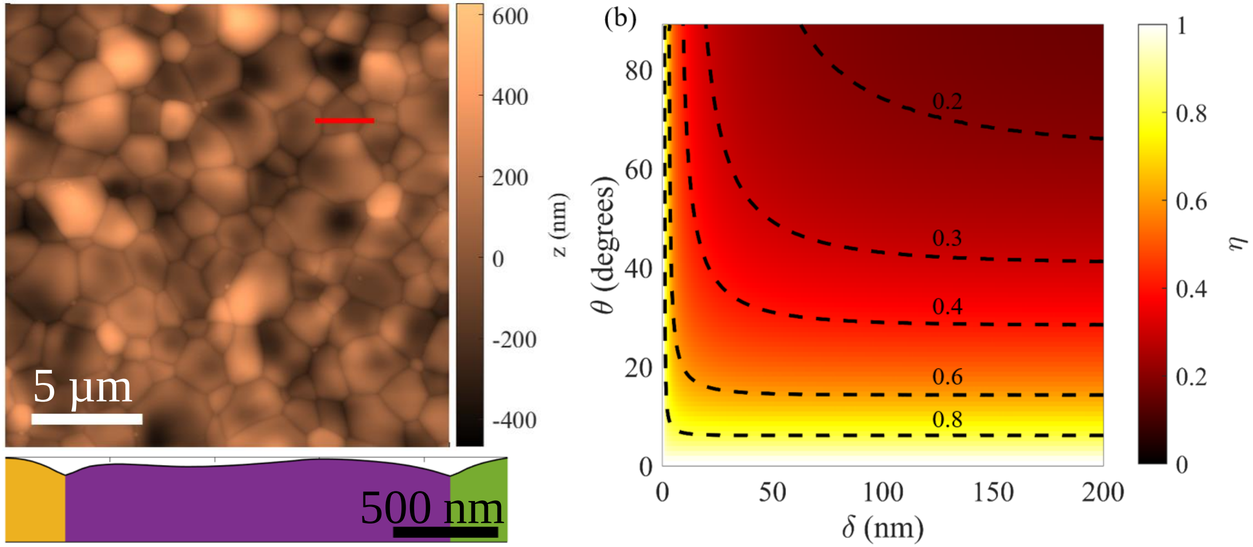
Analysis of Thermal Grooving Effects on Vortex Penetration in Vapor-Diffused Nb_3Sn

Based on our recent work:

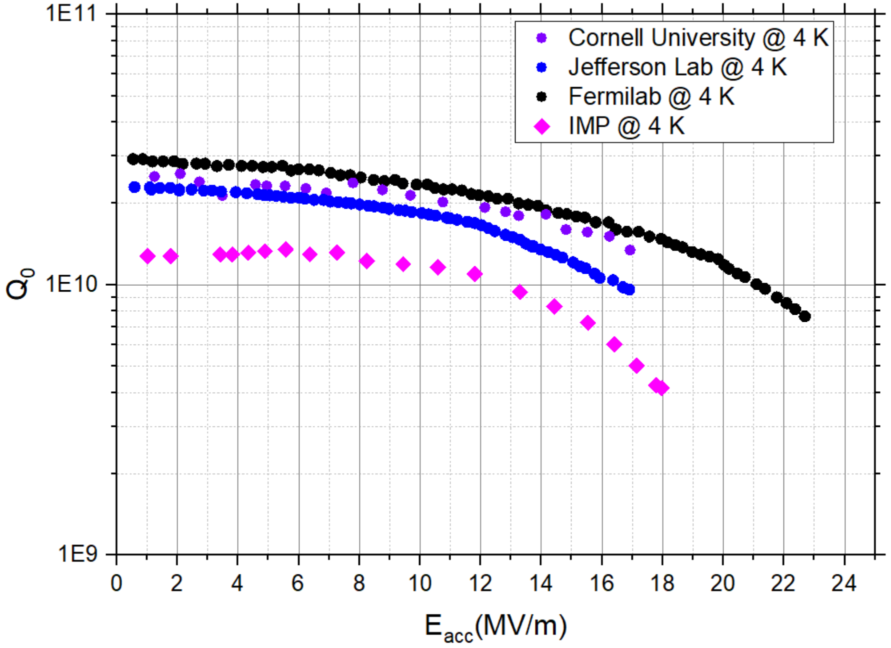
https://arxiv.org/abs/2409.01569



Eric M. Lechner

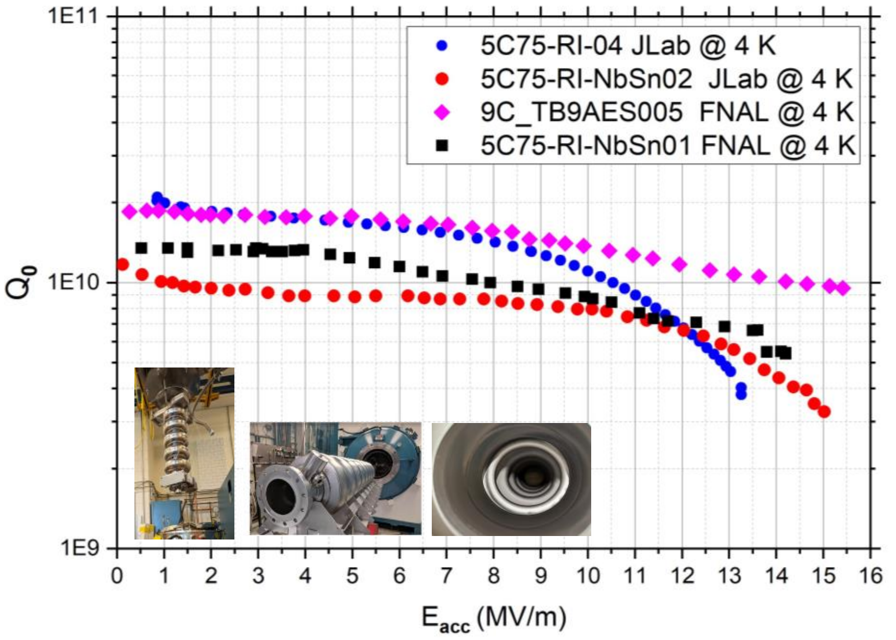
Performance of vapor-diffused Nb_3Sn grown on Nb

R&D 1.3/1.5 GHz single-cell cavity performance



- 1.3/1.5 GHz single-cell cavities can attain an accelerating gradient over 20 MV/m with $Q \sim 10^{10}$.
- Cavities of various frequencies (650 MHz, 952 MHz, 2.6 GHz, 3.6 GHz) coated at different facilities show comparable performance.

Multi-cell cavity performance



- 1.5 GHz five-cell and 1.3 GHz 9-cell cavities were demonstrated to reach $Q \sim 10^{10}$ at 10 MV/m at 4.4 K.
- Maximum gradients achieved up to ~ 20 MV/m.

