Thermal-conductivity-related New Strategy for Breaking the E_{acc} Limit

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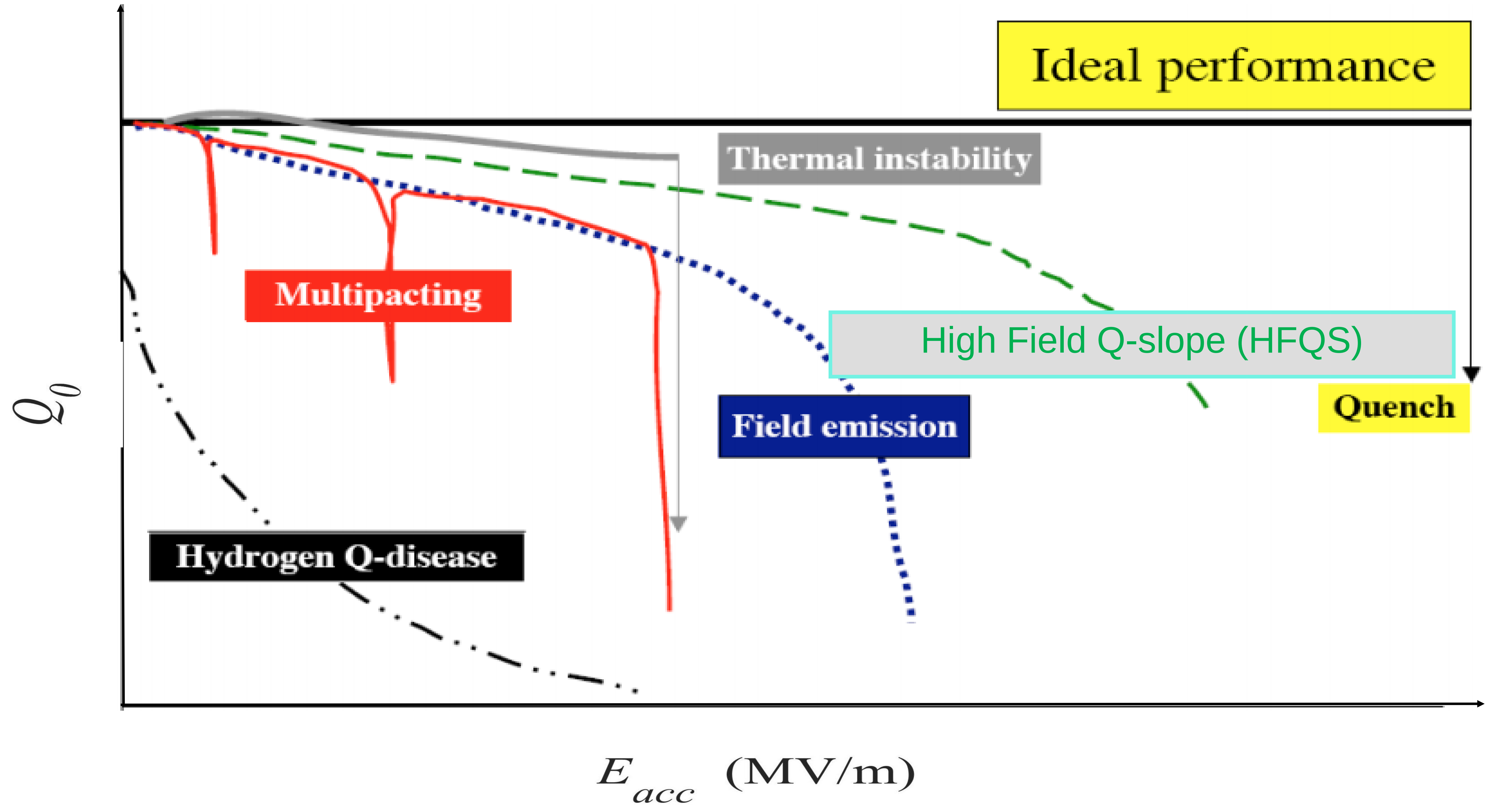
Outline

- E_{acc} Limitations vs. Heat
- Hot Spot and Thermal Conductivity $\boldsymbol{\kappa}$
- New Strategies
  - Outer-wall Groove Structure (OGS)
  - Inner-wall Thermal Conducting Film (ITCF)

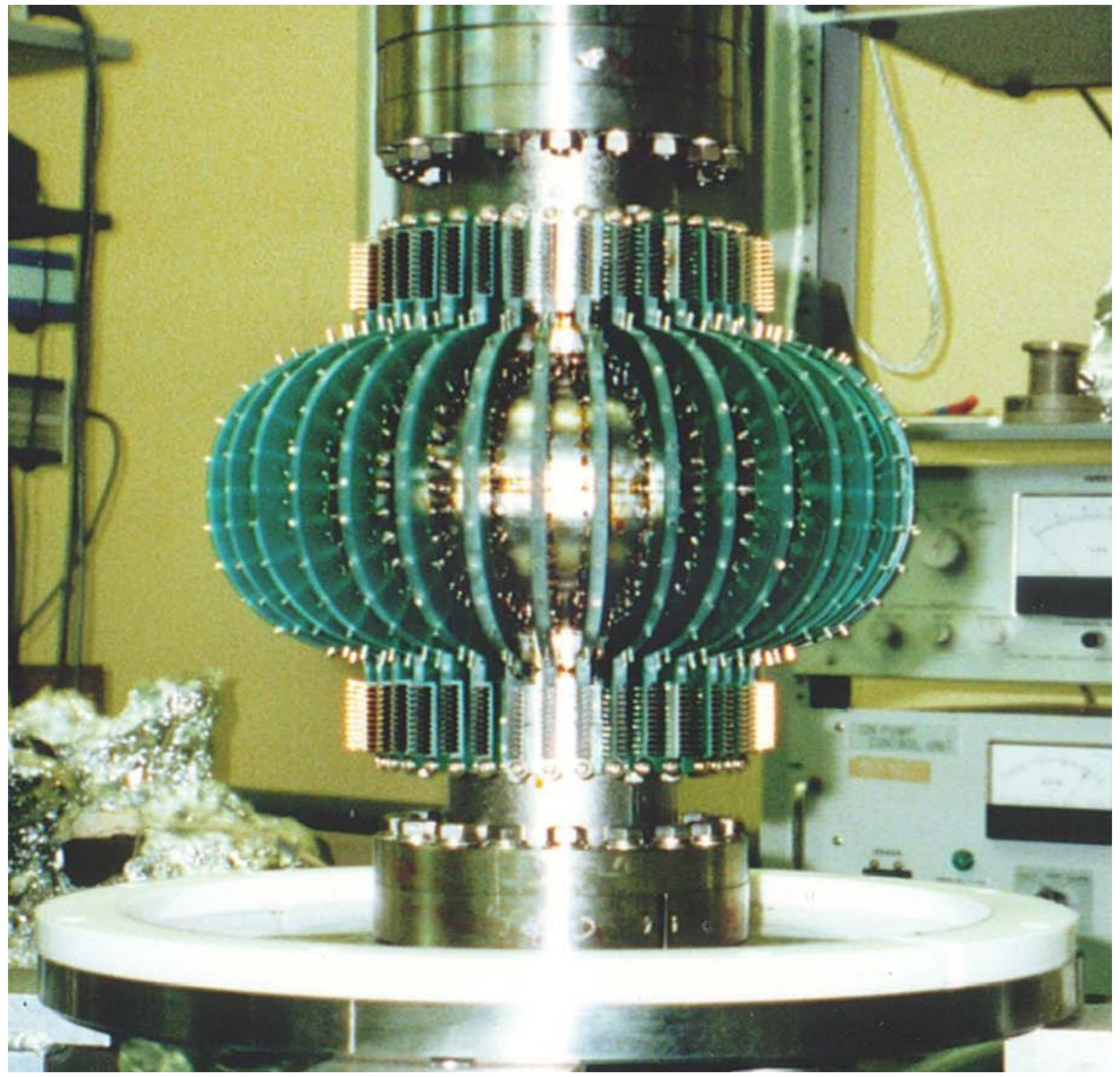
E_{acc} Limitations



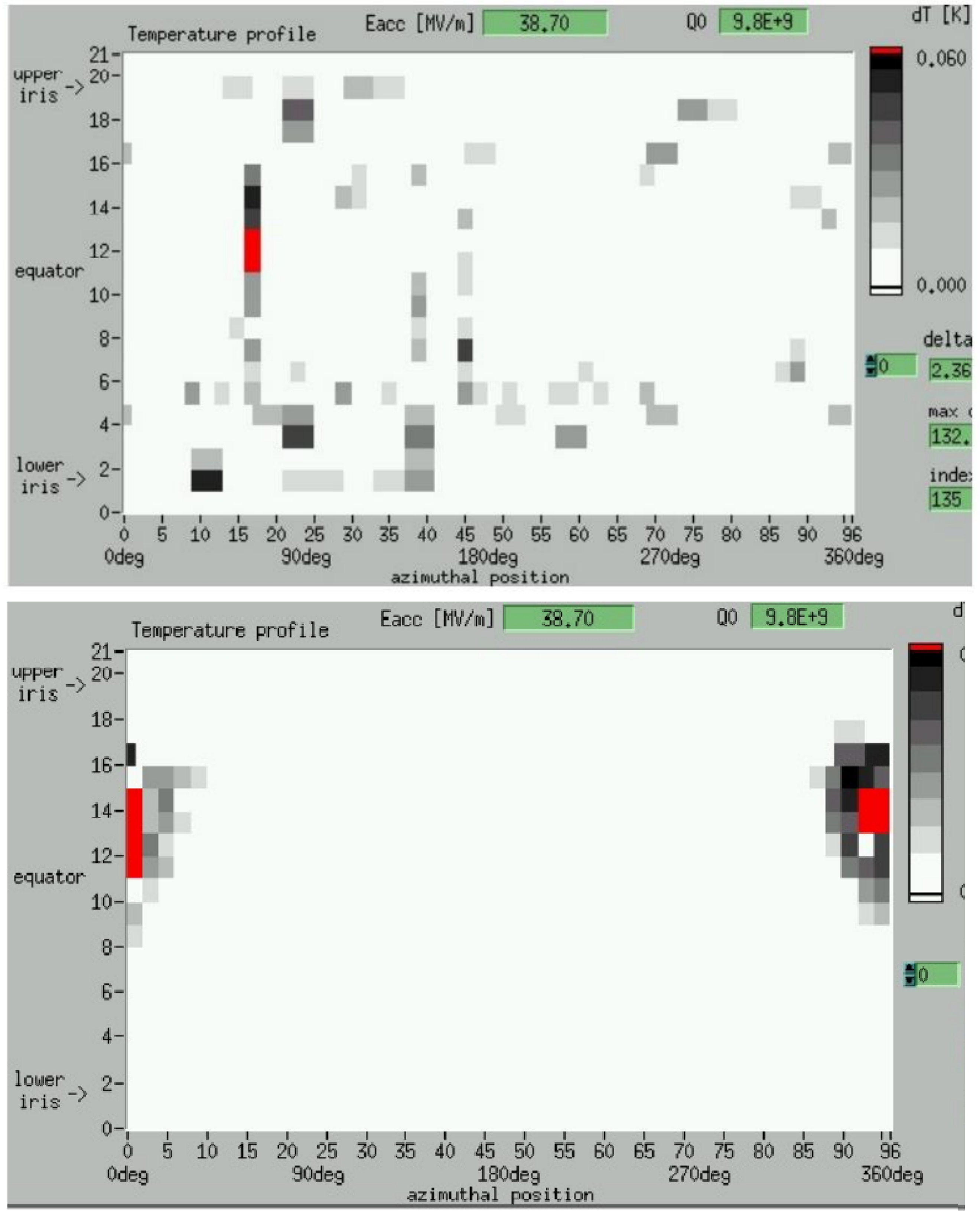
All degradations generate heat, concentrated on isolated areas, have regenerative feedback, and lower the E_{acc} limit.

[1] USPAS lecture notes, S. Belomestnykh, Lecture 1: Introduction, 2017(6)

Appearance: Hot Spots



T-map system in KEK [4]



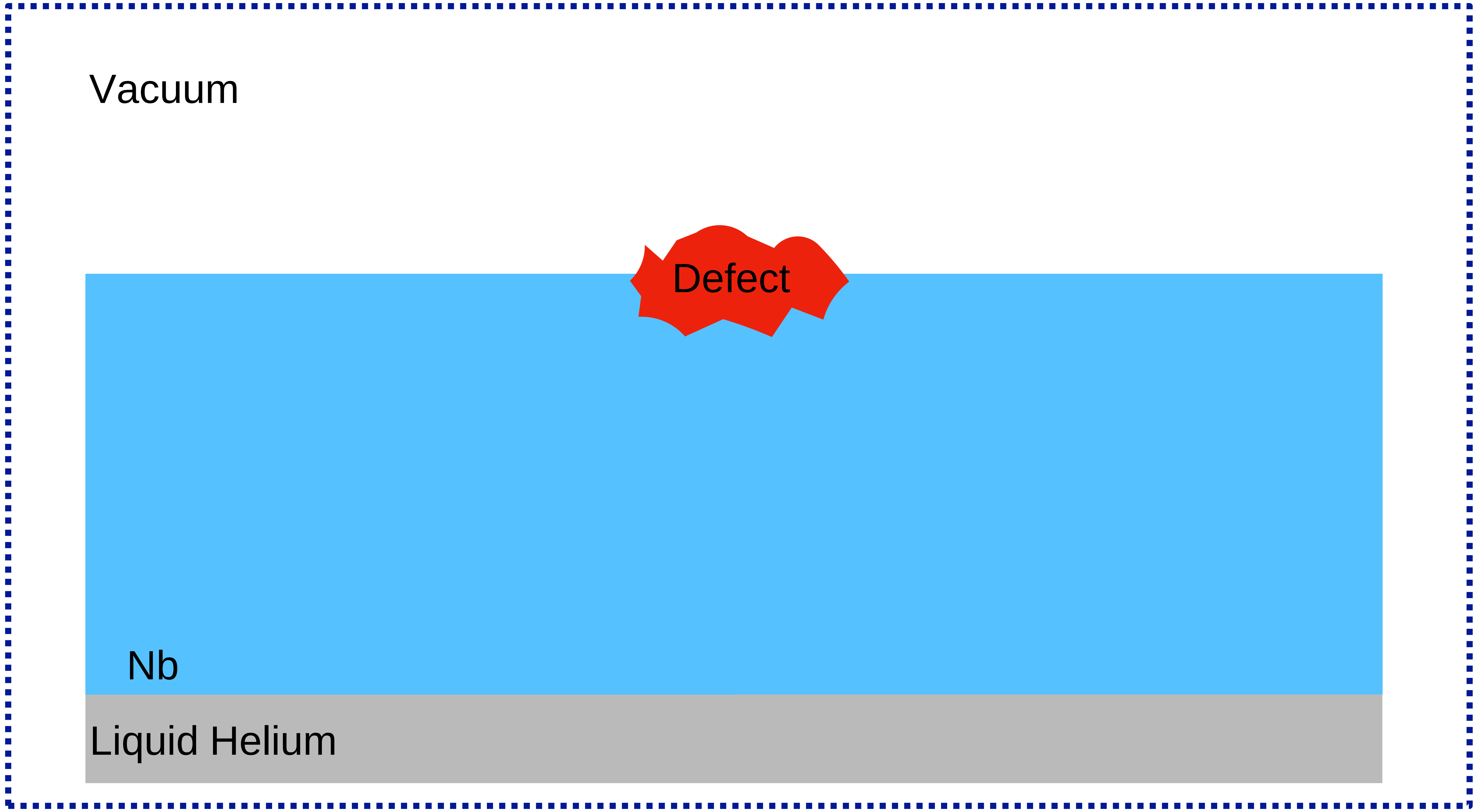
T-mapping for an SRF cavity before quench (up), and after quench (down) [3]

<u>All degradations generate heat, concentrated on isolated areas, have regenerative feedback, and lower the E_{acc} limit.</u>

[1] G. Eremeev and H. Padamsee, EPAC'06, Edinburgh, June 2006, MOPCH176.

[3] D. Reschke, "ANALYSIS OF QUENCHES USING TEMPERATURE MAPPING IN 1.3 GHz SCRF CAVITIES AT DESY", Proceedings of LINAC08, Victoria, BC, Canada, THP016

Appearance: Hot Spots



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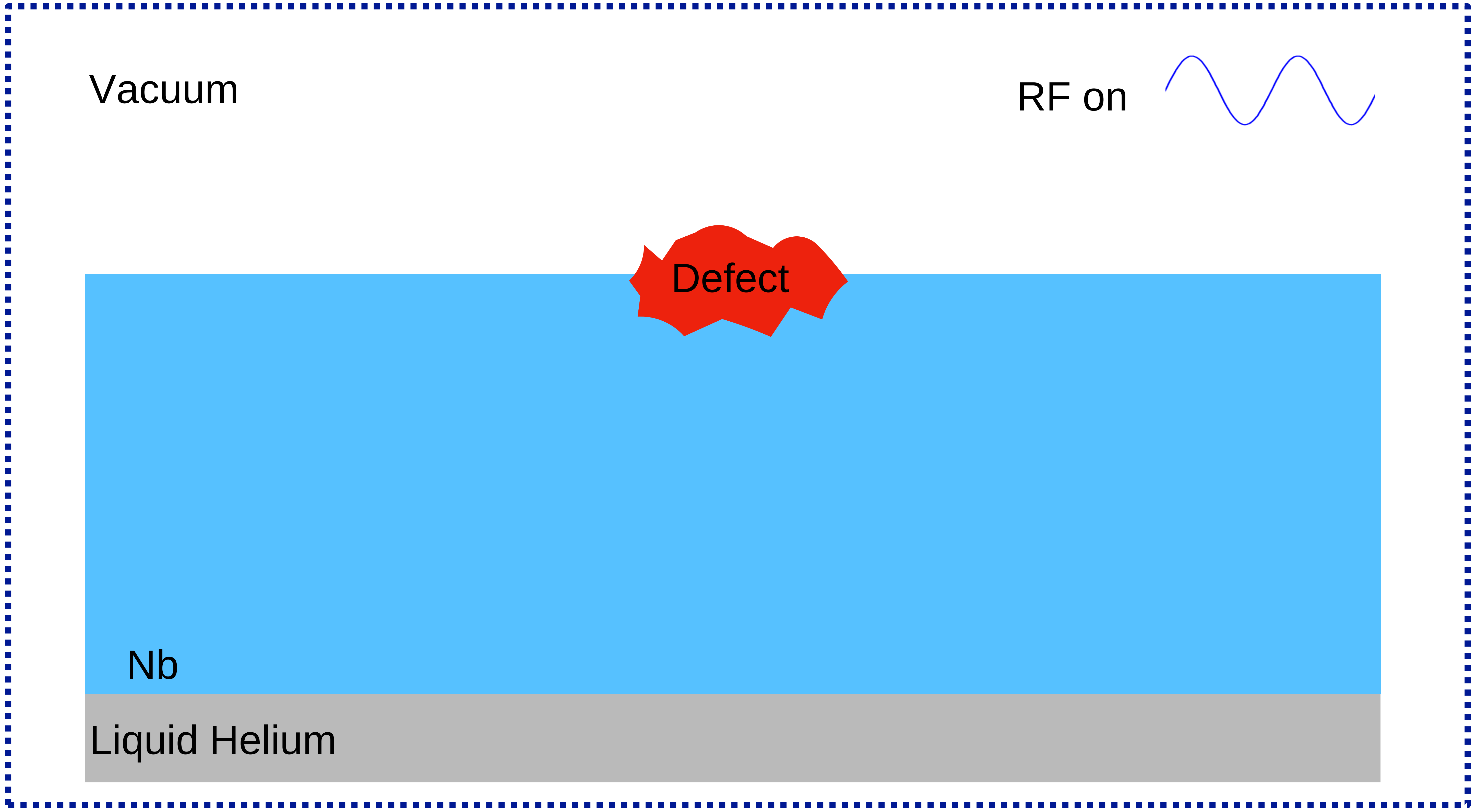

Appearance: Hot Spots

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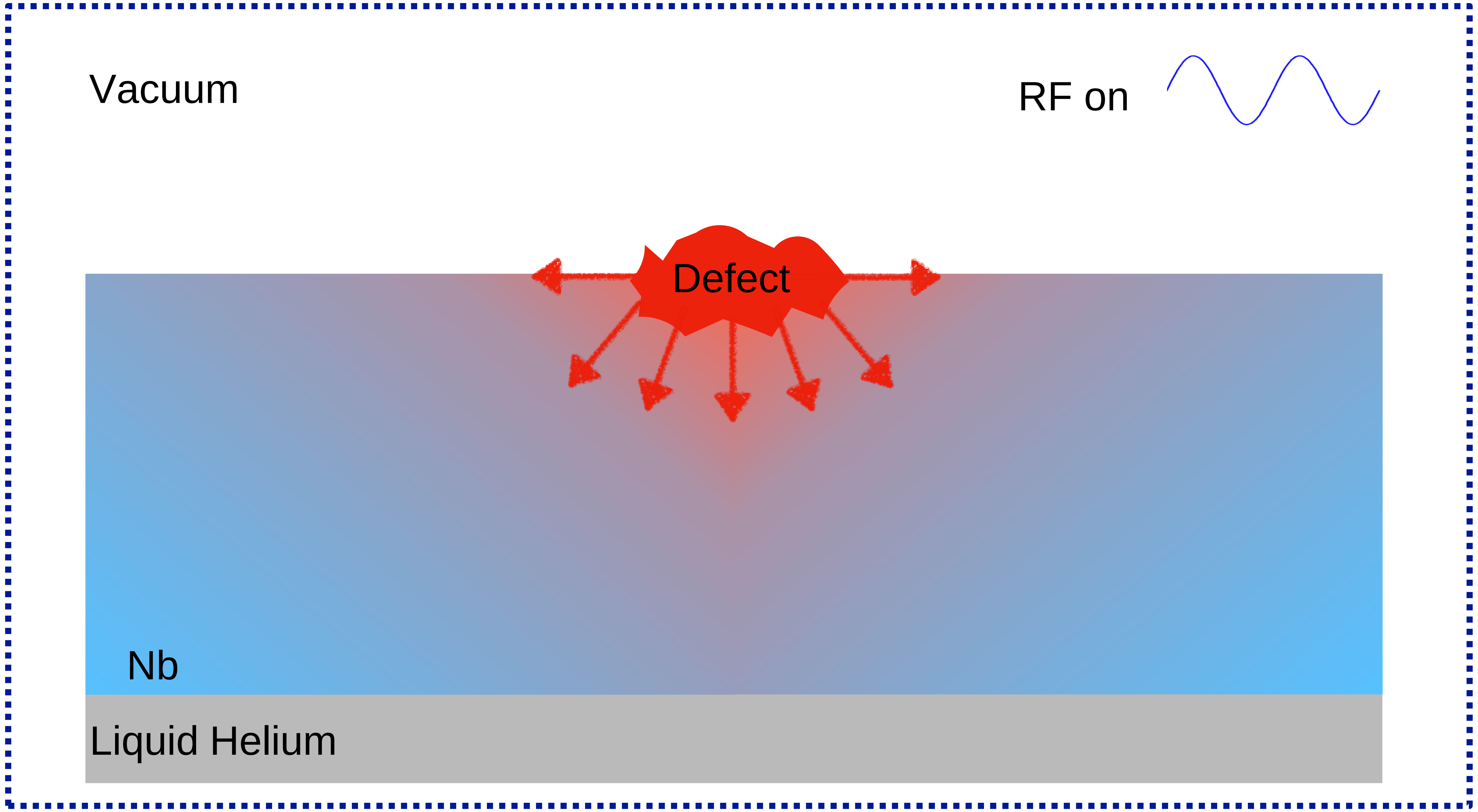
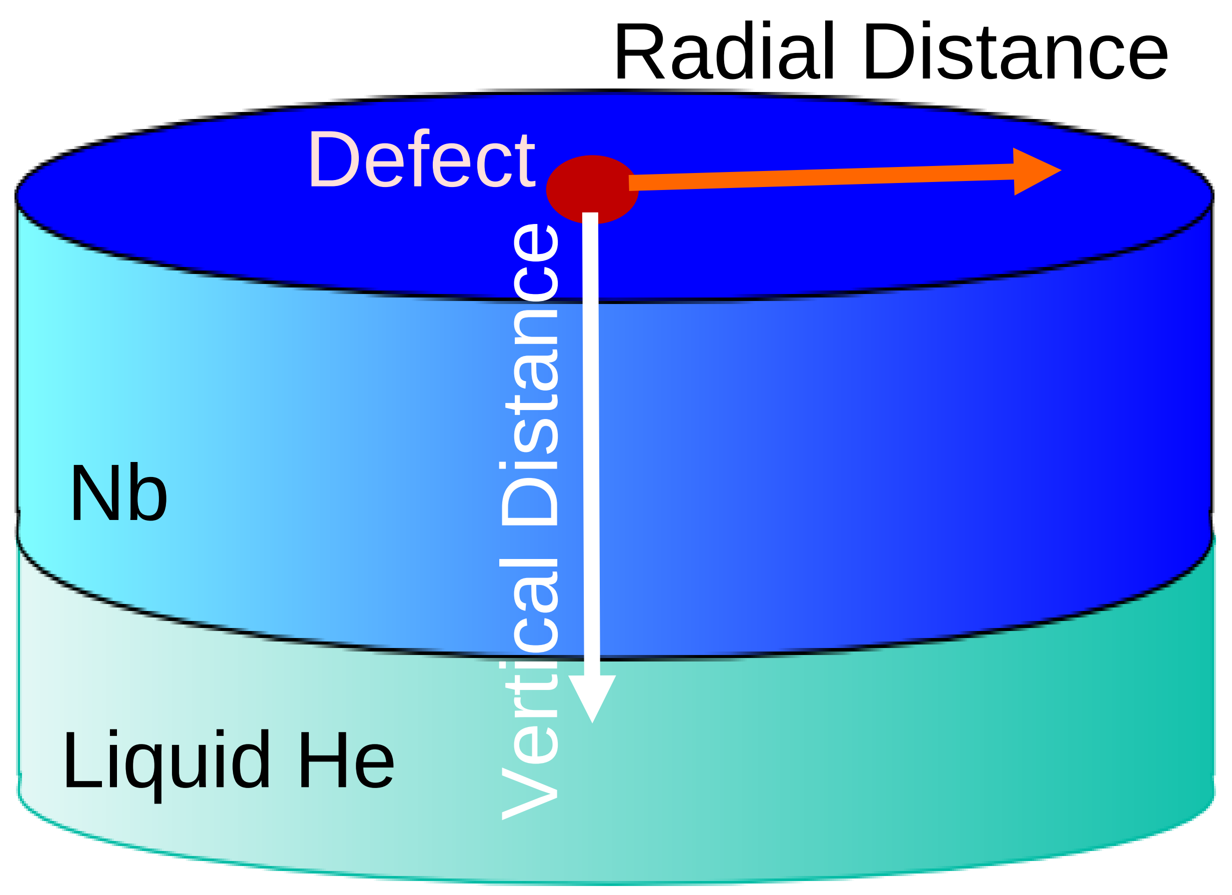
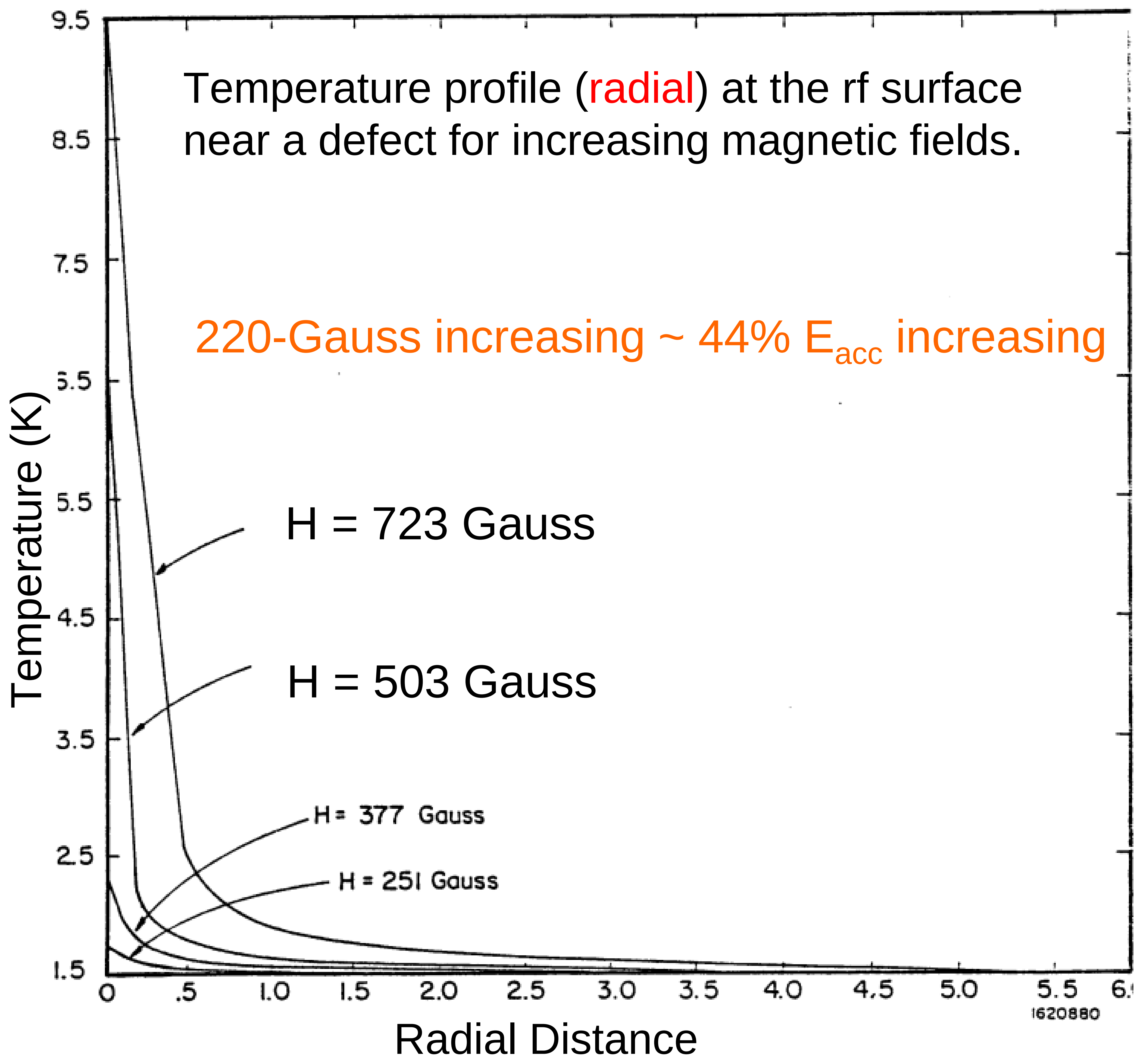


