MICROSCOPIC INVESTIGATION OF MATERIALS LIMITATIONS OF SUPERCONDUCTING RF CAVITIES

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thinfilms and NEW IDEAS for SRF

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This work is funded by US Department of Energy grant # DESC0017931 and CNAM

Outline:

1. What is the issue?
2. Why is SRF material science needed?
3. How Magnetic Microwave Microscopy works?
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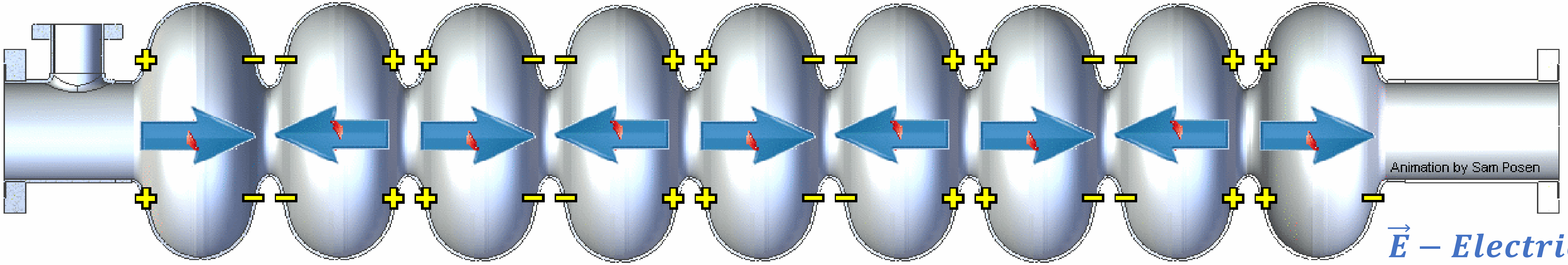
Superconducting Radio Frequency (SRF) Cavity

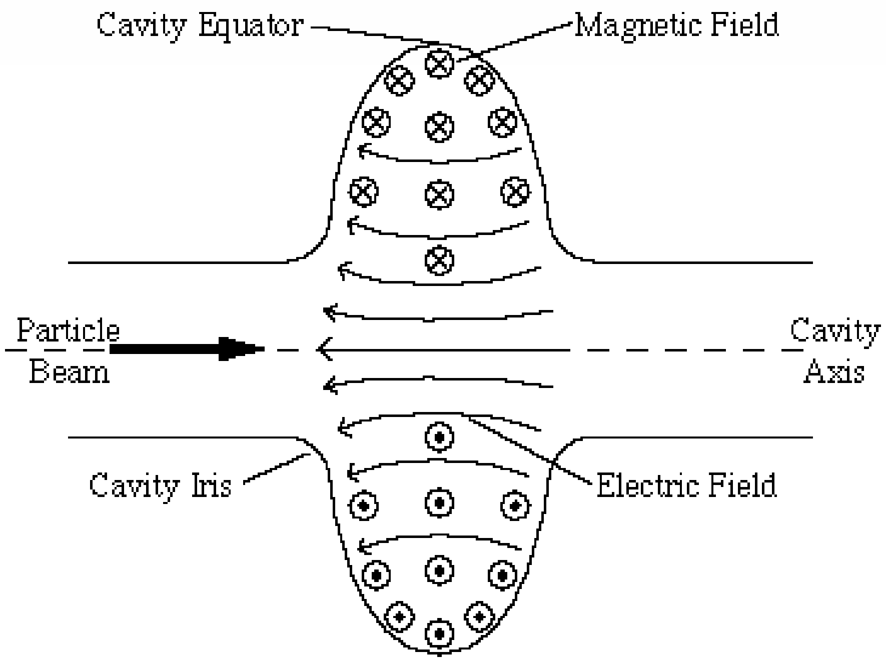


$\vec{E}$ – Electric Field

$\vec{B}$ – Magnetic Field

Charges

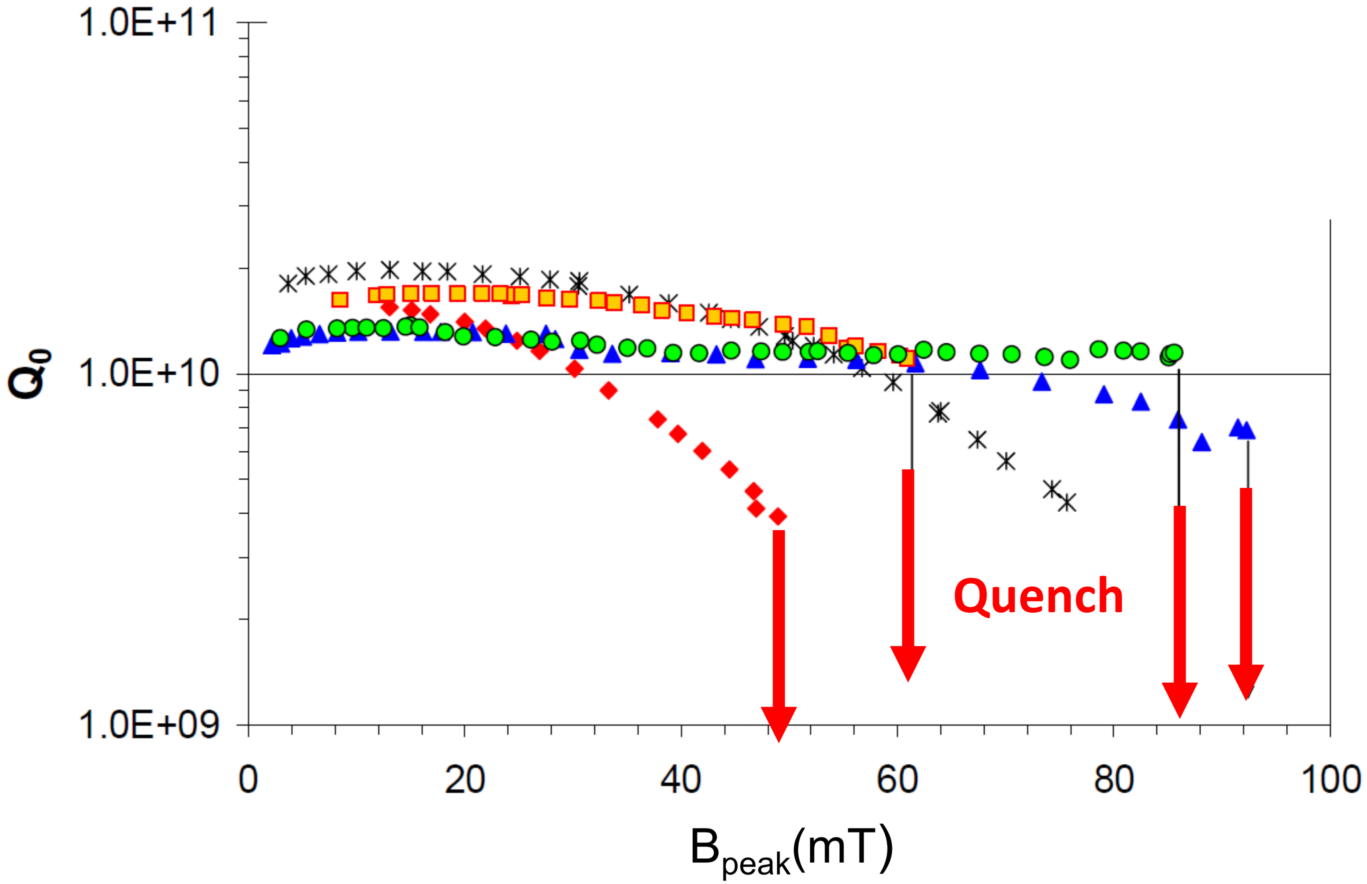
Beam Bunch



https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.buckets_and_bunches
http://mchung.unist.ac.kr/category/notesslides/

Increase Q => decrease required power

Quality factor vs Peak Field



Increase max E_{acc} => decrease accelerator length

Gianluigi Ciovati, Peter Kneisel, and Ganapati R. Myneni "America's Overview of Superconducting Science and Technology of Ingot Niobium" AIP Conference Proceedings 1352, 25 (2011); doi: 10.1063/1.3579221

RF test results at 2.0 K for the 1.497 GHz, 5-cell HC cavity after different surface preparation processes.

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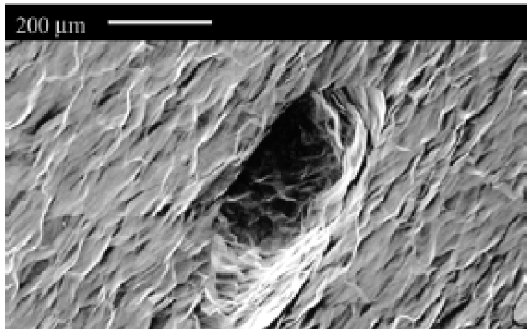
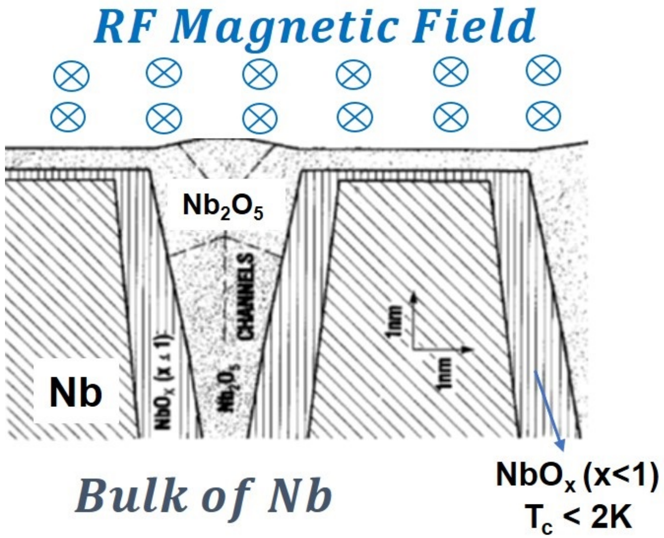
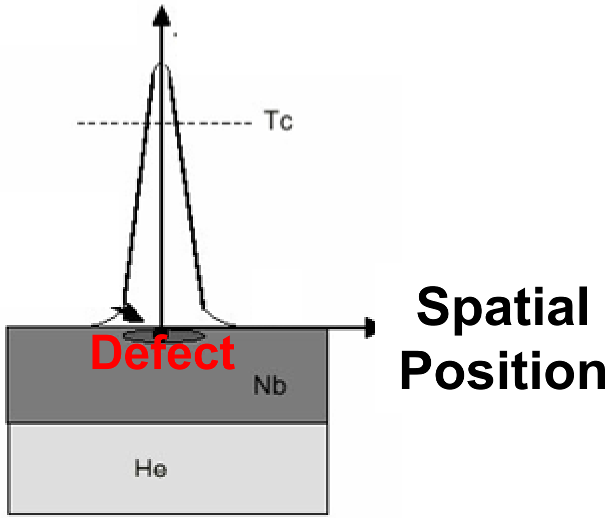
Defects/Processes limiting SRF Performance



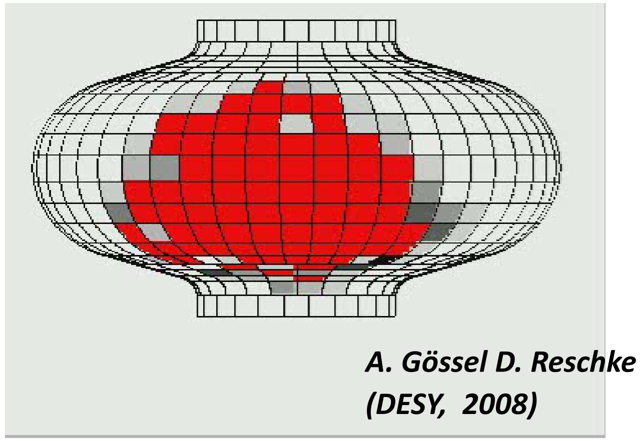
500 x 200 µm pit

1. **Surface Roughness**
2. **Pits**
3. **Welds**
4. **Grain Boundaries**
5. **Nb Oxides**
6. **Hydrogen Poisoning**
7. **Magnetic Impurities**
8. **Trapped Flux**





Cavity Temperature Map



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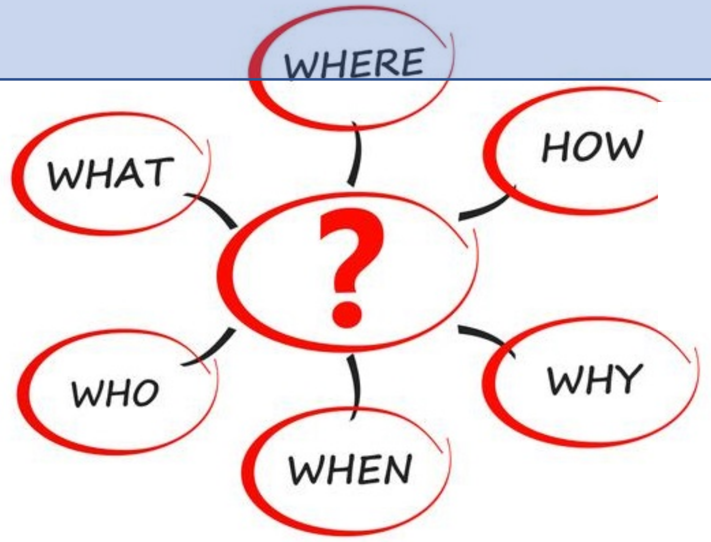
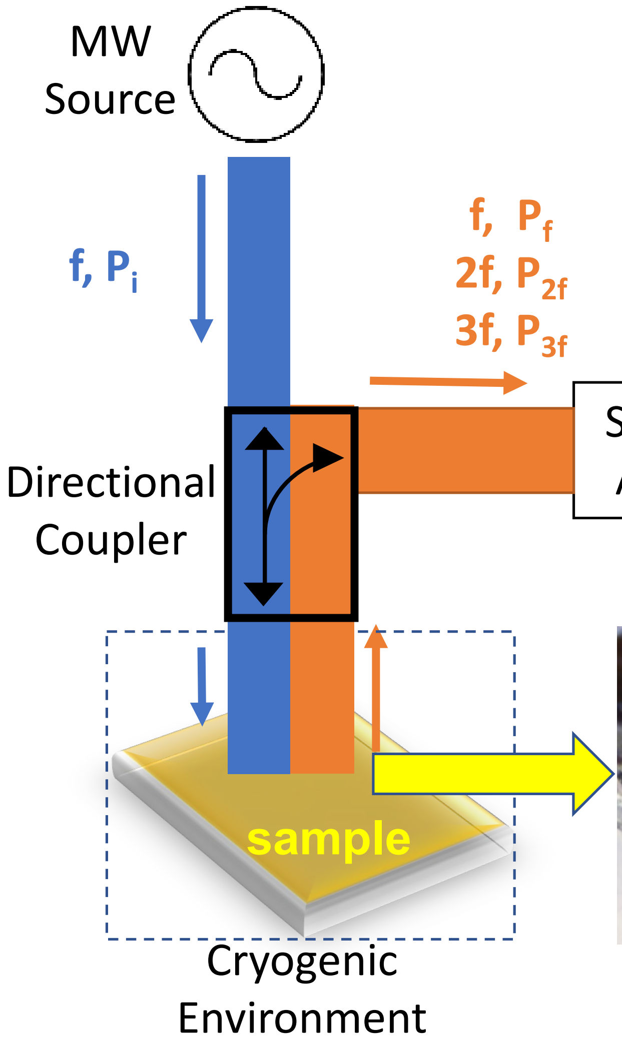
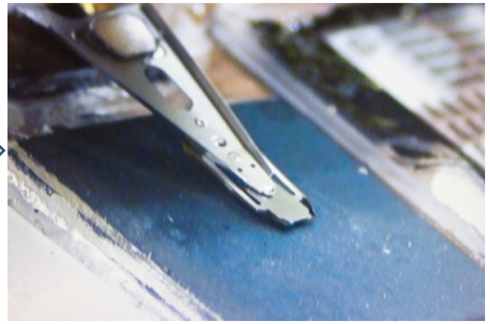
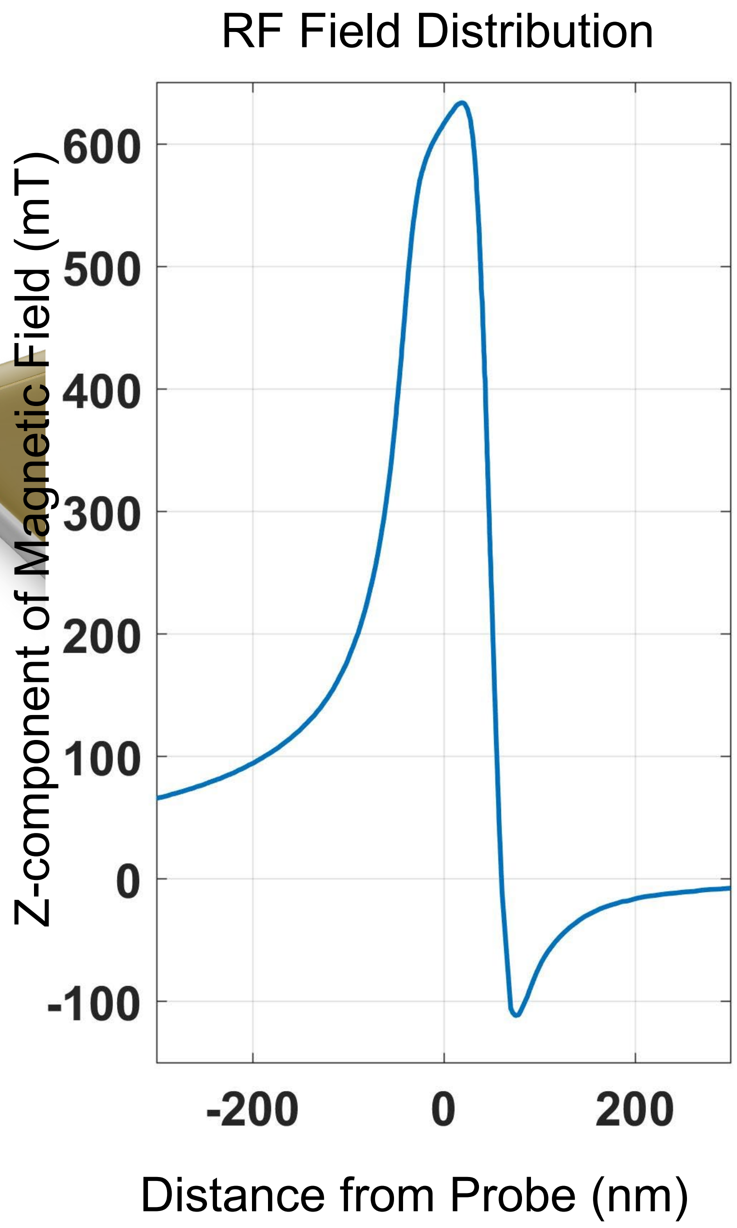


Near-Field B_{rf} Microscope

B_{rf} > 600 mT
Resolution < 100 nm



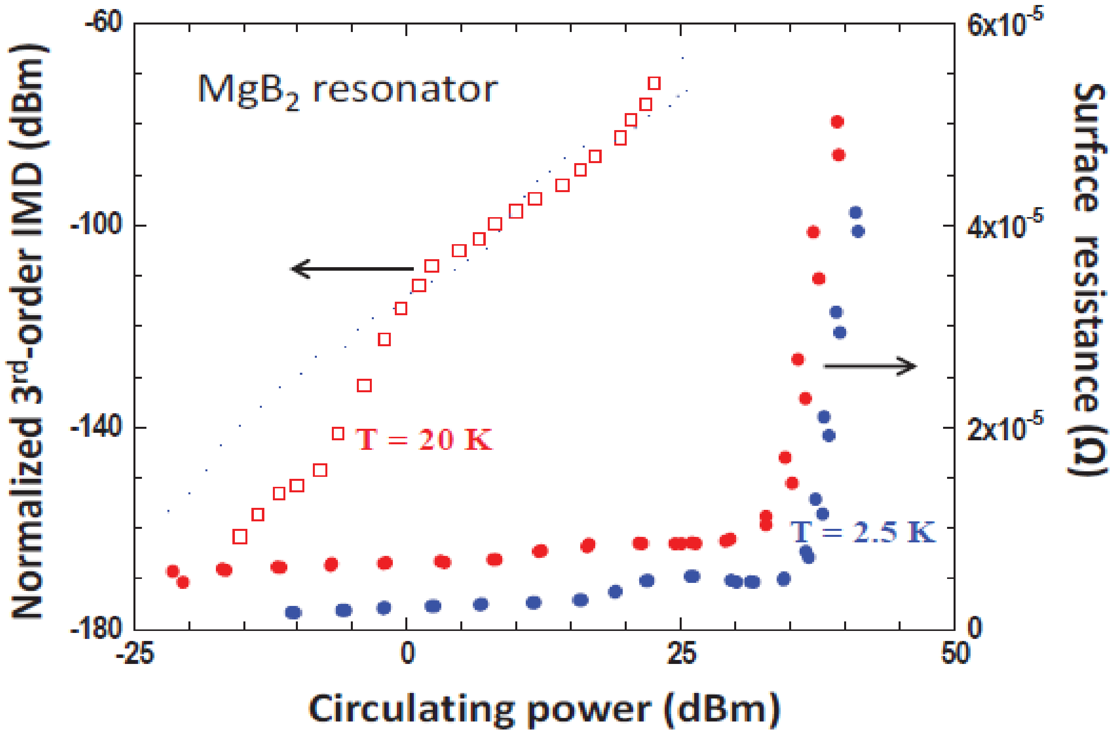




Courtesy
Mike Seigler
Seagate
(Assumes perp. recording, magnetic medium with soft underlayer)

Why Harmonics?

