Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

Field Limitation in Nb_3Sn Cavities

Ryan Porter
Cornell University

Supported by:
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

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

Outline

- Introduce Nb_3Sn
- Standard Nb_3Sn cavity performance
- Experimental data
- Quench models
- Reducing roughness
- Conclusion

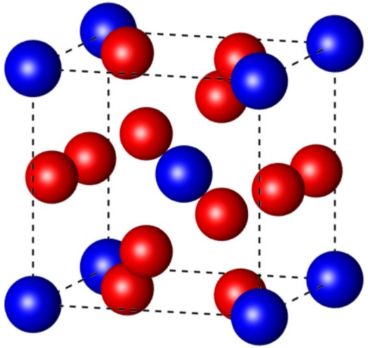
Properties of Nb_3Sn

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

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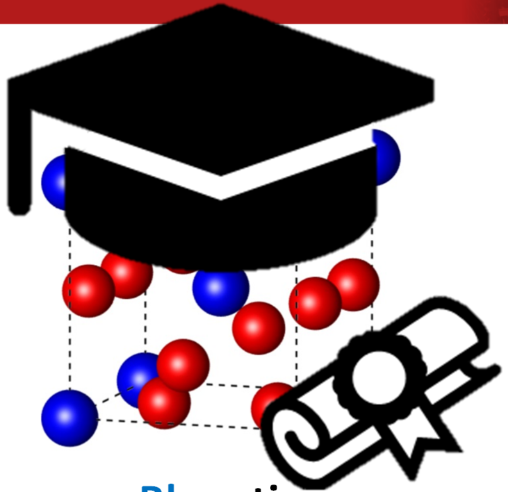

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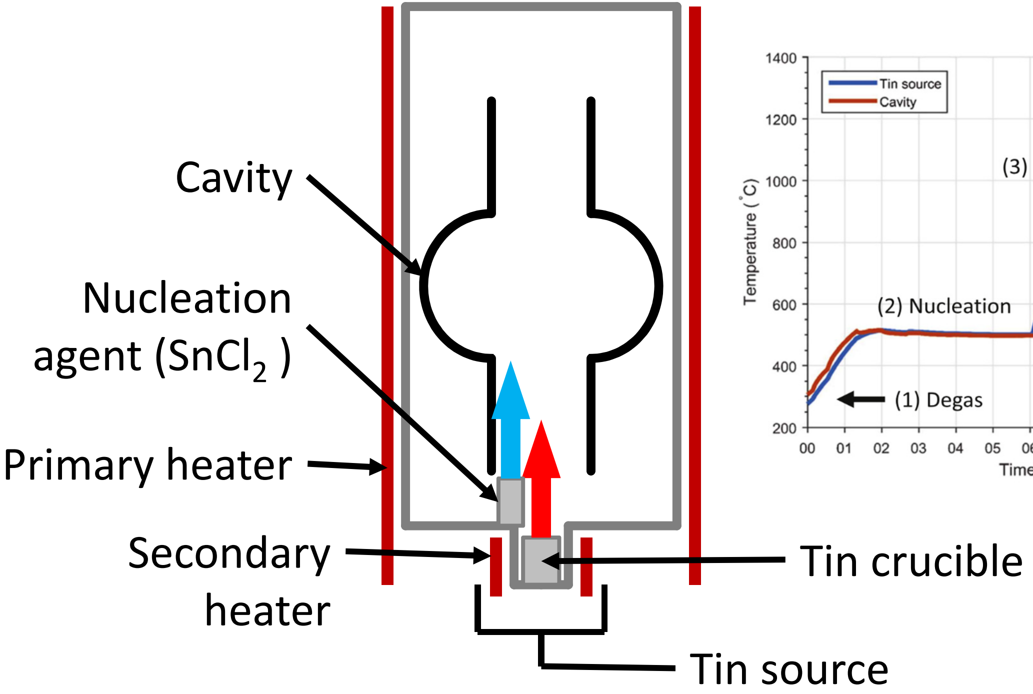
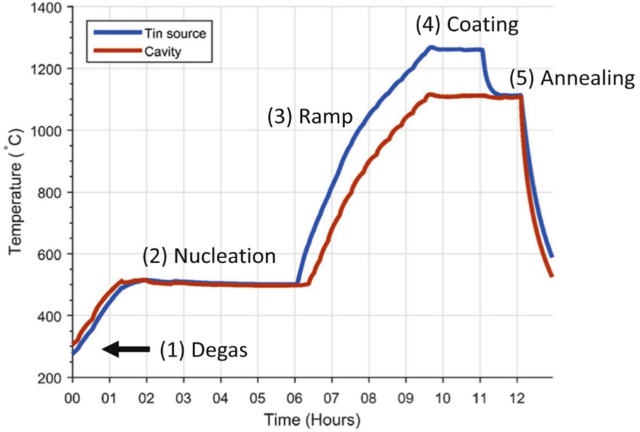
Cornell Nb_3Sn Vapor Diffusion Furnace





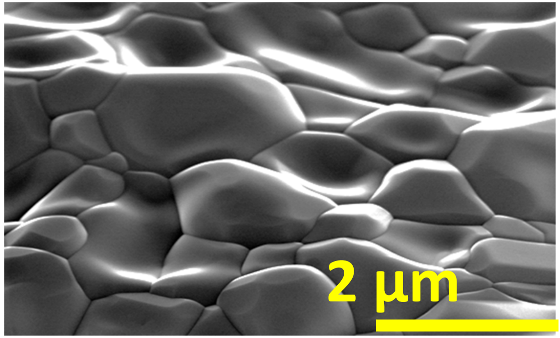
<u>“Wuppertal” configuration</u>, i.e., with secondary heater for the tin source

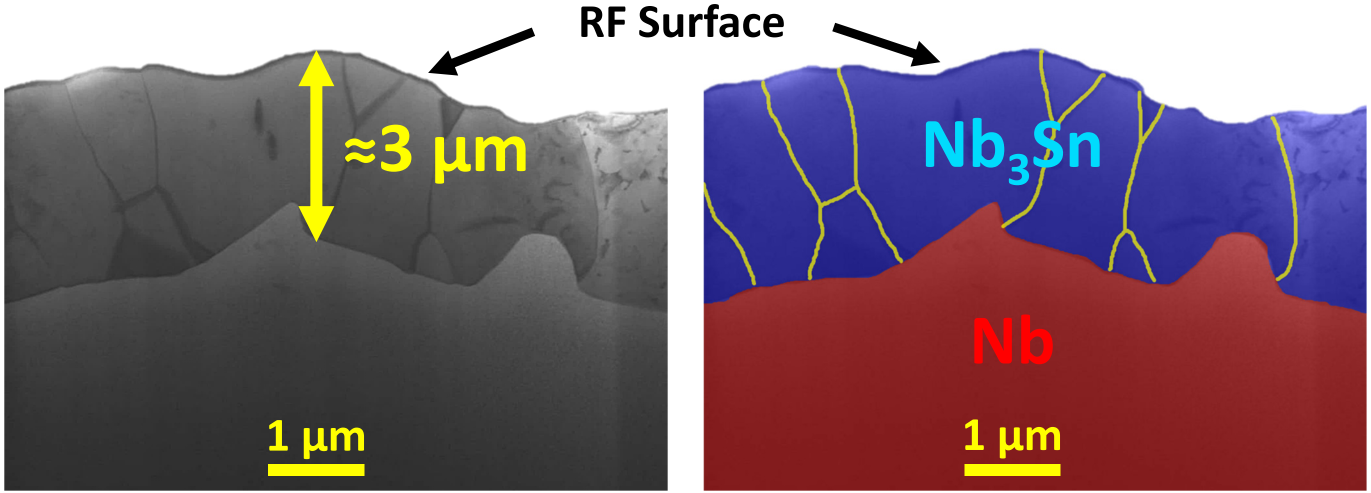
Optimized nucleation and temperature profile