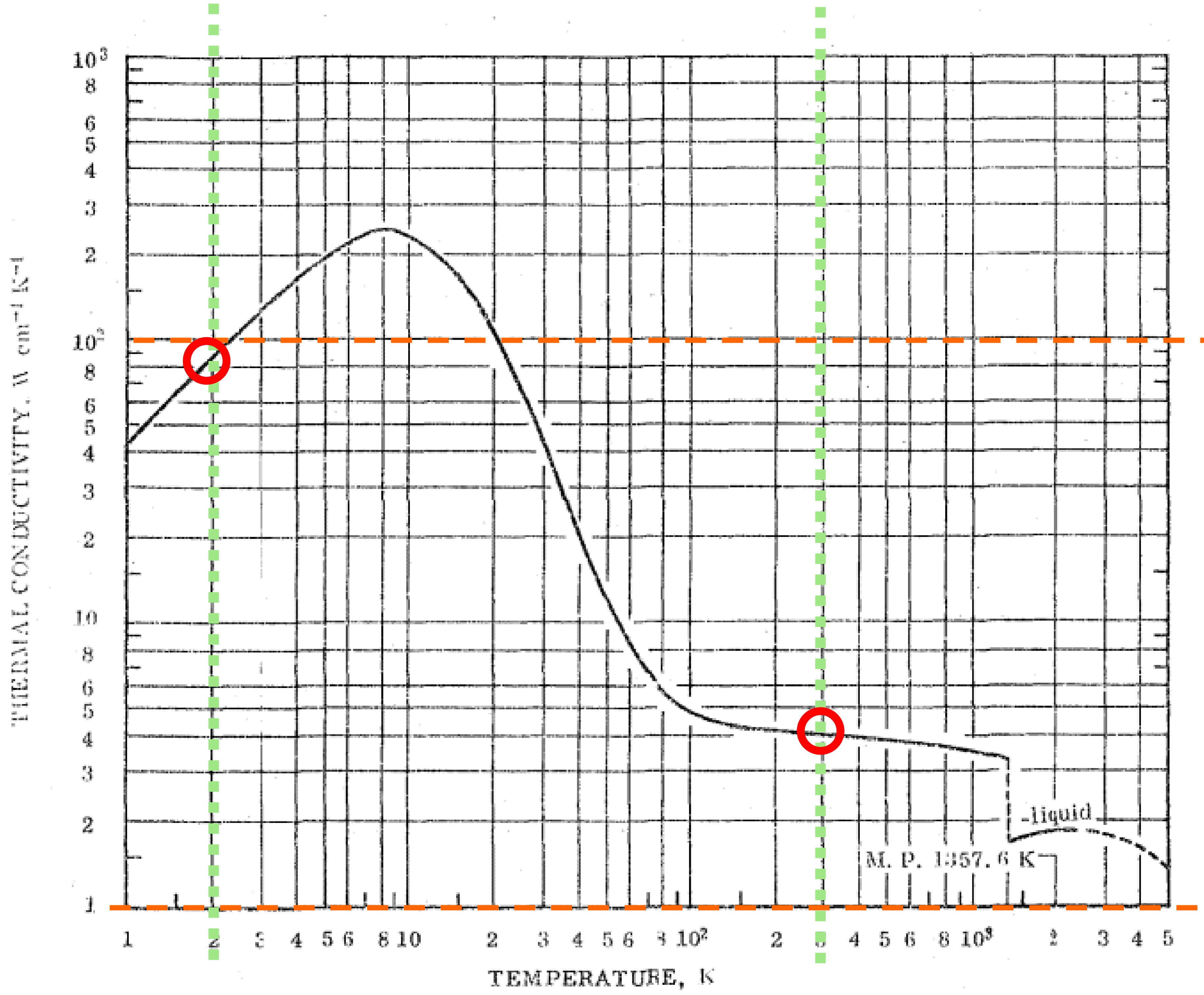
Temperature Distributions and Defects





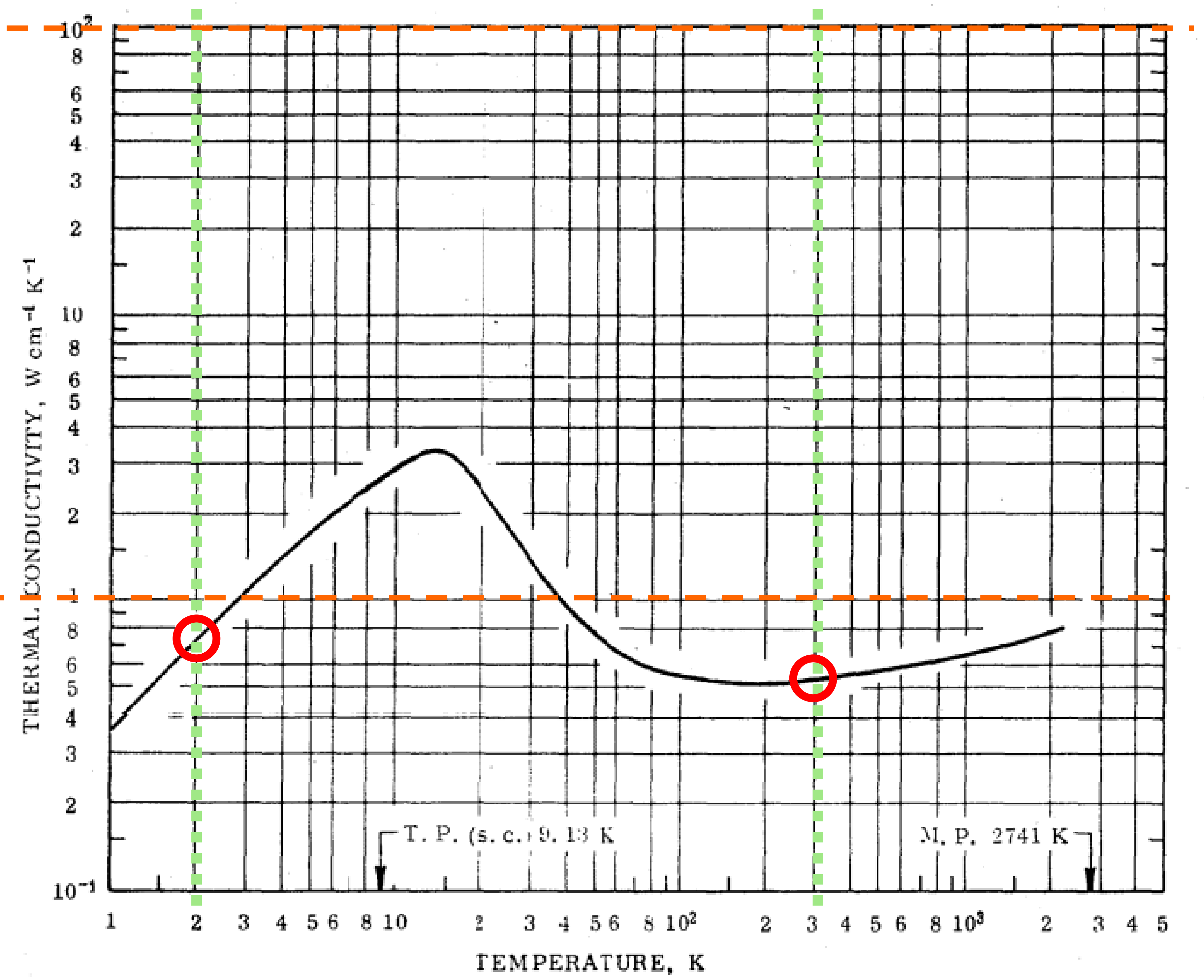
[1] H. Padamsee, HEAT TRANSFER AND MODELS FOR BREAKDOWNhttps://epaper.kek.jp/srf80/papers/srf80-7.pdf

Temperature Distributions and Defects



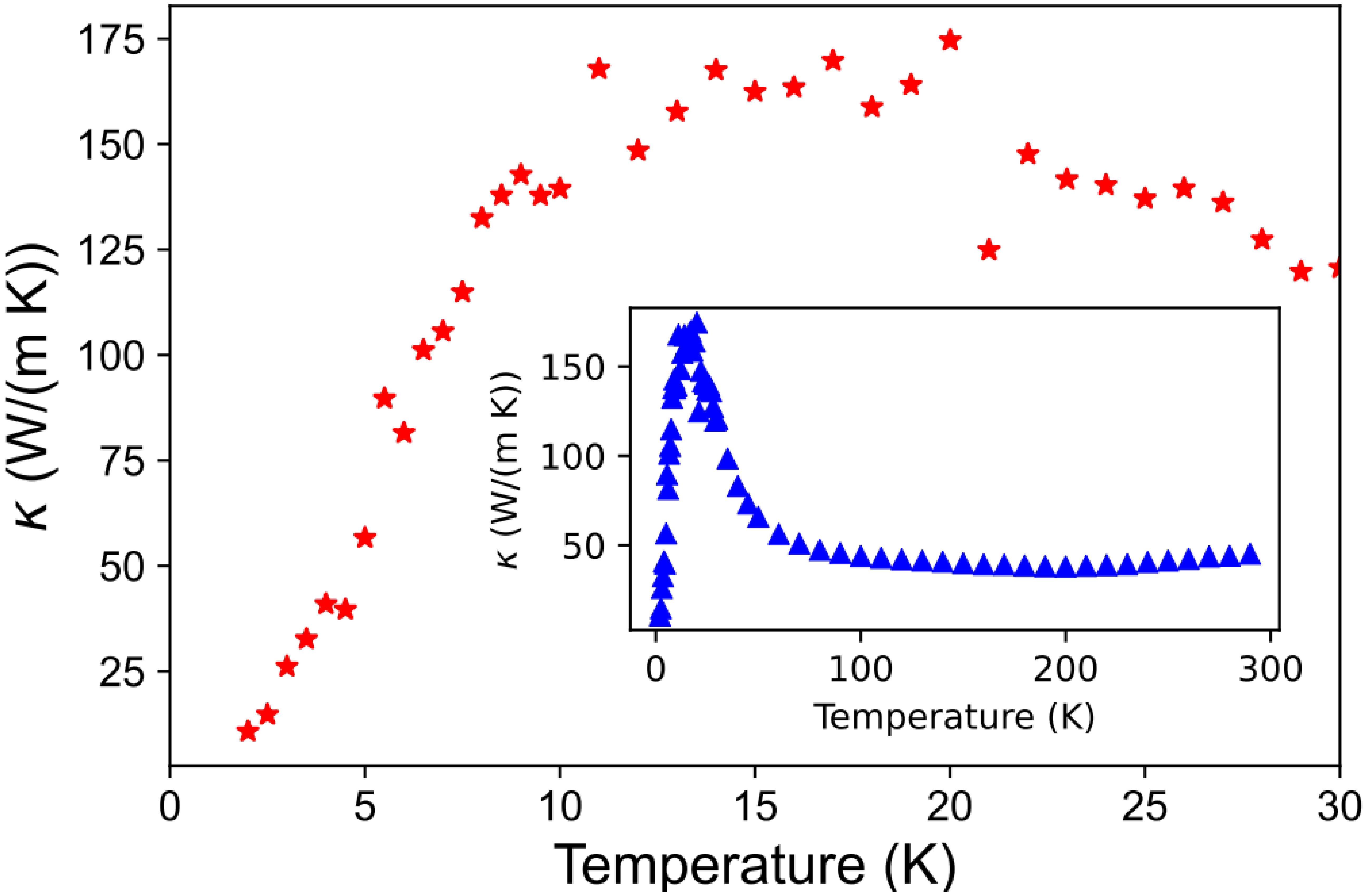
Thermal conductivity κ of Cu:
400 W/(mK) @300K, 8400 W/(mK) @2K

Thermal conductivity κ of Nb:
54 W/(mK) @300K, 70 W/(mK) @2K



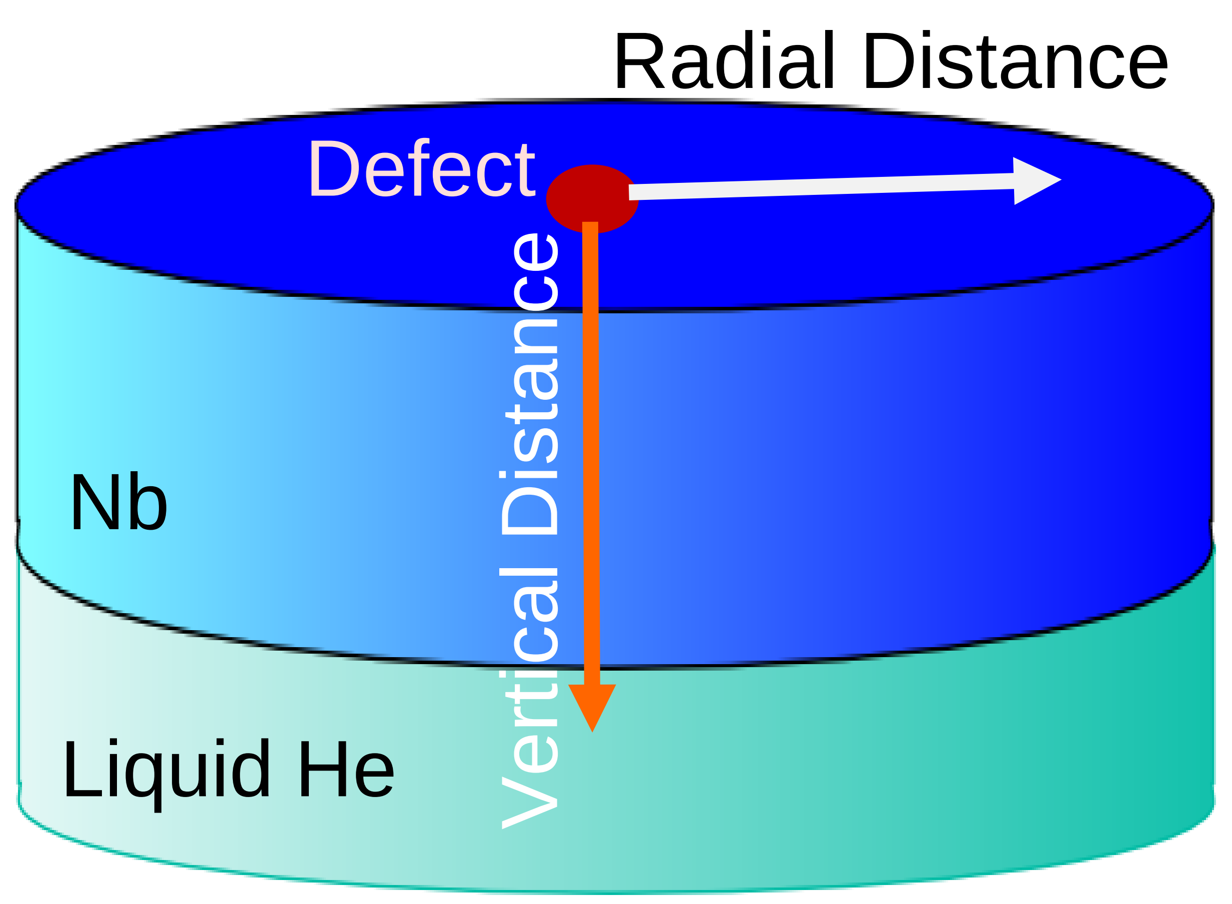
[1] C. Y. Ho, R. W. Powell, and P. E. Liley, Journal of Physical and Chemical Reference Data 1, 279 (1972)

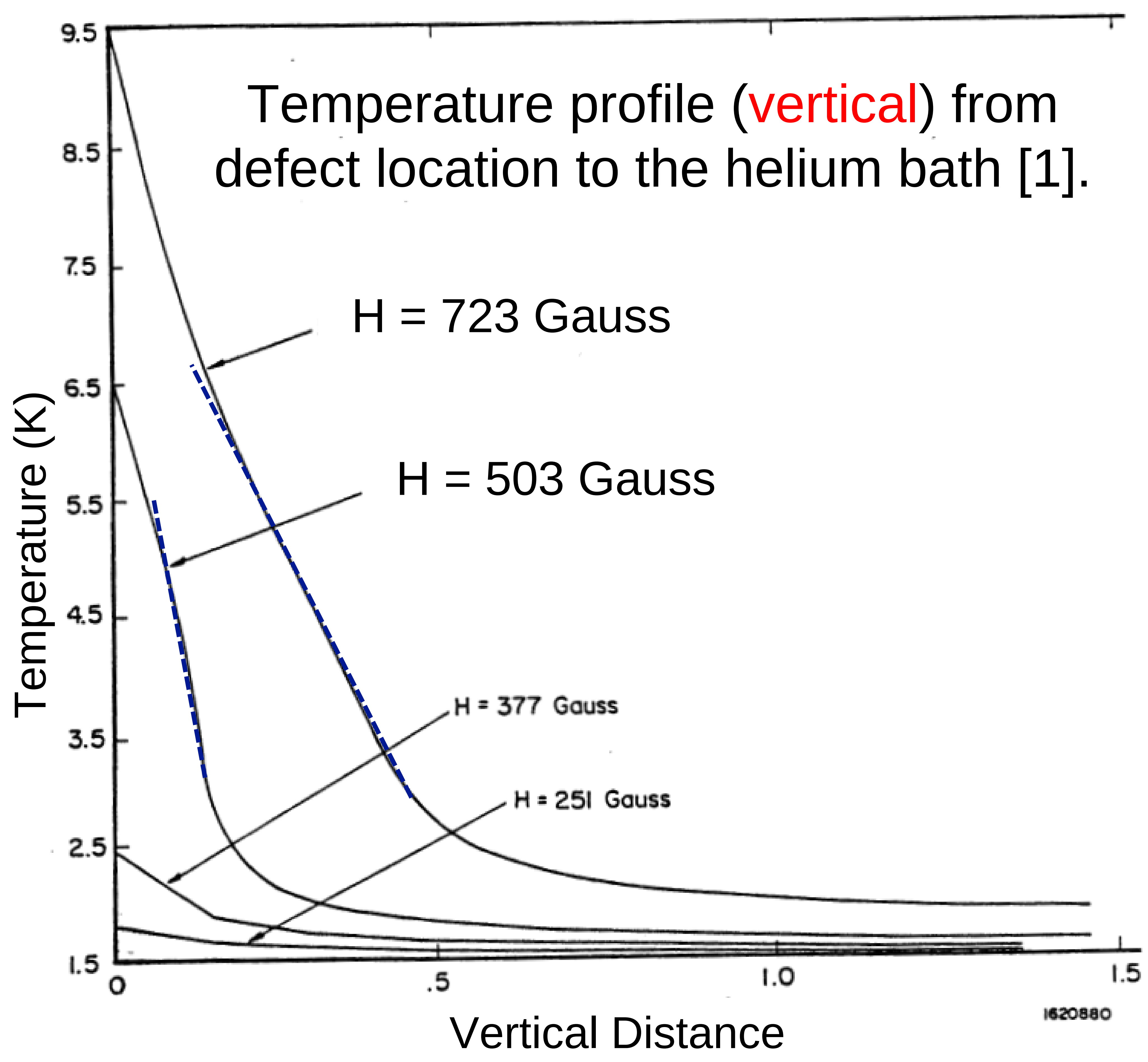
Temperature Distributions and Defects



Thermal conductivity of RRR = 300 samples after BCP and annealing @ IMP.

Temperature Distributions and Defects





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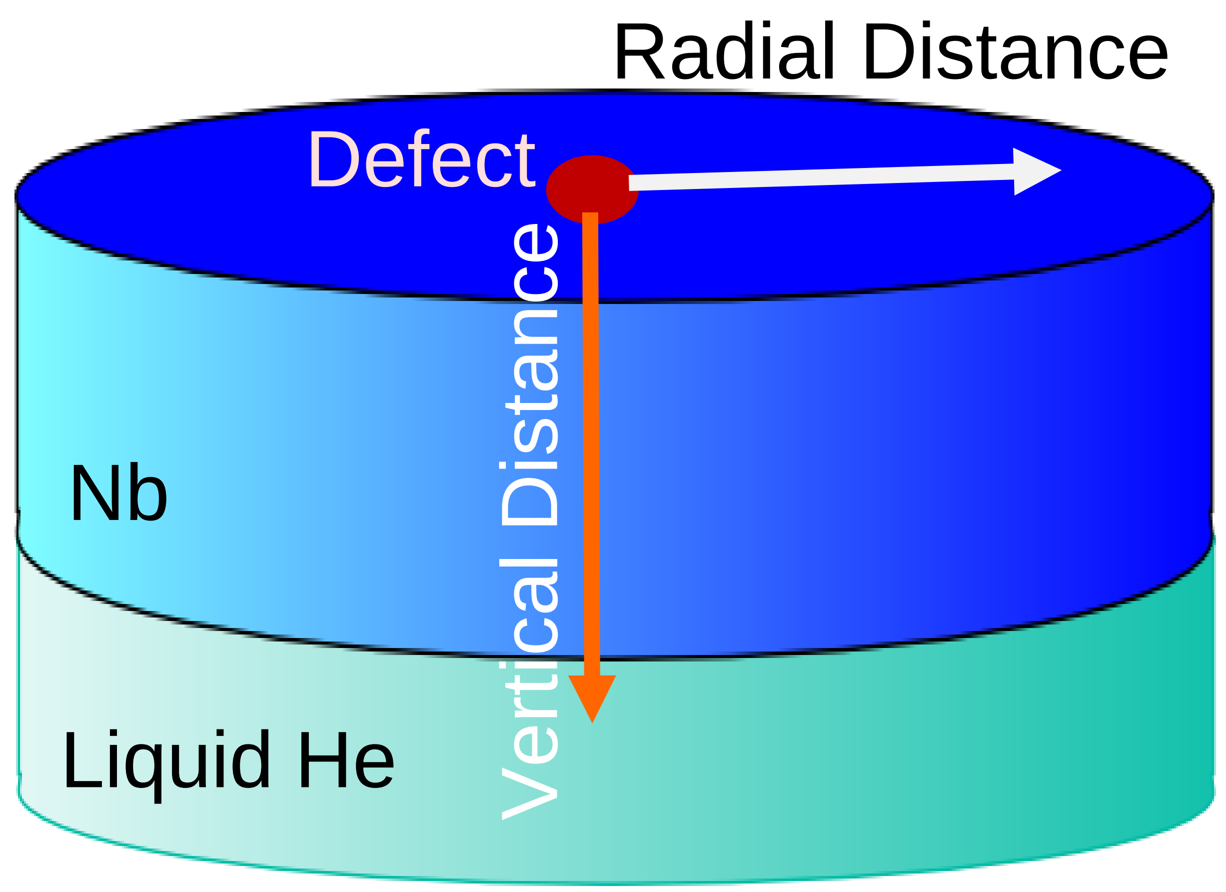

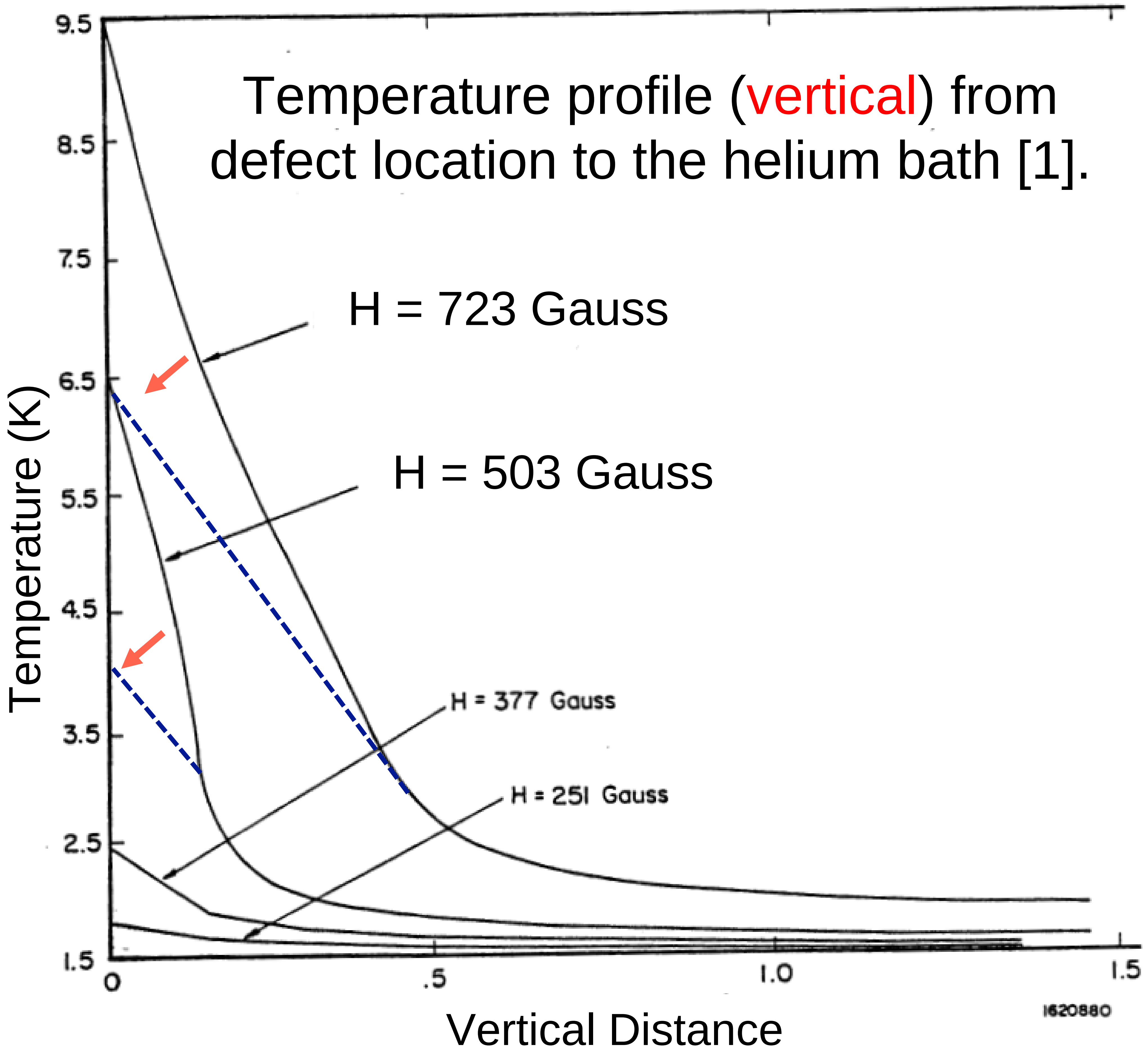

Increase thermal conductivity κ

Decrease center T

Increase E_{acc} limit

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Temperature Distributions and Defects