1)



D. E. Oates, Y. D. Agassi, B. H. Moeckly,

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 17, NO. 2, JUNE 2007

2) **Superconductor is the main source of Nonlinearity**

Advantages of this method

	SRF	Magnetic Probe Microscopy
Temperature	2 K	3.6 K - T_c
RF Magnetic Field	≈ 200 mT	≈ 200 mT
Frequency	1.3 GHz	1.0 – 6.0 GHz

- **RF Characterization**
- **Localized / No Edge Effect**
- **Can Measure Flat Samples of any shape**

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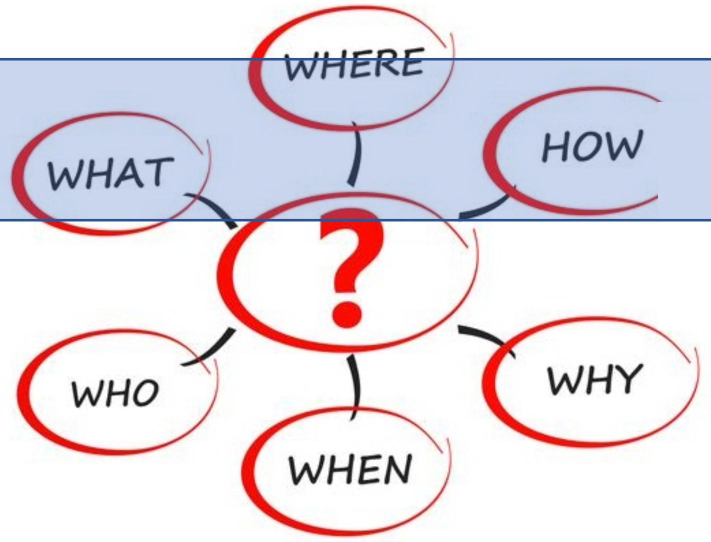
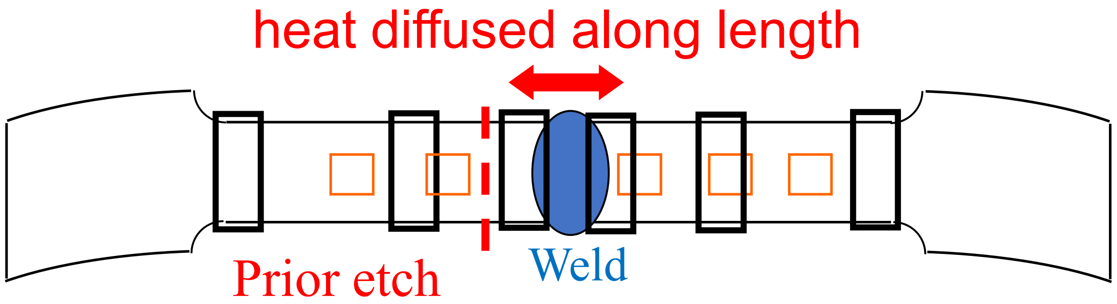


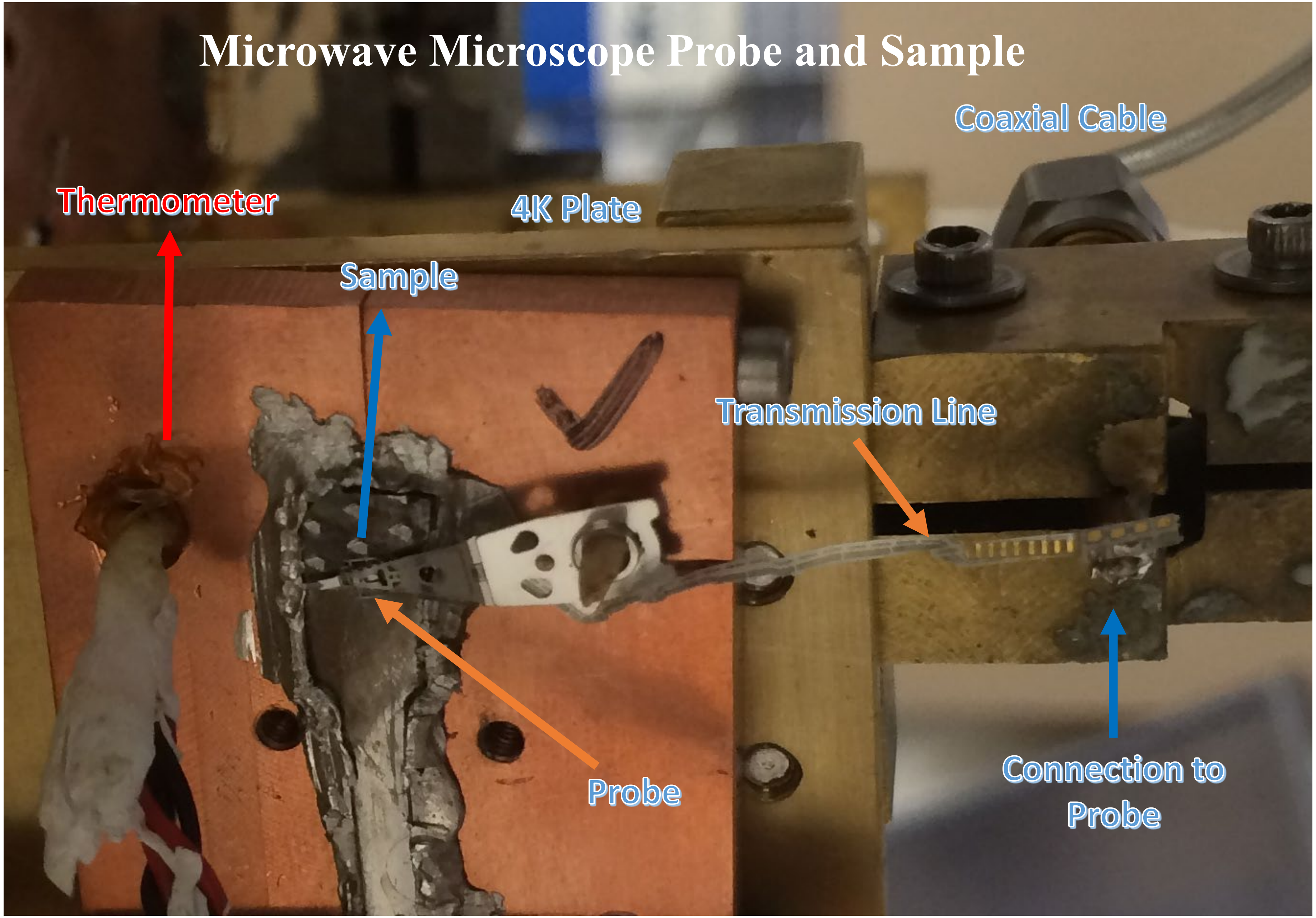
Bulk Nb Sample



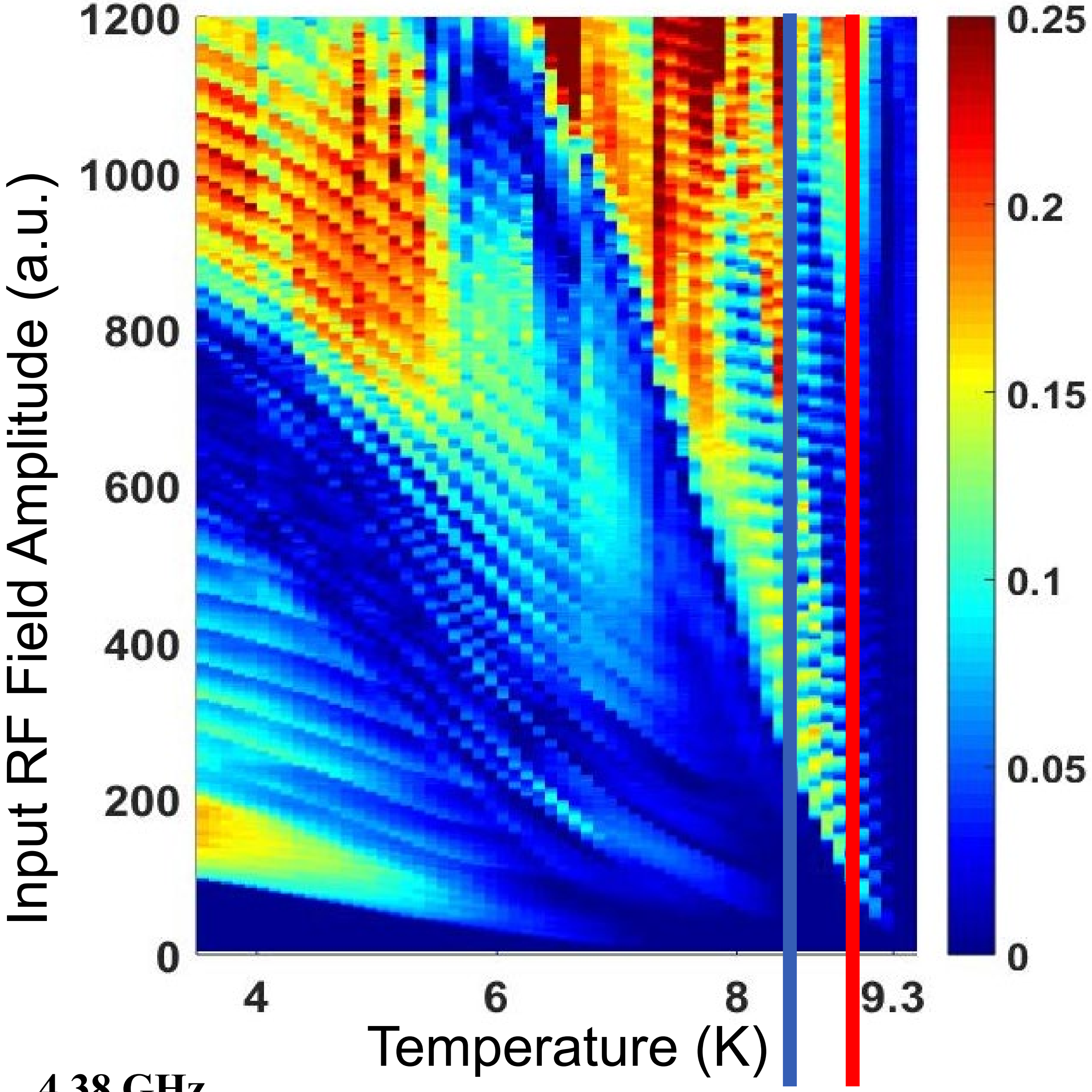
Deformed ($\epsilon \sim 0.4$) single crystals
pulled apart,
Etched for 10 min
then welded back together

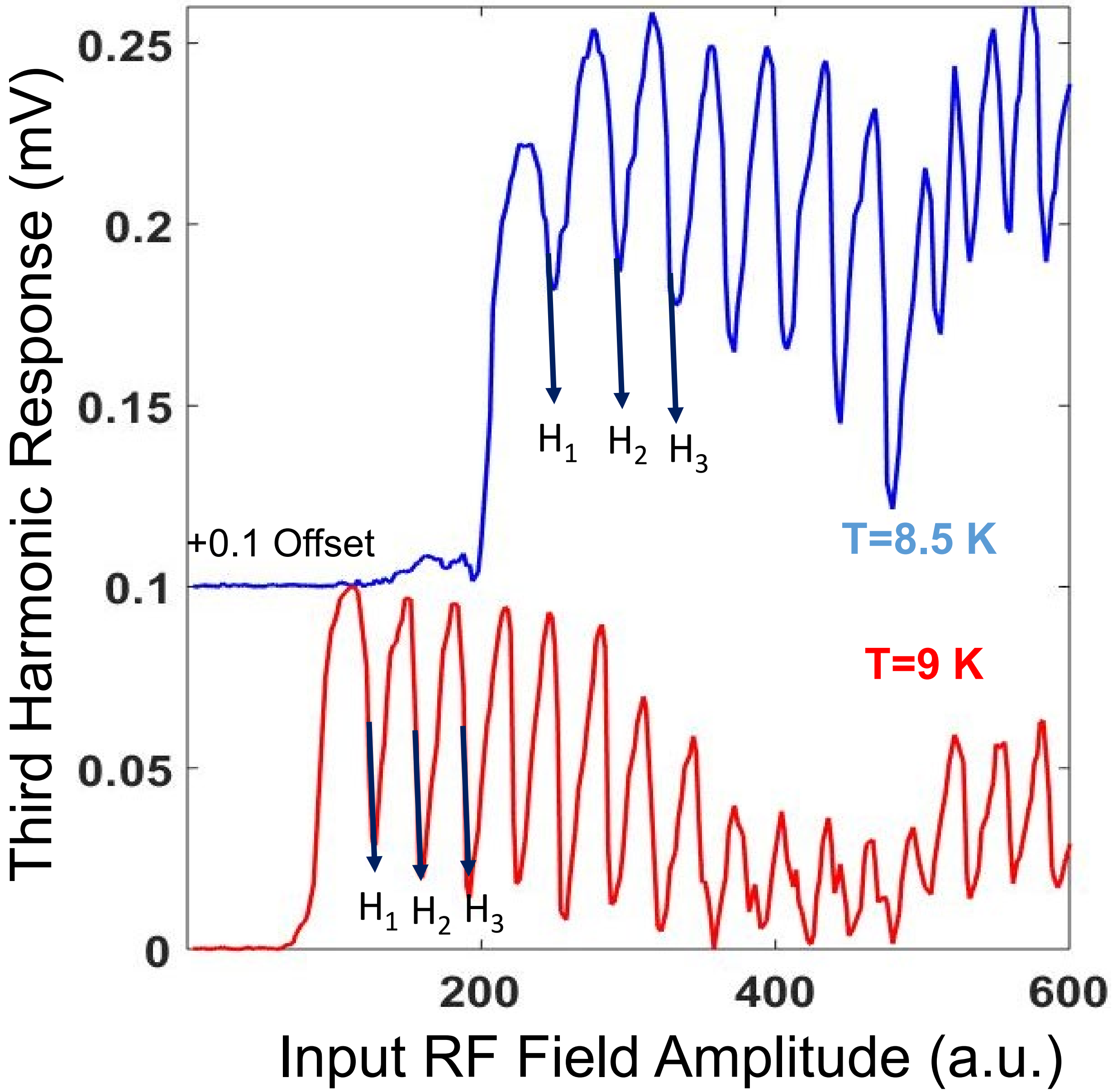
Sample prepared by Tom Bieler,
Michigan State University

MICHIGAN STATE UNIVERSITY


Microwave Microscope Probe and Sample
Coaxial Cable
Thermometer
4K Plate
Sample
Transmission Line
Probe
Connection to Probe

