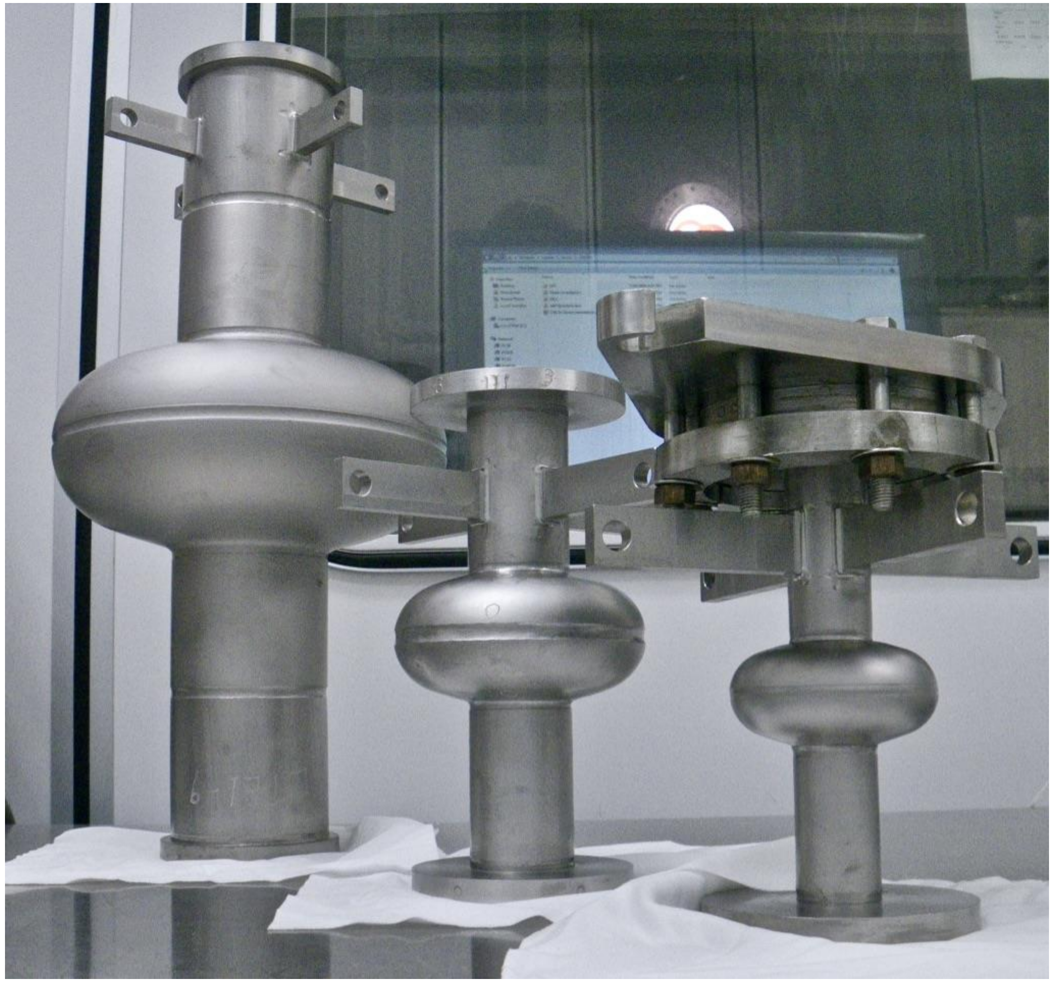
Cryo-Efficiency

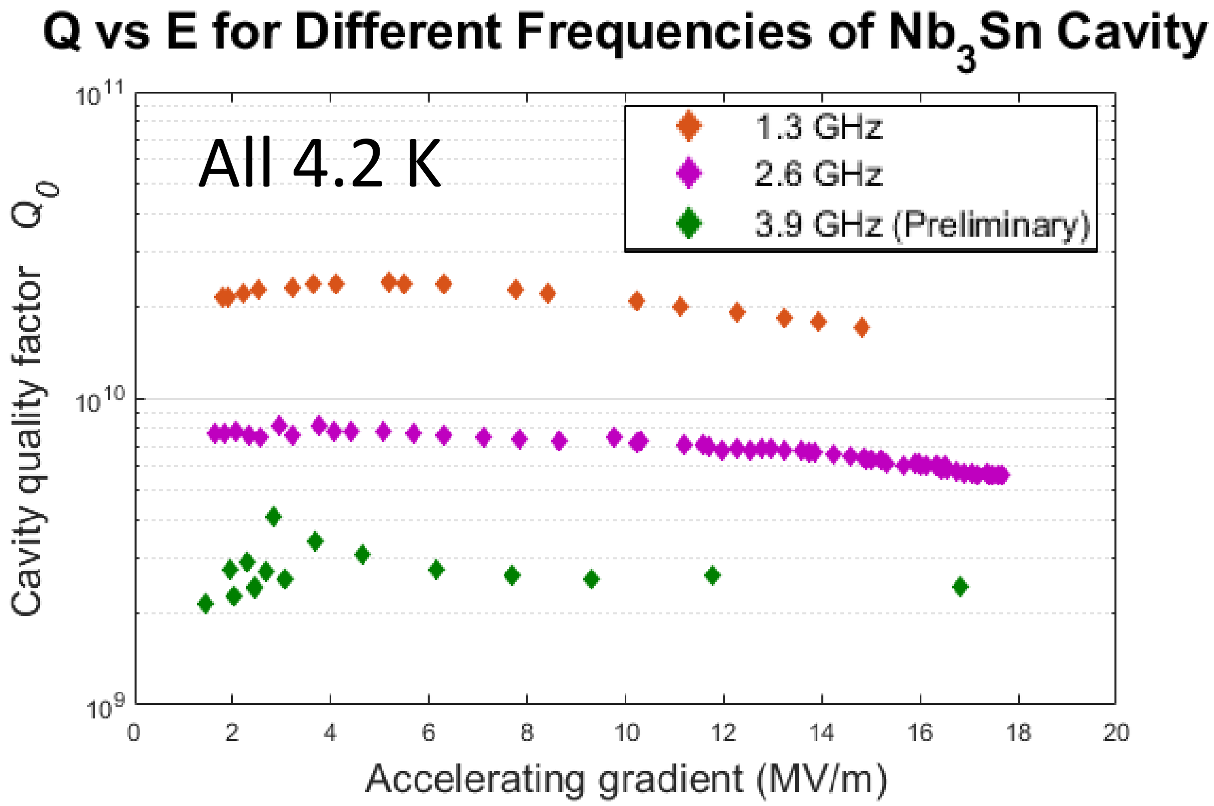


2.6 GHz efficiency just as good!

High Frequency Nb_3Sn Cavities

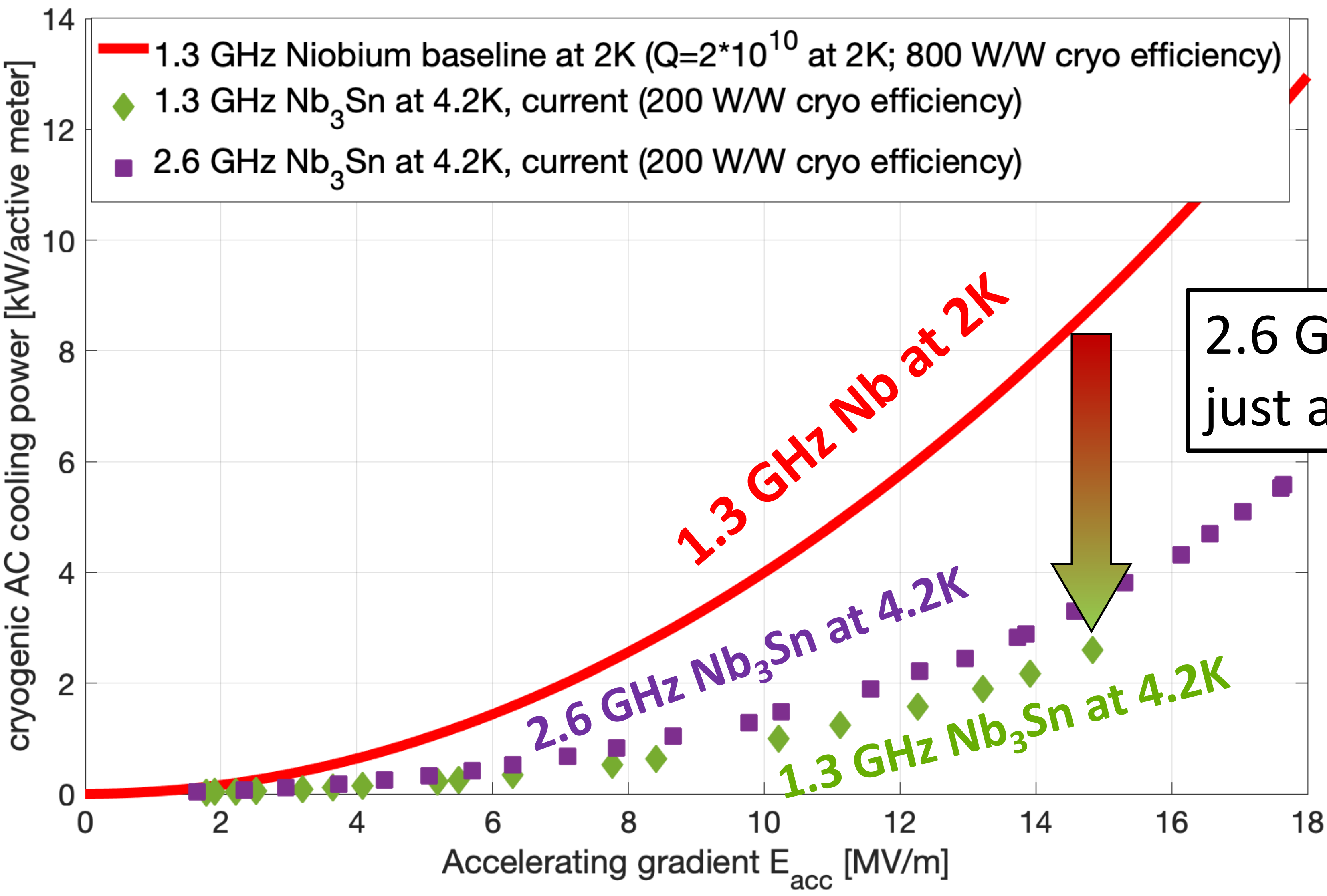
High Frequency Nb_3Sn





Higher frequency -> Smaller cavities-> Material savings

Cryo-Efficiency

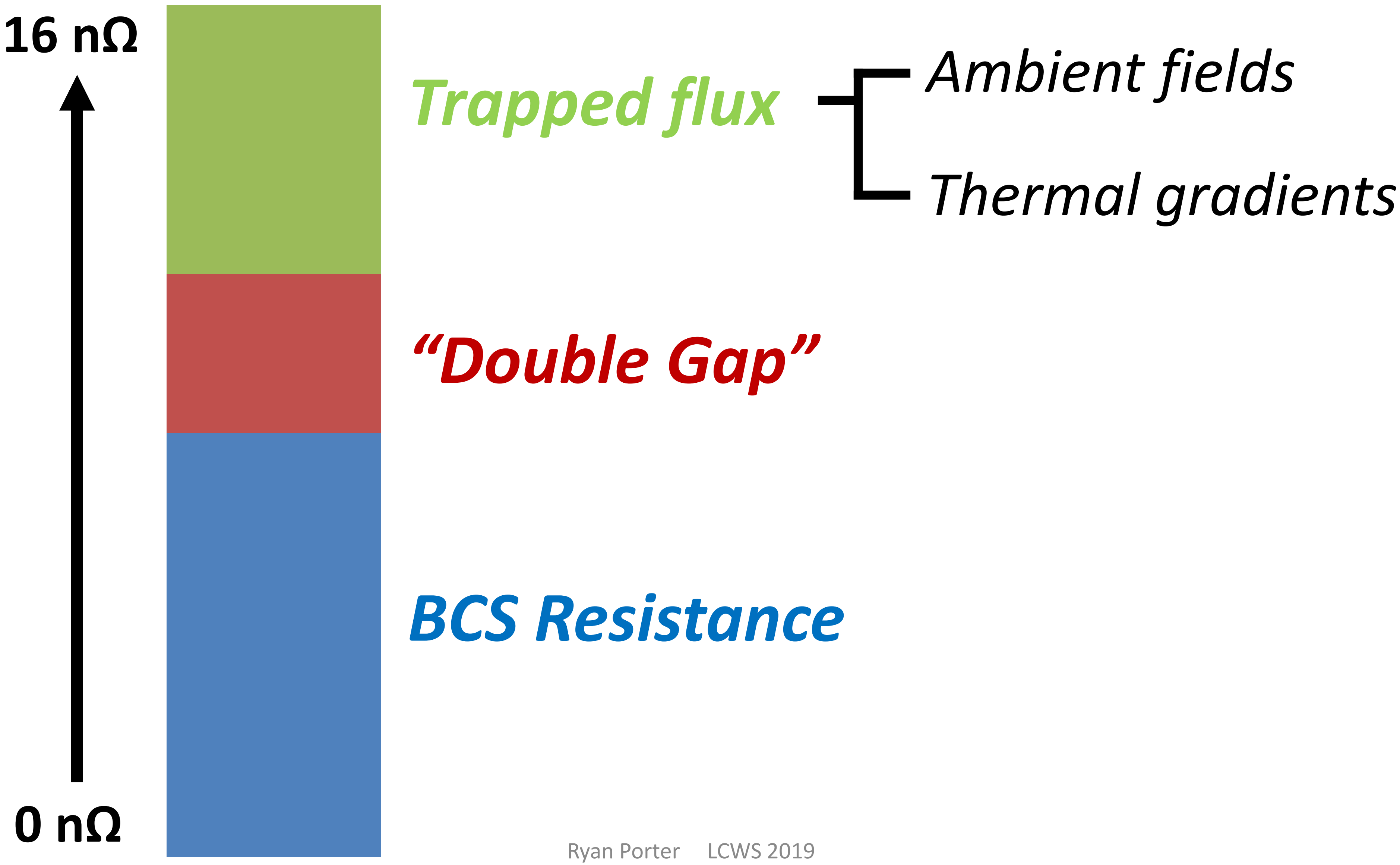


2.6 GHz efficiency just as good!

Increasing Q?

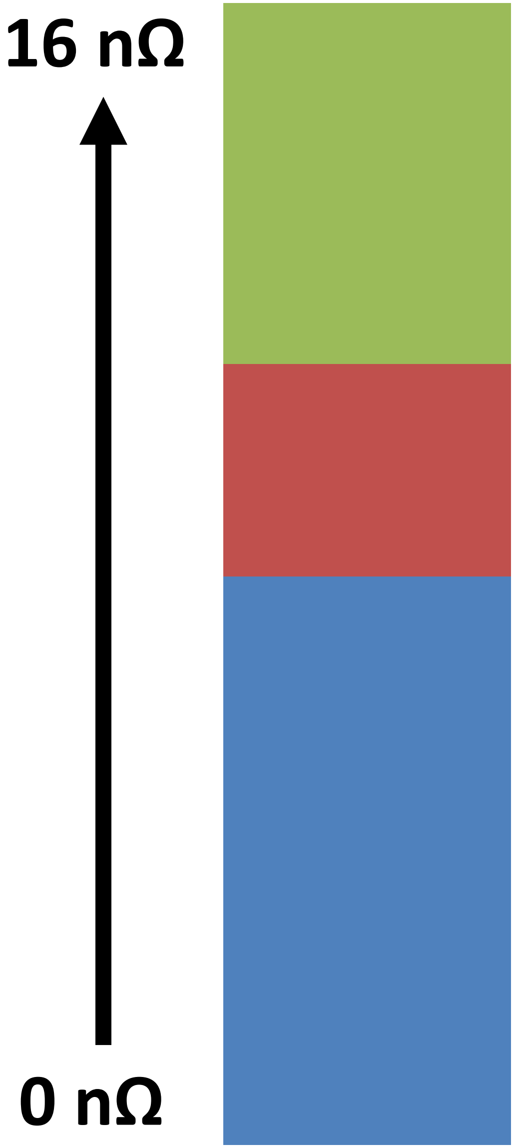
Breaking down the *Q*