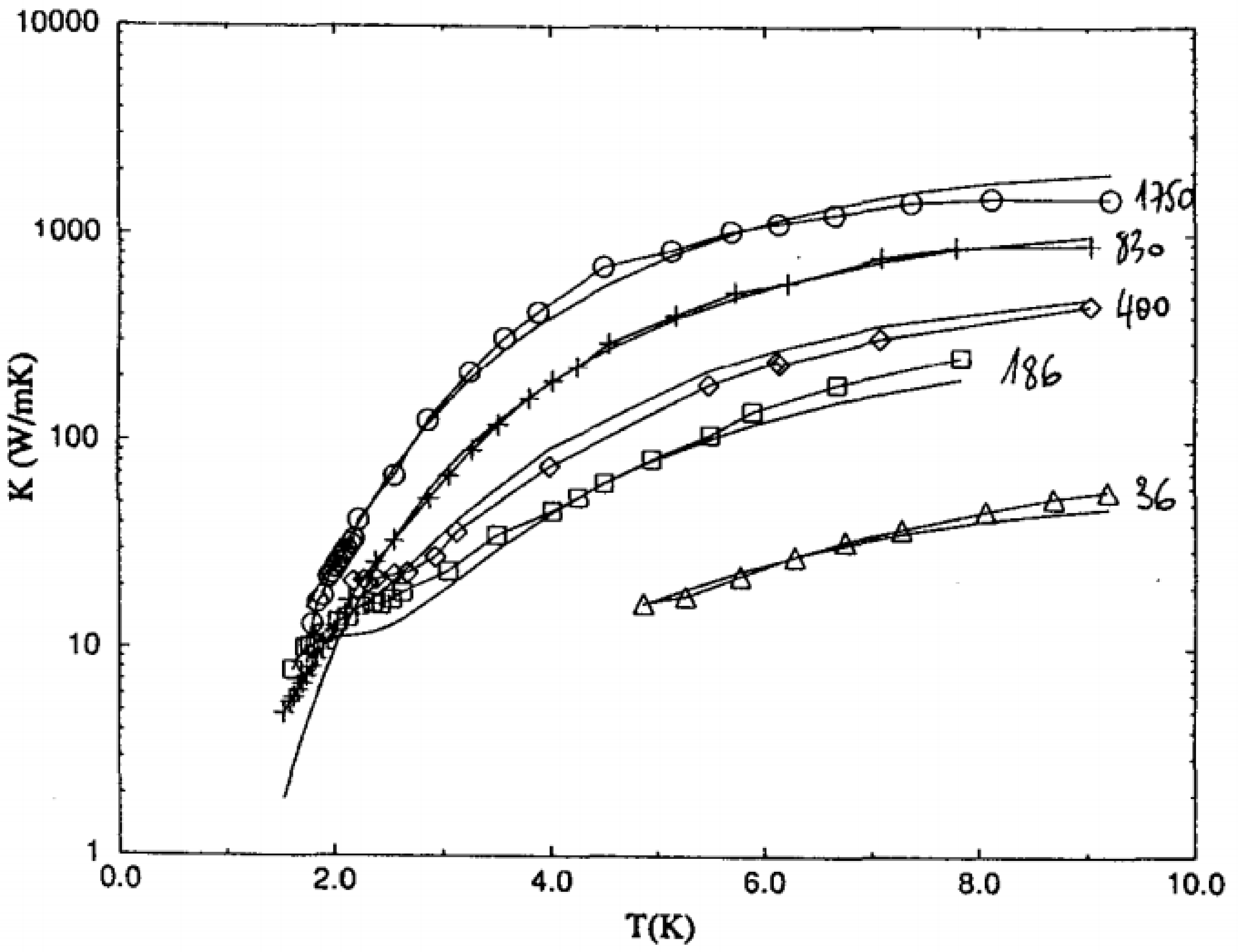
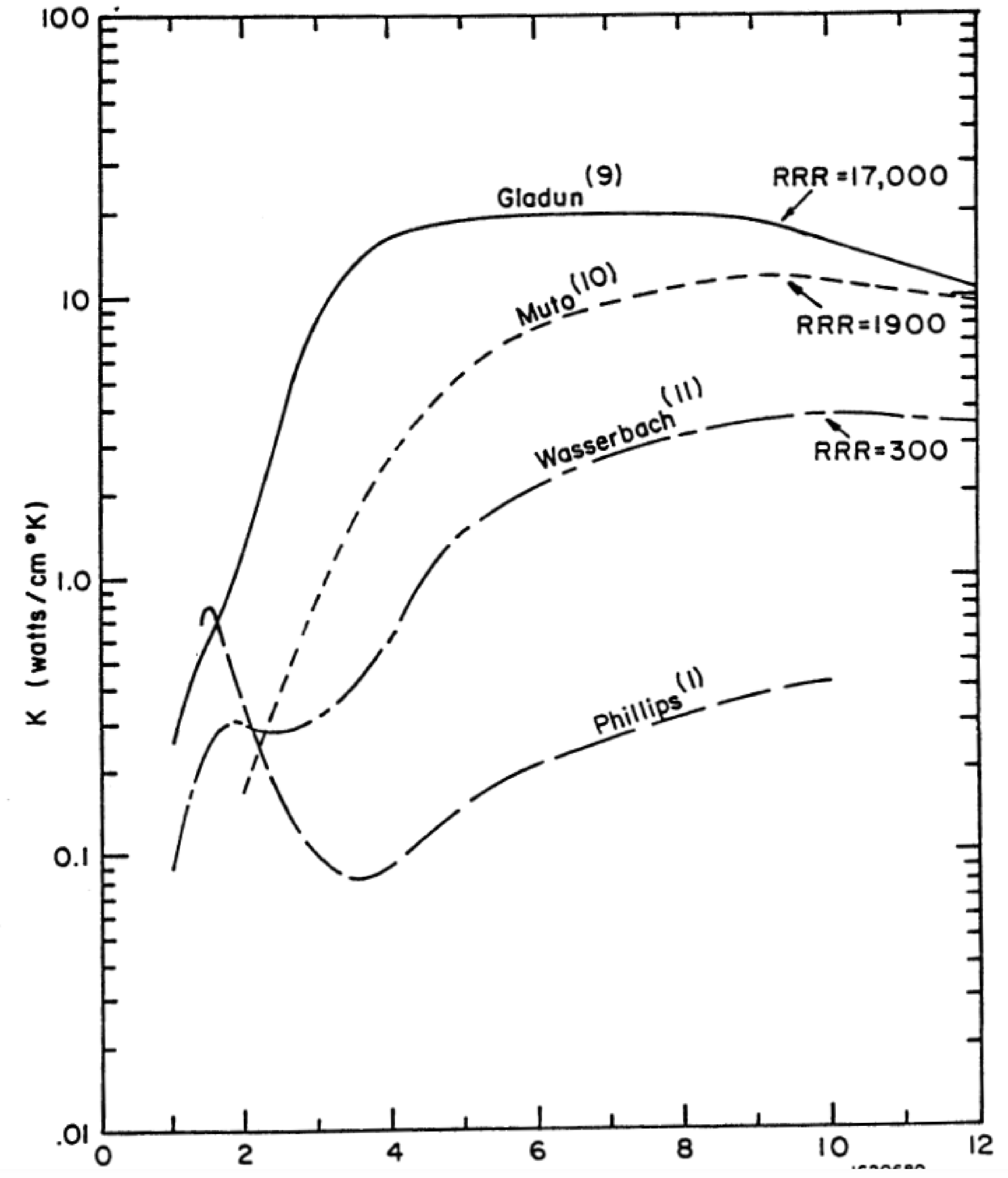


Figure 2 : Comparison of calculated curves K(T) with the best fitted parameters (full line), with experimental plots (line joining symbols), for typical RRR values. [1]



Thermal conductivities of four Nb samples with different residual resistivity ratios (R.R.R.), showing the effect of impurities on the thermal conductivity of Nb. [2]

[1] F.Koechlin, PARAMETRISATION OF THE Nb THERMAL CONDUCTIVITY IN THE SUPERCONDUCTING STATE, SRF 1995
[2] H. Padamsee, HEAT TRANSFER AND MODELS FOR BREAKDOWN, https://epaper.kek.jp/srf80/papers/srf80-7.pdf

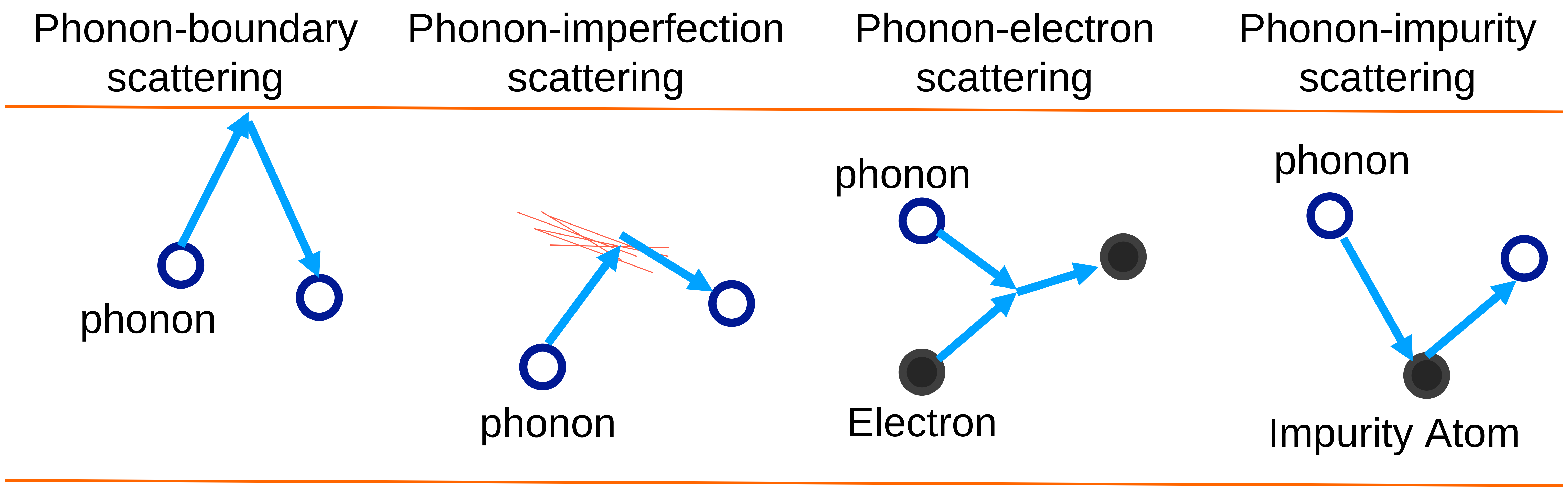
Temperature Distributions and Defects

$\kappa = 1/3\ cv\ell$

c: specific heat

v: phonon velocity

ℓ: phonon mean free path



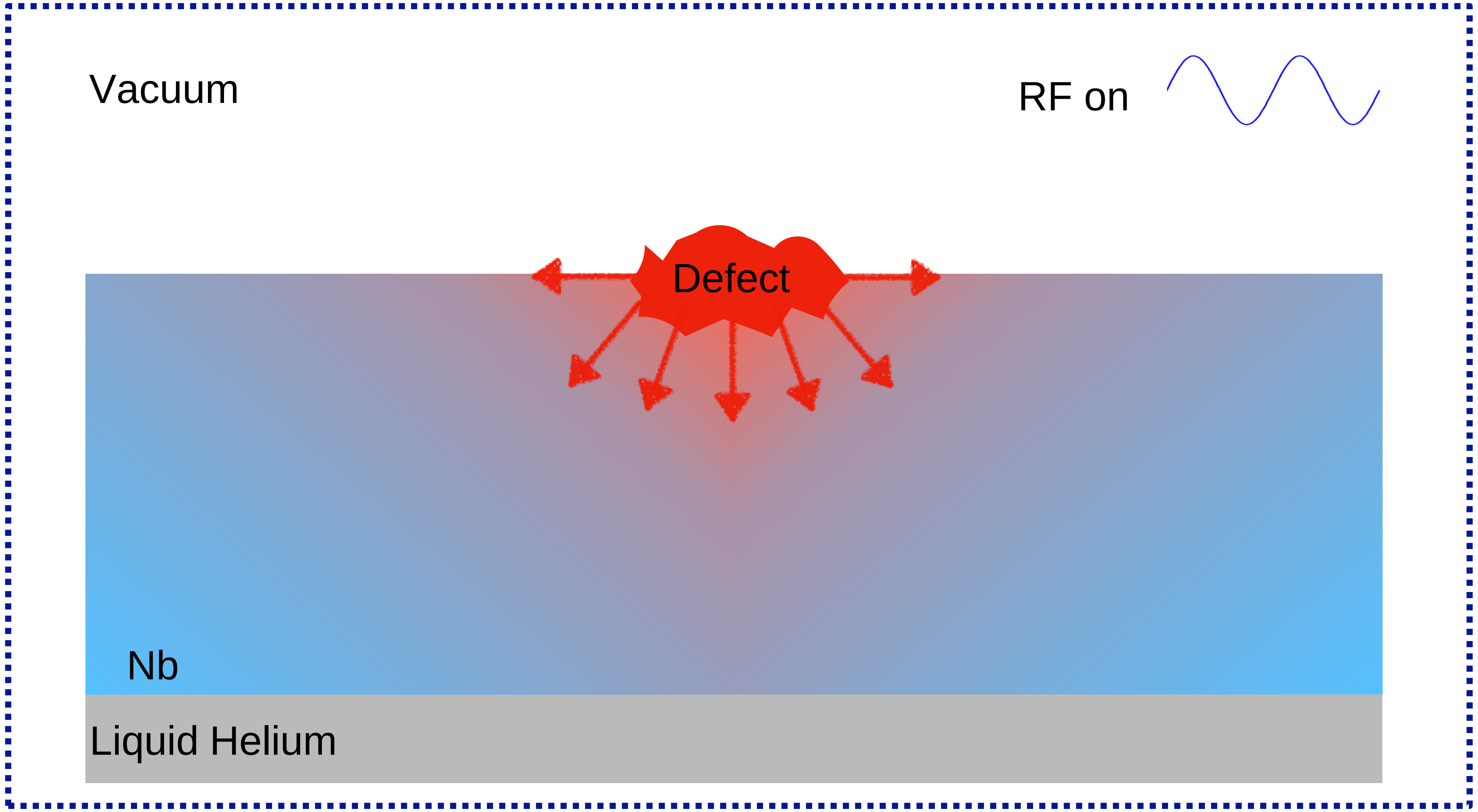
T-dependence of the lattice thermal conductivity κ (~ $cv\ell$)

- Low T: $\kappa \sim c \sim T^3$
- High T: $\kappa \sim \ell \sim 1/T$

[1] Solid State Physics, C. Kittel, p.122

Increase RRR to increase κ

1. EP/BCP/HPR/Plasma cleaning to remove defects
2. Increase thermal conductivity κ



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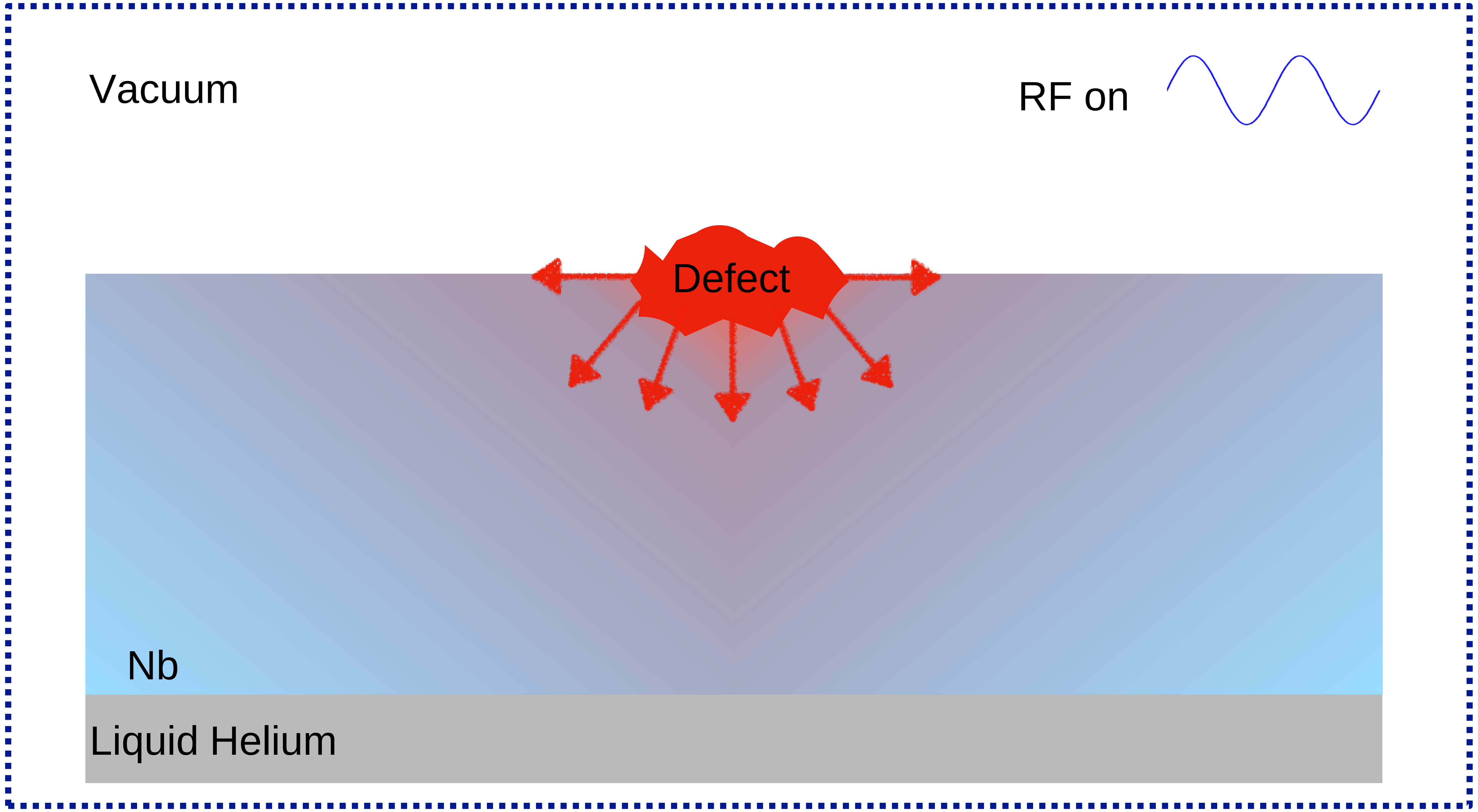
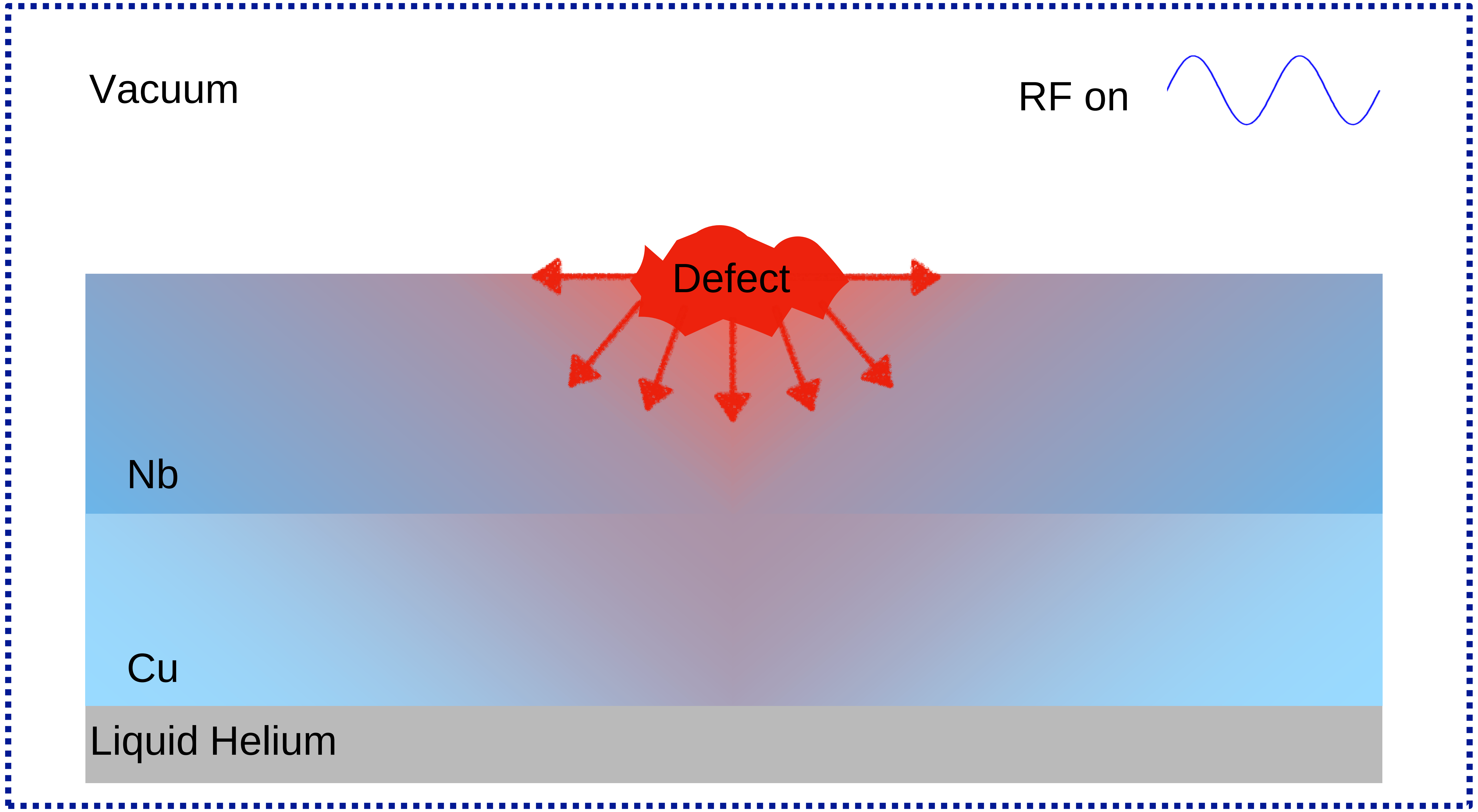


Cu-clad Cavity

1. EP/BCP/HPR/Plasma cleaning to remove defects
2. Increase thermal conductivity κ
3. Add high κ material outside: Cu-clad cavity



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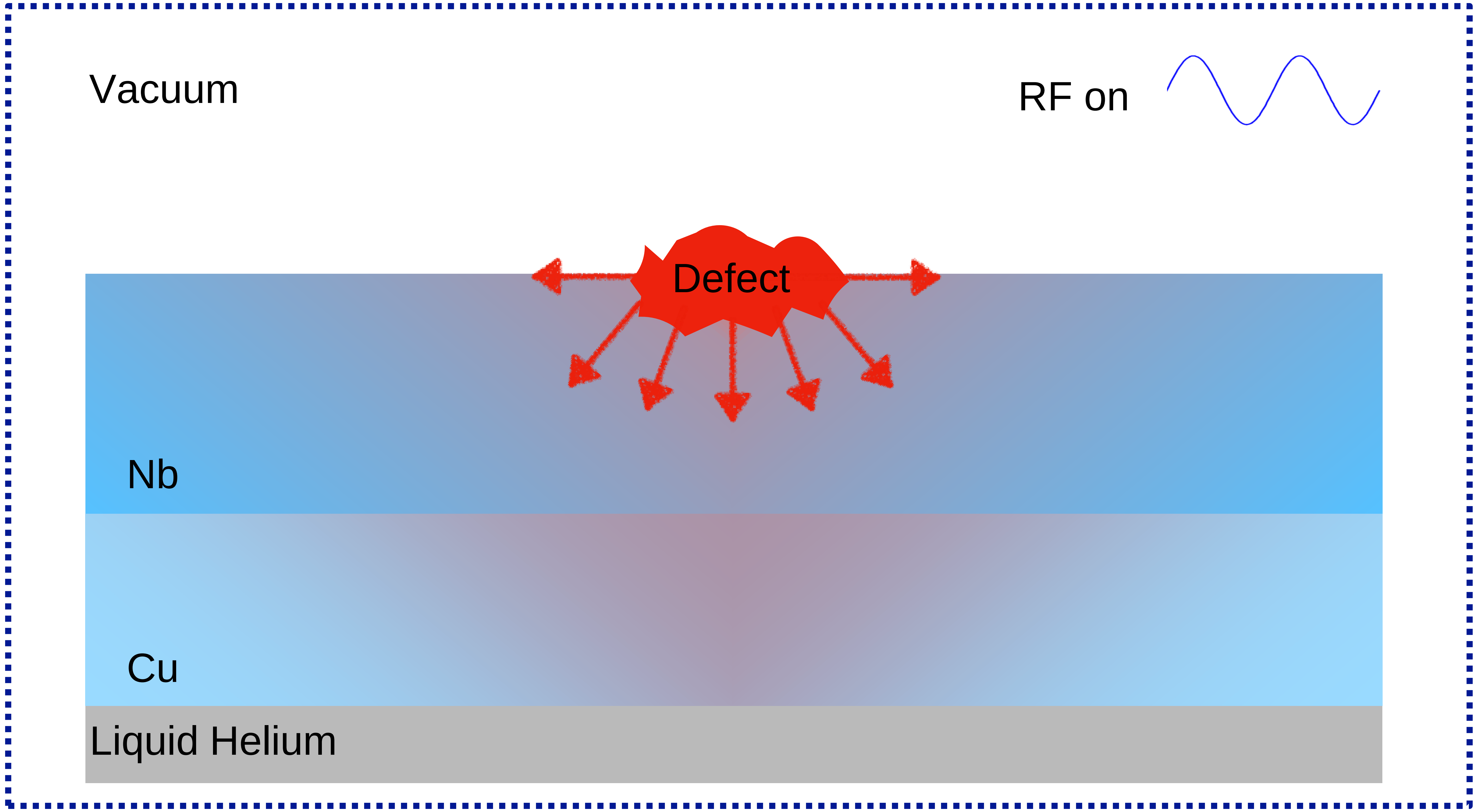
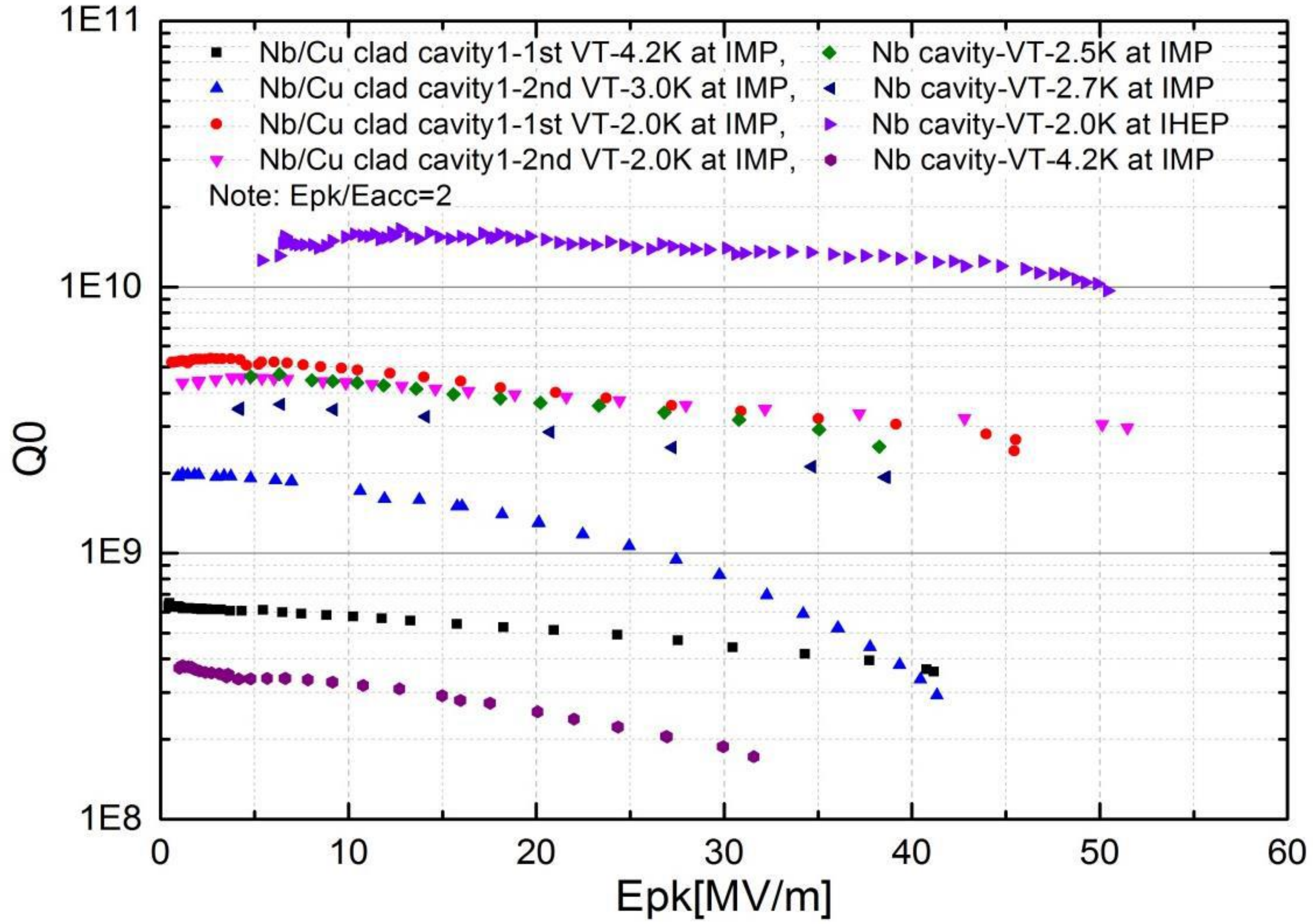


Increase κ: Cu-clad cavity, thin-shell cavity

Cu-clad cavity



IMP thin-shell cavity with fixtures

Medium Field Q Slope

The Halbritter Model:

$$Q(B) = \frac{\Gamma}{R_{s0}}\left[1 - \gamma\left(\frac{B}{B_c}\right)^2 + O(B)^4\right]$$

Medium Field Q-slope:

$$\gamma = \frac{B_c^2}{2\mu_0^2}\frac{\Delta}{k_B T_b^2} R_{BCS}(T_b)\left(\frac{d}{\kappa} + \frac{1}{H_k}\right)$$

R_{s0}: surface resistance at small magnetic fields； B_c = 0.2 T: thermodynamic critical field of niobium； B: peak surface magnetic field； μ_0 is the magnetic permeability, Δ is the superconductor energy gap, k_B is the Boltzmann constant, T_b is the helium bath temperature, $R_{BCS}(Tb)$ is the niobium BCS resistance at the helium bath temperature, d is the cavity wall thickness, κ is the thermal conductivity, and H_k is the Kapitza conductance between niobium and the liquid helium.

$$\kappa_s(T, RRR, l) = R(y)\left[\frac{1}{A\,RRR\,T} + aT^2\right]^{-1} + \left[\frac{1}{DT^2 e^y} + \frac{1}{BlT^3}\right]^{-1} \qquad (39)$$