Bulk Nb Data: Periodicity in Harmonic Response

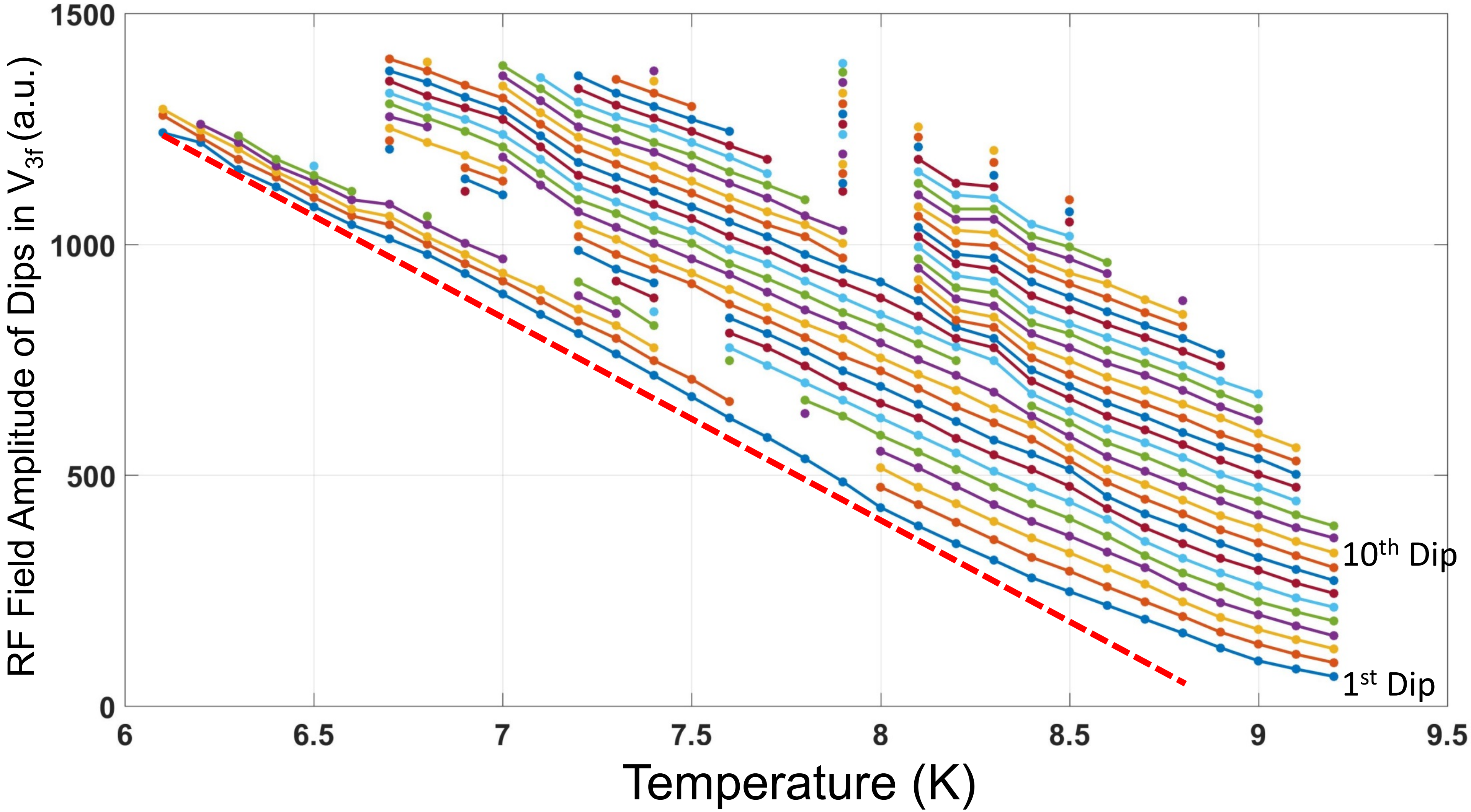




4.38 GHz

Probe background nonlinearity subtracted

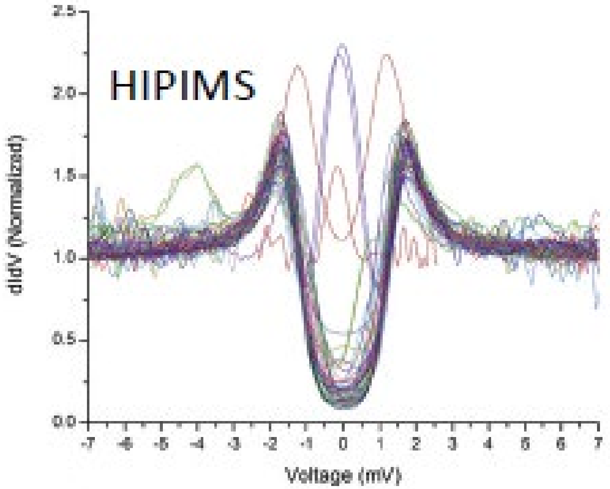
Bulk Nb Data: Closer look at Dips

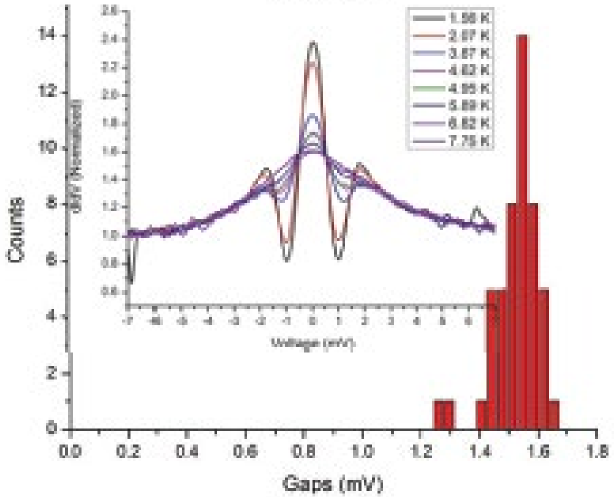


Dots = Data, Lines are a guide to the eye

Nb Film on Copper samples from CERN

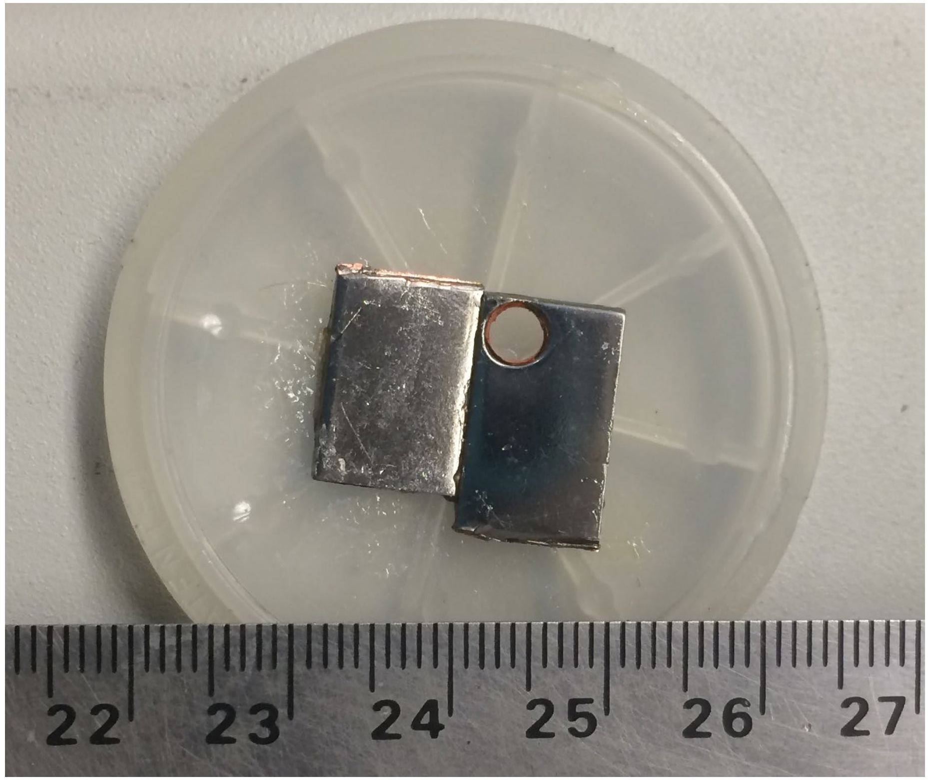
- Deposited by high-power impulse magnetron sputtering (HIPIMS)
- Highly Granular (grain size around 10 nm)
- 1 μm Nb / Cu





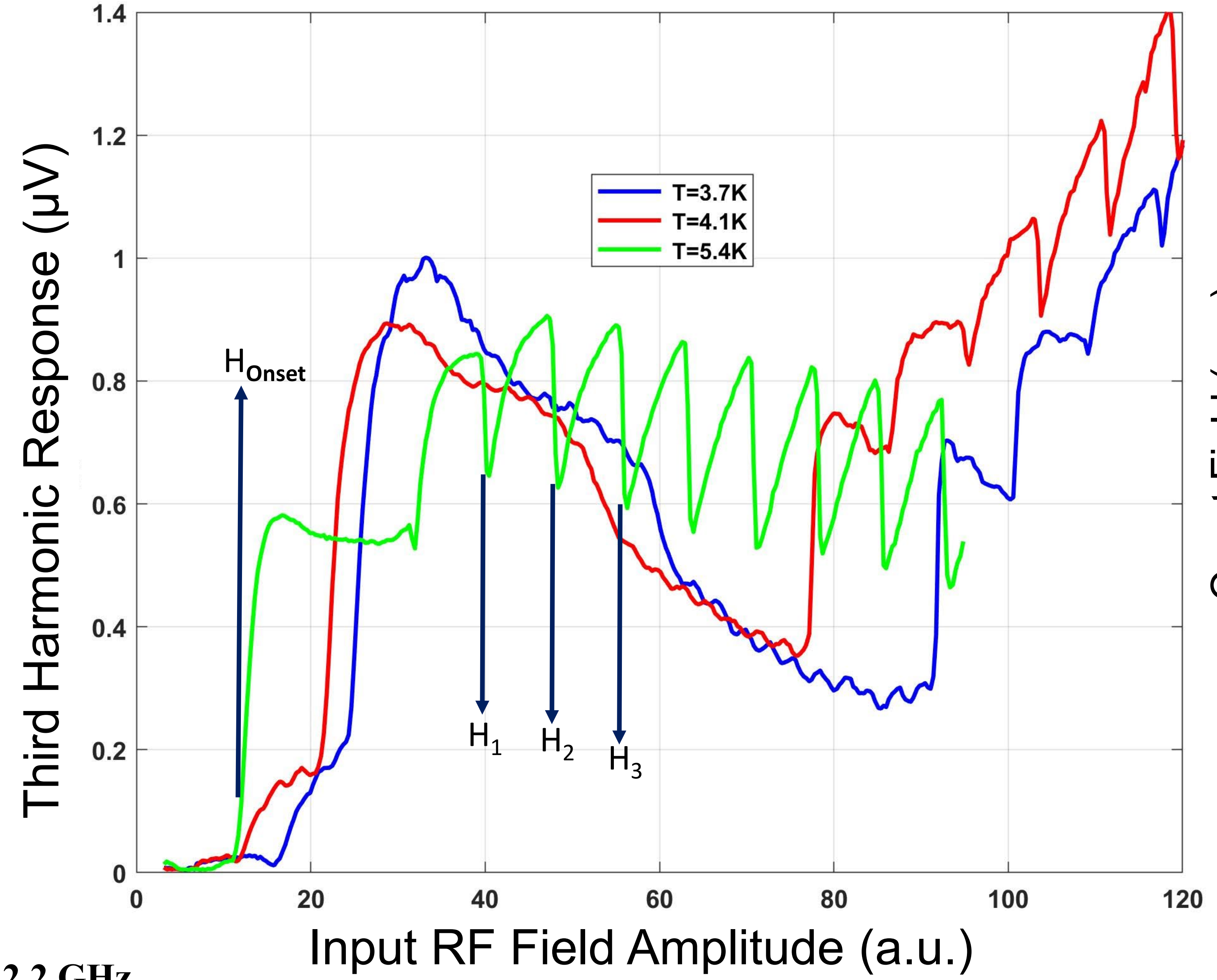
Point Contact Spectroscopy:

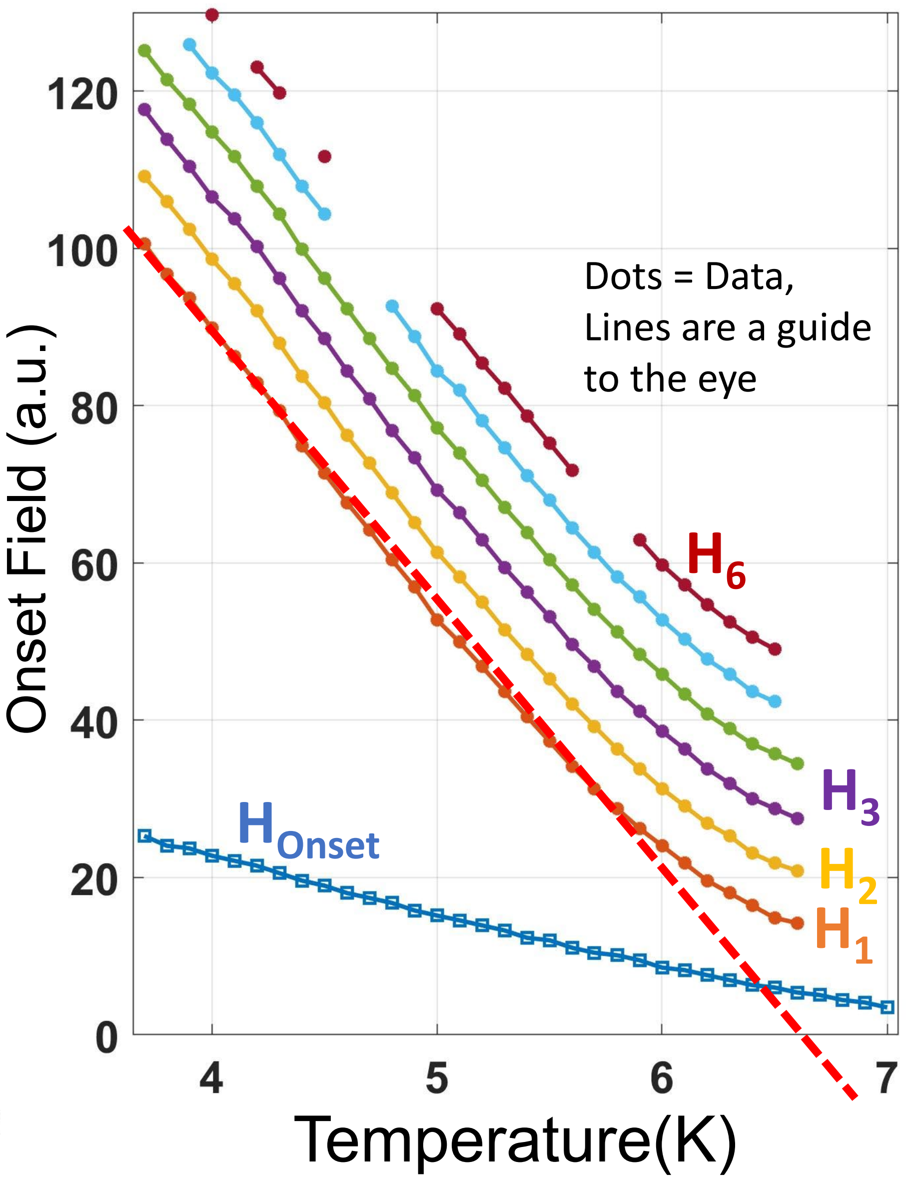
- ✓ **Broadened DOS**
- ✓ **Finite 0-bias conductance (ZBC)**
- ✓ **Numerous ZBCP**



