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# Development of High-performance Niobium-3 Tin Cavities at Cornell University

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**Cornell University (CLASSE), Ithaca, New York**

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SRF 2023 GRAND RAPIDS

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

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This work was performed in part at the Cornell NanoScale Facility, a member of the National Nanotechnology Coordinated Infrastructure (NNCI), which is supported by the National Science Foundation (Grant NNCI-2025233)

# $Nb_3Sn$ Potential



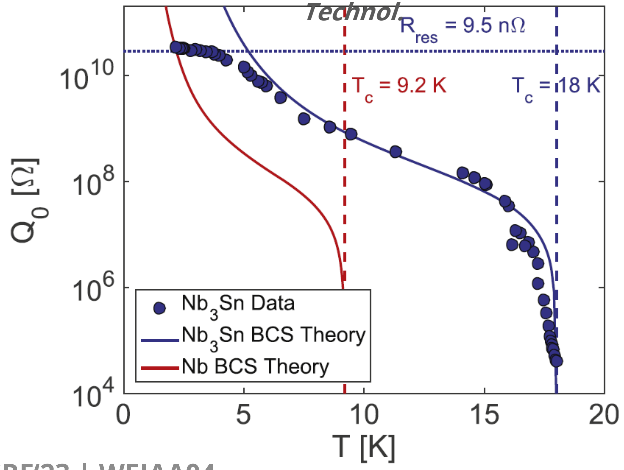
| | Nb | $Nb_3Sn$ |
|---|---|---|
| **Critical Temperature ($T_C$)** | **9 K** | **18 K** |
| **$Q_0$ at 4.2K** | $6 \times 10^8$ | $6 \times 10^{10}$ |
| **Superheating Field ($B_{sh}$)** | **240 mT** | **420 mT** |
| **Max. $E_{acc}$** | **55 MV/m** | **100 MV/m** |

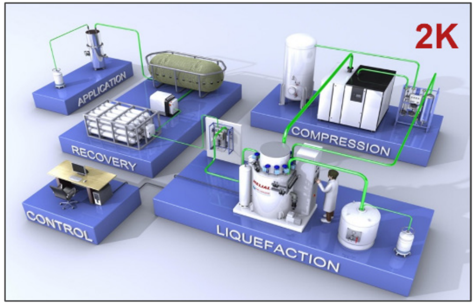
*$Q_0$ given for 1.3 GHz single-cell ILC-shape cavities*

**Higher operating temperature**
**≡ Lower cooling cost and complexity**

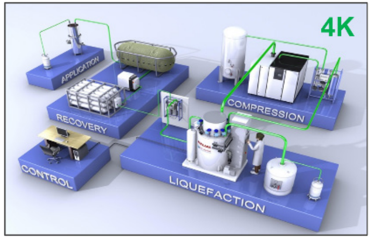
**Higher superheating field $B_{sh}$= higher accelerating gradients: $E_{acc,max} \propto B_{sh}$**

S Posen and D L Hall 2017 *Supercond. Sci. Technol*

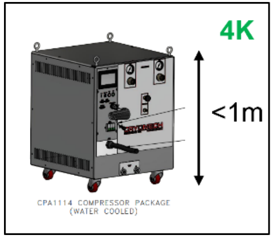



**Large Scale**

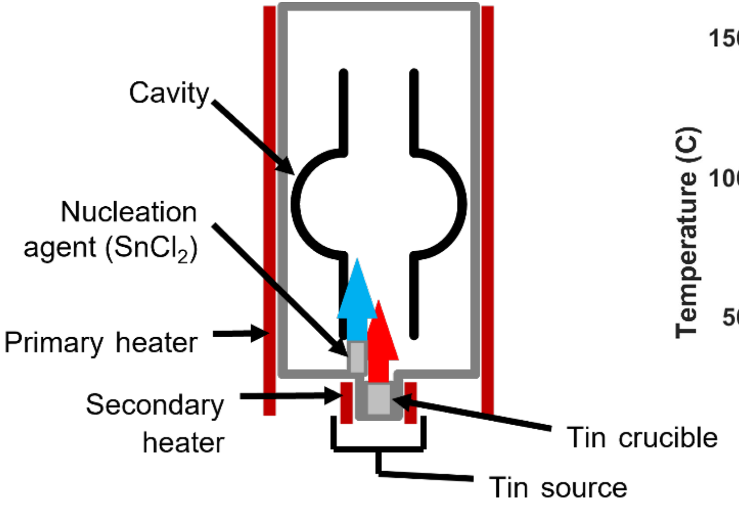


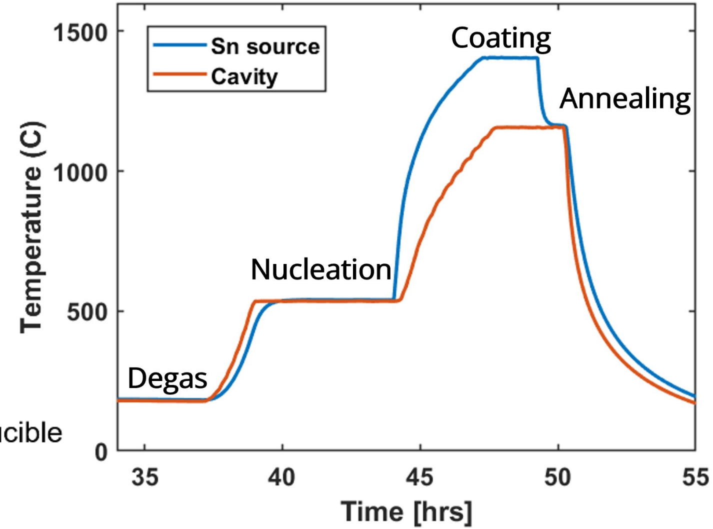

**Small Scale**



# State-of-the-Art: Thermal Vapor Diffusion

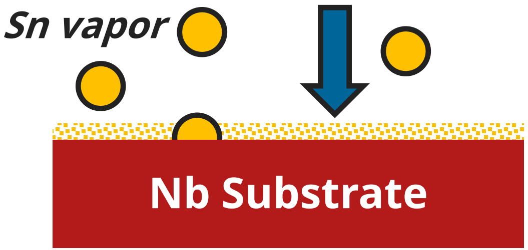


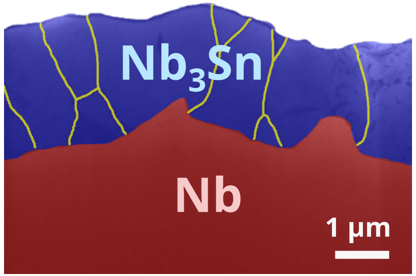




**"Wuppertal" configuration (secondary heater for the tin source)**




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

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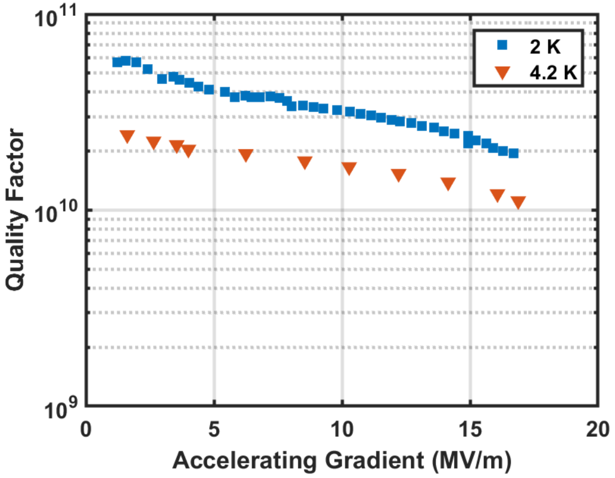
→ **Reproducible performance of ~4 K operation with $Q_0 > 10^{10}$ at typical CW operating fields.**

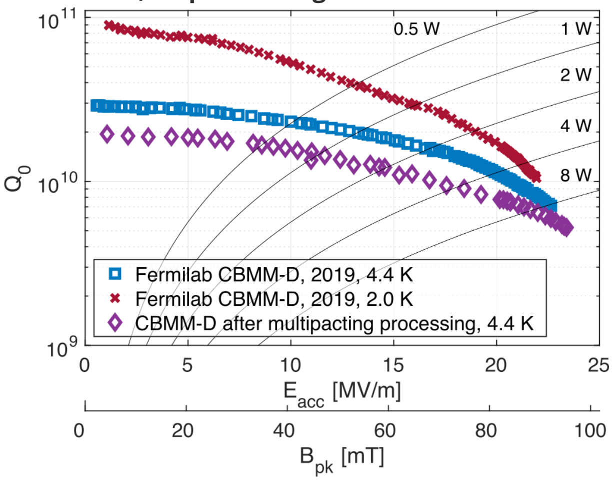
→ **Current quench fields: 16-24 MV/m (FNAL holds world record)**

Cornell University



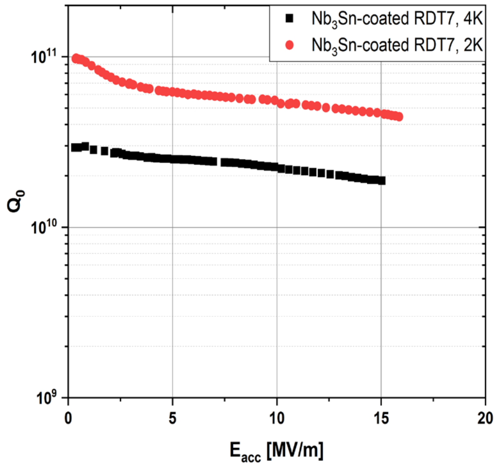

Fermilab

S. Posen, https://doi.org/10.1088/1361-6668/abc7f7




Jefferson Lab

U. Pudasaini, SRF'19




*(Note: Plots are for single cell cavities)*

# State-of-the-art Performance

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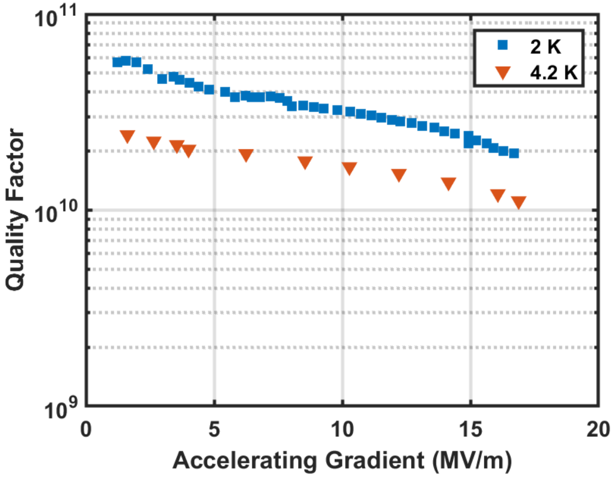


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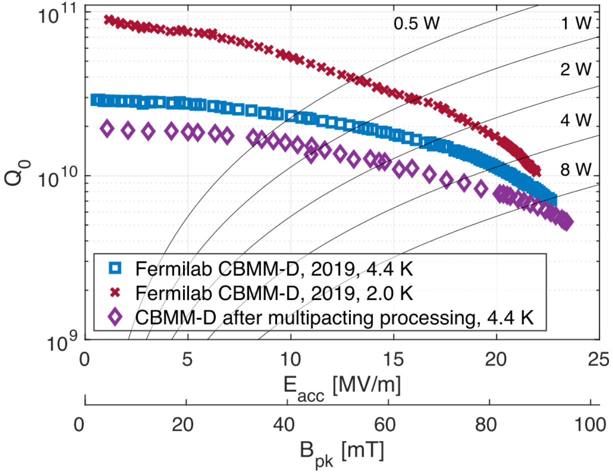


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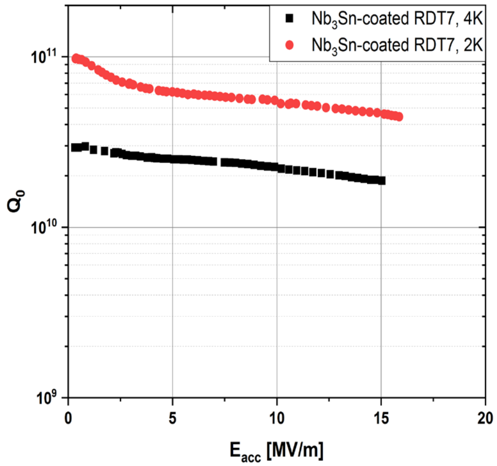


**Efforts continue worldwide to push the limits of Nb3Sn even further!**

***Some presentations here at SRF'23: TUPTB009, TUPTB010, TUPTB014, TUPTB015, TUPTB020, TUPTB065, WEPWB126***

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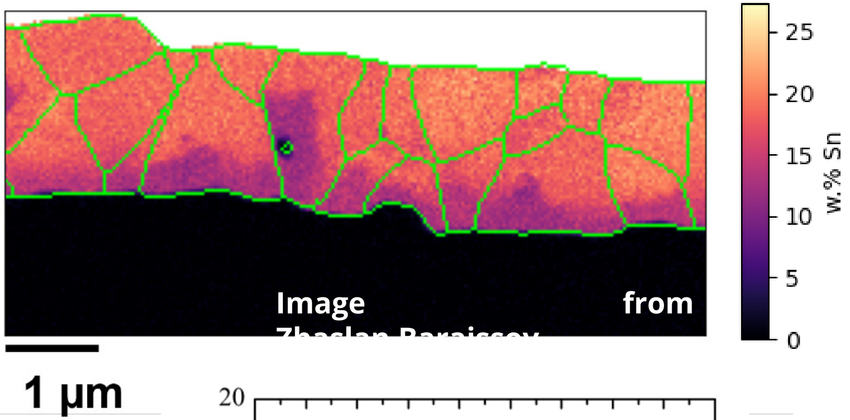
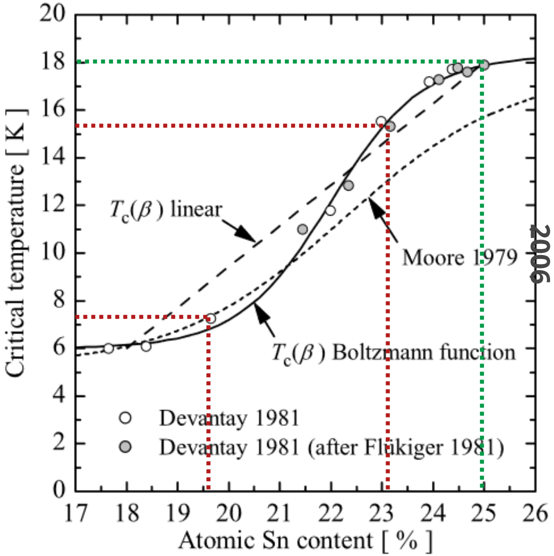
1. **Tin depleted regions**
   → **Tin depleted regions have a low critical temperature**



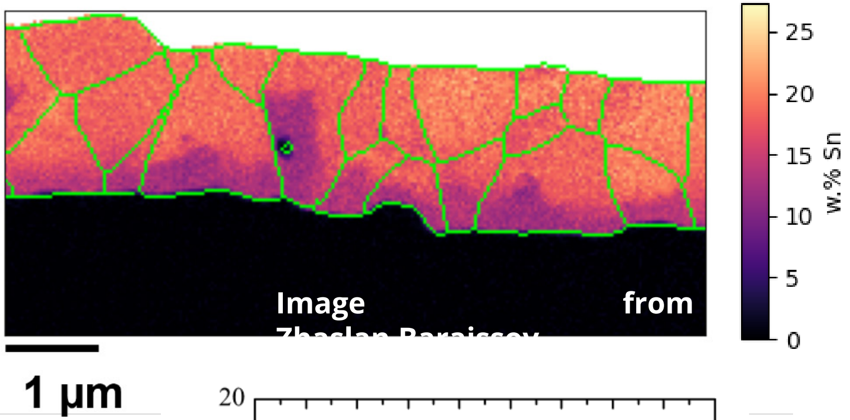



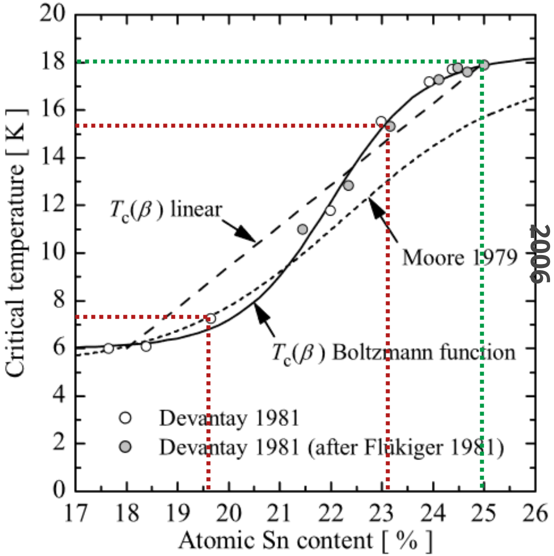

A. Godeke, Supercond. Sci. Tech, 2006

# Limitations

1. **Tin depleted regions**
   → **Tin depleted regions have a low critical temperature**

2. **Uniformity of thickness of film**
   → **Thinner patches expose Nb-Nb3Sn interface (tin depleted)**

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   → Tin depleted regions have a **low critical temperature**

2. **Uniformity of thickness of film**
   → Thinner patches expose Nb-Nb3Sn interface (tin depleted)

3. **Surface roughness**
   → Can cause **field enhancement** and **vortex nucleation**