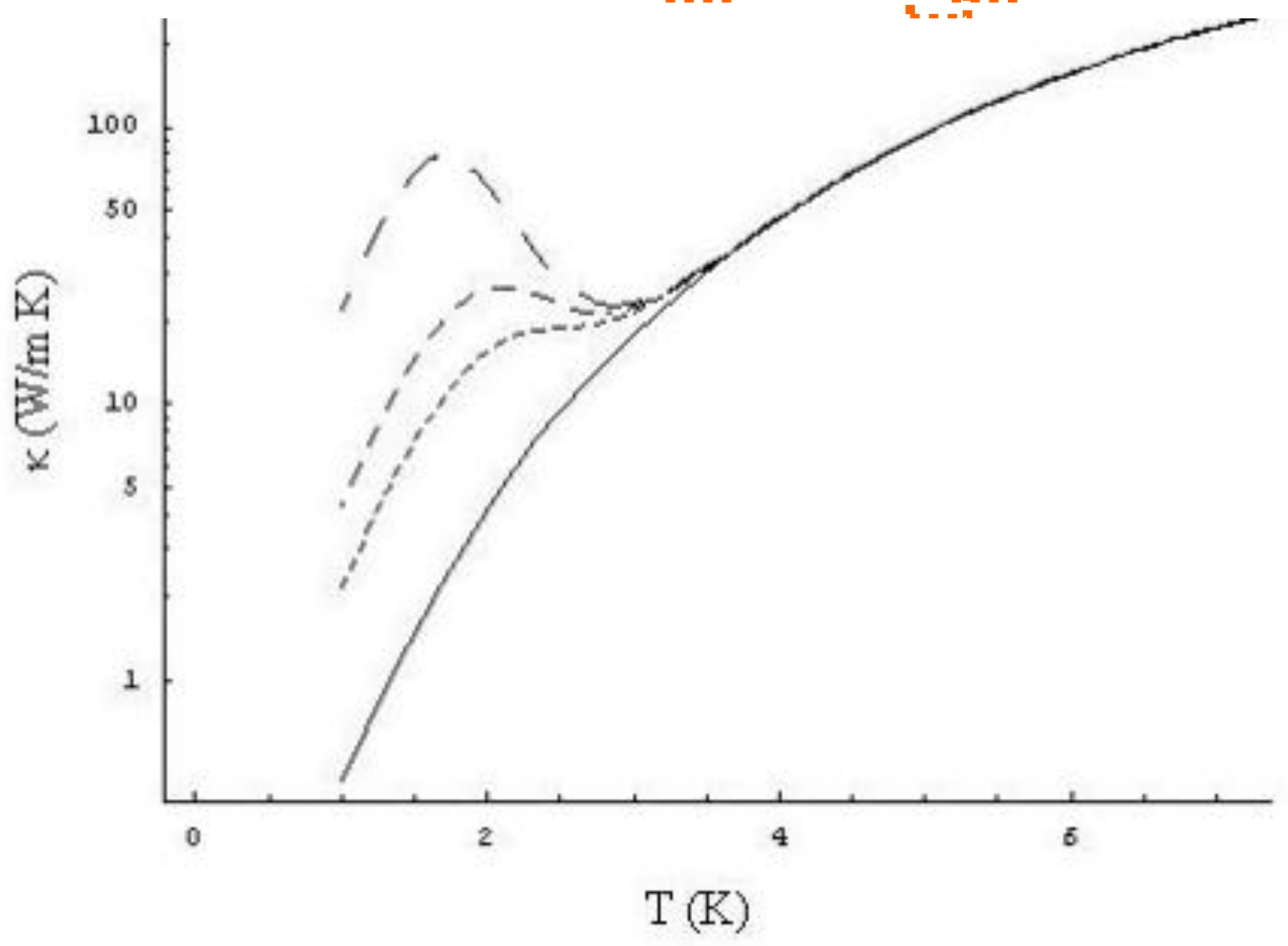
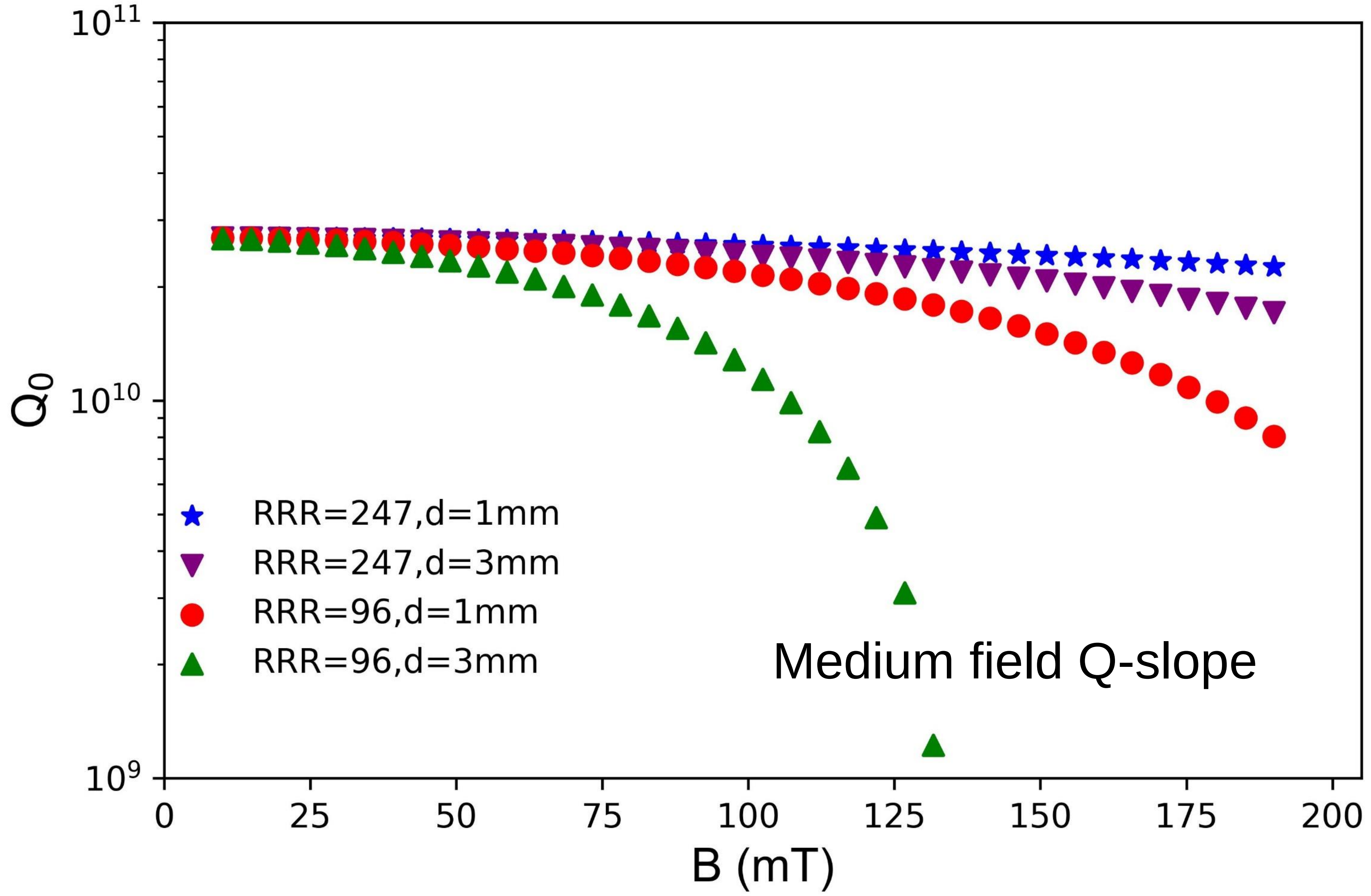


Figure 2: Thermal conductivity versus temperature for RRR = 300 and l = 0.1 mm (solid), 0.5 mm (short dashed), 1.0 mm (medium dashed), and 5.0 mm (long dashed). [2]

[1] J. Halbritter, rf residual losses, surface impedance, and granularity in superconducting cuprates,
[2] J. Vines, Y. Xie, H. Padamsee, Systematic trends for the medium field q-slope, in: Proceedings o
[3] F. Koechlin, B. Bonin, Parametrization of the niobium thermal conductivity in the superconducting state, Superconductor Science and Technology 9 (1996) 453–460

IMP 1 mm thin-shell cavities

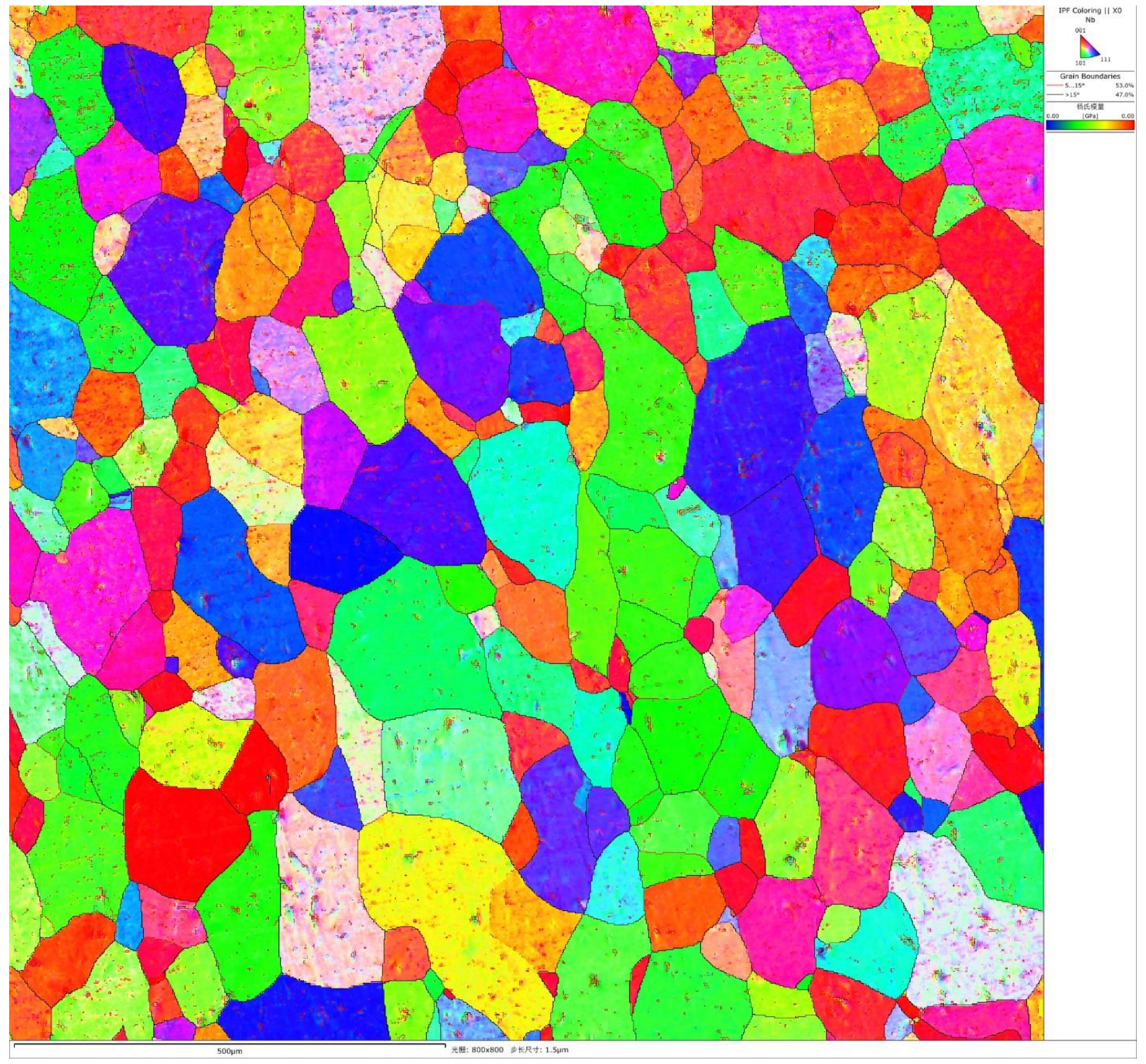
Calculated results using the Halbritter Model.



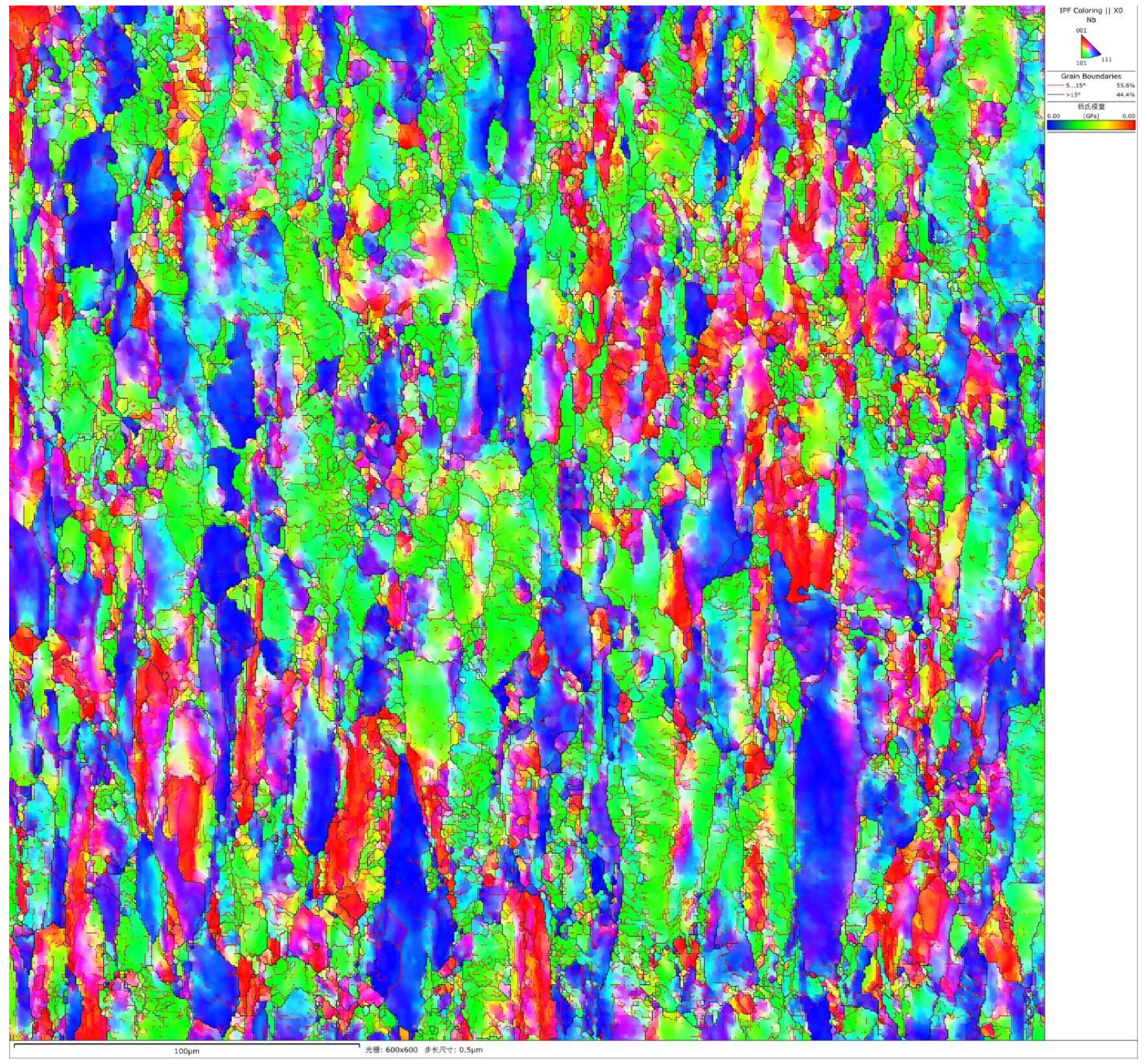
Parameters for IMP 1-mm Cavity

RRR	RRR Measured	Grain Size (l)
300	247	$65.9 \pm 44.8\ \mu m$
40	96	$5.5 \pm 6.1\ \mu m$

EBSD Results



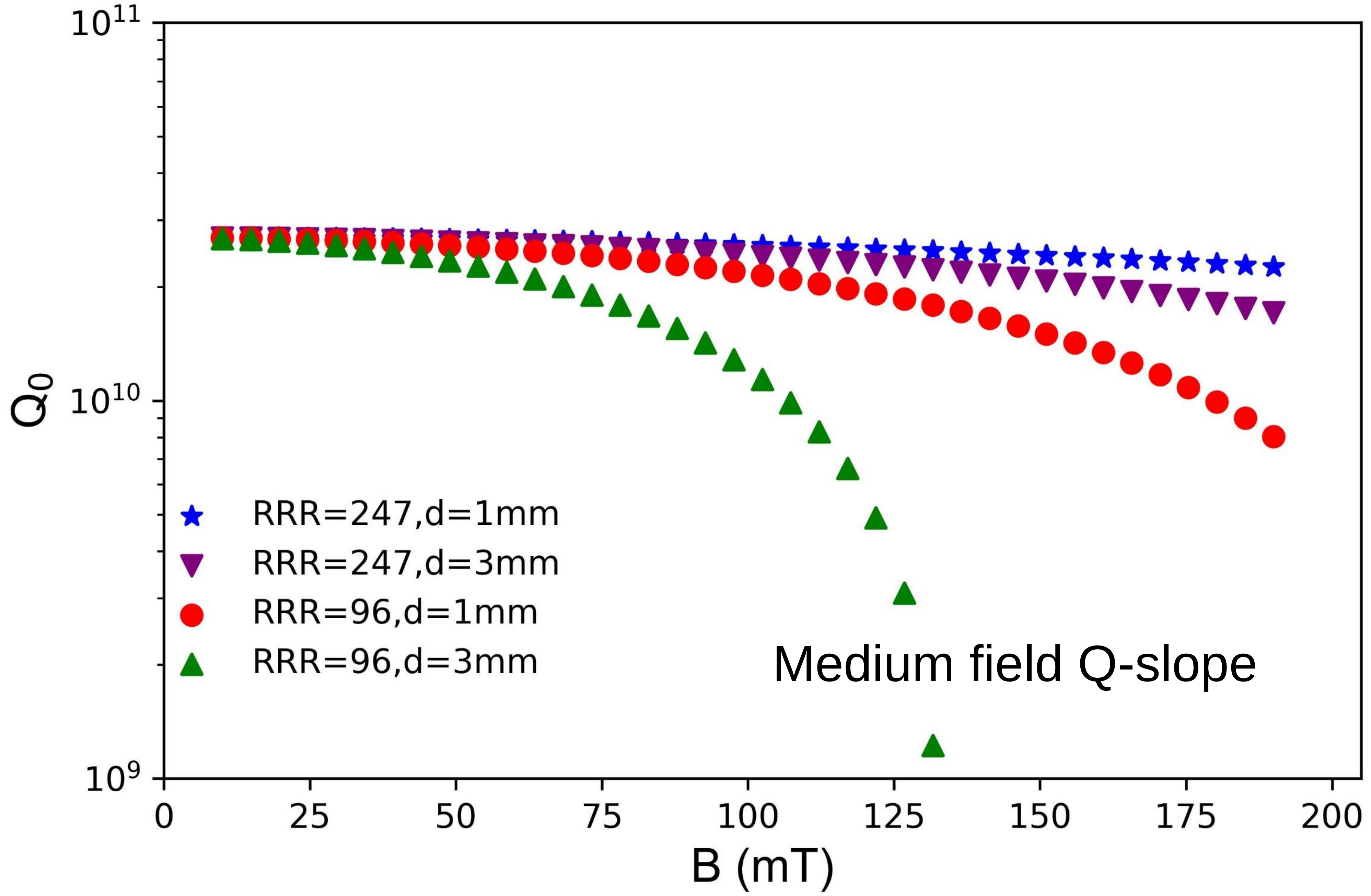
RRR = 247



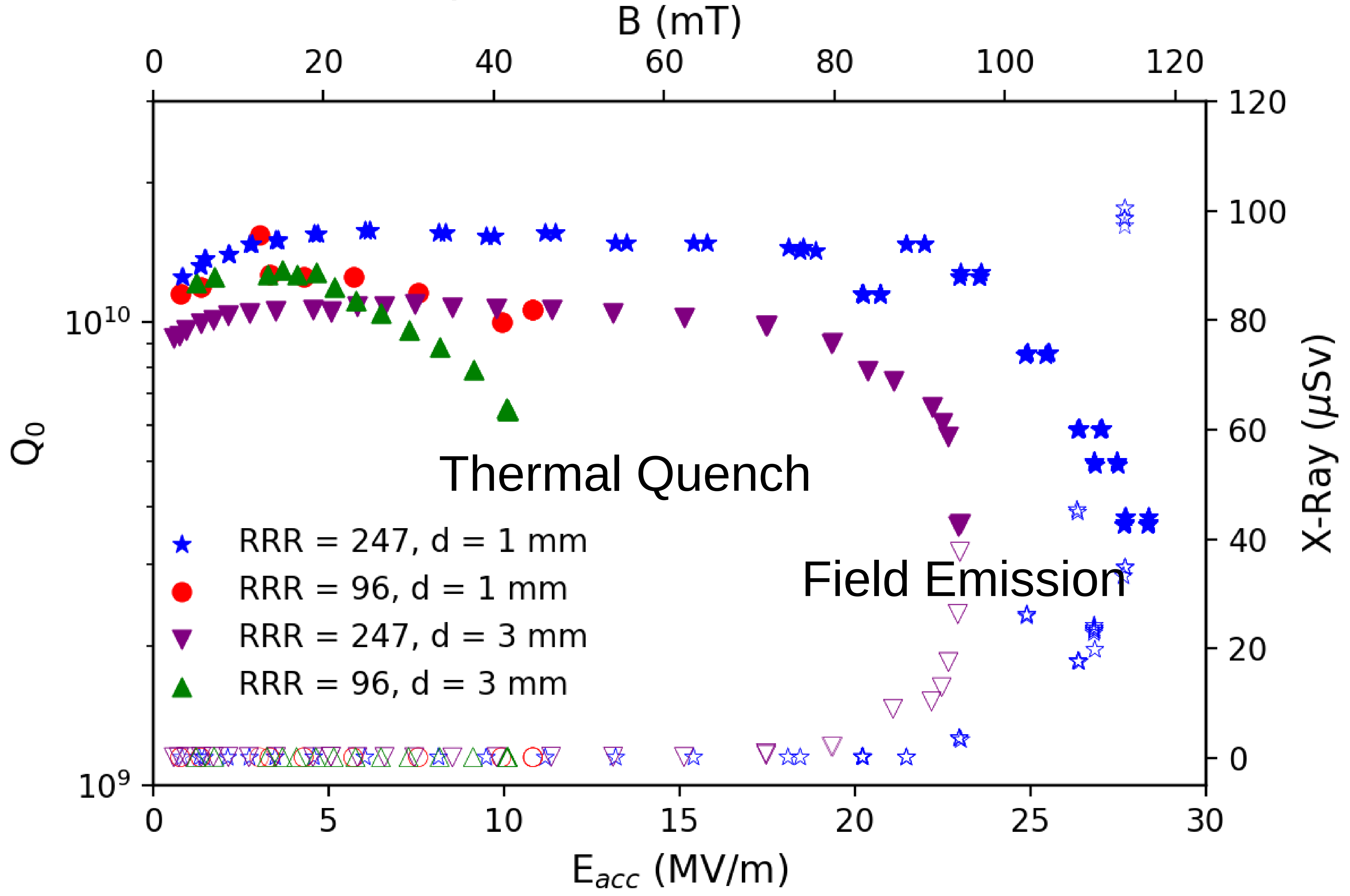
RRR = 96

IMP 1 mm thin-shell cavities

Calculated results using the Halbritter Model.



Experiment results in IMP.



Dead end?

Outer-wall Groove Structure (OGS)

1. EP/BCP/HPR/Plasma cleaning to remove defects
2. Increase thermal conductivity κ
3. Add high κ material outside: Cu-clad cavity
4. Increase contacting area/shorten the distance to liquid He(LHe)

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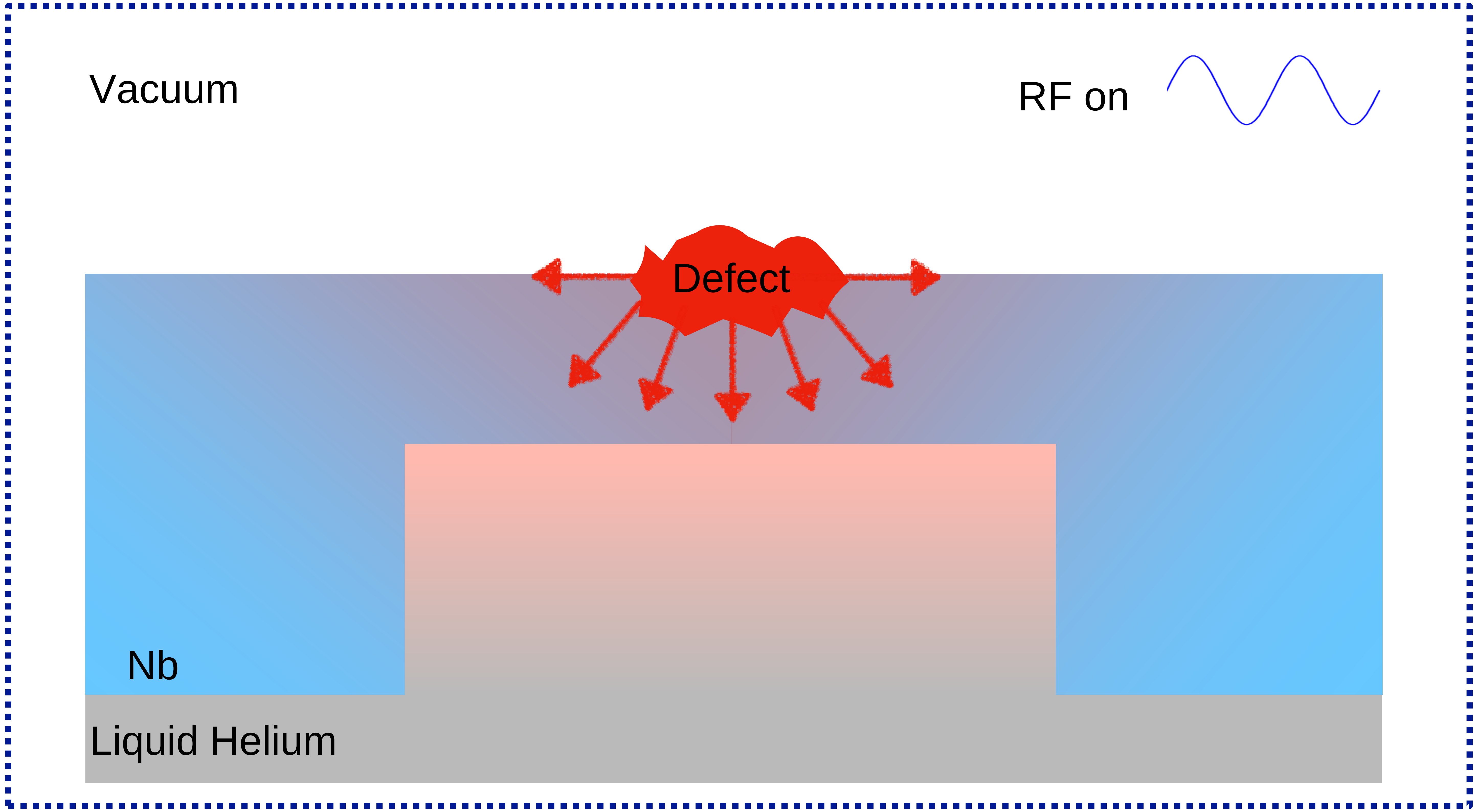


Outer-wall Groove Structure (OGS)

Heat Conduction Equation

Specific Heat

Temperature

Thermal Conductivity

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

Time

Density

Power of Heat source

Outer-wall Groove Structure (OGS)

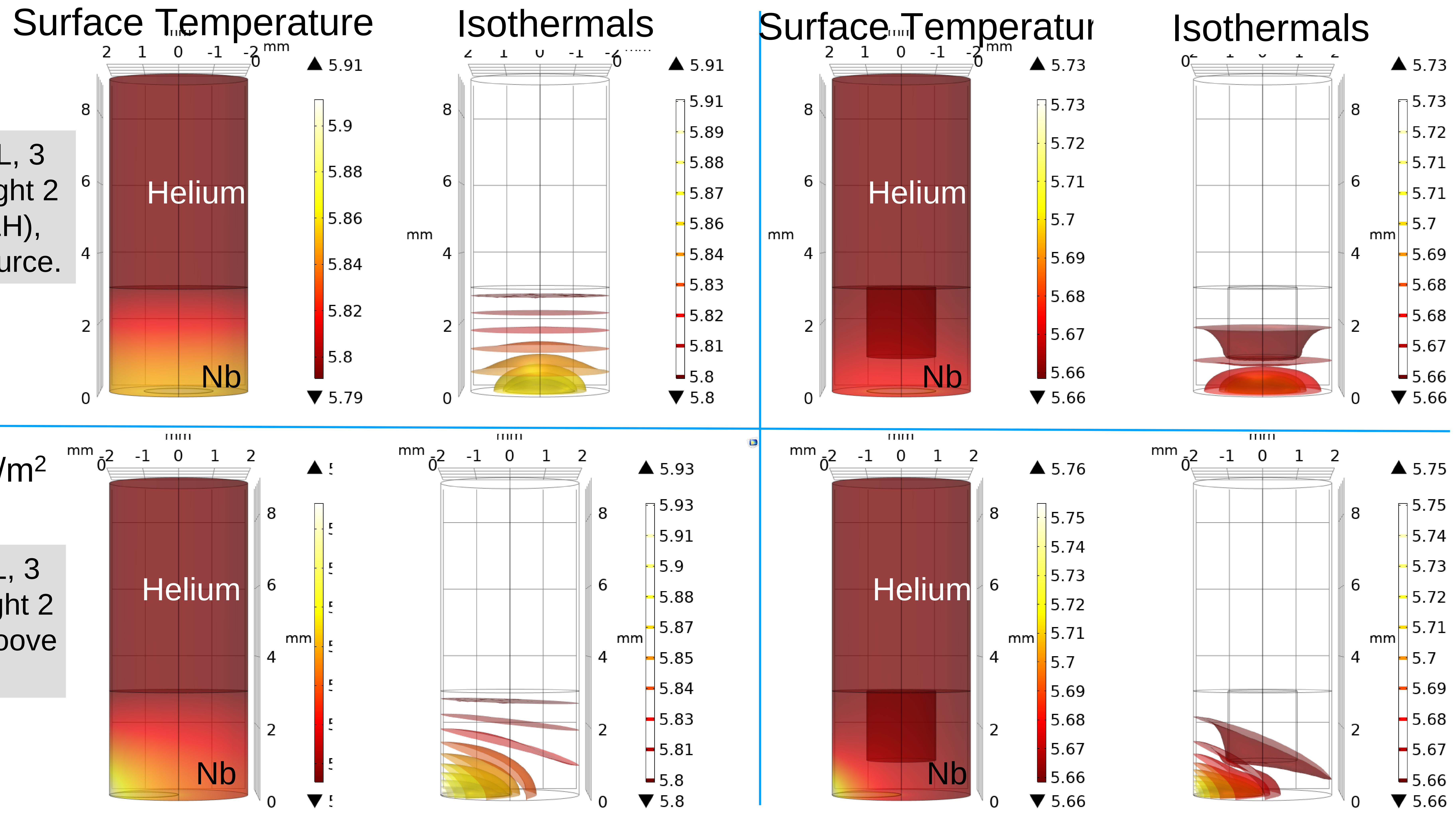
Thermal Simulation, COMSOL, 3 mm wall thickness, groove height 2 mm, filled with liquid helium(LH), groove right above the heat source.