T. Junginger, SRF2015, TUPB042

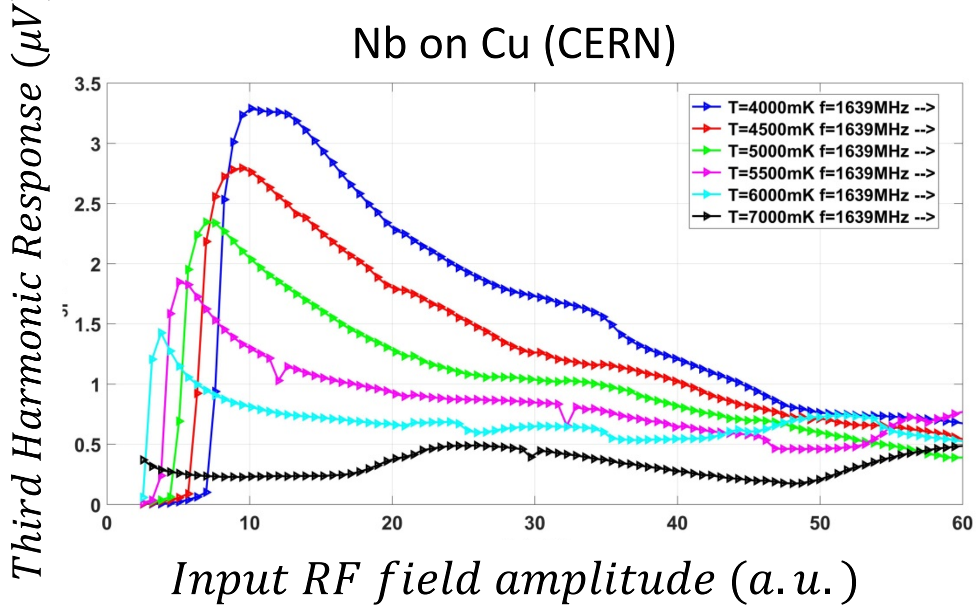
Nb on Copper samples from CERN

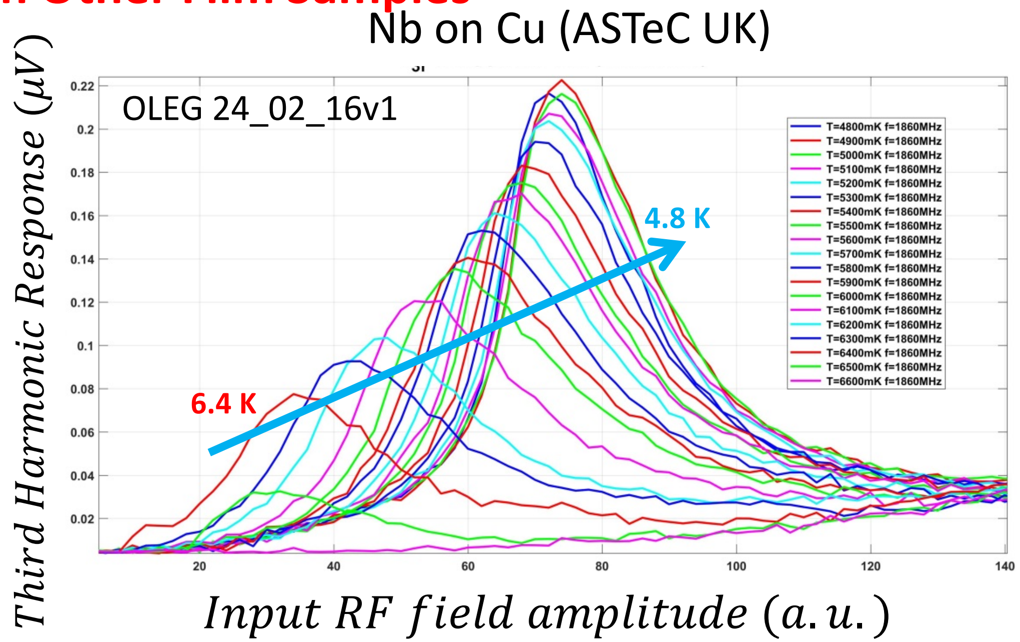


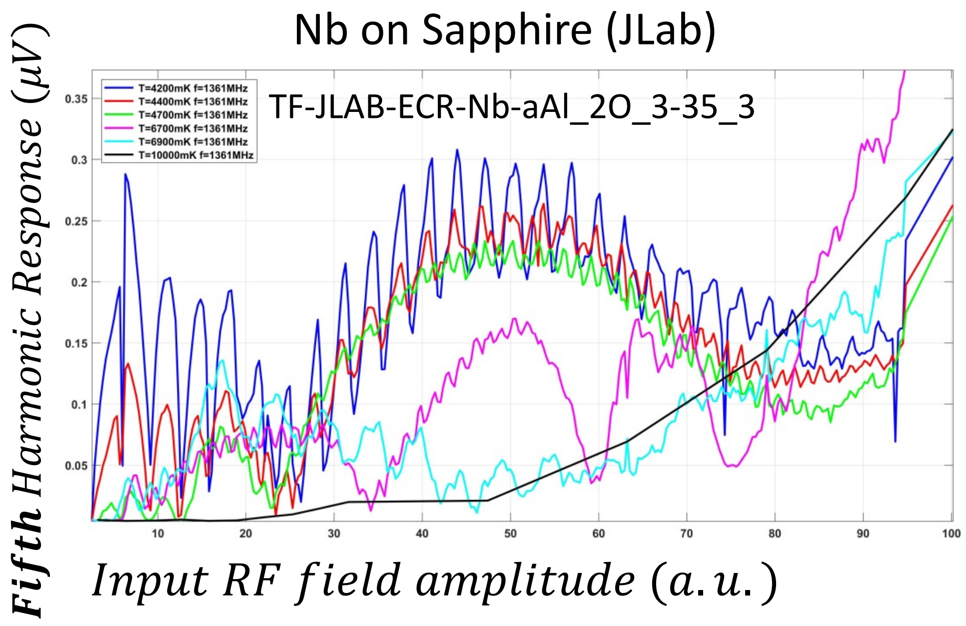


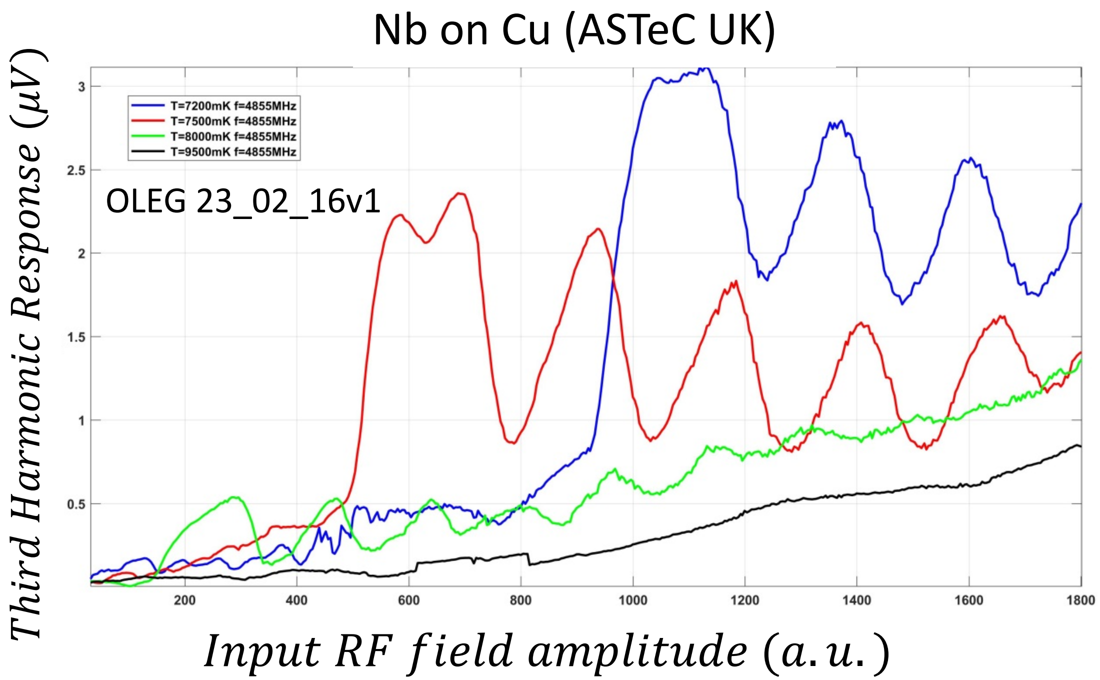
2.2 GHz

Similar Results Seen on Other Film Samples

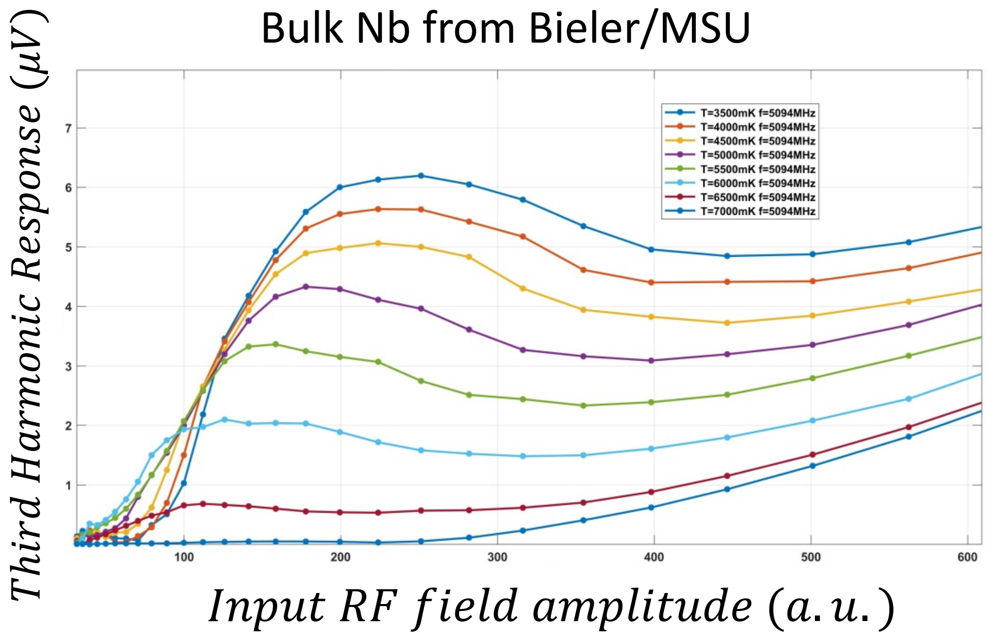


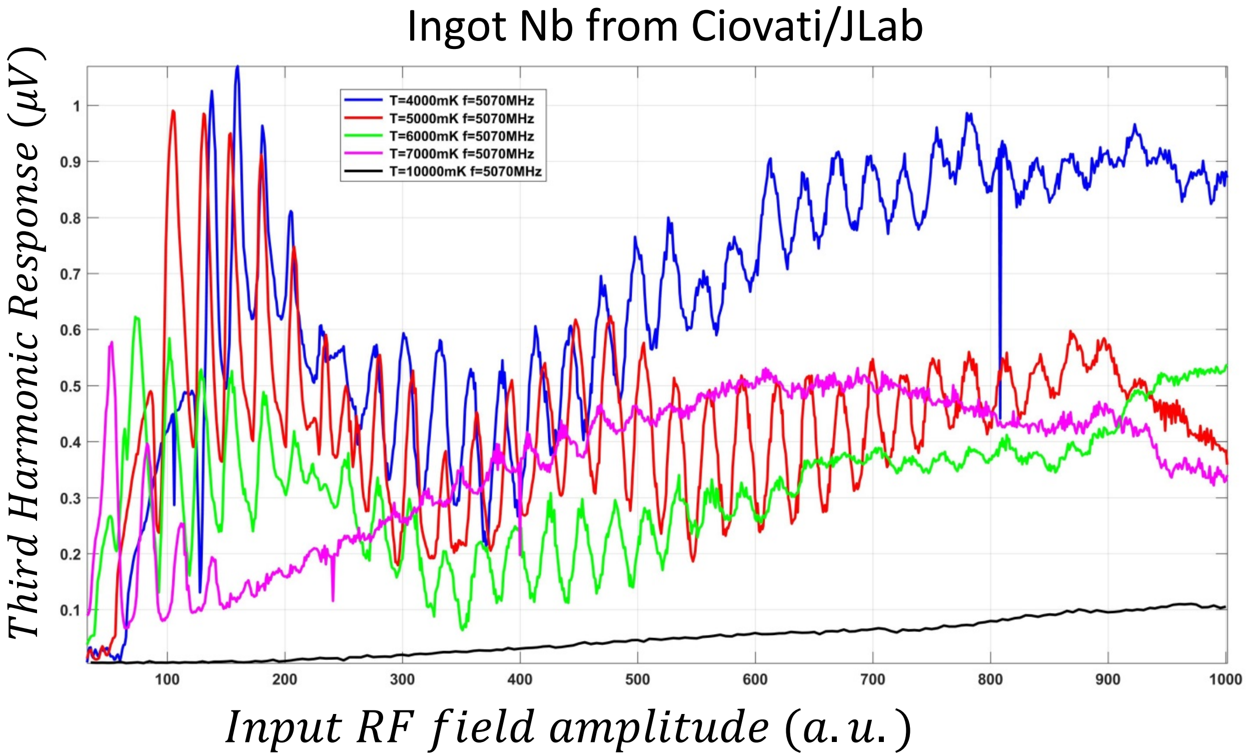






Similar Results Seen on Bulk Samples





Bulk and Film samples can show either periodic or non-periodic harmonic response depending on location

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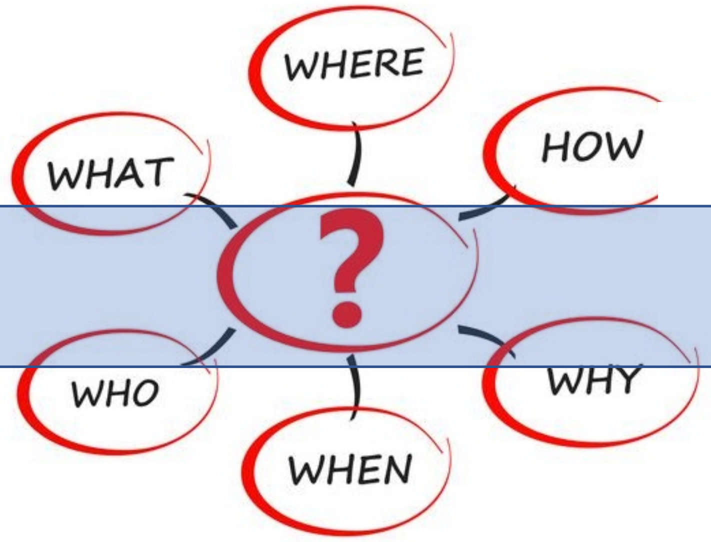
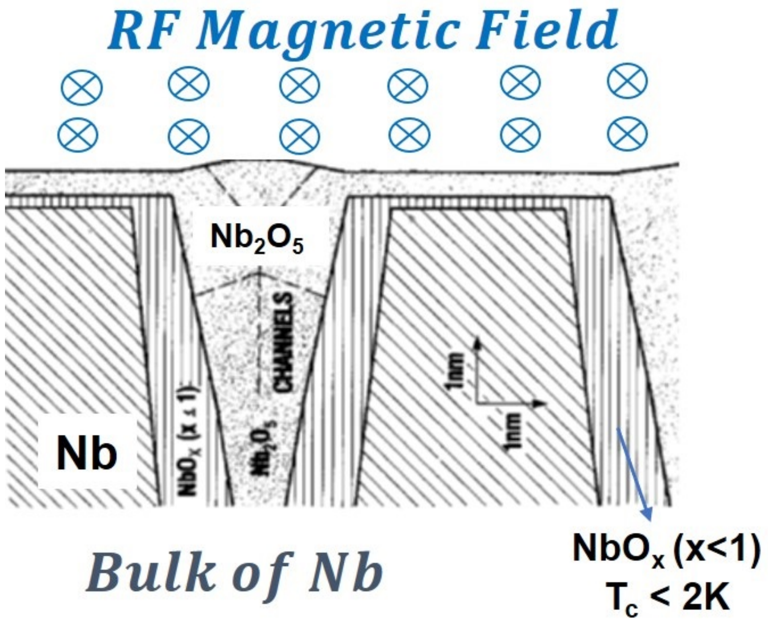
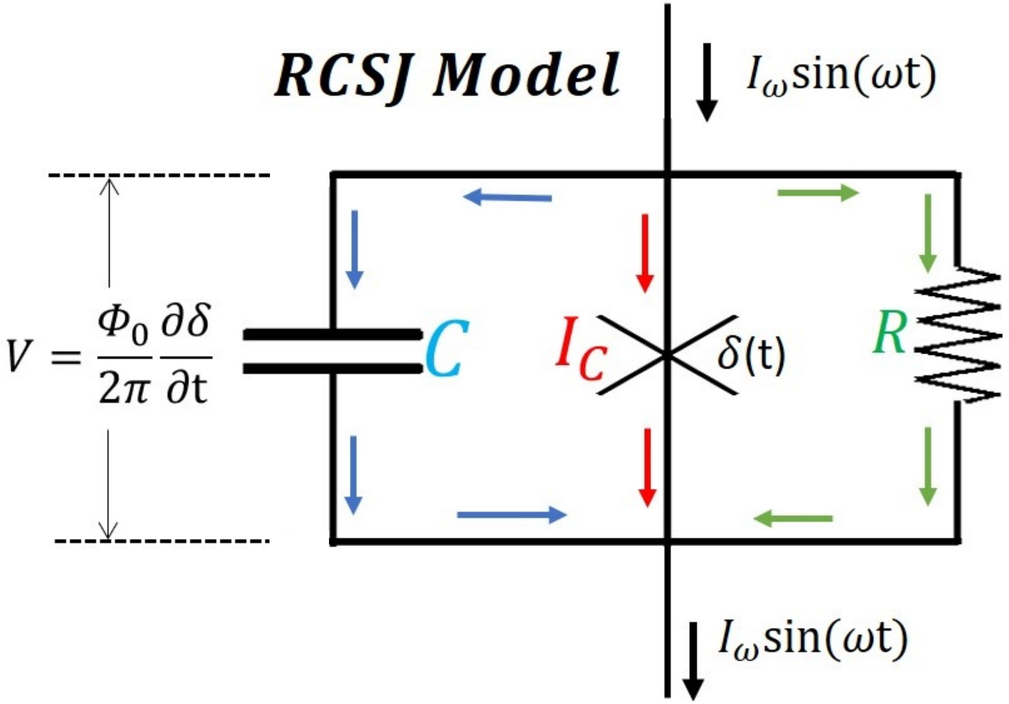


Current Driven Resistively and Capacitively Shunted Josephson Junctions (RCSJ) model



J. Halbritter, " **On the Oxidation and on the Superconductivity of Niobium,"** J. Appl. Phys. A 43, 1 (1987).



$$\frac{\Phi_0 C}{2\pi}\frac{\partial^2\delta}{\partial t^2} + I_C sin\delta + \frac{\Phi_0}{2\pi R_n}\frac{\partial\delta}{\partial t} = I_\omega \sin(\omega t)$$

J. McDonald and John R. Clem, " **Microwave response and surface impedance of weak links,"** Phys. Rev. B 56, 14723 (1997).

Alternative proposal
(Kubo and Gurevich, Monday talk)
S'-I-S layering

Solution to the RCSJ Model

$$\frac{\Phi_0 C}{2\pi}\frac{\partial^2\delta}{\partial t^2} + I_C sin\delta + \frac{\Phi_0}{2\pi R_n}\frac{\partial\delta}{\partial t} = I_\omega \sin(\omega t)$$

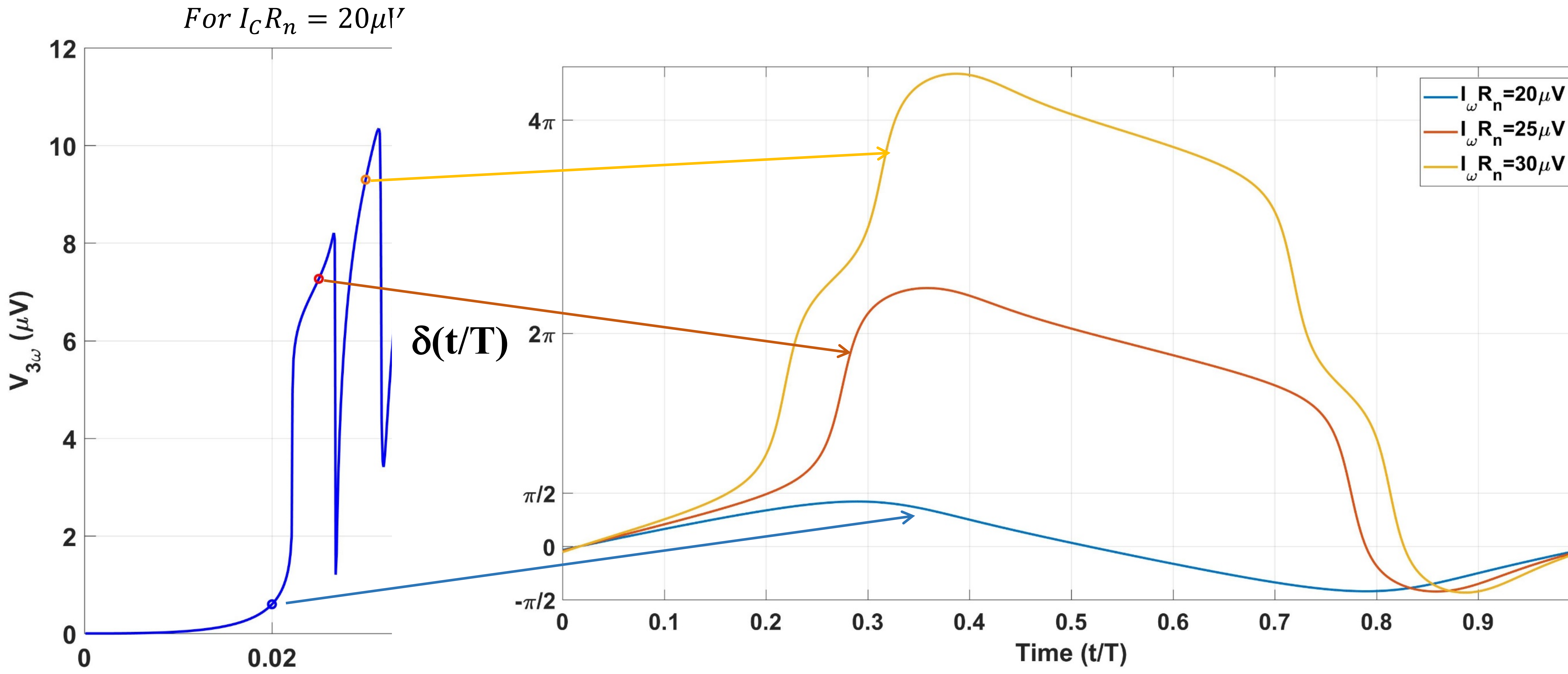
Short Junction Approximation
All Dimensions Perpendicular to the field << λ_J

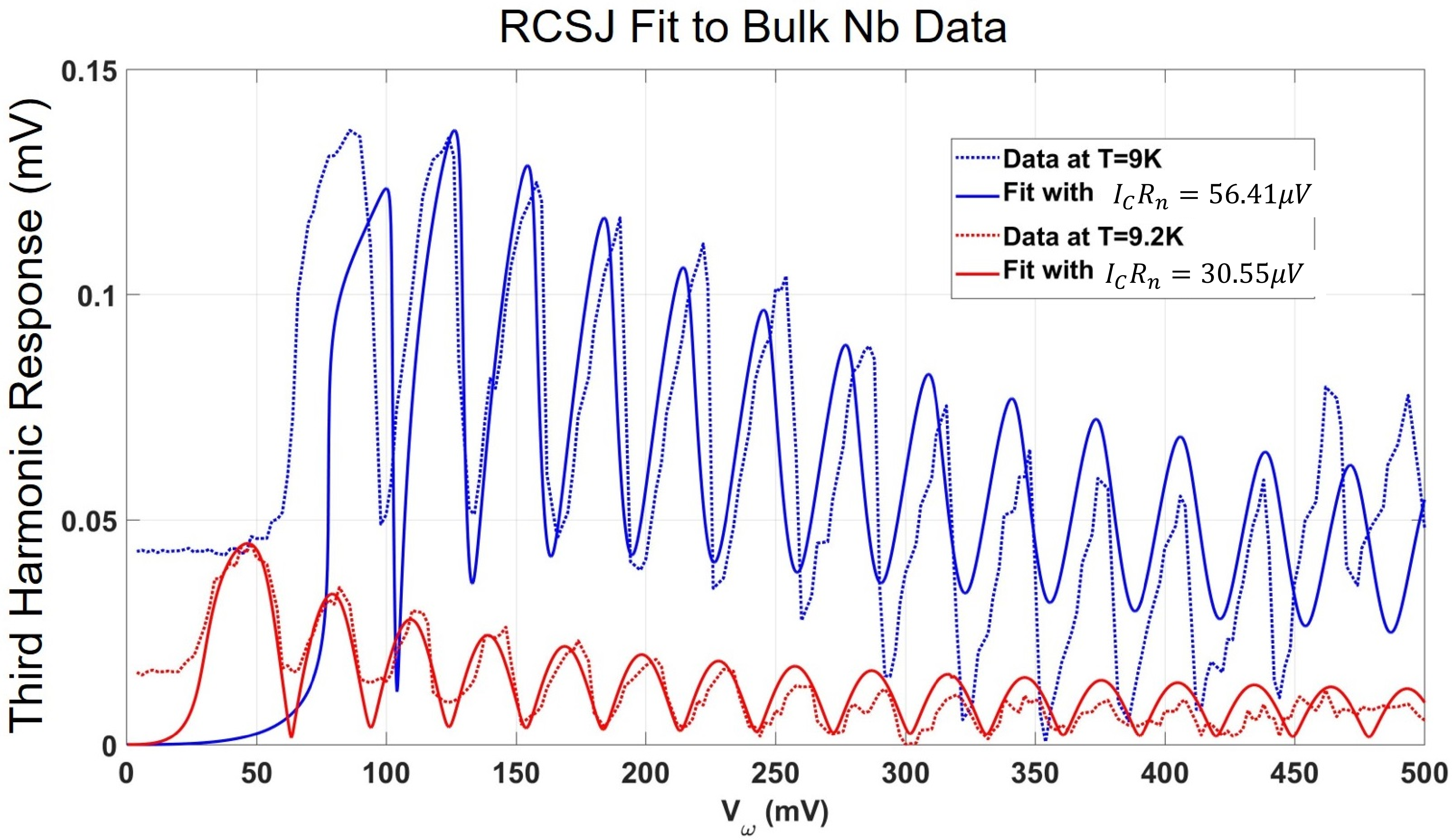
$$(I_C R_n) sin\delta + \frac{\Phi_0}{2\pi}\frac{\partial\delta}{\partial t} = (I_\omega R_n)\sin(\omega t)$$