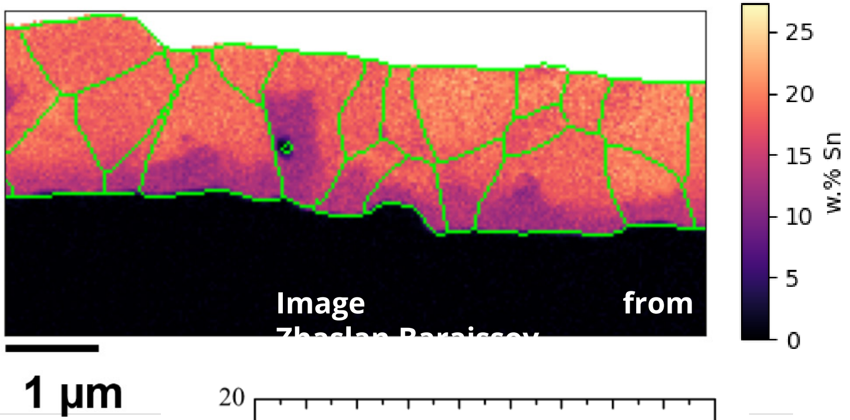
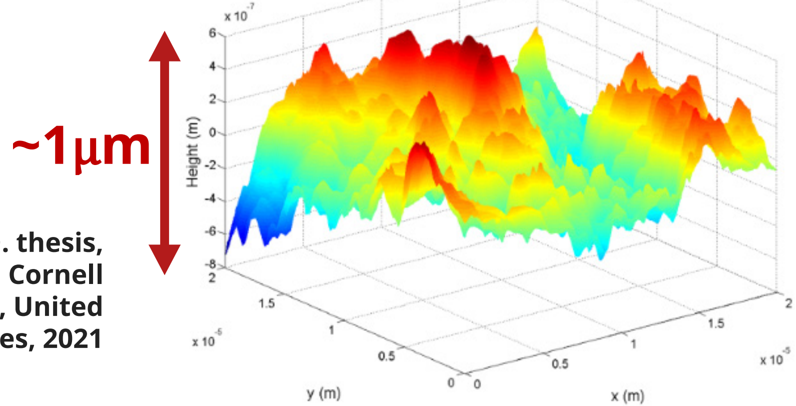
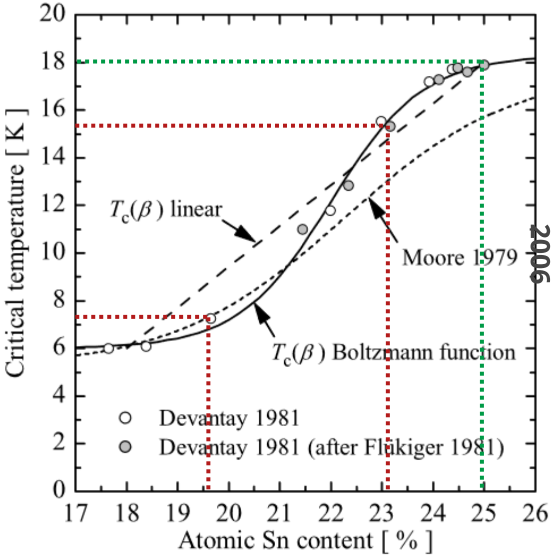



Image from Zhaslan Baraissov




R. D. Porter, Ph.D. thesis, Phys. Dept., Cornell University, Ithaca, United States, 2021

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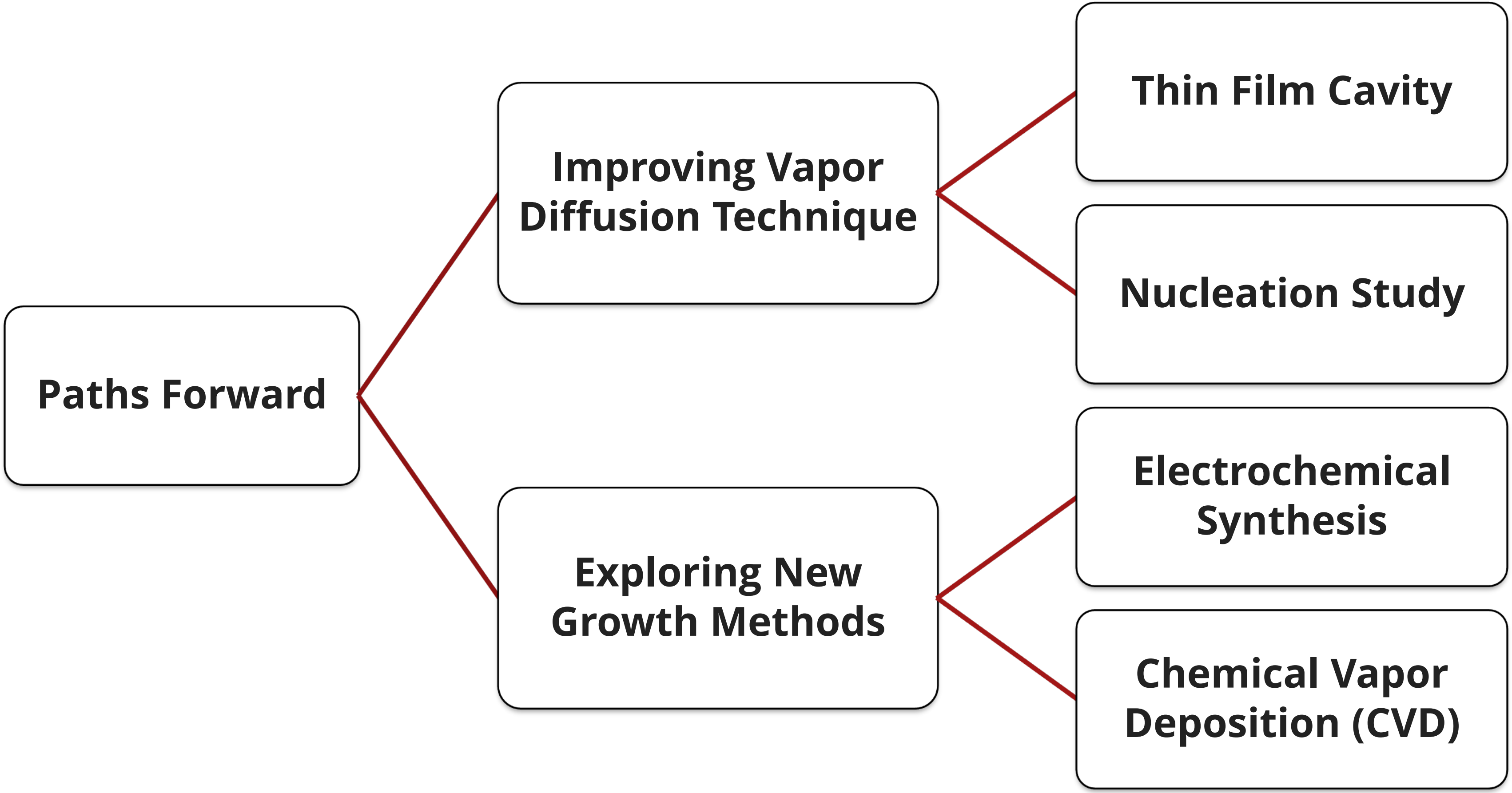
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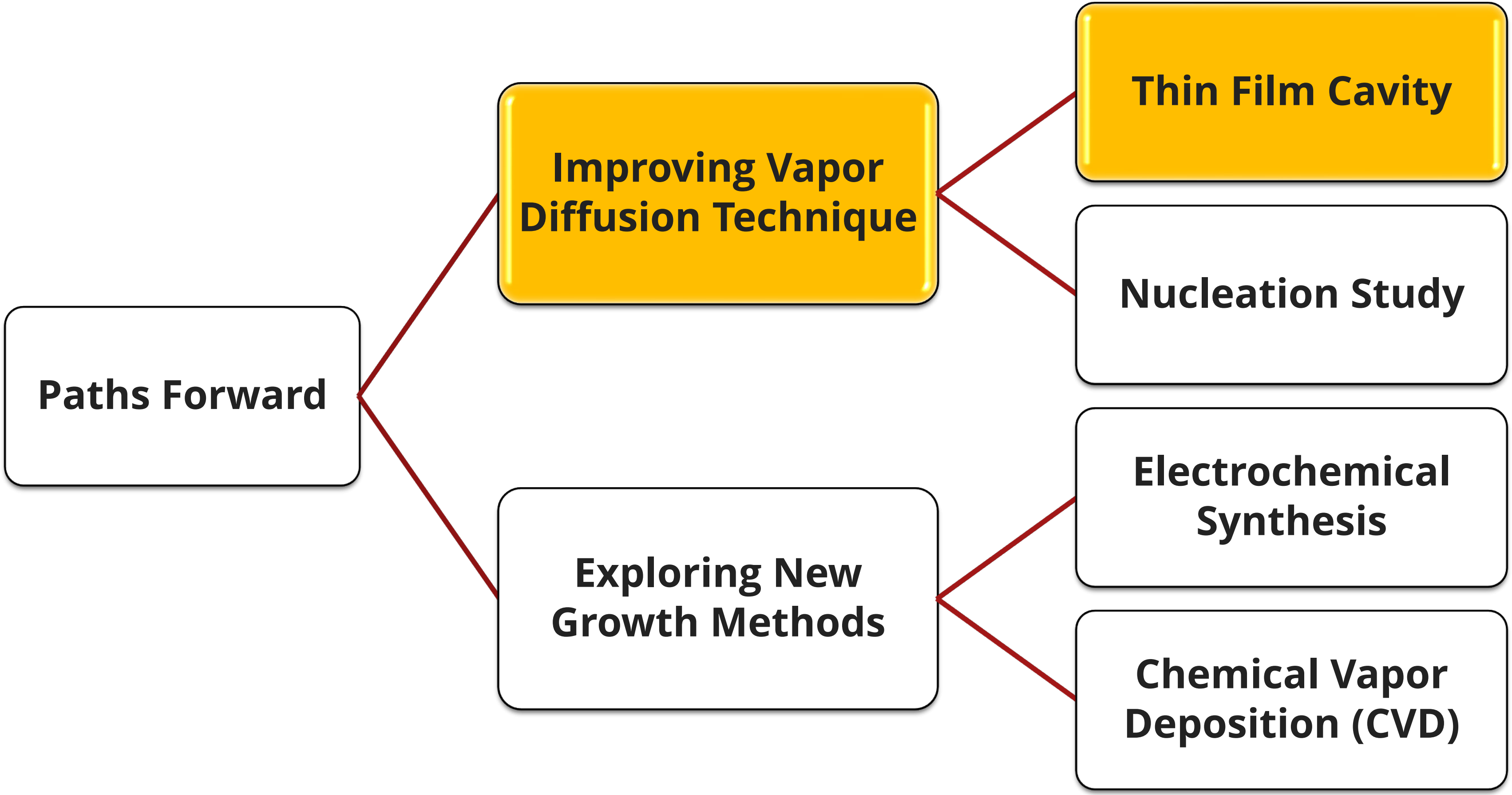
Exploring New Growth Methods
Thin Film Cavity
Nucleation Study
Electrochemical Synthesis
Chemical Vapor Deposition (CVD)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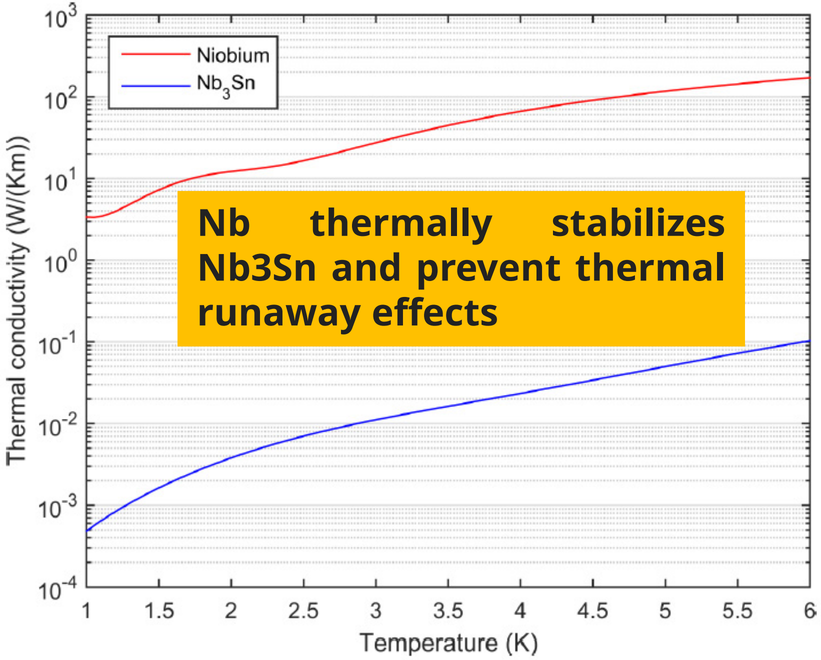
# Why thin films?

**1. Thermal instability was identified as a major component of $Nb_3Sn$ cavity quench.**




**Nb thermally stabilizes Nb3Sn and prevent thermal runaway effects**

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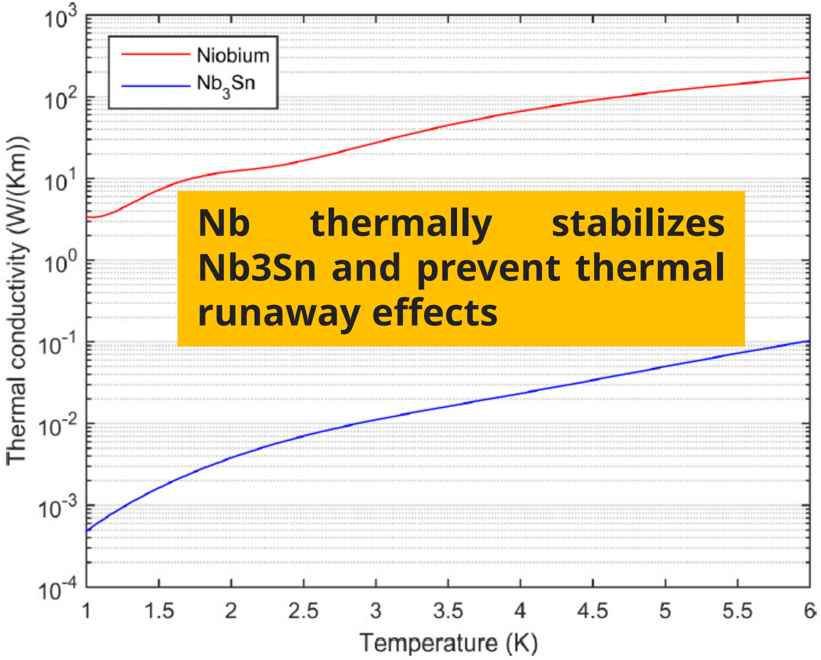
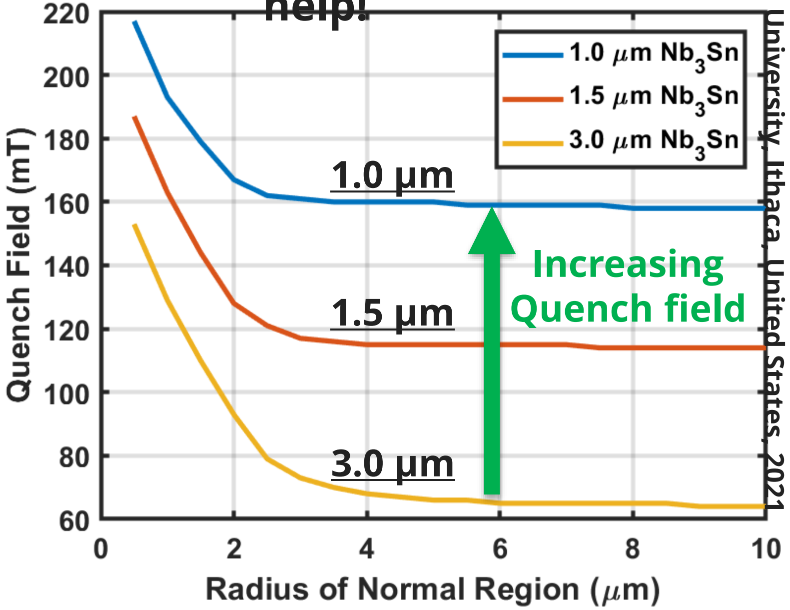



Thin films help!