U.Pudasaini et al. "Managing Sn-Supply to Tune Surface Characteristics of Vapor-Diffusion Coating of Nb_3Sn", presented at the SRF'21, East Lansing, MI, USA, Jun.-Jul. 2021, doi:10.18429/JACoW-SRF2021-TUPTEV013.
S. Posen et al. "Advances in Nb_3Sn superconducting radiofrequency cavities towards first practical accelerator applications" Superconductor Science and Technology. 2021 Jan 11;34(2):025007.
D. Hall, "New Insights into the Limitations on the Efficiency and Achievable Gradients in Nb_3Sn SRF Cavities", PhD thesis, Cornell University (2017).
G. Jiang et al.. Understanding and optimization of the coating process of the radio-frequency Nb3Sn thin film superconducting cavities using tin vapor diffusion method. Applied Surface Science. 2024 Jan 15;643:158708.
G. Eremeev "Progress in Nb3Sn developments for CEBAF-style quarter cryomodule" TTC-2022,

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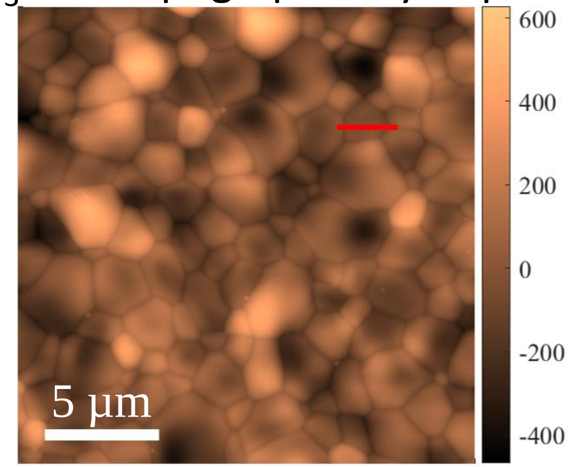
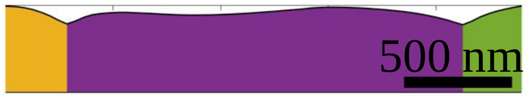
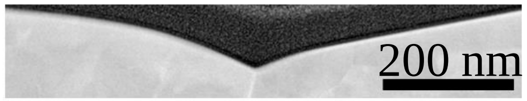
Introduction – Topographic Defects

Nb_3Sn is topographically imperfect







[1]

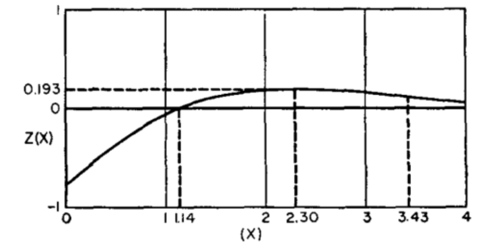
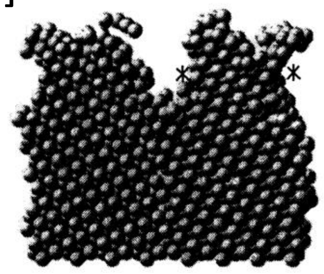


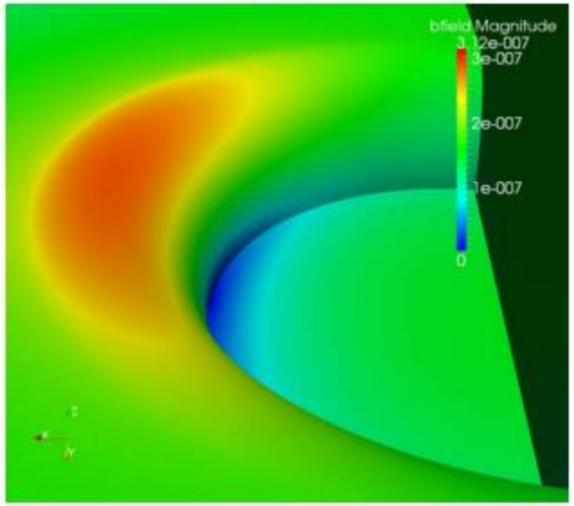
FIG. 3. Normalized profile shape due to surface diffusion

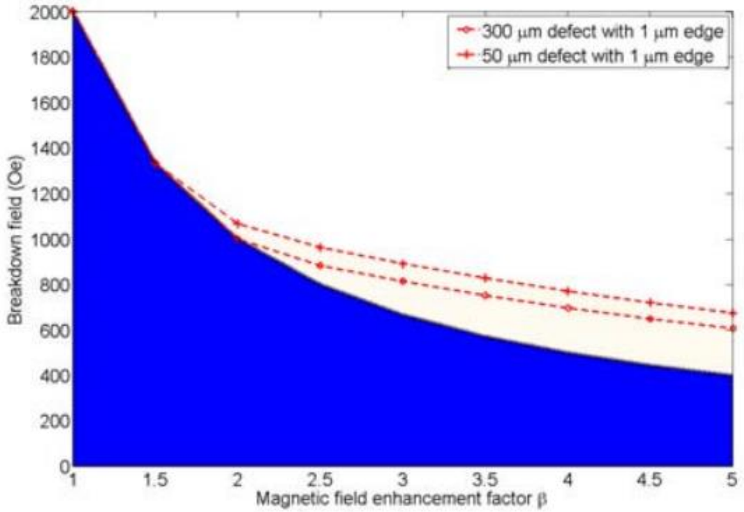
[2]



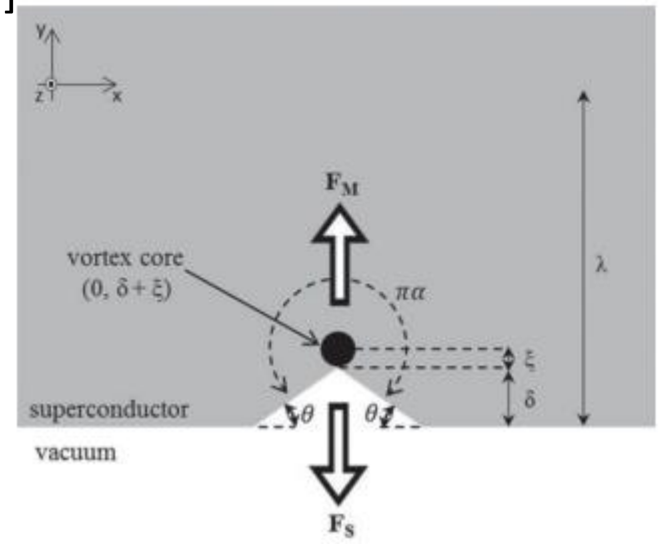
Step 210,000

[3]





[4]