$\boldsymbol{I_C R_n}$ - Fitting Parameter
$\boldsymbol{I_\omega R_n}$- ScalingFactor * Input RF Field Amplitude (a.u.)

$$\boldsymbol{\delta(t) \to V(t) \to V_{3\omega}}$$

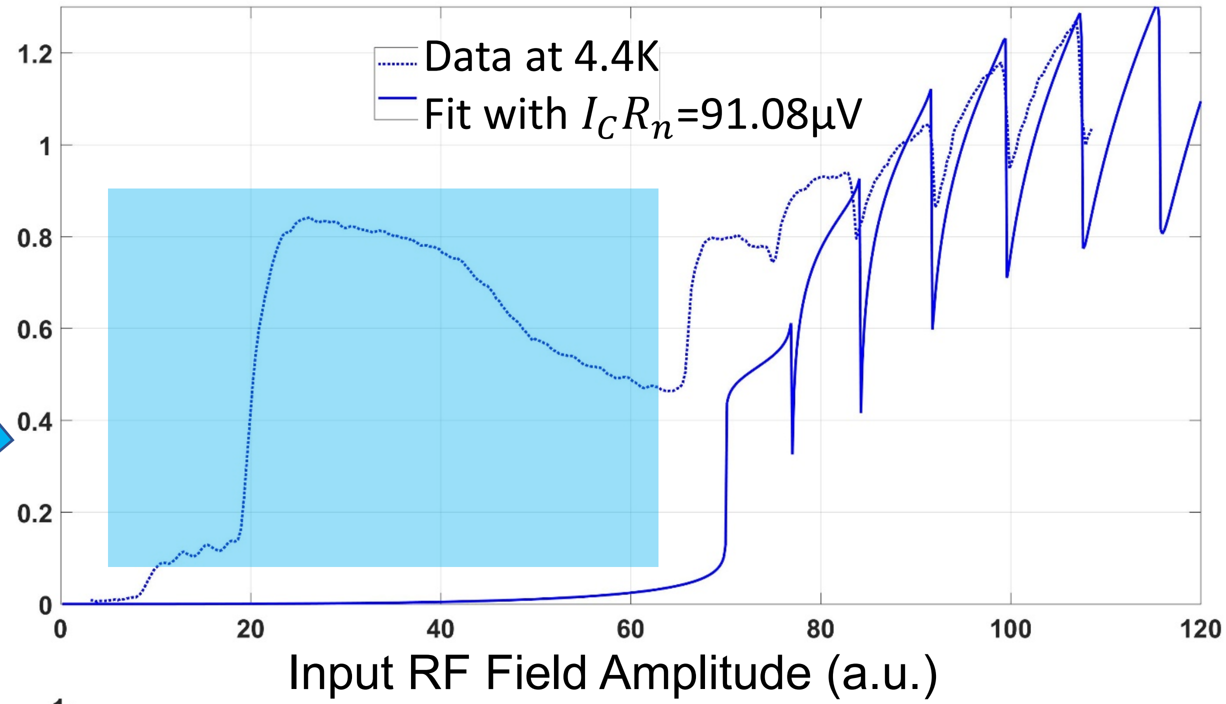
Example Solution to the RCSJ Model



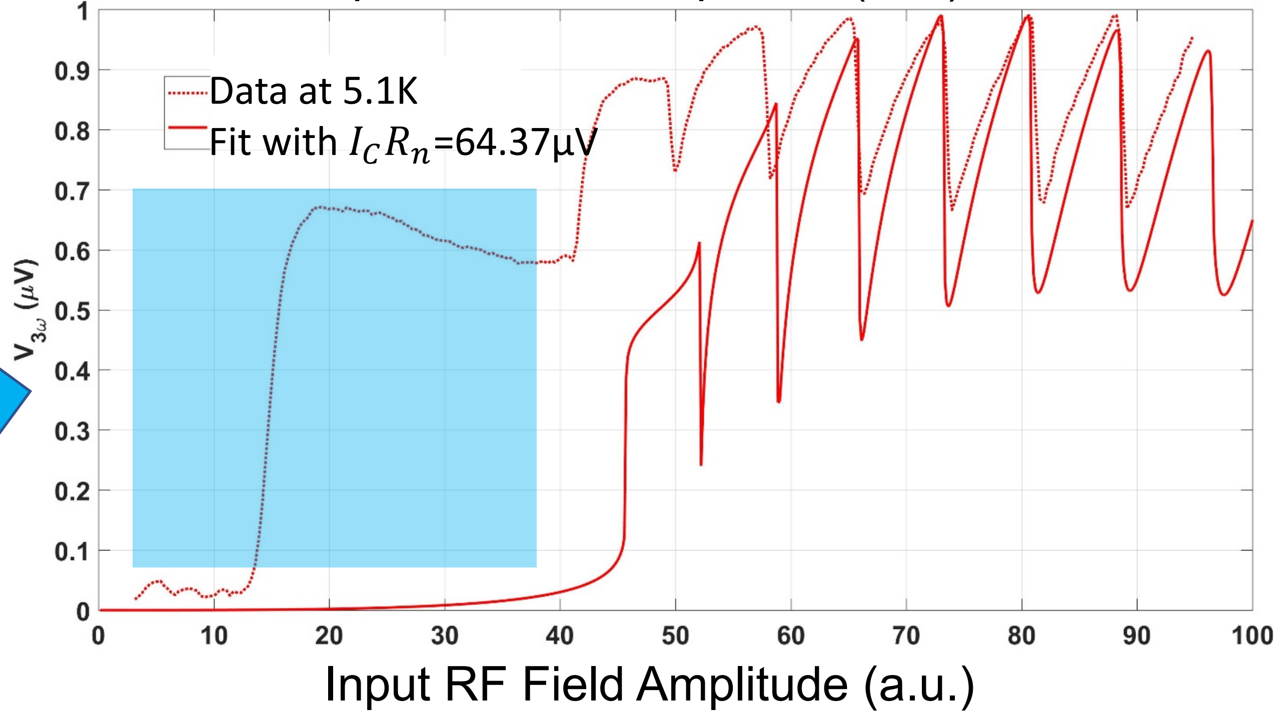


RCSJ Fit to Bulk Nb Data
Third Harmonic Response (mV)
0.15
0.1
0.05
0
0
50
100
150
200
250
300
350
400
450
500
V_ω (mV)
Data at T=9K
Fit with $I_C R_n = 56.41\mu V$
Data at T=9.2K
Fit with $I_C R_n = 30.55\mu V$

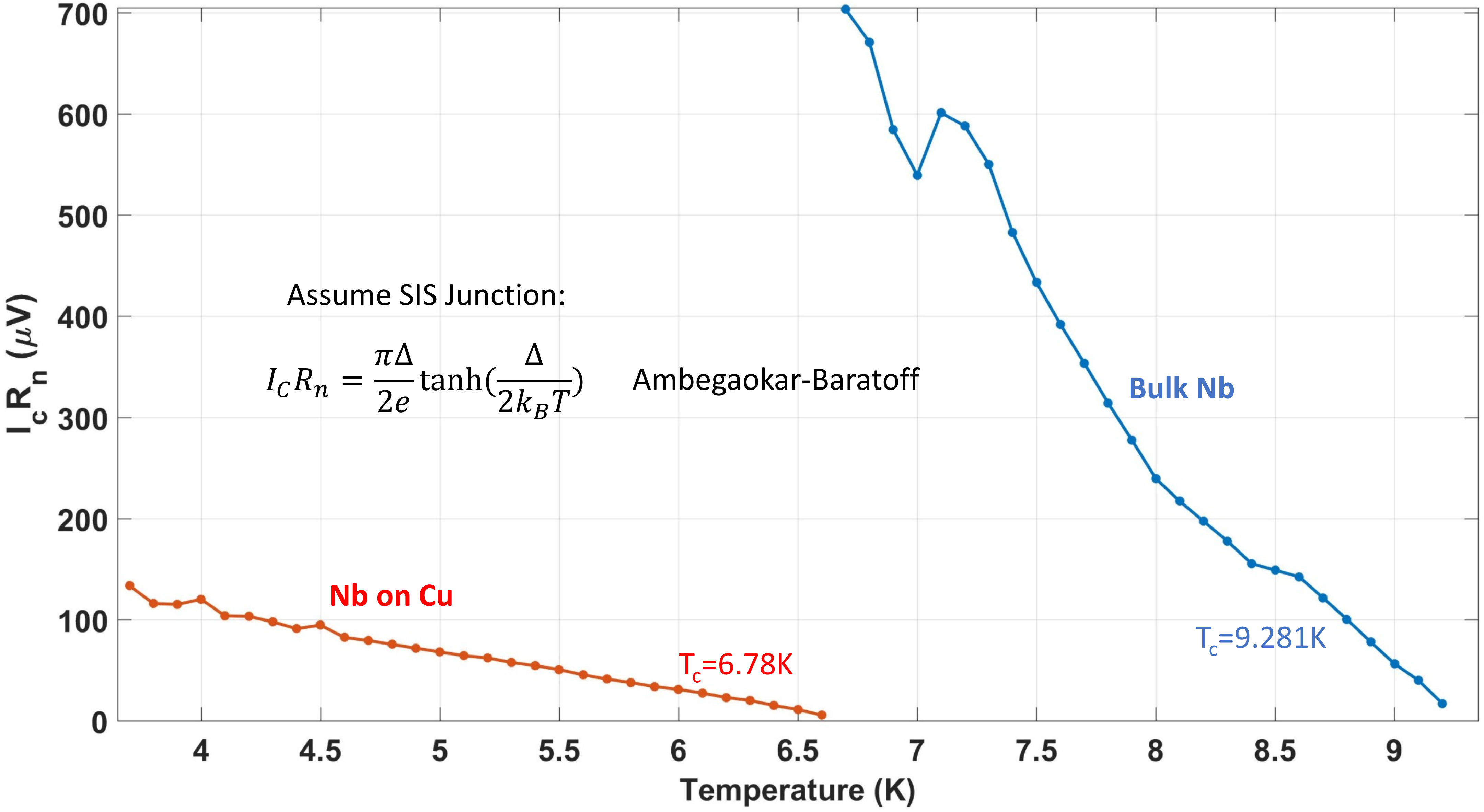
Nb on Cu Data
measured at f = 2.2 GHz



Nonperiodic low input RF field data is not fitted and has a different origin.

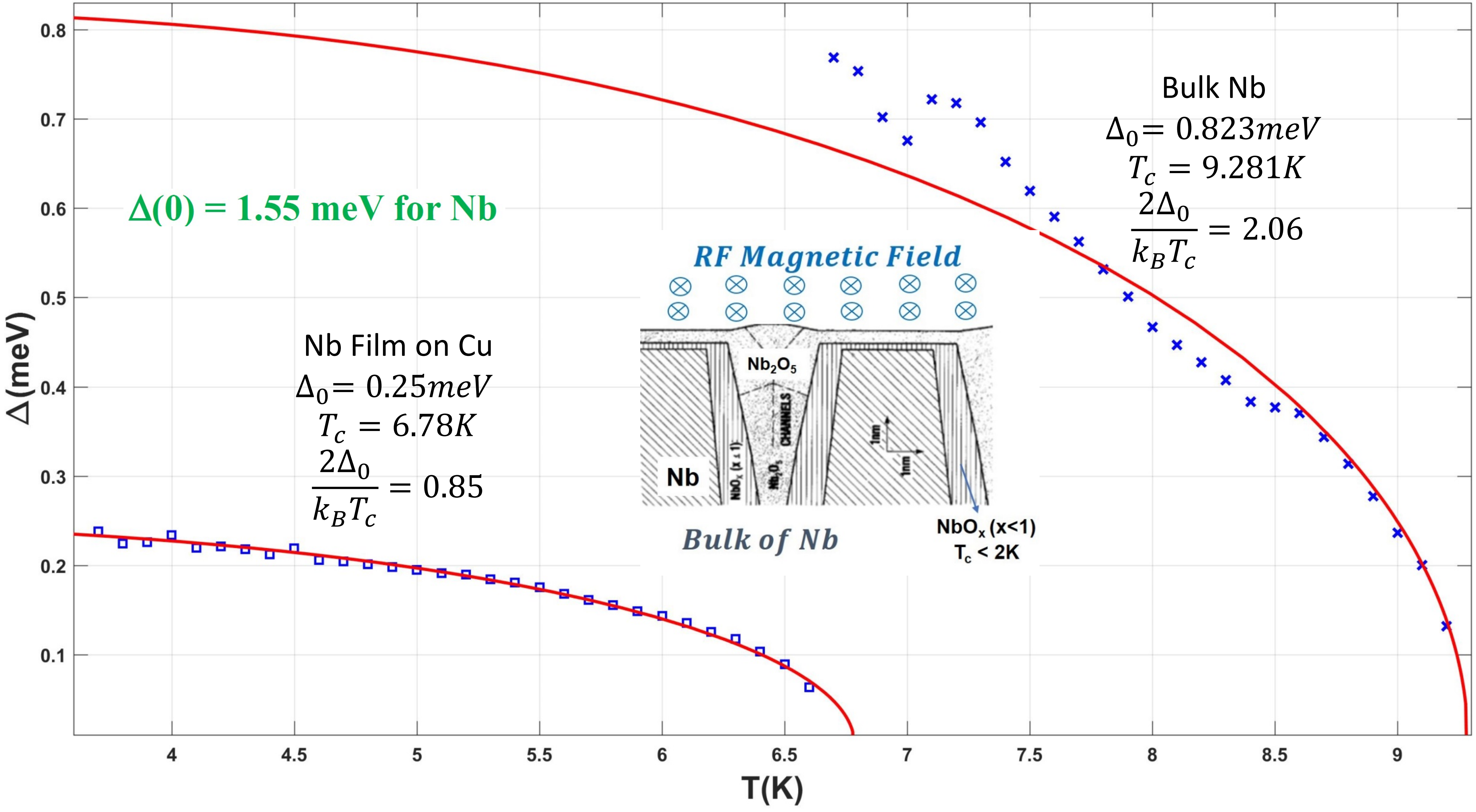


Junction Critical Current



Deduced Energy Gap Temperature Dependence

Assuming AB SIS Tunneling in the JJ



Other Sources of Nonlinear Response

RF Vortex Entry and Motion in the Superconductor

PHYSICAL REVIEW B 77, 104501 (2008)

Dynamics of vortex penetration, jumpwise instabilities, and nonlinear surface resistance of type-II superconductors in strong rf fields

A. Gurevich[1] and G. Ciovati[2]

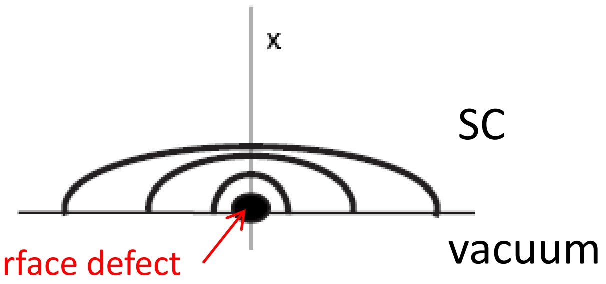
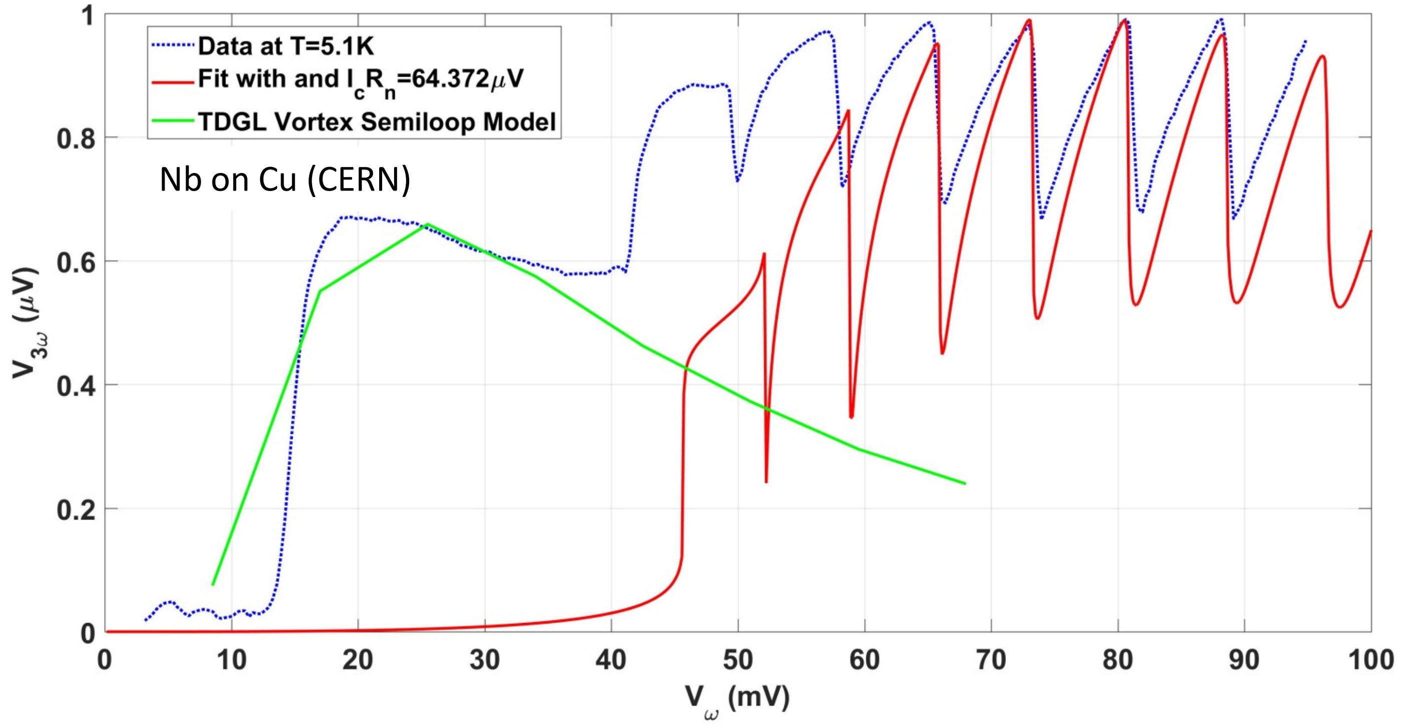


FIG. 2. Snapshots of an expanding vortex semiloop emerging from a surface defect (black dot). The quicker expansion of the loop



Normalized TDGL Equations

$$\eta \frac{\partial \Psi}{\partial t} = -\left(\frac{i}{\kappa}\vec{\nabla} + \kappa\vec{A}\right)^2 \Psi + (1 - T - |\Psi|^2)\Psi$$

$$\vec{\nabla} \times \vec{\nabla} \times \vec{A} = \underbrace{-\sigma \frac{\partial \vec{A}}{\partial t}}_{J_n} \underbrace{- \frac{i}{2\kappa^2}\left(\Psi^* \vec{\nabla}\Psi - \Psi \vec{\nabla}\Psi^*\right) - |\Psi|^2 \vec{A}}_{J_s}$$