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

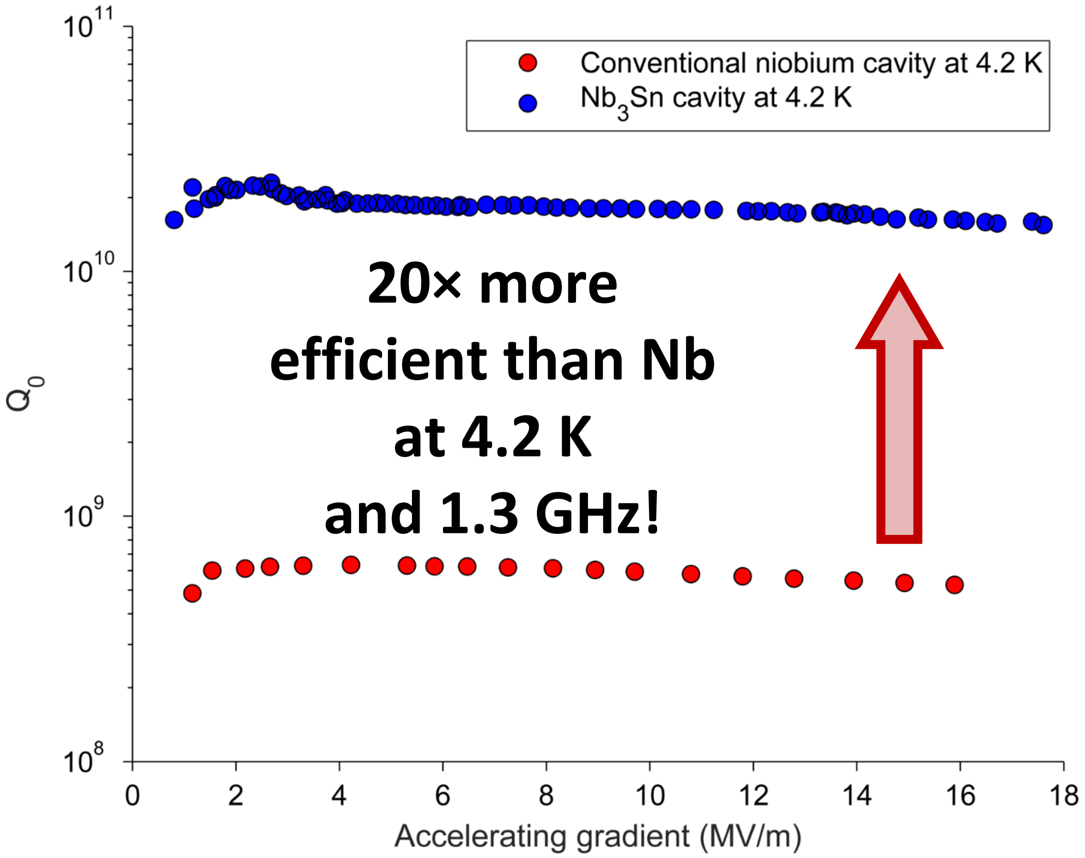
Nb_3Sn Coatings

Nb_3Sn forms a polycrystalline layer on the surface of the niobium

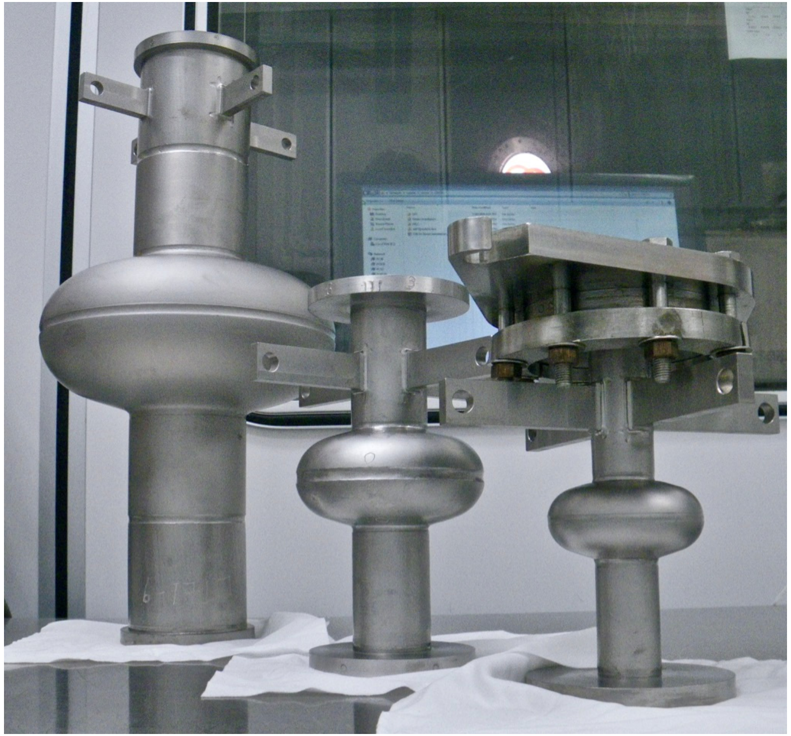


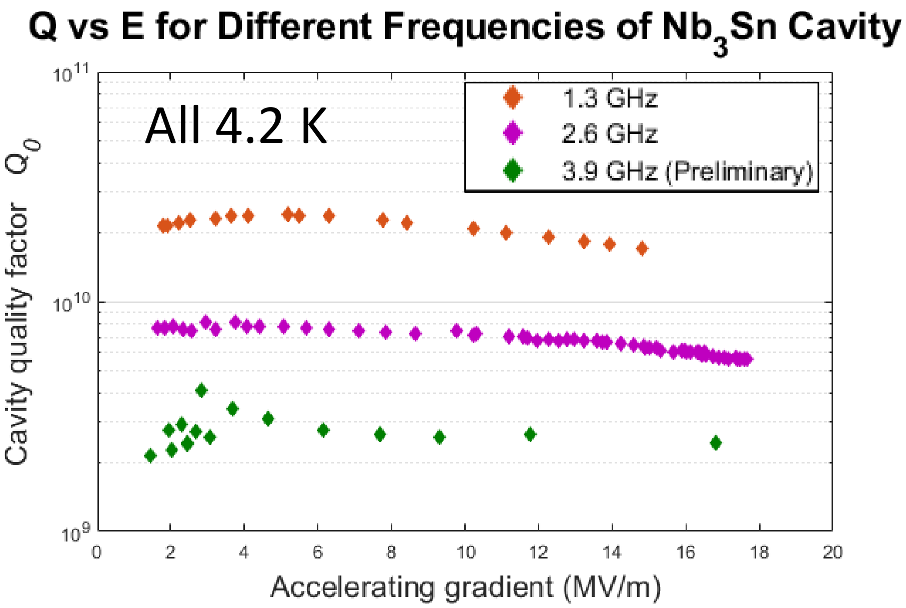


Comparison to Niobium

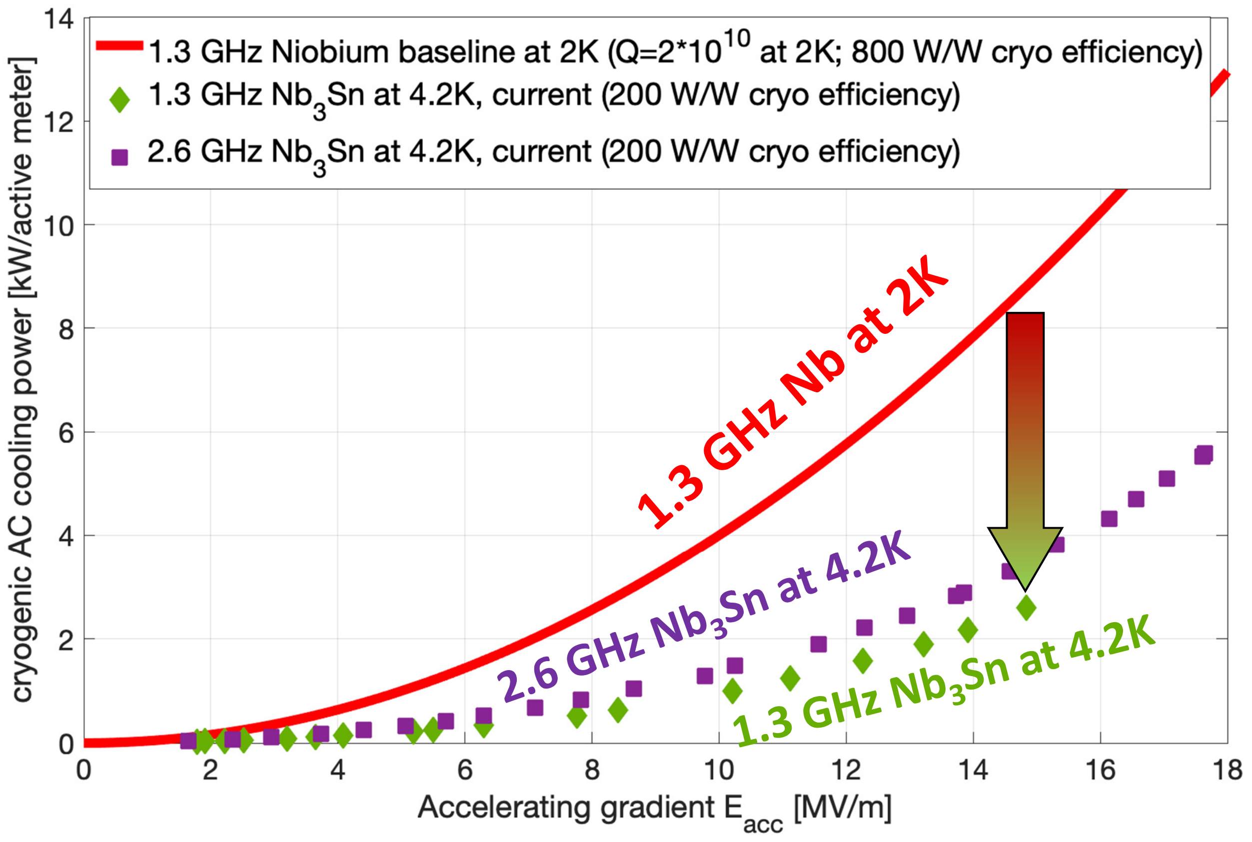


High Frequency Nb_3Sn

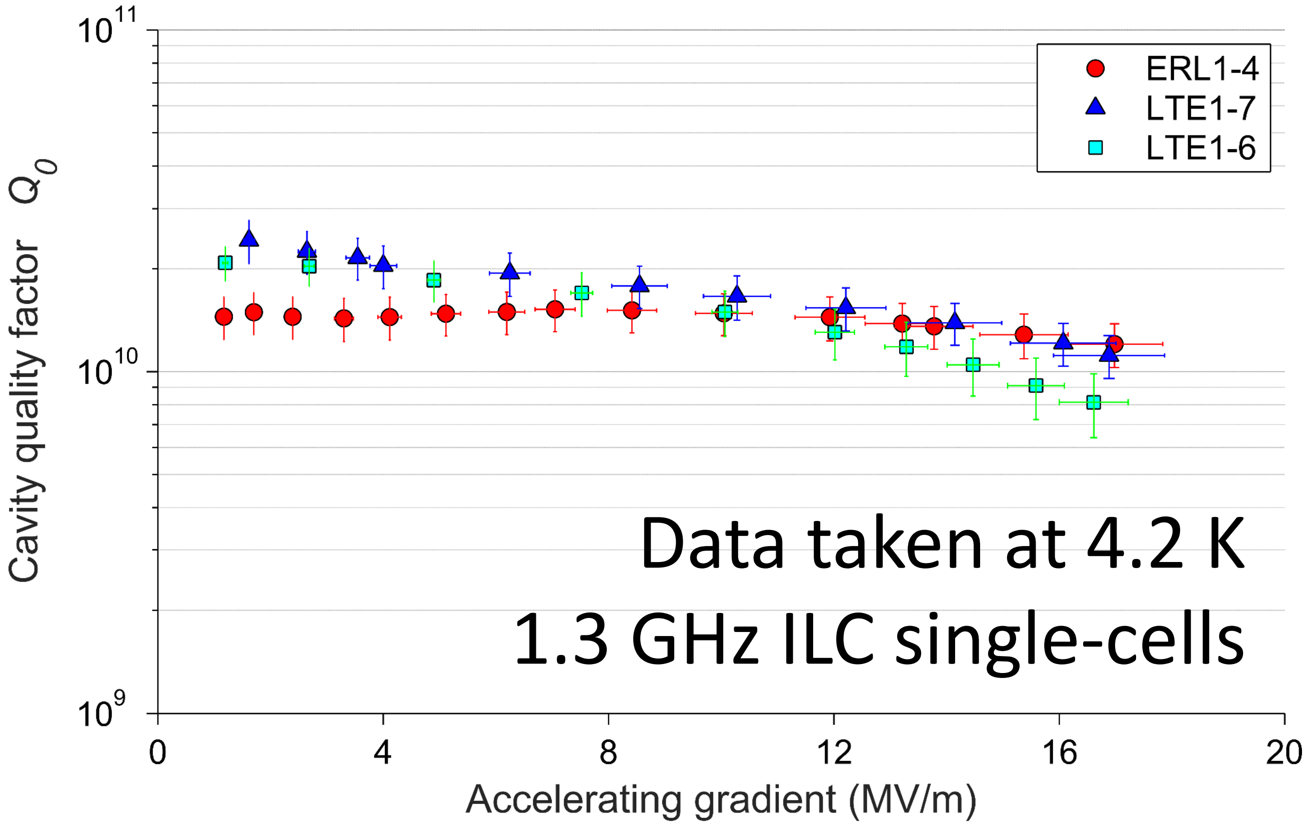




Cryo-Efficiency



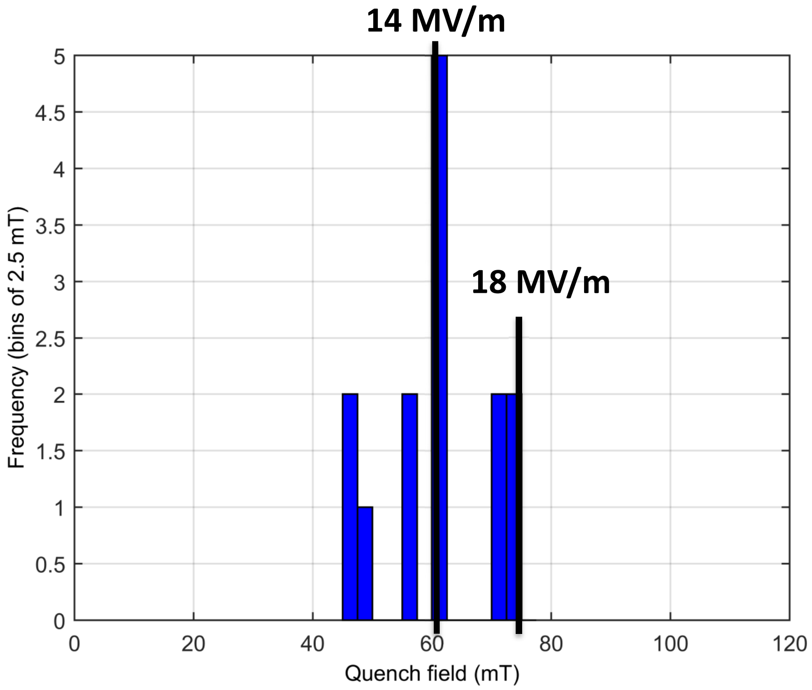
Current performance



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**!