κ_{LHe} =30000 W/(mK)

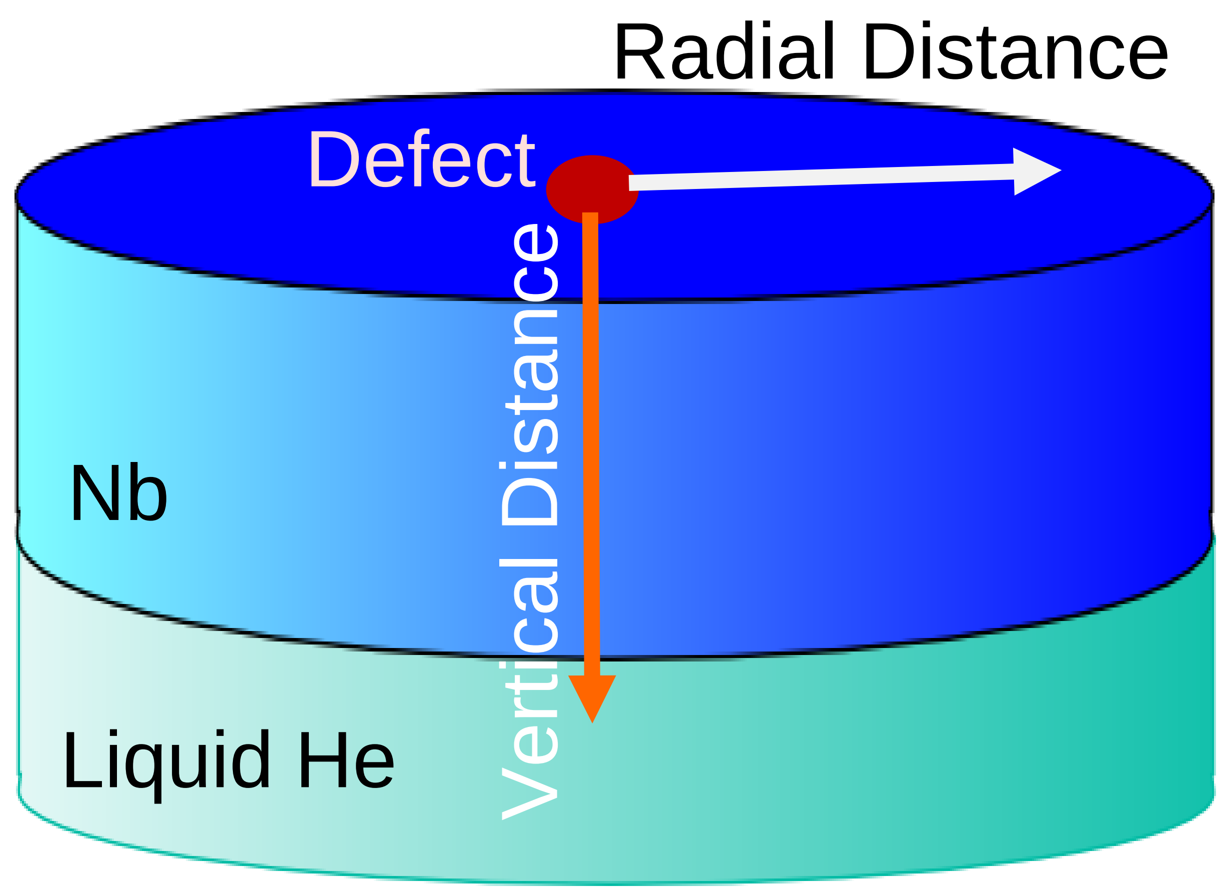
κ_{Nb} =100 W/(mK)

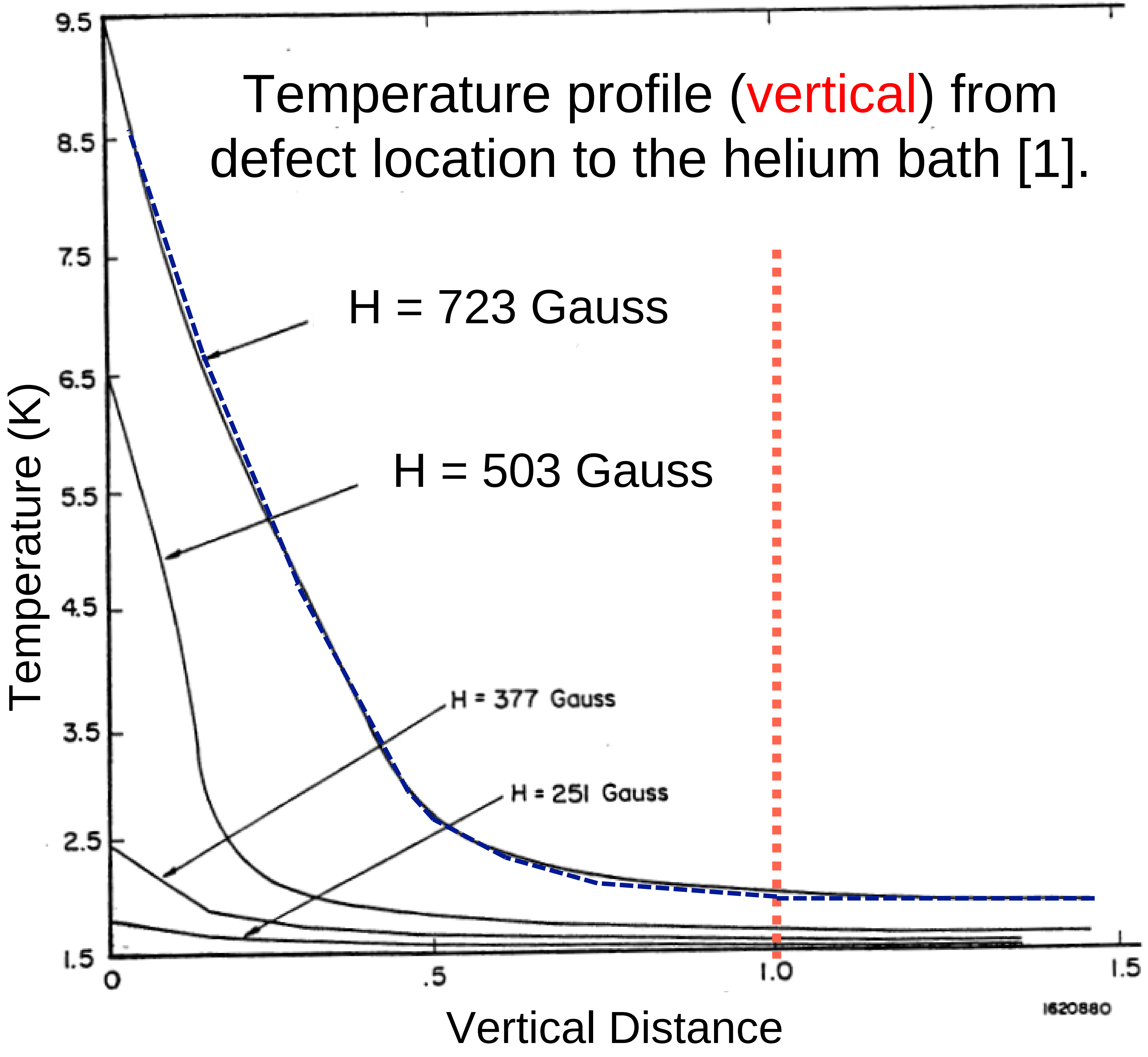
Heat source power: 1000 W/m^2

Thermal Simulation, COMSOL, 3 mm wall thickness, groove height 2 mm, filled with liquid helium, groove 1 mm off the heat source.



Temperature Distributions and Defects





Increase thermal conductivity κ

⇩

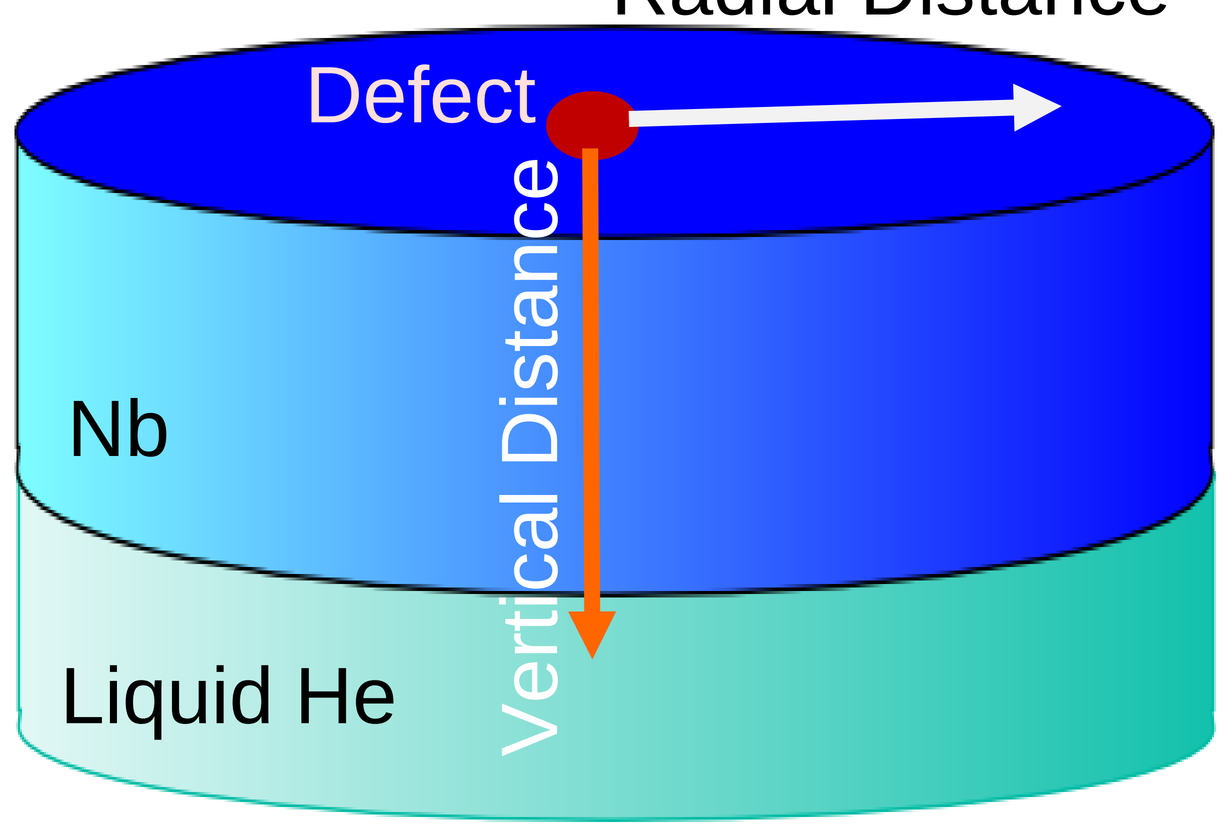
Decrease center T

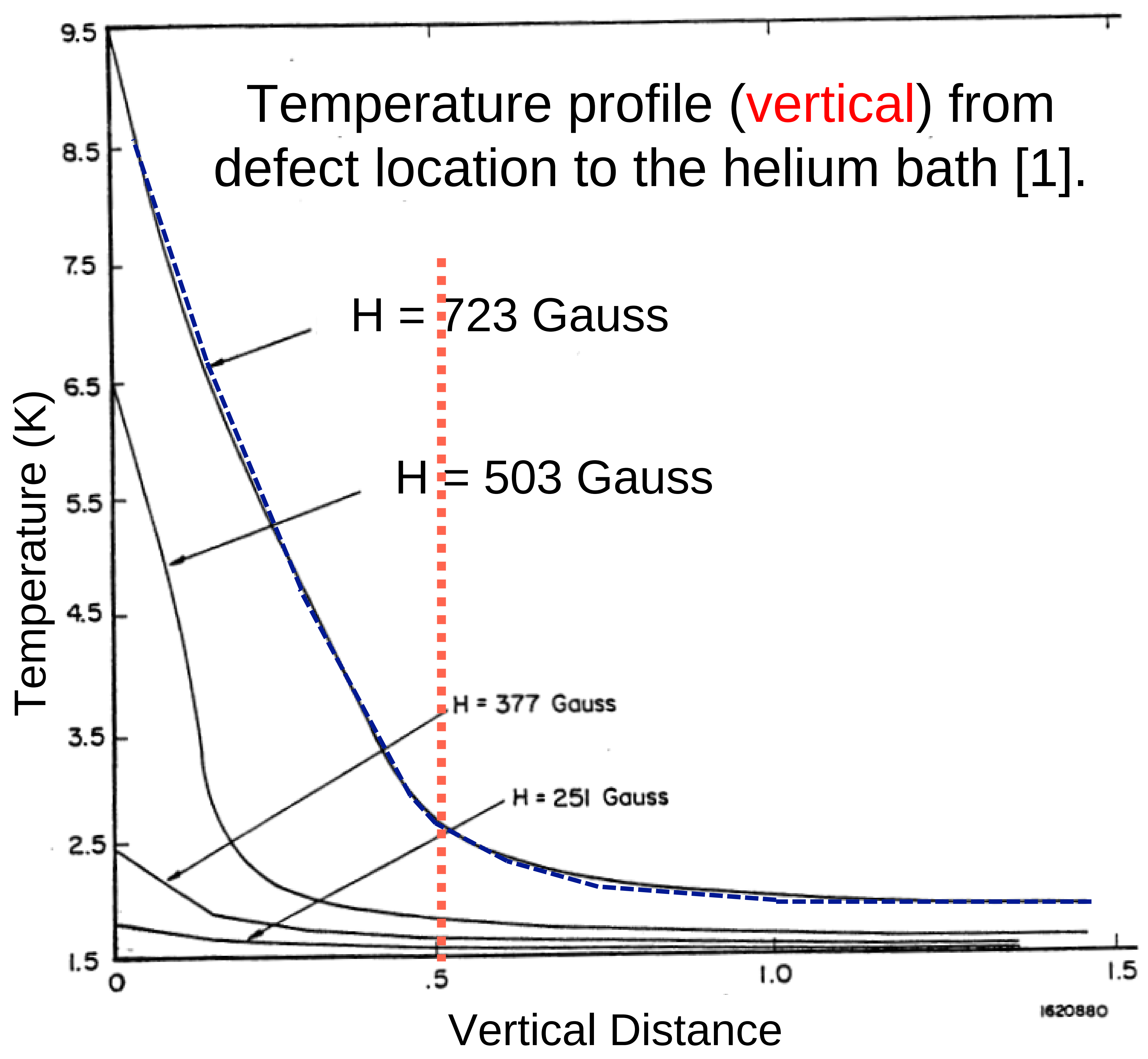
⇩

Increase E_{acc} limit

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

Temperature Distributions and Defects





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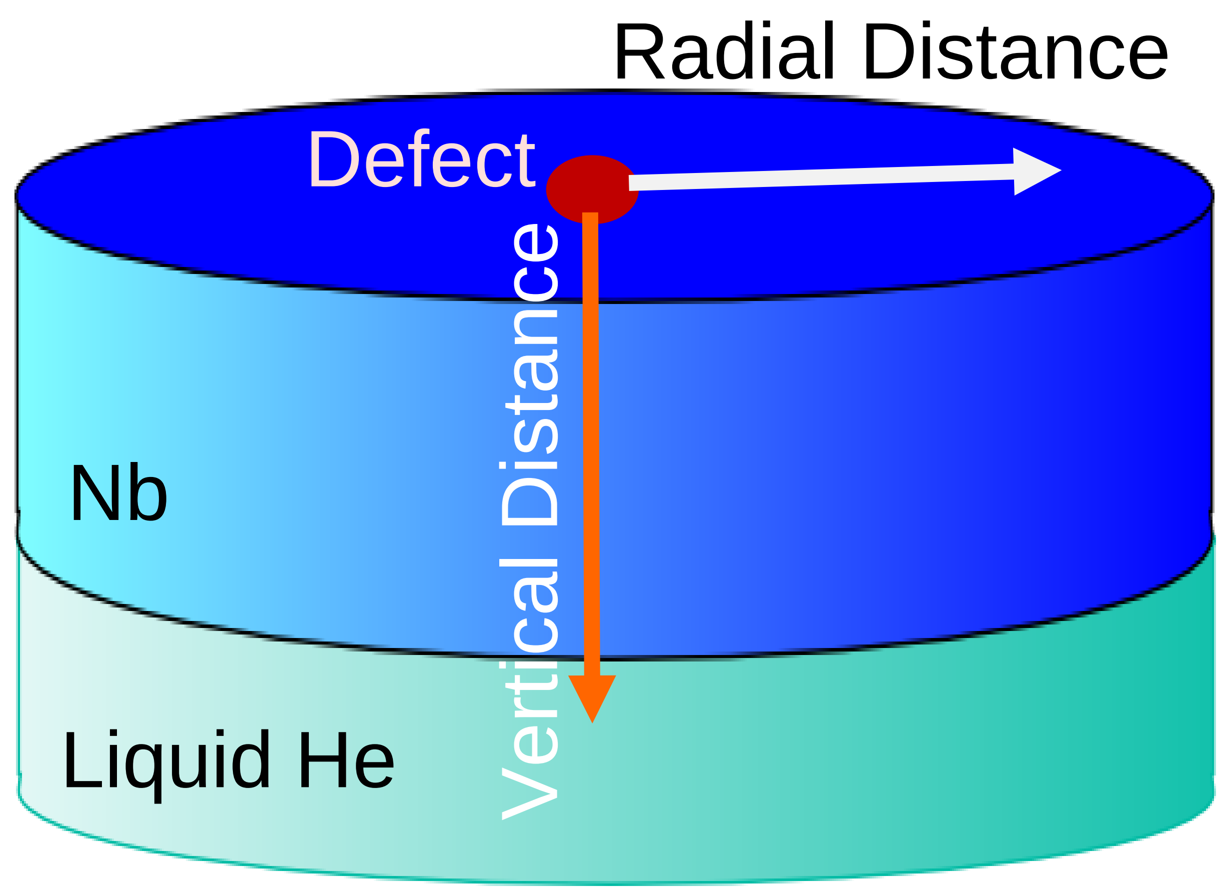

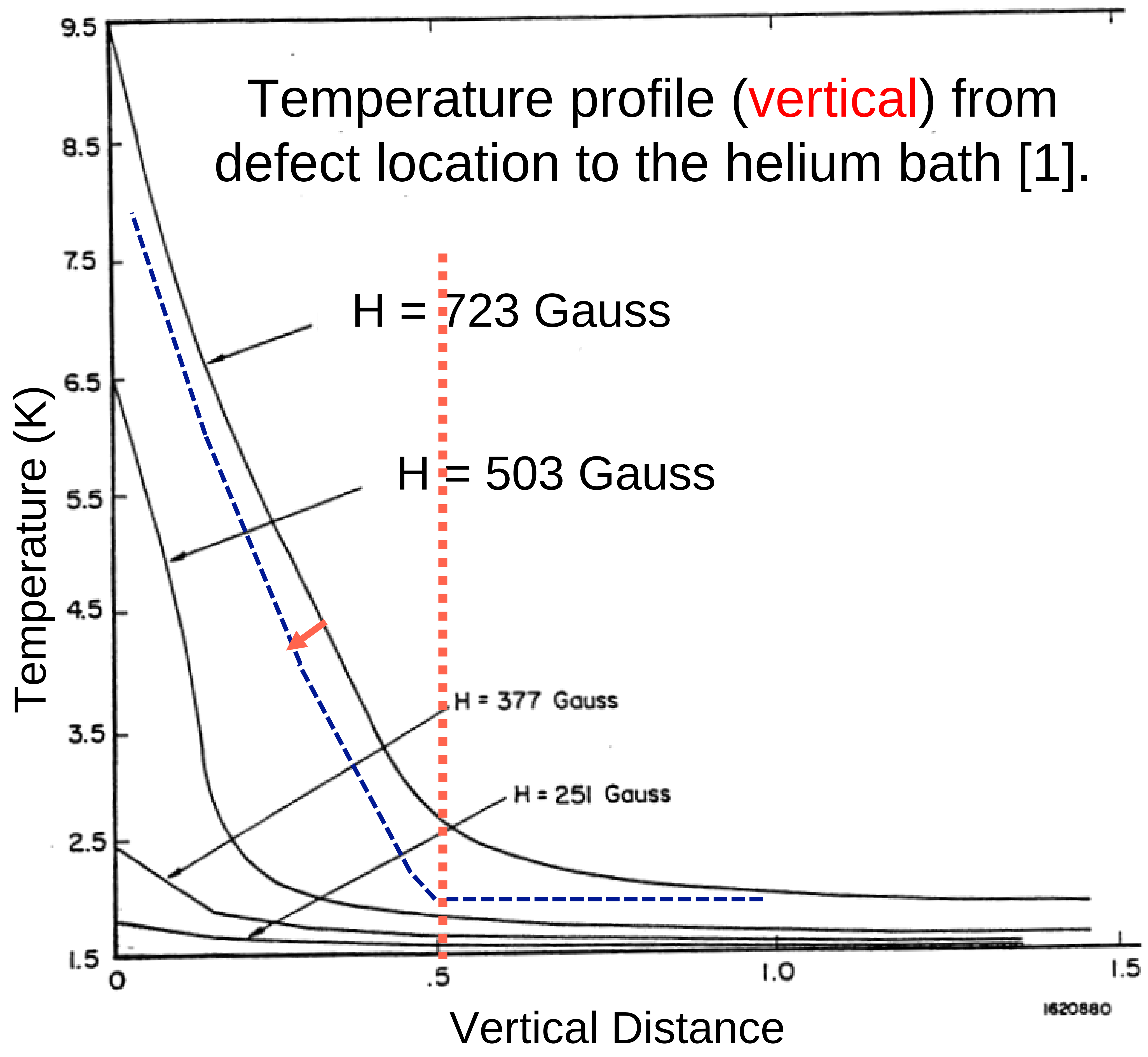

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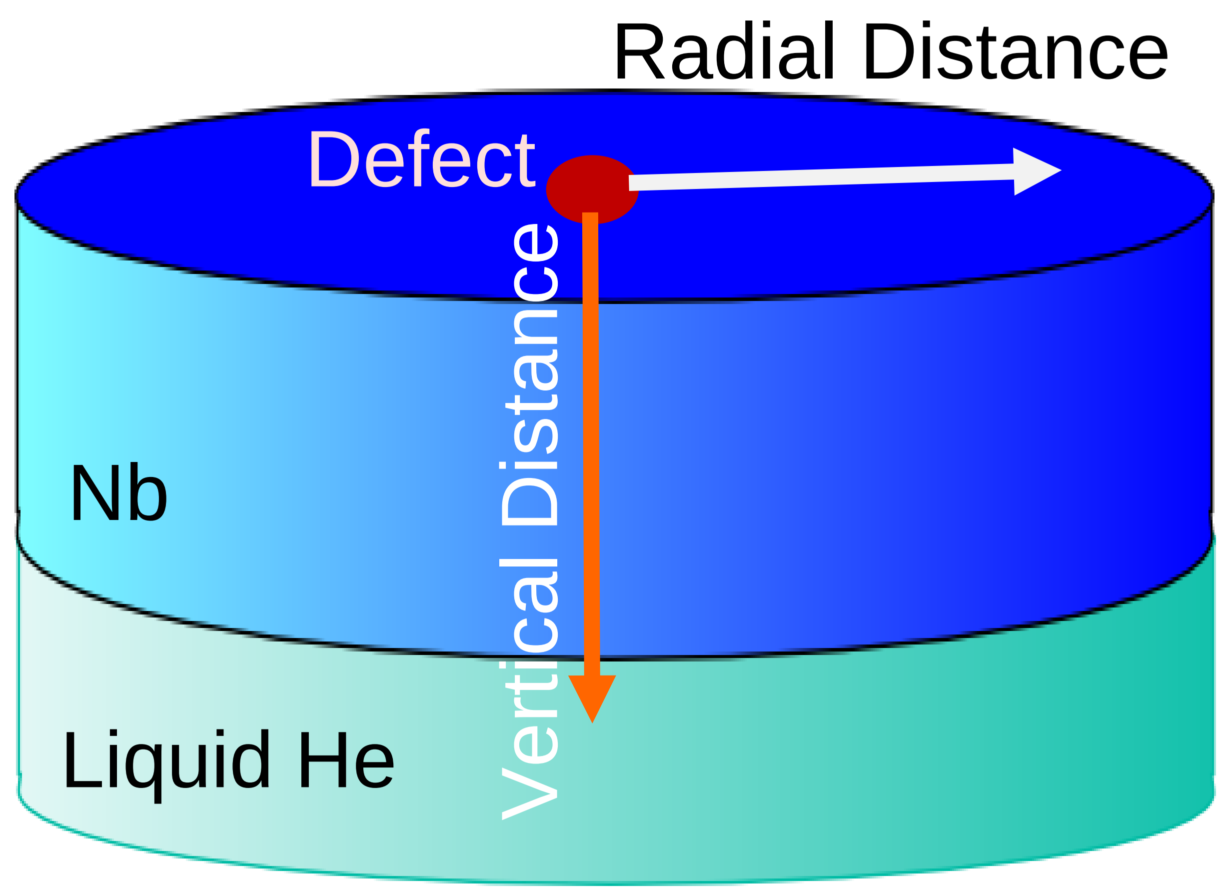