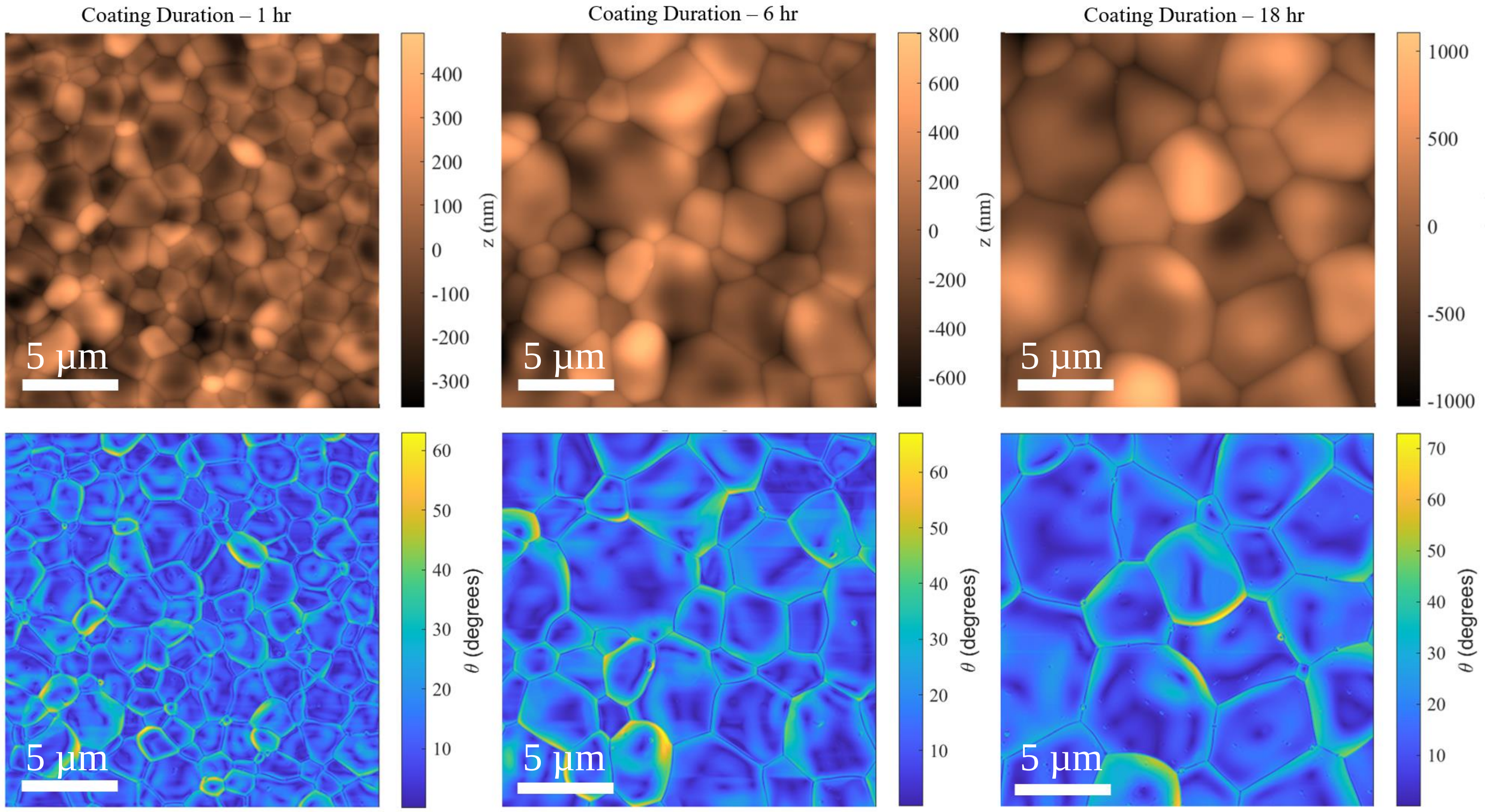
- Topographic defects produce local field enhancements due to the nature of the Meissner current. It has been proposed that this may turn regions of the cavity normal conducting and lead to thermal instabilities.
- Topographic defects may also reduce the local superheating fields. This reduces the field required to nucleate dissipative vortex semiloops and trigger thermal instabilities.

[1] Mullins, W.W., 1957. *Journal of Applied Physics*, *28*(3), pp.333-339.
[2] Iwasaki, Tomio, et al. *JSME international journal. Ser. A, Mechanics and material engineering* 40.1 (1997): 15-22.
[3] Xie , et al. Quench Simulation Using a Ring-Type Defect Model SRF'11, 2011
[4] Kubo, Takayuki, *Progress of Theoretical and Experimental Physics* 2015.6 (2015): 063G01.

Topography Nb_3Sn – Evolution with Coating Duration

Investigation

- Study samples coated from 1 to 78 hours (6 samples)
- 10x areas randomly sampled via AFM from each sample



Increased coating duration results in:

- Thickening of the coating
- Grain growth
- Roughening of the surface
- Grooves are on the order of 100 nm deep (comparable to the penetration depth)

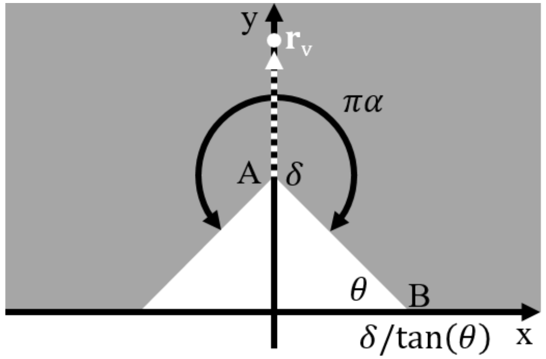
Slope angle calculation

$$\cos\theta = \hat{\mathbf{z}} \cdot \hat{\mathbf{n}} = \hat{\mathbf{z}} \cdot \frac{(-h_x, -h_y, 1)}{(1 + h_x^2 + h_y^2)^{\frac{1}{2}}}$$

- Access to h_x, h_y is given by the extension of the Savitzky-Golay filter for surfaces [1]
- High slope angles exist regardless of coating duration

[1] Lechner, Eric M., et al. *Physical Review Accelerators and Beams* 26.10 (2023): 103101.

Superheating Field Suppression

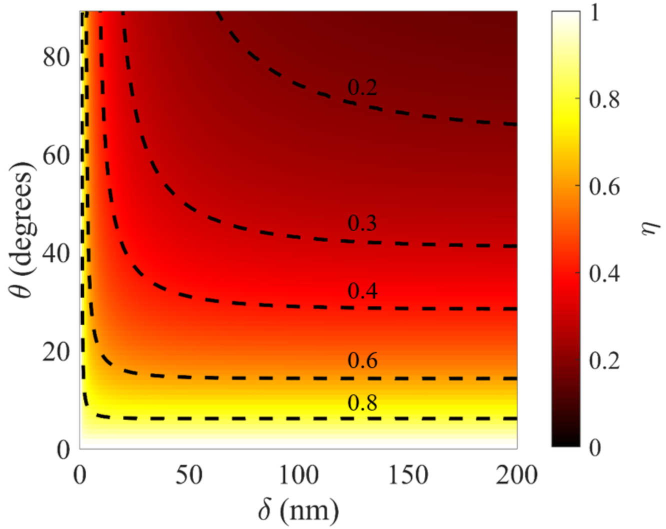


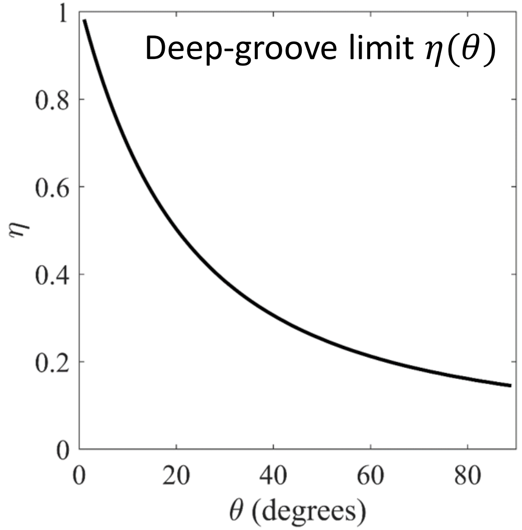
Limitations:

Calculation is performed in the London theory

1. Neglects the BCS current-field relation

$\xi = 3$ nm and $\lambda = 120$ nm used to represent Nb_3Sn





Force on vortex from magnetic field

$$\mathbf{F_M} = \mathbf{J_M} \times \phi_0 \hat{\mathbf{z}}$$

$$\nabla^2 B_z = \frac{1}{\lambda^2} B_z$$

$$\mathbf{J_M} = \nabla \times \mathbf{B}/\mu_0$$

$$\epsilon(\mathbf{r}) = |\mathbf{J}(\mathbf{r})|/J_0$$

Force from the surface: $\boldsymbol{J_{V+I}} \cdot \hat{\boldsymbol{n}} = 0$

$$\mathbf{F_S} = \mathbf{J_I} \times \phi_0 \hat{\mathbf{z}}.$$

$$\frac{2\pi\mu_0\lambda^2}{\phi_0}\Phi_I(x,y) = \tilde{\Phi}_I(x,y) = \mathrm{Re}\left(-i\ln(w - w_0^*)\right)|_{w=F^{-1}(x,y)}$$

$$\mathbf{J_I} = -\nabla\Phi_I$$

$\mathbf{r_v} = (\delta + \xi)\hat{\mathbf{y}}$ - London theory vortex nucleation position