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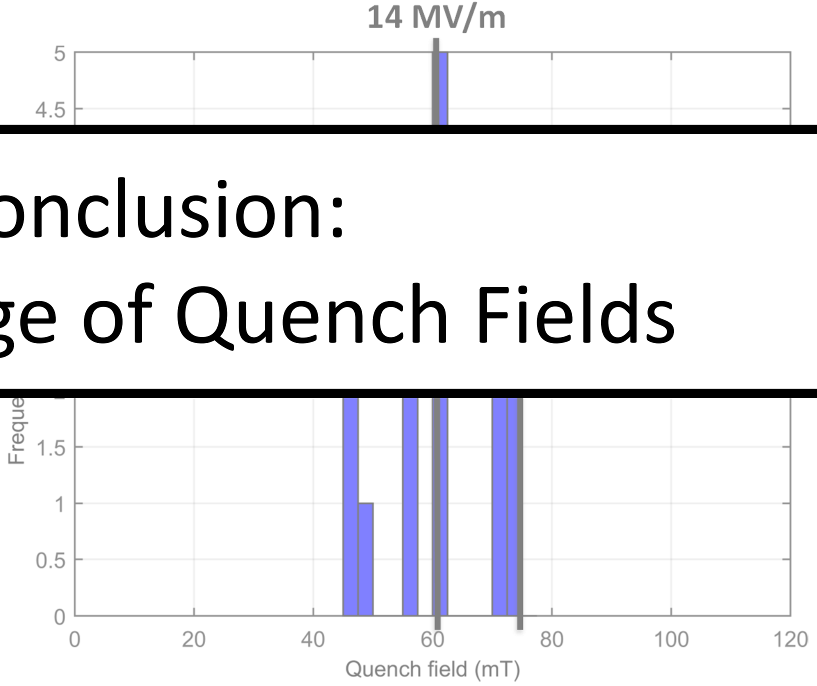
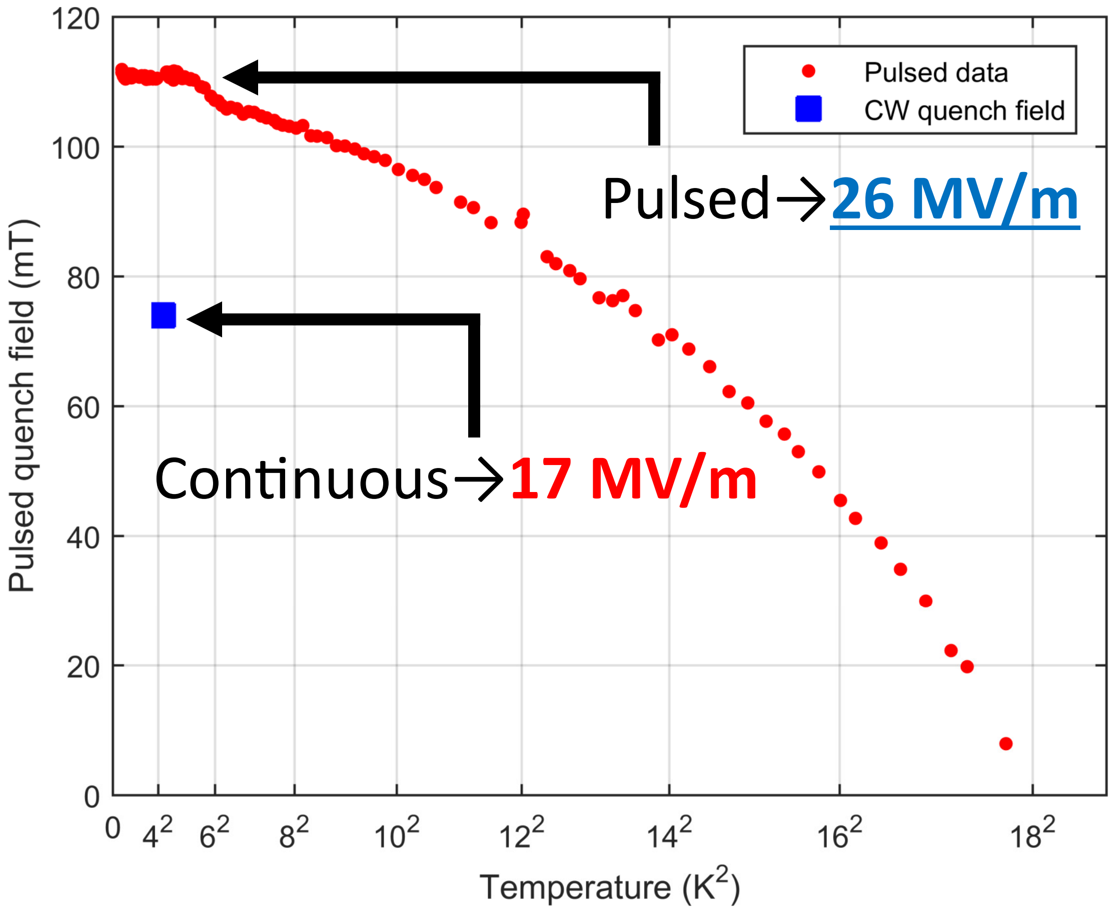


Conclusion:
Small Range of Quench Fields

What is limiting the quench field?

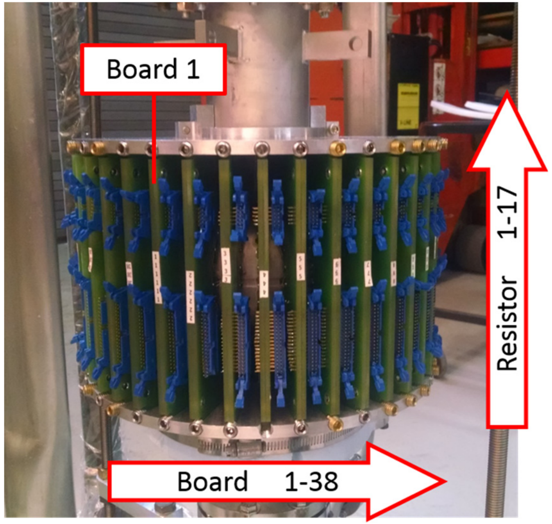
Experimental data

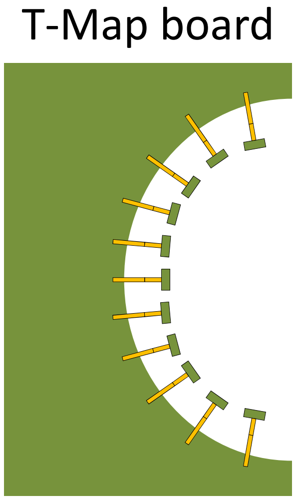
Pulsed quench field

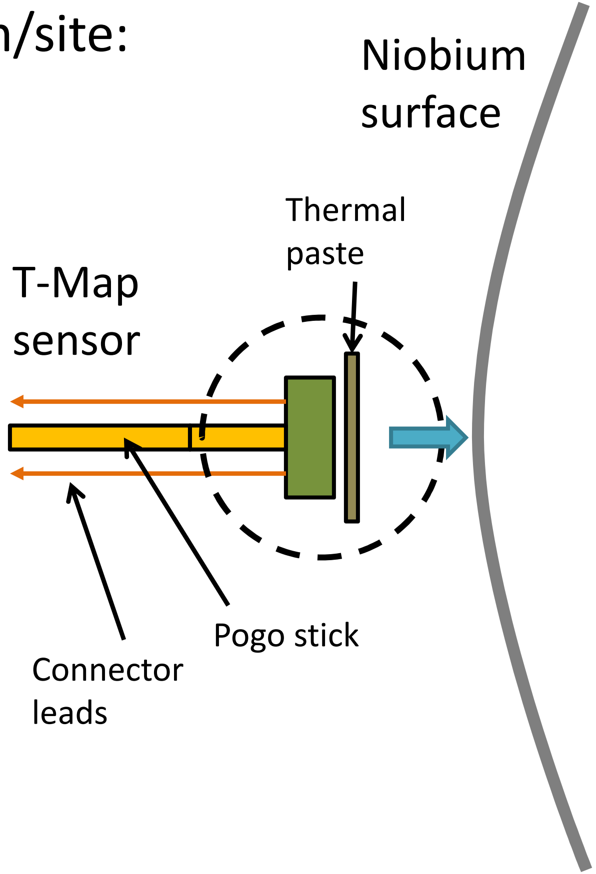


T-Map experiment

Use temperature map to look for quench mechanism/site:

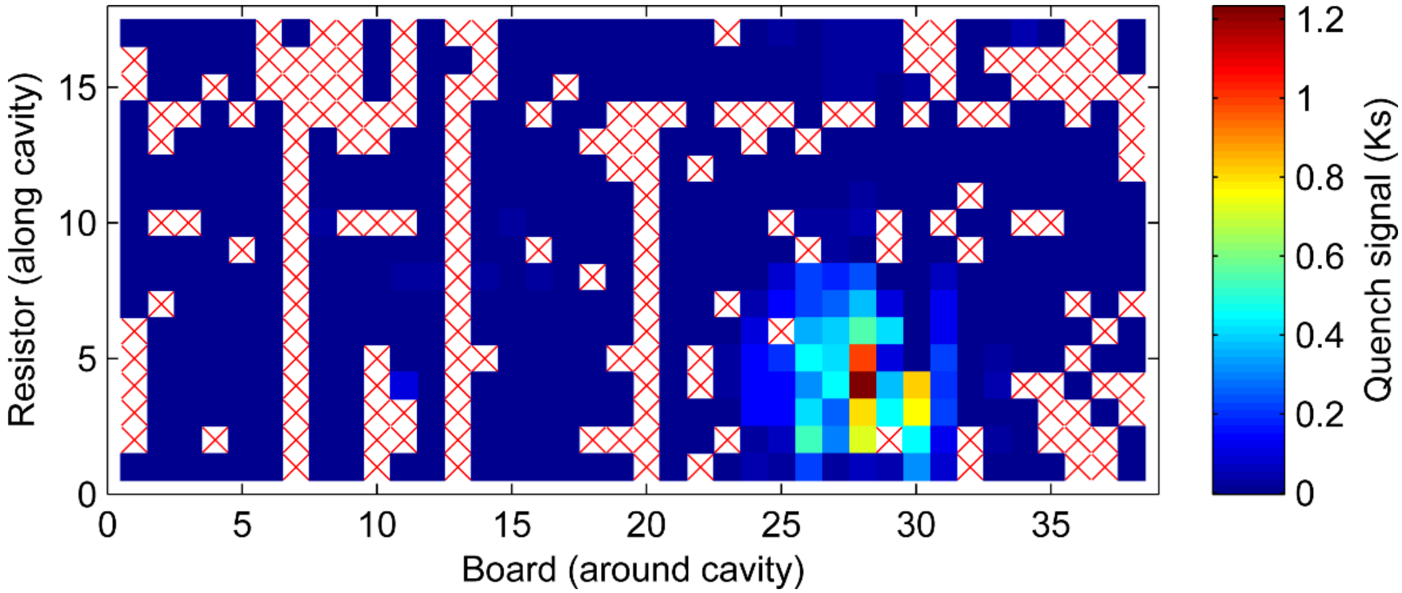






Localised quench

Nb_3Sn cavities are limited by a quench at a localized spot



What could be at fault?

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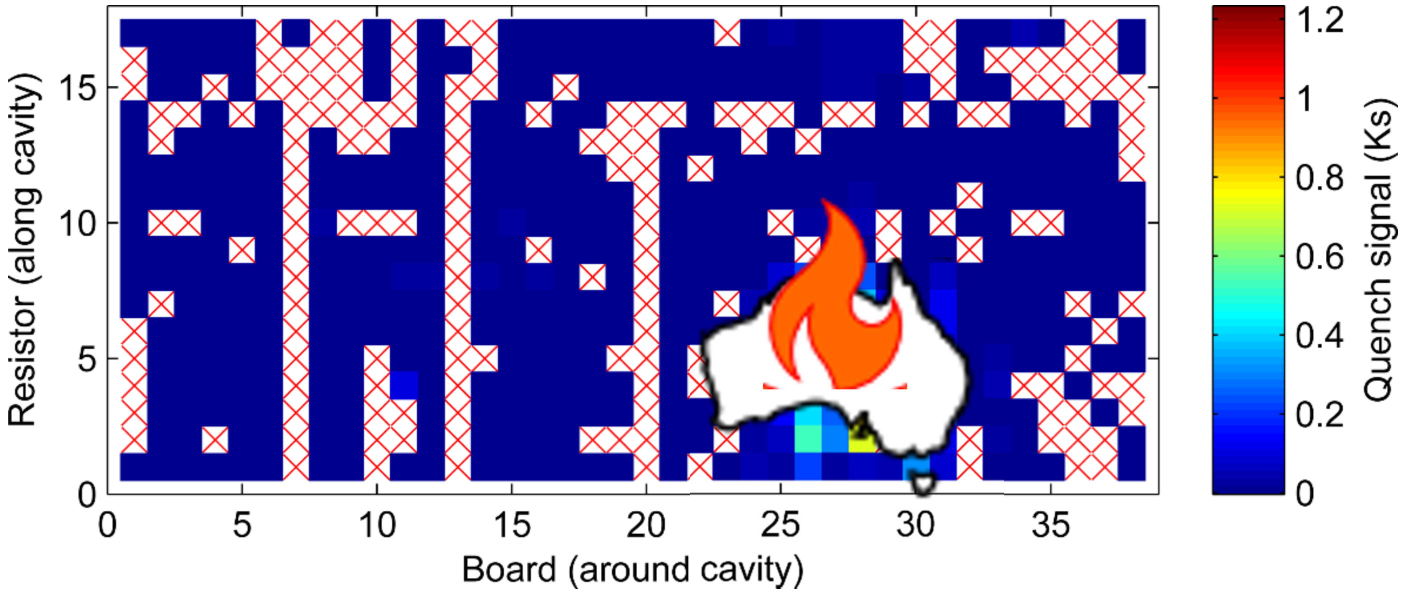