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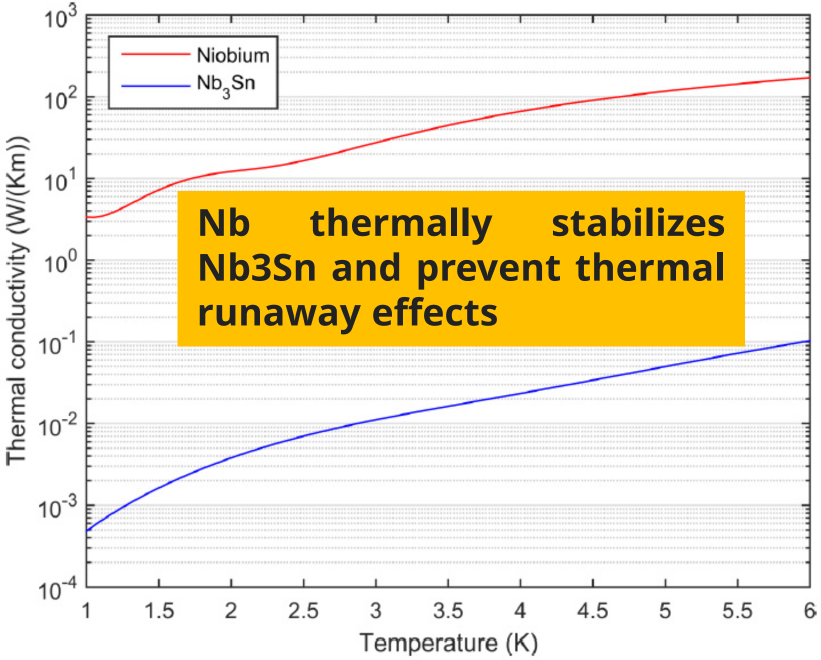


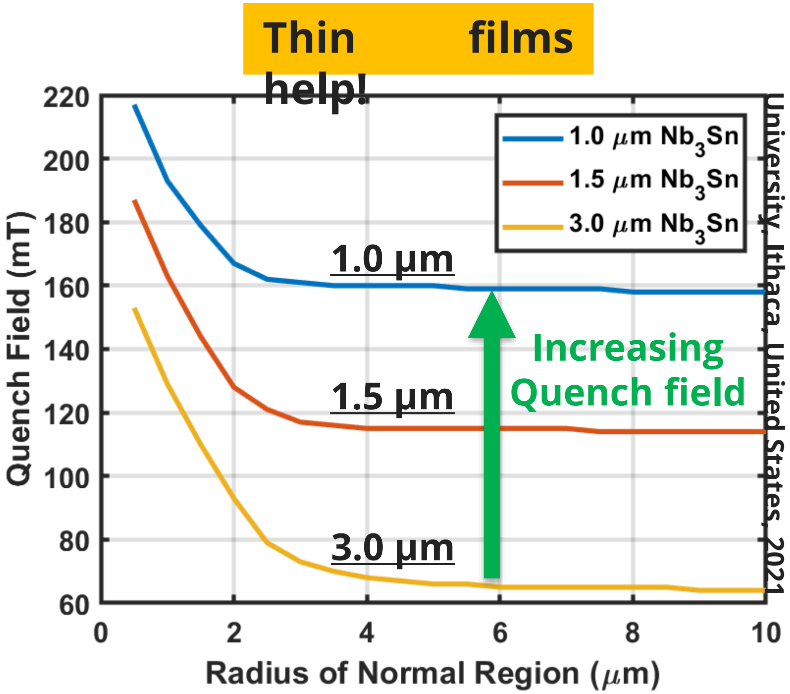


R. D. Porter, Ph.D. thesis, Phys, Dept., Cornell University, Ithaca, United States, 2021

**2. Thinner films are smoother! (Pudasaini, WEIAA03)**

**The FNAL cavity which reached 24 MV/m had a shiny thin-film $Nb_3Sn$ coating. (S. Posen, https://doi.org/10.1088/1361-6668/abc7f7)**

# Thin Film Cavity

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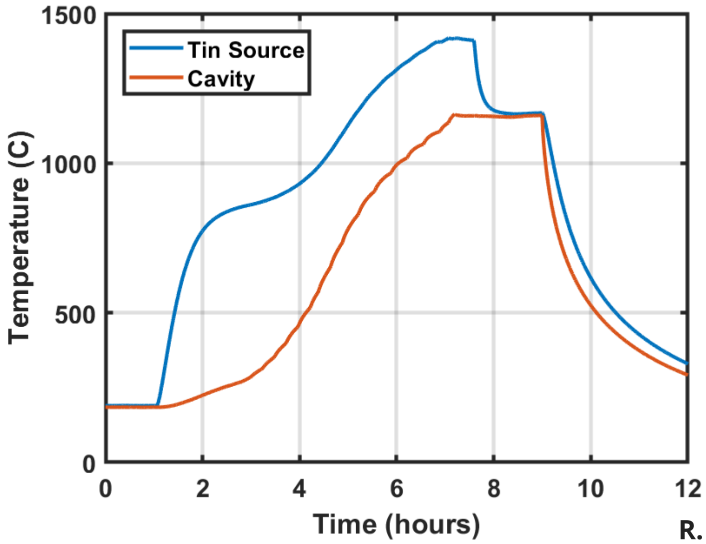
**New recipe (inspired by FNAL) :**
→ **Increase Sn vapor pressure from start**
→ **Shorter coating time**
→ **Skip the 5-hour nucleation**




R. D. Porter, Ph.D. thesis, Phys, Dept., Cornell University, Ithaca, United States, 2021

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**New recipe (inspired by FNAL) :**
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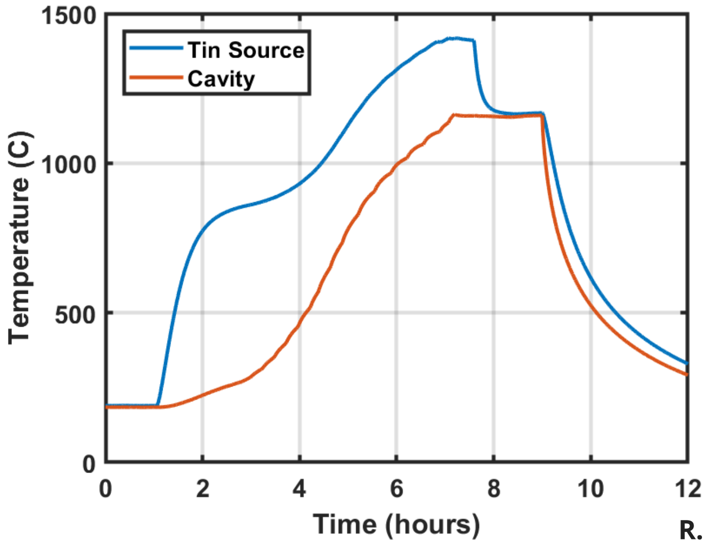
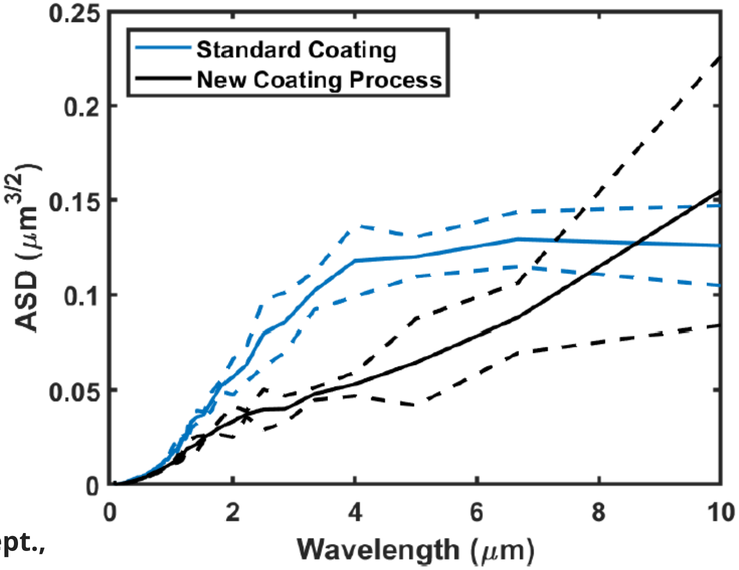
→ **Shorter coating time**
→ **Skip the 5-hour nucleation**

**Result:**
→ **Lower surface roughness!**
→ **Lower BCS resistance, but higher $R_0$ and similar quench fields (suspect due to patchy regions)**




R. D. Porter, Ph.D. thesis, Phys, Dept., Cornell University, Ithaca, United States, 2021

# Thin Film Cavity

New recipe:
→ Increase Sn vapor pressure from start
→ S…
→ S…

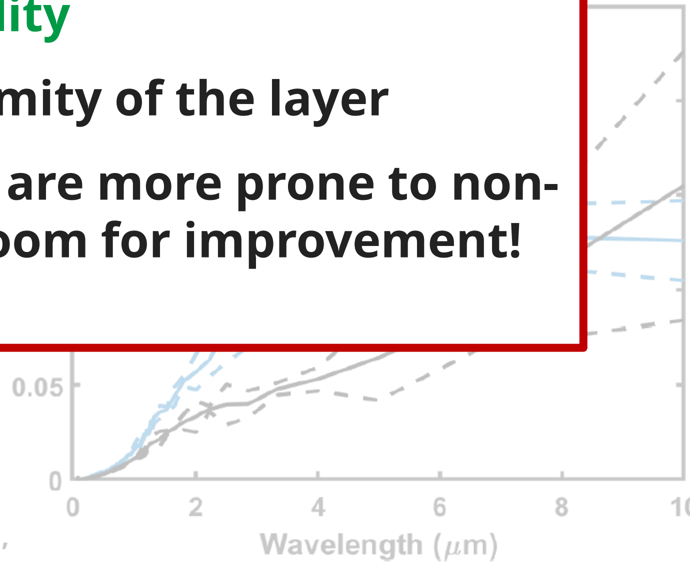
Result:
→ Lower surface roughness! (Ra = 94nm)
→ Lower BCS resistance, but higher $R_0$

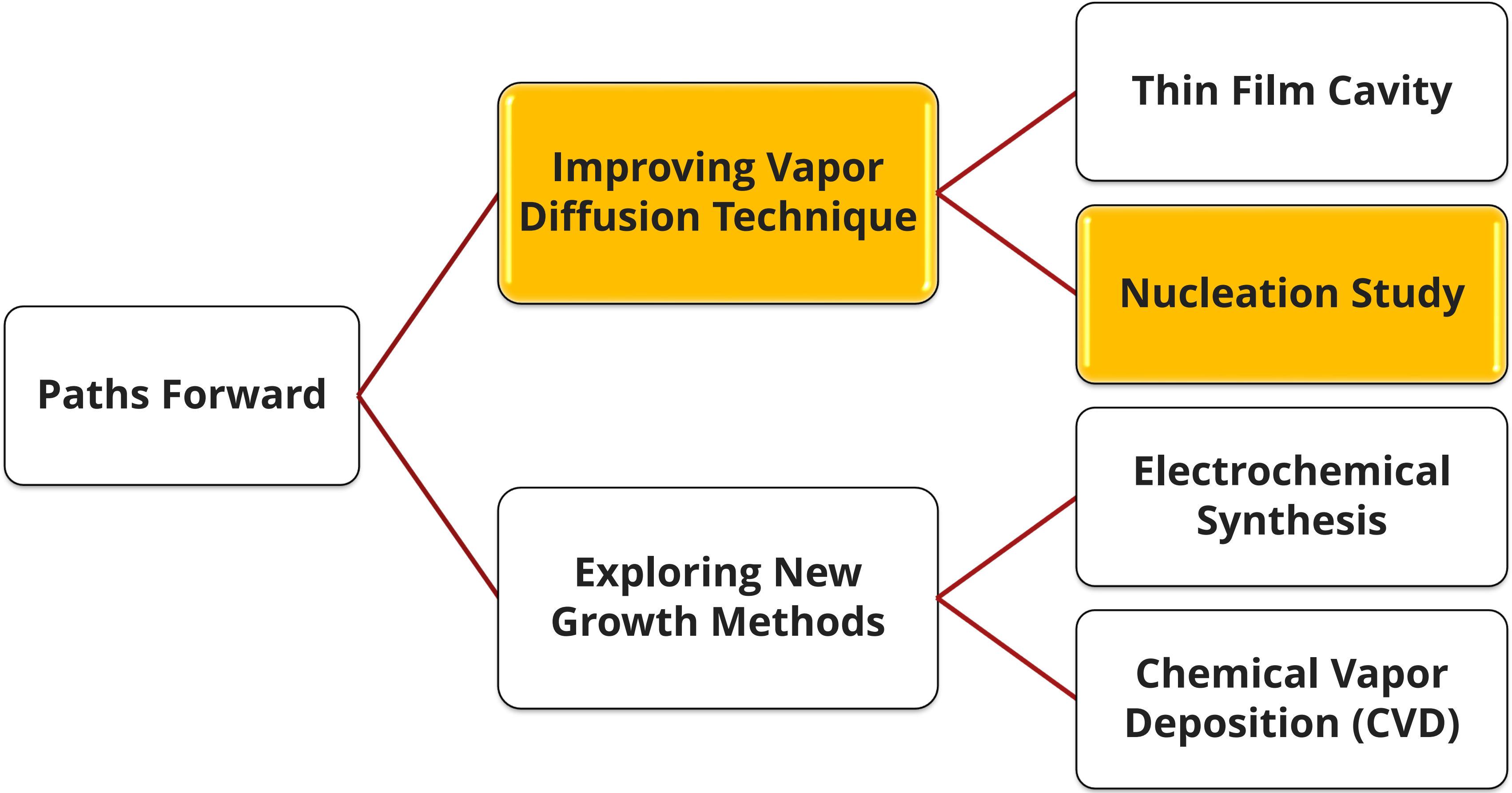
**Thinner $Nb_3Sn$ films show promise to achieve higher gradients due to better thermal stability**

**Key challenge: controlling the uniformity of the layer**

→ **<u>Reproducibility is an issue</u> as thin films are more prone to non-uniform patchy regions, but there is room for improvement!**


R. D. Porter, Ph.D. thesis, Phys, Dept., Cornell University, Ithaca, United States, 2021

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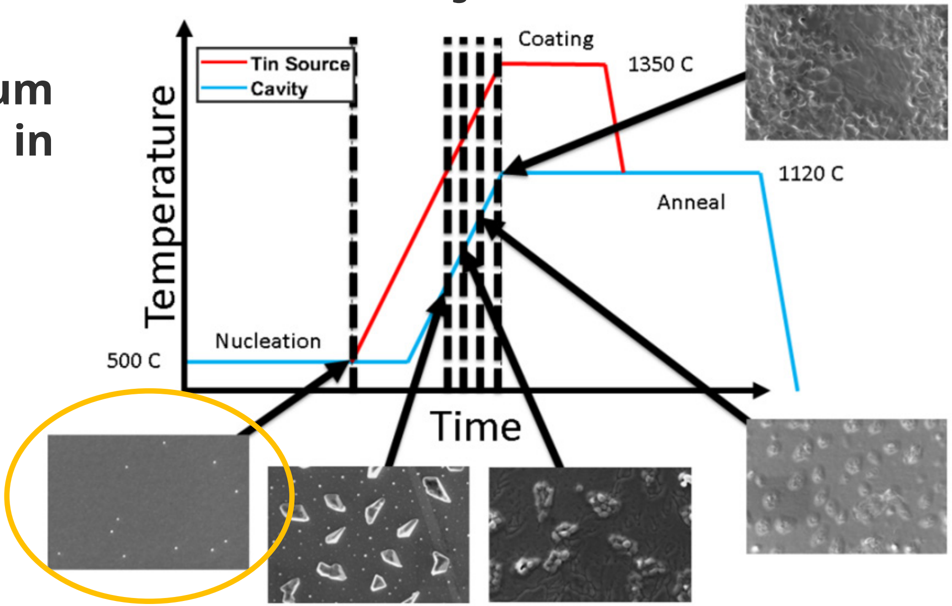
# Vapor Diffusion – Nucleation Study

**Goal:** Minimize tin depleted regions and achieve a smooth $Nb_3Sn$ film.

**Motivation:** The surface of the niobium oxide structure plays an important role in the nucleation of $SnCl_2$.



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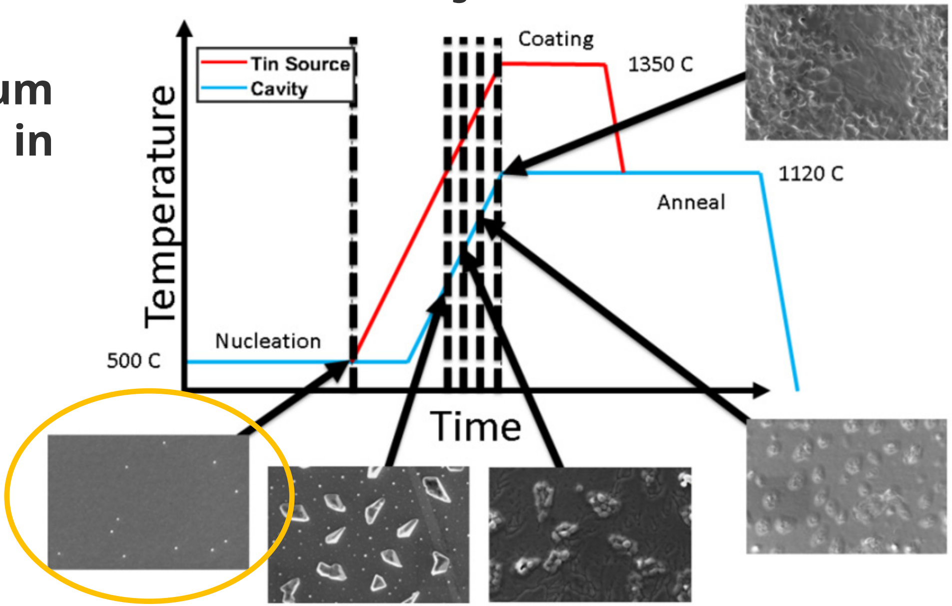
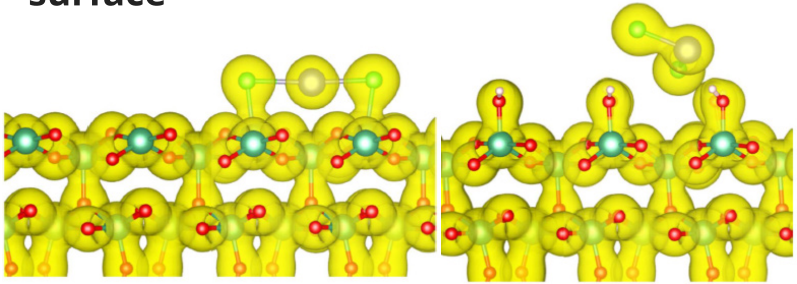



$SnCl_2$ molecules with (right) and without (left) passivating OH groups covering the surface



N. Sitaraman, "Theory work on SRF materials", Ph.D. thesis, Phys, Dept., Cornell University, Ithaca, United States, 2022

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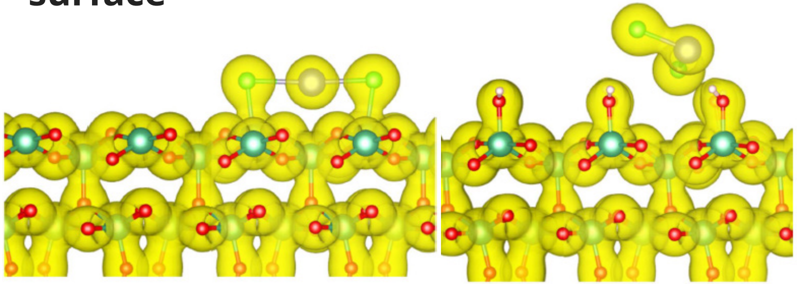

