Status of the Inner-wall Thermal Conducting Film (ITCF) Study

SRF Group – LINAC Center - IMP, CAS
Didi Luo, Jing Zhang

2024.09.19
E-mail: luodidi@impcas.ac.cn

Outline

1. Background: Importance of High Thermal Conductivity
2. Idea of Inner-wall Thermal Conducting Film (ITCF) + Simulation
3. Nb Thermal Conductivity as Baseline
   - Model and Calculation
   - Nb Sample Test
4. Preliminary Result of ITCF
   - Coating Quality
   - Thermal Conductivity Measurement
5. Summary and Future Work

Background

RF Dissipation

$$P_{loss} = \frac{1}{2}\int_S R_s|\mathbf{H}|^2\,ds$$

Quality Factor

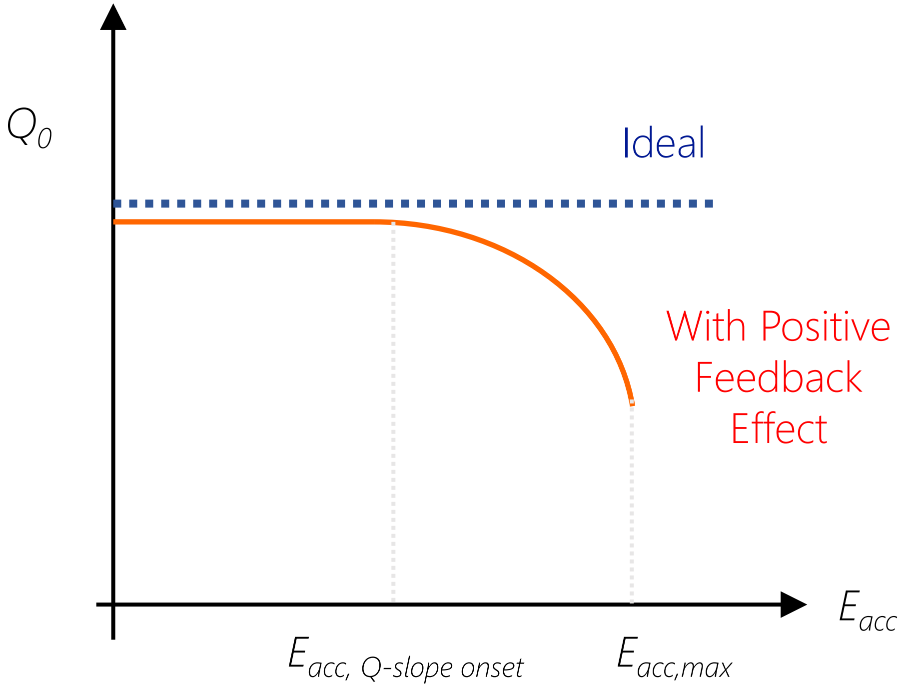
$$Q = \frac{\omega_0 U}{P_{loss}} = \frac{constant}{R_S} = \frac{\Gamma}{R_S}$$

Surface Resistance R_s derived from P_{loss} :

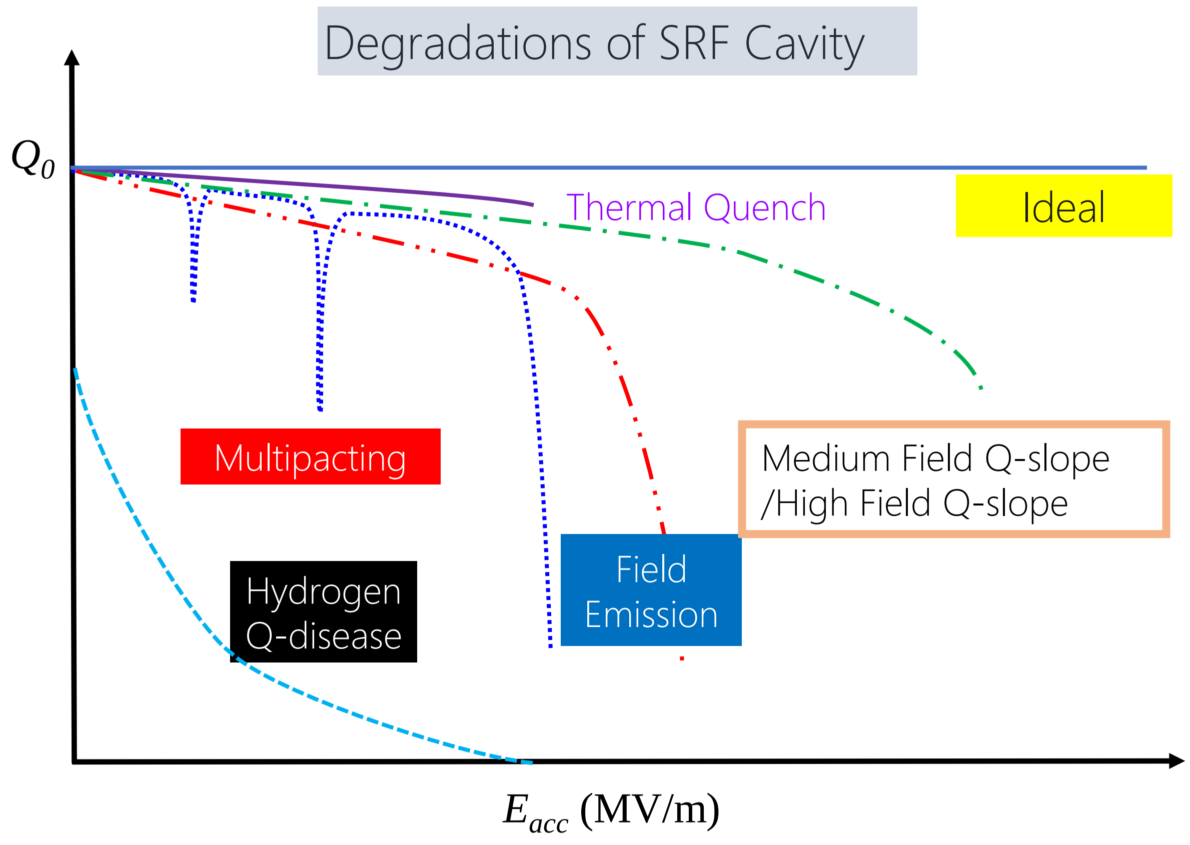
Independent of T $R_{BCS}(T)$

$$R_s = A_s\omega^2\exp\left(-\frac{\Delta(0)}{k_B T}\right) = R_0 + R_{BCS}$$

$$R_{BCS}(T) = \frac{Af^2}{T}e^{-\frac{\Delta}{k_B T}}$$



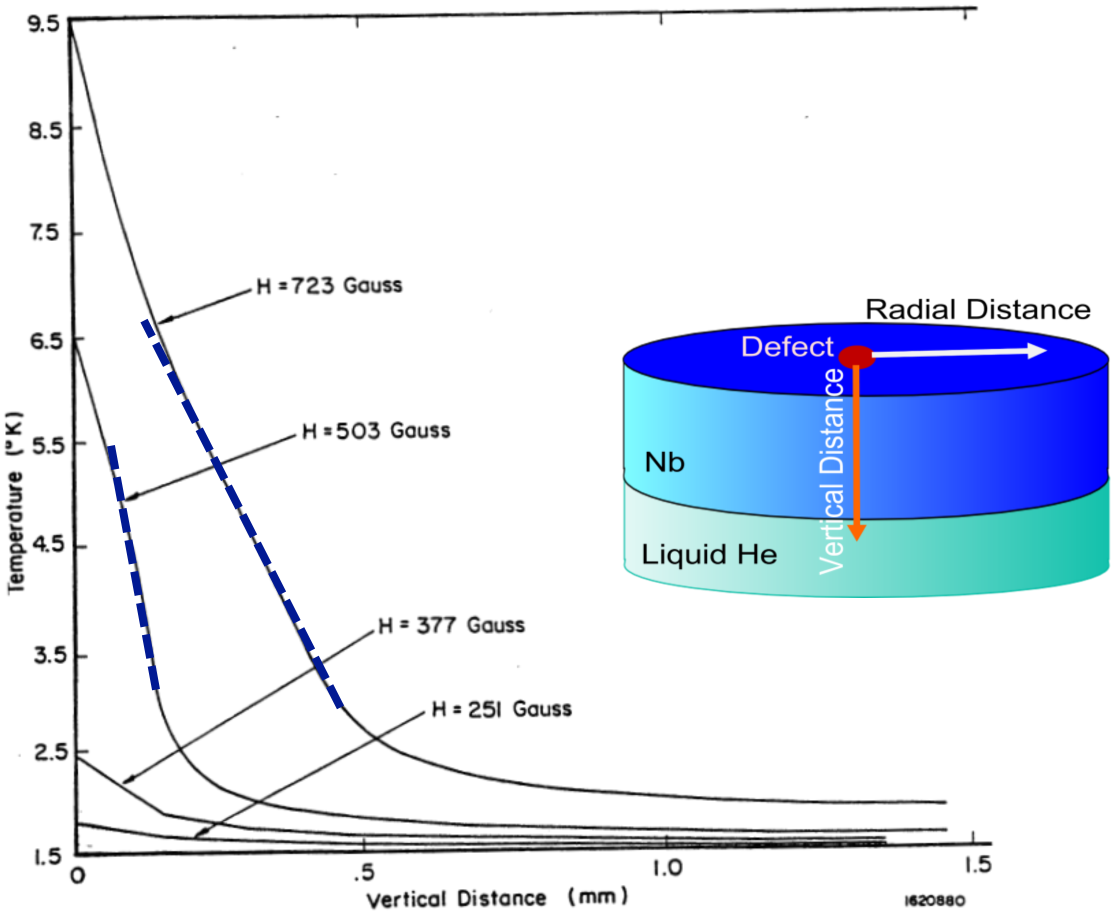
Background



Degradations of SRF Cavity

The Necessity of High Thermal Conductivity

T distribution with multiple *B* field

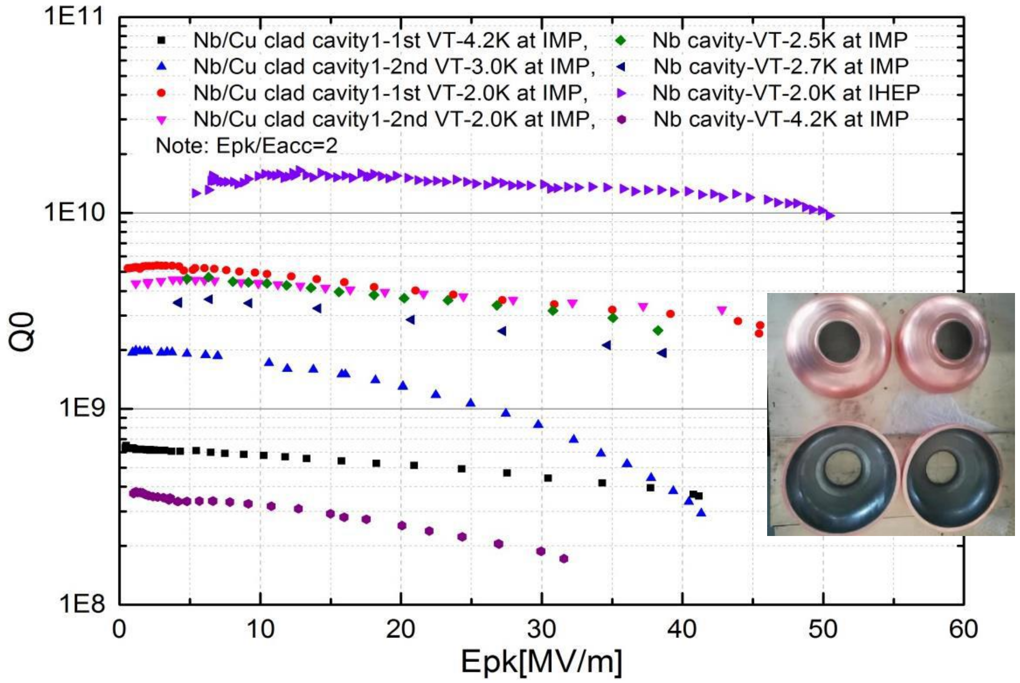


T distribution with multiple *B* field (From defect to Liquid He) [1].