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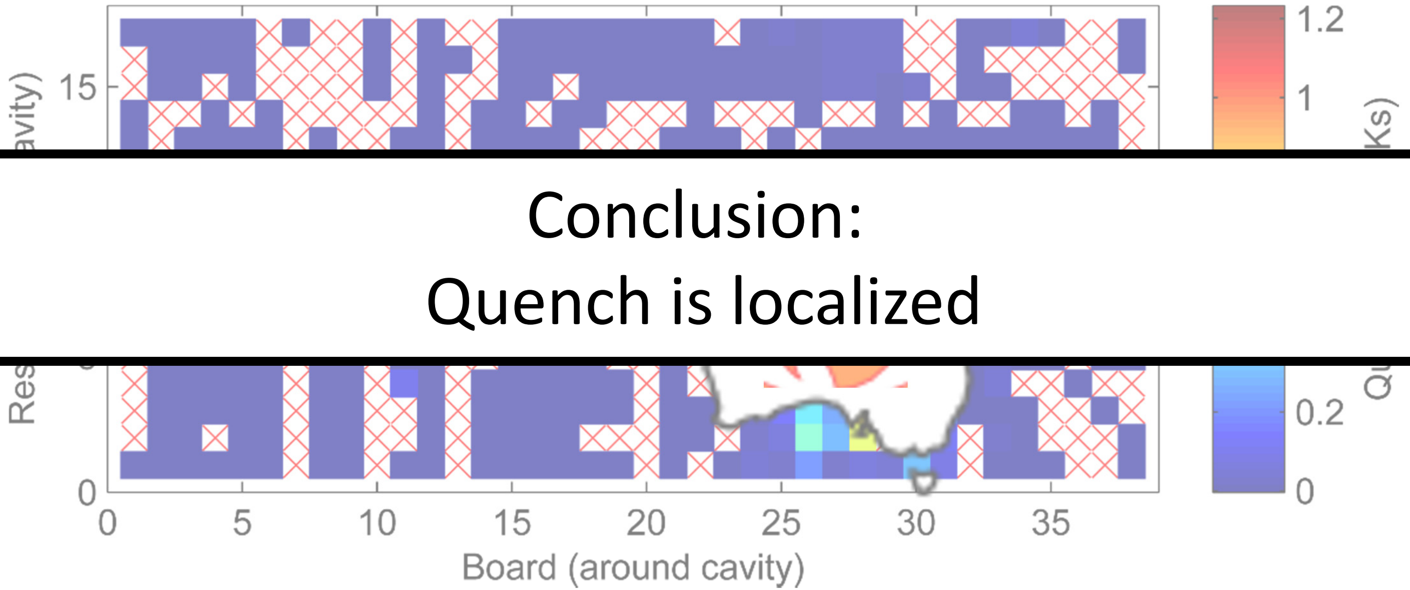
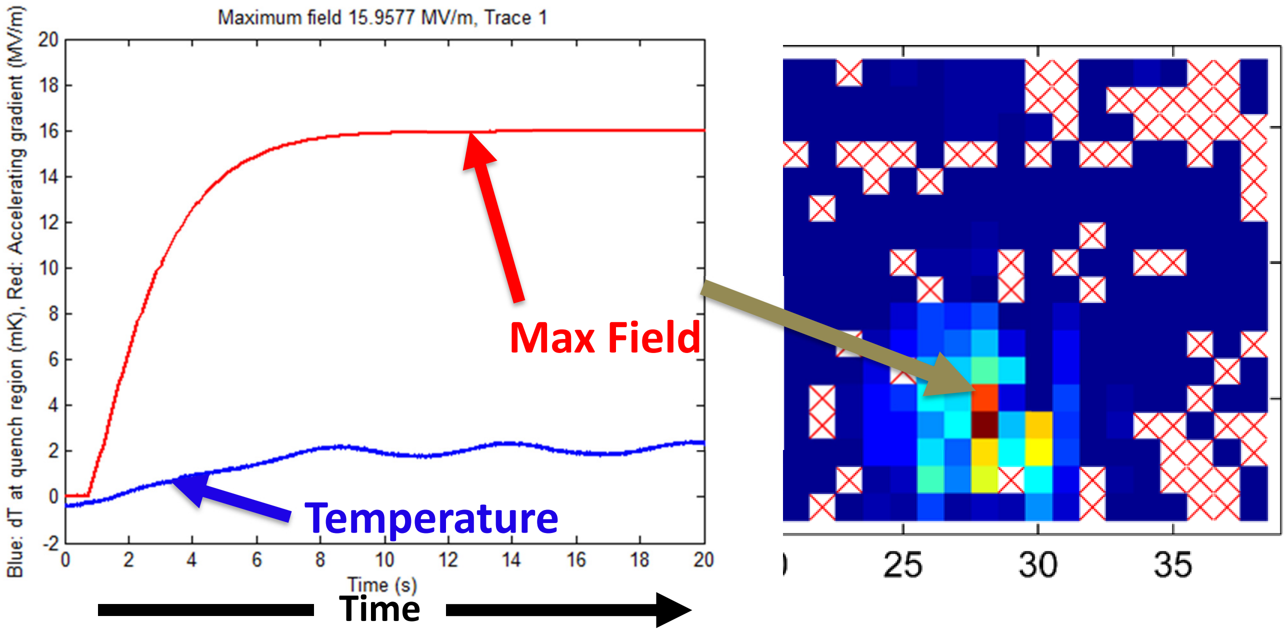


Conclusion:
Quench is localized

What could be at fault?

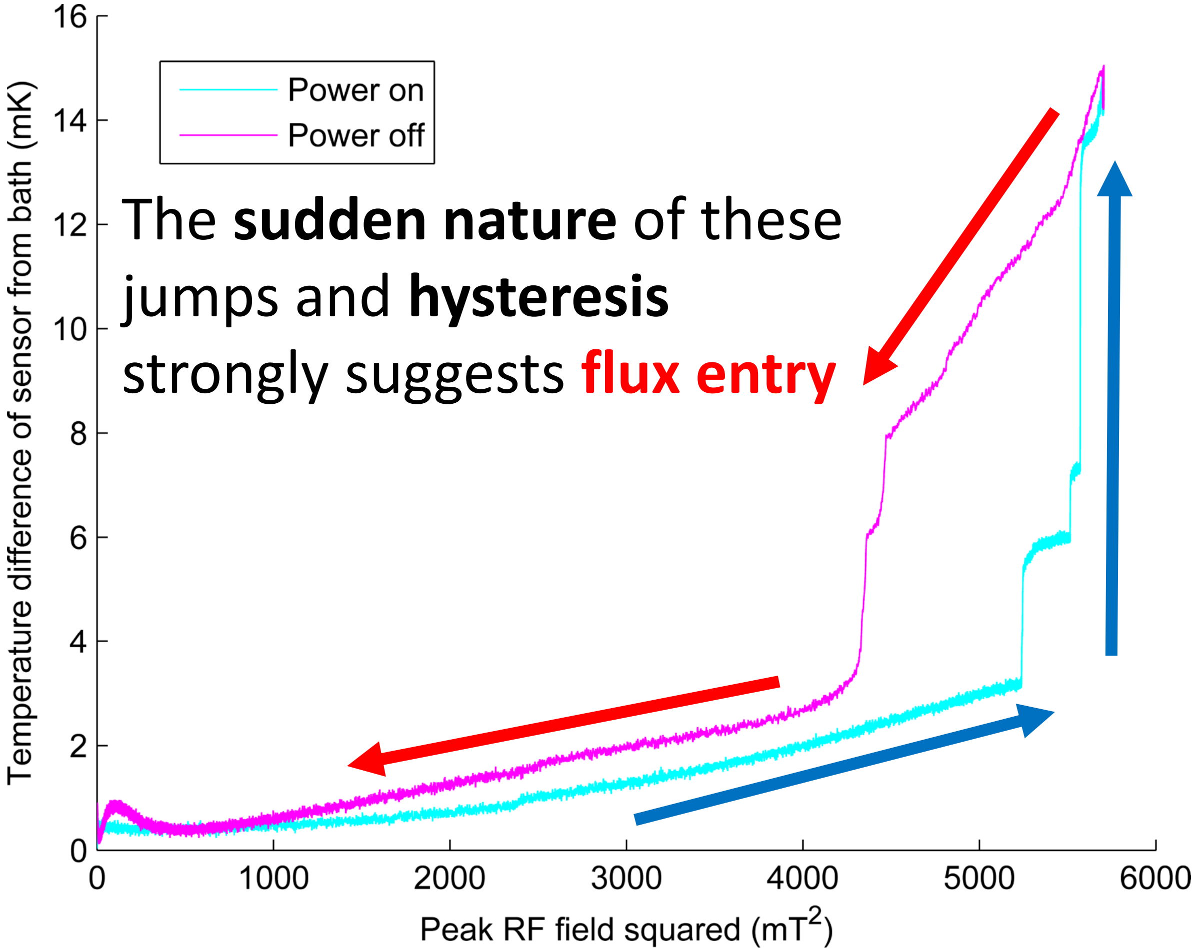
Near quench behavior

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

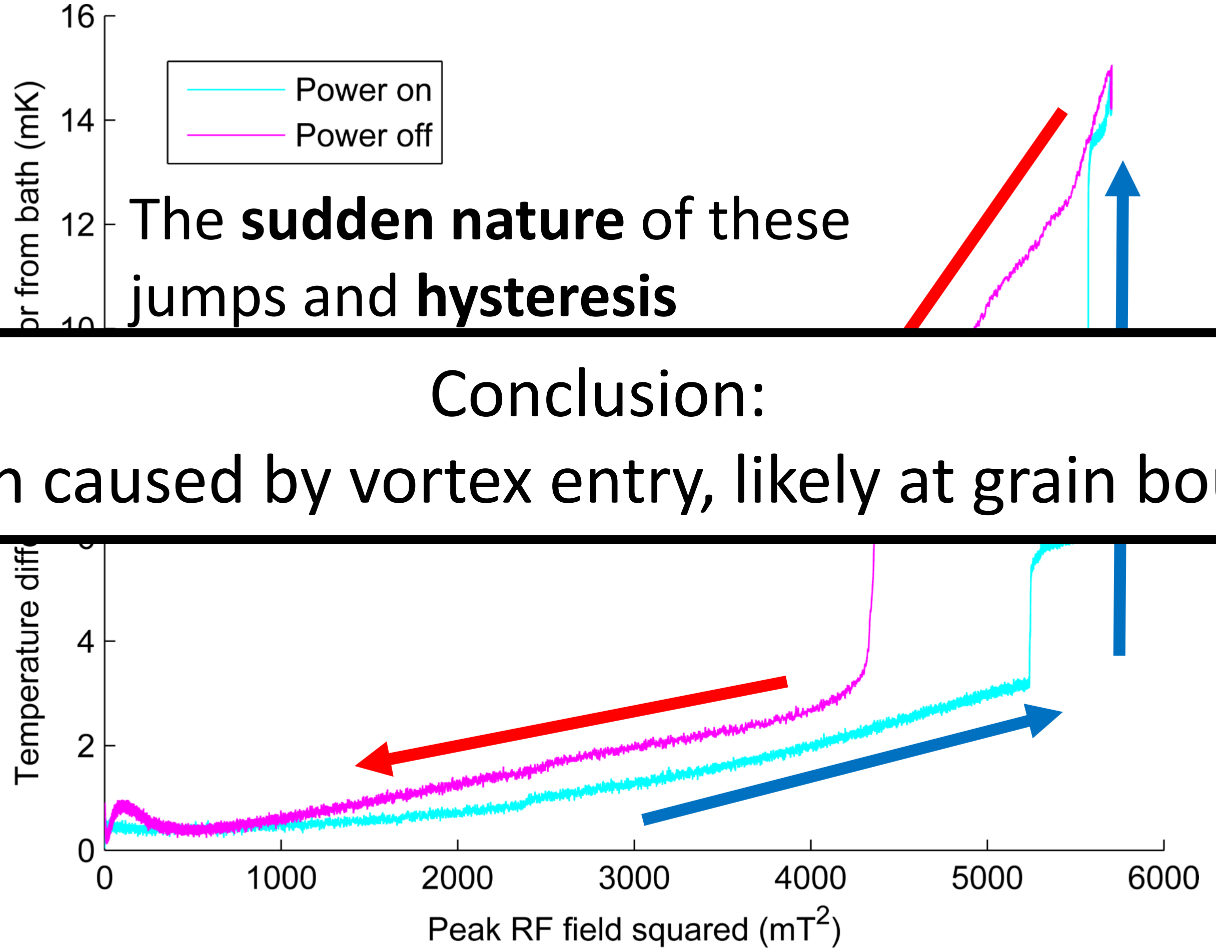


- Sudden jumps in temperature

Near quench behaviour



Near quench behaviour

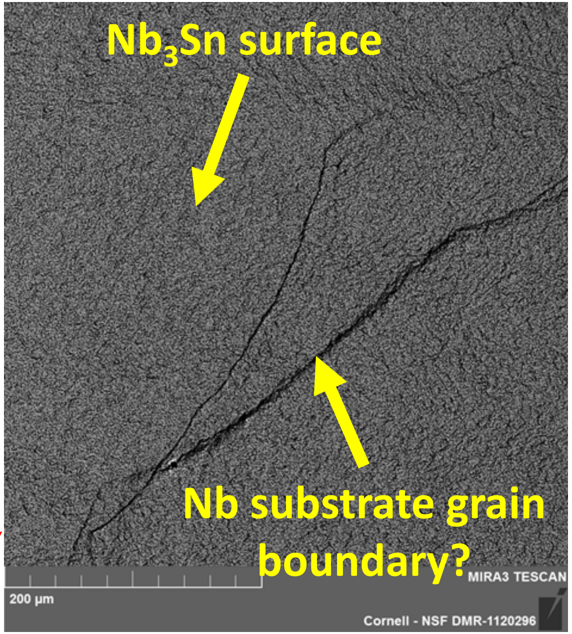


The **sudden nature** of these jumps and **hysteresis**

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

What is happening at the surface?