$\mathbf{F_S} + \mathbf{F_M} = \mathbf{0}$ - Condition for vortex nucleation

Geometrically suppressed B_s

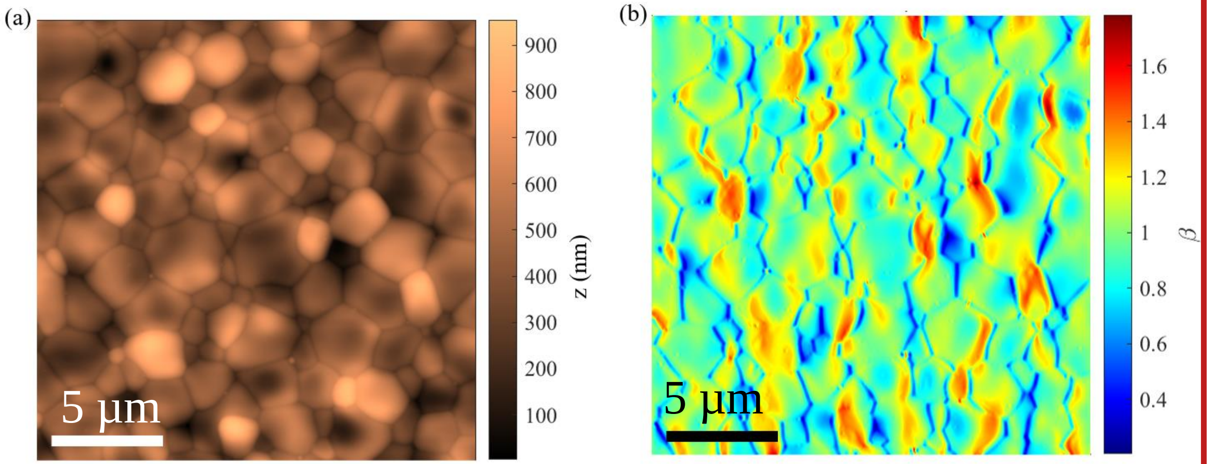
$$B_s^* = \frac{2\xi|-\nabla\tilde{\Phi}_I(\mathbf{r_v})|}{\epsilon(\mathbf{r_v})} B_s$$

Superheating field suppression (SFS) factor

$$\eta(\xi,\lambda,\delta,\theta) = \frac{2\xi|-\nabla\tilde{\Phi}_I(\mathbf{r_v})|}{\epsilon(\mathbf{r_v})}$$

MFE & SFS

Magnetic Field Enhancement Factor



[1] *Perfect Electrical Conductor Model*

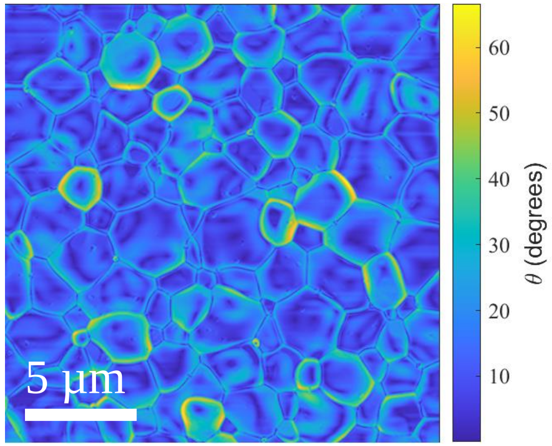
$$\beta(\mathbf{r}) = |\mathbf{B}(\mathbf{r})|/B_0$$

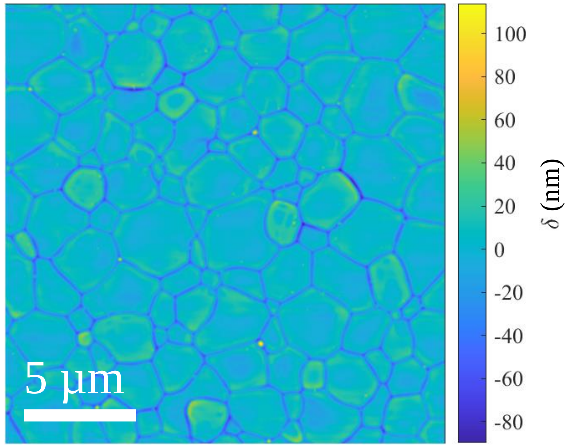
$$\nabla^2\psi = 0$$

$$\nabla\psi\cdot\hat{x} = B_0,\ \nabla\psi\cdot\hat{y} = 0 \text{ and } \nabla\psi\cdot\hat{n} = 0$$

$$\psi(x, y, z_{max} = 6\ \mu m) = -B_0 x \qquad \mathbf{B}(\mathbf{r}) = B_0\hat{x}$$

Superheating Field Suppression Factor



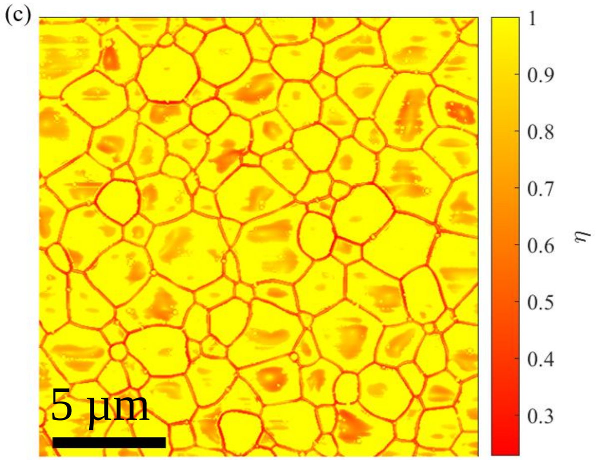


London Model

compute $\theta(\boldsymbol{r})$ and $\delta(\boldsymbol{r})$

$$\eta(\xi, \lambda, \delta, \theta) = \frac{2\xi|-\nabla\tilde{\Phi}_I(\mathbf{r_v})|}{\epsilon(\mathbf{r_v})}$$

$\xi = 3$ nm and $\lambda = 120$ nm used to represent Nb_3Sn



[1] Lechner, Eric M., et al. *Physical Review Accelerators and Beams* 26.10 (2023): 103101.