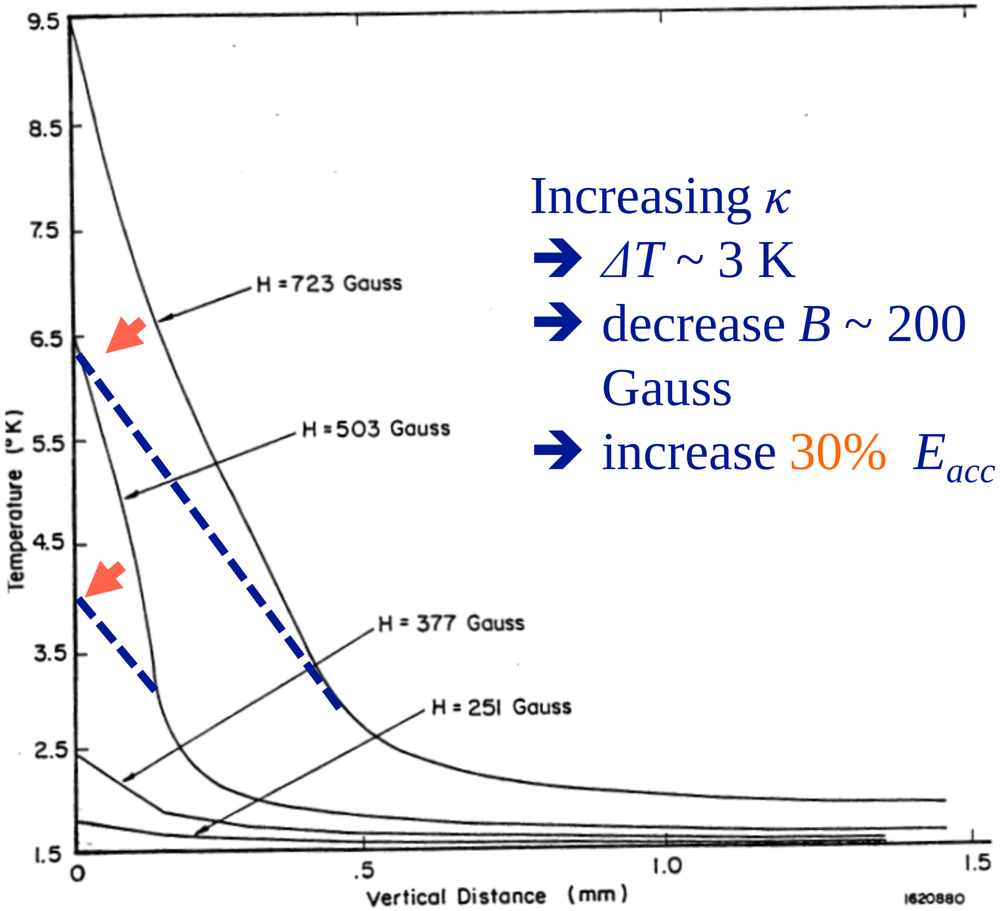
[1] , H. Padamsee, HEAT TRANSFER AND MODELS FOR BREAKDOWN, https://epaper.kek.jp/srf80/papers/srf80-7.pdf

The Necessity of High Thermal Conductivity

T distribution with multiple *B* field



Nb Cu Clad Cavity in IMP



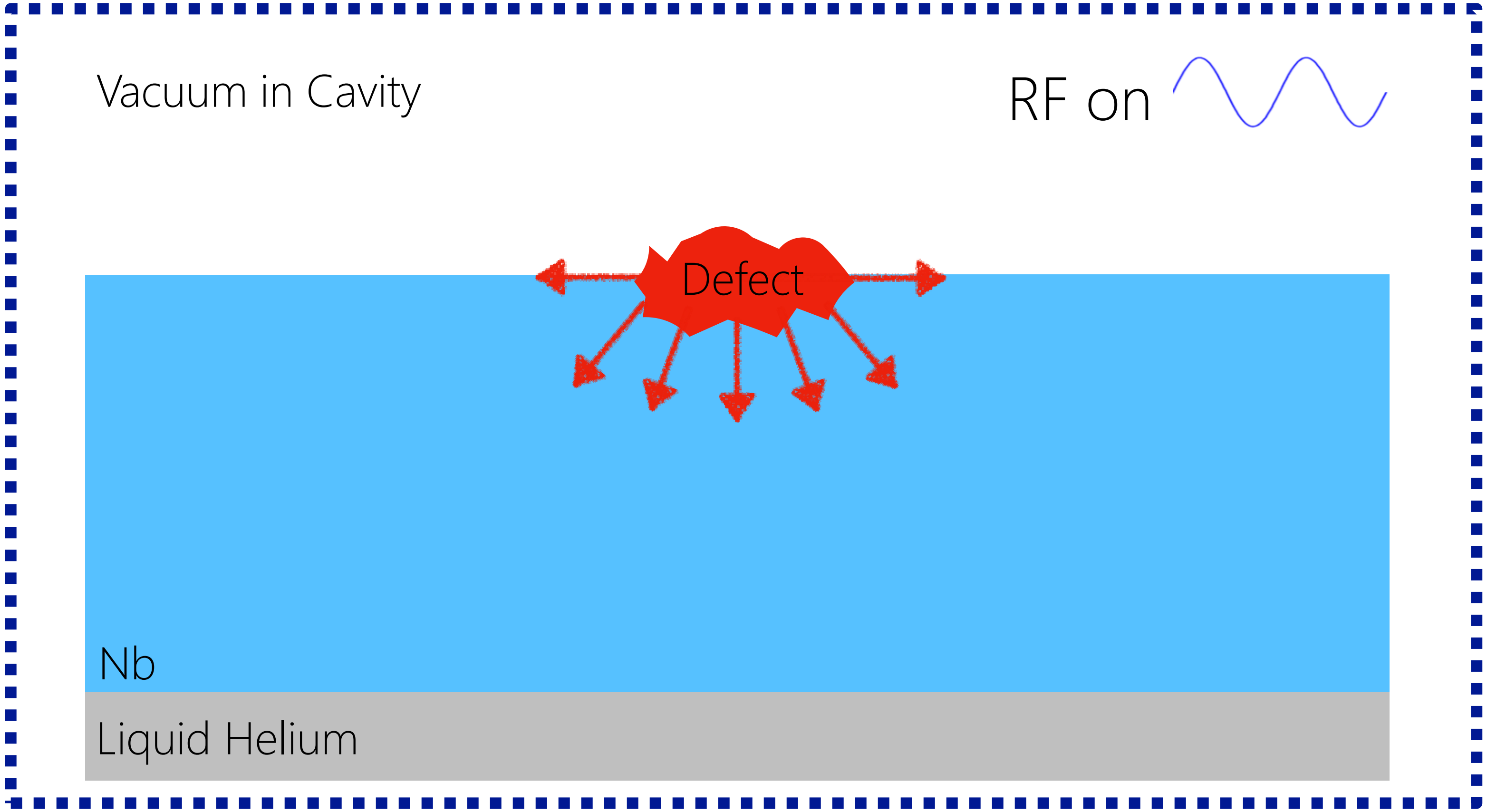
Increasing κ
➔ $\Delta T \sim 3$ K
➔ decrease $B \sim 200$ Gauss
➔ increase 30% E_{acc}

T distribution with multiple *B* field (From defect to Liquid He) [1].

[1] , H. Padamsee, HEAT TRANSFER AND MODELS FOR BREAKDOWN, https://epaper.kek.jp/srf80/papers/srf80-7.pdf

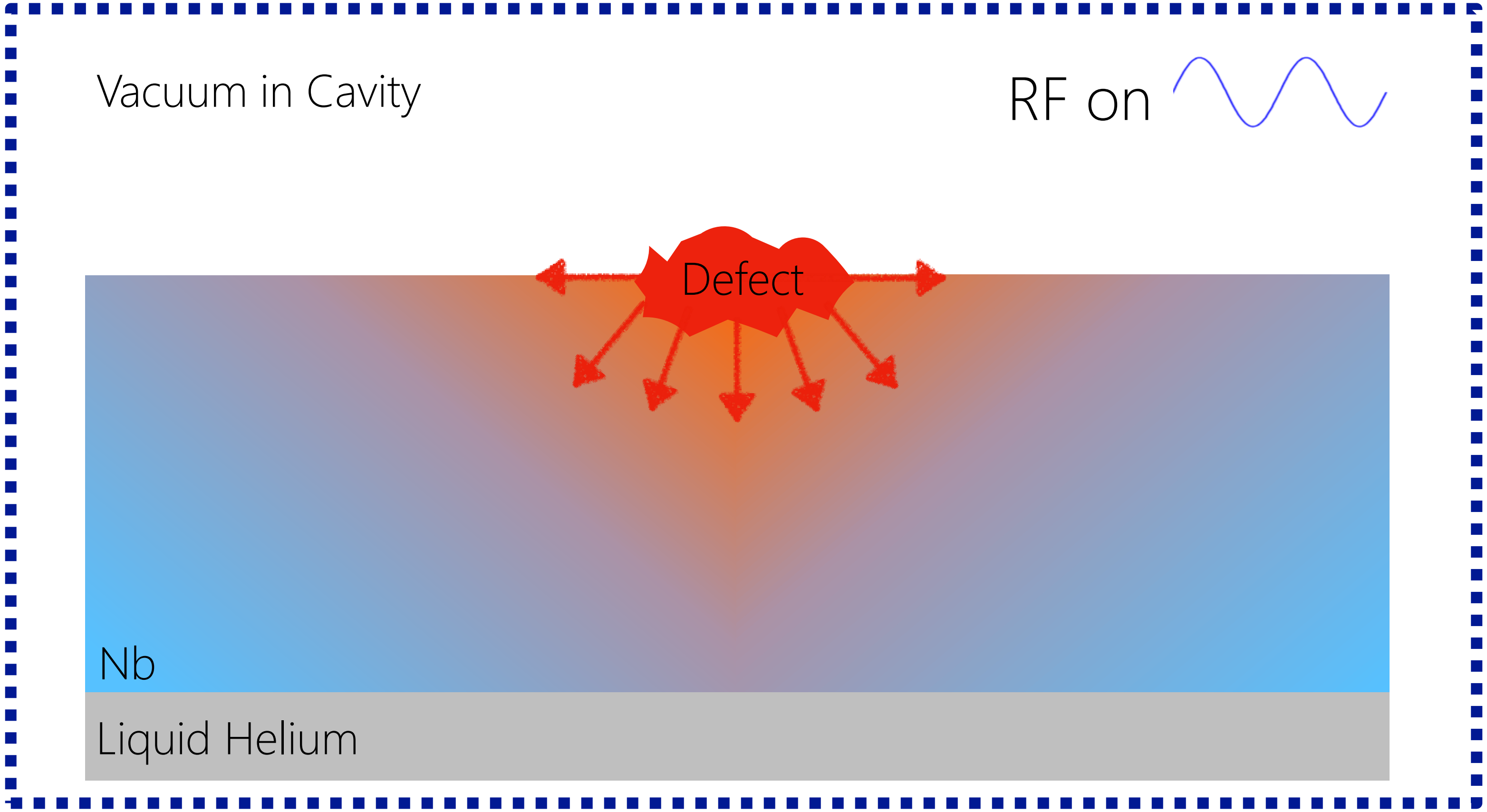
Idea of Inner-wall Thermal Conducting Film (ITCF)

RF dissipation on a defect



Idea of Inner-wall Thermal Conducting Film (ITCF)