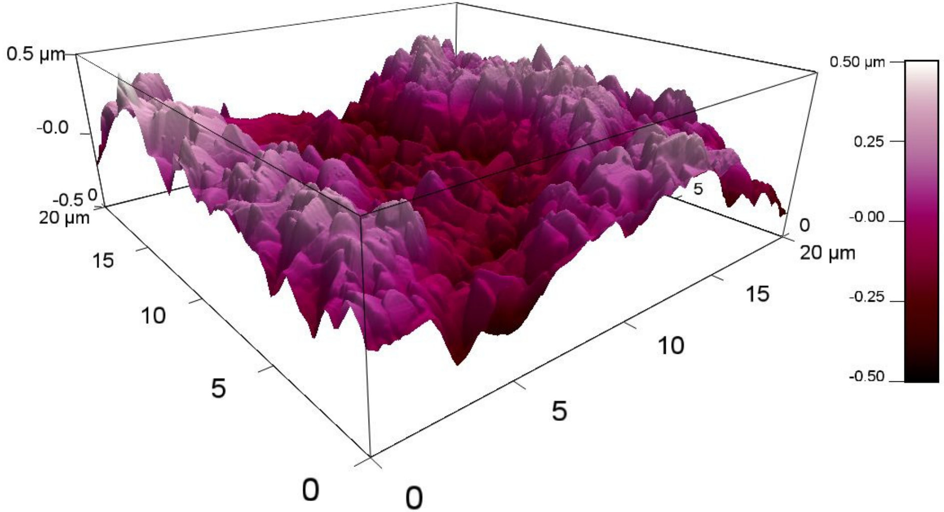
- Cut out this region and examined with microscopy
- Nothing obvious except Nb grain boundary cliff
  - Rough Surface



Quench Site

Surface Roughness

- Nb_3Sn we create is rougher than EP Nb
  - ~1 µm peak to peak
- This causes large enhancement of the surface magnetic field

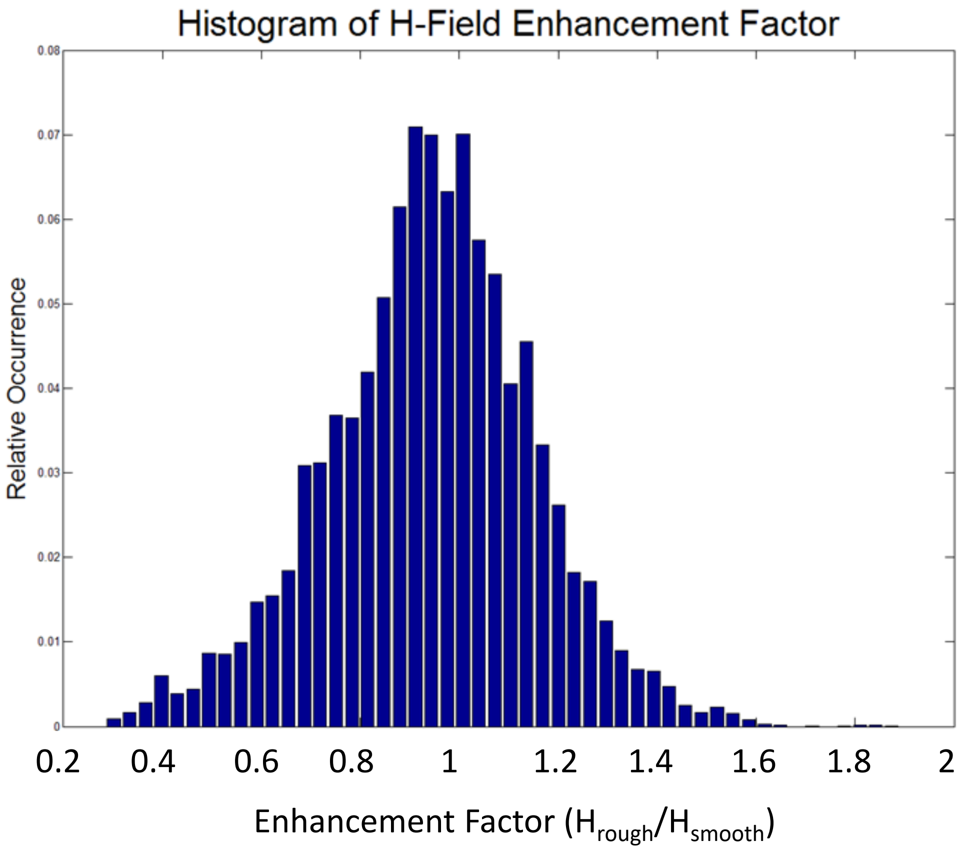


Field Enhancement

- 1 % surface > 50% magnetic field enhancement
- Lowers defect "activation" field

17 MV/m x 1.50 field enhancement -> **25 MV/m**

  - Reducing surface roughness (growth, post-treatment) could increase quench field



Field Enhancement

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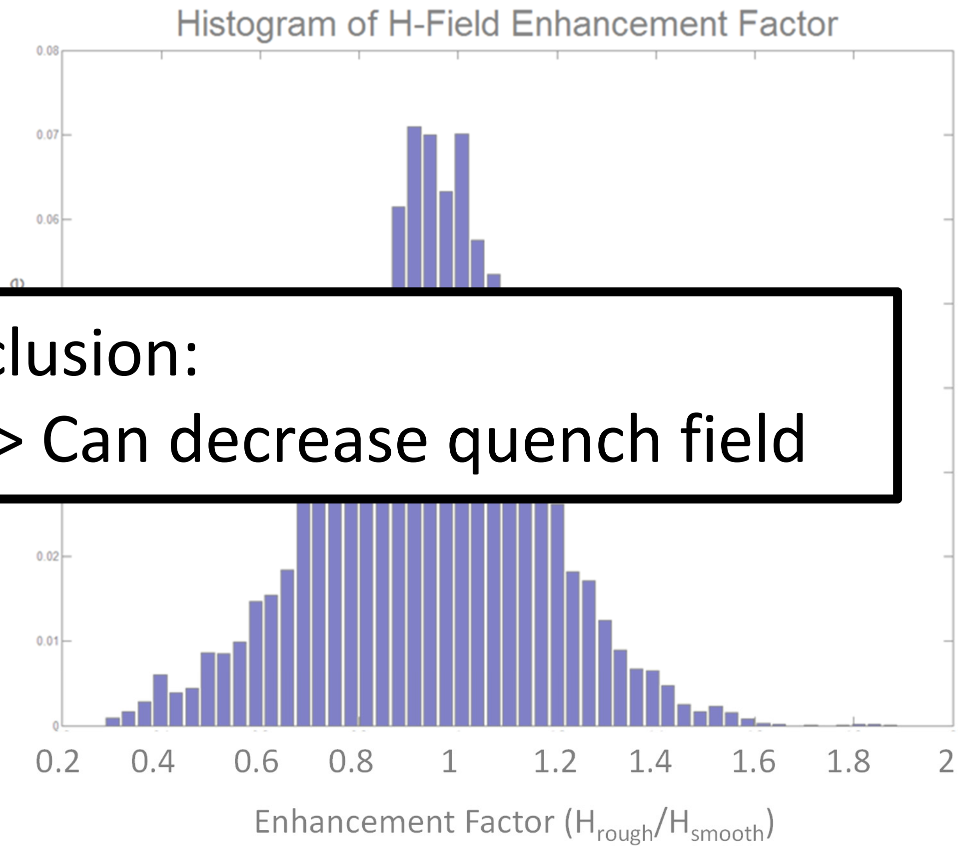
17 N

Conclusion:

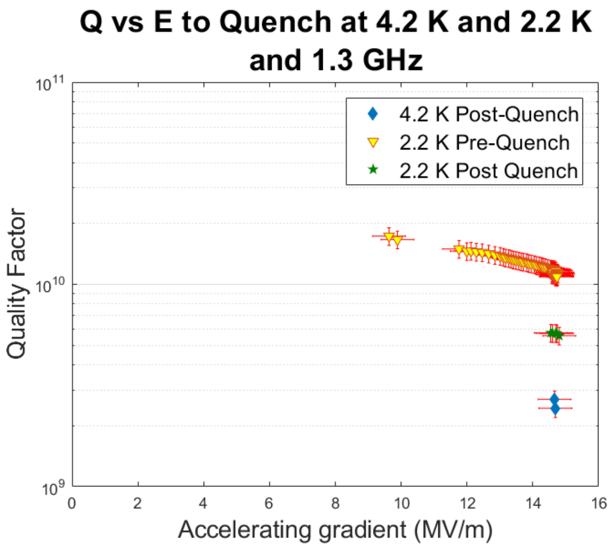
High surface roughness -> Can decrease quench field

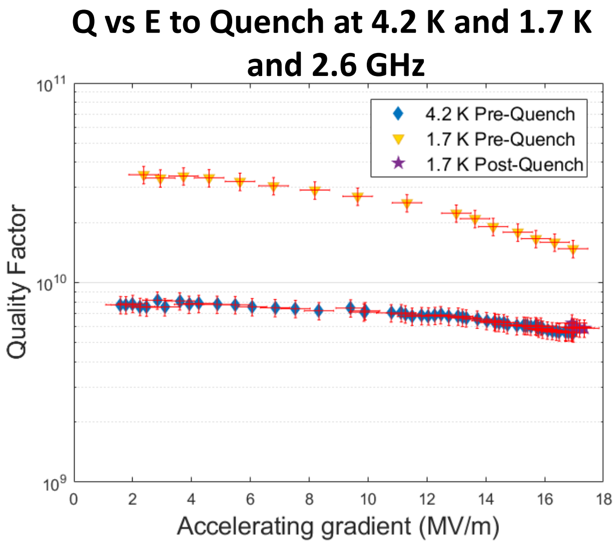
  - Reducing surface roughness (growth, post-treatment) could increase quench field



Quench Field Temperature Dependence

- Quench 4.2 K vs 2 K
  - Quench fields within ~1% (~3.4% error bar)
- No temperature dependence of quench field!
  - Limits possible quench mechanisms