$\kappa = \frac{\lambda(0)}{\xi(0)}$; $\eta = \frac{\tau_{GL}}{\tau_0}$; $\vec{B} = \vec{\nabla} \times \vec{A}$; $\vec{E} = -\frac{\partial \vec{A}}{\partial t}$; T=Temperature;

$$|\Psi|^2 = \begin{cases} 1 - \text{Superconducting State} \\ 0 - \text{Normal State} \end{cases}$$

Length measured in units of $\lambda(0)$

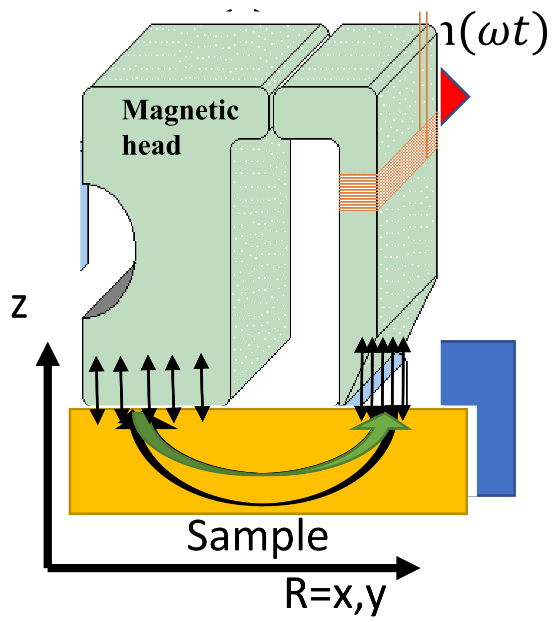
TDGL Equations

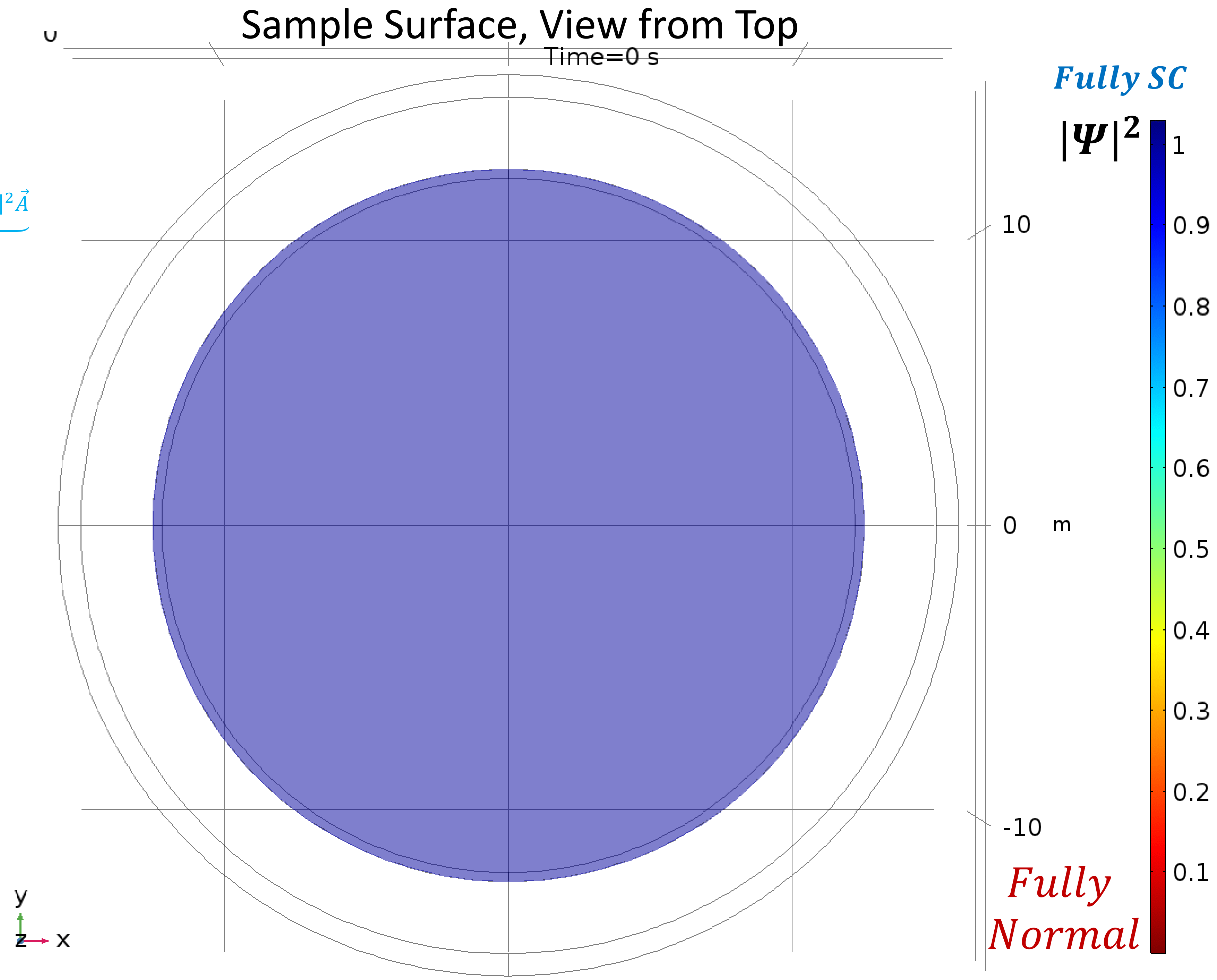
$$\eta \frac{\partial \Psi}{\partial t} = -\left(\frac{i}{\kappa}\vec{\nabla} + \kappa \vec{A}\right)^2 \Psi + (1 - T - |\Psi|^2)\Psi$$

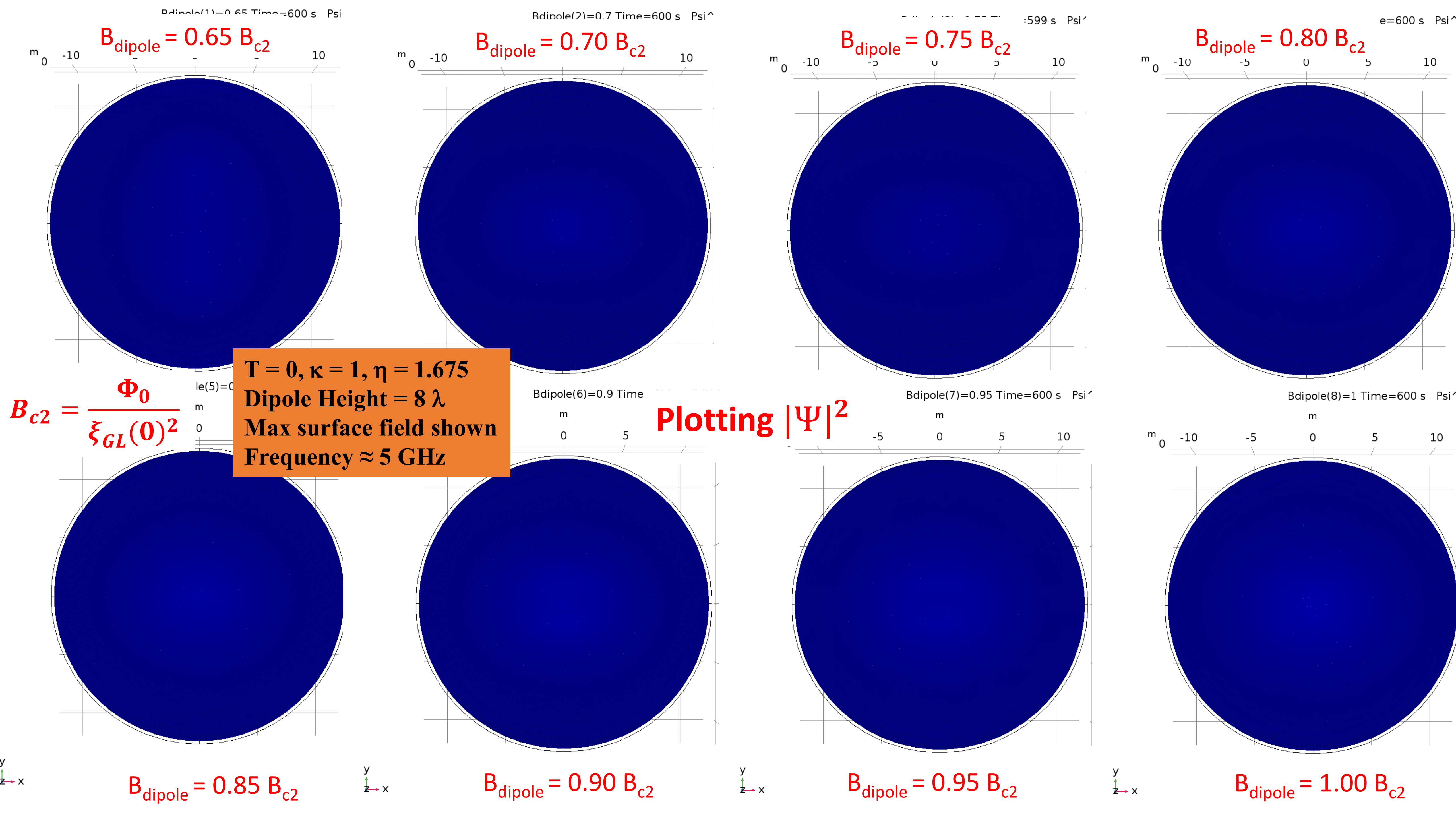
$$\vec{\nabla} \times \vec{\nabla} \times \vec{A} = \underbrace{-\sigma \frac{\partial \vec{A}}{\partial t}}_{J_n} \underbrace{- \frac{i}{2\kappa^2}(\Psi^* \vec{\nabla}\Psi - \Psi \vec{\nabla}\Psi^*) - |\Psi|^2 \vec{A}}_{J_s}$$

T = 0, κ = 1, η = 1
Dipole Height = 10 λ
Max surface field = 0.8 B_{c2}
Frequency ≈ 500 MHz
NO DEFECTS

Side View:







B_dipole = 0.65 B_c2
B_dipole = 0.70 B_c2
B_dipole = 0.75 B_c2
B_dipole = 0.80 B_c2
Bdipole(6)=0.9 Time
Bdipole(7)=0.95 Time=600 s Psi
Bdipole(8)=1 Time=600 s Psi
B_c2 = Φ_0 / ξ_GL(0)^2
T = 0, κ = 1, η = 1.675
Dipole Height = 8 λ
Max surface field shown
Frequency ≈ 5 GHz
Plotting |Ψ|^2
B_dipole = 0.85 B_c2
B_dipole = 0.90 B_c2
B_dipole = 0.95 B_c2
B_dipole = 1.00 B_c2

Horizontal RF Dipole Above Superconductor

κ = 1

η = 1.675

T = 0

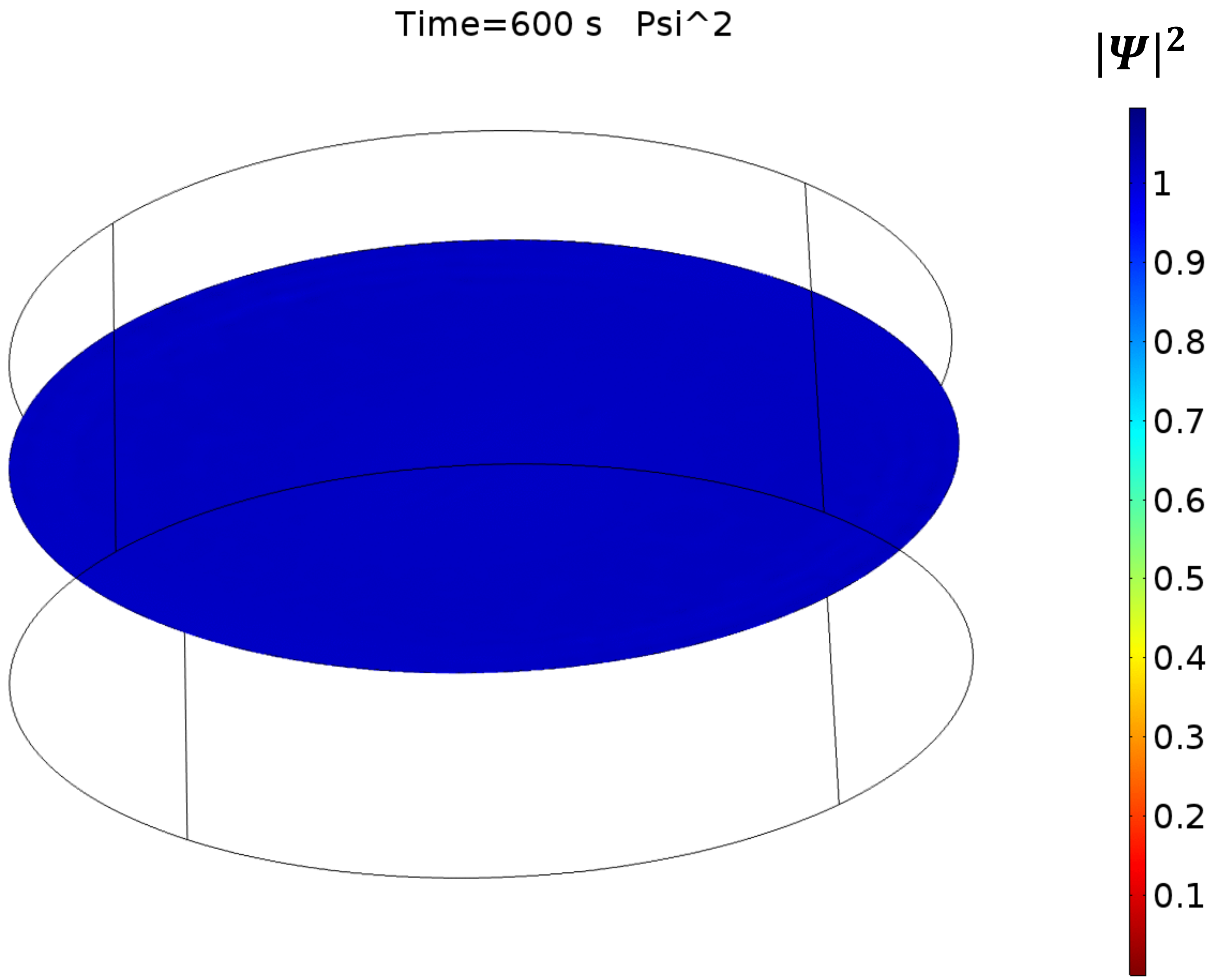
H_{dipole} = 8 λ

B_{dipole} = 0.75 B_{c2}

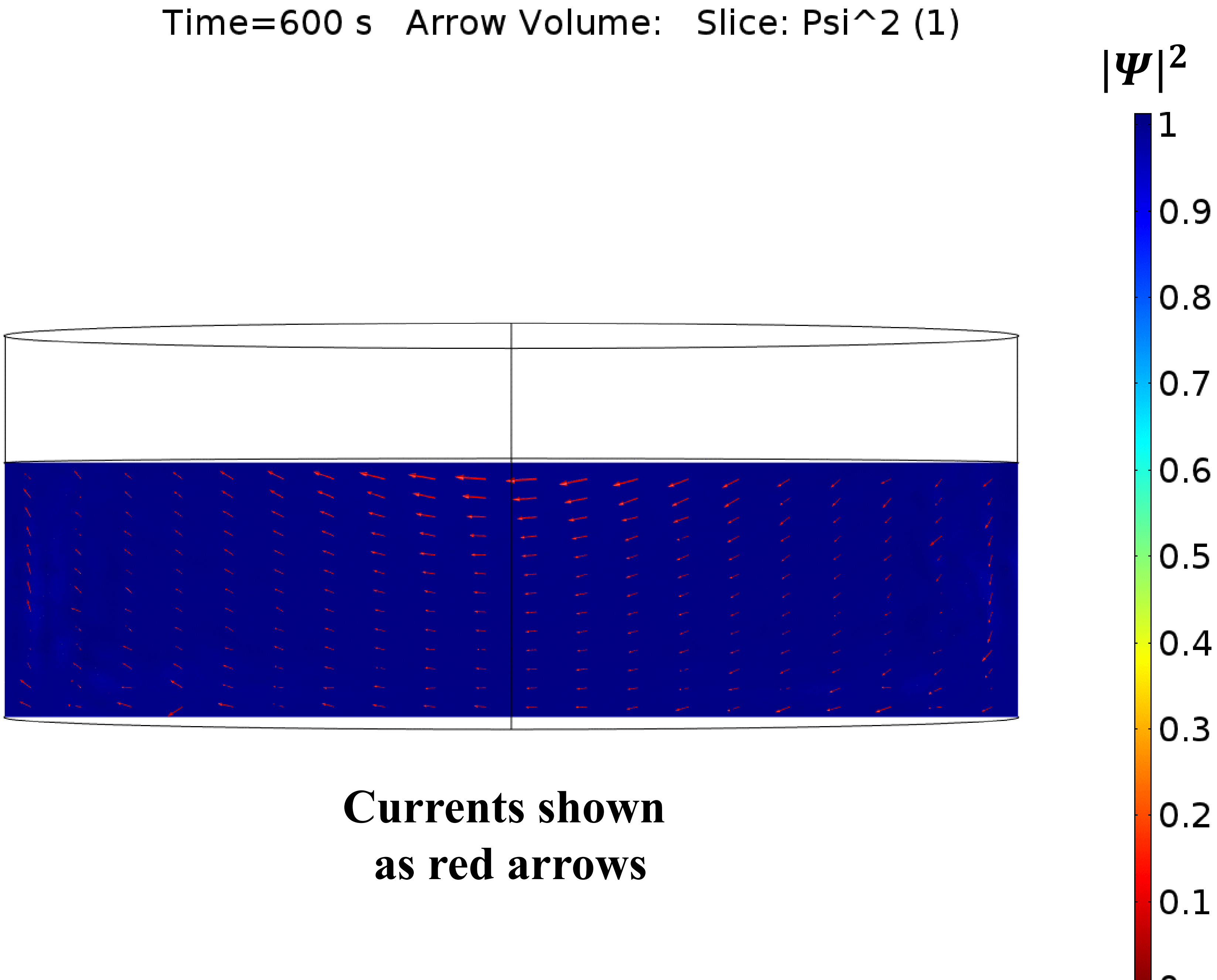
Period = 200 τ_0

Frequency ≈ 5 GHz

NO DEFECTS



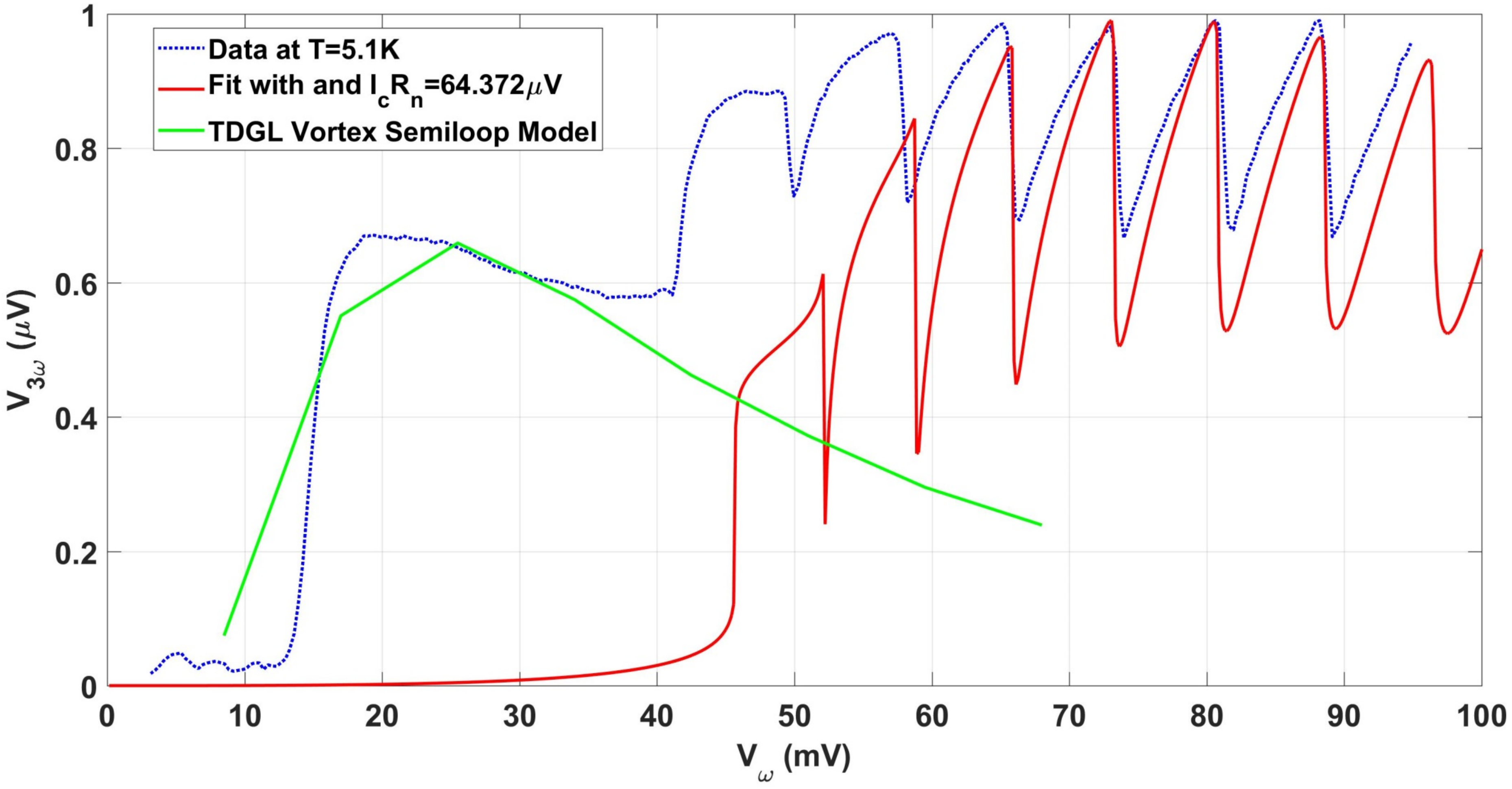
Horizontal RF Dipole Above Superconductor