RF dissipation on a defect

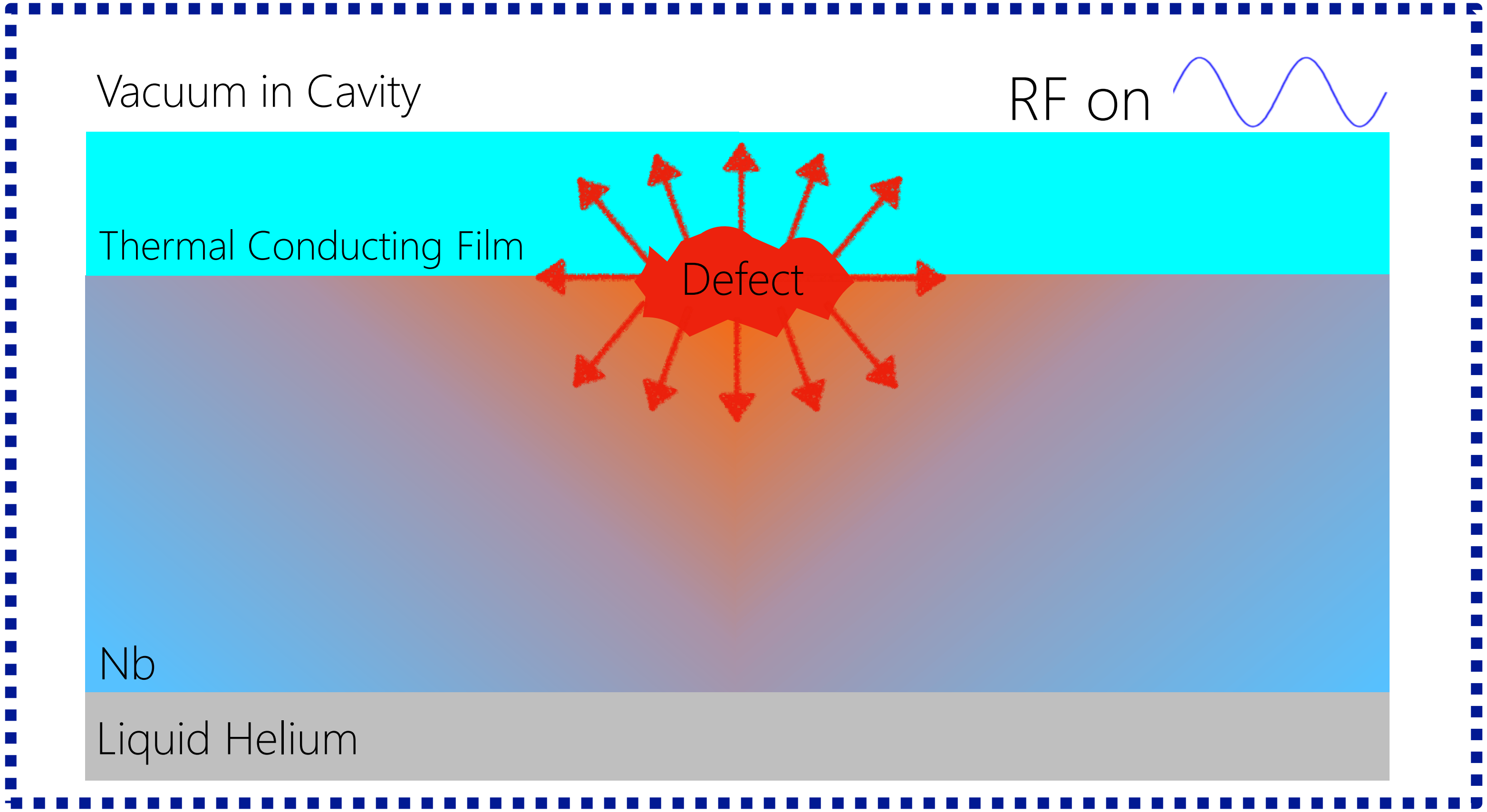


Idea of Inner-wall Thermal Conducting Film (ITCF)

RF dissipation on a defect

Inner-wall Thermal Conducting Film (ITCF), an extra thermal conducting route

- Select low tanδ material: No RF dissipation

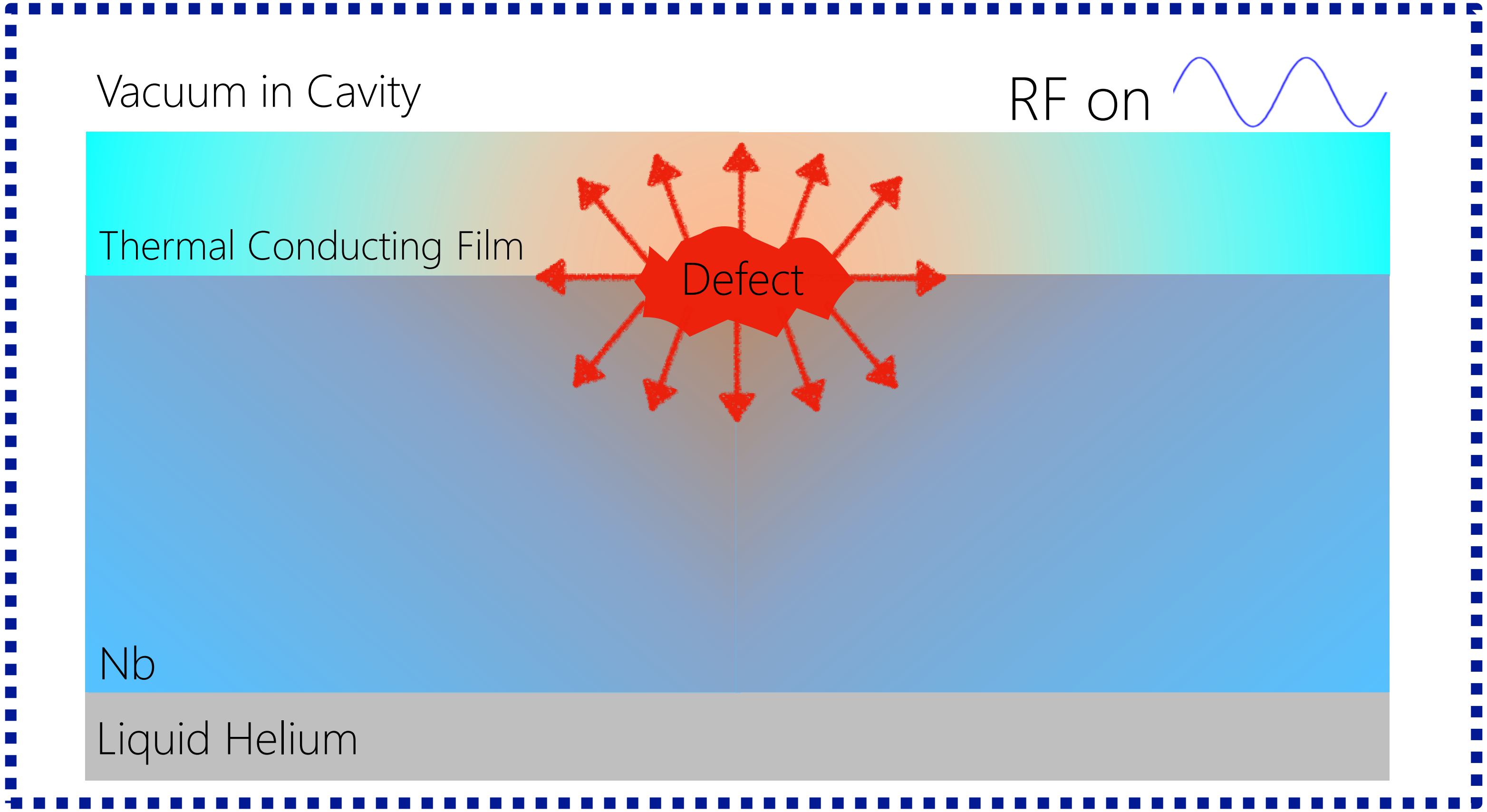


Idea of Inner-wall Thermal Conducting Film (ITCF)

RF dissipation on a defect

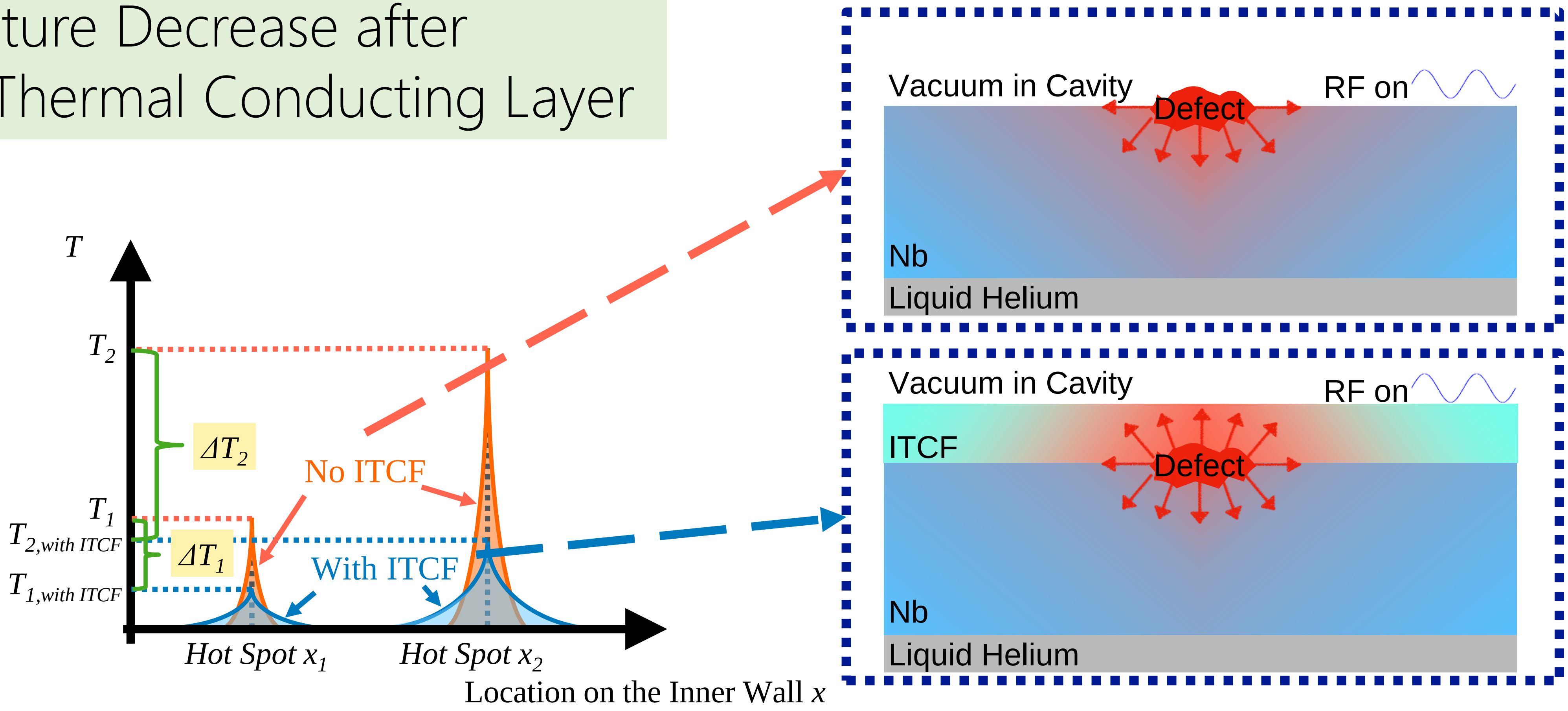
Inner-wall Thermal Conducting Film (ITCF), an extra thermal conducting route

- Select low tanδ material: No RF dissipation
- ITCF direct contact to heat source, high efficiency
- Can combine any cavity (Nb, Nb_3Sn, MgB_2, SIS)



Idea of Inner-wall Thermal Conducting Film (ITCF)