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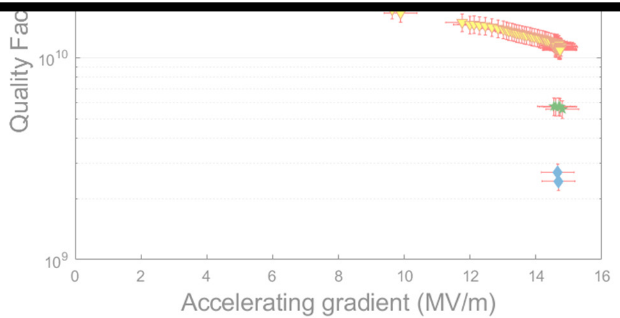
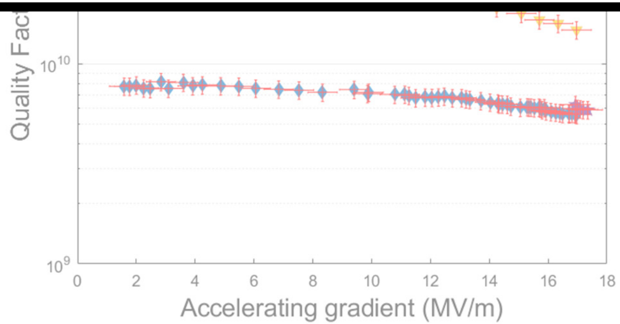
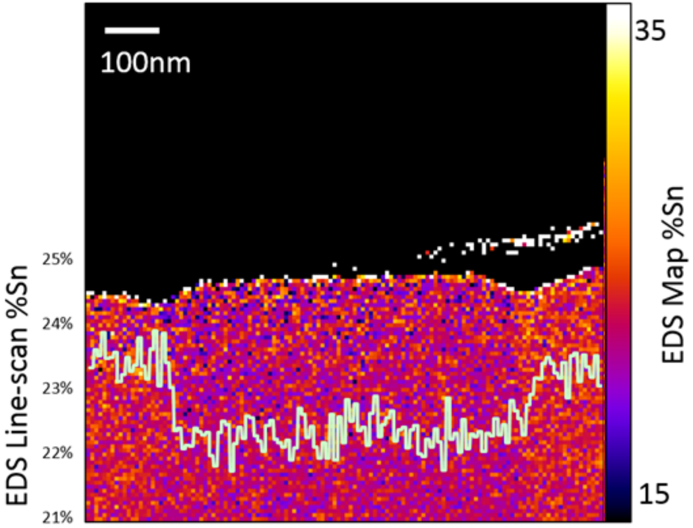
Conclusion:
Quench Mechanism Temperature Independent

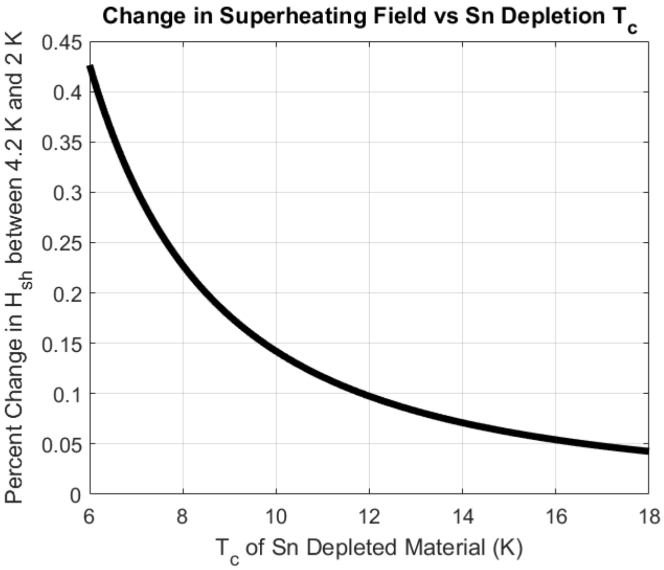




Quench Field Impact of Sn Depletion

- Could Sn depleted regions cause quench?
  - Quench field change with temperature **too small**



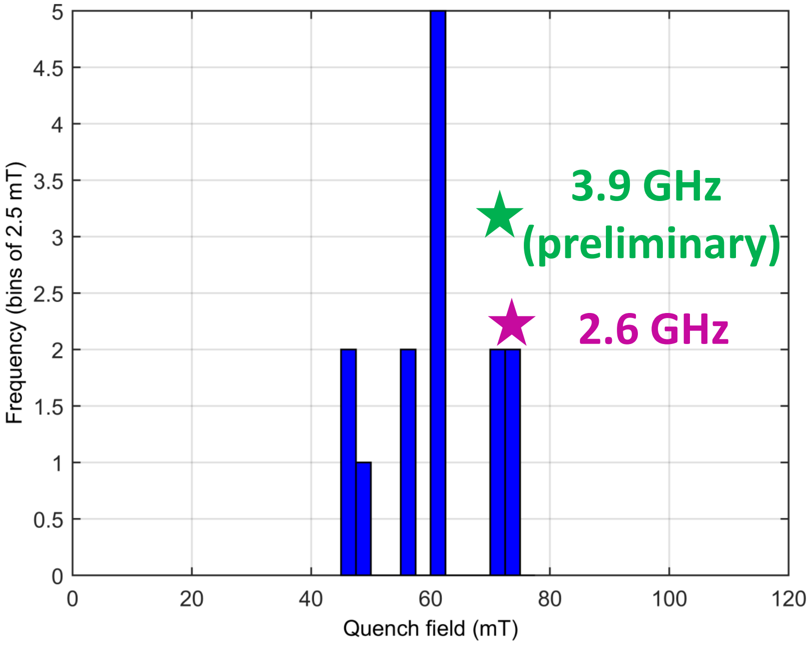


Quench Field Frequency Dependence

The 2.6 GHz Nb_3Sn cavities' quench field is consistent with 1.3 GHz Nb_3Sn cavities.

Results show quench defect does not depend on frequency!

-> Limits possible defects that cause quench



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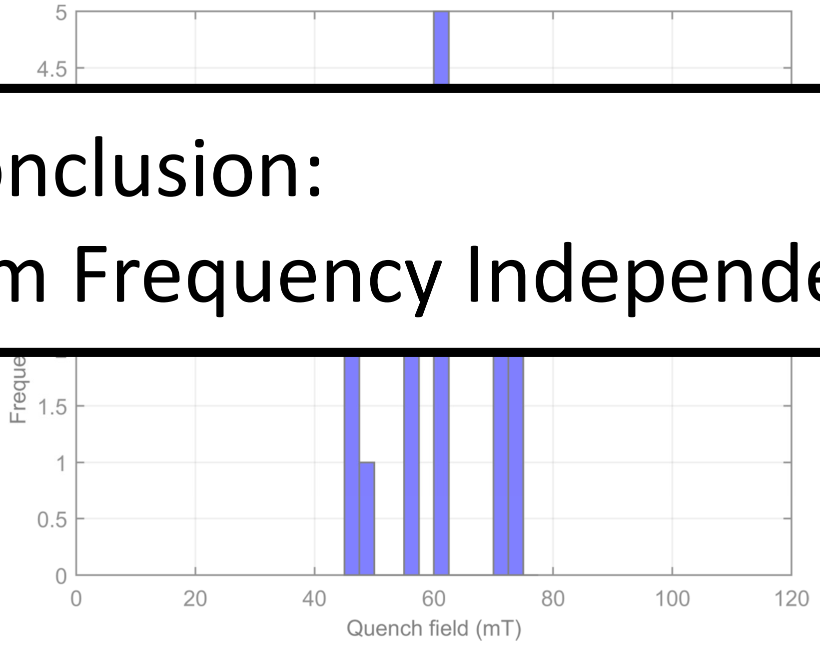


Conclusion:

Quench Mechanism Frequency Independent

-> Limits possible defects that cause quench

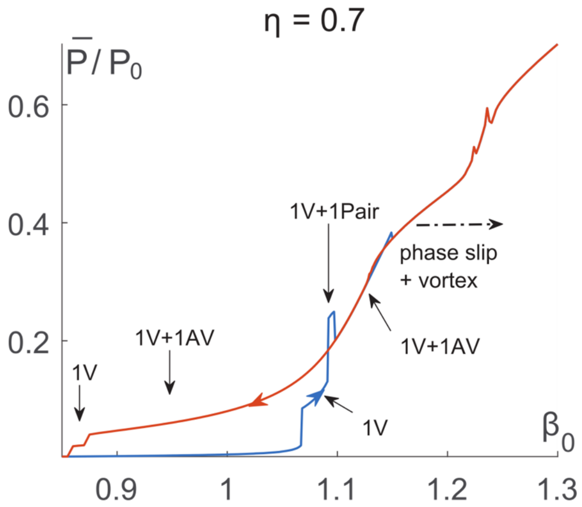
Experimental Data Summary

- Narrow range of quench fields
- Quench localized
- Quench site warms just before quench + quantized
  - Vortex entry
- High surface roughness -> Can decrease quench field
- No temperature dependence
- No frequency dependence

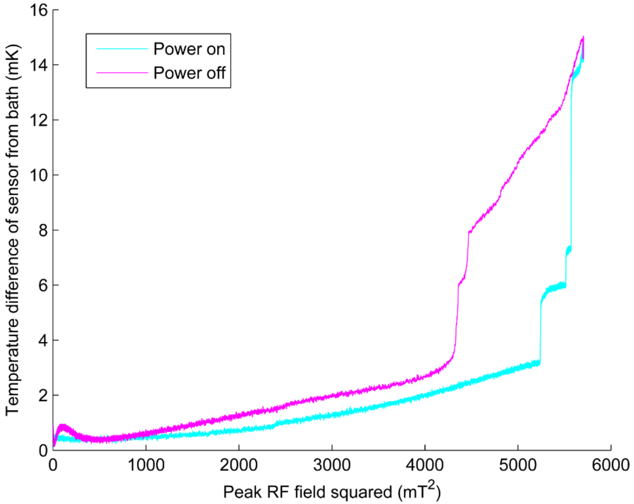
Models of Quench

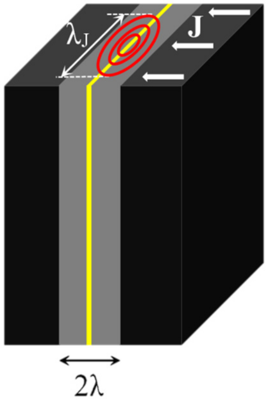
Grain boundary flux penetration

Power dissipated



Increasing current across boundary



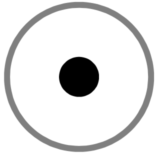


Ahmad Sheikhzada and **Alex Gurevich**

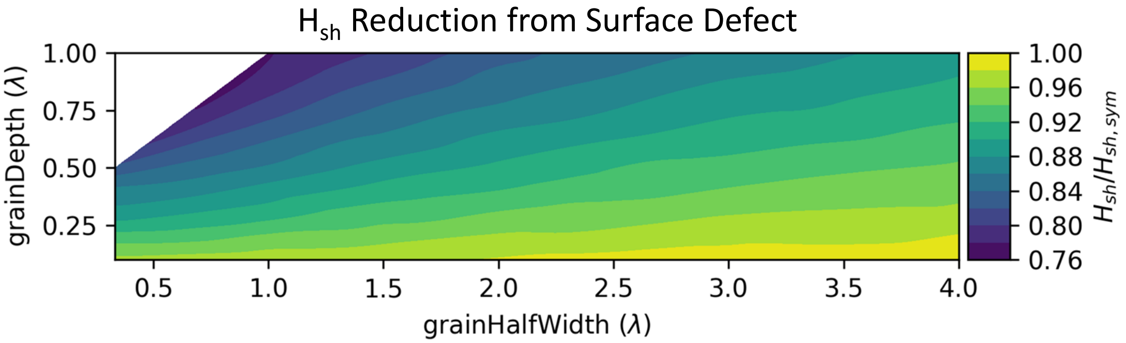
Physical Review B **95**, 214507 (2017)

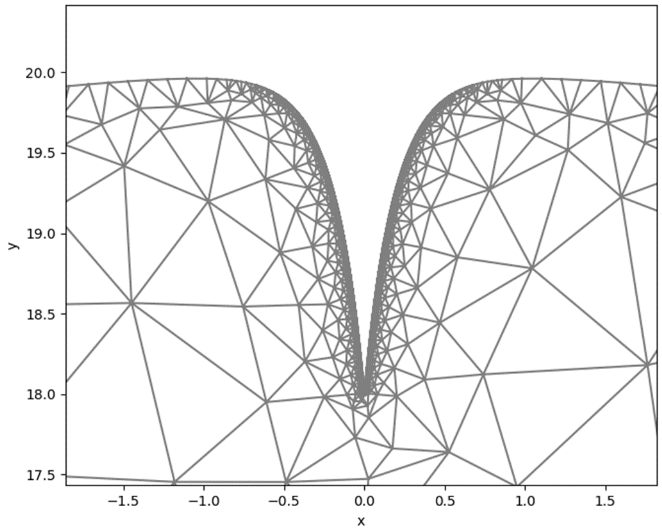
arXiv:1702.02843

Ginzburg-Landau Simulation of Vortex Nucleation In Grain Boundaries



- Center for Bright Beams (CBB):
  A. R. Pack, M. Transtrum (BYU): MOP017
- Poor grain boundary geometry -> lower flux entry field
- Geometry effect: T, f independent*