Surface resistance at 4.2 K and 10 MV/m



Breaking down the *Q*

Surface resistance at 4.2 K and 10 MV/m



Trapped flux
- *Ambient fields*
- *~~Thermal gradients~~*

"Double Gap"

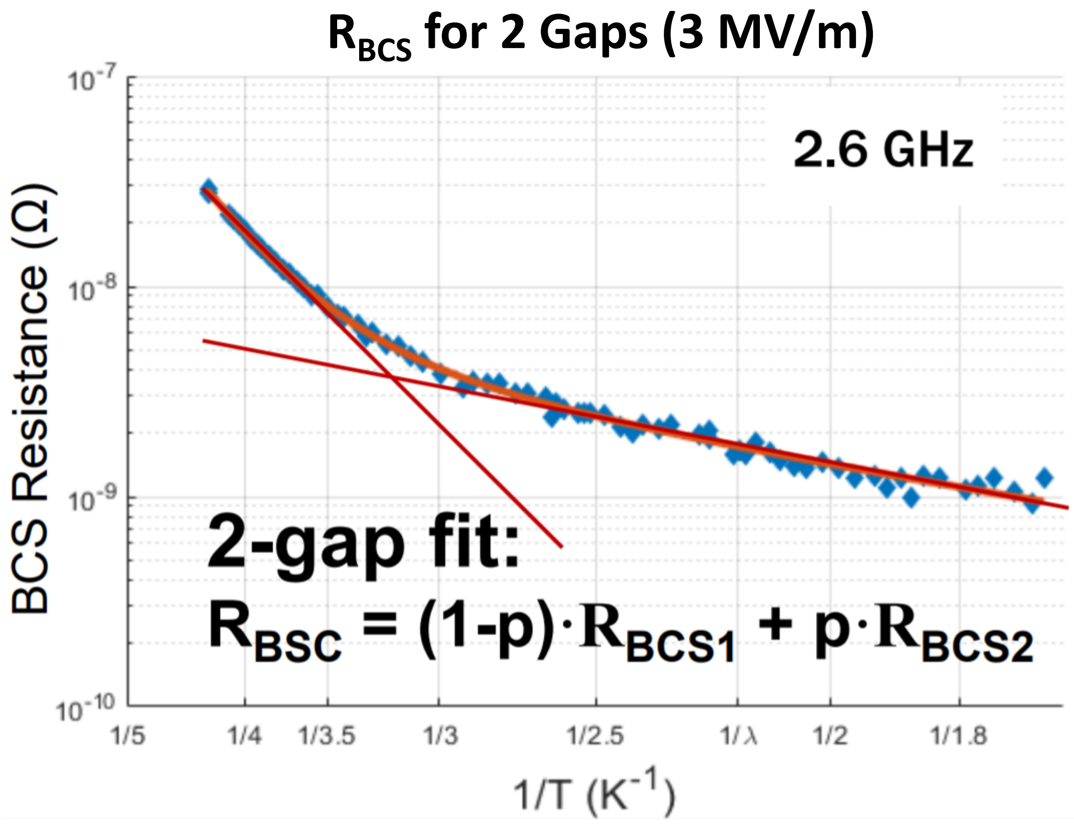
BCS Resistance

Good magnetic shielding can eliminate

"Double Gap"

- "BCS" resistance shows two slope behavior
- Cause still under investigation:
  - Well fit for "2-gap" BCS
    - Multiple regions of "Sn depleted" Nb_3Sn?
  - Dirty surface layers?