Temperature Decrease after Adding Thermal Conducting Layer

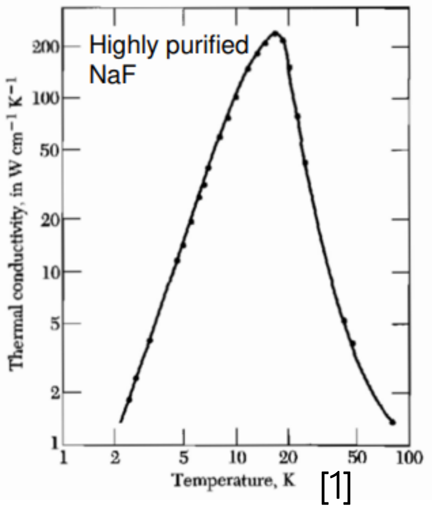


Material Selection: Thermal Conductivity

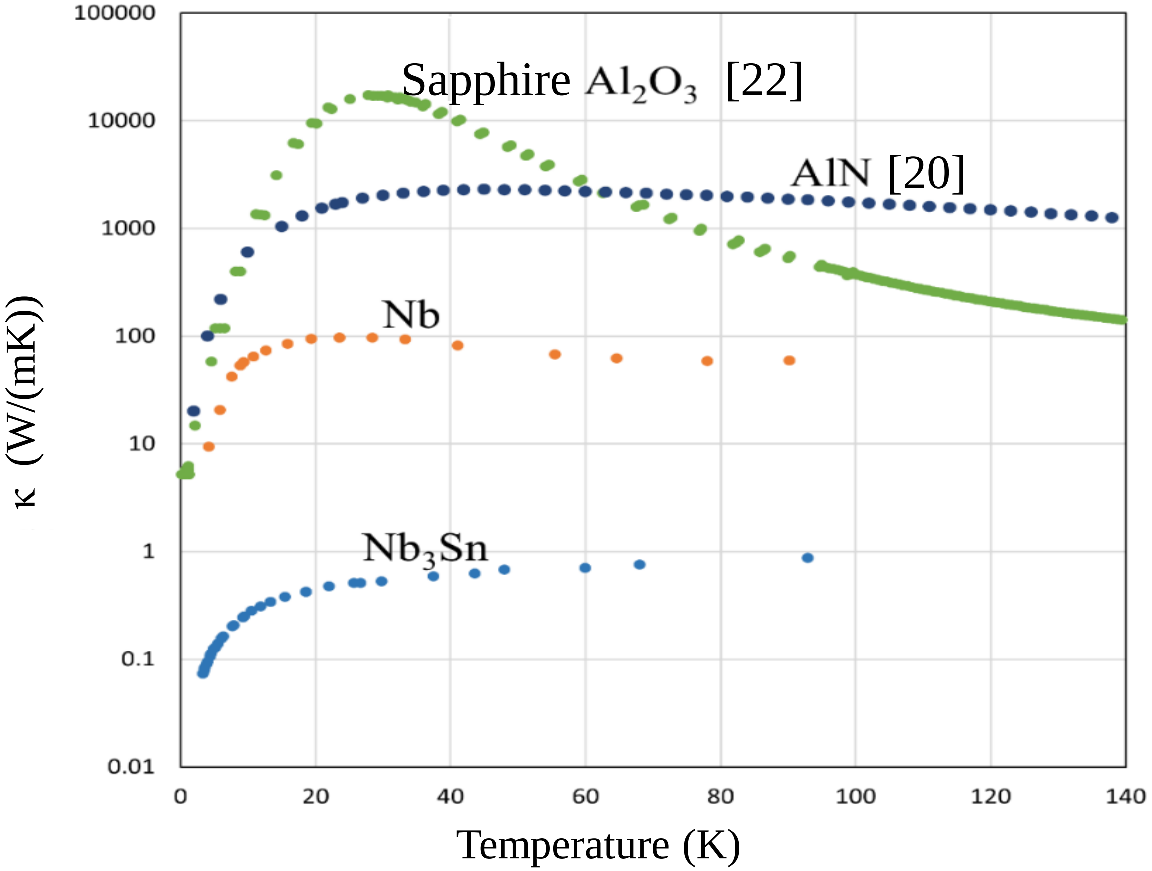
1. Relatively high κ at 2K – 4K (atomic crystal, low κ at low T)
    - SiC: κ ~ 100 W/(mK) @ 10K, rule out

$K\ (\sim cv\ell)$ • Low T: $K \sim c \sim T^3$

• High T: $K \sim \ell \sim 1/T$



[1]



[1] Boer and Pohl, Semiconductor Physics 2018

[17] Fuschillo, N., B. Lalevic, and N.K. Annamalai, *Dielectric properties of amorp*
145-154.

[20] Morelli, D.T. and G.A. Slack, High Lattice Thermal Conductivity Solids, in High Thermal Conductivity Materials, S.L. Shindé and Goela, Editors. 2006, Springer New York: New York, NY. p. 37-68.

[22] Inc., R.S. Sapphire Optical and Thermal Properties Graph. 2021; Available from: https://rayotek.com/PDF/Sapphire-Optical-and-Thermal-Properties-Graph.pdf.

[41] Microwave101. Alumina 99.5% Encyclopedia. 2023; Available from: https://www.microwaves101.com/encyclopedias/alumina-99-5.

[42] Microwave101. Sapphire Encyclopedia. 2023; Available from: https://www.microwaves101.com/encyclopedias/sapphire.

[43] Microwave101. Aluminum Nitride Encyclopedia. 2023; Available from: https://www.microwaves101.com/encyclopedias/aluminum-nitride#.

Material Selection: Other Requirement

1. Relatively high κ at 2K – 4K (atomic crystal, low κ at low T)
2. Dielectric with low loss tangent $tan\delta$

- Nb_2O_5 $tan\delta$ = 0.05 @ 0.2 MHz

3. Easy to coat to µm level, similar crystal structure with Nb
4. SEY?

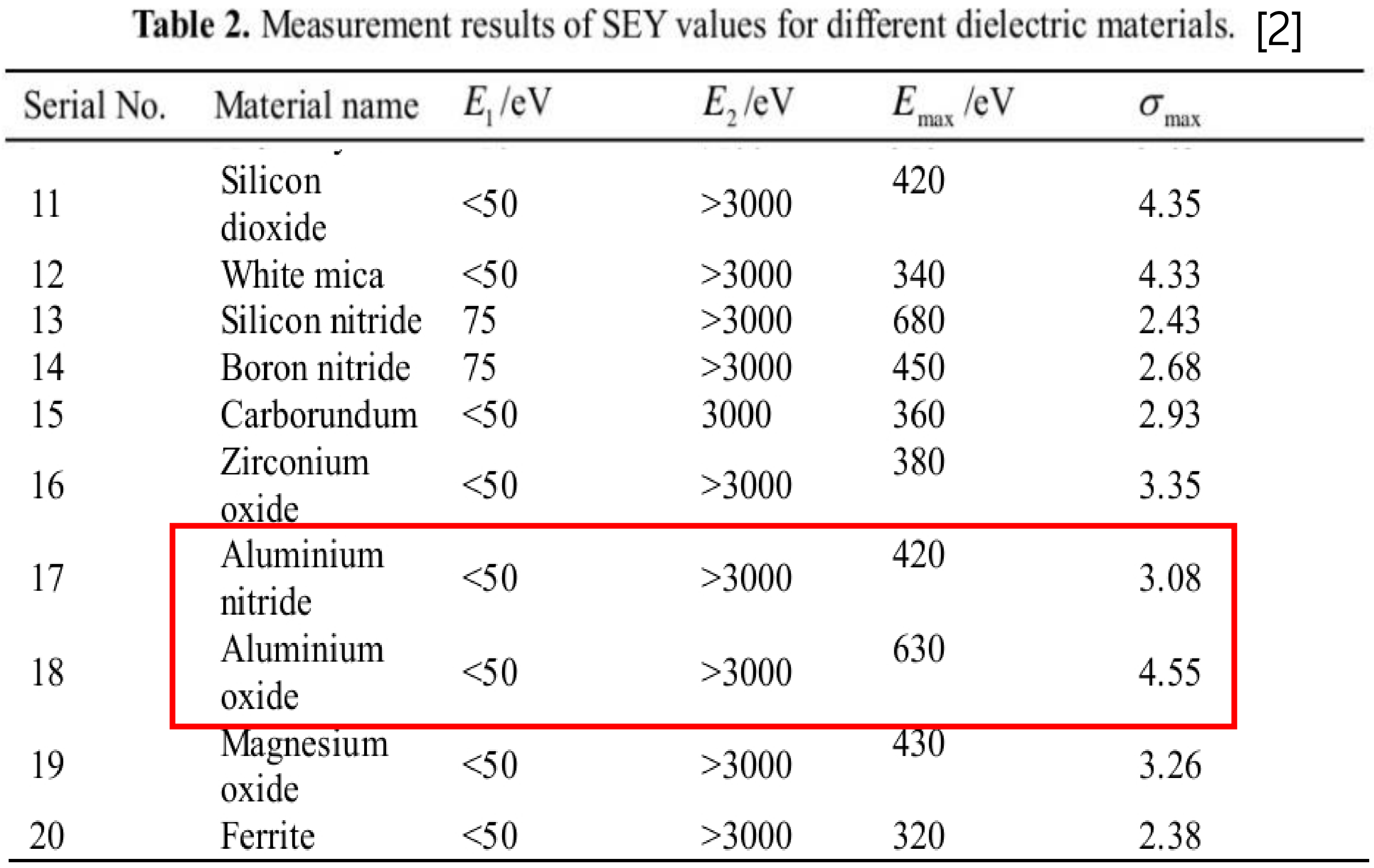


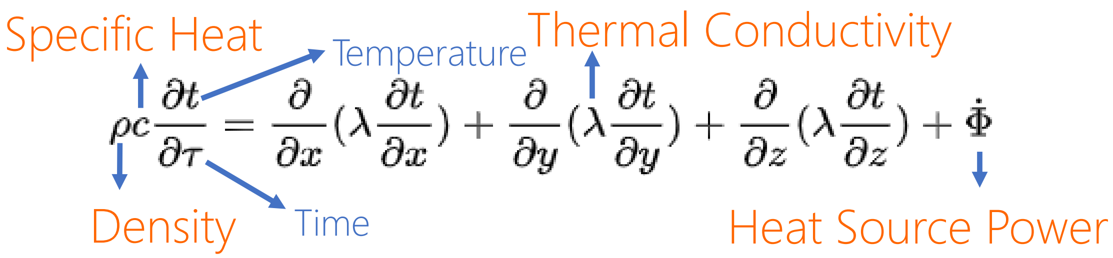
Table 2. Measurement results of SEY values for different dielectric materials. [2]

Serial No.	Material name	E_1/eV	E_2/eV	E_{max}/eV	σ_{max}
11	Silicon dioxide	<50	>3000	420	4.35
12	White mica	<50	>3000	340	4.33
13	Silicon nitride	75	>3000	680	2.43
14	Boron nitride	75	>3000	450	2.68
15	Carborundum	<50	3000	360	2.93
16	Zirconium oxide	<50	>3000	380	3.35
17	Aluminium nitride	<50	>3000	420	3.08
18	Aluminium oxide	<50	>3000	630	4.55
19	Magnesium oxide	<50	>3000	430	3.26
20	Ferrite	<50	>3000	320	2.38

[2] Ling Huang and Qian Wang 2023 J. Phys.: Conf. Ser. 2433 012002
[17] Fuschillo, N., B. Lalevic, and N.K. Annamalai, *Dielectric properties of amorphous Nb2O5 thin films.* Thin Solid Films, 1975. **30**(1): p. 145-154.
[20] Morelli, D.T. and G.A. Slack, High Lattice Thermal Conductivity Solids, in High Thermal Conductivity Materials, S.L. Shindé and J.S. Goela, Editors. 2006, Springer New York: New York, NY. p. 37-68.
[22] Inc., R.S. Sapphire Optical and Thermal Properties Graph. 2021; Available from: https://rayotek.com/PDF/Sapphire-Optical-and-Thermal-Properties-Graph.pdf.
[41] Microwave101. Alumina 99.5% Encyclopedia. 2023; Available from: https://www.microwaves101.com/encyclopedias/alumina-99-5.
[42] Microwave101. Sapphire Encyclopedia. 2023; Available from: https://www.microwaves101.com/encyclopedias/sapphire.
[43] Microwave101. Aluminum Nitride Encyclopedia. 2023; Available from: https://www.microwaves101.com/encyclopedias/aluminum-nitride#.