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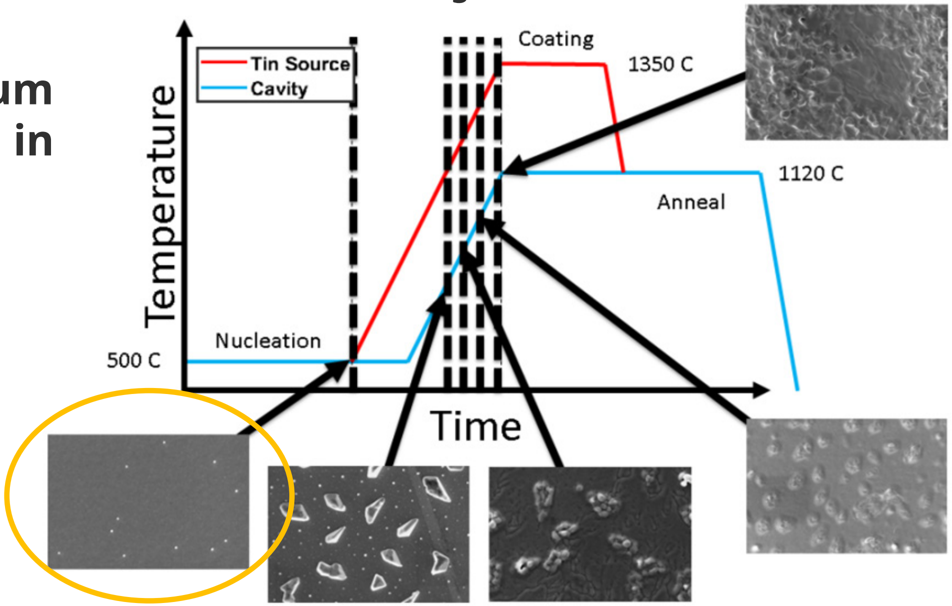
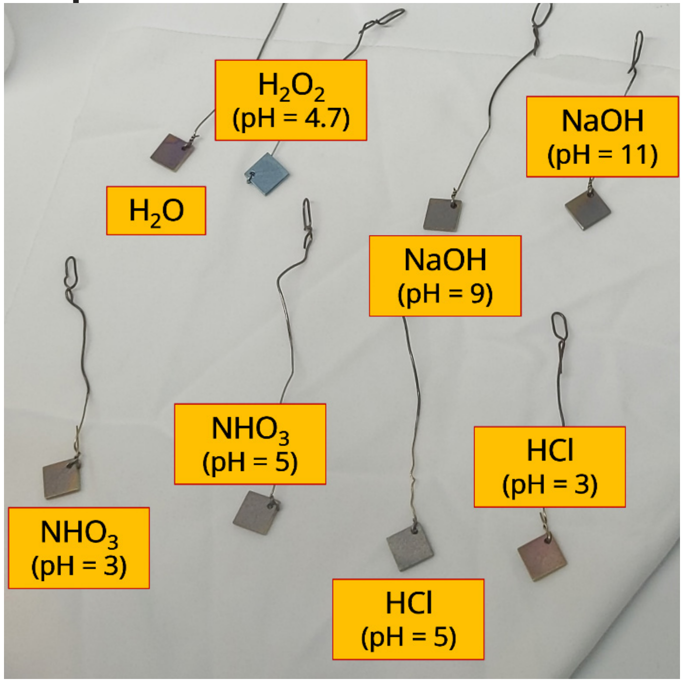


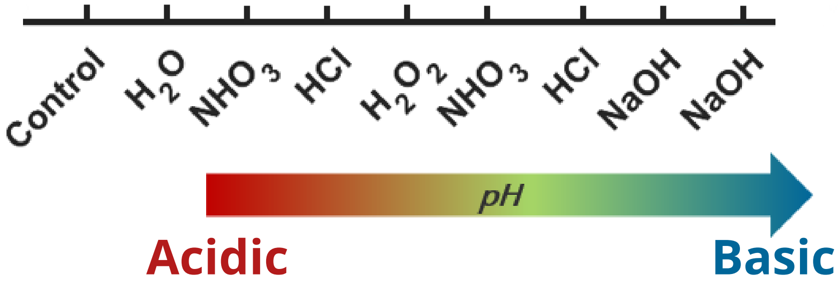

**Can we experimentally promote more uniform nucleation through adding or removing OH groups from the oxide?**

# Sample Preparation

**Samples were electropolished, anodized and soaked in chemical treatments in a nitrogen atmosphere.**

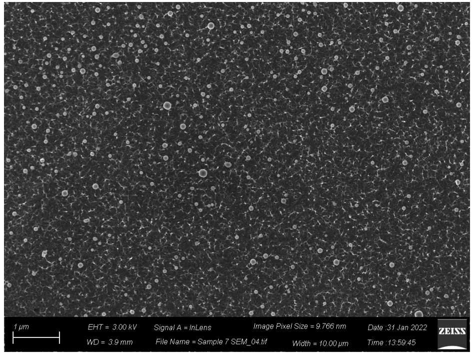



**The samples (control sample not shown) after being soaked in the chemical treatments.**

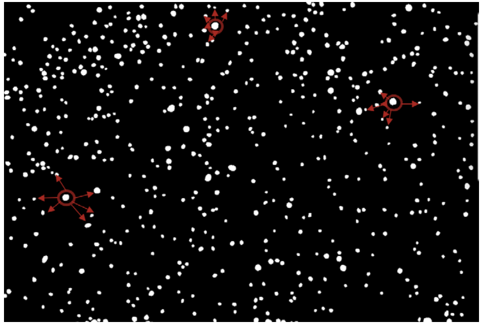



**The furnace run was stopped after the nucleation step and the samples were taken out for surface characterization and analysis.**

1. **Scanning Electron Microscopy (SEM)**
   → **extract information about distribution of nucleation sites (*"droplets"*)**




**Post-processing**



**Density**

**Avg. distance to six nearest neighbors**

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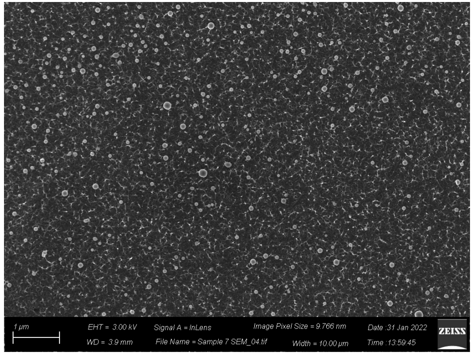


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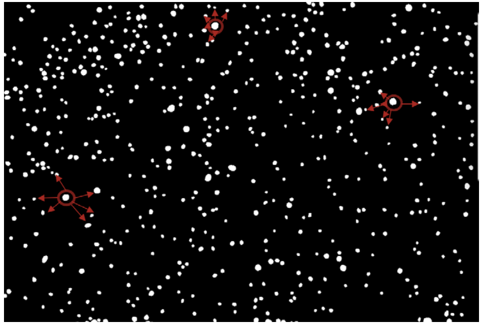
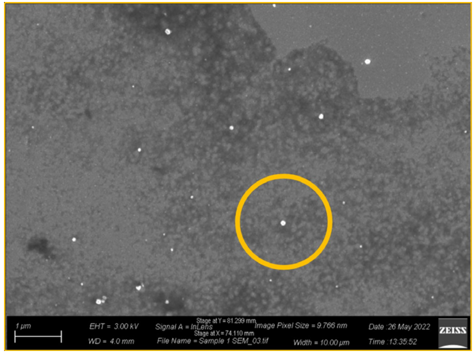


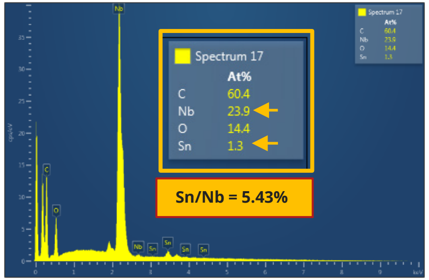
**Density**

**Avg. distance to six nearest neighbors**

2. **Energy Dispersive Spectroscopy (EDS)**

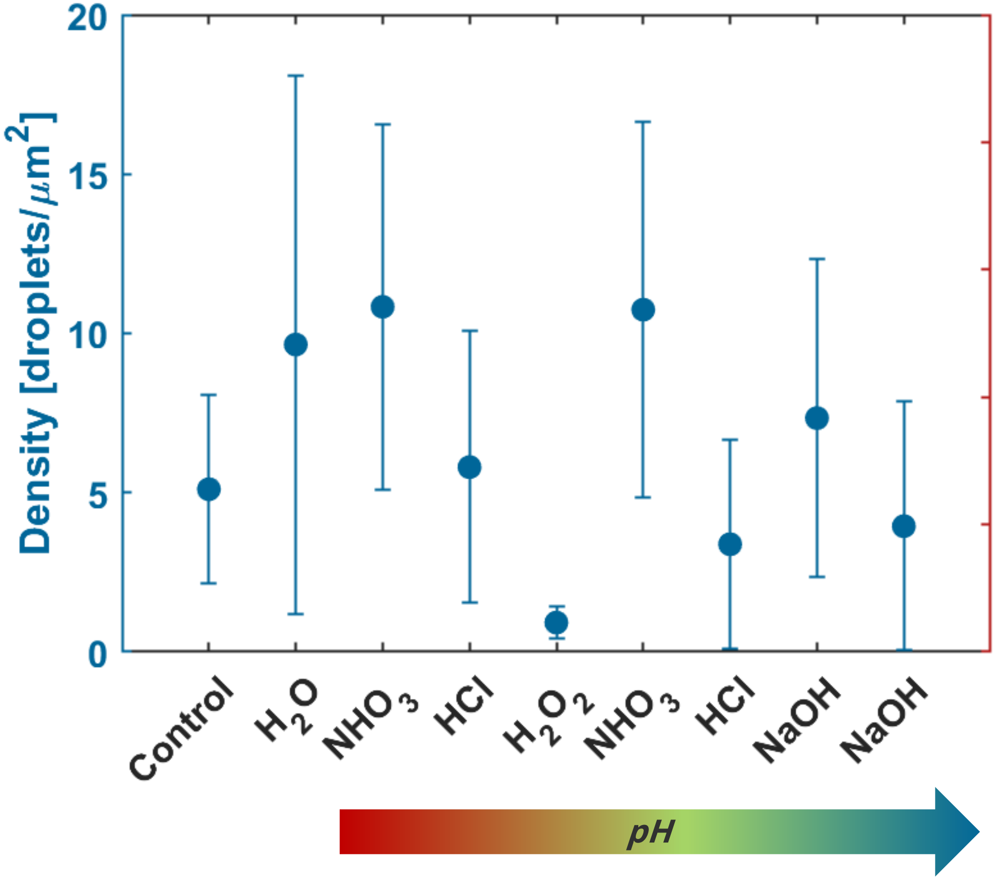
→ **extract information about elemental composition (Sn:Nb atomic**

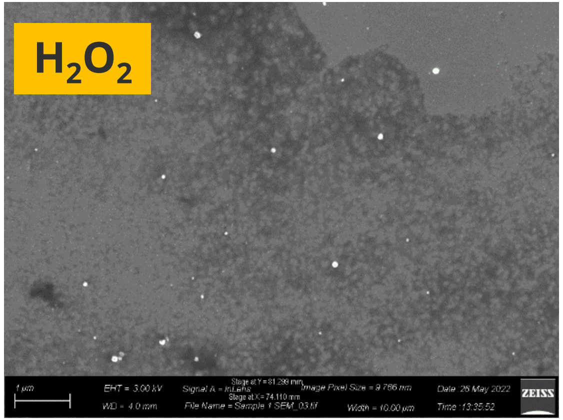


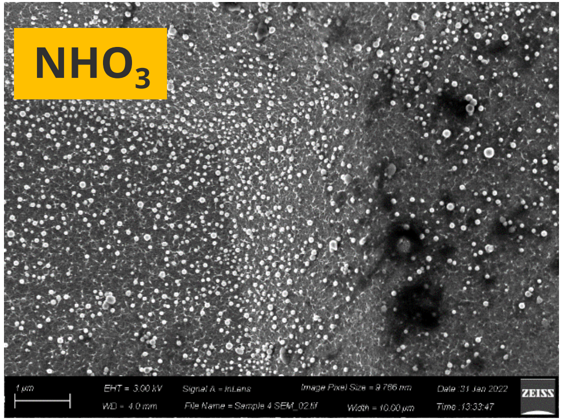




**Establish relative comparison of the Sn:Nb at. % ratio among our samples.**

# Distribution of Nucleation Sites



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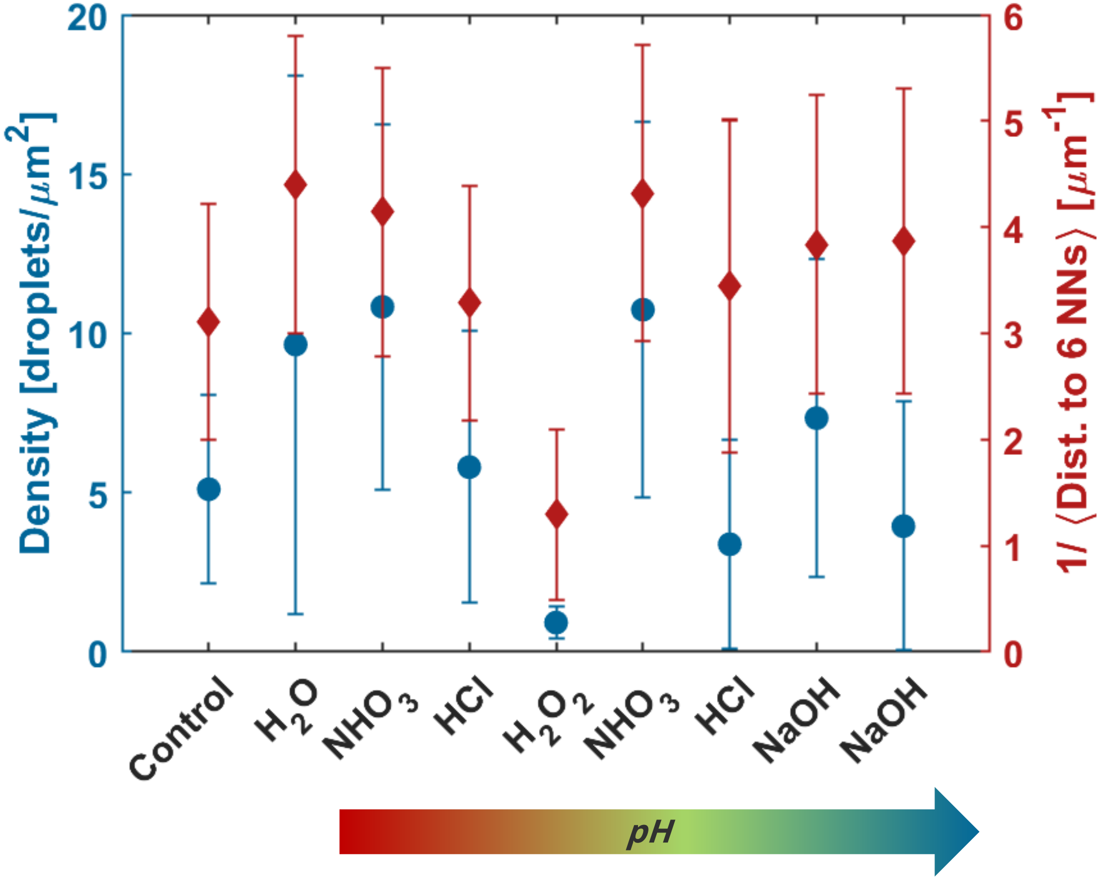