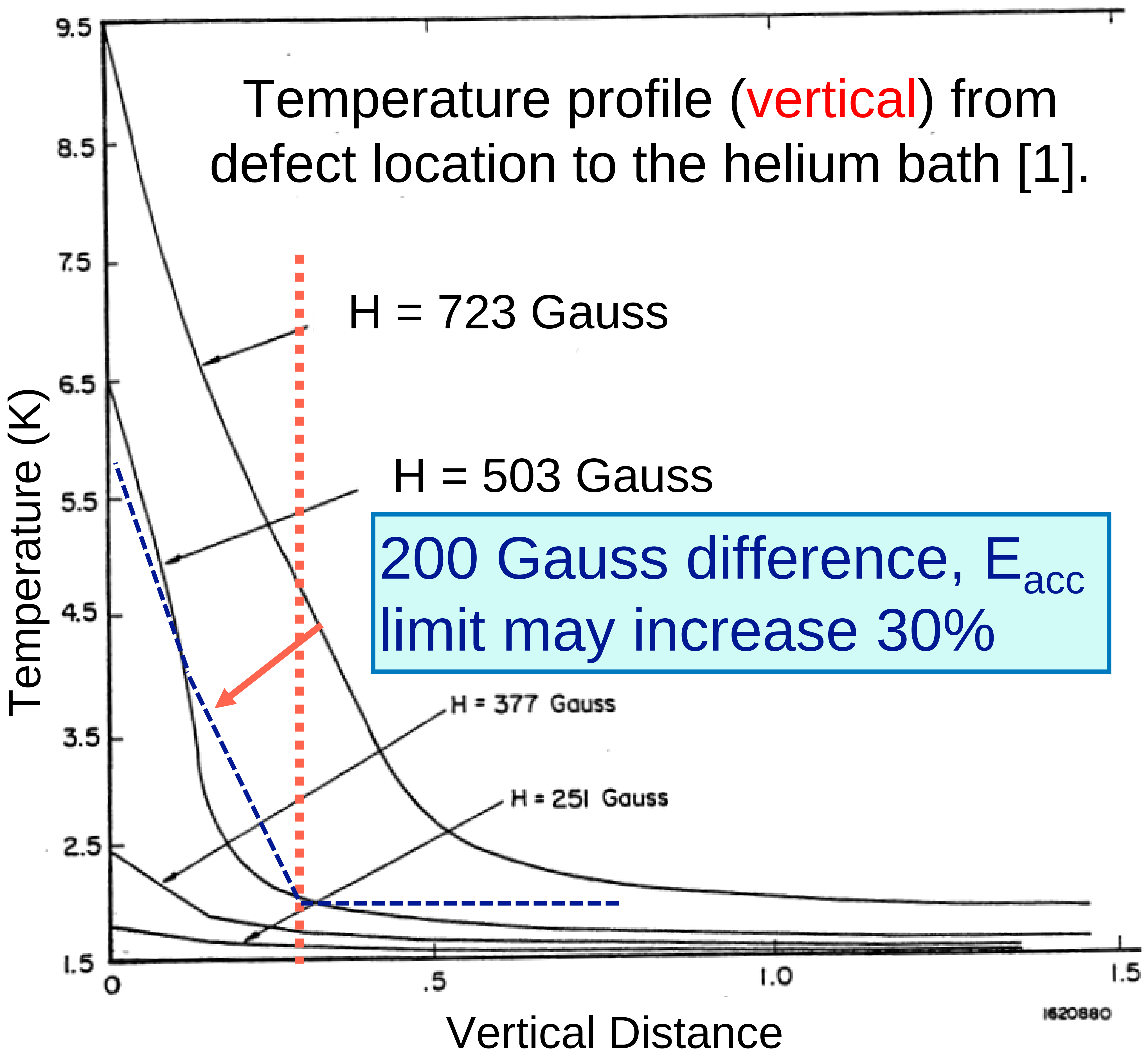

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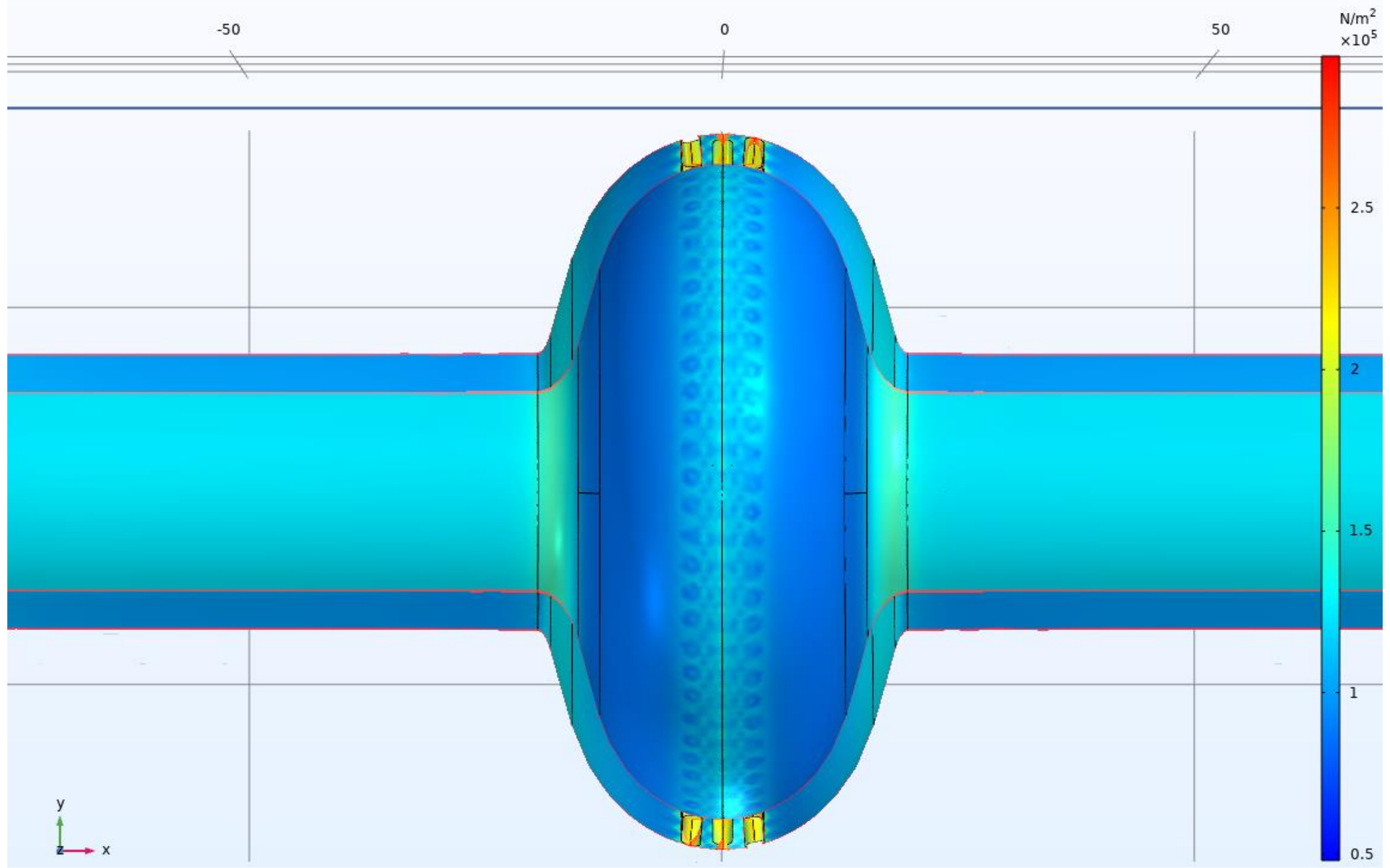
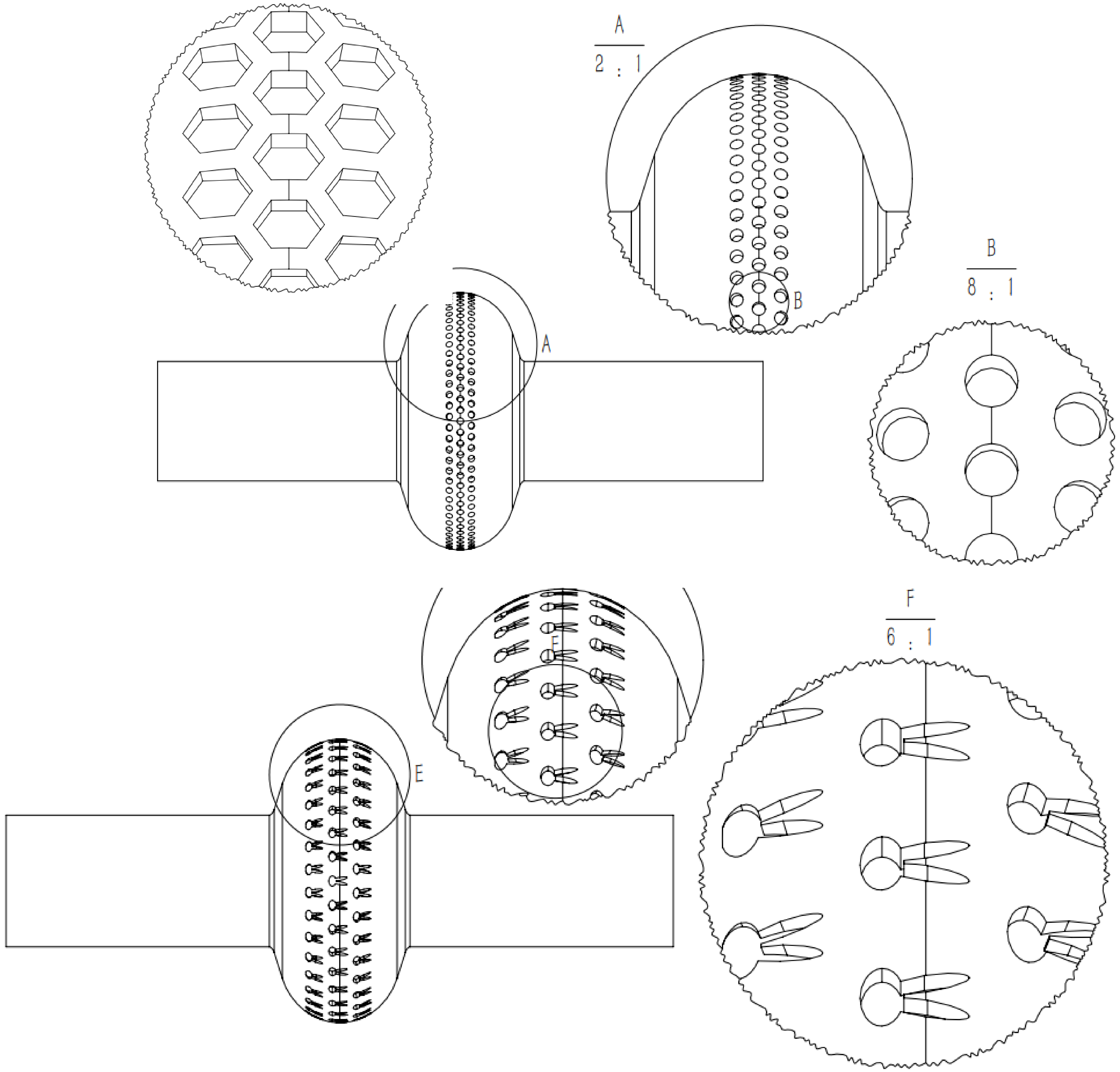
Outer-wall Groove Structure (OGS)

Mechanics Simulation, COMSOL, 3.9 GHz cavity, 3 mm wall thickness, 4 atm pressure, groove height 2.9 mm.



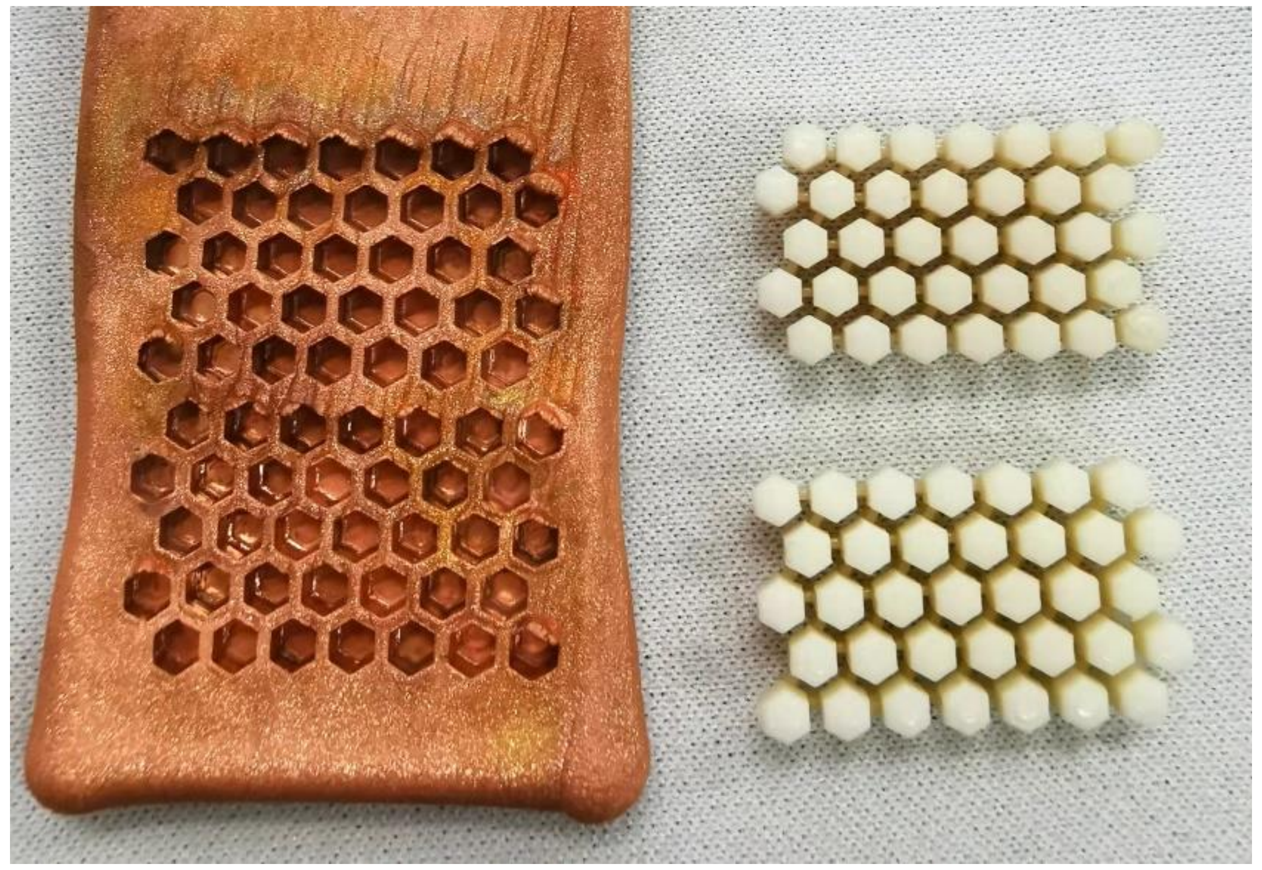
Wall thickness at the groove 100 μm, pressure on the inner wall still lower than the Iris area.



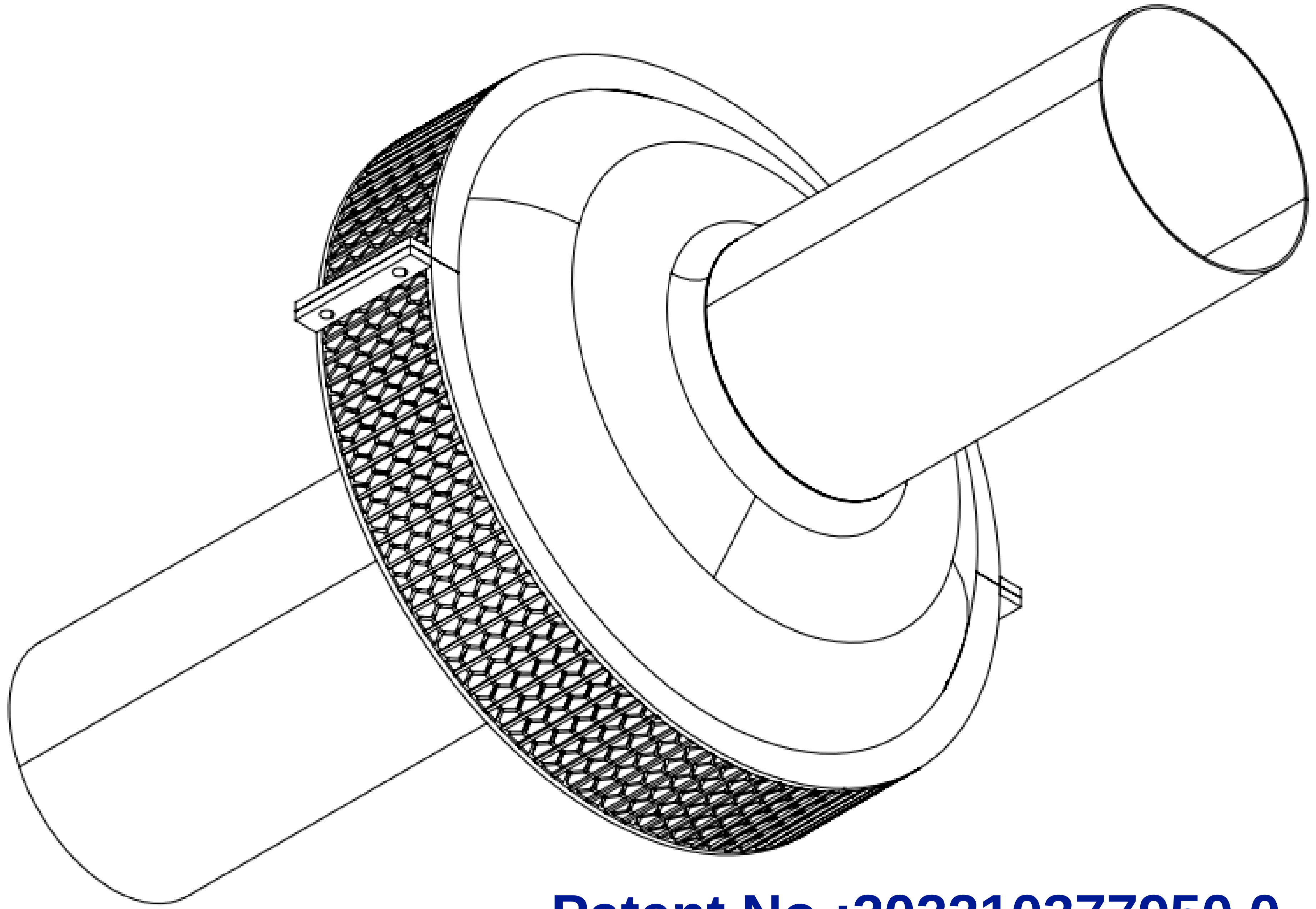
Outer-wall Groove Structure (OGS)

- CNC machining or thin-shell cavity + electroplating high thermal conductivity metals with a mold
- All over the cavity or only at the high H region

Honeycomb structure mold electroplating



Designed mold for cavity electroplating

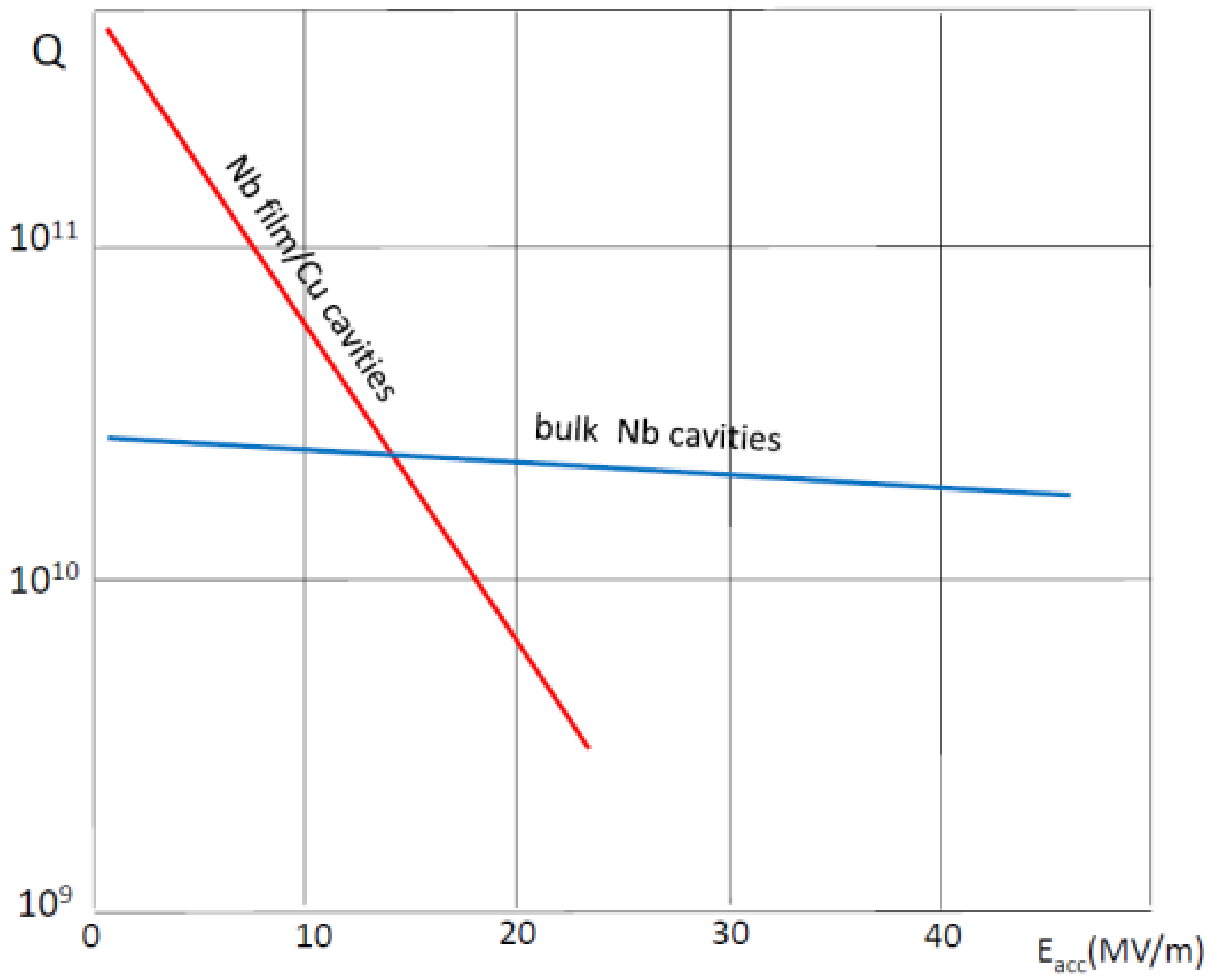


Patent No.:202210377950.0

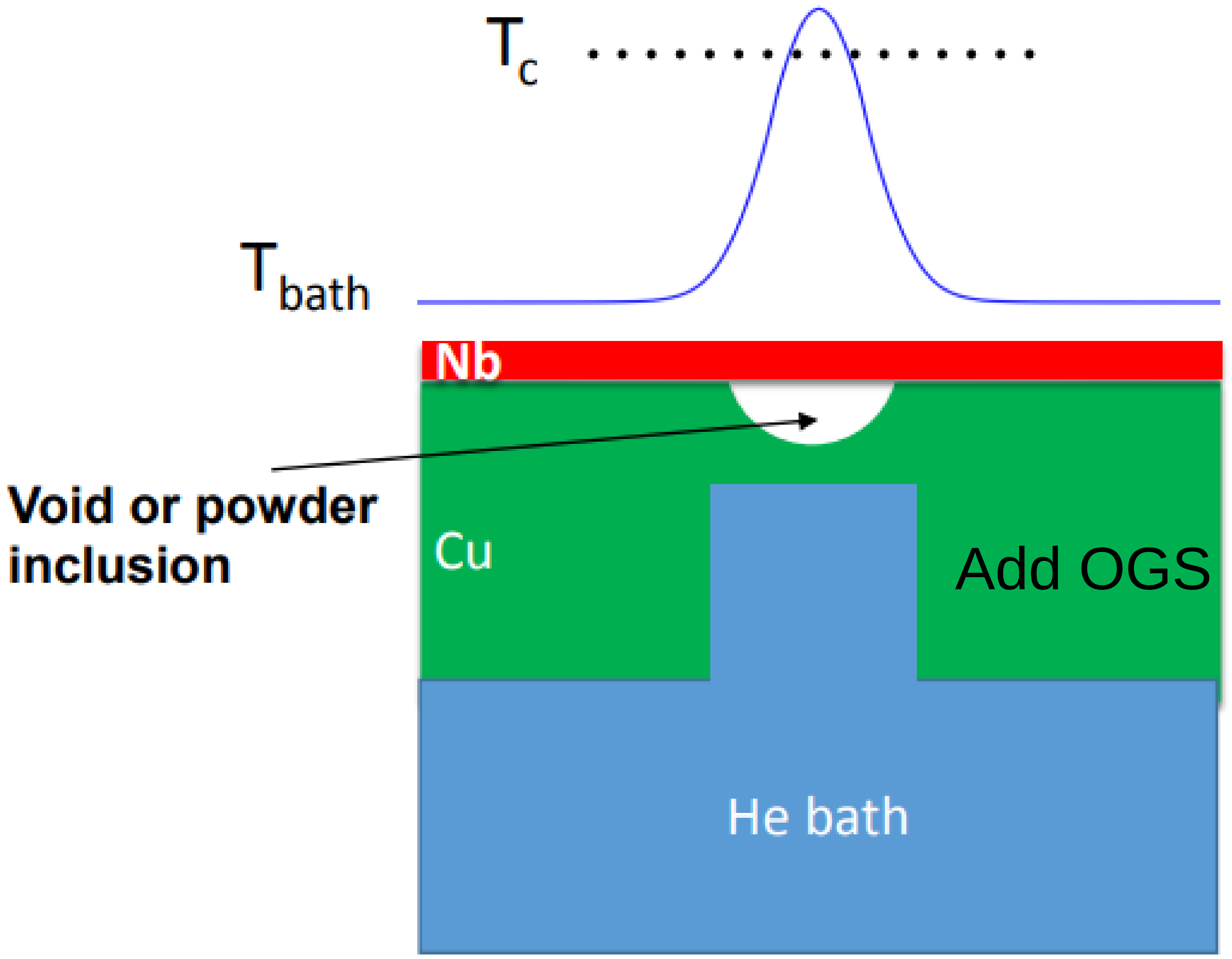
Related work is ongoing…

Anymore?

Nb/Cu Clad Cavity Interface Defect



Large Q-solpe in Nb film/Cu cavities [1]



Thermal Boundary Resistance (TBR) $R_{Nb/Cu}$ Model [1]

[1] Ruggero Vaglio, Thermal boundary resistance model and defect statistical distribution in Nb/Cu cavities, https://accelconf.web.cern.ch/srf2017/talks/tuyba02_talk.pdf

Higher T Operation of Nb_3Sn Cavity

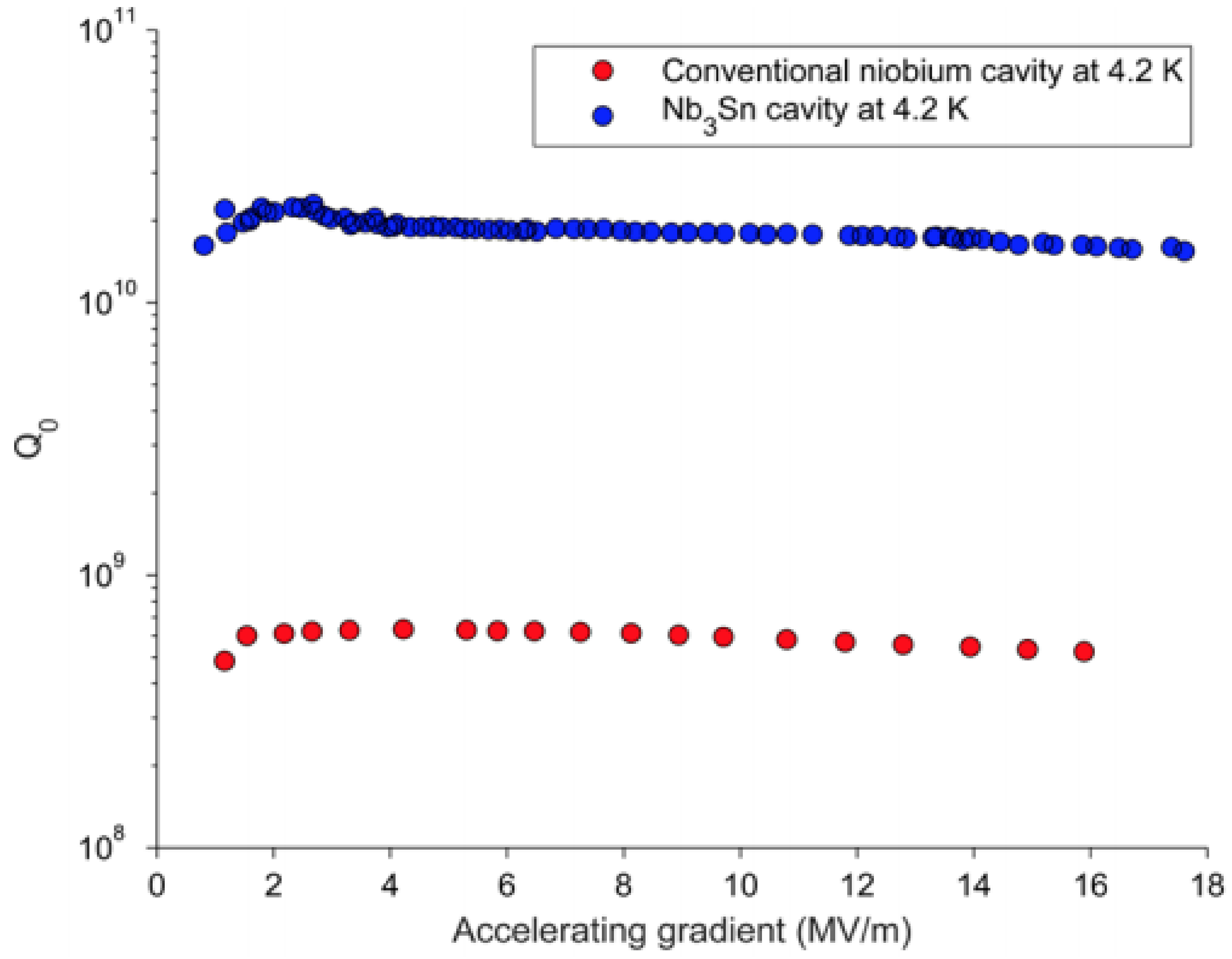


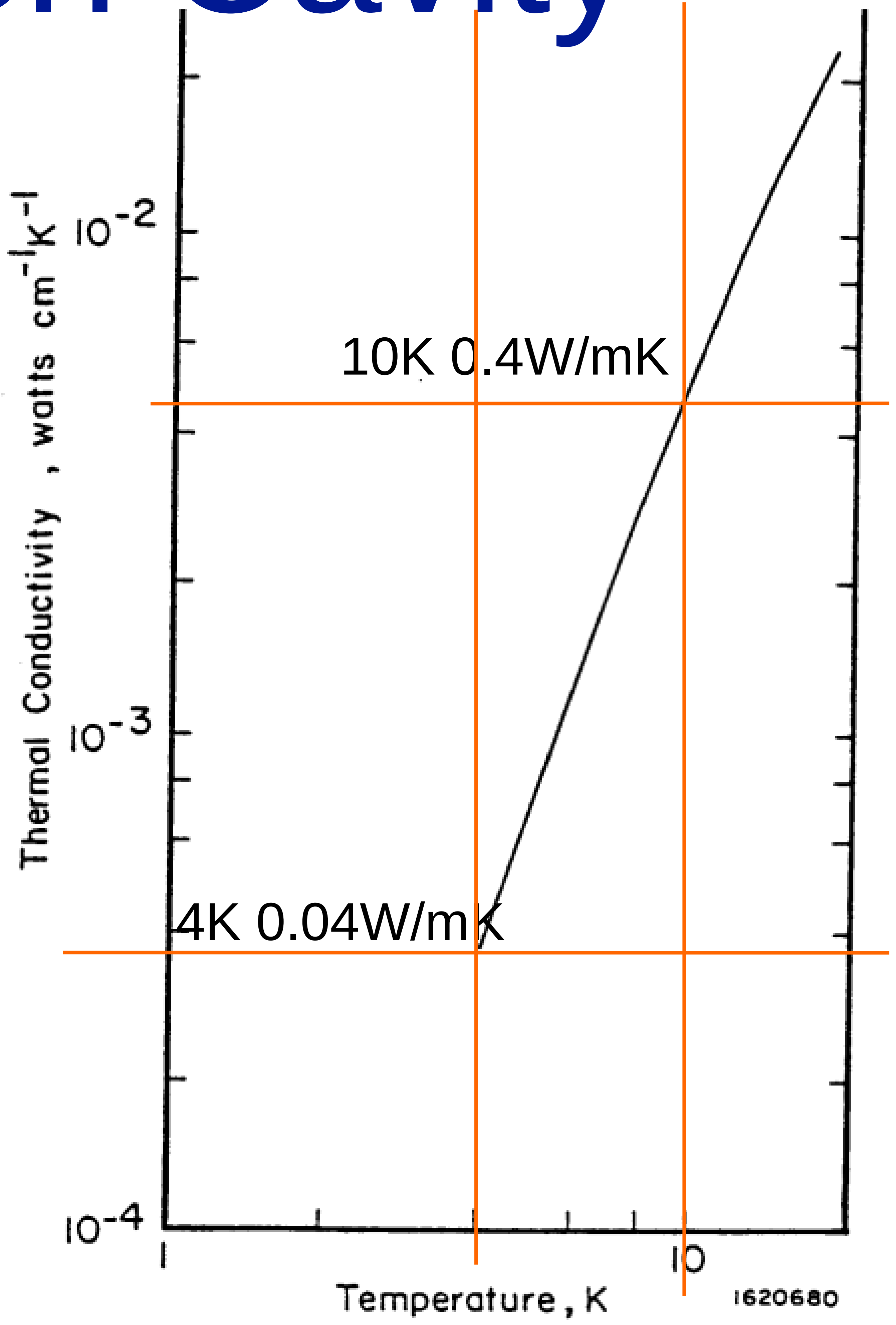
Figure 2: Q versus E performance of a Nb_3Sn cavity versus a Nb cavity at 4.2 K and 1.3 GHz. [3]