COMSOL Simulation Results

Fourier's Law of Heat Conduction



Specific Heat

Temperature

Thermal Conductivity

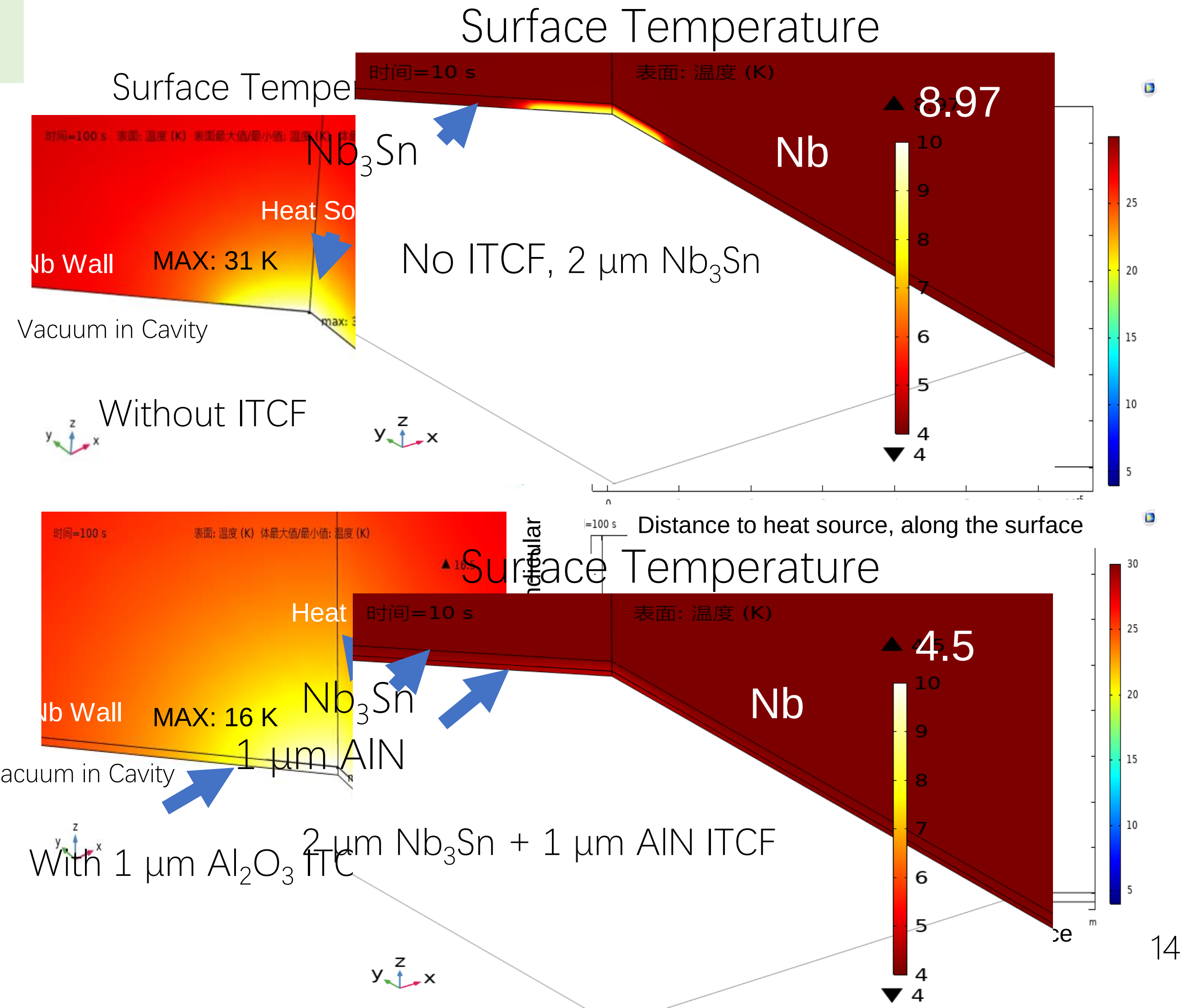
$$\rho c\frac{\partial t}{\partial \tau} = \frac{\partial}{\partial x}(\lambda\frac{\partial t}{\partial x}) + \frac{\partial}{\partial y}(\lambda\frac{\partial t}{\partial y}) + \frac{\partial}{\partial z}(\lambda\frac{\partial t}{\partial z}) + \dot{\Phi}$$

Density

Time

Heat Source Power

1. Adding ITCF decreases the center temperature (31 K to16 K in this case)
2. The ITCF conducts the heat into the distance and flattens the isothermals
3. Worse baseline κ improves more if add ITCF: Nb_3Sn?



Thermal Conductivity of Nb (Baseline)

Model

SRF cavity operation ~ B_{c1}, only considering electron and phonon transfer heat

κ for NC:

$$\kappa_n(T, RRR, l) = \left[\frac{1}{A\,RRR\,T} + aT^2\right]^{-1} + \left[\frac{1}{DT^2} + \frac{1}{BlT^3}\right]^{-1}$$

κ for SC:

$$\kappa_s(T, RRR, l) = R(y)\left[\frac{1}{A\,RRR\,T} + aT^2\right]^{-1} + \left[\frac{1}{DT^2e^y} + \frac{1}{BlT^3}\right]^{-1}$$

Energy Gap/k_BT:

$$y = \frac{\Delta(T)}{k_BT} \approx \frac{\Delta(0)}{k_BT}\left[\cos\left(\frac{\pi T^2}{2T_c^2}\right)\right]^{\frac{1}{2}}$$

Ratio of SC electrons over NC electrons:

$$R(y) = \frac{12}{\pi^2}\left[f(y) + y\ln(1+e^{-y}) + \frac{y^2/2}{1+e^y}\right] \quad , \quad f(y) = \int_0^\infty \frac{zdz}{1+e^{z+y}}$$

A = 0.141 W K^{-2} m^{-1}, a = 7.52 × 10^{-7} W^{-1} K^{-1} m, B = 4.34 × 10^3 W K^{-4} m^{-2}, 1/D = 2.34 × 10^2 $W^{-1}K^3$m [1]

[1] F.Koechlin, and B.Bonin, PARAMETRISATION OF THE NIOBIUM THERMAL CONDUCTIVITY IN THE SUPERCONDUCTING STATE, SRF1995 Gif-sur-Yvette, France, srf95f24

Thermal Conductivity of Nb (Baseline)

Introducing $T_c(B)$ to the equation

Below B_{c2}, the influence of B on κ of a superconductor (simplified for **static** magnetic fields) primarily arises from breaking Cooper pairs, leading to changes in the energy gap or, alternatively, manifesting as changes in T_c:

$$B_{c2} = B_{c2,T=0}\left[1 - \left(\frac{T_c}{T_{c,B=0}}\right)^2\right]$$

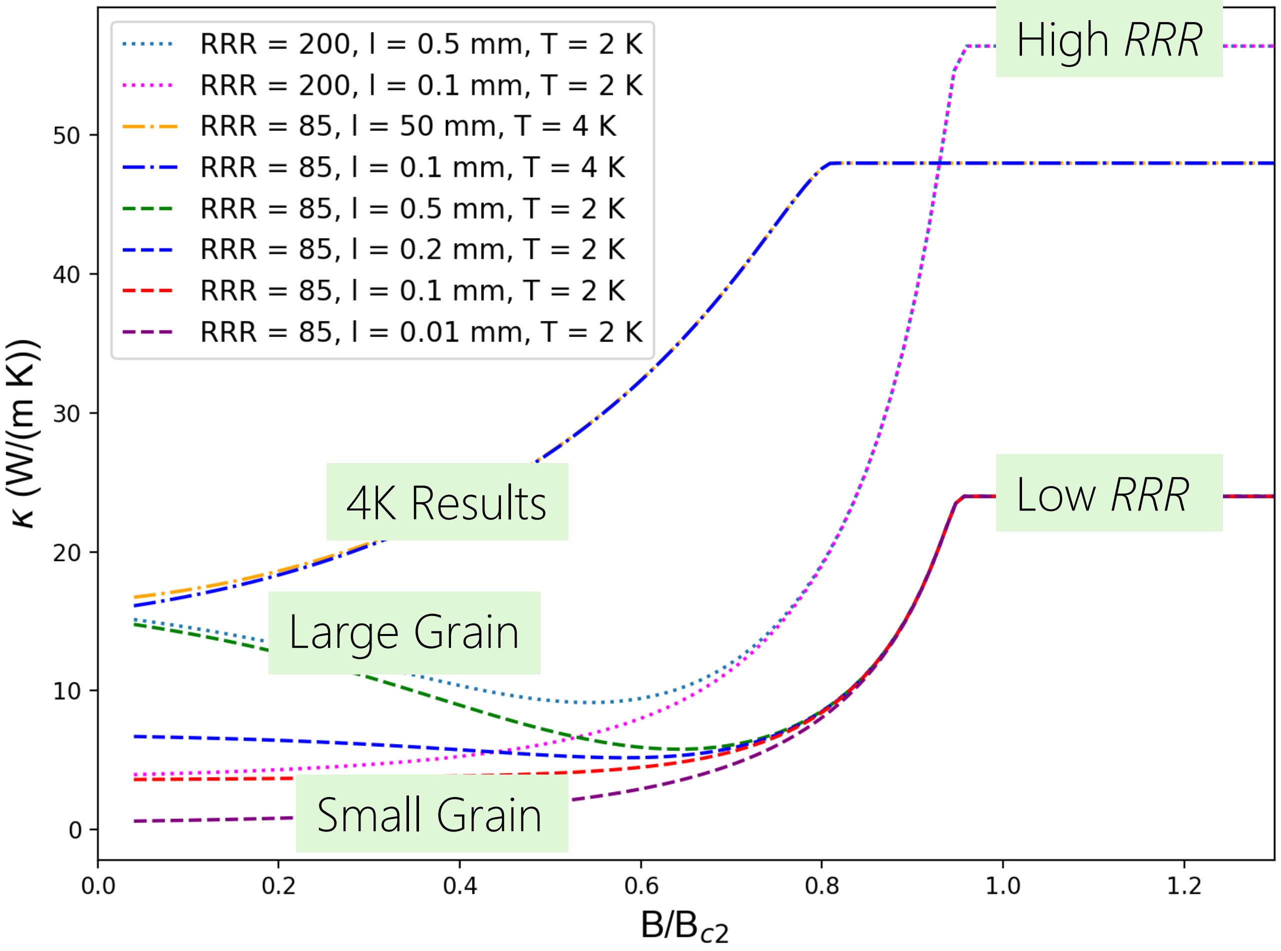
$$T_c(B) = T_{c,B=0} \times \sqrt{1 - \frac{B}{B_{c2}}}$$

- Add an extra parameter to manipulate κ and get an extra equation

By substituting the expression for $T_c(B)$ into y, and then substituting y into κ_S, use Python code to calculate the κ for high-purity (RRR=200 is chosen for calculation) and low-purity (RRR=85 is chosen for this calculation, corresponding to the test value of the sample used in subsequent experiments) materials.

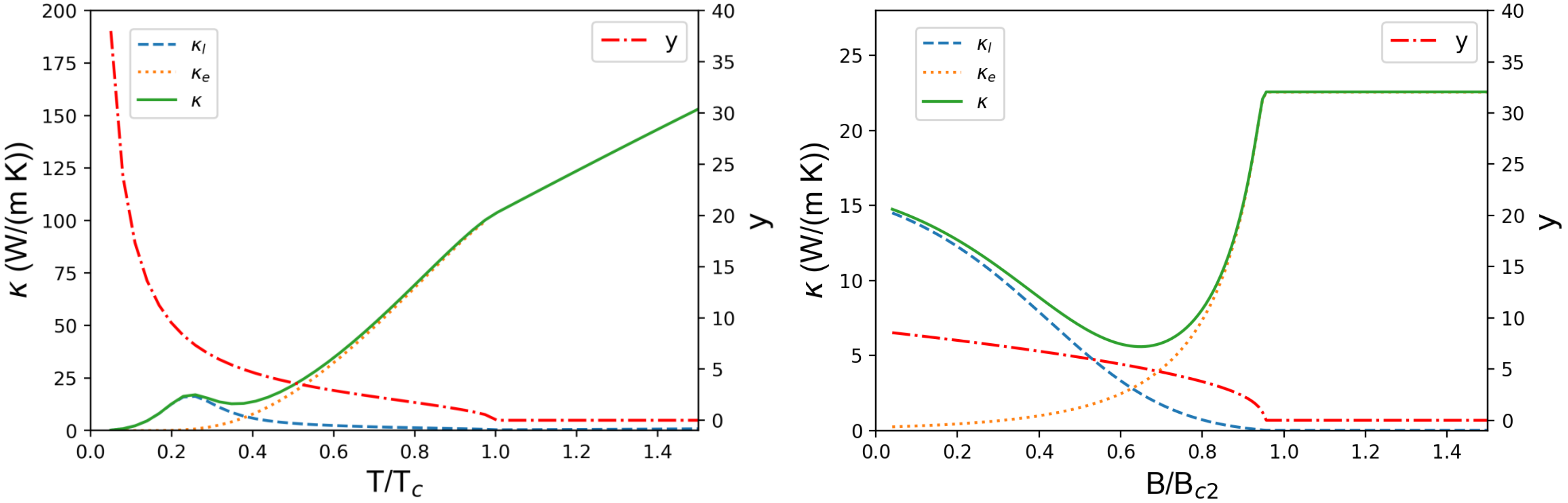
Calculated κ vs *B for* Nb (using Python)

1. Large-grain low-*RRR* *κ(B)* shows valley on the curve
2. (Relatively) Small grain *κ(B)* curve no valley
3. @4K, the influence of grain size on the *κ(B)* curve is low



Thermal conductivity vs B/B_{c2} for multiple parameters.