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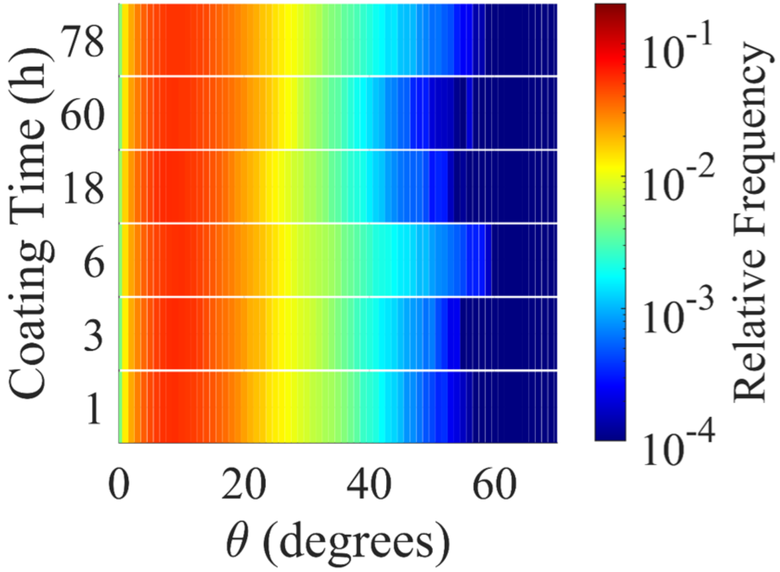
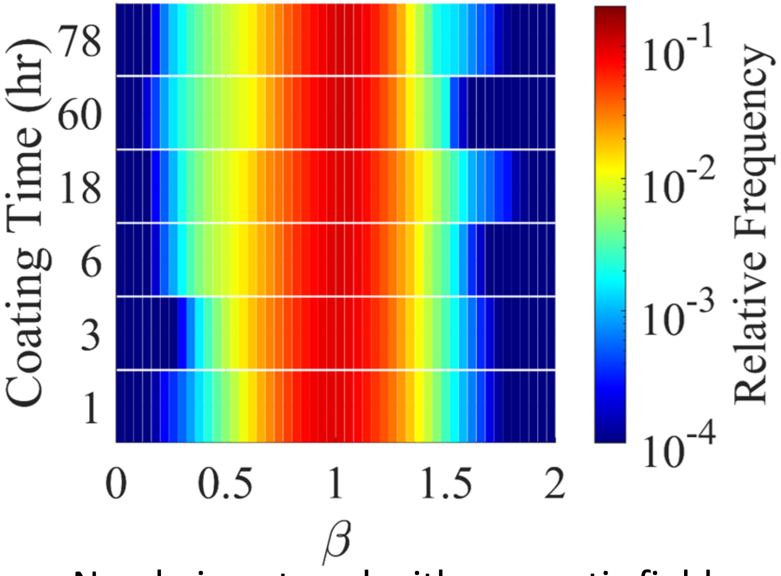
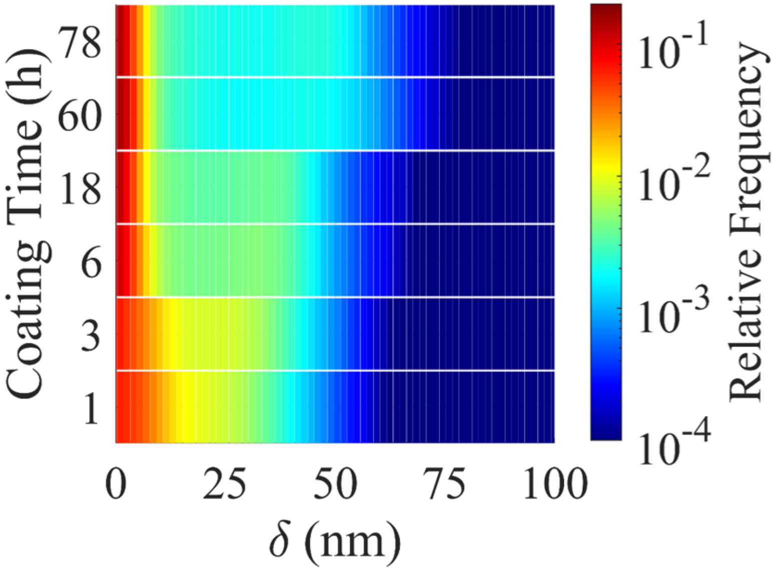
Results

<u>Increased coating duration results in:</u>





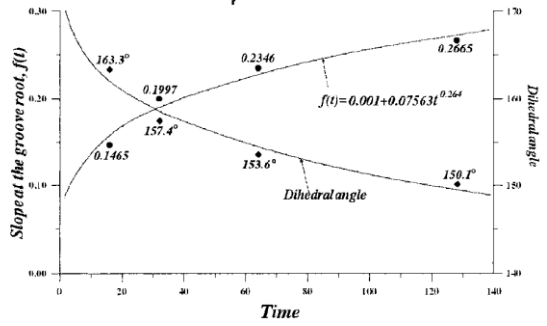


- No obvious trend with slope angles

[1] Thermal grooves are often considered to retain the groove angle during annealing

$$\tan\beta \equiv m$$

[2]



- No obvious trend with magnetic field enhancement factors.
- Peak MFE factors between 1.5 and 2

[1]

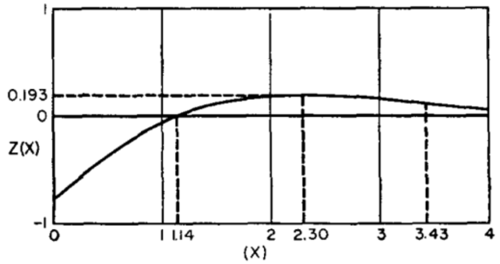


FIG. 3. Normalized profile shape due to surface diffusion.

$$y(x,t)=m(Bt)^{\frac{1}{4}}Z\left[\frac{x}{(Bt)^{\frac{1}{4}}}\right]$$ - self-similarity

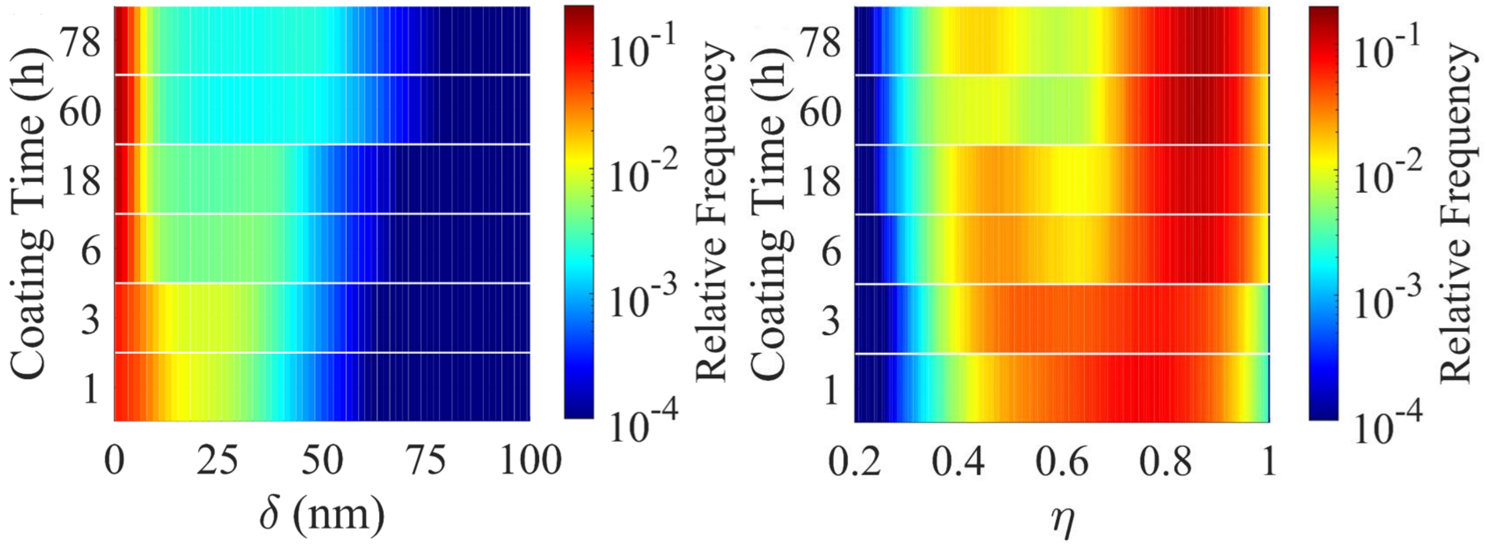
$$s=4.6(Bt)^{\frac{1}{4}}$$
$$d=0.973m(Bt)^{\frac{1}{4}}$$

- Increase in groove depth is clearly observed

[1] $$d=0.973m(Bt)^{\frac{1}{4}}$$

[1] Mullins, W.W., 1957. *Journal of Applied Physics*, *28*(3), pp.333-339.
[2] Zhang, W., P. Sachenko, and J. H. Schneibel. *Journal of materials research* 17.6 (2002): 1495-1501.