Nb and Nb_3Sn superconductivity[1]

Material	T_c (K)	λ_L (nm)	H_c (Oe)	H_{SH} (Oe)
Nb	9.2	40	2000	2300
Nb_3Sn	18	110	5350	4000

Nb and compound's thermal conductivity

Material	κ (W/m·K)
Nb	10
Nb_2O_5	1- 2.5 [4]
Nb_xN_y	1 [5]
Nb_3Sn	2 [6]

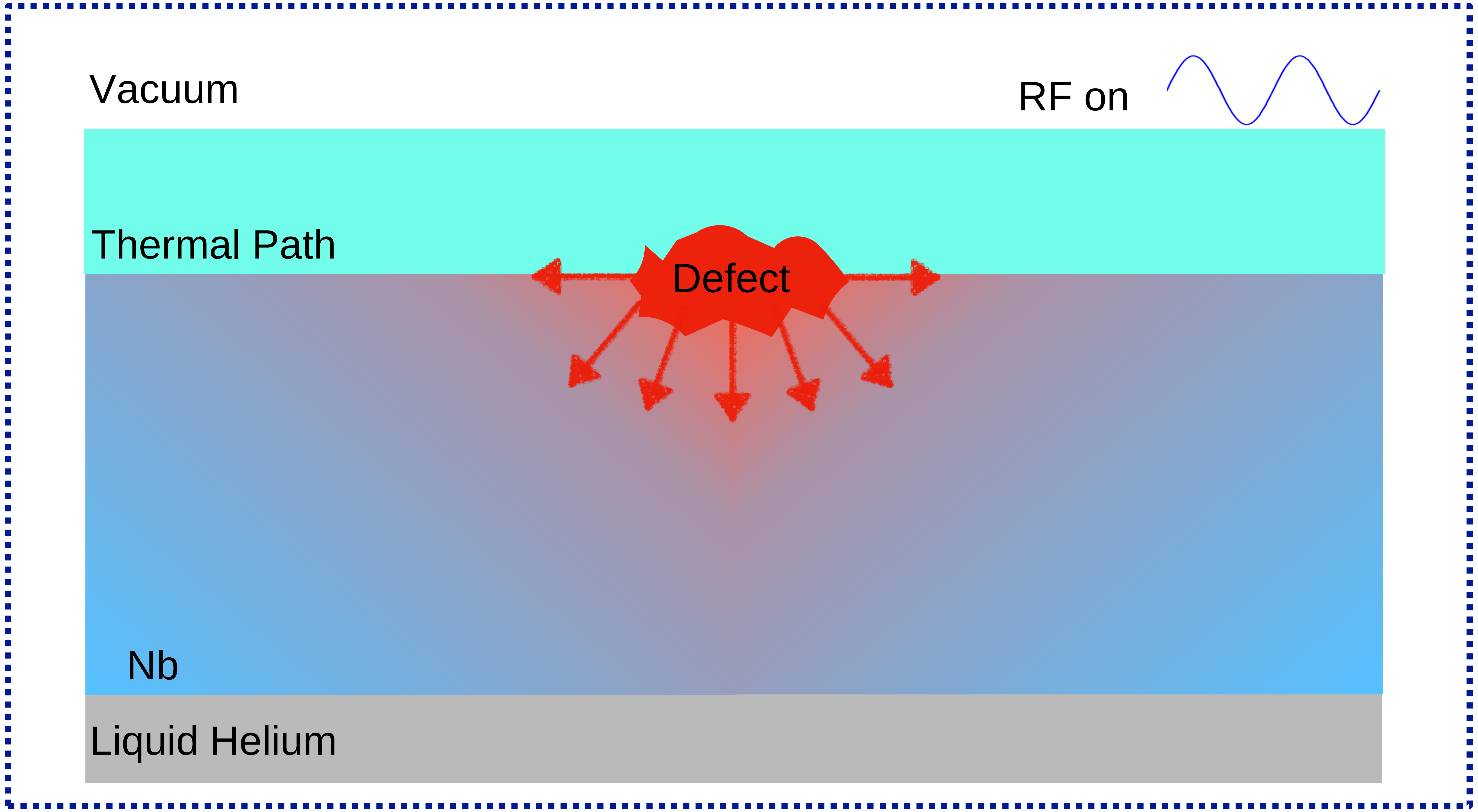


Thermal Conductivity of Nb_3Sn [2]

[1] Hasan Padamsee, Jens Knobloch and Tom Hays, RF Superconductivity for Accelerators, Second Edition, WILEY-VCH, p325
[2] H. Padamsee, HEAT TRANSFER AND MODELS FOR BREAKDOWNhttps://epaper.kek.jp/srf80/papers/srf80-7.pdf
[3] R.D. Porter, https://accelconf.web.cern.ch/linac2018/papers/tupo055.pdf
[4] Flaminio R, Franc J, Michel C, Morgado N, Sassolas B. "A study of coating mechanical and optical losses in view of reducing mirror thermal noise in gravitational wave detectors". Classical & Quantum Gravity. 2009;27(8):84030-8
[5] Wedenig R, et al. "Superconducting NbN microstrip detectors". Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 1999;433(3):646-63.https://doi.org/10.1016/S0168-9002(99)00476-3
[6] Thermal Conductivity of Industrial Nb3Sn Wires Fabricated by Various Techniques. M. Bonura, and C. Senatore, https://arxiv.org/pdf/1212.2879.pdf

Inner-wall Thermal Conducting Film (ITCF)

1. EP/BCP/HPR/Plasma cleaning to remove defects
2. Increase thermal conductivity κ
3. Add high κ material outside: Cu-clad cavity
4. Increase contacting area/shorten the distance to liquid He(LHe)
5. Adding an extra thermal path: cavity inner wall



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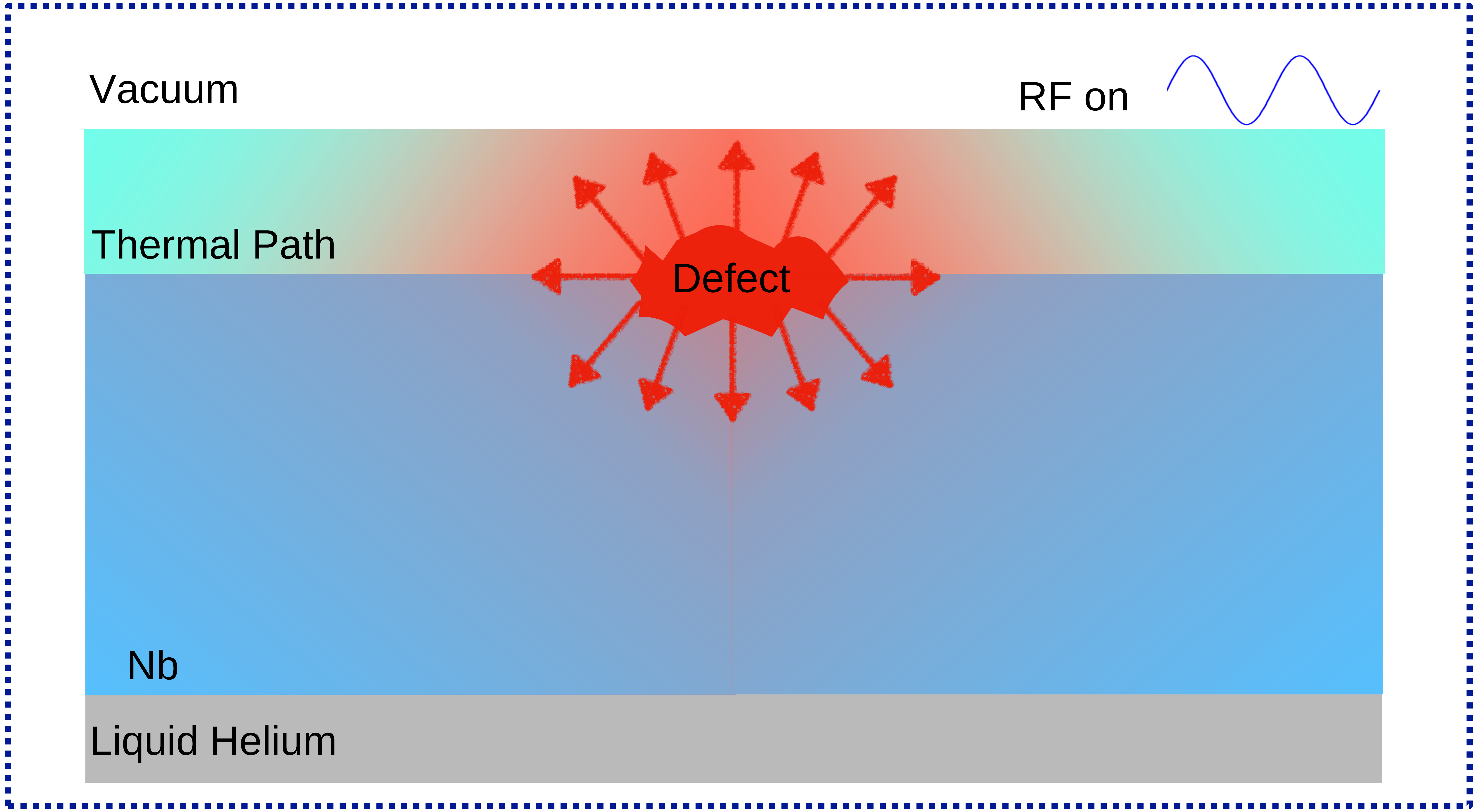
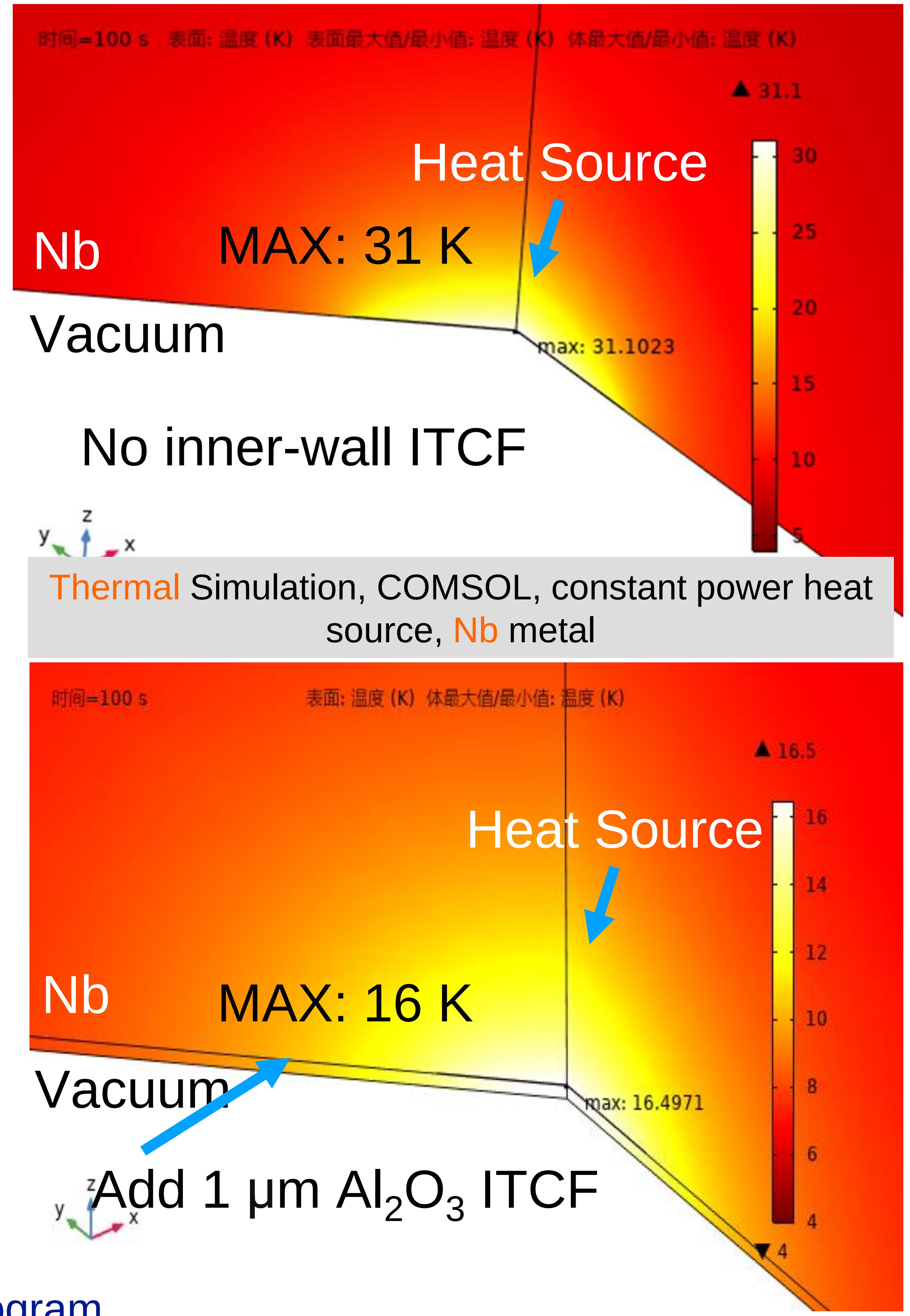


Inner-wall Thermal Conducting Film (ITCF)

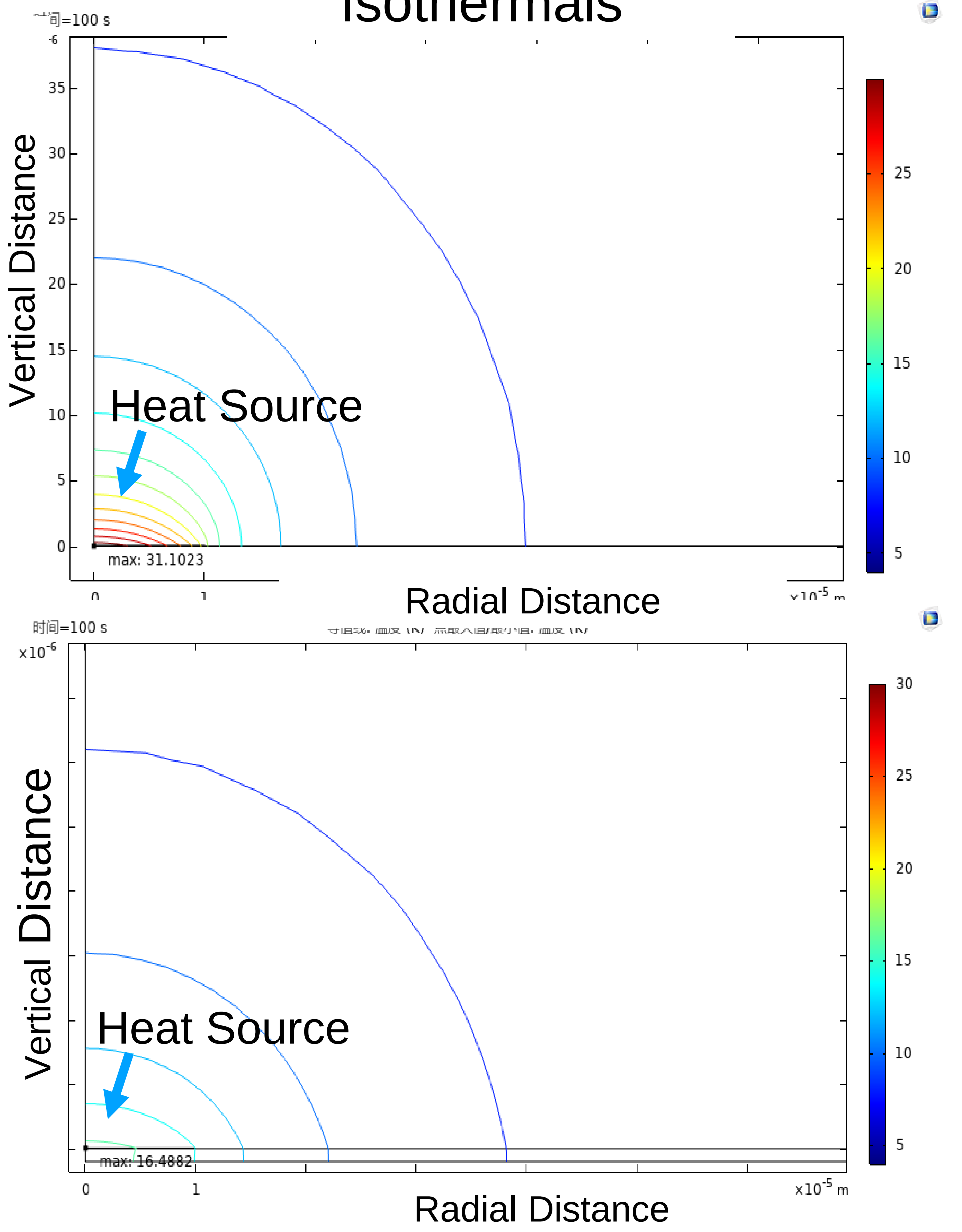
COMSOL Simulation Result：

- Adding ITCF decreases the center temperature (31 K to16 K in this case)
- The ITCF conducts the heat into the distance and flattens the isothermals
- Worse baseline thermal conductivity improves more if add ITCF: Nb_3Sn?

Surface Temperature



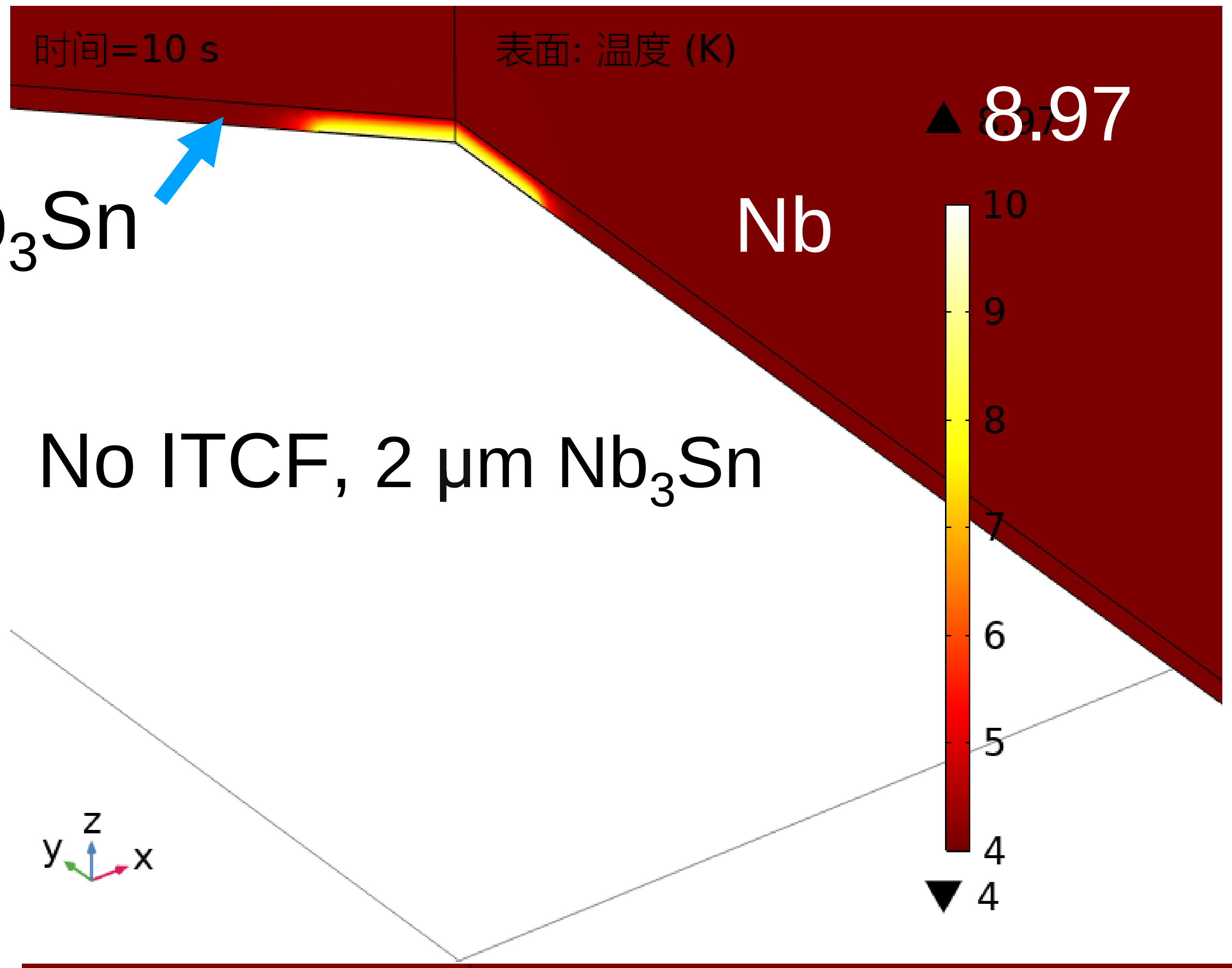
Isothermals



Work supported by the CAS Special Research Assistant (SRA) Program.

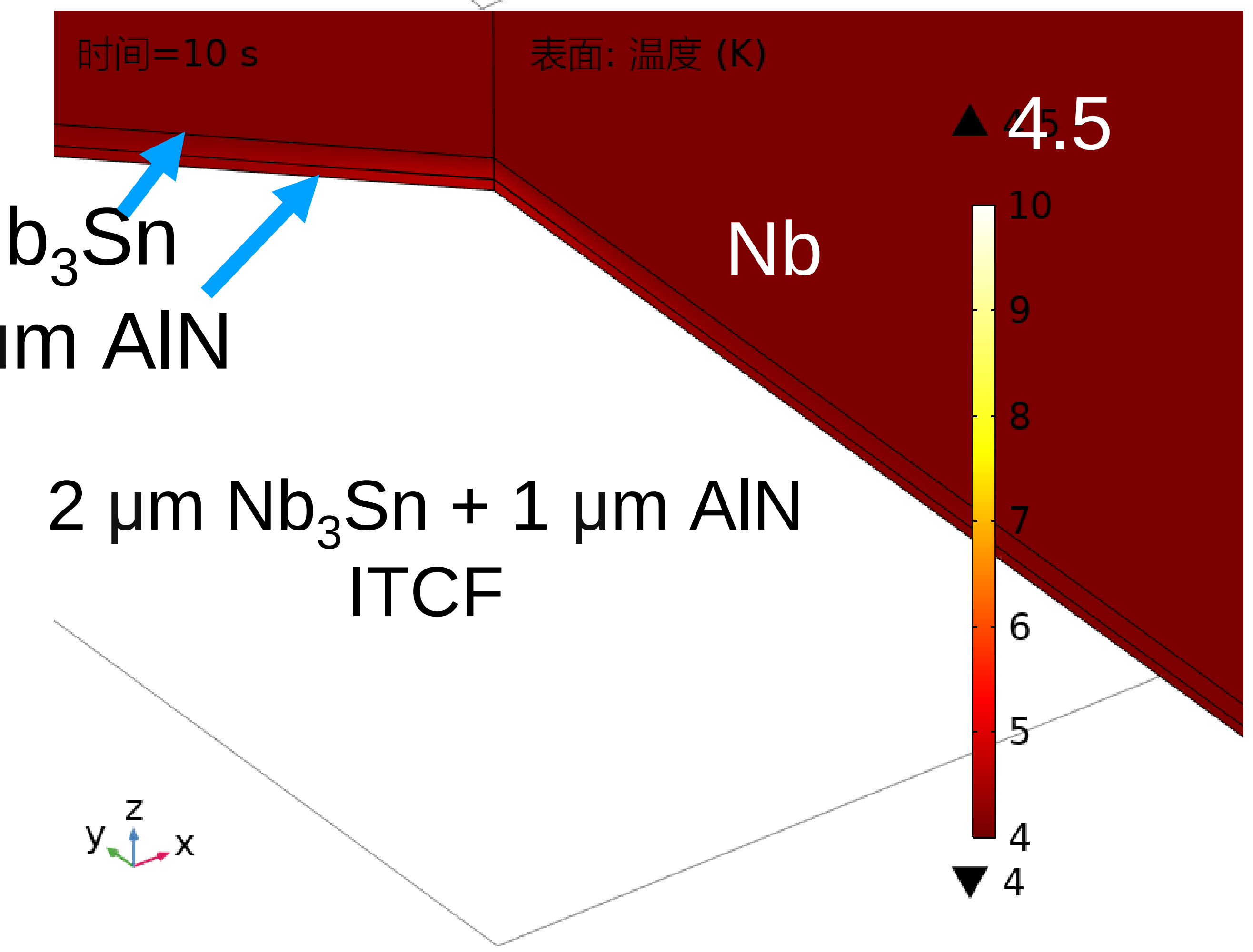
Inner-wall Thermal Conducting Film (ITCF)

Surface Temperature



Nb_3Sn

No ITCF, 2 μm Nb_3Sn



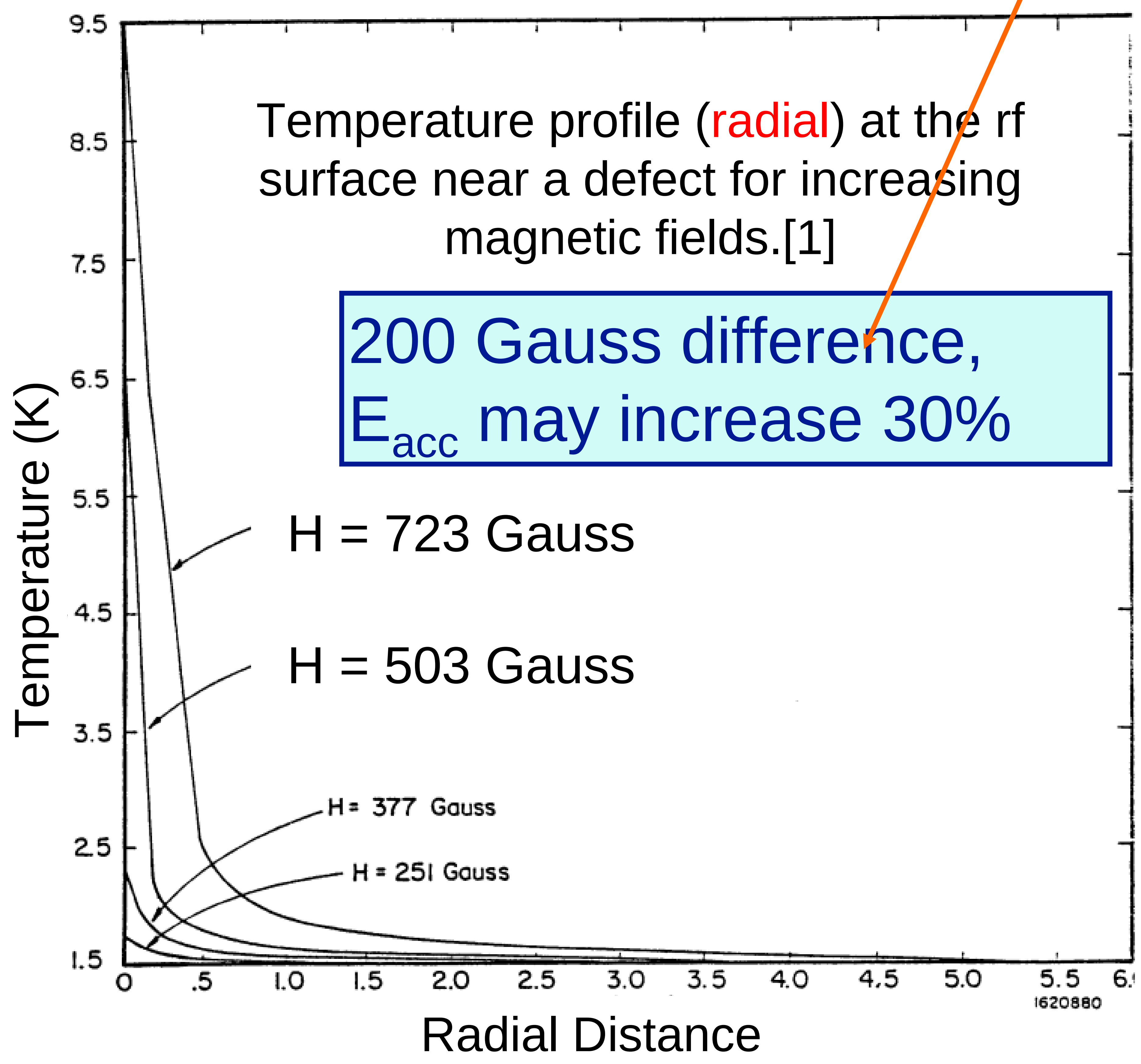
Nb_3Sn

1 μm AlN

2 μm Nb_3Sn + 1 μm AlN ITCF

Nb_3Sn Simulation Result：

- Center temperature drop from 8.97 K to 4.5 K



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

Inner-wall Thermal Conducting Film (ITCF)

ITCF requirement:

- Inner-wall
- Dielectric: not interacting with RF, need low loss tangent
- All over the cavity or only coat the high H region
- μm thickness enough