- **Good news:**
  - Removing will increase Q:
    - $Q_{2.6\text{ GHz, }4.2\text{ K}} \rightarrow 9 \cdot 10^9$
    - $Q_{1.3\text{ GHz, }4.2\text{ K}} \rightarrow 2.3 \cdot 10^{10}$
      $\rightarrow 3.5 \cdot 10^{10}$ with good magnetic shielding



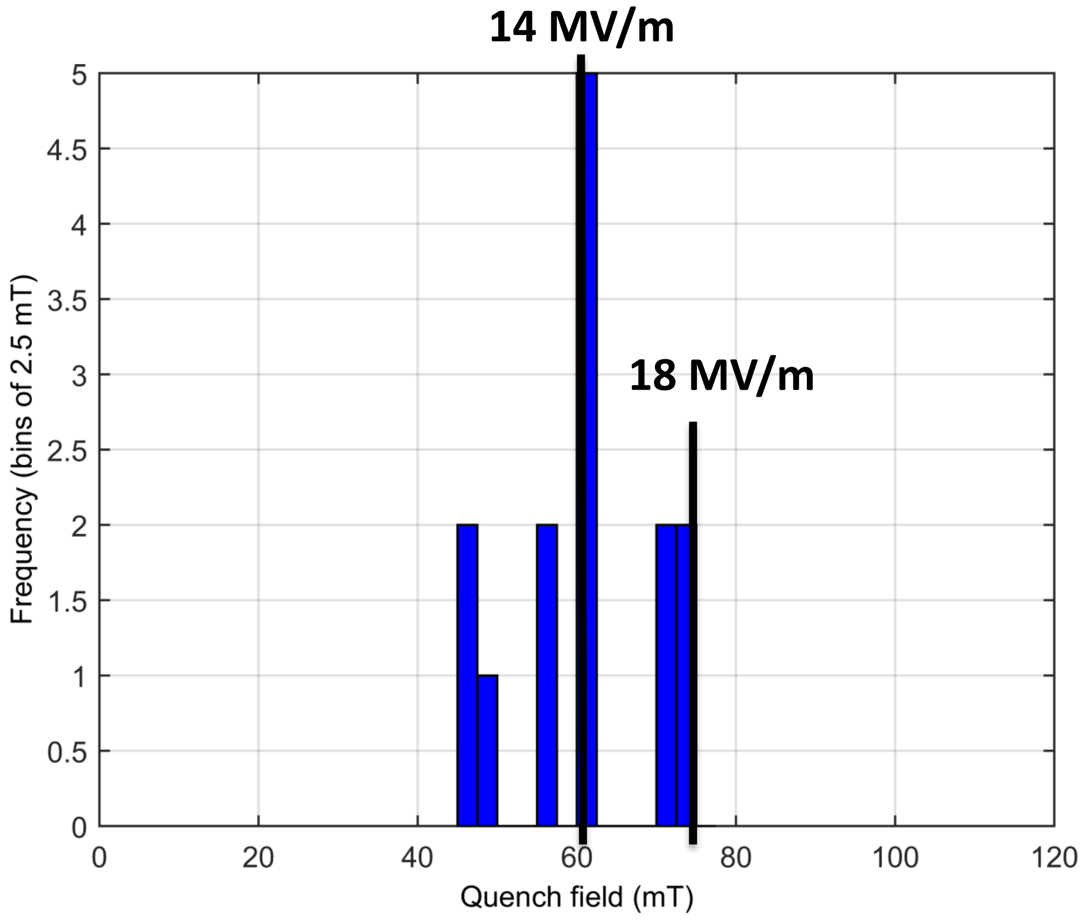
$R_0 \sim 5.5$ nΩ (from trapped magnetic flux)

Increasing E_{acc}

Limitations in quench field

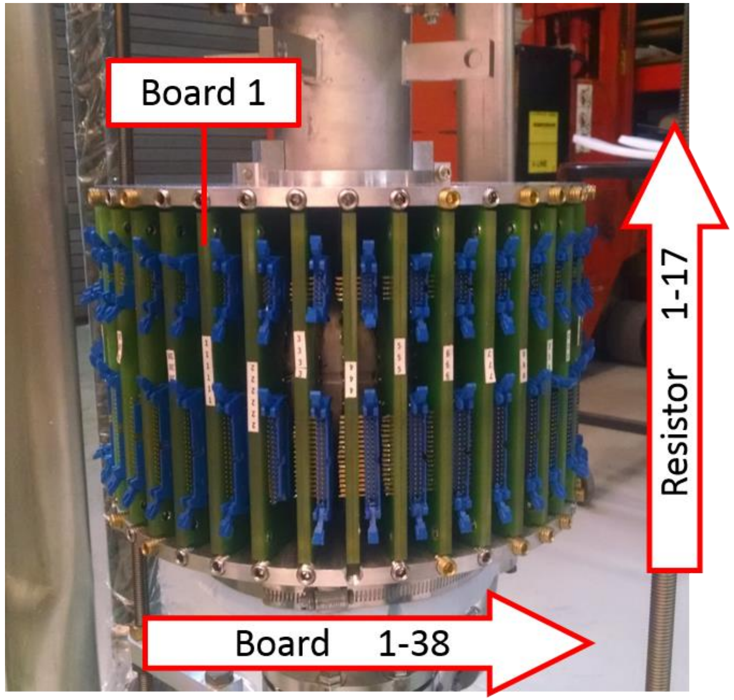
Nb_3Sn cavities consistently quench at fields between **14 and 18 MV/m in CW operation**

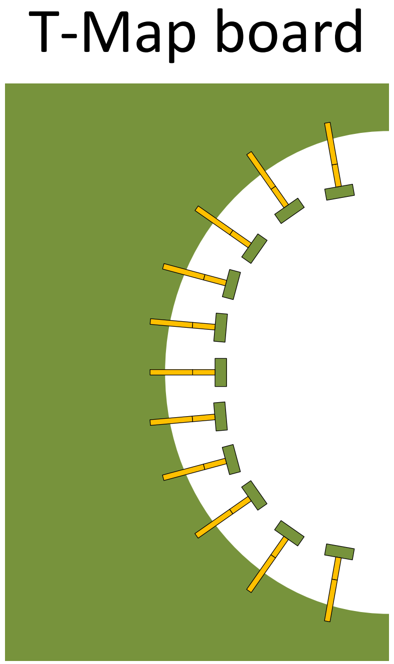
The superheating field suggests we can achieve fields up to **96 MV/m**!

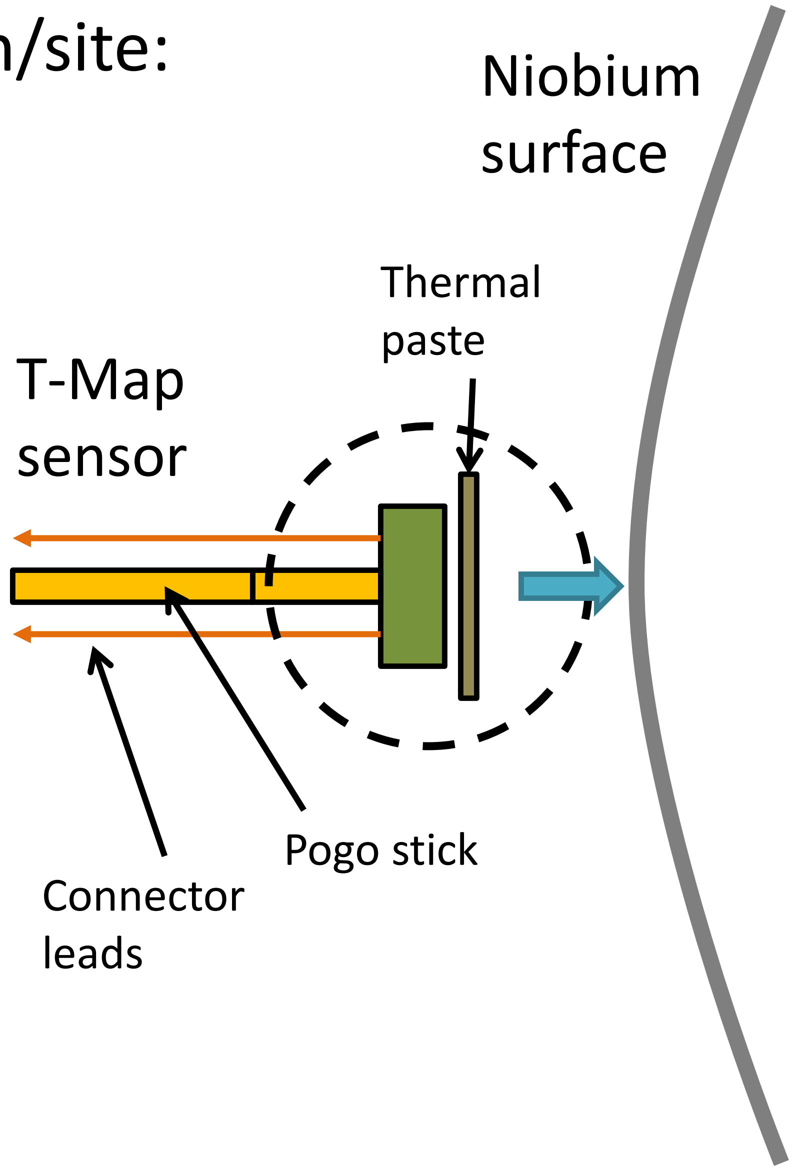


T-Map experiment

Use temperature map to look for quench mechanism/site:

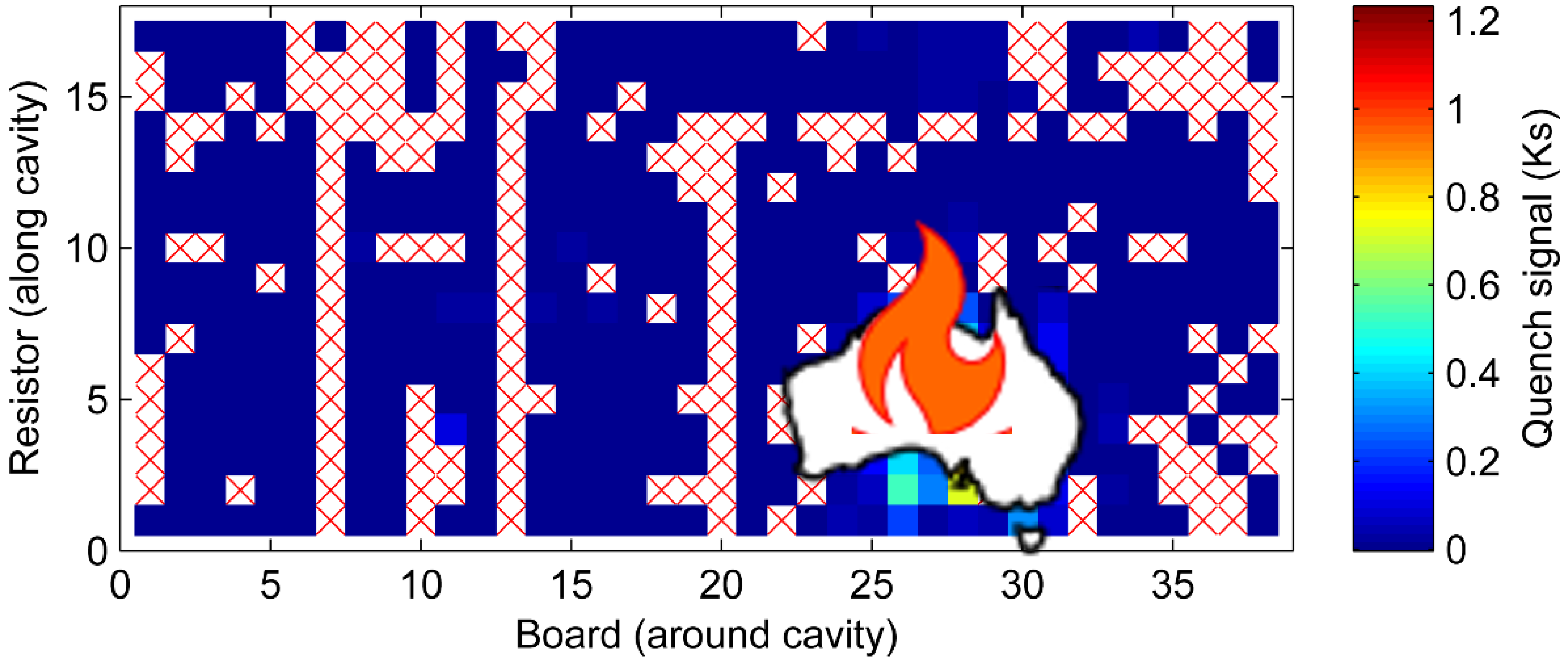






Localised quench

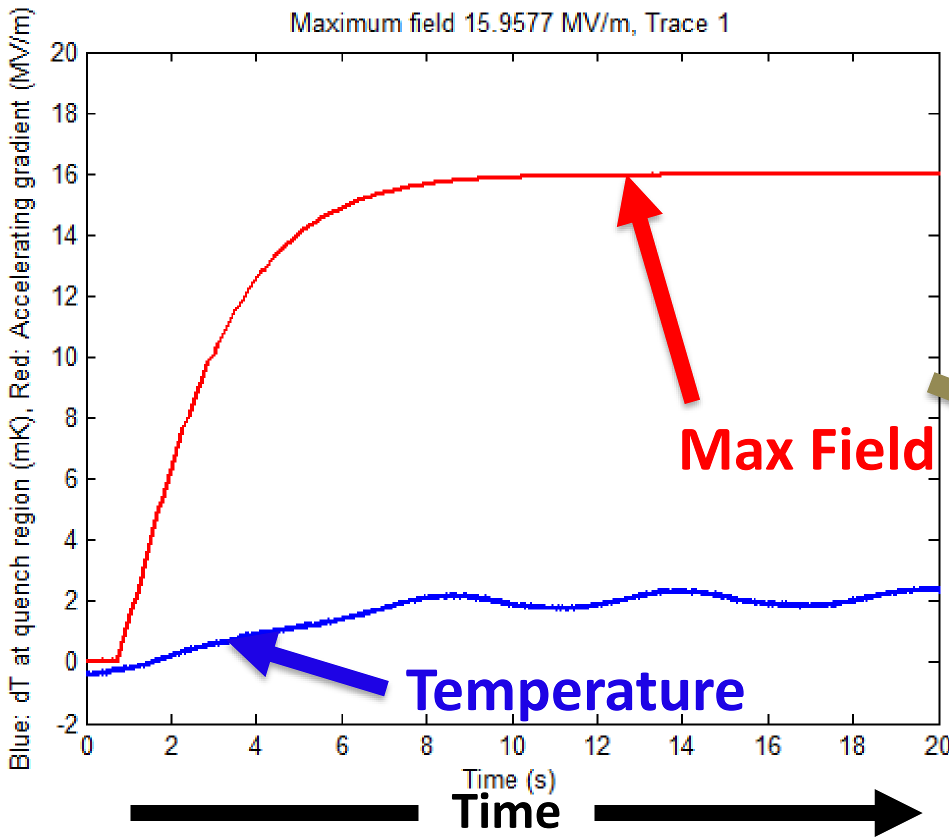
Nb_3Sn cavities are limited by a quench at a localized spot

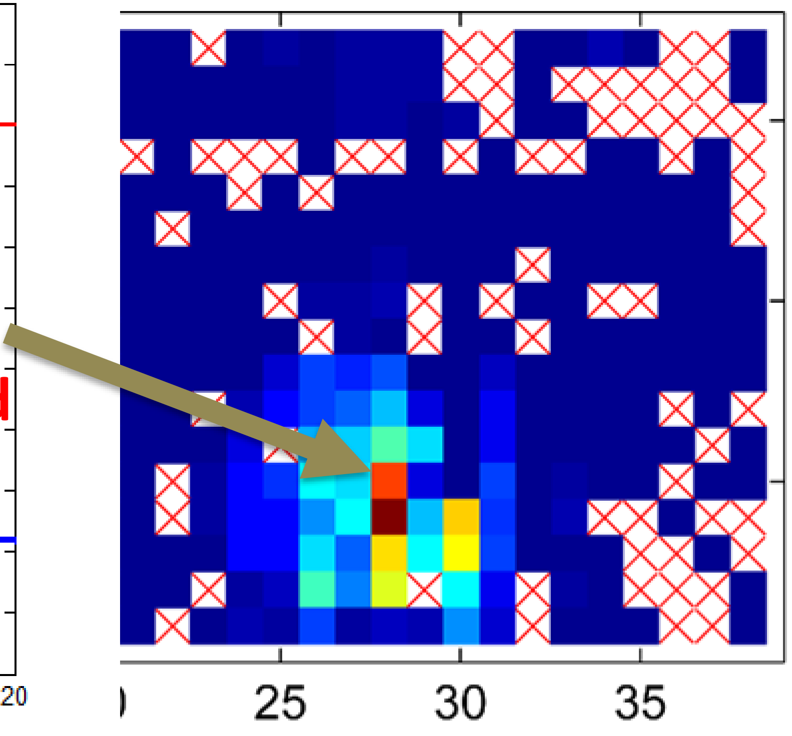


What could be at fault?

Near quench behavior

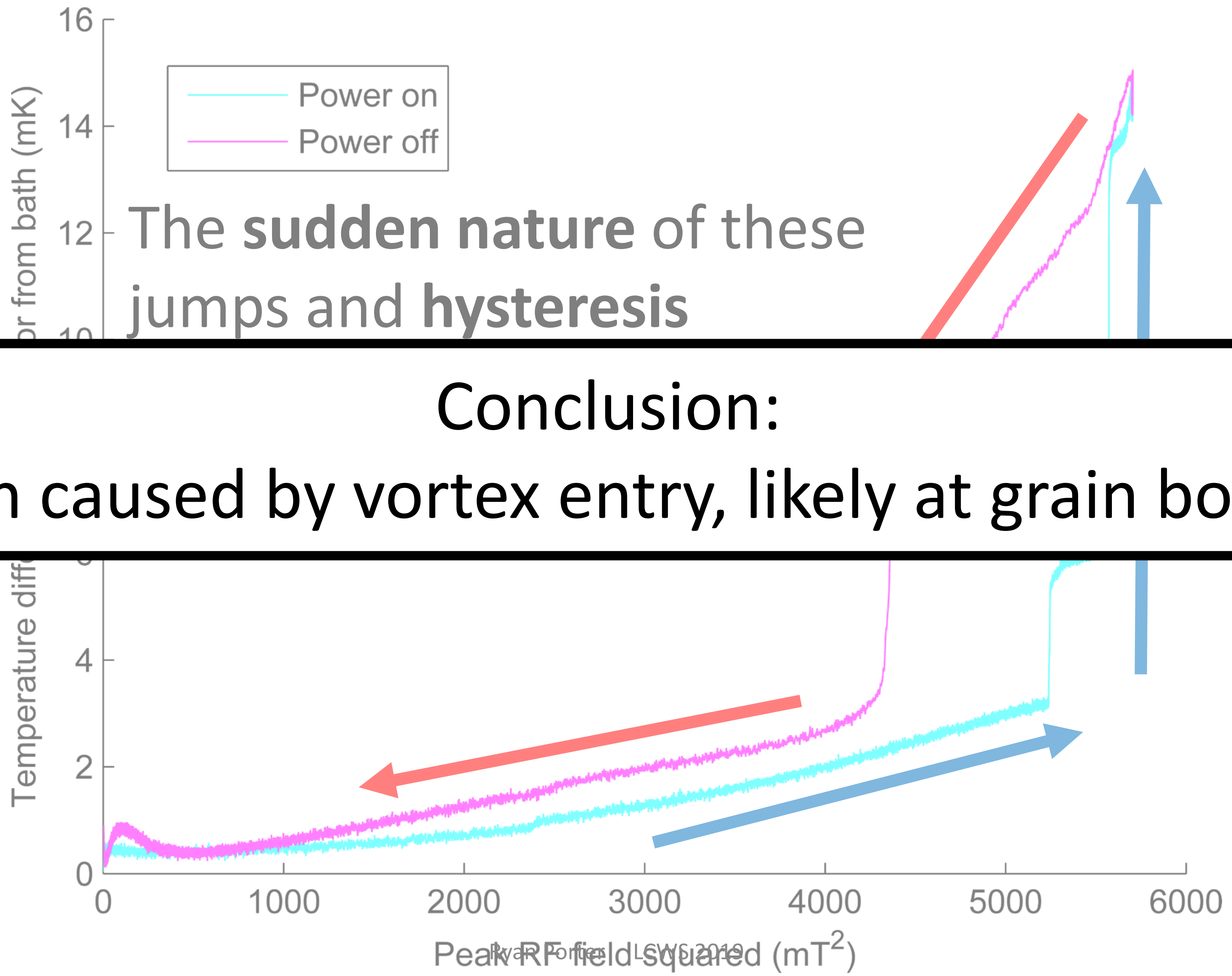
- Measure temperature of sensor near the quench point as field is increased