Results



- Bifurcation in the deviation between background plane and the topography
- This bifurcation is more clearly reflected in the SFS factor. During short annealing times
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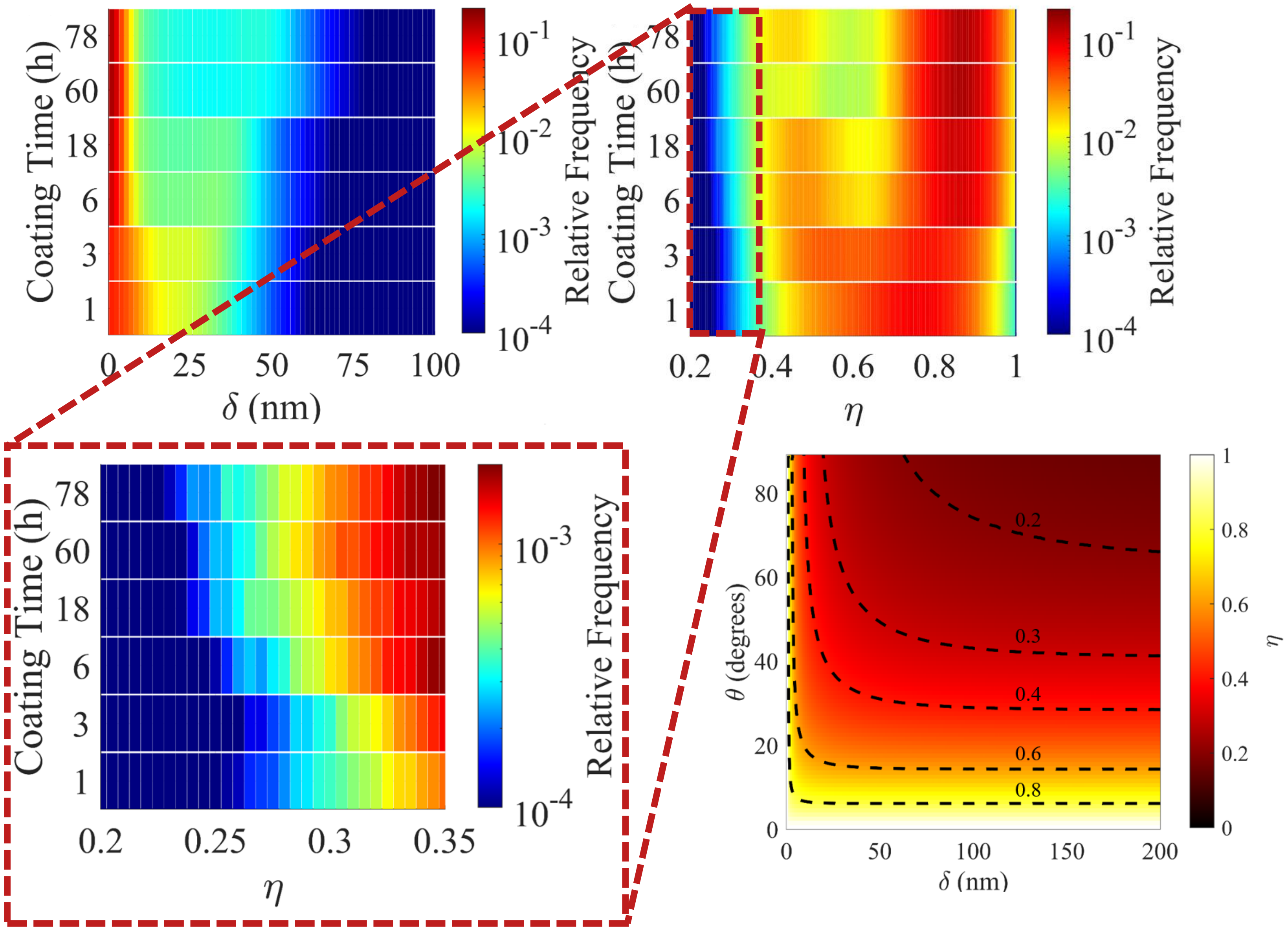
Results



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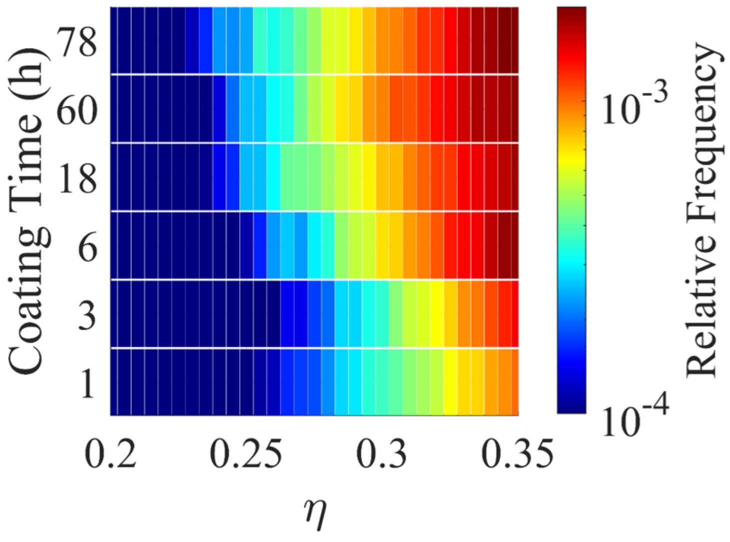
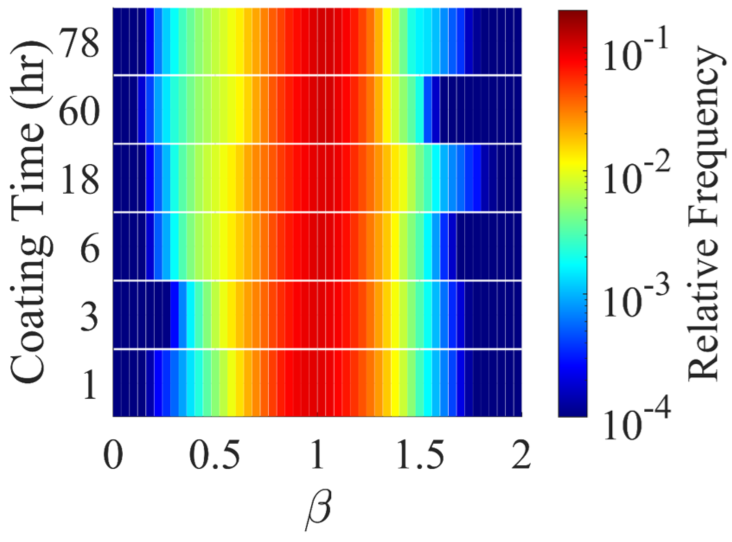
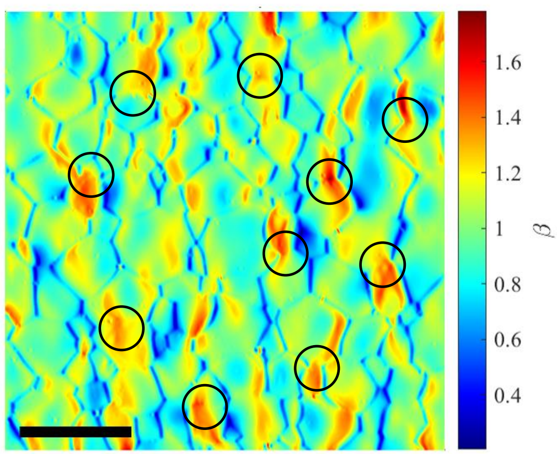
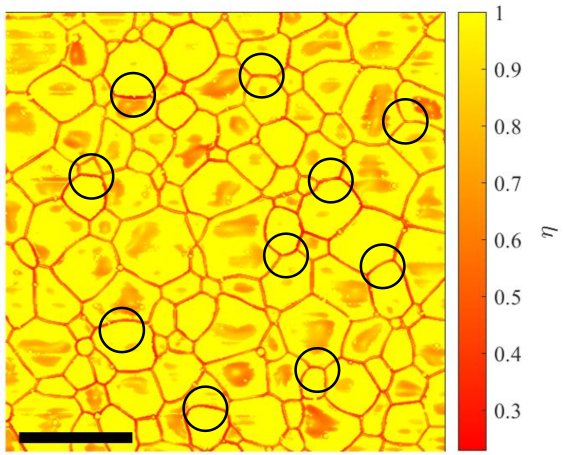
Discussion