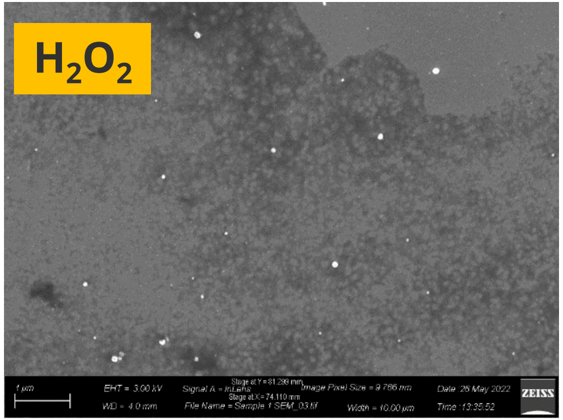


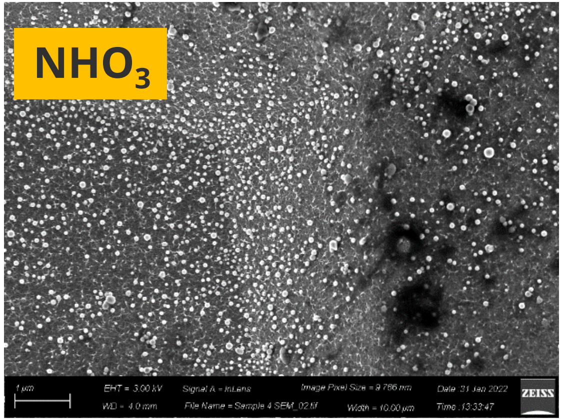

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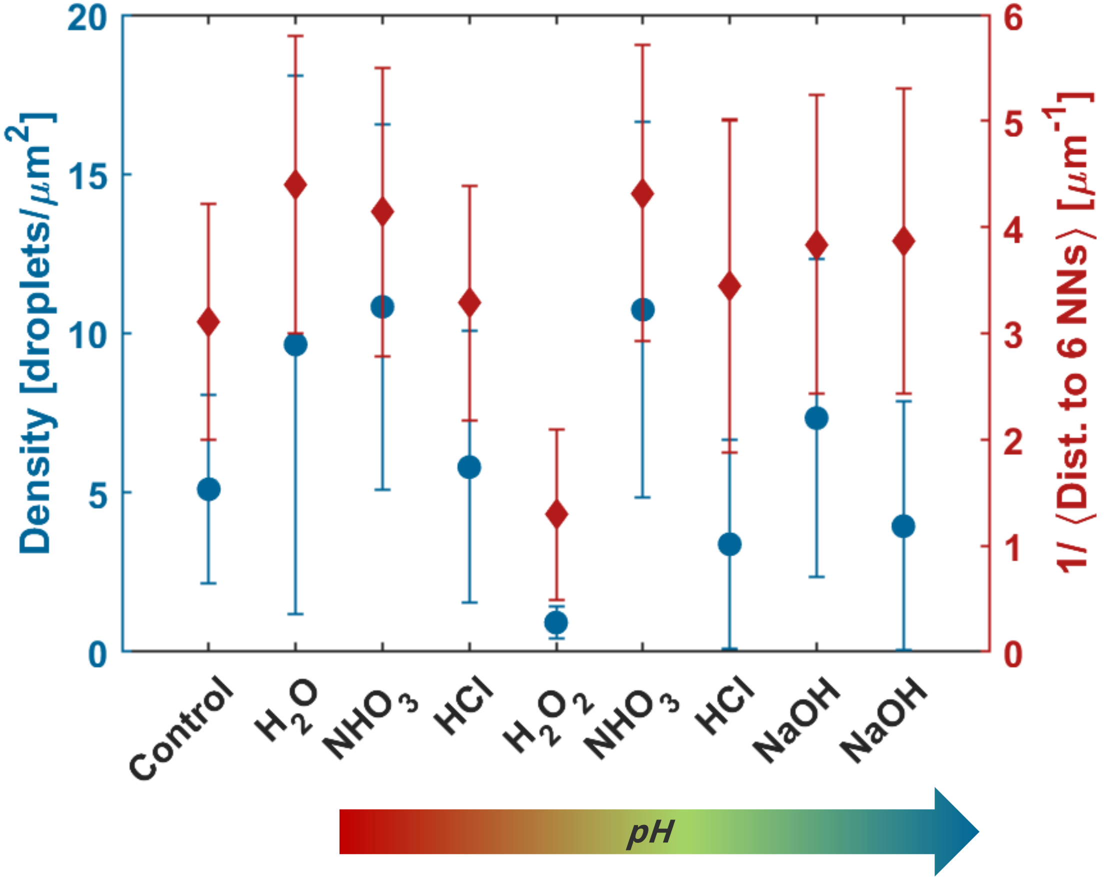
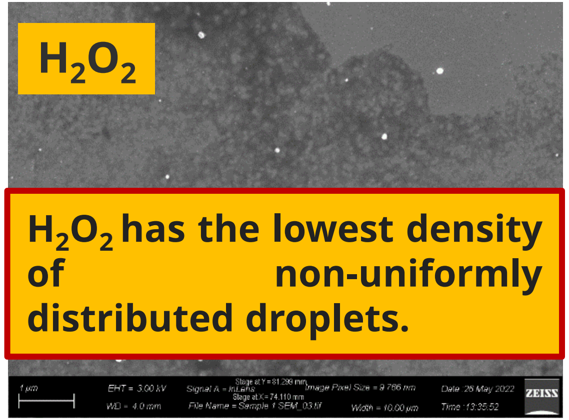
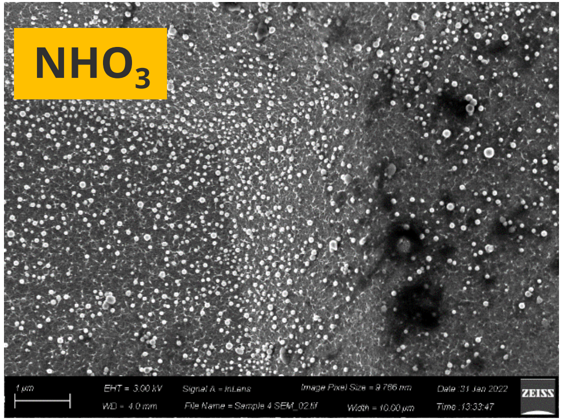


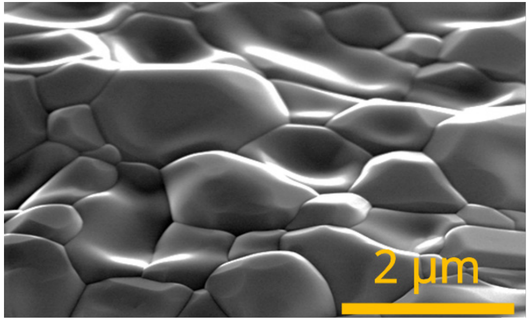




**$H_2O_2$ has the lowest density of non-uniformly distributed droplets.**



# Predicting Thin Film Regions

$Nb_3Sn$ grains have ~1 μm$^2$ area.




We want <u>at least</u> 1 nucleation site per intended grain:

1. How many imaged areas had a density of less than one particle per 1 μm$^2$ area?
2. How many avg. distances to 6 nearest neighbors exceed 1 μm?

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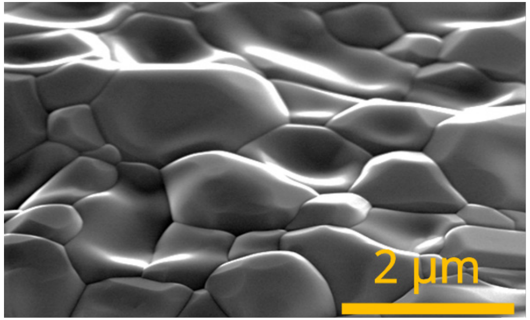


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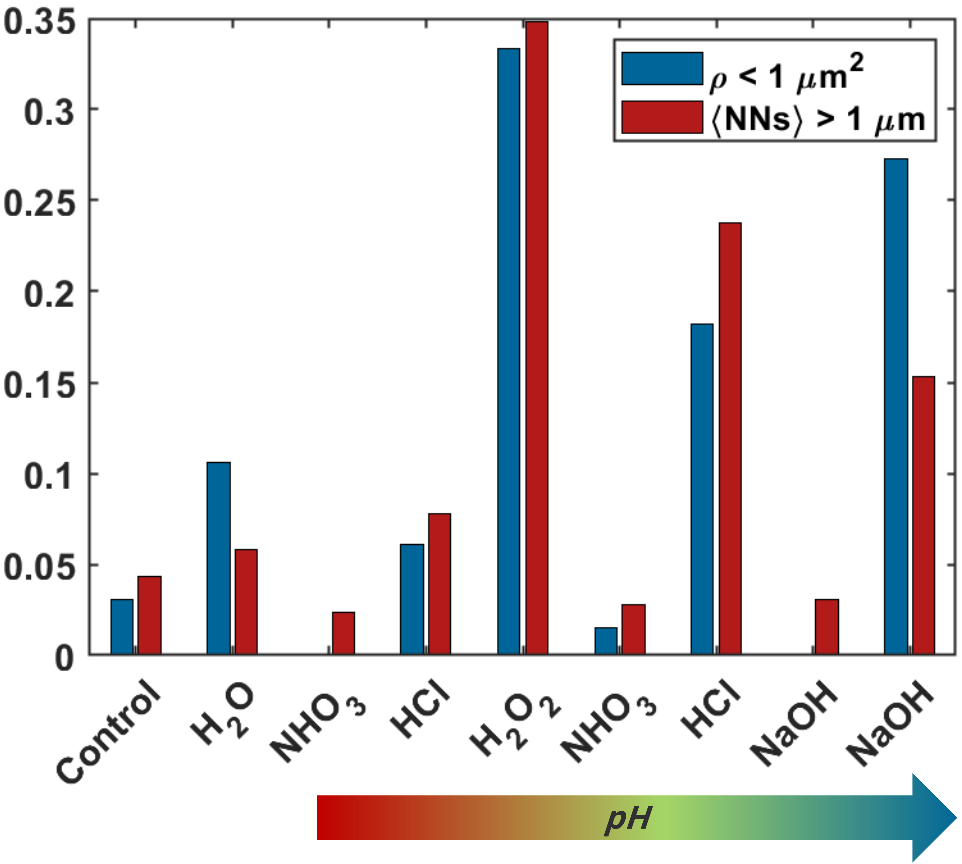

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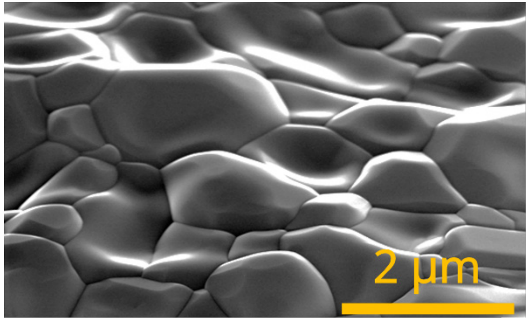


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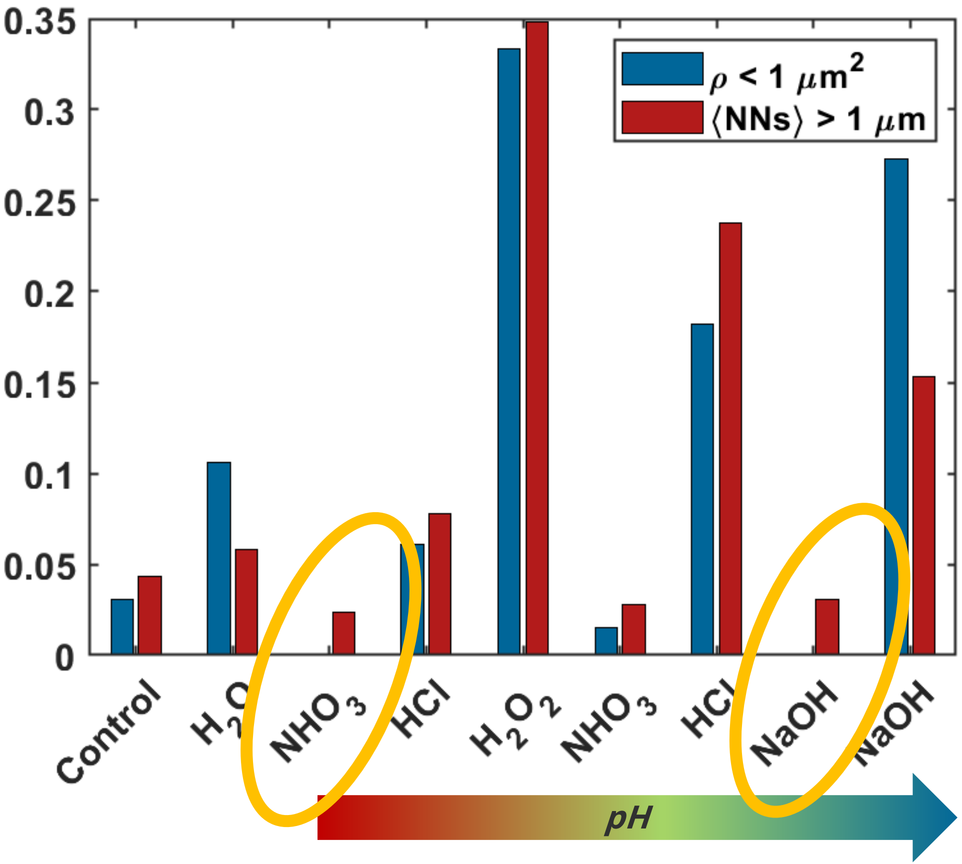
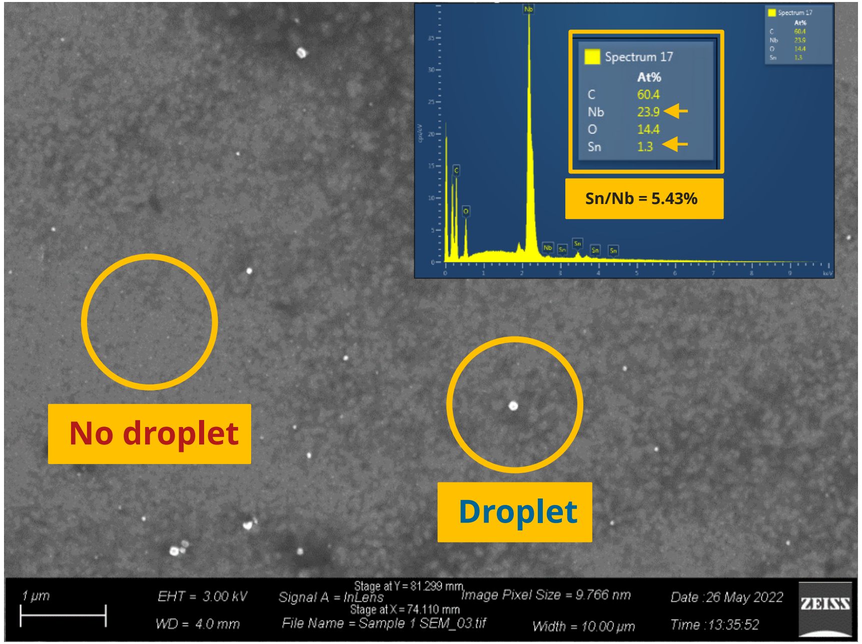


# Are these droplets actually tin?



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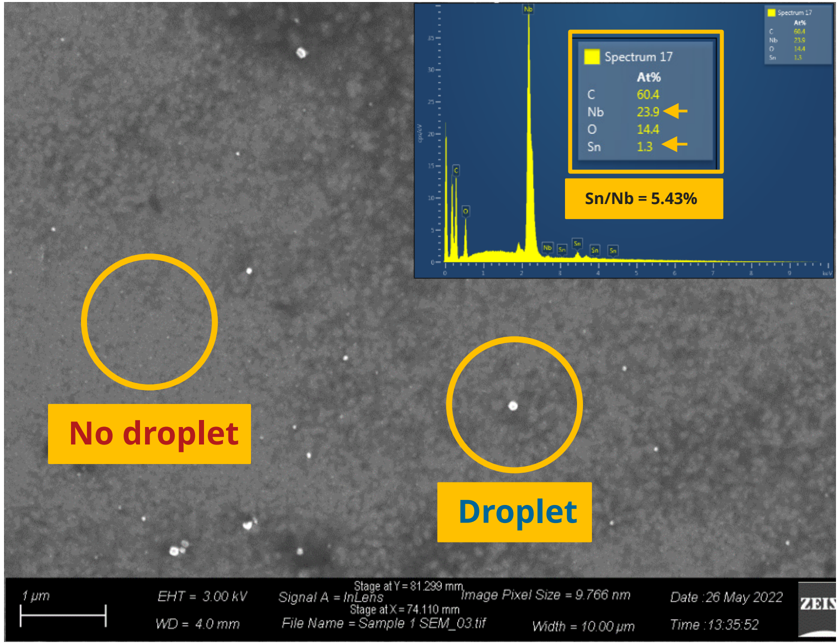