*in cavity operating range (f << $1/T_{vortex\ nucleation}$, T << T_c)

Grain Boundary Flux Penetration (BYU)

Ginzburg-Landau Simulation of Vortex Nucleation In Grain Boundaries

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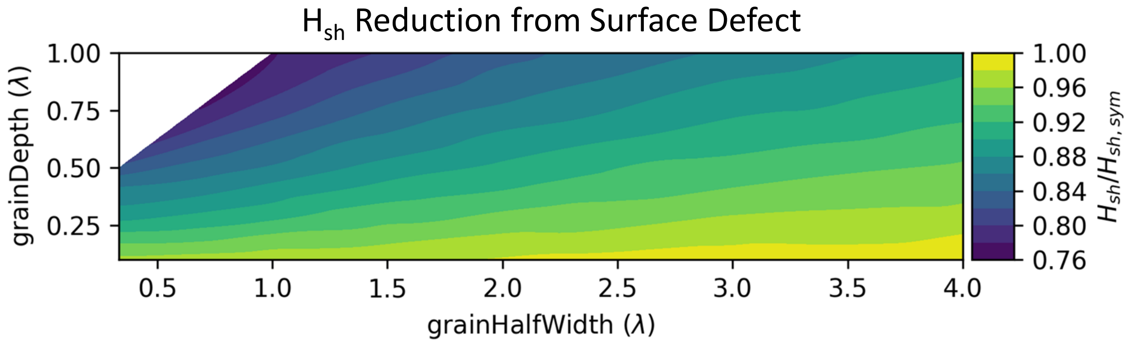

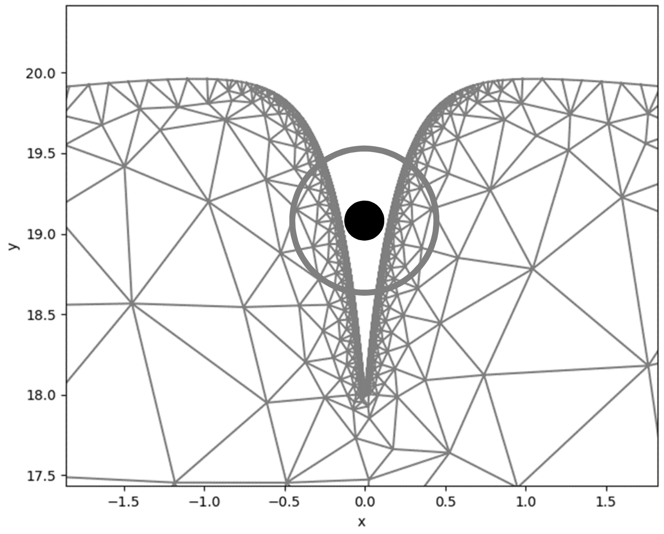

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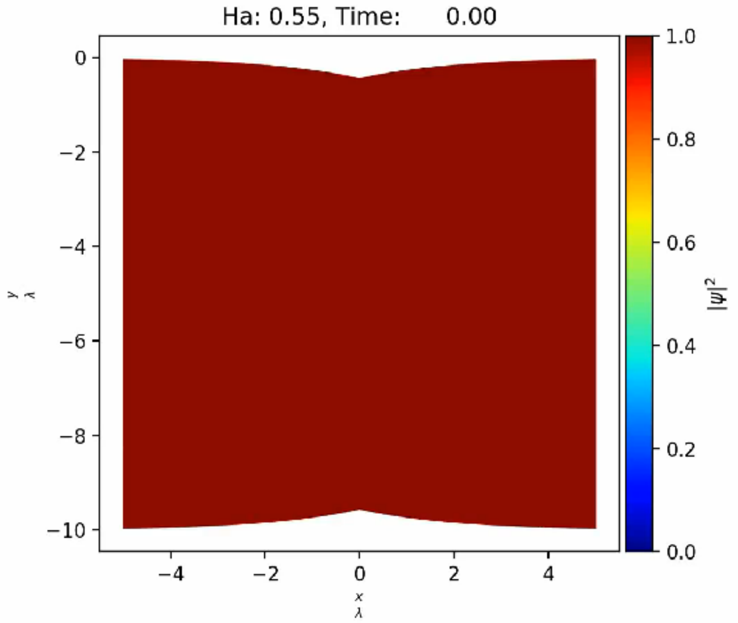
Grain Boundary Pinning (BYU)

A. R. Pack, M. Transtrum (BYU):



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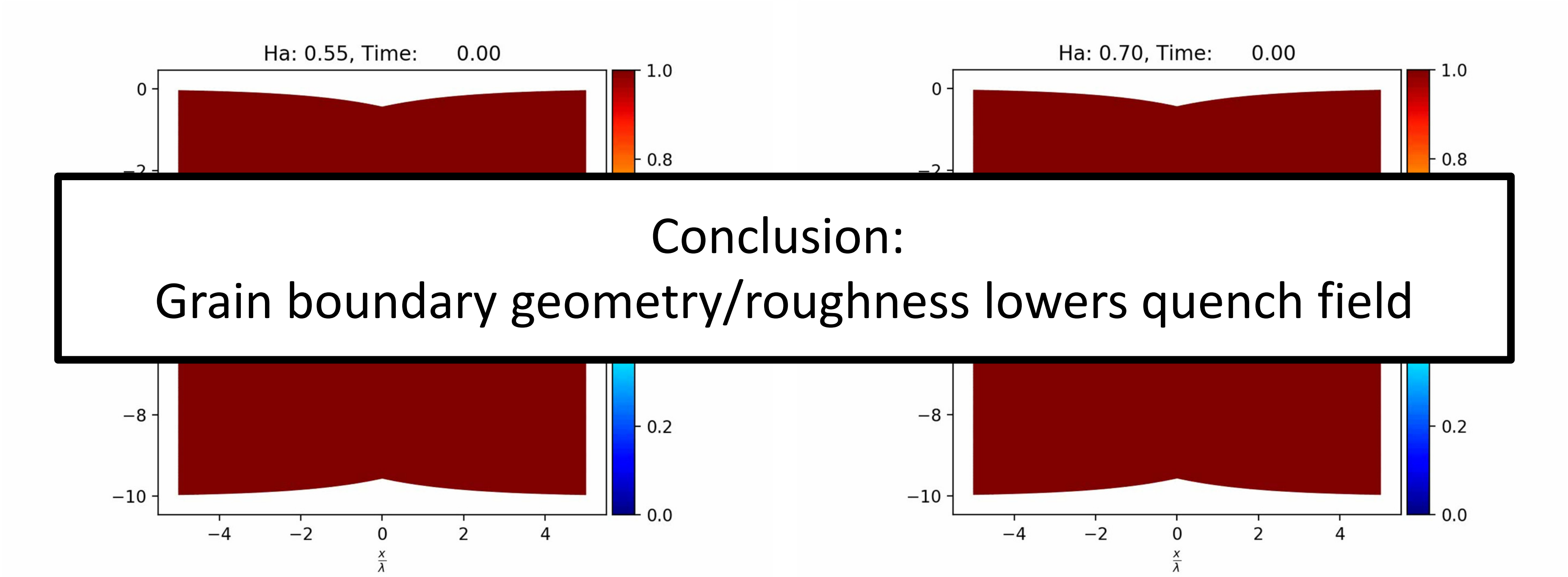
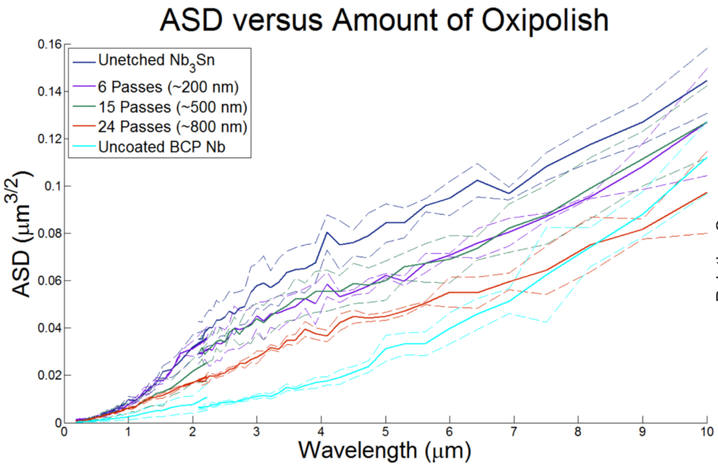


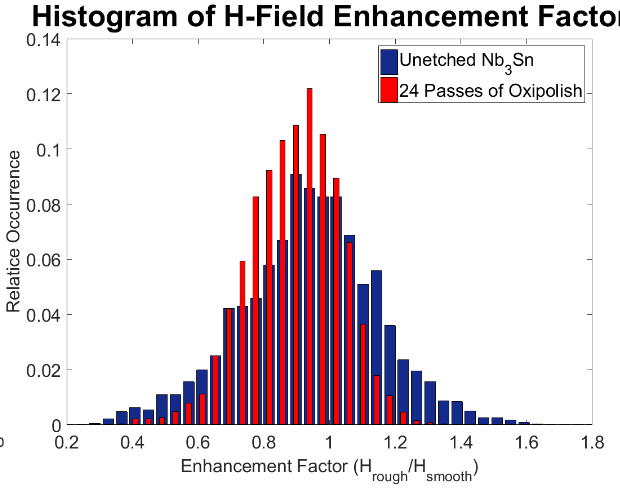
Conclusion:
Grain boundary geometry/roughness lowers quench field

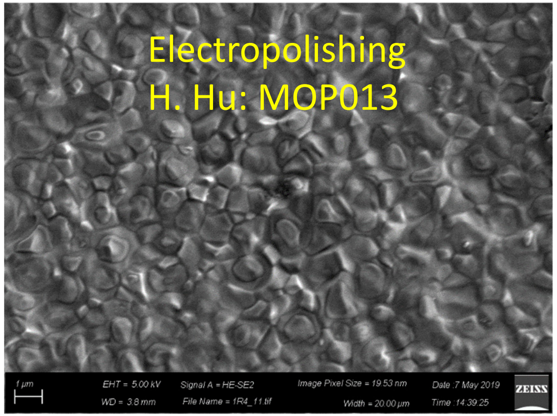
Reducing Surface Roughness

Surface Treatment

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

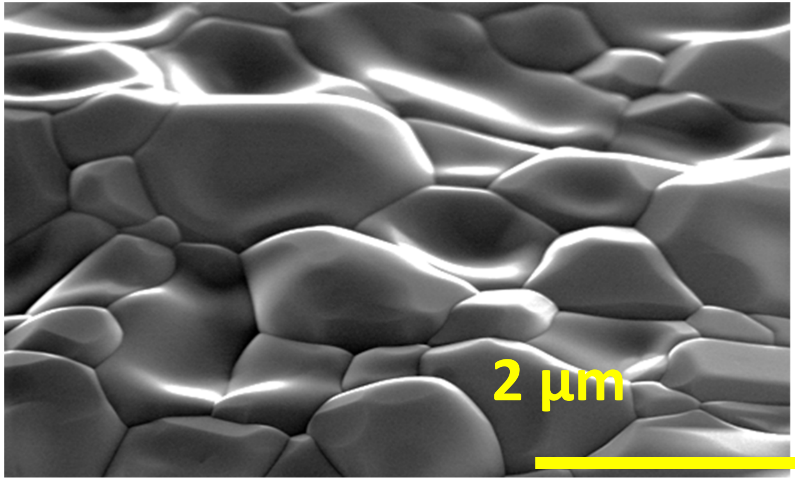




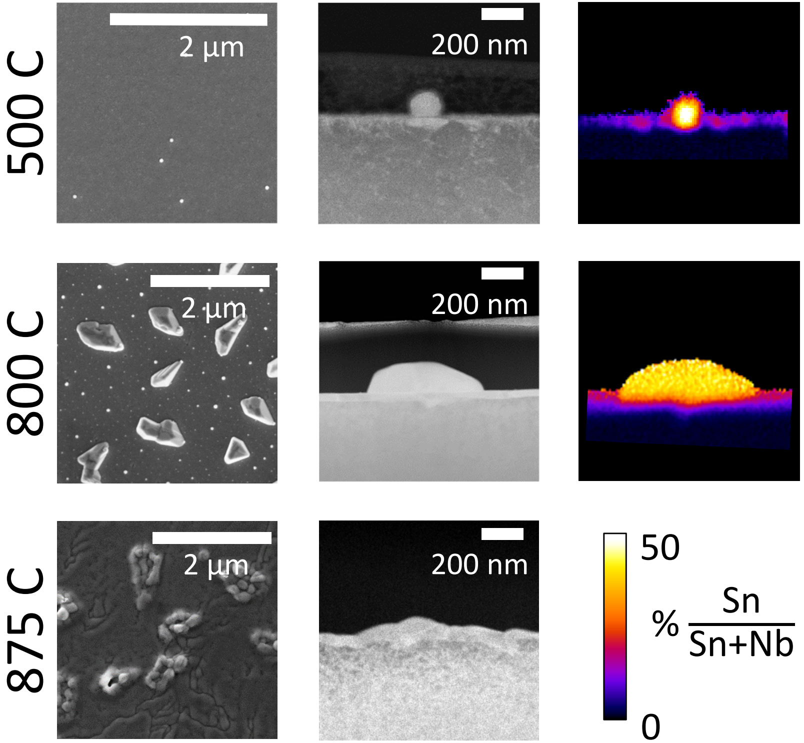


Why is Nb_3Sn Rough?