Explanation of the "Valley" on the *κ(B)* curve for some parameters

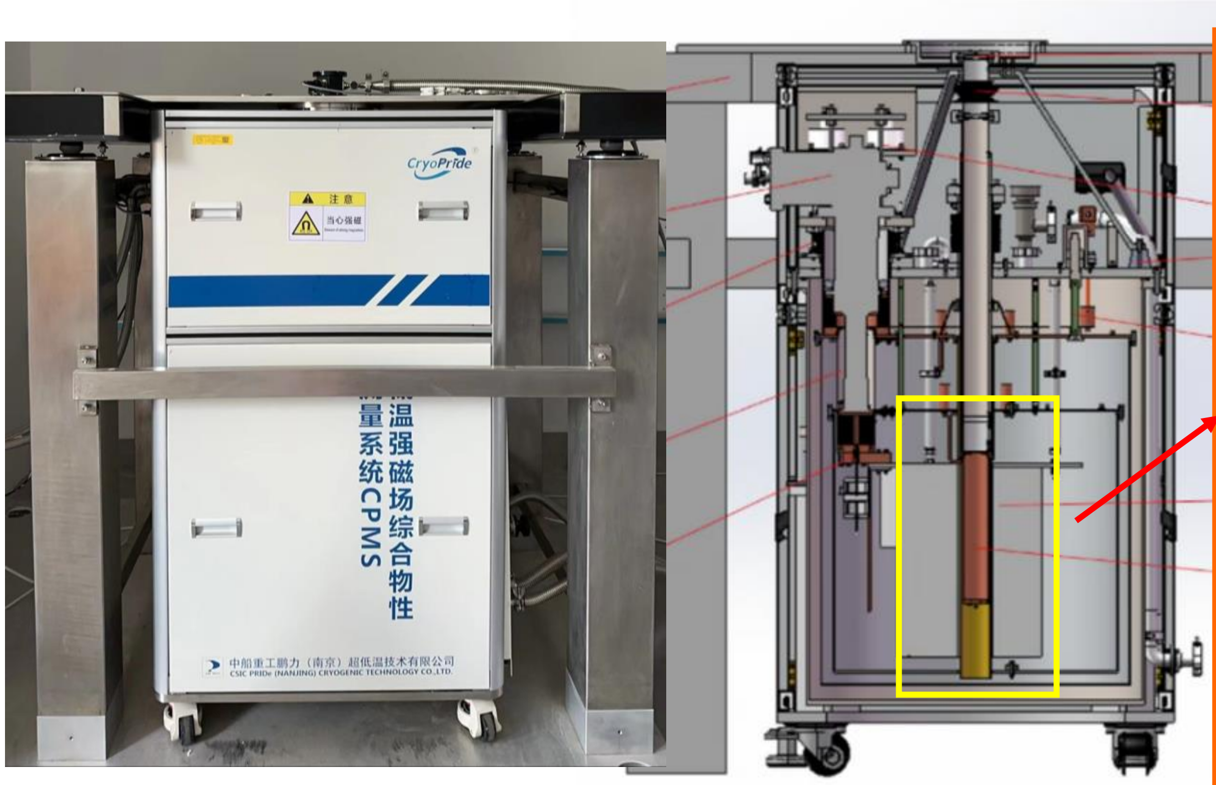


RRR = 85, *l* = 0.5 mm, the increase in *T* @ *B* = 0 mT and the increase in *B* @ *T* = 2 K both change *κ* and the y-value (right vertical axis).

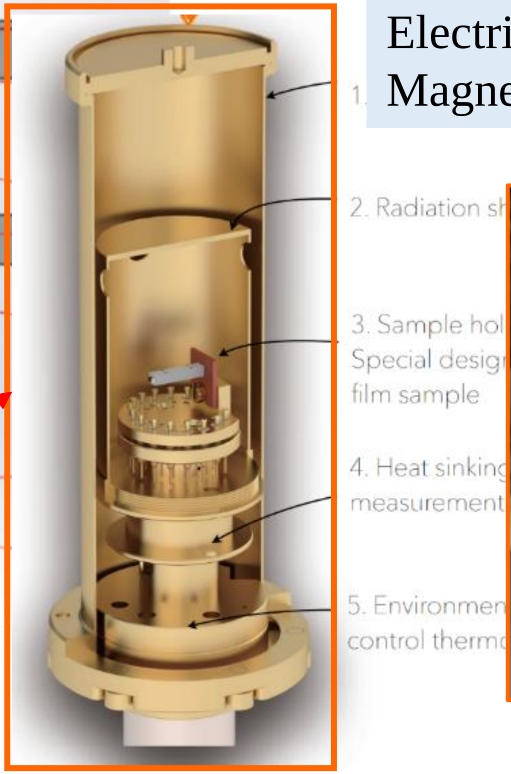
1. At low *T* & *B*, κ_l (for lattice) dominates. *T* or *B* increase breaks Cooper pairs, κ_e increase and gradually dominants κ
2. As the *T* rises, increasing $n_{e,nc}$ enhances phonon scattering, adding a decrease κ_l (instead of monotonically increasing with *T*) when the decreasing is obvious (in some range of RRR and grain size) => phonon peak
3. As the *B* rises, the growing $n_{e,nc}$ enhances phonon scattering, leading to a decrease in κ_l and an increase in κ_e => "valley"

Testing System

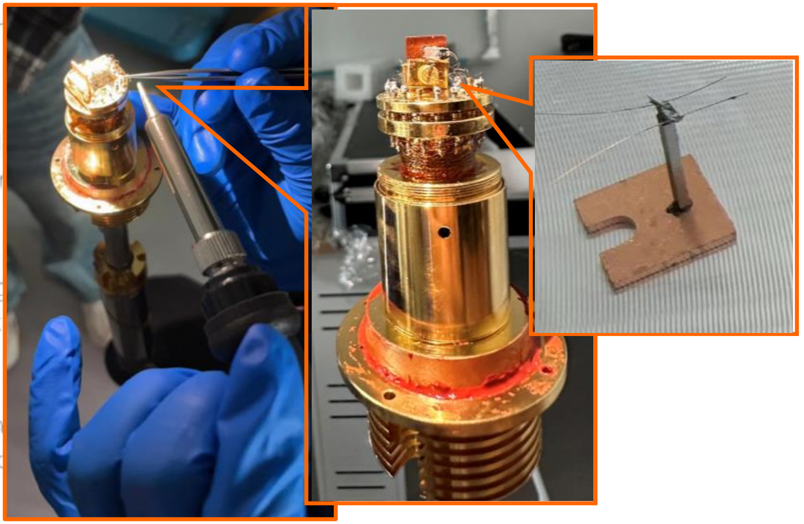
Cryogen-free magnets Property Measurement System (CPMS) [1]



Electrical and thermal module ready for test
Magnetic module not ready yet



Sample Stick



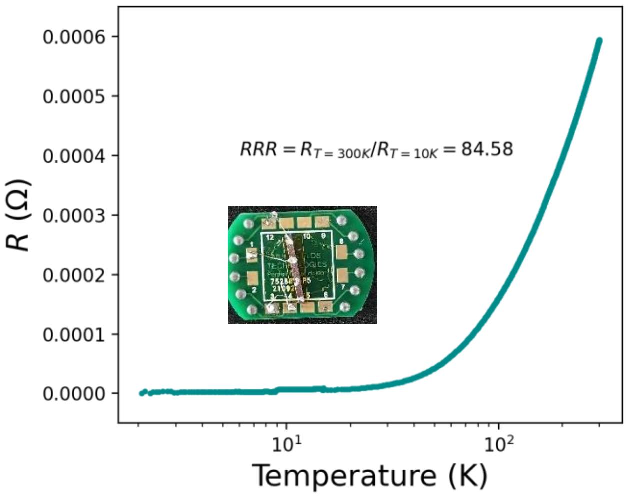
Thermal test sample holder & sample

[1] CSSC Pride, https://www.724pridecryogenics.com/en/

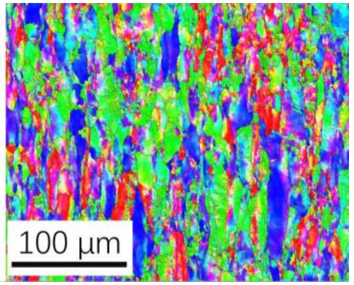
Sample Test of Nb

Sample test, Electrical

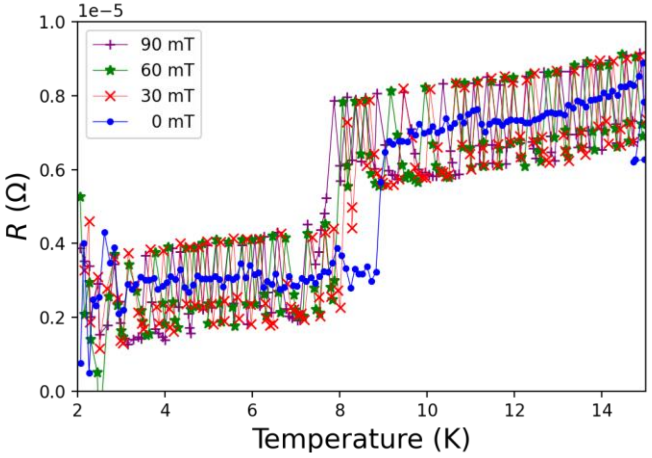
To validate our computational findings, we conducted electrical and thermal transport measurements on a low-purity niobium sample with dimensions of 10*1*1 mm (supplier-provided RRR=40, grain size approximately 0.01 mm).