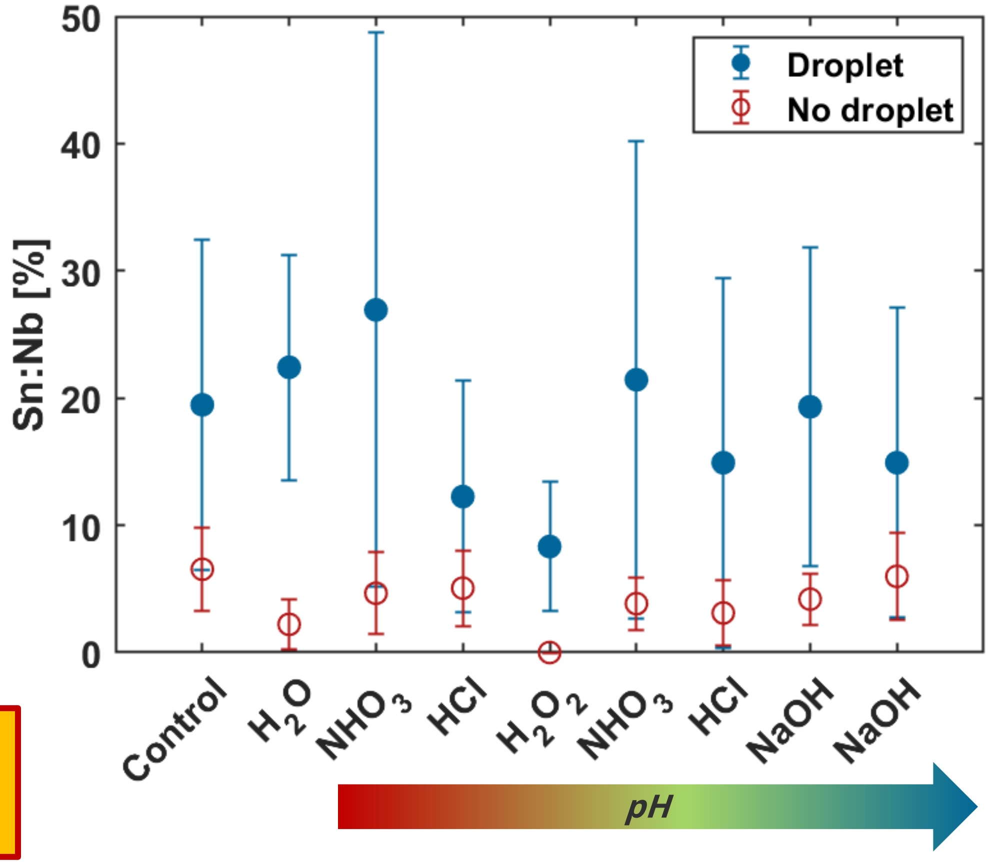


**All samples (except $H_2O_2$) have tin present even when no droplets are seen in the SEM image!**

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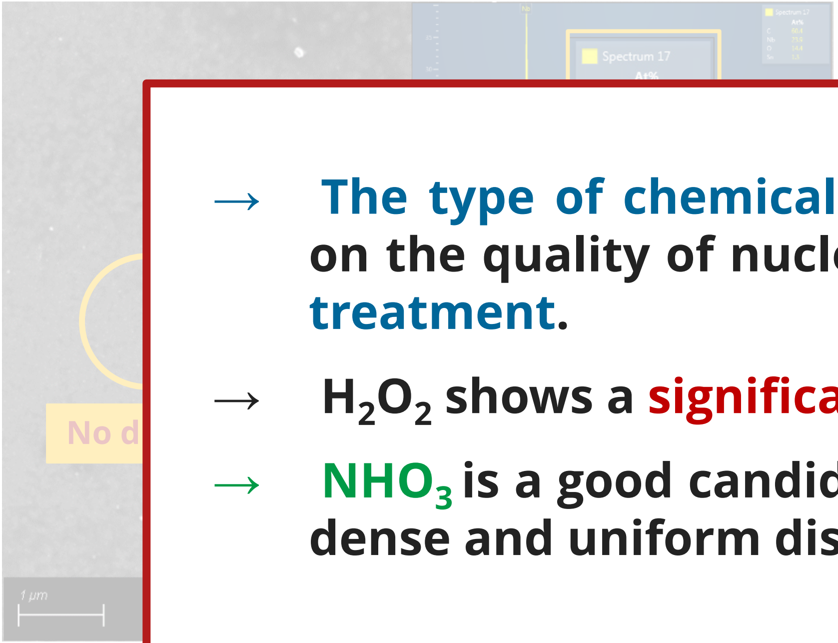
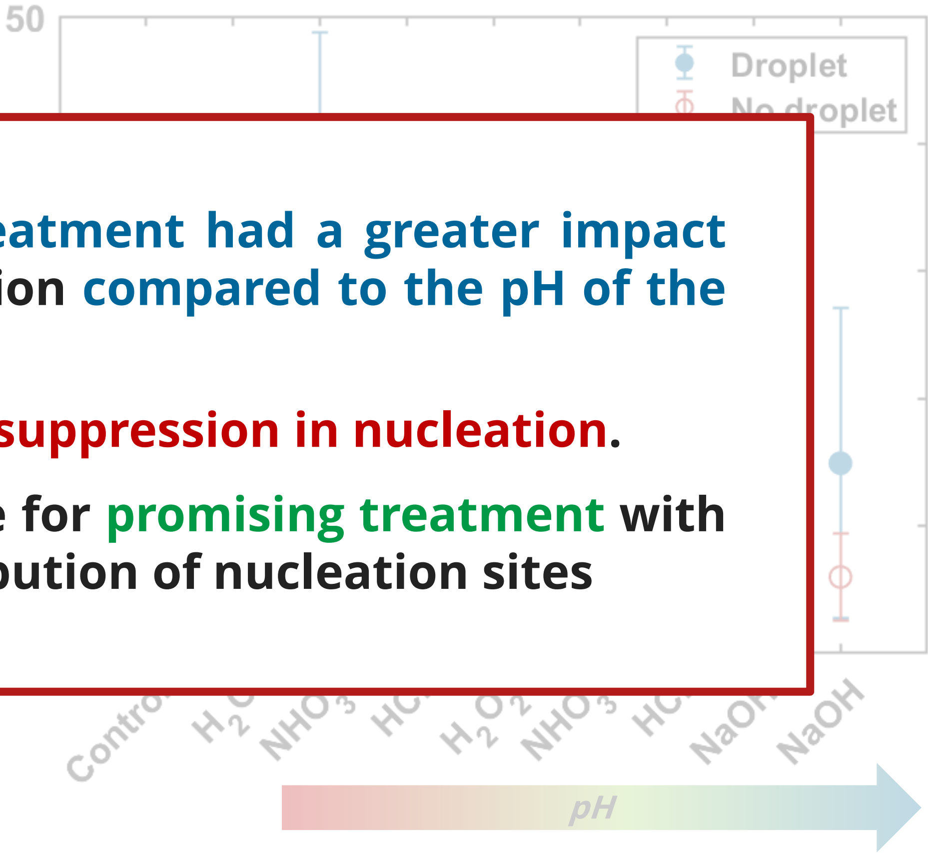


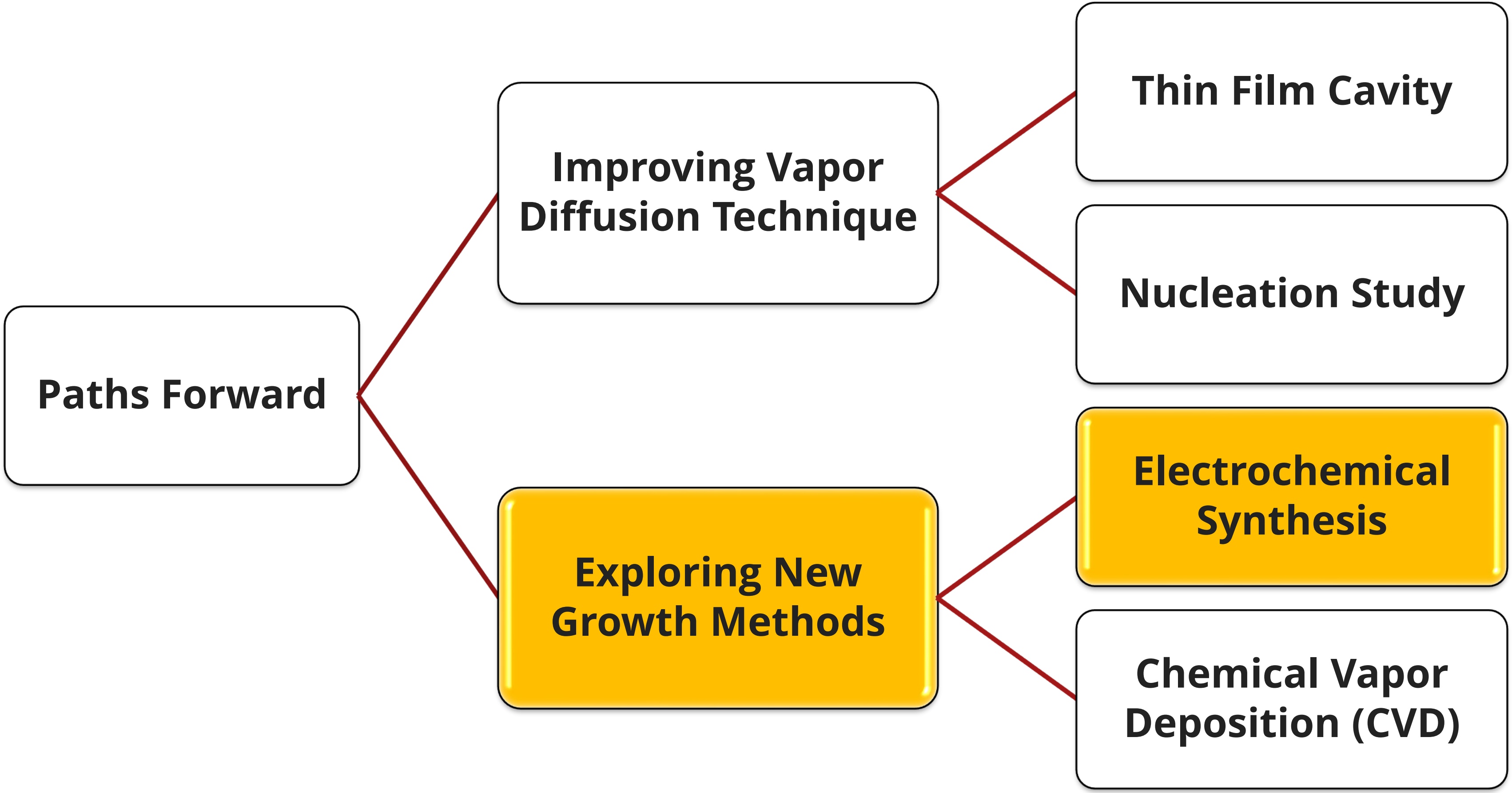




→ **The type of chemical treatment had a greater impact on the quality of nucleation compared to the pH of the treatment.**

→ **$H_2O_2$ shows a significant suppression in nucleation.**

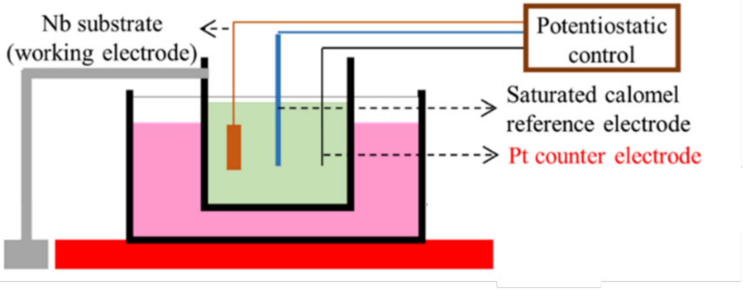
→ **$NHO_3$ is a good candidate for promising treatment with dense and uniform distribution of nucleation sites**

All samples (except $H_2O_2$) have tin present even when no droplets are seen in the SEM image!


Paths Forward
Improving Vapor Diffusion Technique
Thin Film Cavity
Nucleation Study
Exploring New Growth Methods
Electrochemical Synthesis
Chemical Vapor Deposition (CVD)

# Cornell $Nb_3Sn$ Electroplating Breakthrough

(1)




**Pre-deposition of Sn onto Nb**

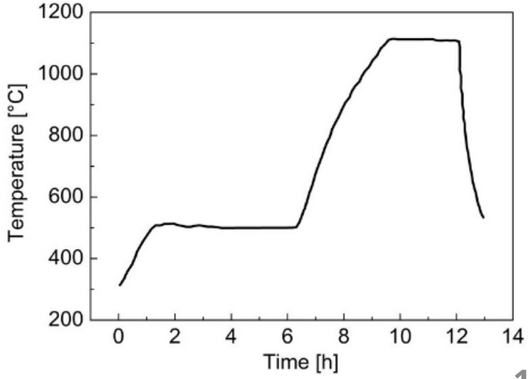
**Sn film**

**Nb substrate**

**Advantages:**

- **Promotes uniform distribution of nucleation (↓ surface roughness)**
- **Provides sufficient Sn supply in critical times**

**Post Annealing**




(2)

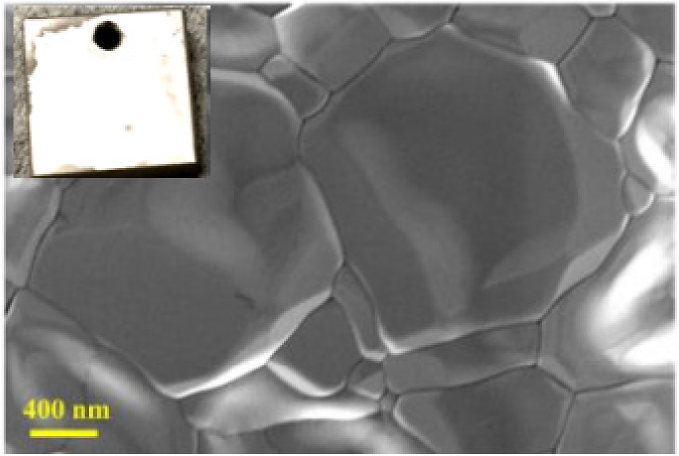
**Conversion to stoichiometric $Nb_3Sn$**

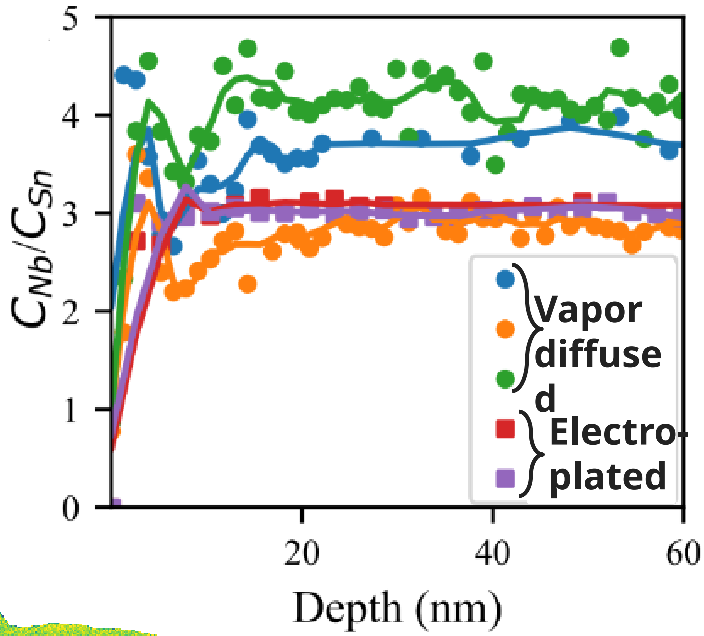
**$Nb_3Sn$ film**

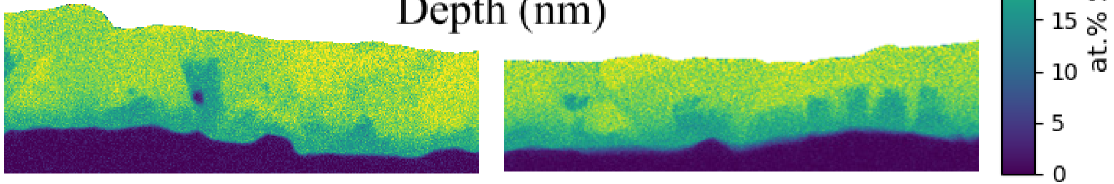
**Nb substrate**

**This method was developed by Zeming Sun Sun et al., https://doi.org/10.48550/arXiv.2302.02054**

Sample studies have shown low surface roughness and little variation in Sn concentration with depth.




Vapor diffused $Nb_3Sn$ Electroplated $Nb_3Sn$

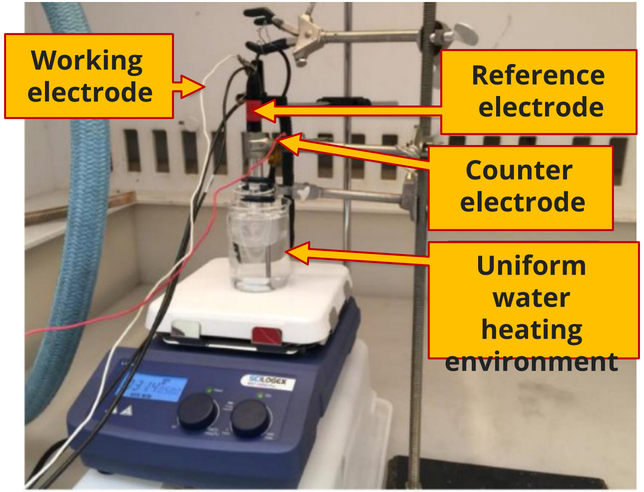
Images from Zhaslan Baraissov

This method was developed by Zeming Sun

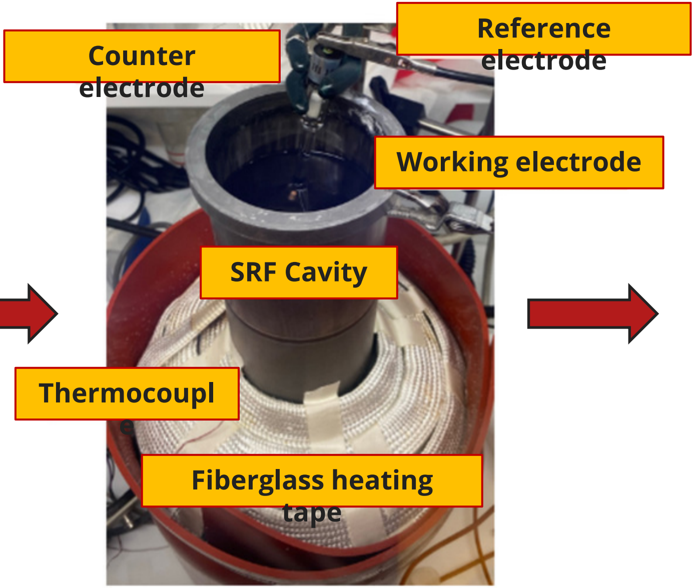
Sun et al., doi: 10.48550/arXiv.2302.02054

# Scaling up to 1.3 GHz cavity

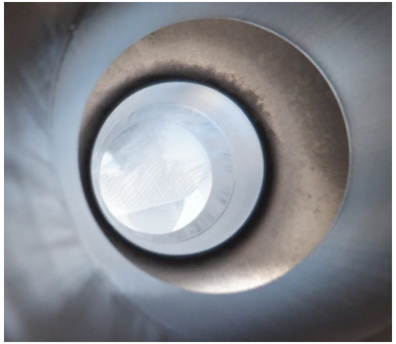
## Samples




## 1.3 GHz cavity




## Post-annealing



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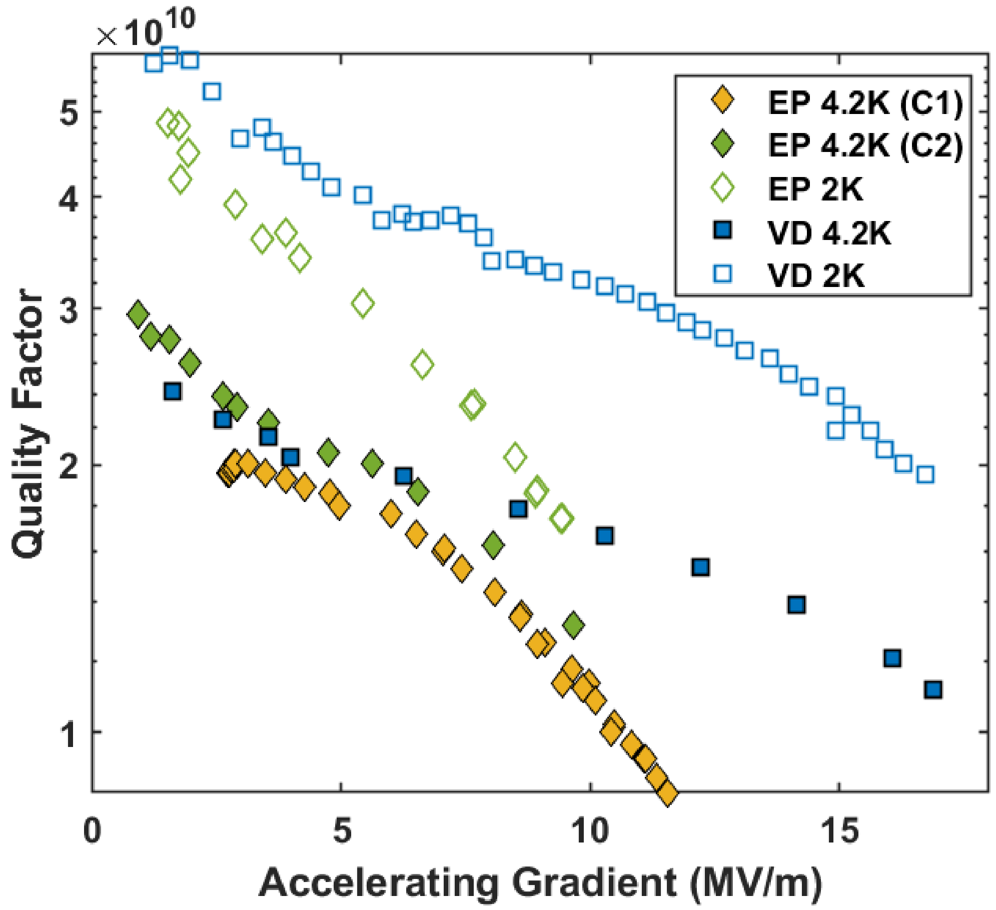
# RF Results