- Considering only the effects of superheating field suppression on the superheating field (~400 mT) peak magnetic fields of 107-128 mT may be expected.
- Peak magnetic field enhancement values fall around ~1.7.
- There are many locations where MFE and SFS overlap. This may reduce further reduce the field of vortex penetration by $B^*_{max} = \left(\frac{\eta}{\beta}\right) B_{max}$. The combined effect can reduce peak magnetic field to ~51-77mT (12-18MV/m in TESLA-shaped cavities).
- While this is in qualitative agreement with the field limitation in Nb_3Sn, there are many loss mechanisms which should be considered ***before*** topography.

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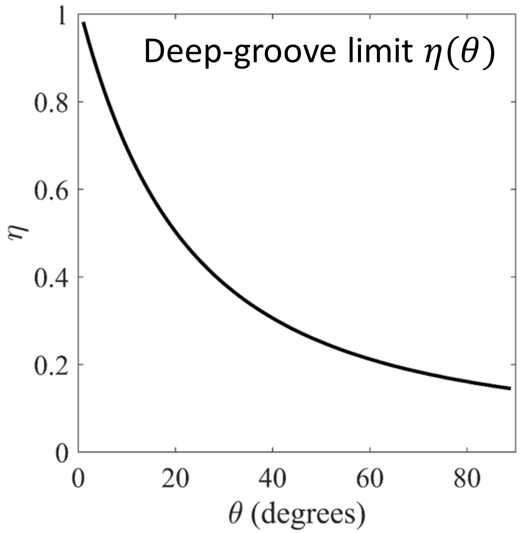
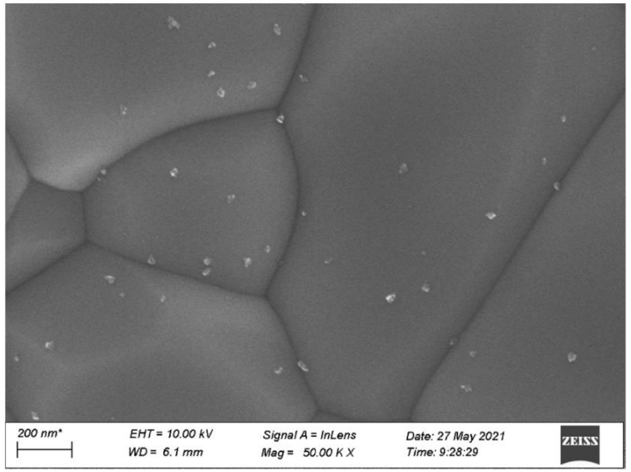
Discussion – Other Performance Limiting Mechanisms

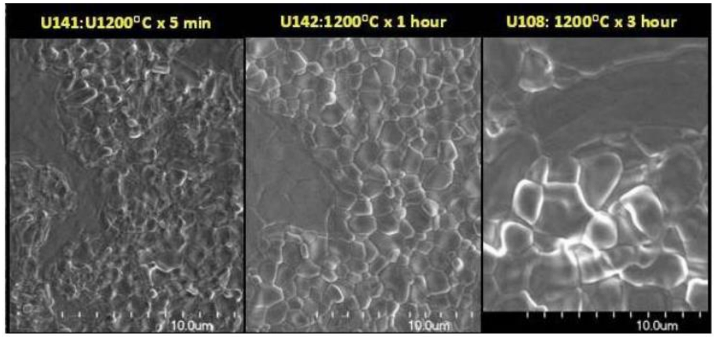


The deep-groove limit suggests that you should not see Q-slopes below 50 mT, yet many examples of this exist.

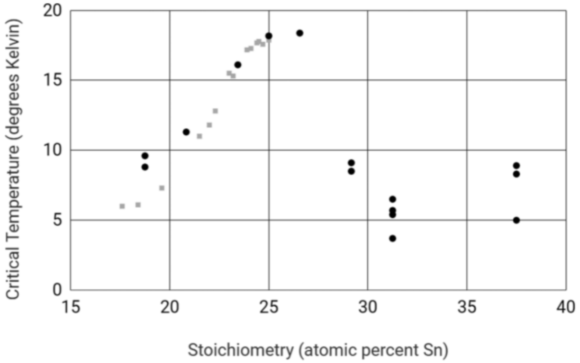
[1] Sn droplets

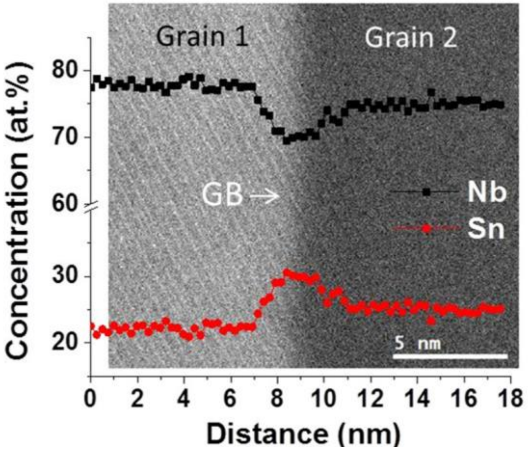


[2] Thin patchy regions

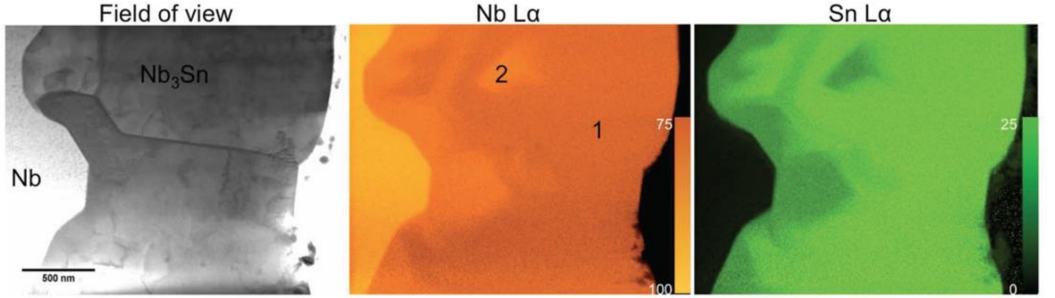


[3] Off-stoichiometry





[4]



[1] Jiang, Guangze, et al. *Applied Surface Science* 643 (2024): 158708
[2] Pudasaini, Uttar, et al. *Proc. 18th Int. Conf. RF Superconductivity (SRF'17)*. 2017.
[3] Carlson, Jared, et al. *Physical Review B* 103.2 (2021): 024516.
[4] Becker, Chaoyue, et al. *Applied Physics Letters* 106.8 (2015).