Currents shown as red arrows

TDGL Harmonic Response May Explain Onset of V_{3f} in Nb Films

T = 8.5 K, κ = 1, η = 1.675
Dipole Height = 12 λ
Max surface field = 0.05 – 0.6 B_{c2}
Period = 200 τ_0
Frequency ≈ 5 GHz



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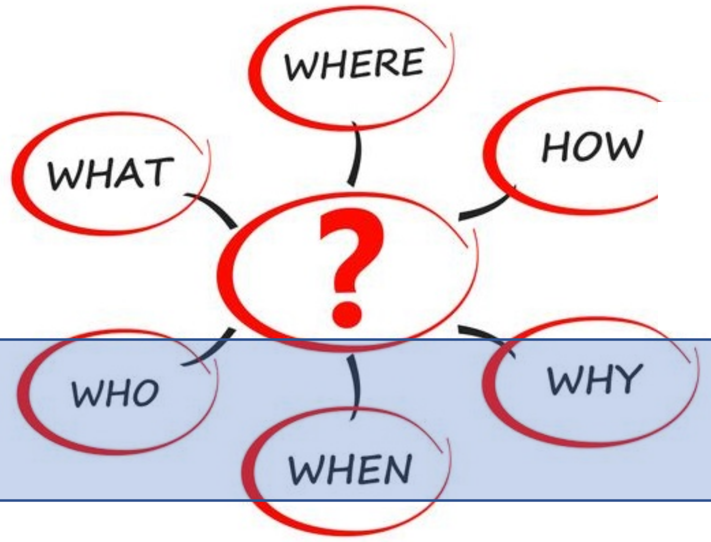


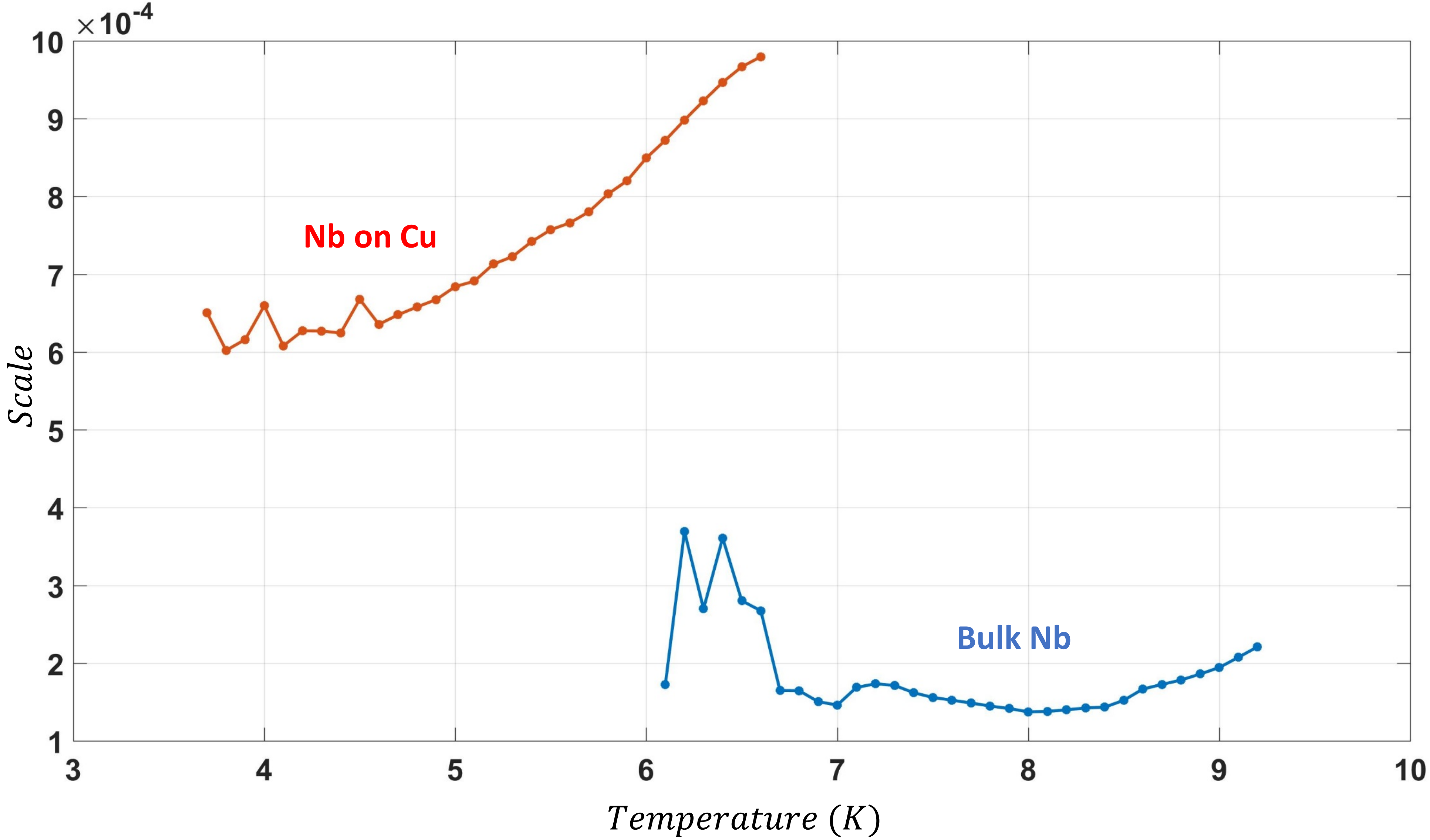
Summary

- **We validate the existence of weak-links on the surface of Nb**
- **Magnetic Microwave Microscopy can be used to extract local T_c and Effective BCS Gap at the weak-link**

Future Work

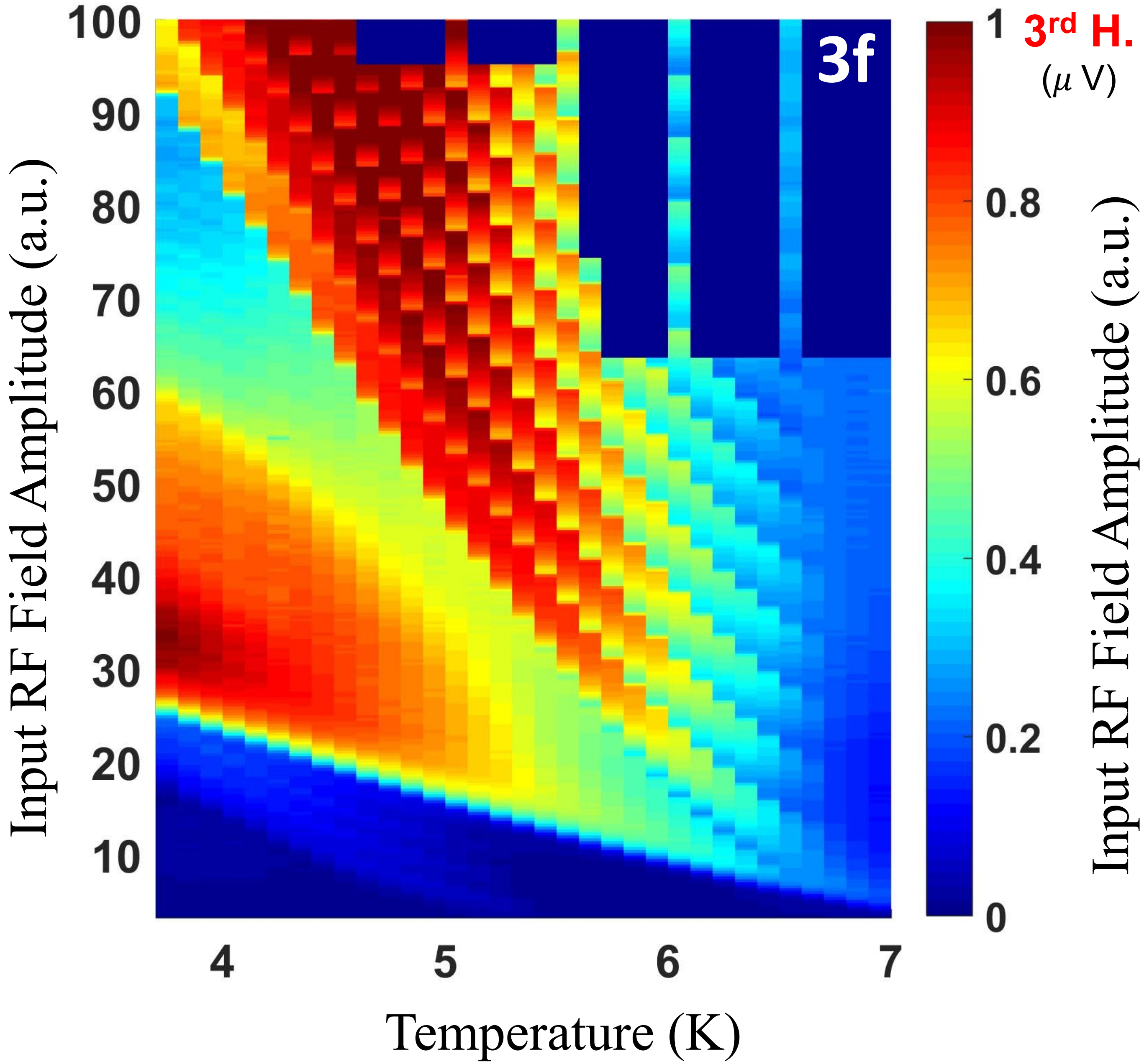
- **TDGL Simulations are being performed to study "pedestal" data on thin films**
- **Raster Scanning over known defect while imaging onset field**
- **Measurement of multilayer/single layer samples**

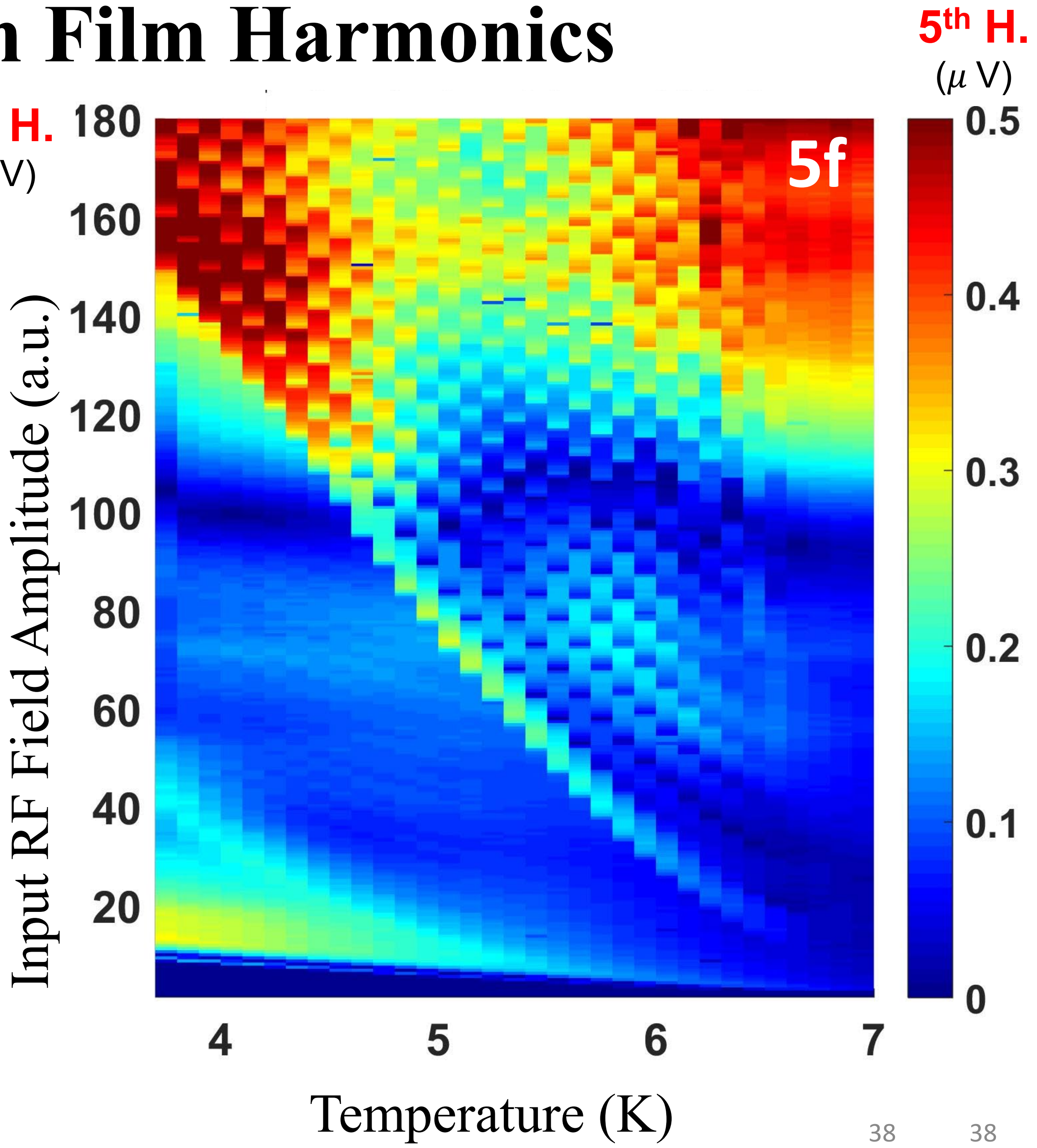
fin



×10^-4
10
9
8
7
6
5
4
3
2
1
Scale
3
4
5
6
7
8
9
10
Temperature (K)
Nb on Cu
Bulk Nb