**$Q_0$ at 4.2K > $10^{10}$**

**Quench field was ~13MV/m**

**This is the first-ever alternative growth method of $Nb_3Sn$ to achieve such high performance!**

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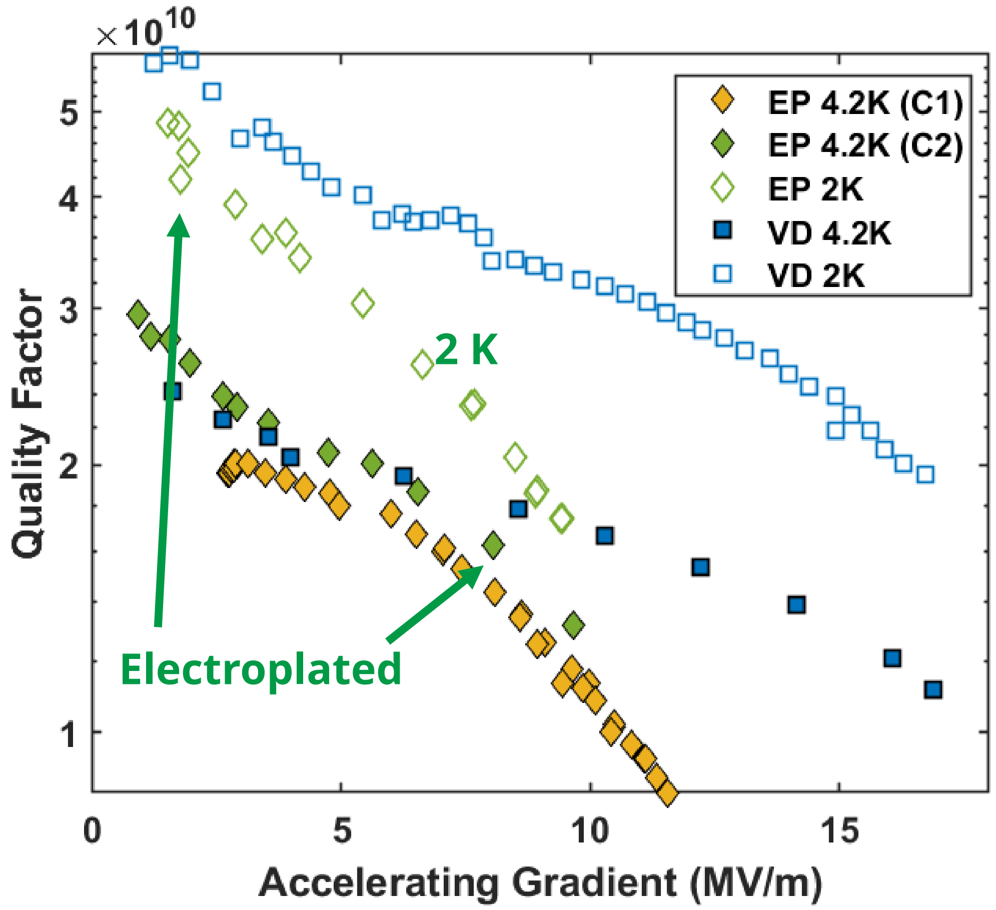


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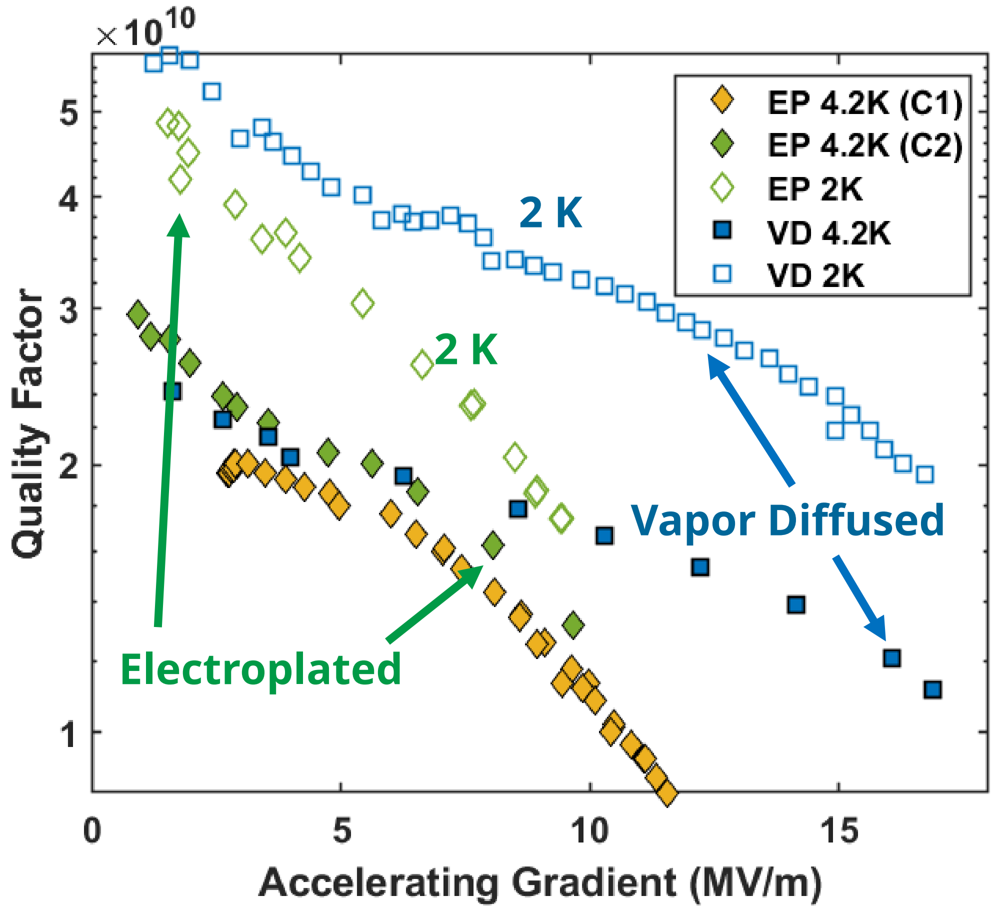


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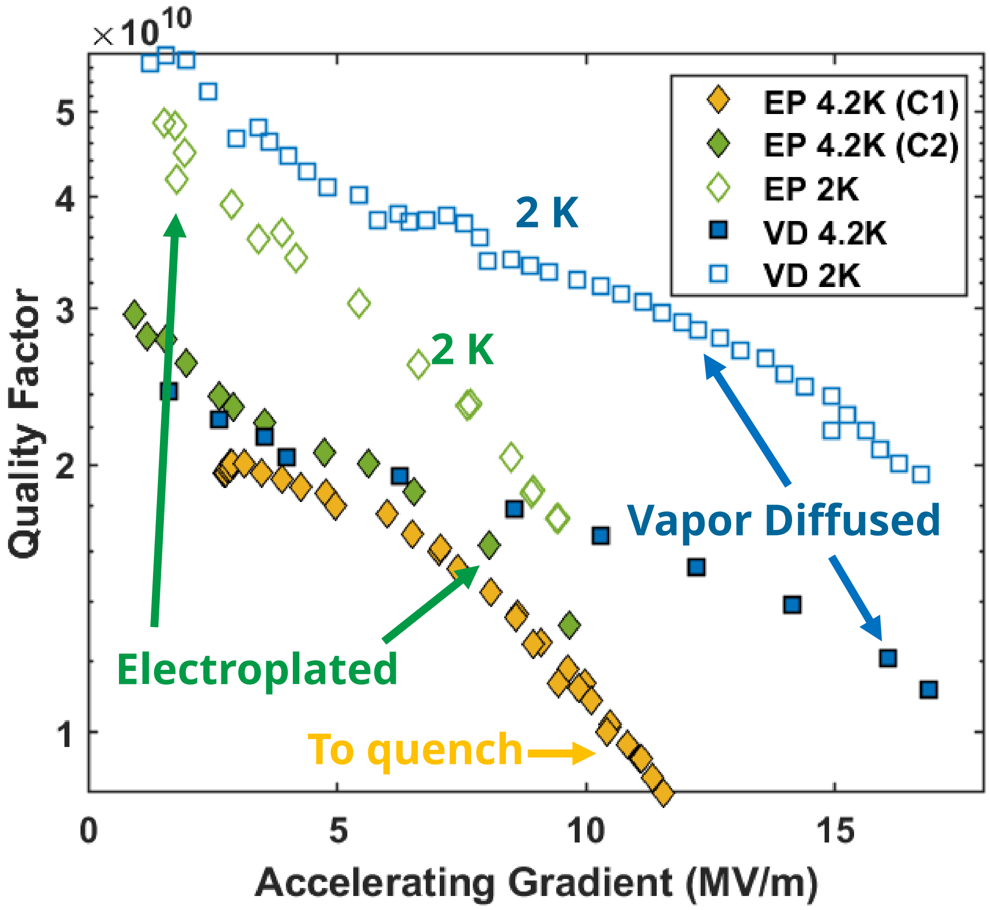


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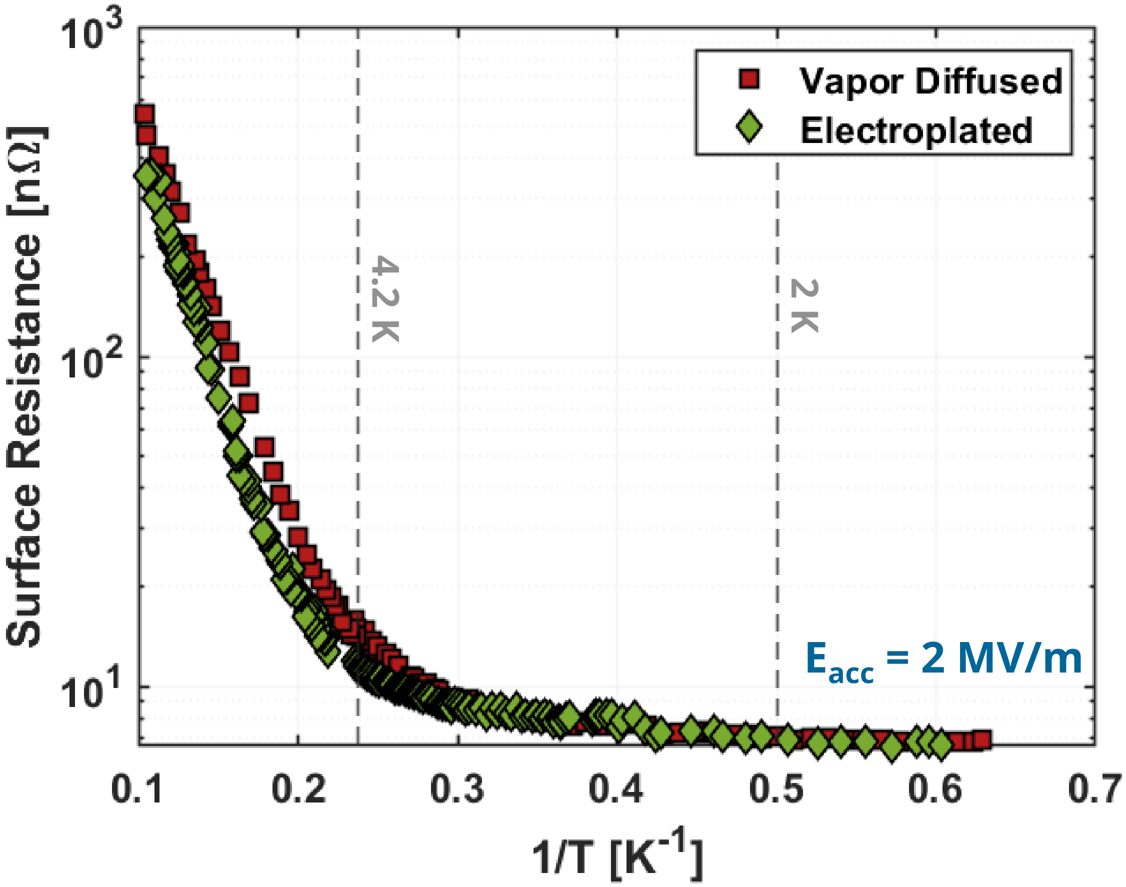
# Surface Resistance



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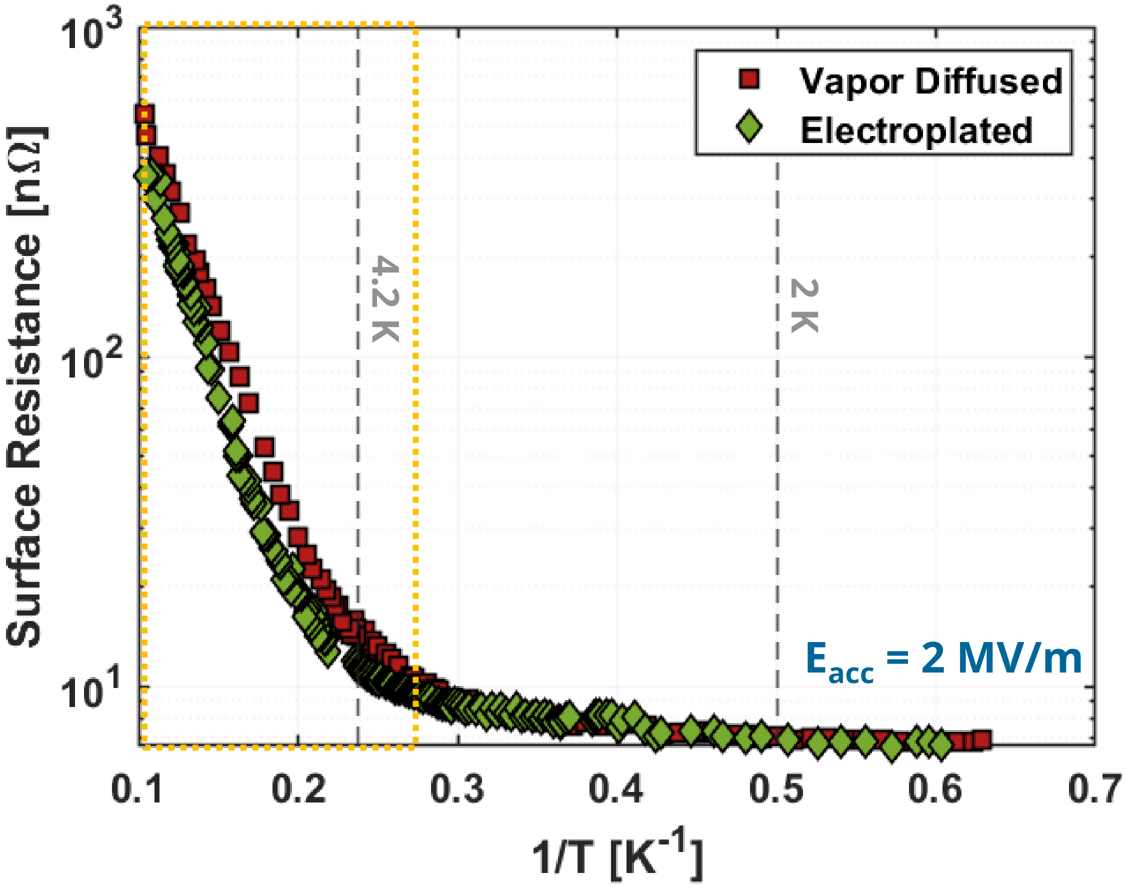

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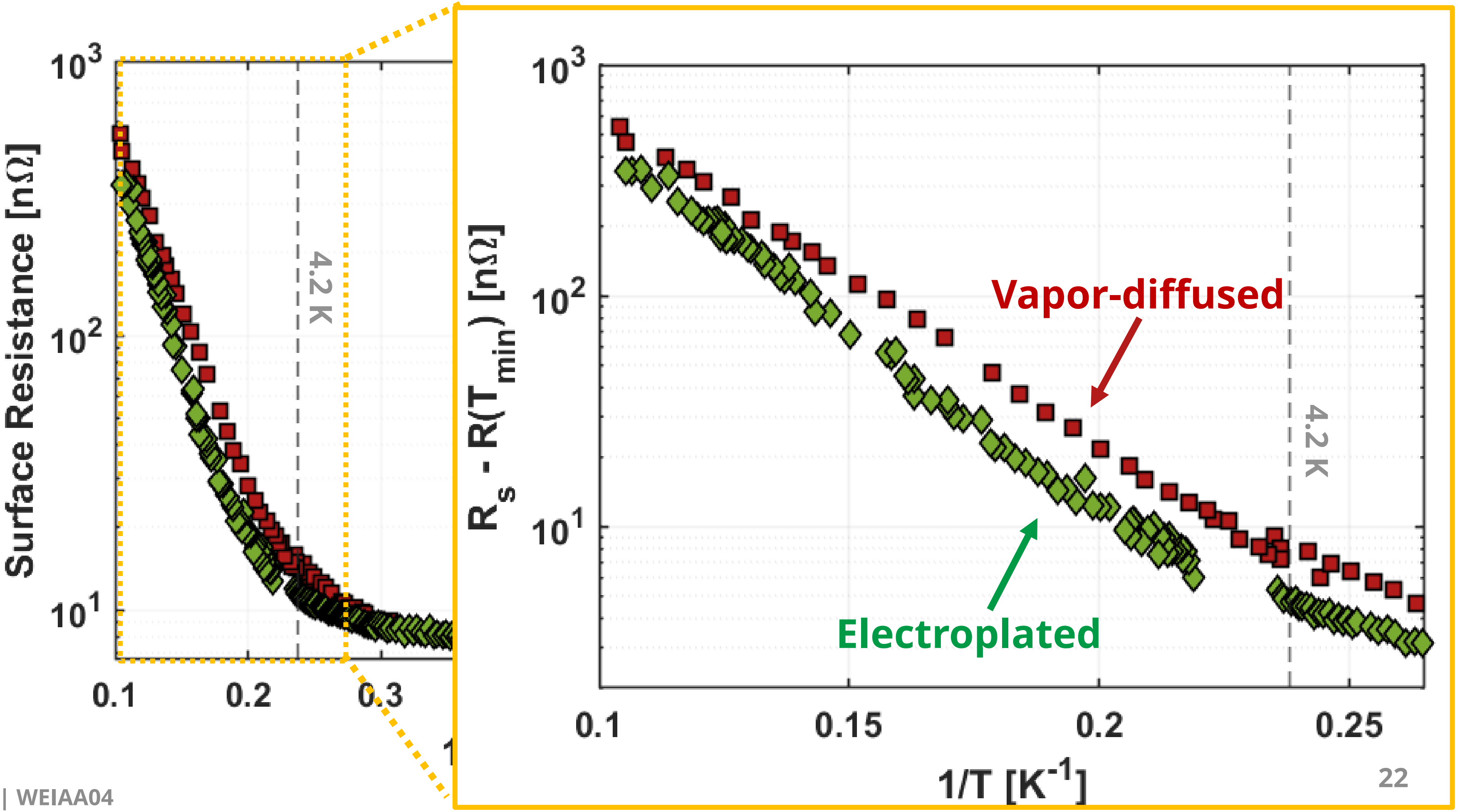