- Sudden <u>jumps in temperature</u>

Near quench behaviour



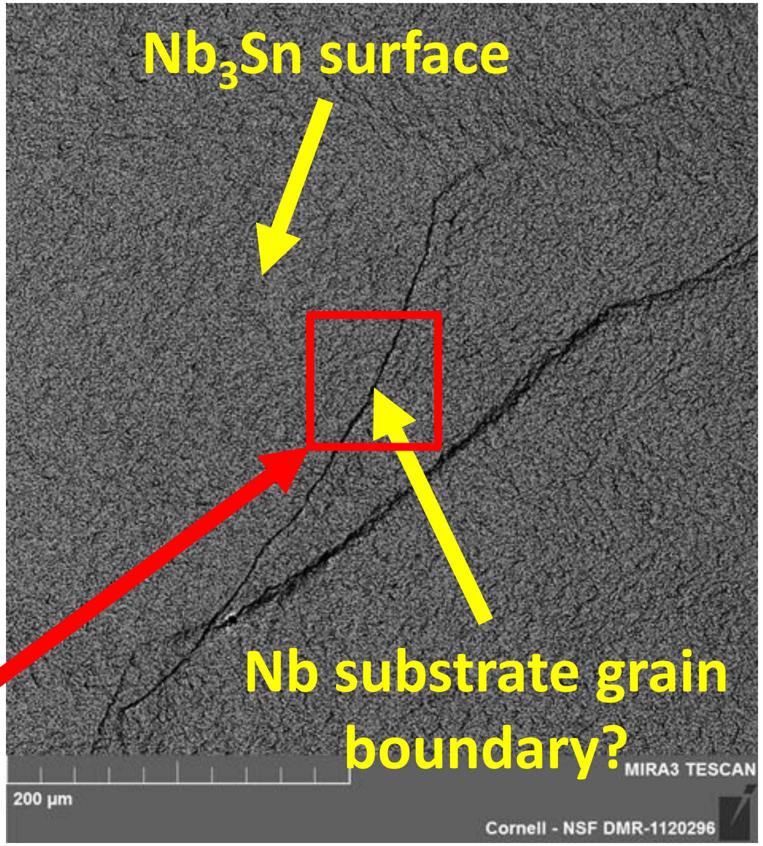
The **sudden nature** of these jumps and **hysteresis**

Conclusion:
Quench caused by vortex entry, likely at grain boundary

Cavity Autopsy – Anything on Surface?

- Cut out this region and examined with microscopy
- Nothing obvious except Nb grain boundary cliff
  - Rough Surface

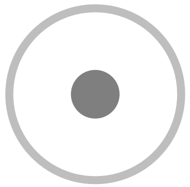
Quench Site



Surface Roughness and Quench Fields

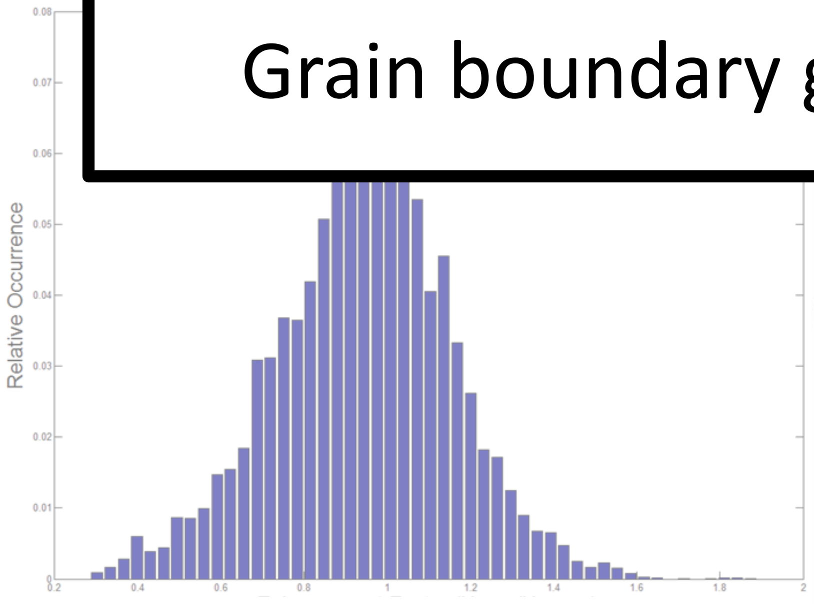
Surface Roughness:

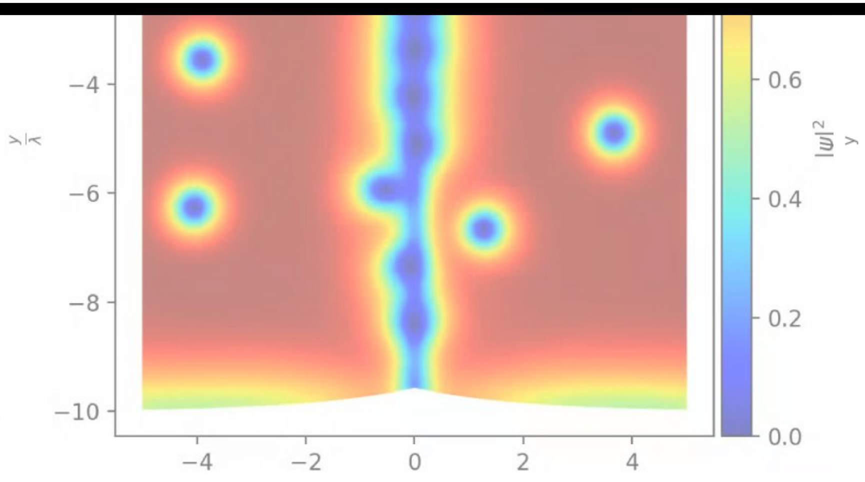
- Rough surface → increased magnetic field on some surfaces
  - Quench field decreased by 1/3 (?)
- Poor grain boundary geometry can decrease magnetic flux entry barrier
  - A. R. Pack, M. Transtrum (BYU): SRF'19: MOP017

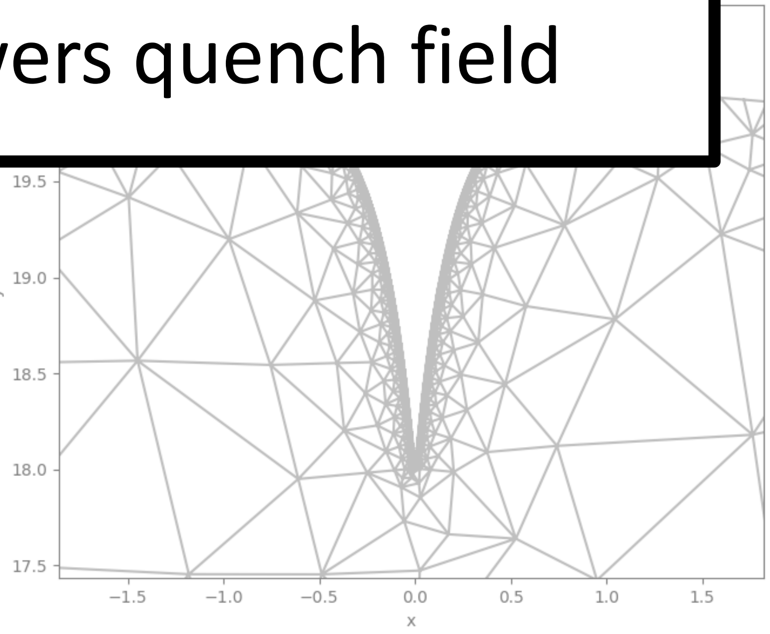


Conclusion:

Grain boundary geometry/roughness lowers quench field

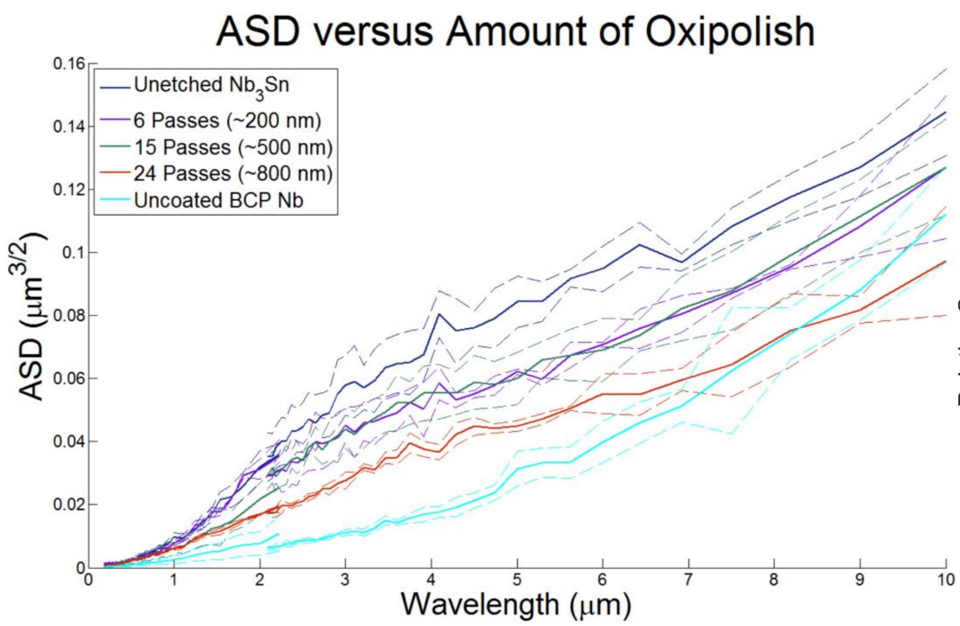


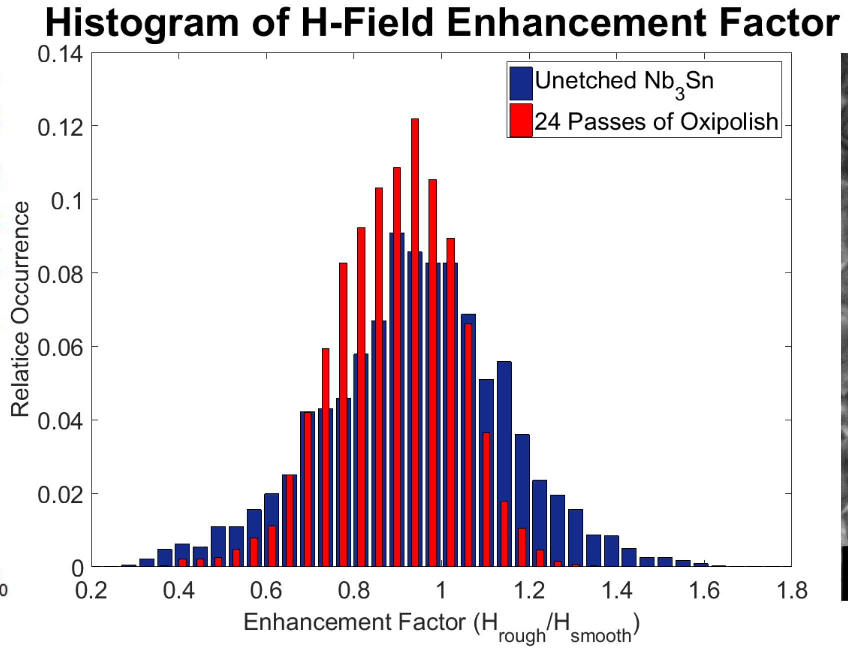


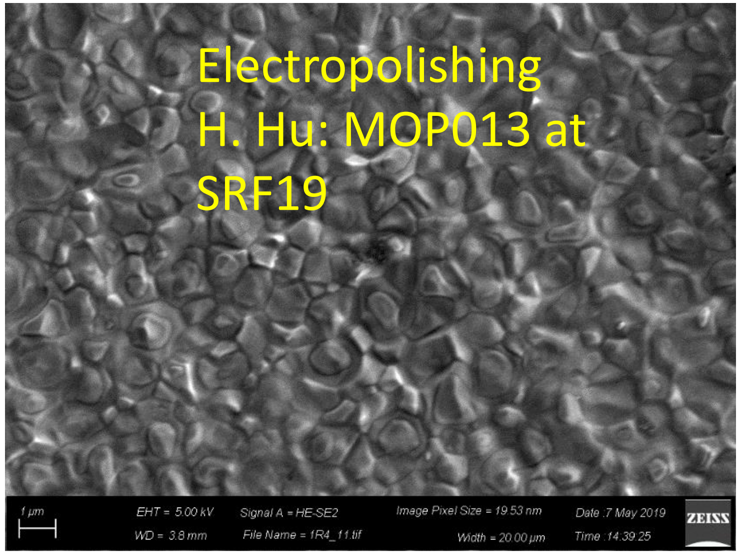


Surface Polishing

- Developing surface treatments to reduce surface roughness
- Early result: Oxypolishing **halves roughness and surface field enhancement** with 800 nm removal

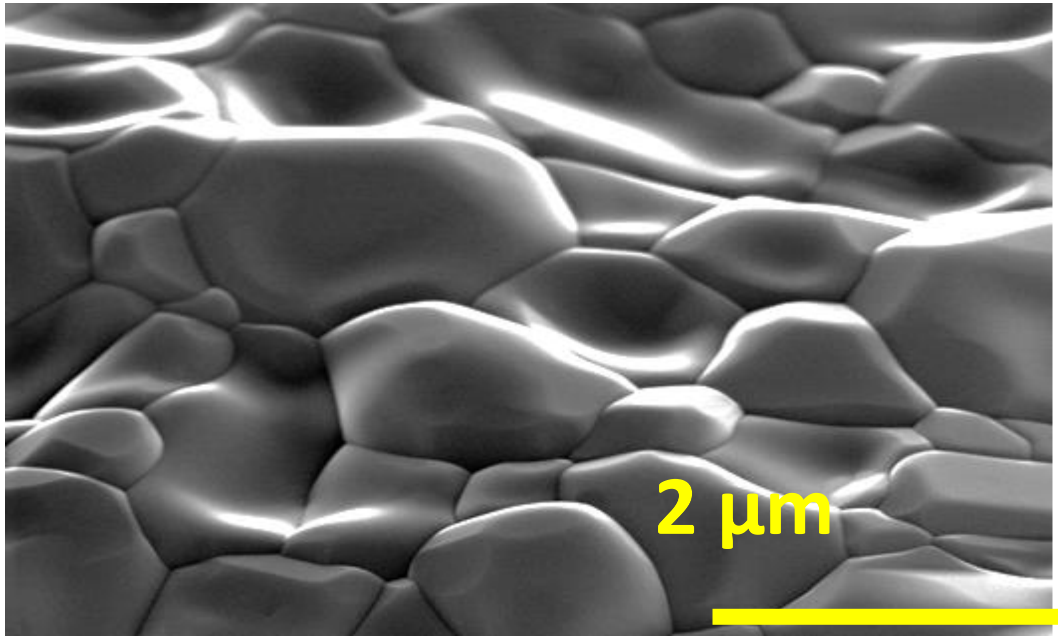




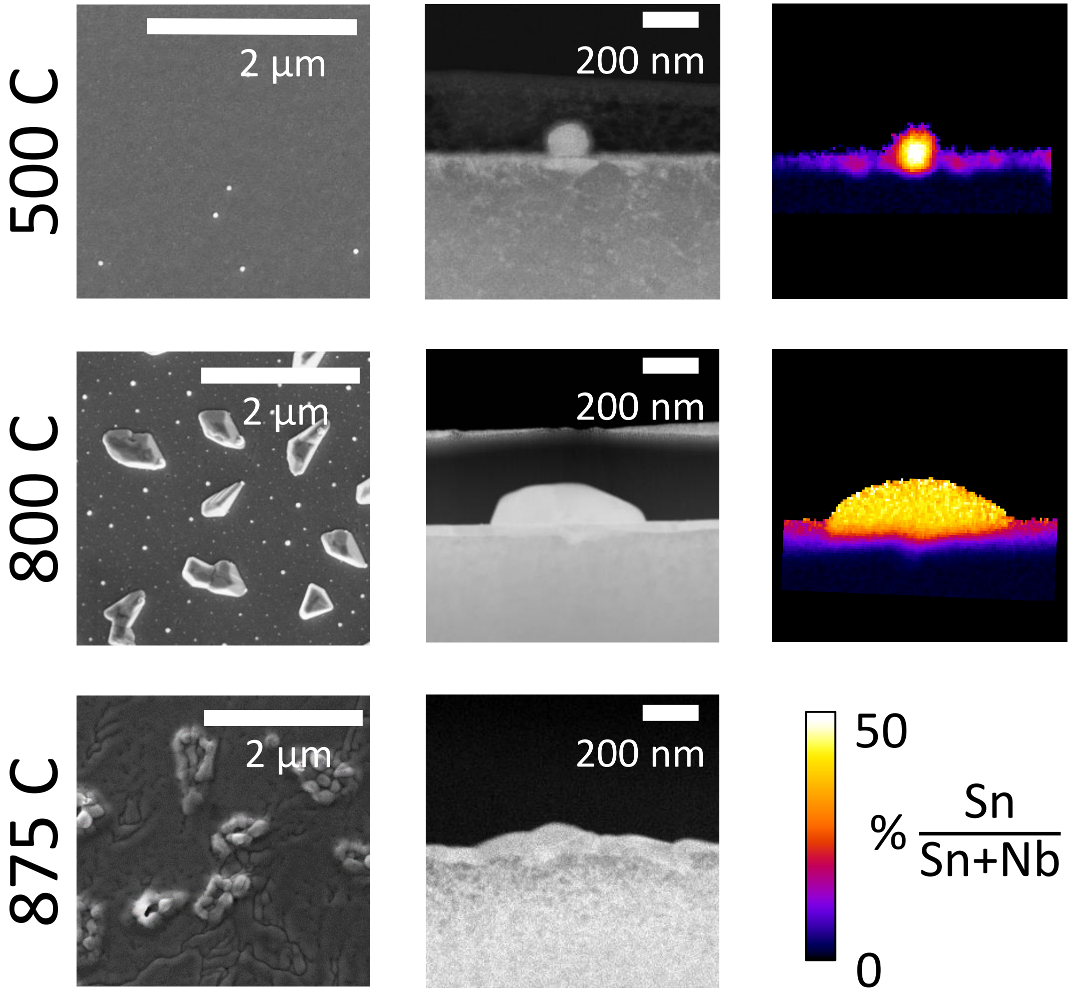


Why is Nb_3Sn Rough?

- Nb_3Sn roughness comes from growth
  - Bad Sn nucleation -> rough surface
  - Good Sn nucleation -> smooth surface



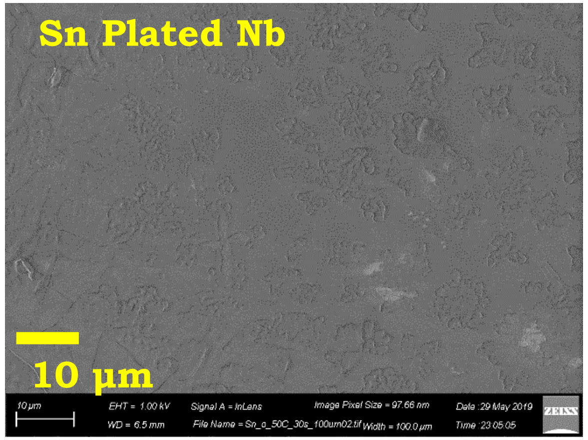
Nb_3Sn Growth:



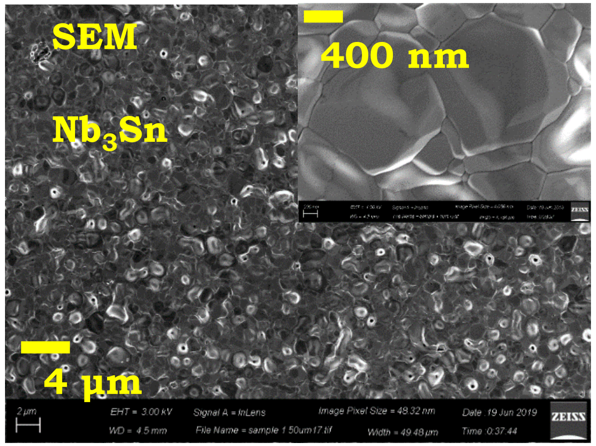
Sn Electroplating

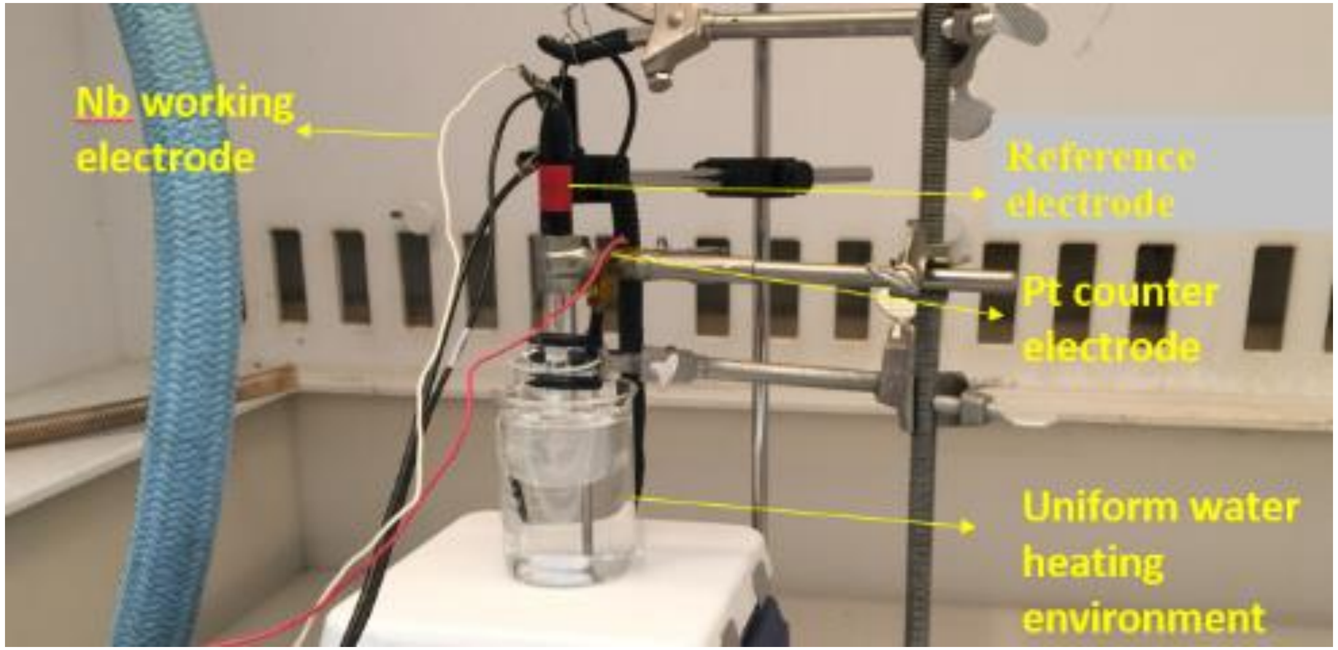
Zeming Sun (Cornell):

- Electroplate Sn onto Nb before heat treatment
  - > Grow smoother Nb_3Sn



Heat Treatment

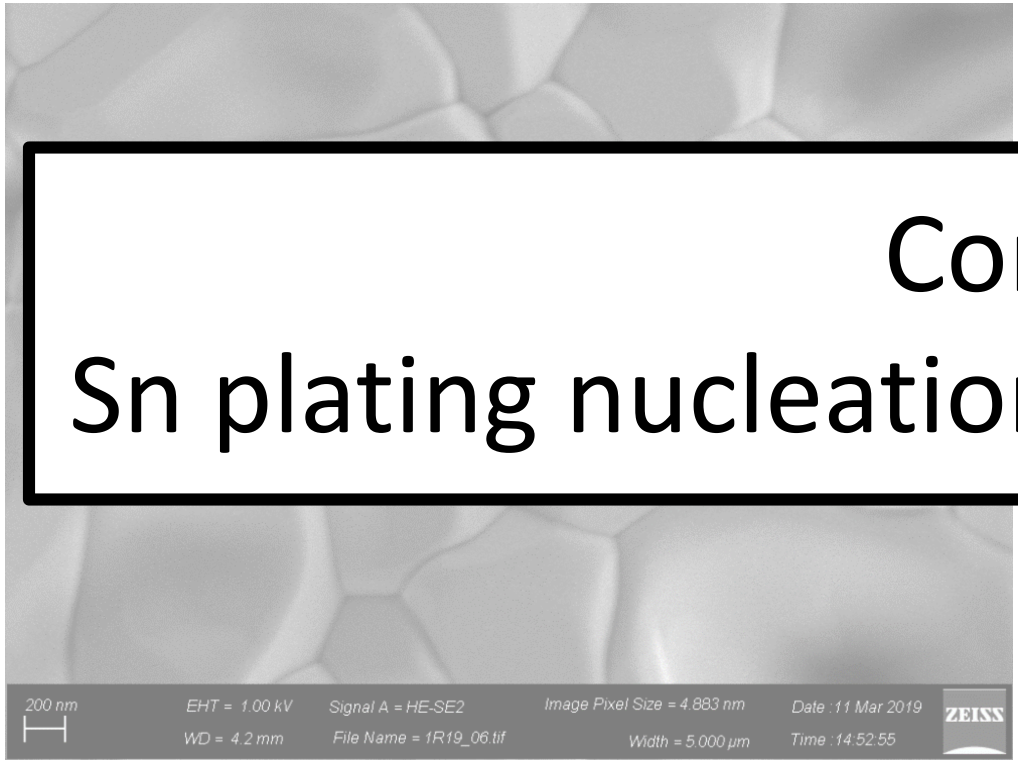


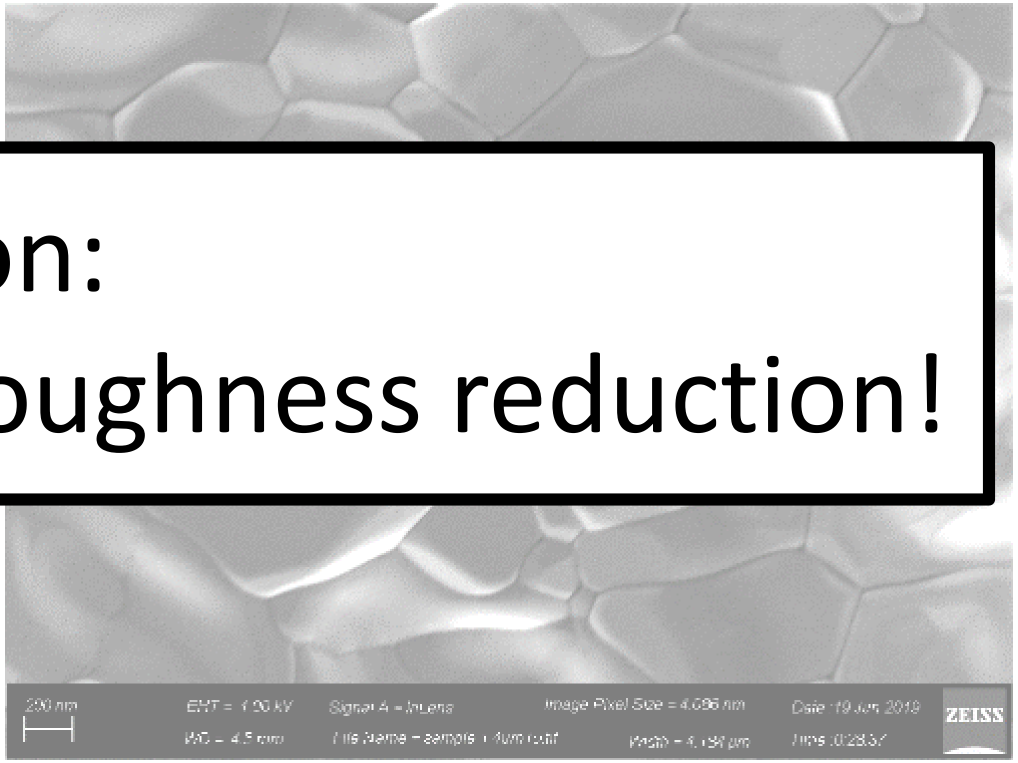


Sn Electroplating

Sn_2Cl Nucleation → "Sn Plating Nucleation"

$R_a \sim 300$ nm → $R_a \sim 70$ nm





Conclusion:

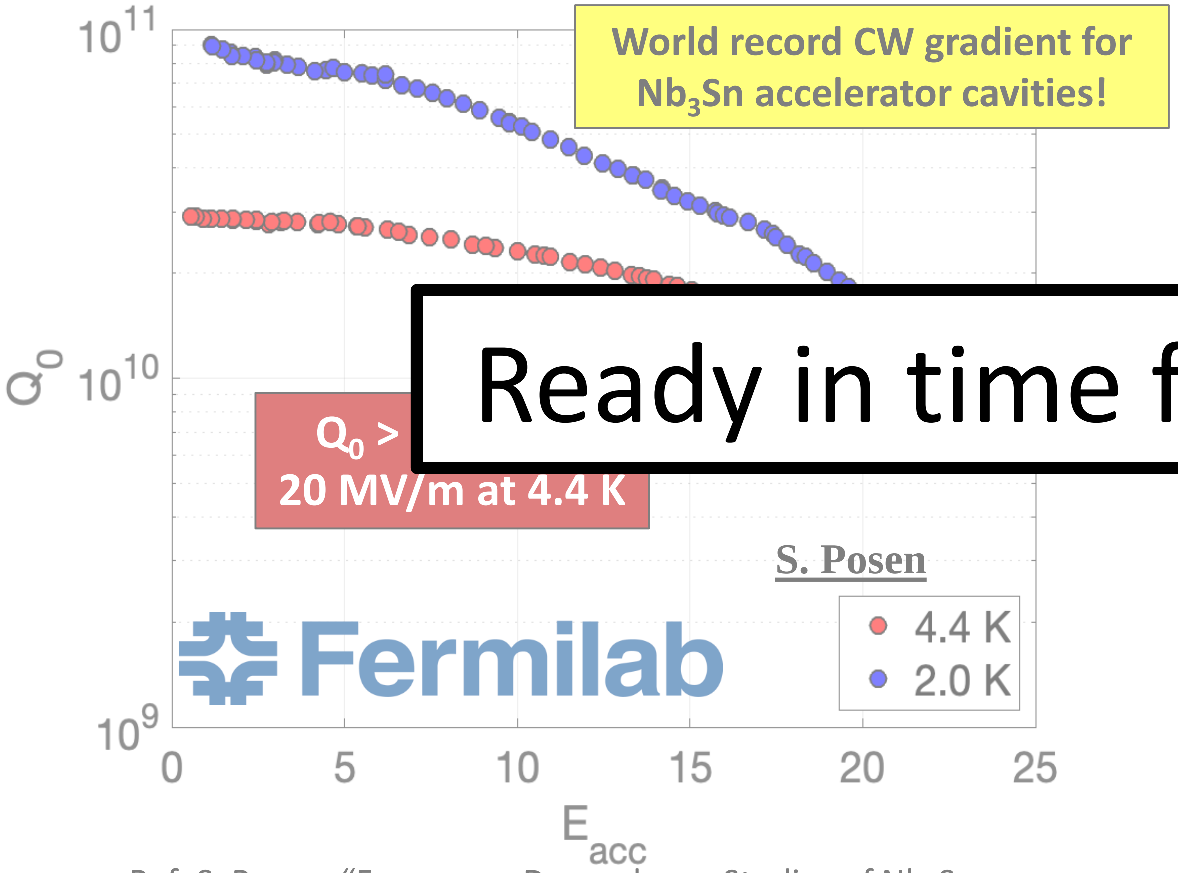
Sn plating nucleation 5 x roughness reduction!