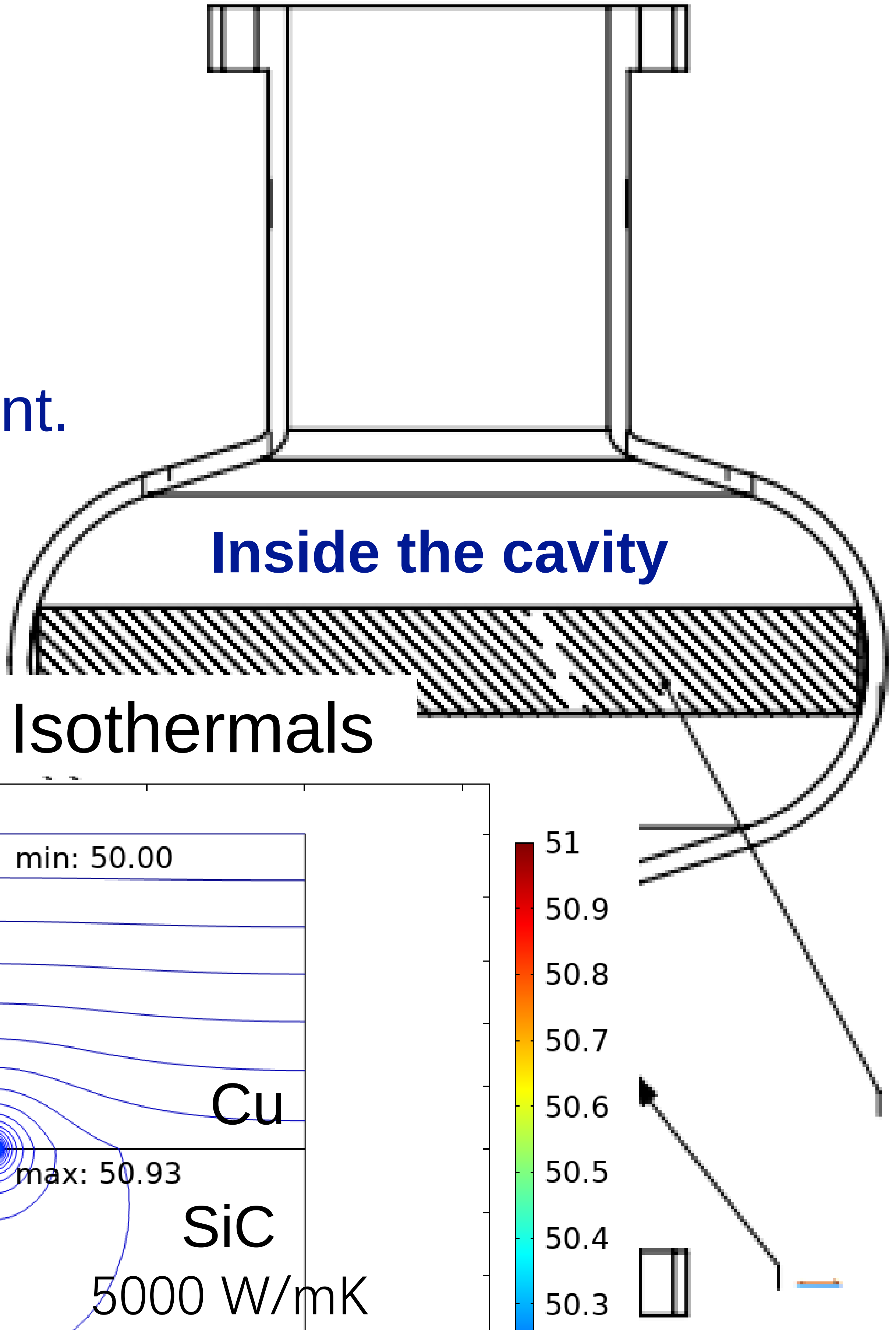
Some ITCF

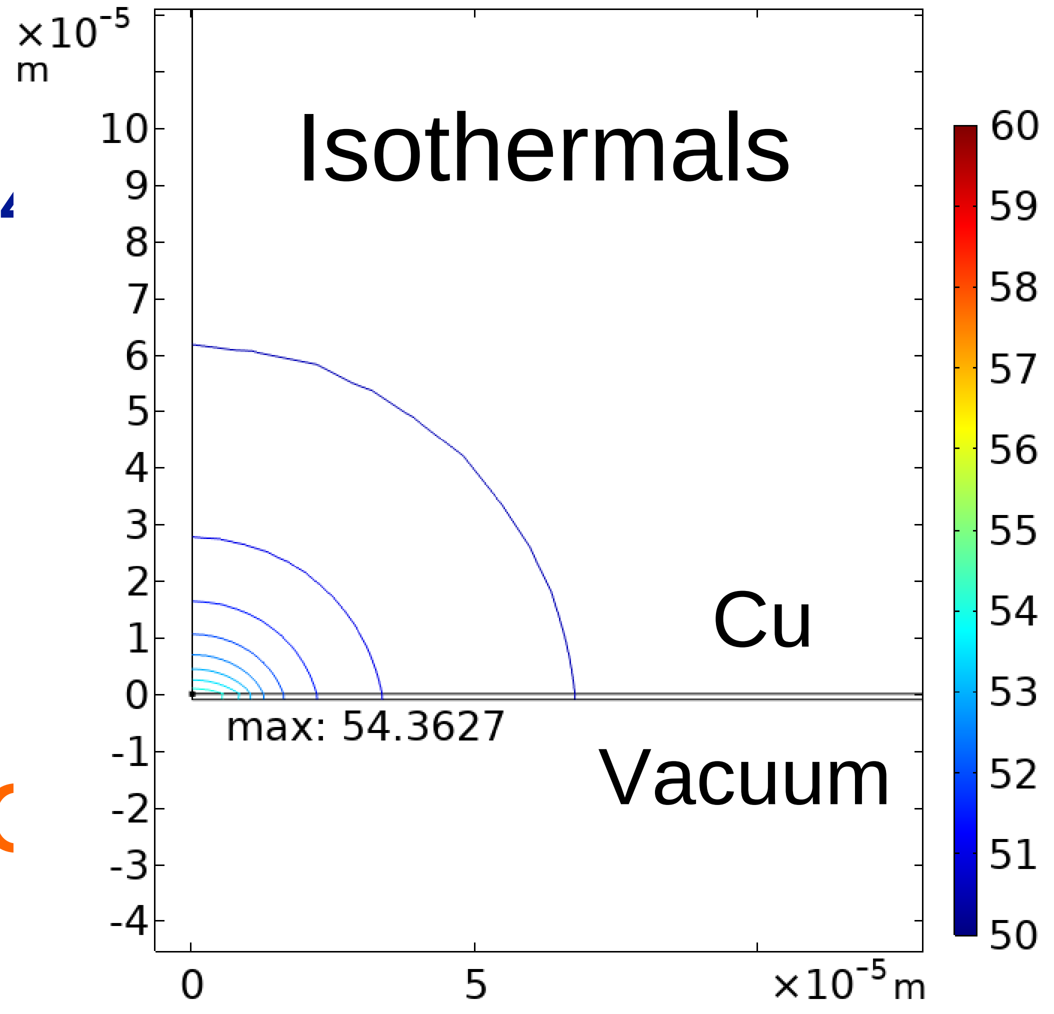
MgB_2 (T_c =

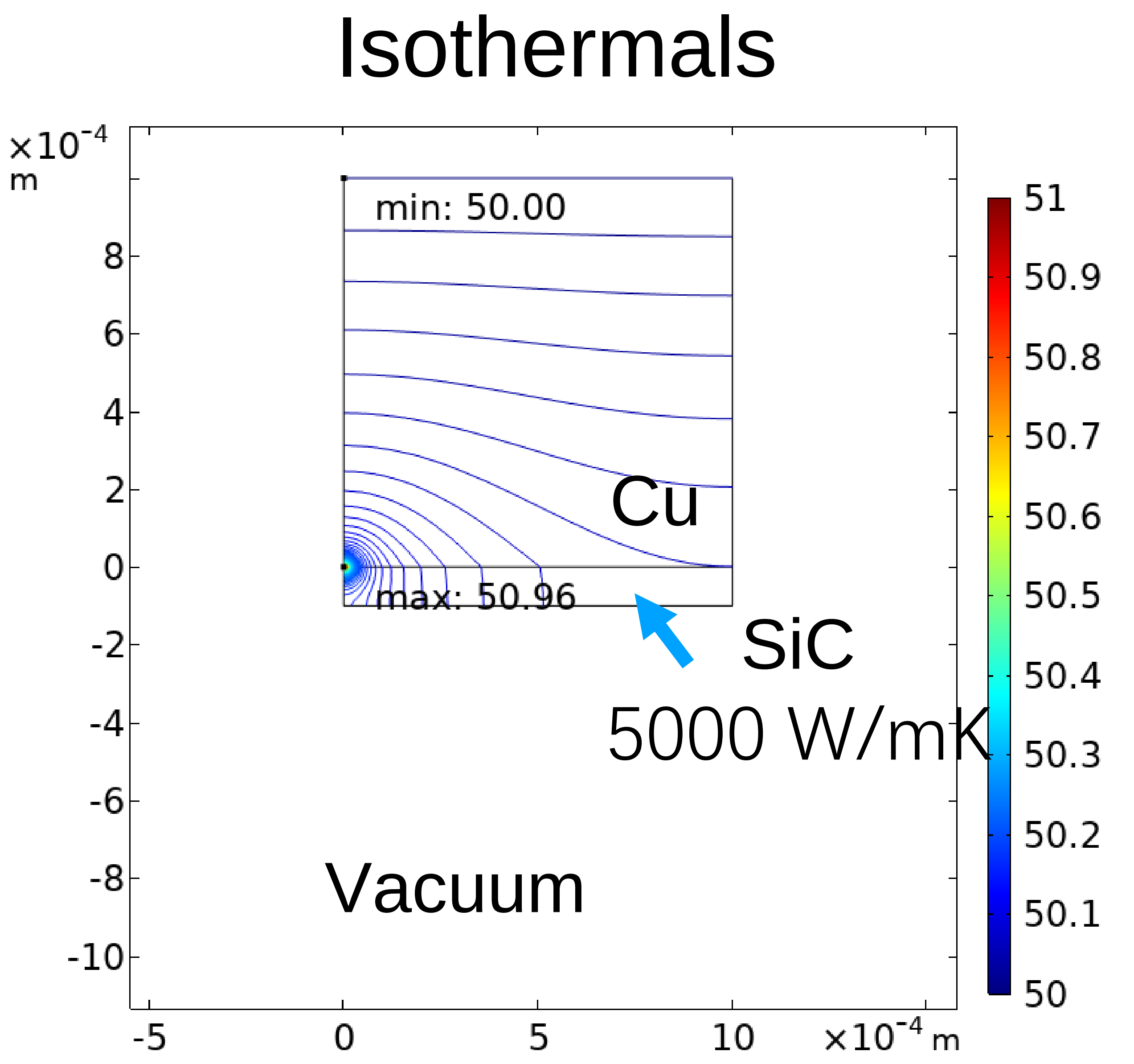
Related wo

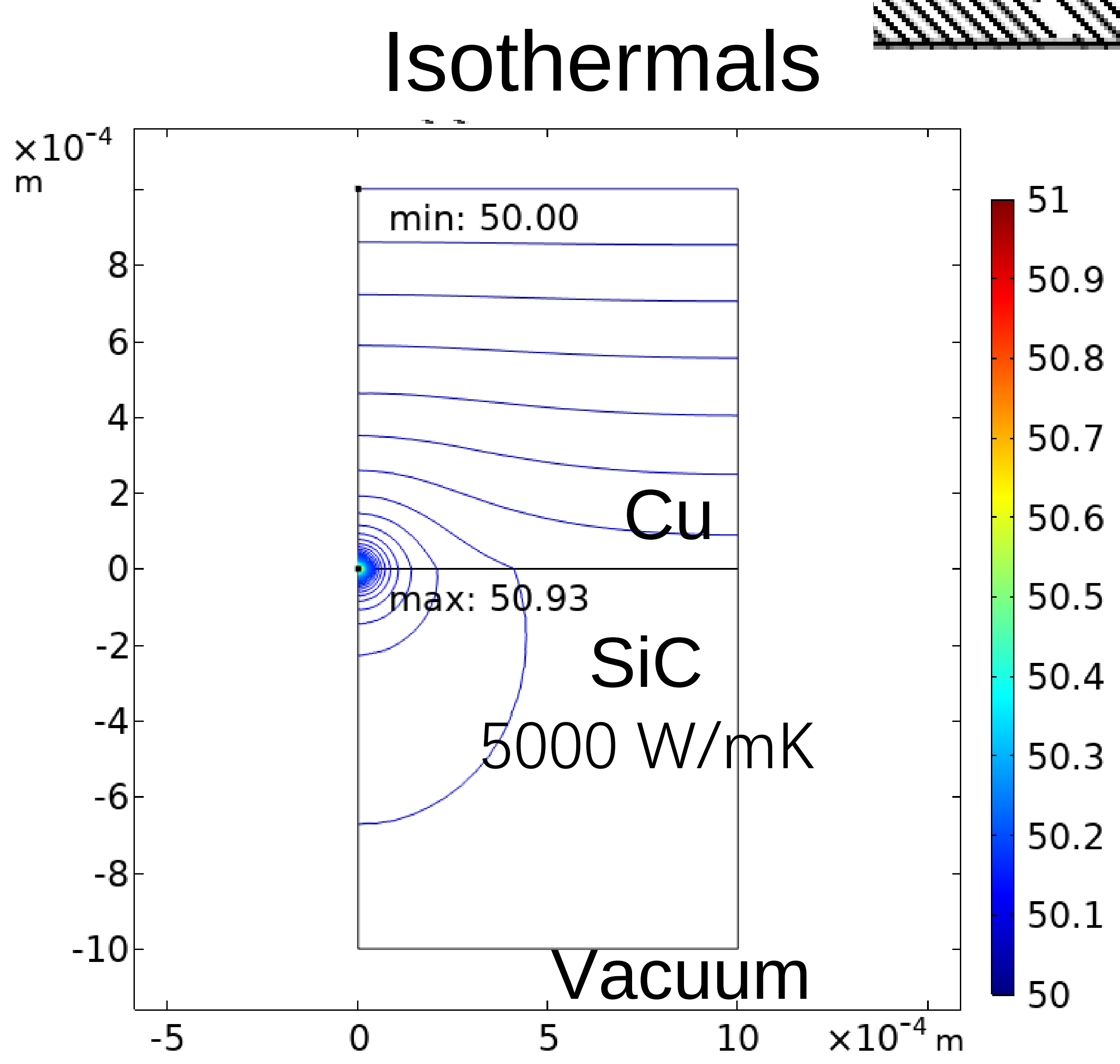
The outer wall already has LH superfluid.

Not DC, normal conducting metal will have current.









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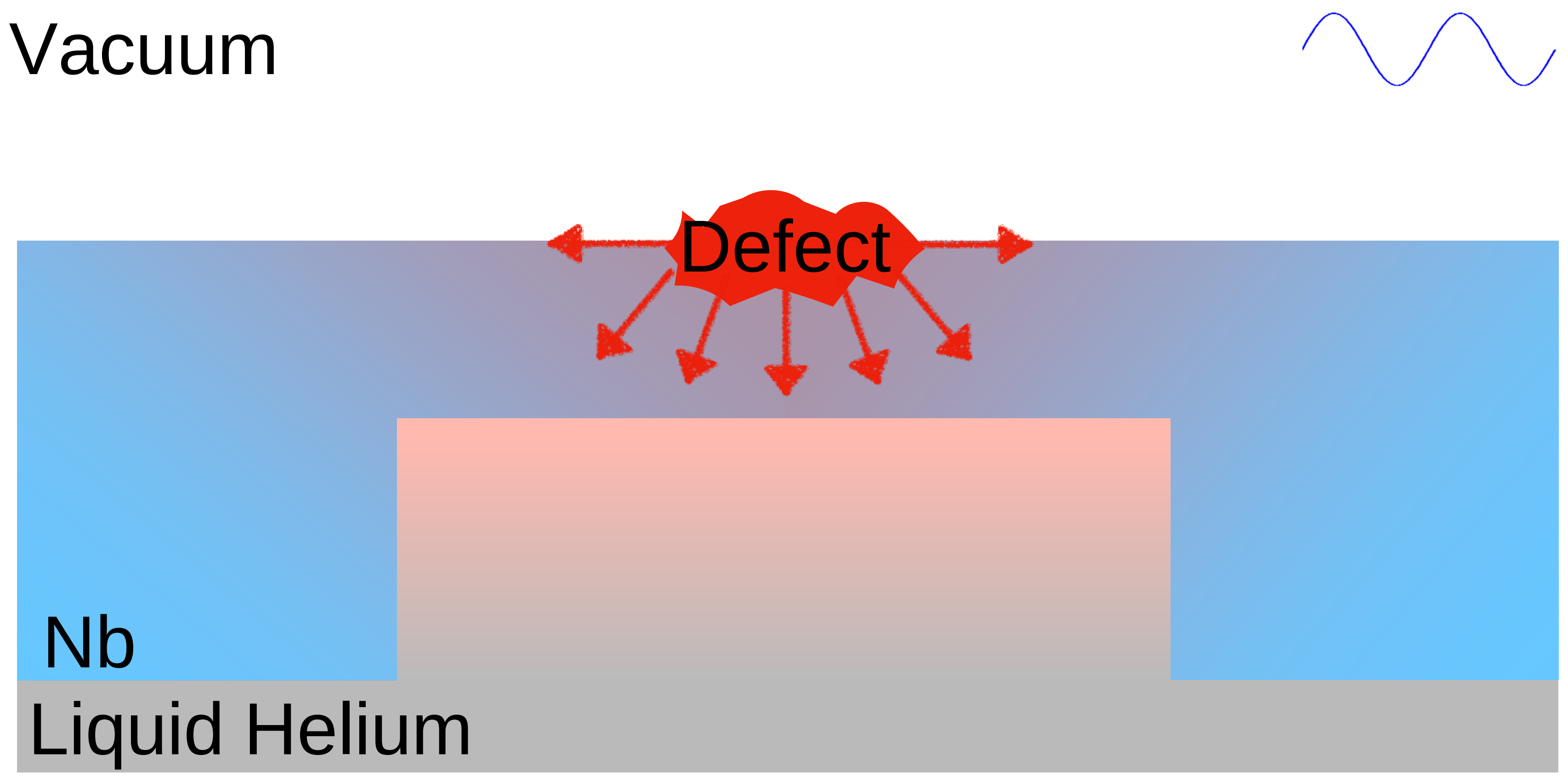
Summary

We started with the cavity degradations' appearance and found two strategies to increase the cavity's thermal conductivity--- the outer-wall groove structure (OGS) and the inner-wall thermal conducting film (ITCF). We performed COMSOL simulations and found them effective. We hope these two structures can improve the thermal conductivity, thus increasing the cavity's E_{acc} limit.

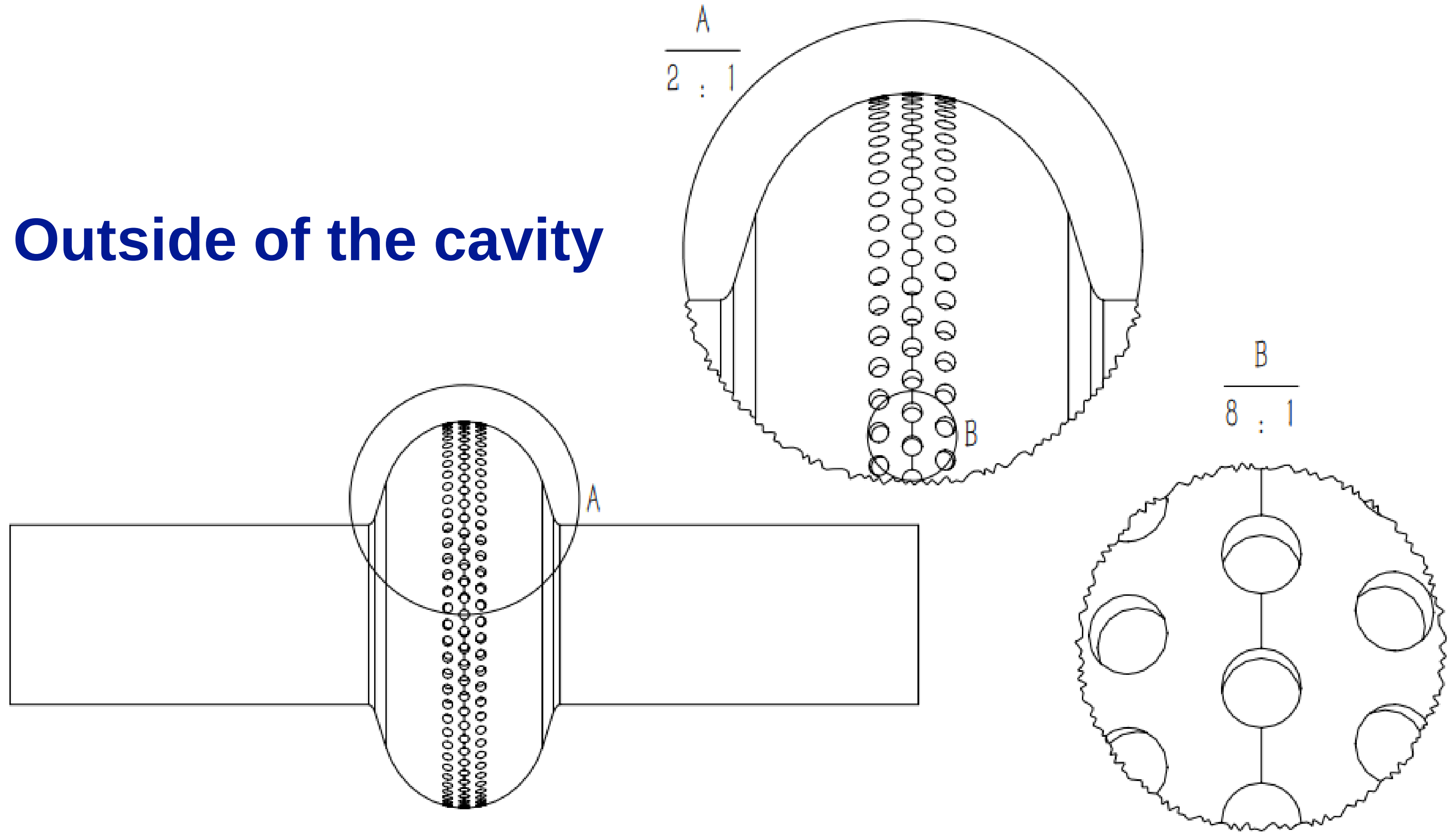
Thank you!

Thermal-conductivity-related New Strategy for Breaking the E_{acc} Limit

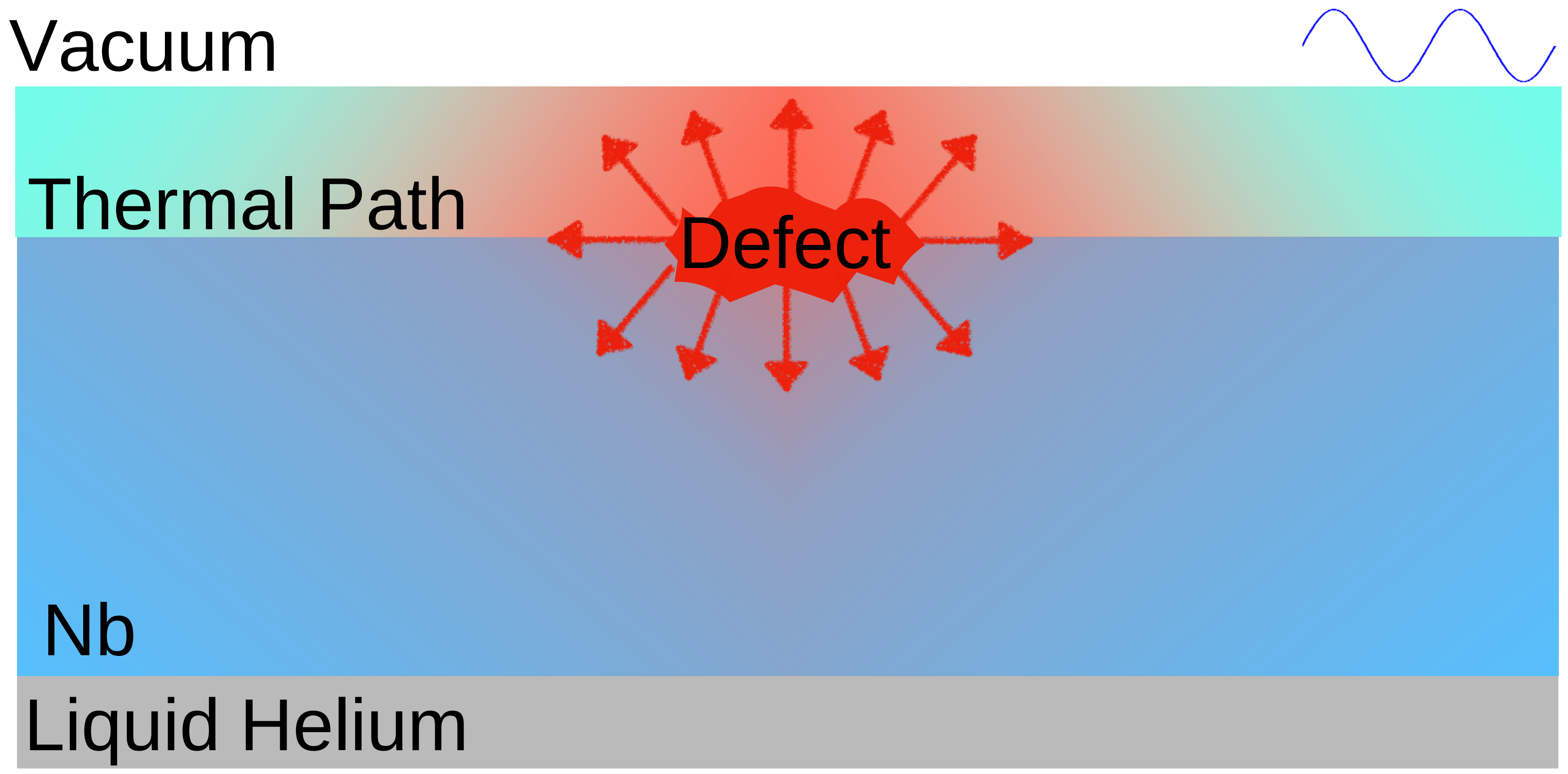
OGS



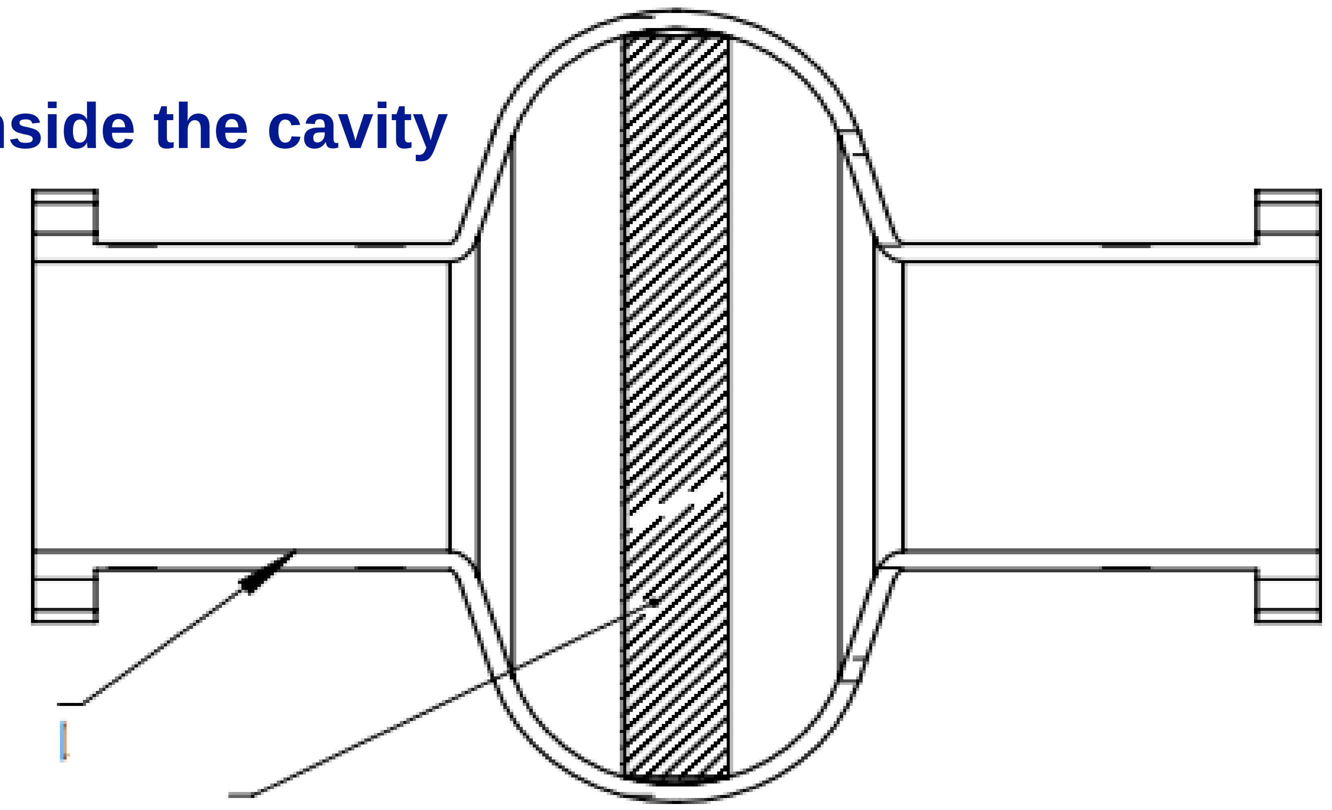
Outside of the cavity



ITCF



Inside the cavity



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