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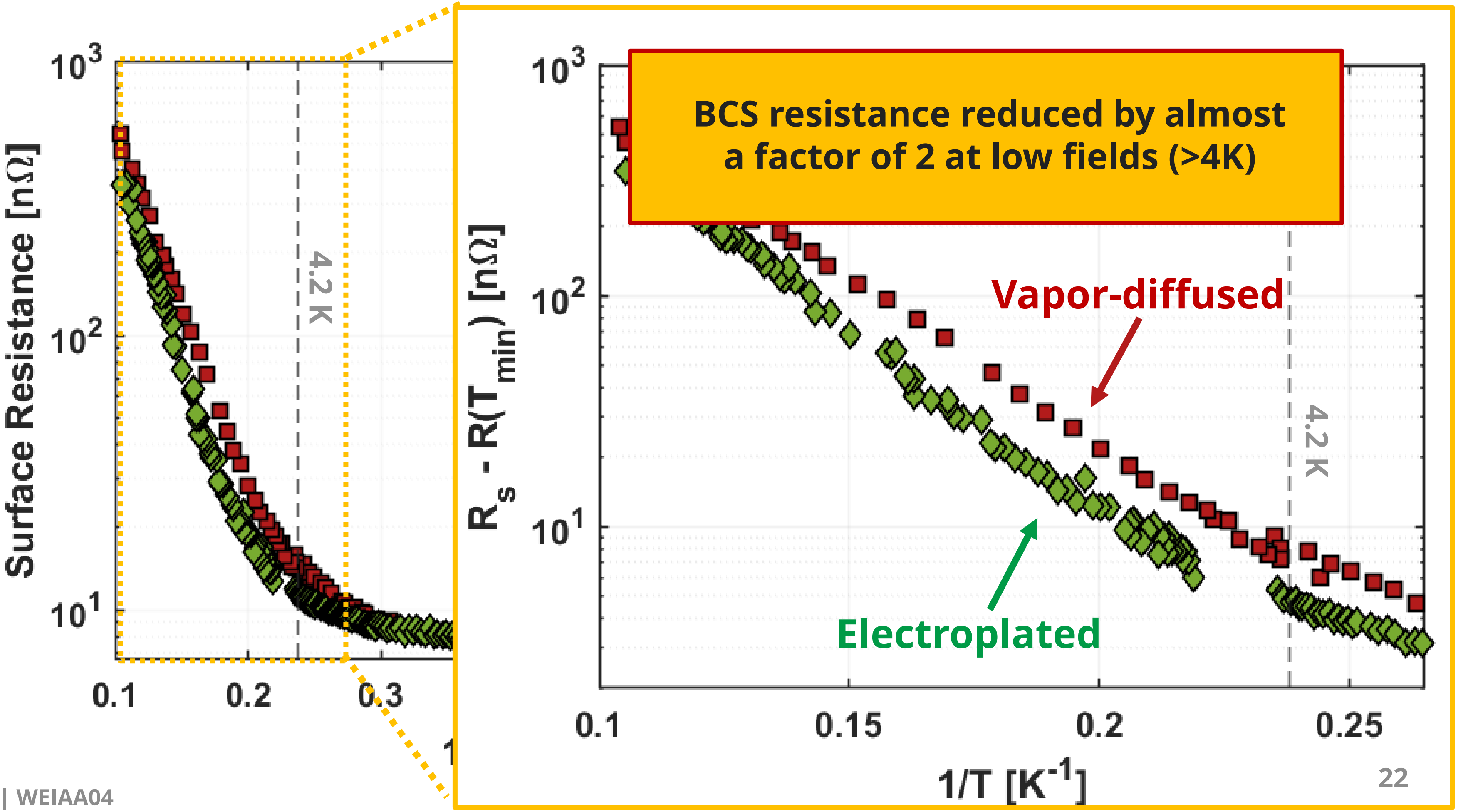
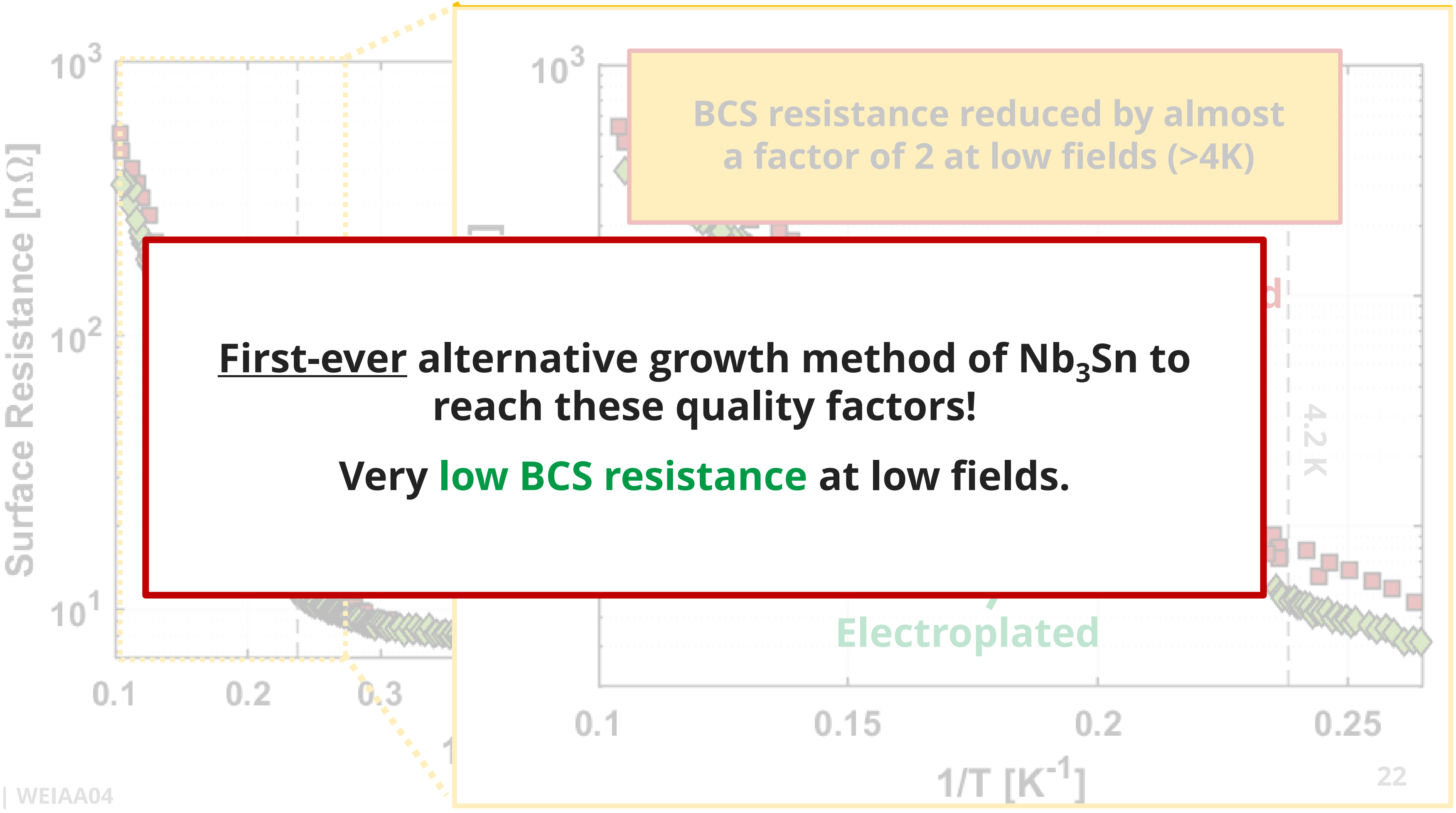
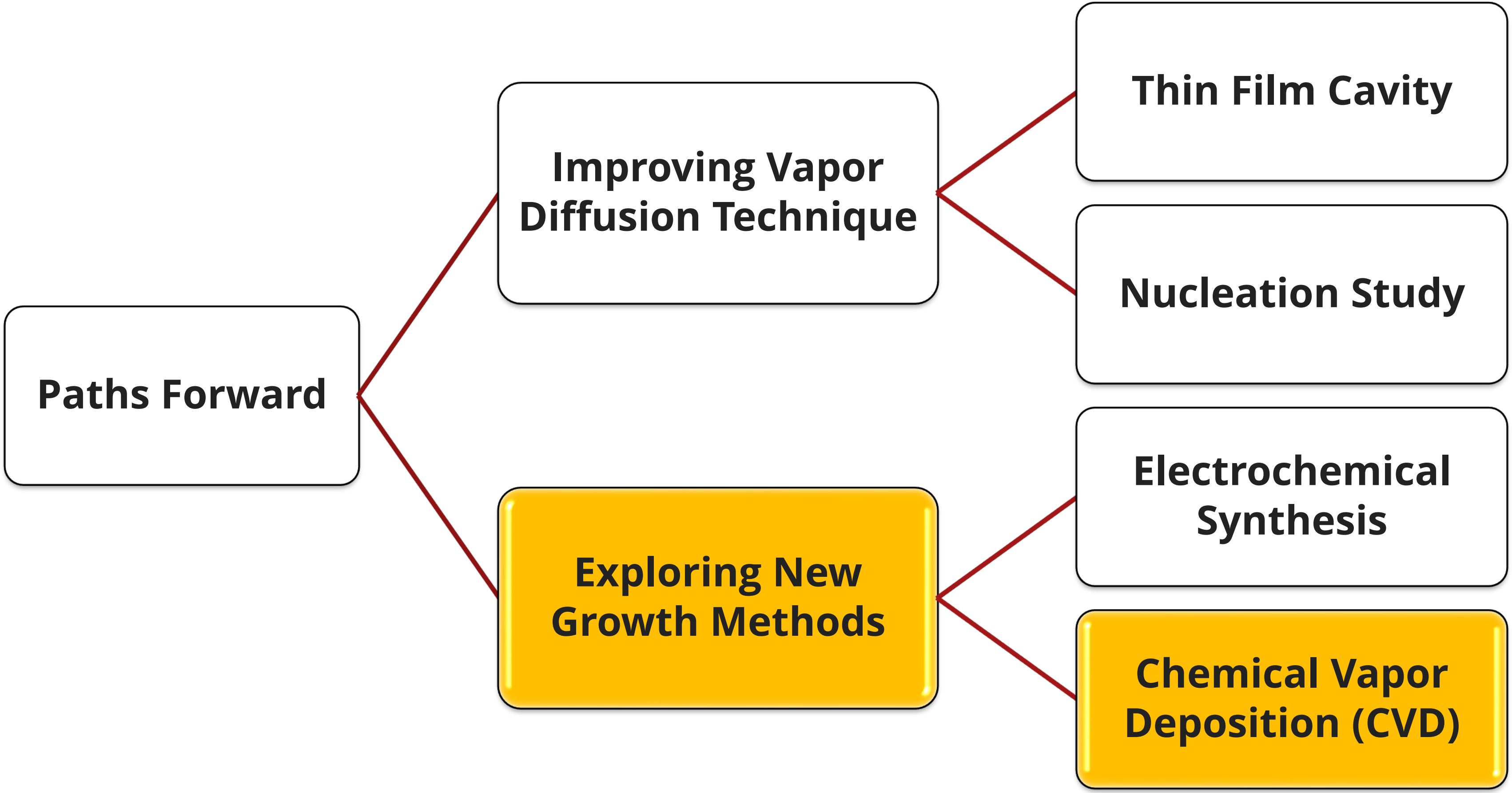





__First-ever__ alternative growth method of $Nb_3Sn$ to reach these quality factors!

Very low BCS resistance at low fields.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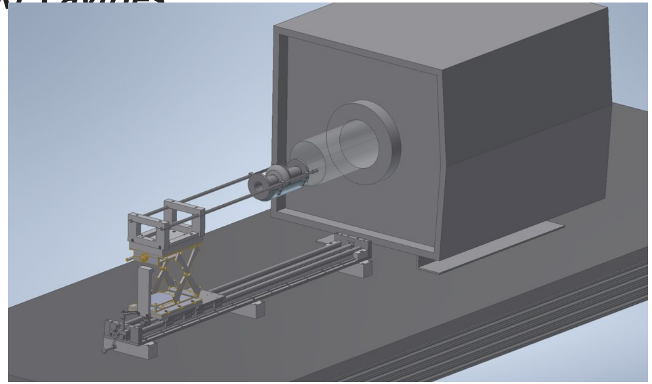
# Chemical Vapor Deposition (CVD)

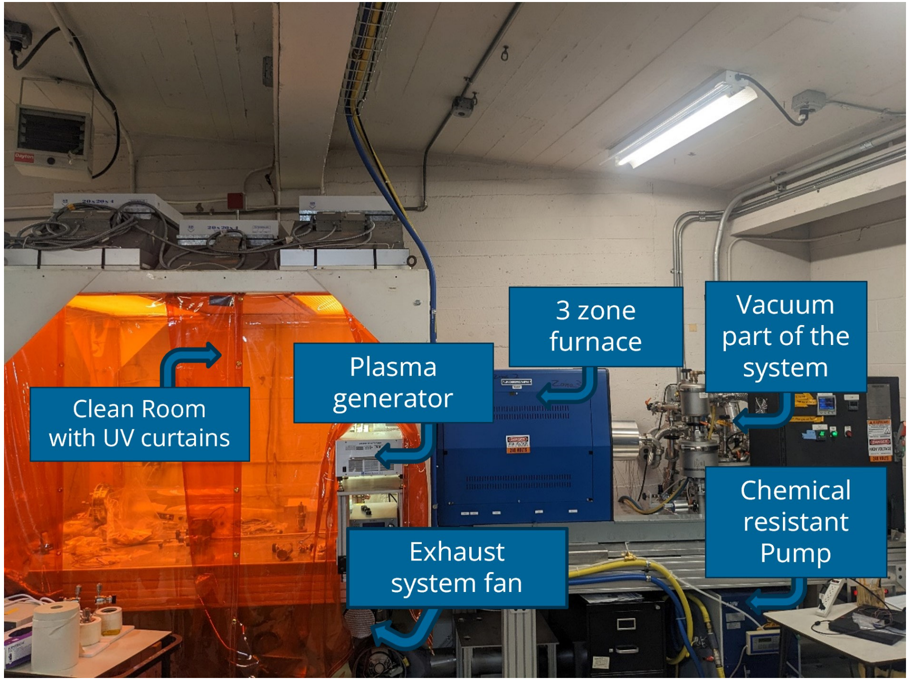
**CVD is an alternative method for depositing thin films**

→ **allows for precise control over the properties of the deposited films**

**CVD furnace is being commissioned at Cornell University as a potential path to grow high-quality $Nb_3Sn$ films (among other SRF materials)**

→ **See Gabriel Gaitan's poster MOPMB015**
***"Development of a Plasma-Enhanced Chemical Vapor Deposition System for High-Performance SRF Cavities"***





# Key Achievements

**Chemical pre-treatments of the niobium oxide have an effect in the nucleation of tin in vapor-diffused-based growth ⟹ new knob to turn to achieve thinner, smoother films of uniform thickness and composition**

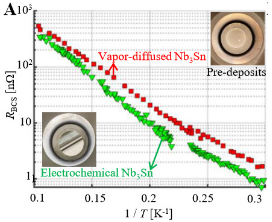
**Electrochemical deposition (followed by thermal annealing): First-ever alternative growth method to achieve such high performance ($Q_0 > 10^{10}$ and low BCS resistance)**

## $Nb_3Sn$ Cornell Submissions @ SRF'23

**Nucleation Study**

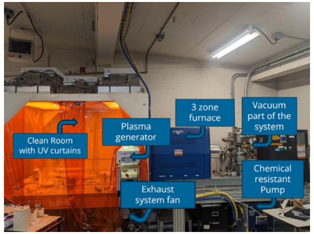
**SUSPB026 / MOPMB093**

**Electroplating**



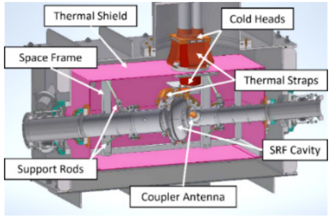

**TUPTB006**

**CVD**




**SUSPB009 / MOPMB015**

**$Nb_3Sn$ Cryomodule R&D**




**SUSPB027, SUSPB028, THIXA05**