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



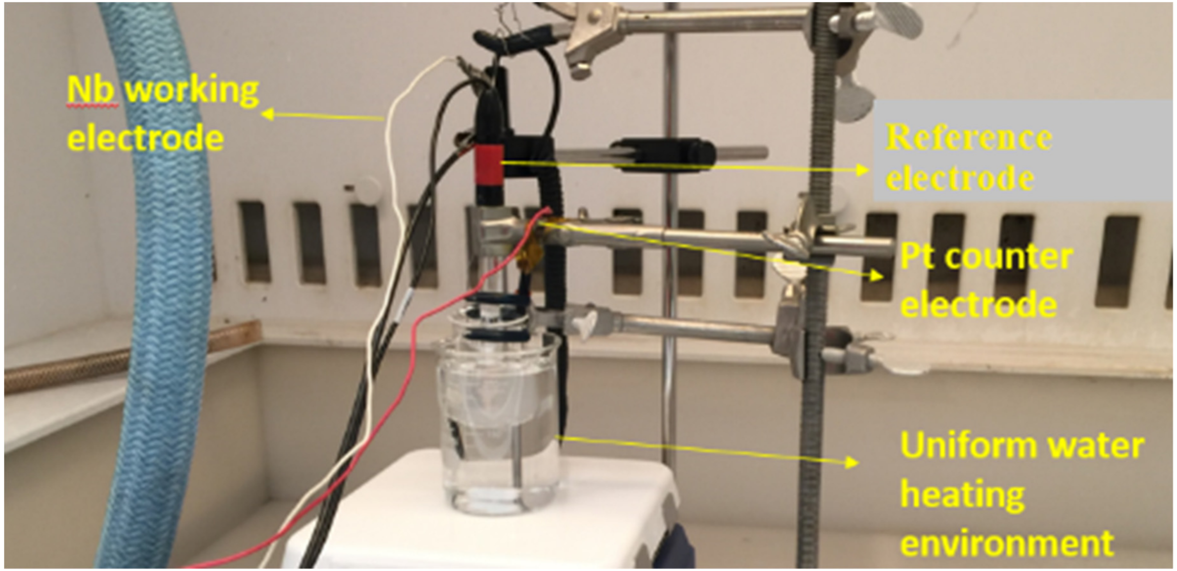
Nb_3Sn Growth:



Sn Electroplating

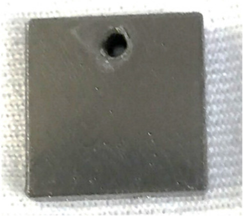
Zeming Sun (Cornell):

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



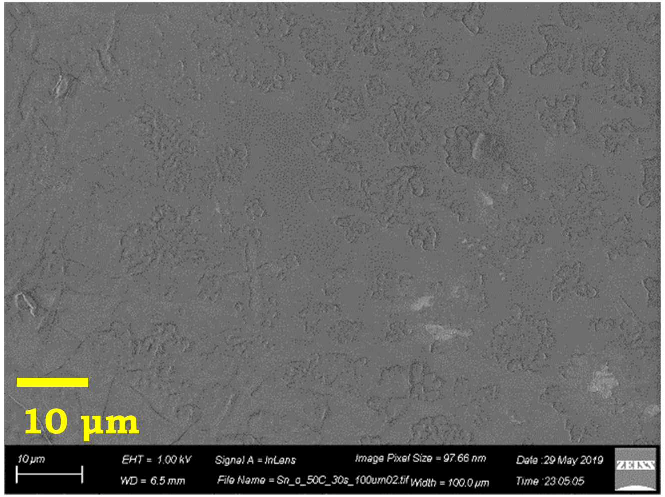
Sn Electroplating

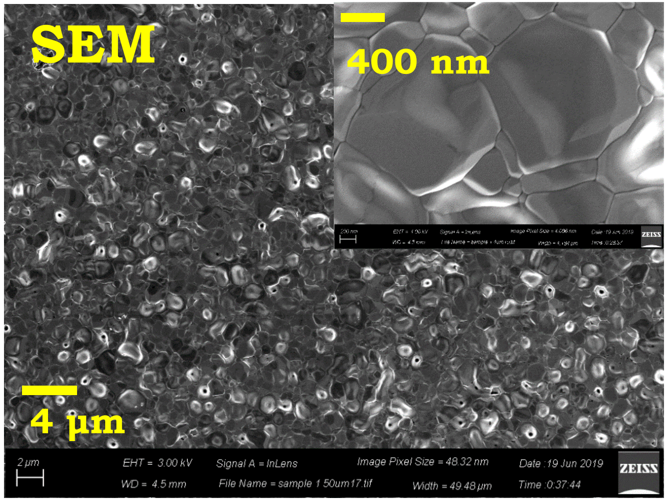
Coated Sn



Nb_3Sn

Heat Treatment





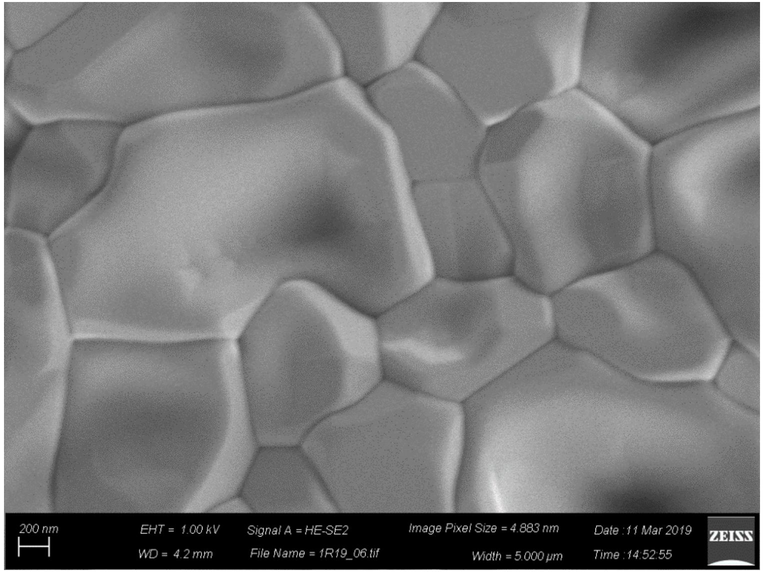
Sn Electroplating

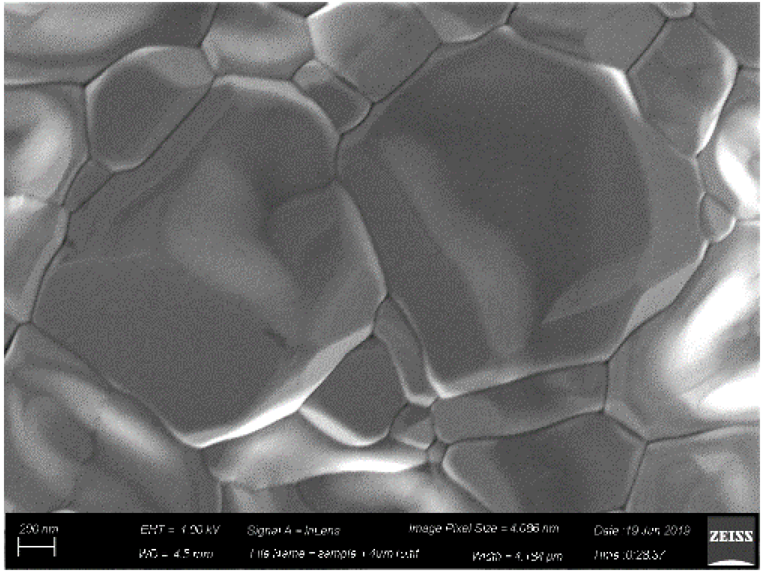
Sn_2Cl Nucleation

$R_a \sim 300$ nm

"Sn Plating Nucleation"

$R_a \sim 60$ nm



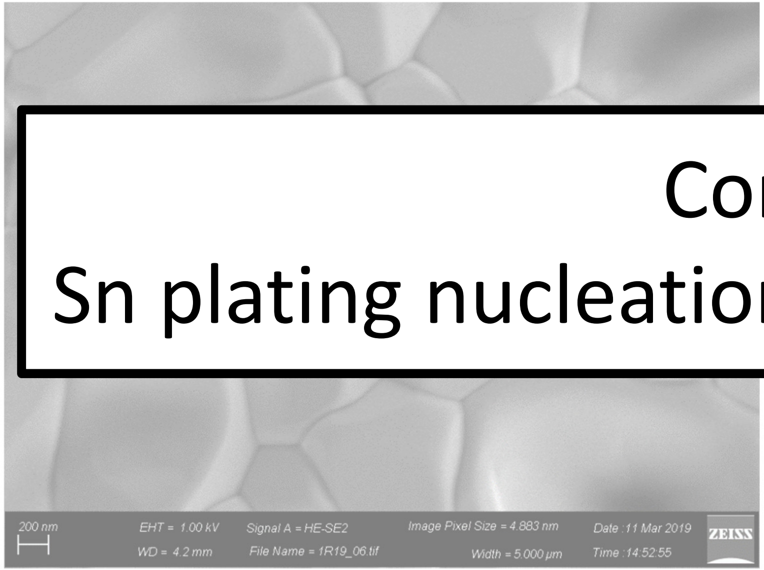


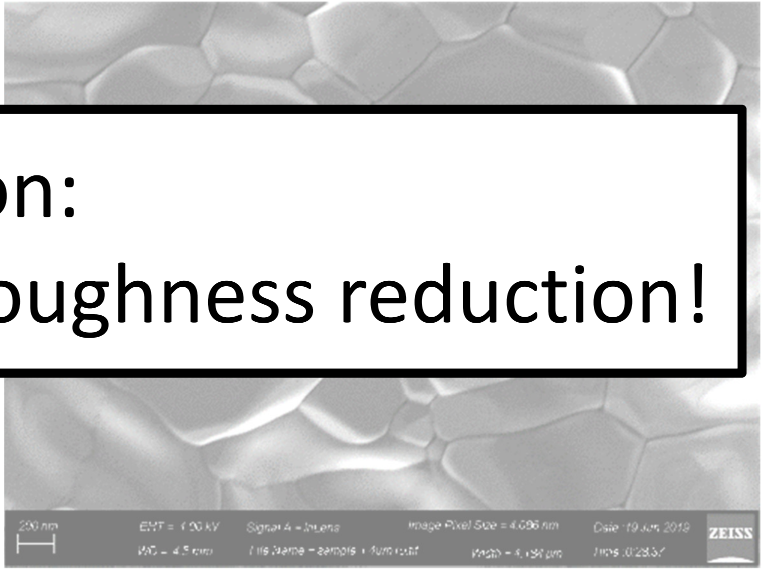
Next step: Grow entire cavity using Sn plating

Sn Electroplating

Sn_2Cl Nucleation → "Sn Plating Nucleation"

$R_a \sim 300$ nm → **$R_a \sim 60$ nm**





Conclusion:
Sn plating nucleation 5 x roughness reduction!

Next step: Grow entire cavity using Sn plating

Conclusions

- From experiment:
  - Claim: Vortex entry at grain boundaries a likely quench mechanism
- Reducing surface roughness is a critical next step
- Can grow smoother Nb_3Sn with Sn plating

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