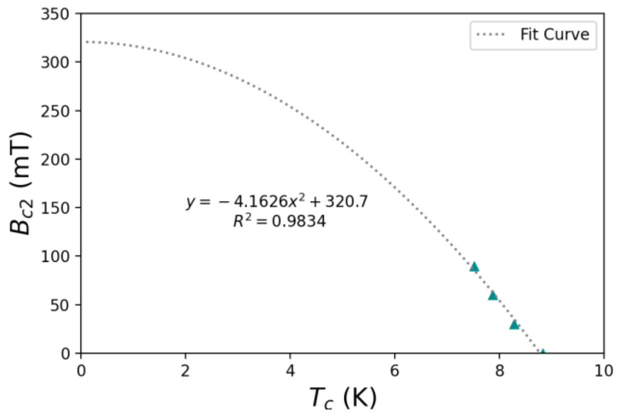
R(*T*) Curve of Nb, *RRR* = 85



EBSD of same batch sample



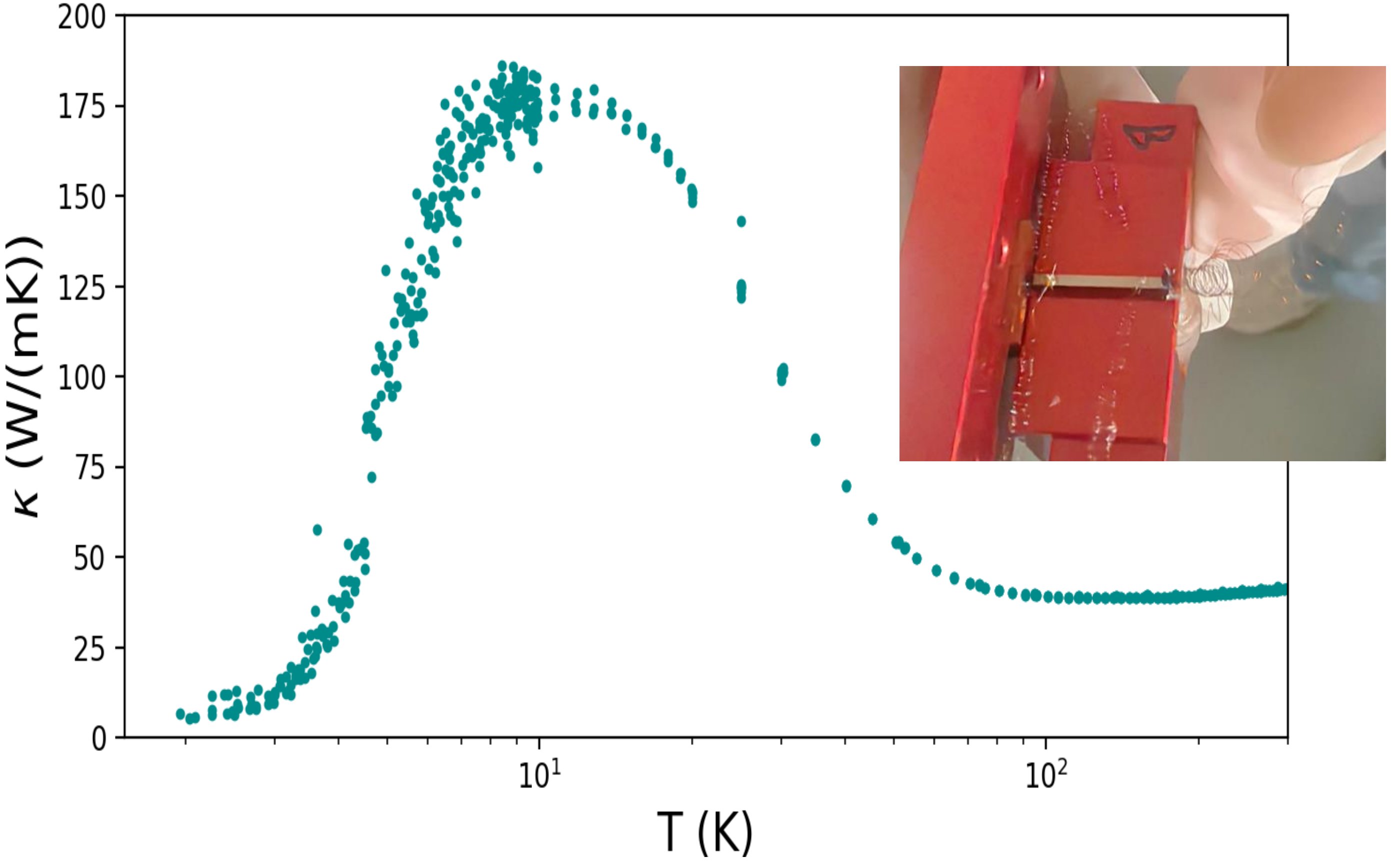
R(*T*) Curves of Nb Samples under Various Magnetic Fields



Fitted B_{c2} vs. T_c,$B_{c2}(0) \approx 320.7$ mT

Sample Test of Nb

Sample test, Thermal

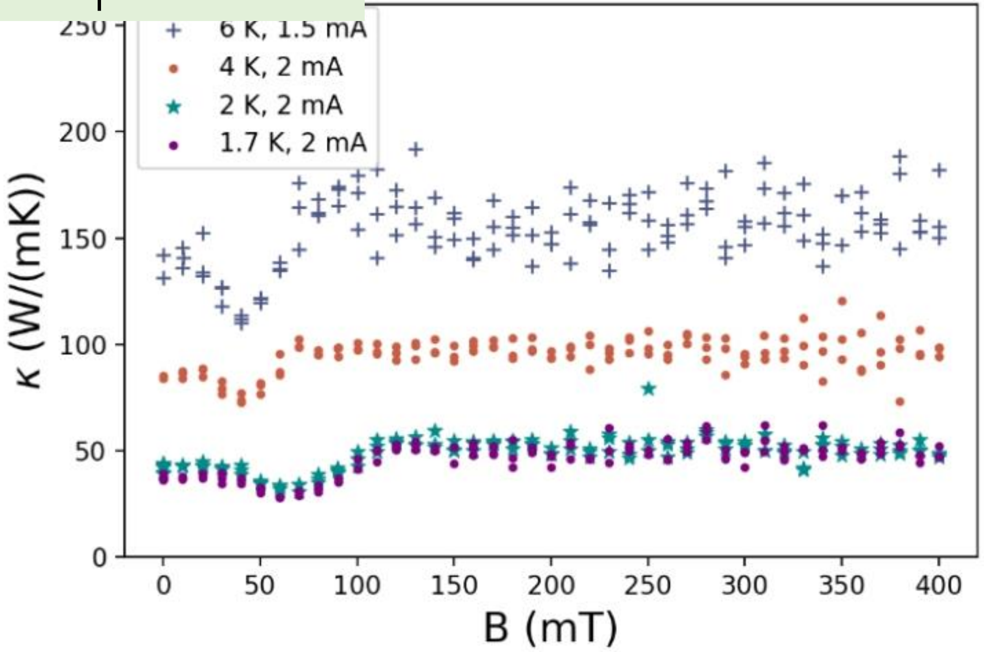


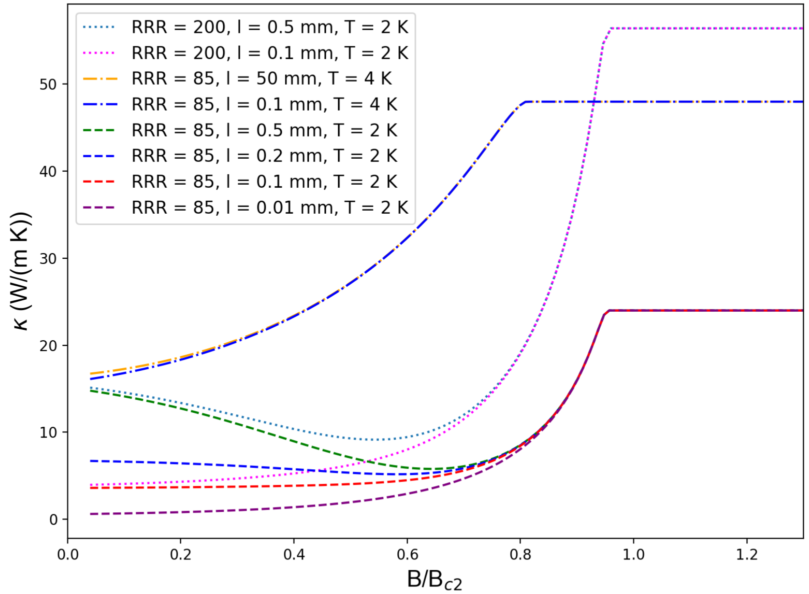
$\kappa(T)$ of Nb Sample @ B = 0 mT

Sample Test of Nb

Sample Test

Thermal Conductivity at multiple Temperature for increasing Magnetic Field

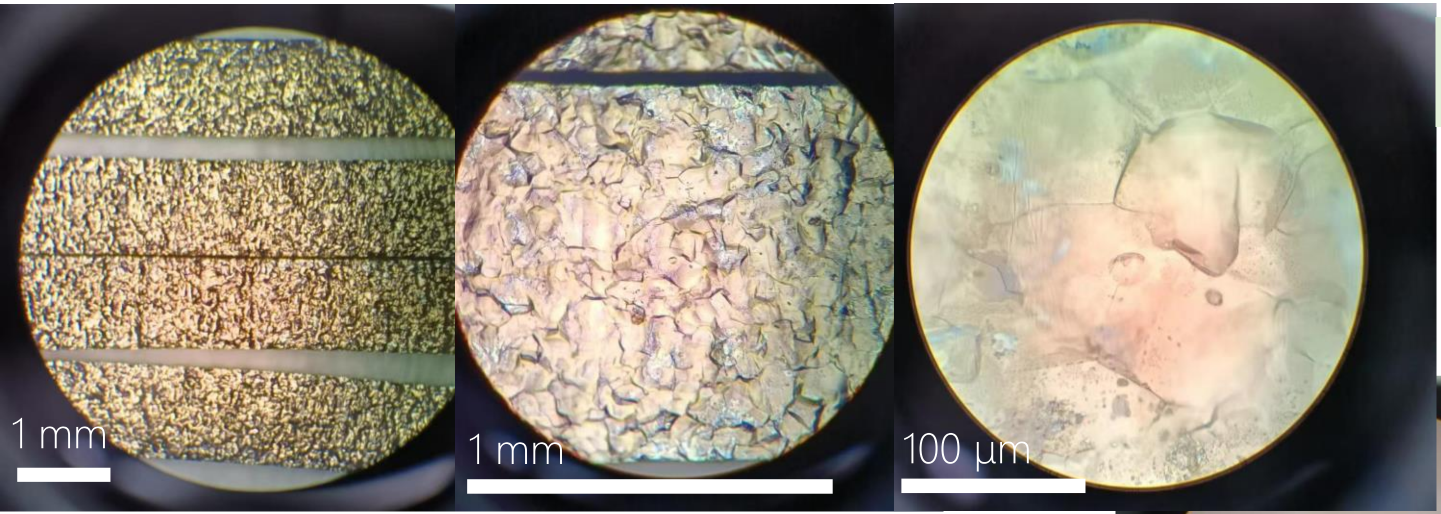




1. At temperatures of 2 K, 4 K, and 6 K, valley observed in thermal conductivity within the low magnetic field range, while thermal conductivity remains constant at higher magnetic fields (up to 700 mT for 2K test).
2. The overall κ values are higher than calculated, with values around 50 W/(mK) at 2 K.
3. Test results indicate that below B_c, fluctuations in κ are more pronounced, reaching over 30%, vortex contribution, grain shape (long and narrow), defect?

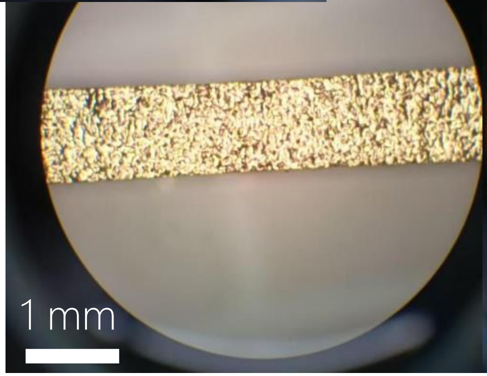
Preliminary Results of Thermal Conducting Film

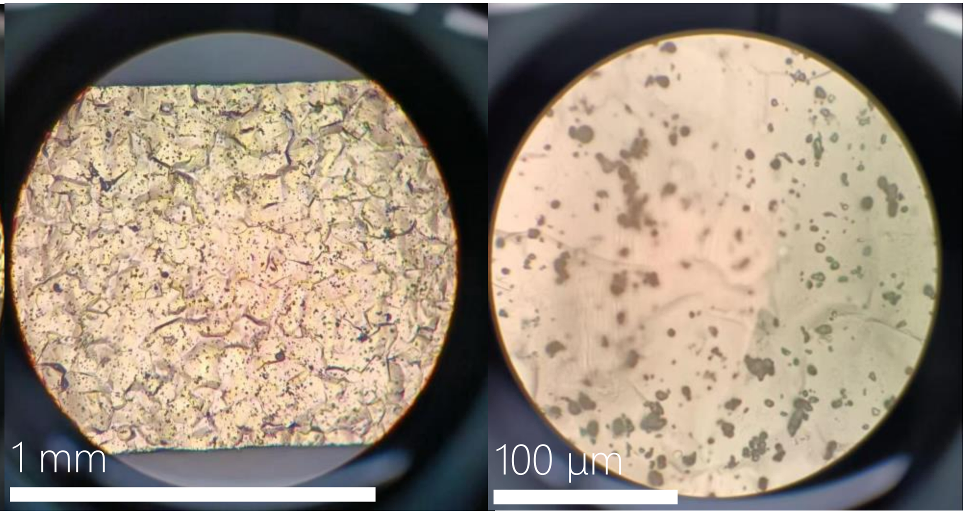
Coating Quality



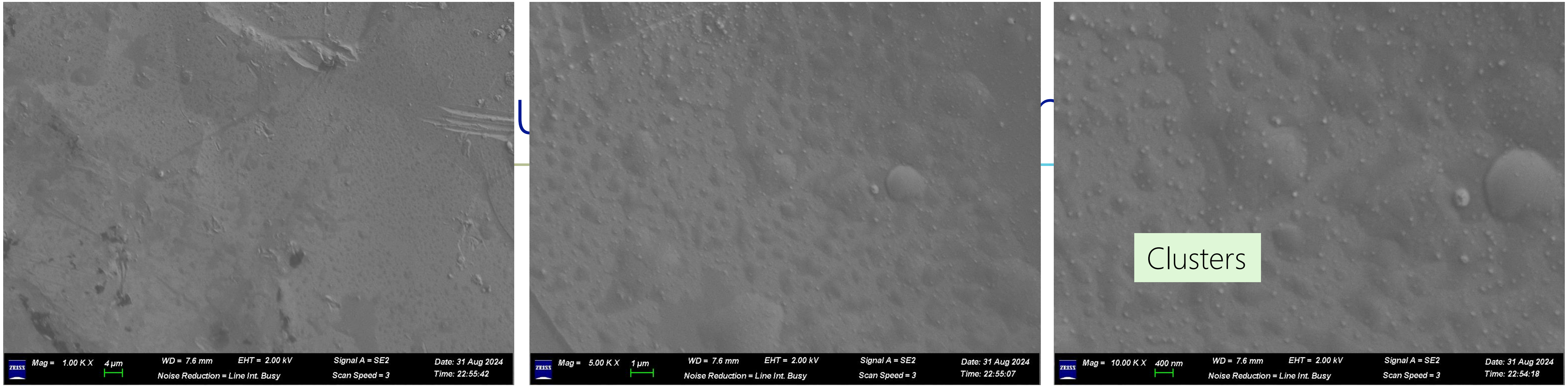
BCP + ALD **20 nm Al_2O_3**
Optical Microscope (50x, 200x, 1000x)