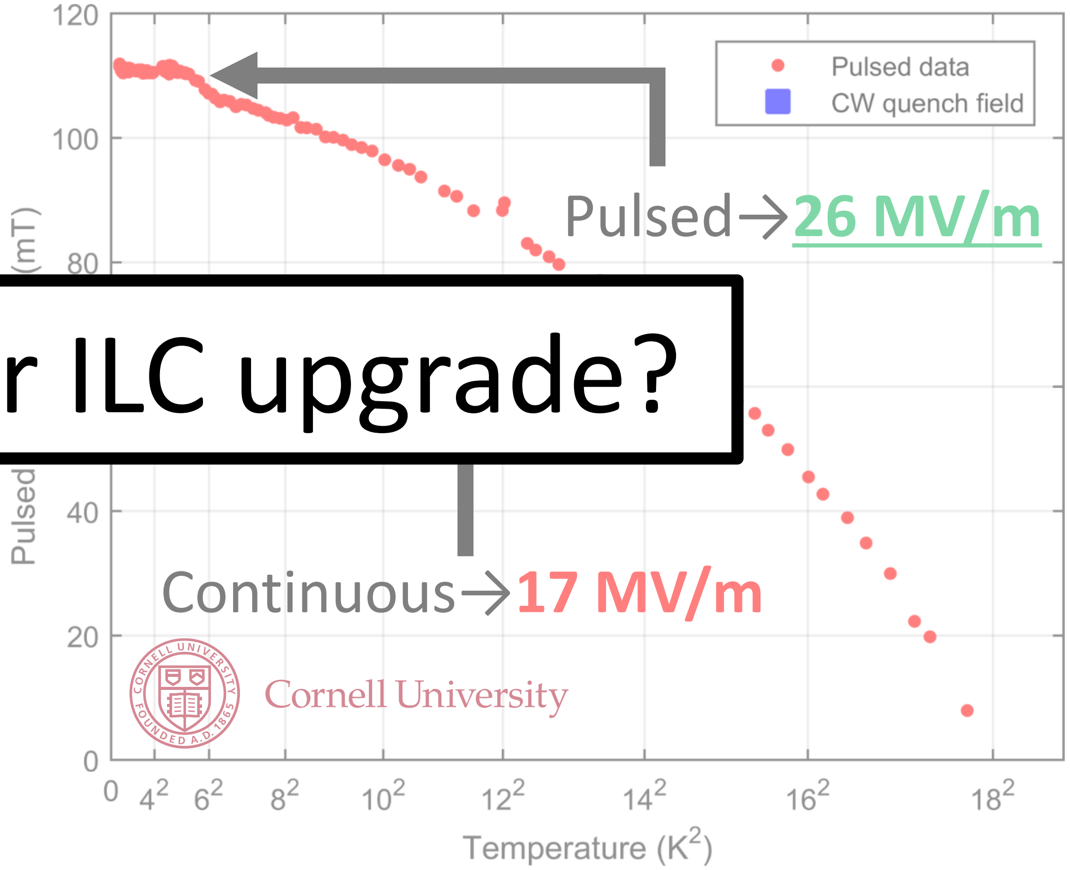
Next step: Grow entire cavity using Sn plating

Outlook

Nb_3Sn Outlook: Making Great Progress!

- Sam Posen (FNAL) reached **22 MV/m** in CW operation (Nb_3Sn world record)!
- **Pulsed** operation can reach **25 MV/m**
  - Does not (yet) reach ILC spec. but reaches old TESLA spec.



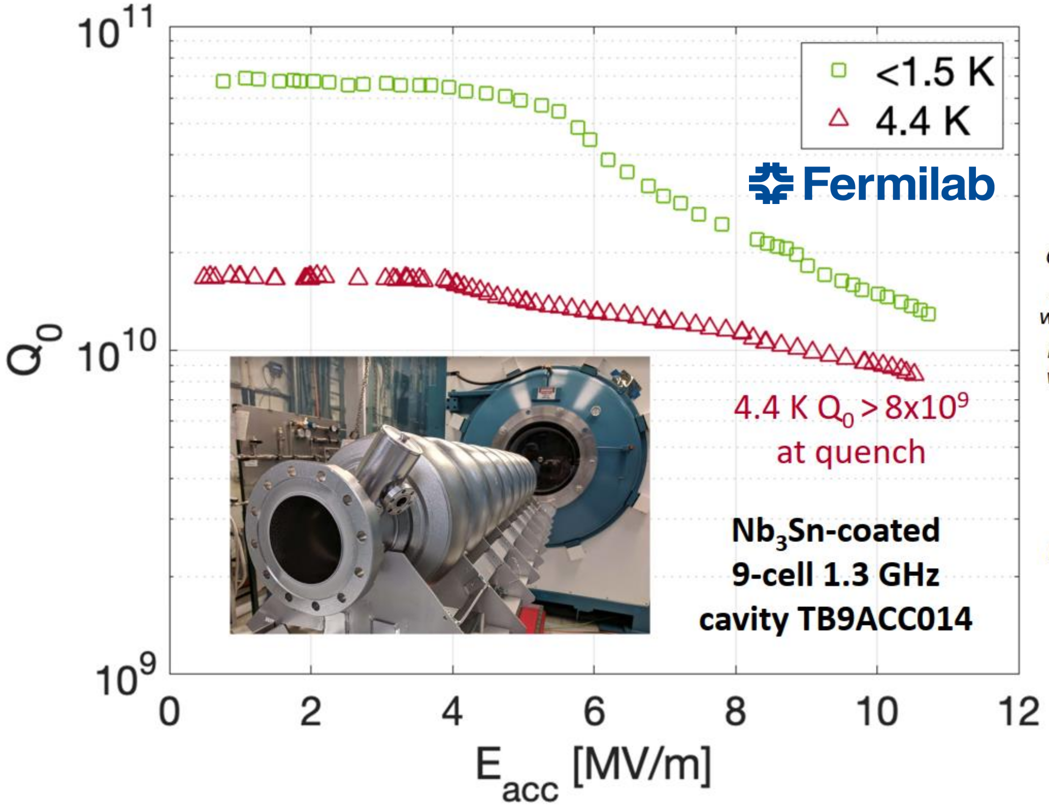


Ready in time for ILC upgrade?

Ref: S. Posen, "Frequency Dependence Studies of Nb_3Sn Cavities," presented at TTC 2019, Vancouver, Canada, Feb. 2019

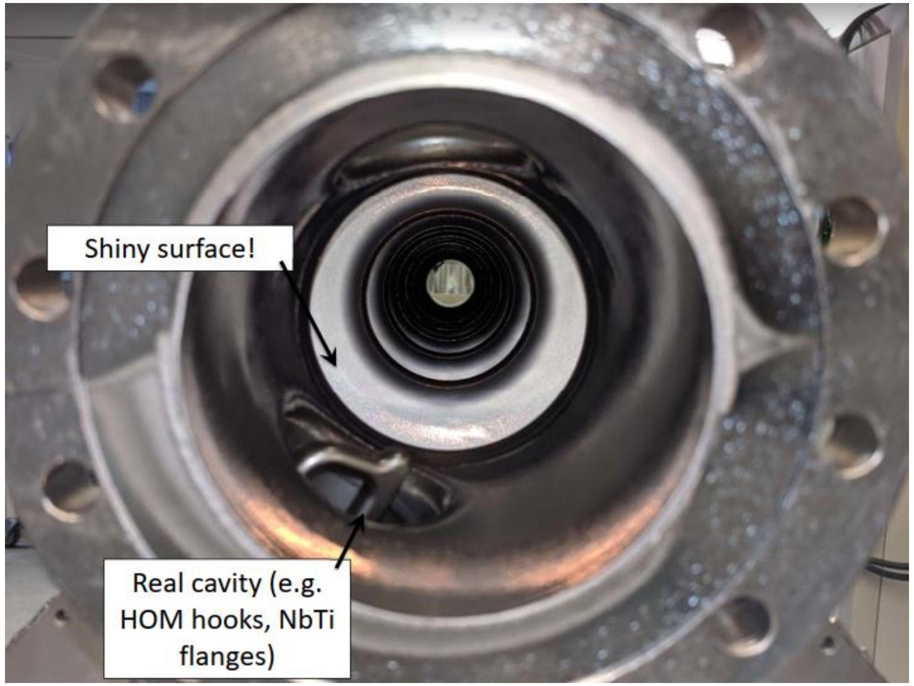
9-Cell Cavity Work at Fermilab

- Sam Posen (Fermilab) completed a first coating of a **9-cell cavity**
  - Real cavity that could be put in cryomodule
- **E_{acc} ~ 10.5 MV/m, $Q \sim 8 \times 10^9$** at 4.4 K!
- First attempt: expect even better results soon!



Cavity was not field flatness tuned nor was flatness checked prior to test. Cavity will be tested again after these steps.

Includes correction for stainless steel flanges 2x0.8 nΩ



Ref: S. Posen et. al., "Nb_3Sn at Fermilab: Exploring Performance," in Proc. of SRF2019, Hamburg, Germany, July 2019

Conclusions

- **3 x more efficient** than clean Nb
  - Can further **double efficiency**
  - **Lower dynamic load**
- **4.2 K** operation
  - **Lower static load**
  - **Simpler cryogenics system**
- 2.6 GHz cavity just as efficient
  - **Smaller cavities -> Lower Cost**
- Can reach **23 MV/m** CW (FNAL)
- Can reach **25 MV/m** pulsed (Cornell)
- Reducing surface roughness is a critical next step to improve quench fields
  - **Can grow smoother Nb_3Sn** with Sn plating
  - Only need 25% increase in E_{acc} for ILC operating spec

Acknowledgements

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NSF Award 1734189: 2.6 GHz and 3.9 GHz tests and R&D
Center for Bright Beam (NSF Award 1549132): Materials studies

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with special thanks to

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Prof. David A. Muller	Dr. Daniel Hall	Alden Pack	Terri Gruber
Prof. James P. Sethna	Dr. Sam Posen	James Sears	Paul Bishop
Prof. Mark Transtrum	Paul Cueva	Greg Kulina	Adam Holic

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