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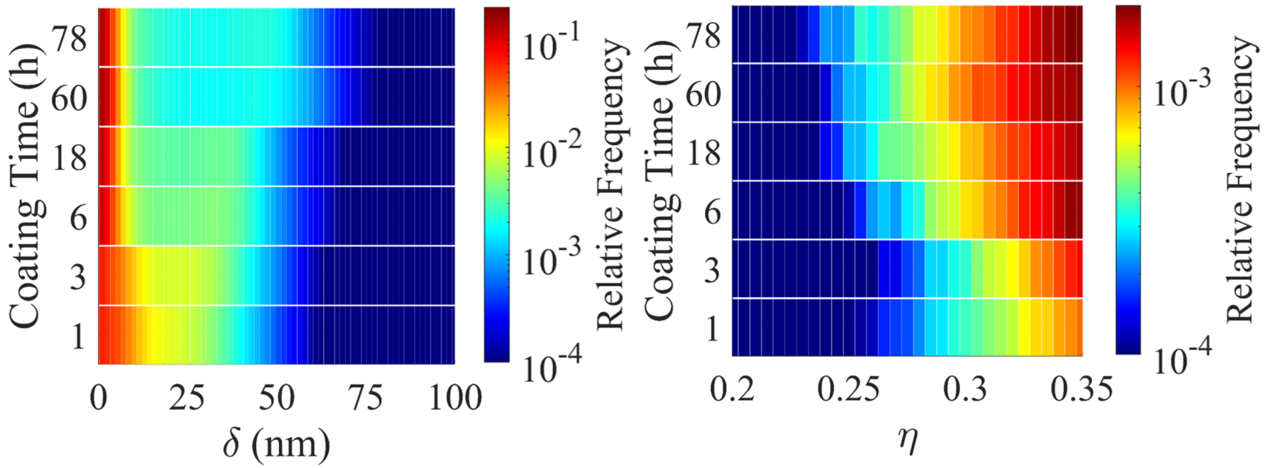
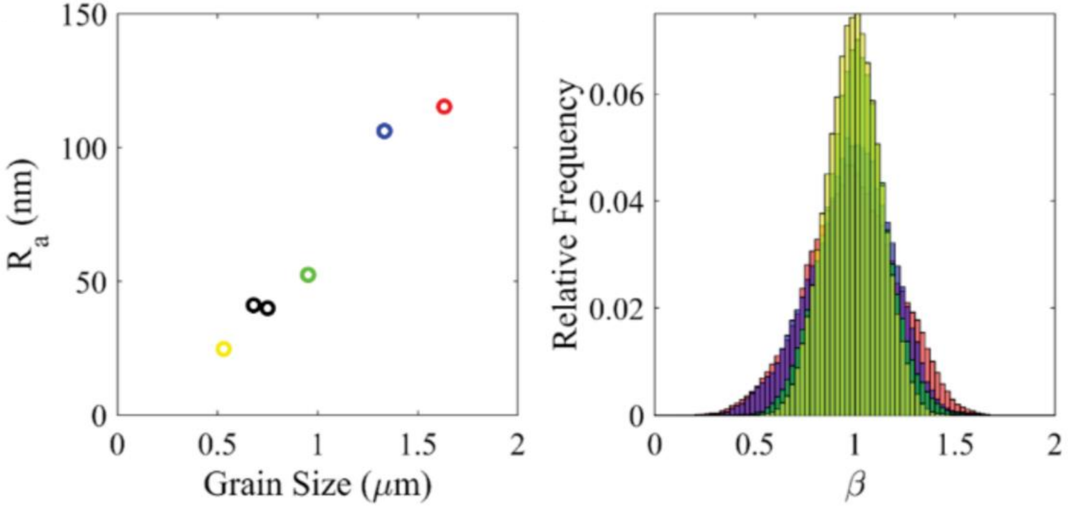
Discussion – How Can The Suppression Factor Be Improved?



Short coating durations at 1200 °C tend to reduce groove depths

[1]



Temperature may play a role in surface

[2]

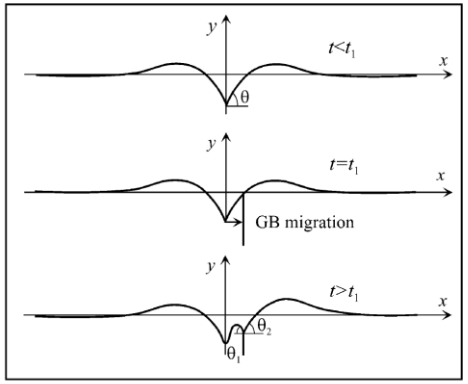
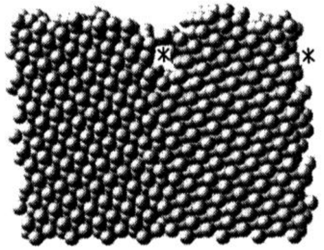


Fig. 9 A model of GB grooving with the instantaneous GB jump during annealing

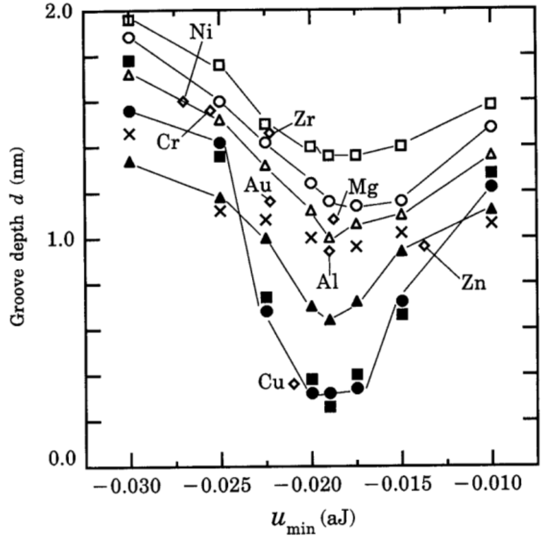
Encourage grain boundary migration

[3]



Step 210,000

Fig. 8 Grain boundary grooving with Cu atoms at $T = 600$ K



Include impurities

[1] U. Pudasaini et al. SRF’23 (Grand Rapids, MI, USA). JACoW Publishing, Geneva, Switzerland, 2023.
[2] Rabkin, E., et al. *Journal of materials science* 41 (2006): 5151-5160.
[3] Iwasaki, Tomio, et al. *JSME international journal. Ser. A, Mechanics and material engineering* 40.1 (1997): 15-22.

Conclusions & Future Work

Conclusions

- Developed a simple model to calculate the superheating field suppression factor in the London theory.
- We have shown that superheating field suppression may be a large contributor to peak field degradation in dense, stoichiometric Nb_3Sn. The effect of which is compounded by local magnetic field enhancement.
- We hope that this work inspires more physically justified theories to make estimates of the geometrically suppressed superheating field in the deeper type-II limit where Nb_3Sn resides.

Future work

- Compare the topography from witness samples and performance of Nb_3Sn coated cavities.

Acknowledgments

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M.C. DiGuilio (VT)

Others

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M.J. Kelley

C.E. Reece