1. We did not make perfect substrate before coating (rough surface)
2. After ALD, no much changes on the surface morphology, similar to Nb surface
3. After 1 µm AlN DCMS, no cracking, see bubbles or clusters?



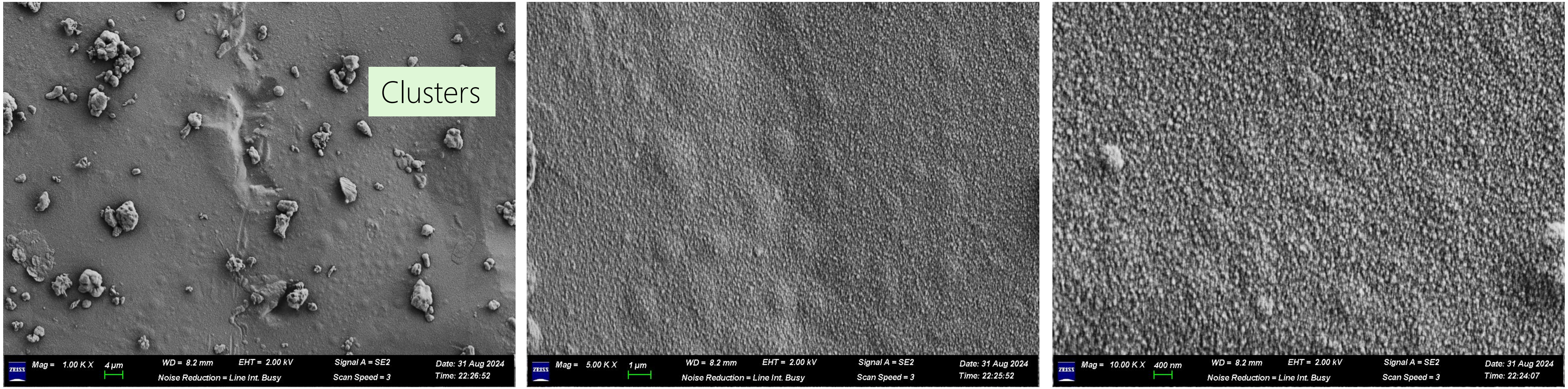


BCP + ALD **20 nm Al_2O_3** + Magnetic Sputtering **1 µm AlN**
Optical Microscope (50x, 200x, 1000x)



Clusters

BCP + ALD **20 nm Al_2O_3** Scan Electron Microscope (SEM)

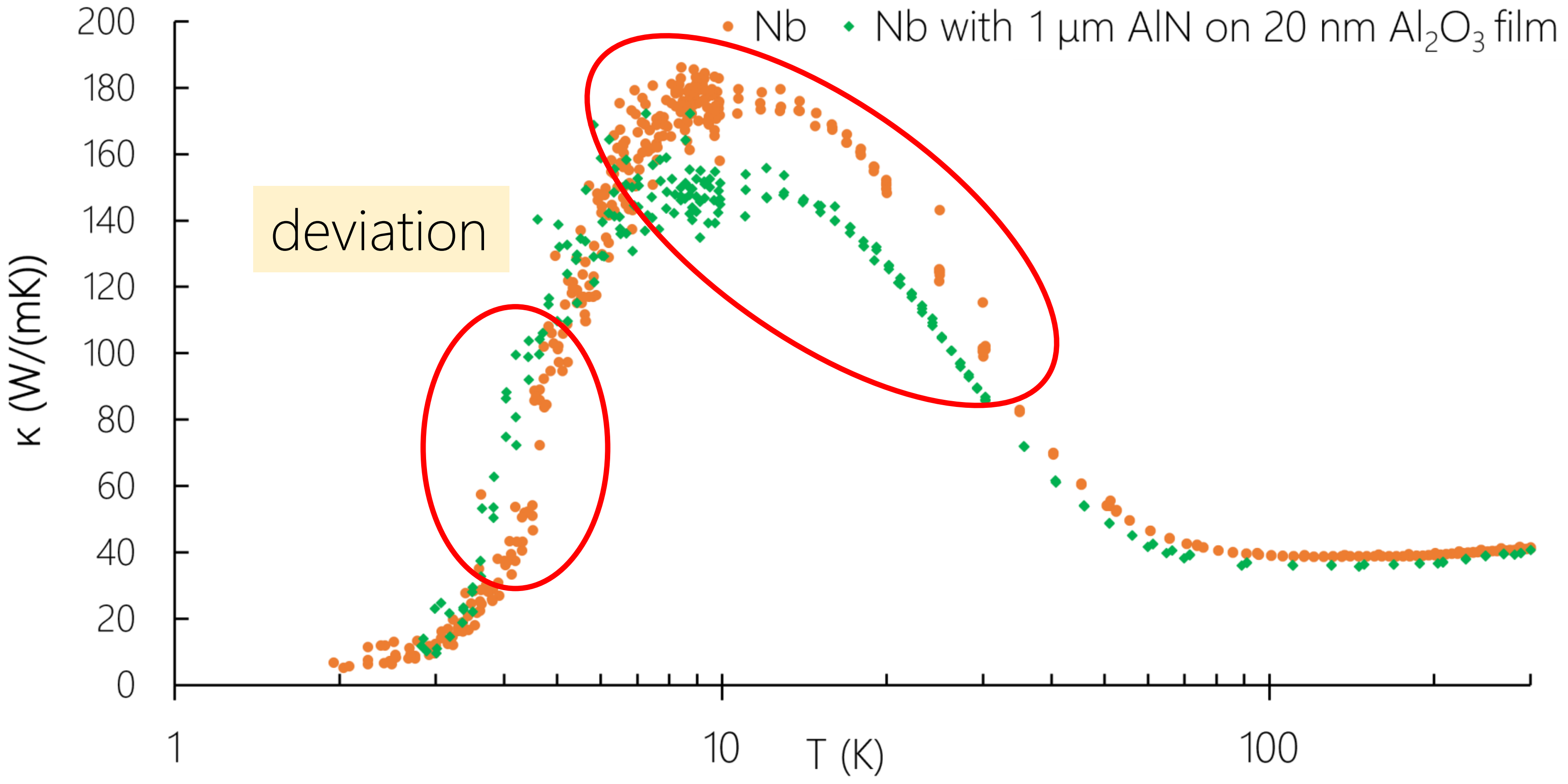


Clusters

BCP + ALD **20 nm Al_2O_3** + Magnetic Sputtering **1 µm AlN** Scan Electron Microscope (SEM)

Thermal Conductivity of the Coated Sample

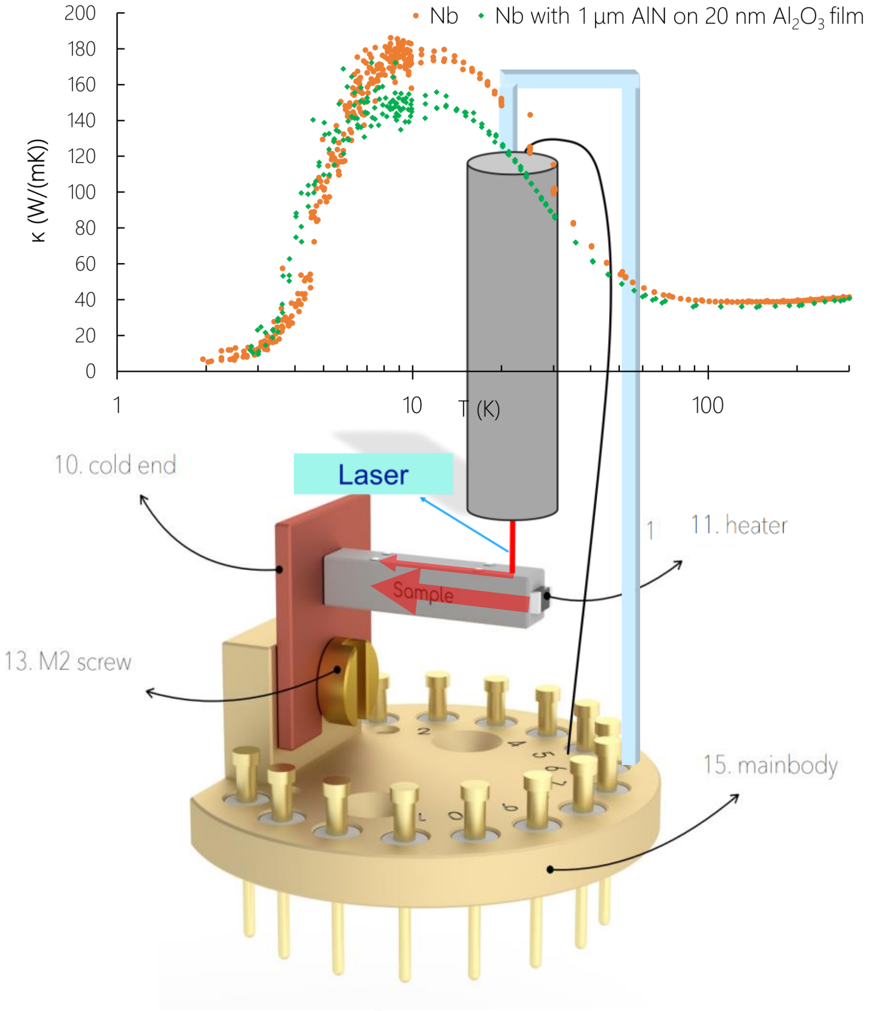
Preliminary Result



Thermal Conductivity of the Coated Sample

Ongoing/Future Work

1. Statistic test results of $\kappa_{sample}(T)$
2. Error analysis: size variation, ITCF on the side
3. Separate the κ_{Nb} and κ_{film}, by adding B field, each B get an extra equation with two unknowns
4. Upgrade thermal test module with laser heating (more like RF heating on the metal surface instead of on the side), considering material absorption
5. Optimizing film quality (annealing, change MS parameters, cleaning…)



Summary

1. Review of ITCF Concept and Film Selection
2. Calculation and Testing of Thermal Conductivity in Nb Samples
    - Utilizing Python, serving as a baseline for subsequent sample testing.
    - Valley on the $\kappa(B)$ curve
3. Preliminary ALD+MS Coating Samples
    - no cracking, clusters exist
    - thermal conductivity deviates from the Nb baseline: higher κ @ 3-5K
4. Ongoing Work:
    - Error analyzing, test system upgrading, and coating process optimizing.

Thank you for your attention!

This work was supported by the Young Scientists Fund of the National Natural Science Foundation of China (Grant No. 12105335), National Natural Science Foundation of China General Program (Grant No. 12375155) and Large Research Infrastructures China initiative Accelerator Driven System (Grant No. 2017- 000052-75-01-000590).