Periodicity of Nb Thin Film Harmonics





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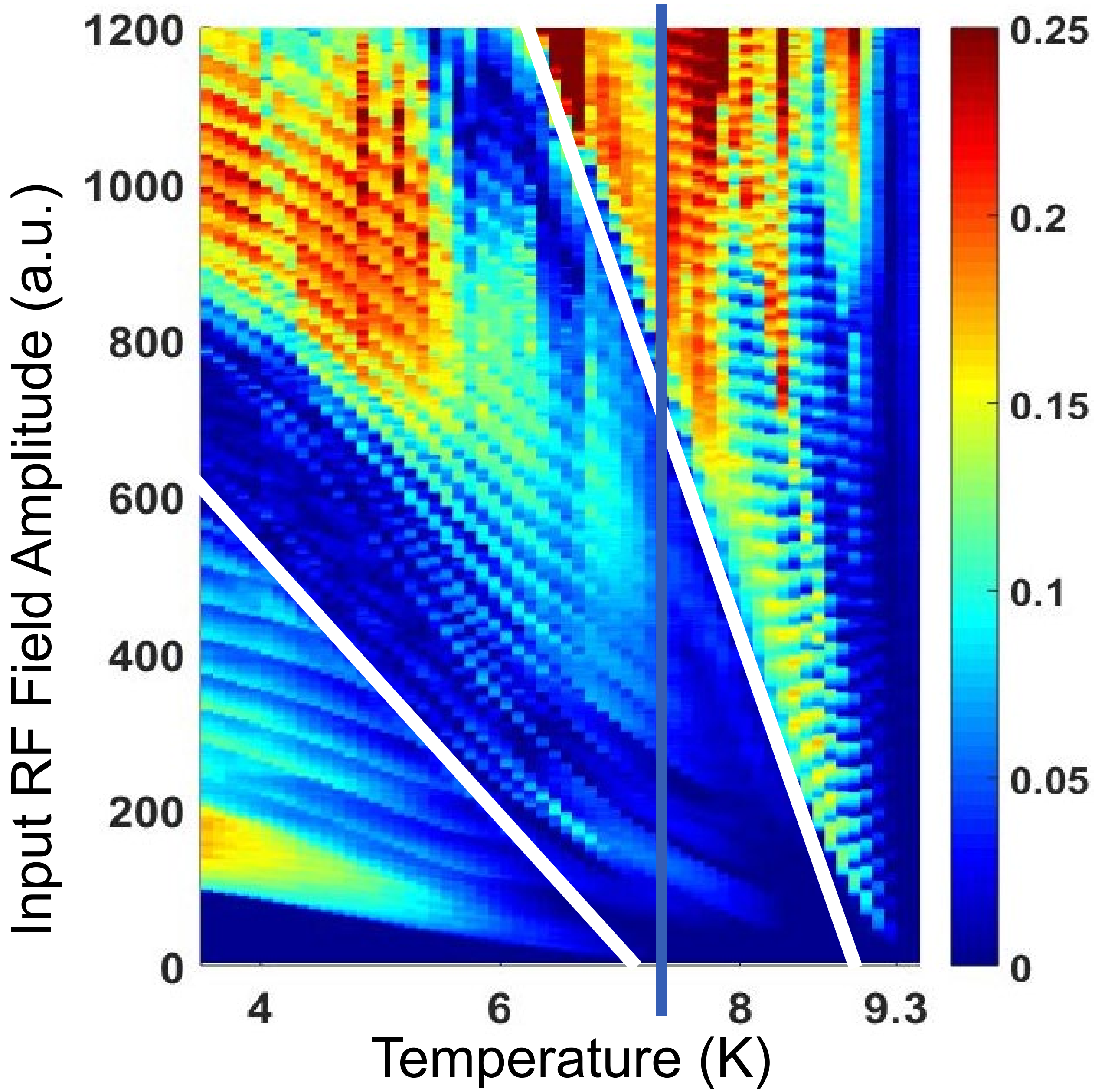
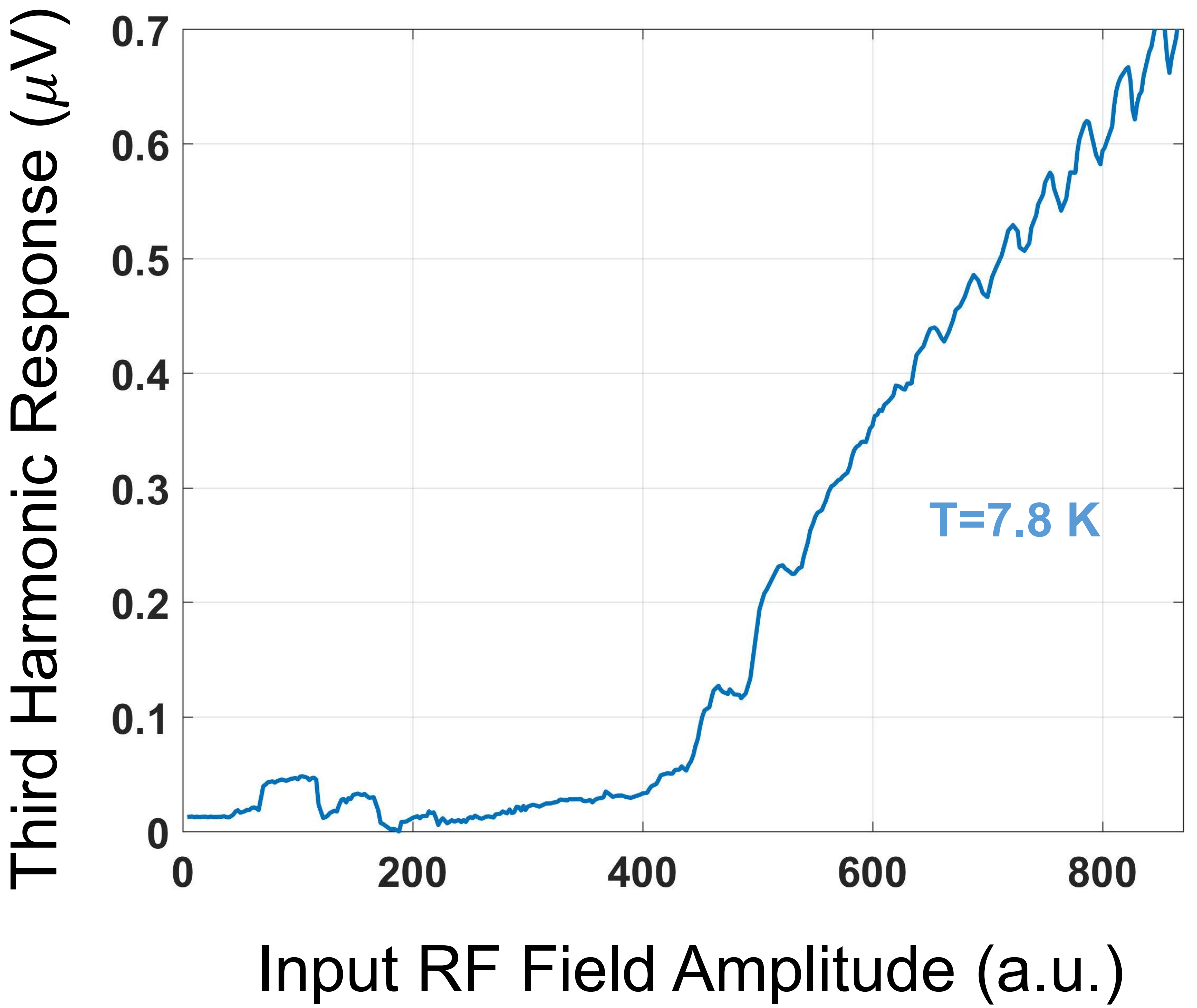
Bulk Nb Data: Multiple Periodicity in Harmonic Response





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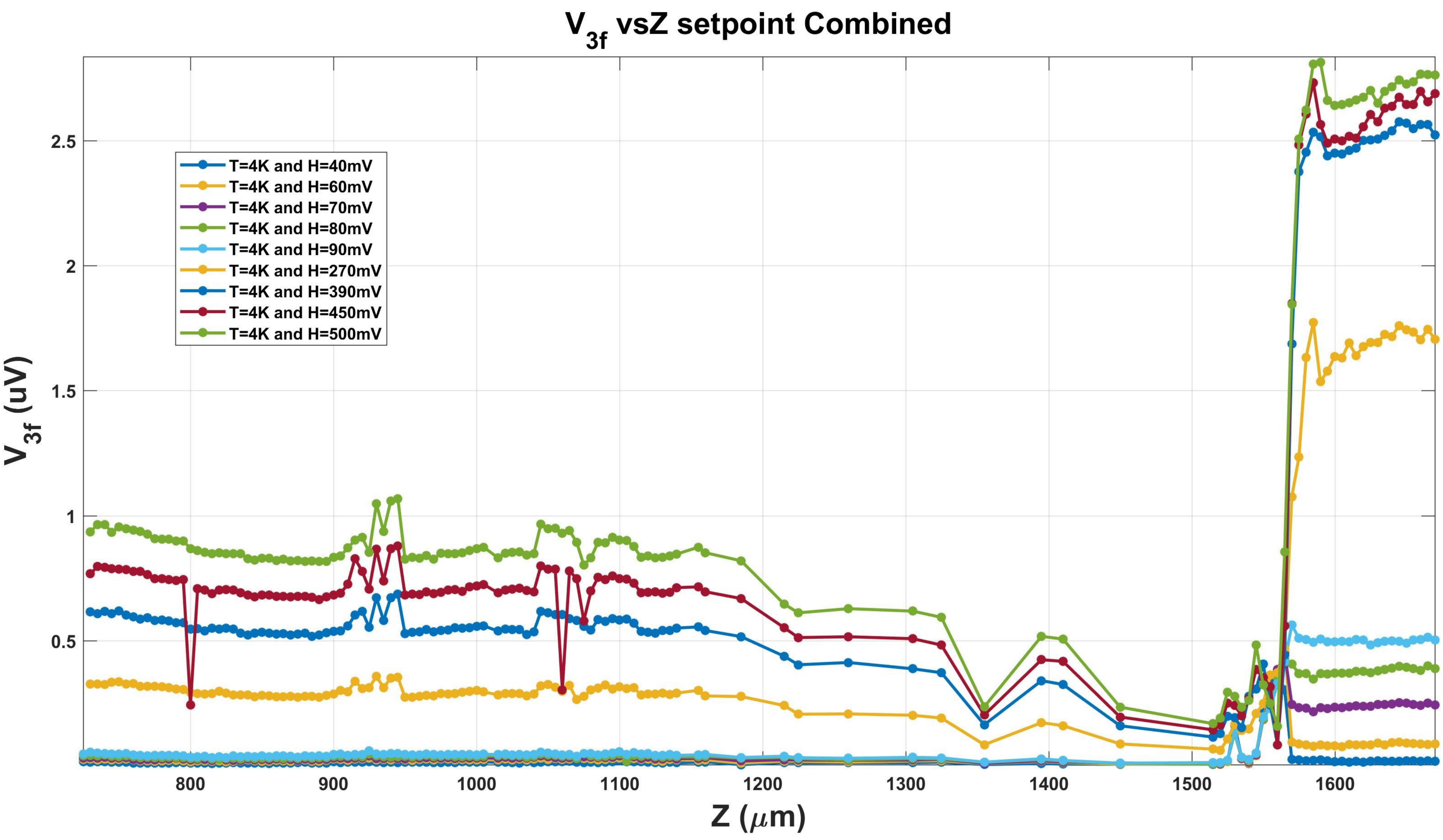
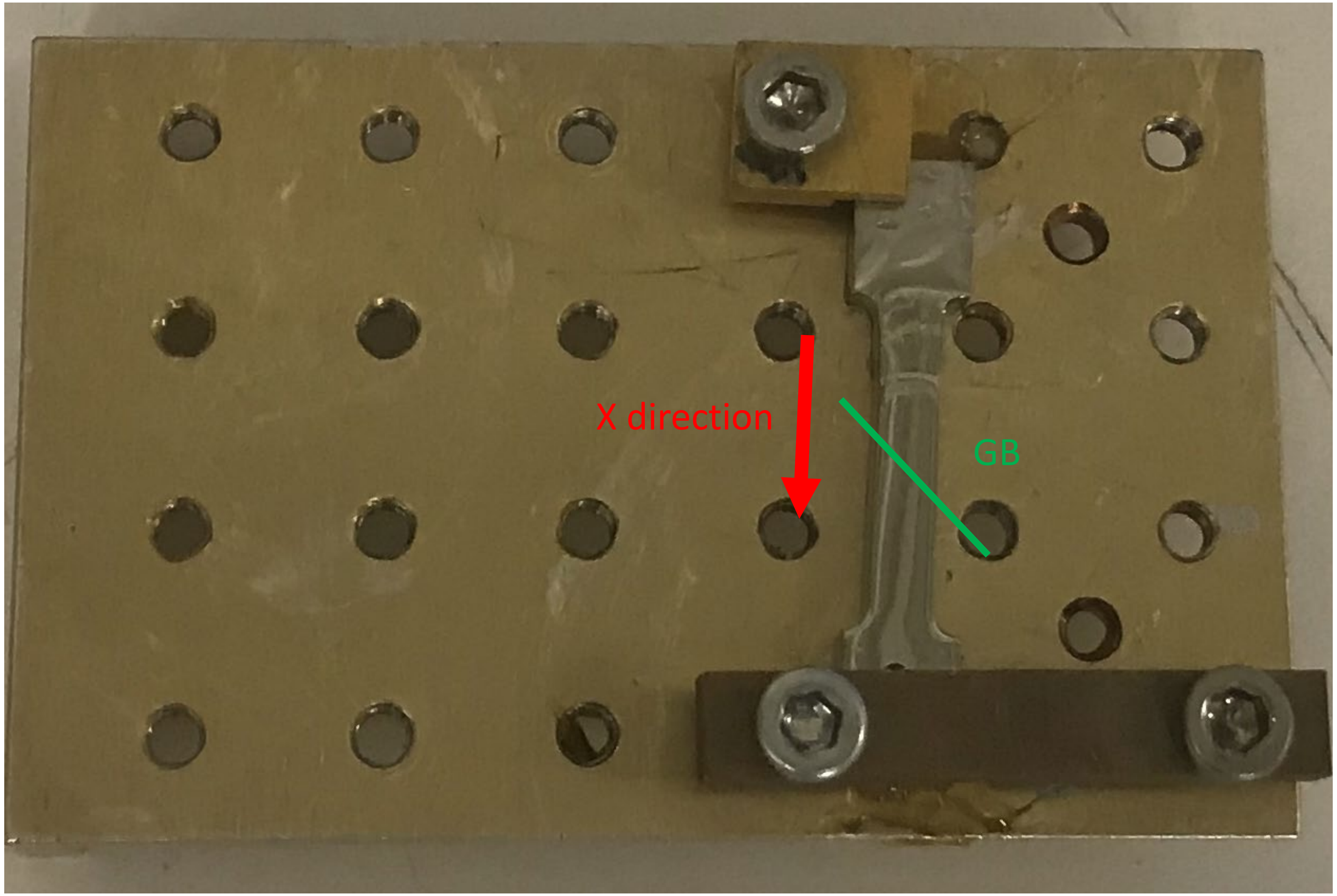
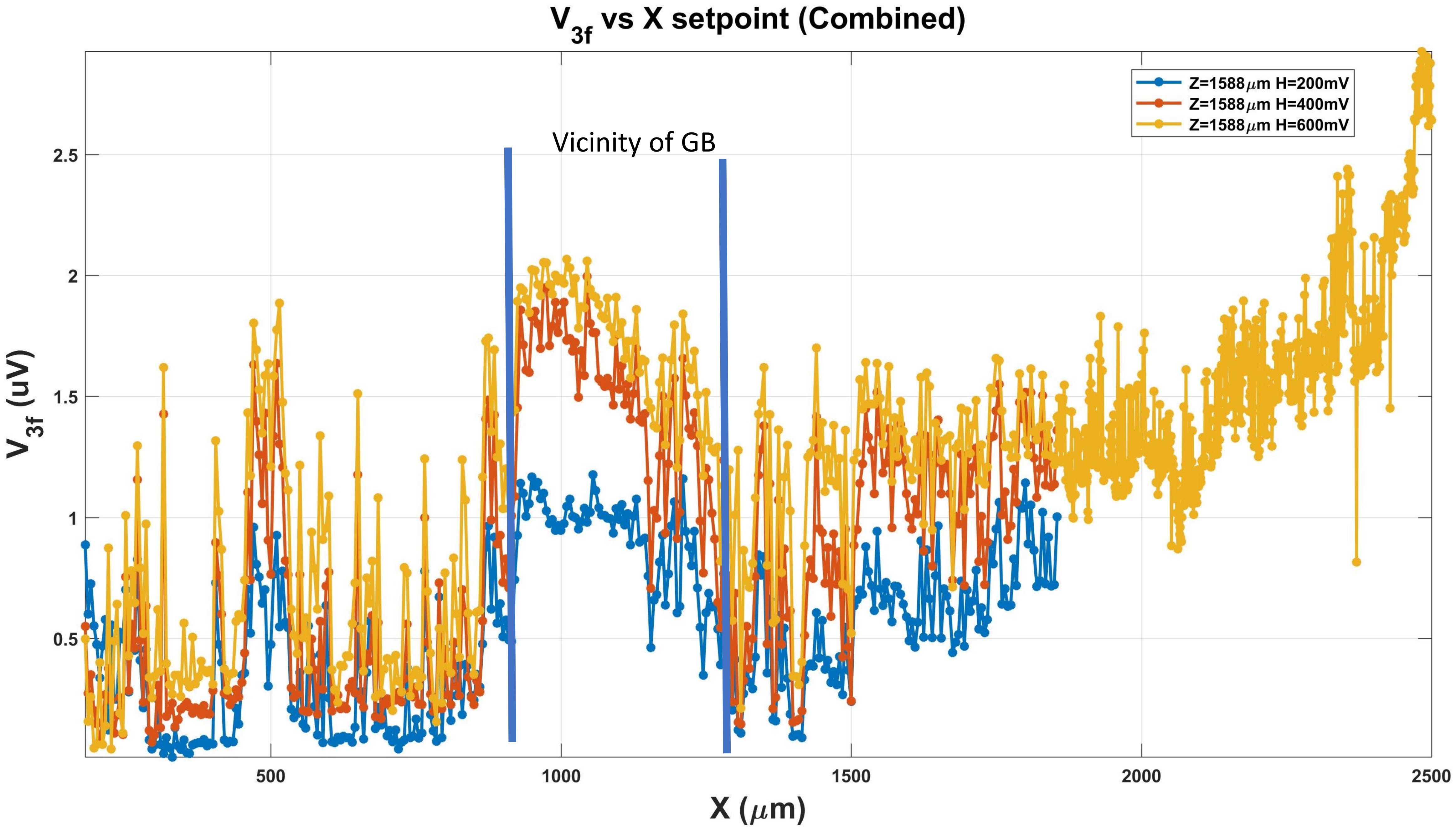


V_{3f} vsZ setpoint Combined
T=4K and H=40mV
T=4K and H=60mV
T=4K and H=70mV
T=4K and H=80mV
T=4K and H=90mV
T=4K and H=270mV
T=4K and H=390mV
T=4K and H=450mV
T=4K and H=500mV
V_{3f} (uV)
2.5
2
1.5
1
0.5
800
900
1000
1100
1200
1300
1400
1500
1600
Z (μm)



X direction
GB



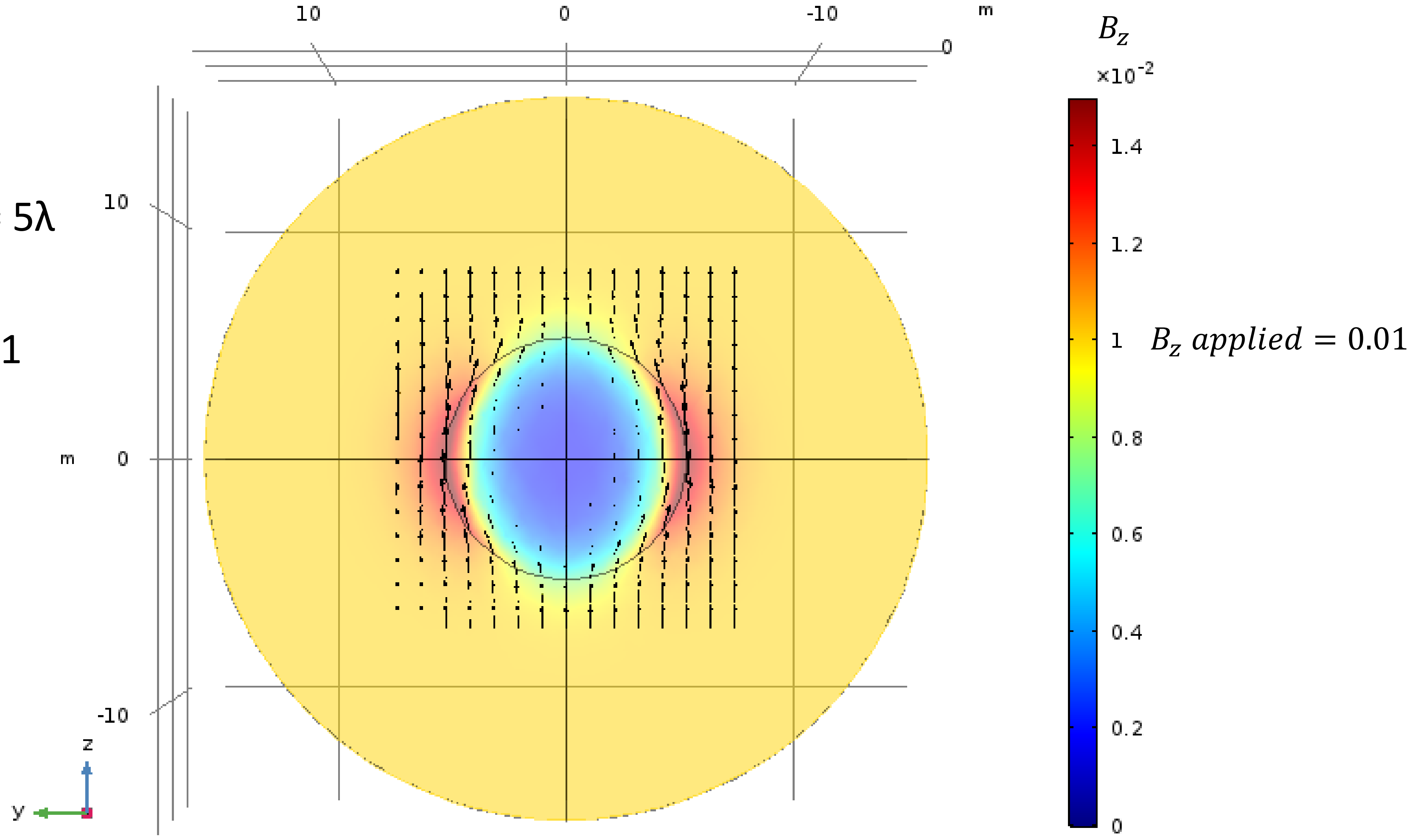
V3f vs X setpoint (Combined)
Z=1588μm H=200mV
Z=1588μm H=400mV
Z=1588μm H=600mV
Vicinity of GB
V3f (uV)
2.5
2
1.5
1
0.5
500
1000
1500
2000
2500
X (μm)

Superconducting Sphere in a Uniform Static Magnetic Field

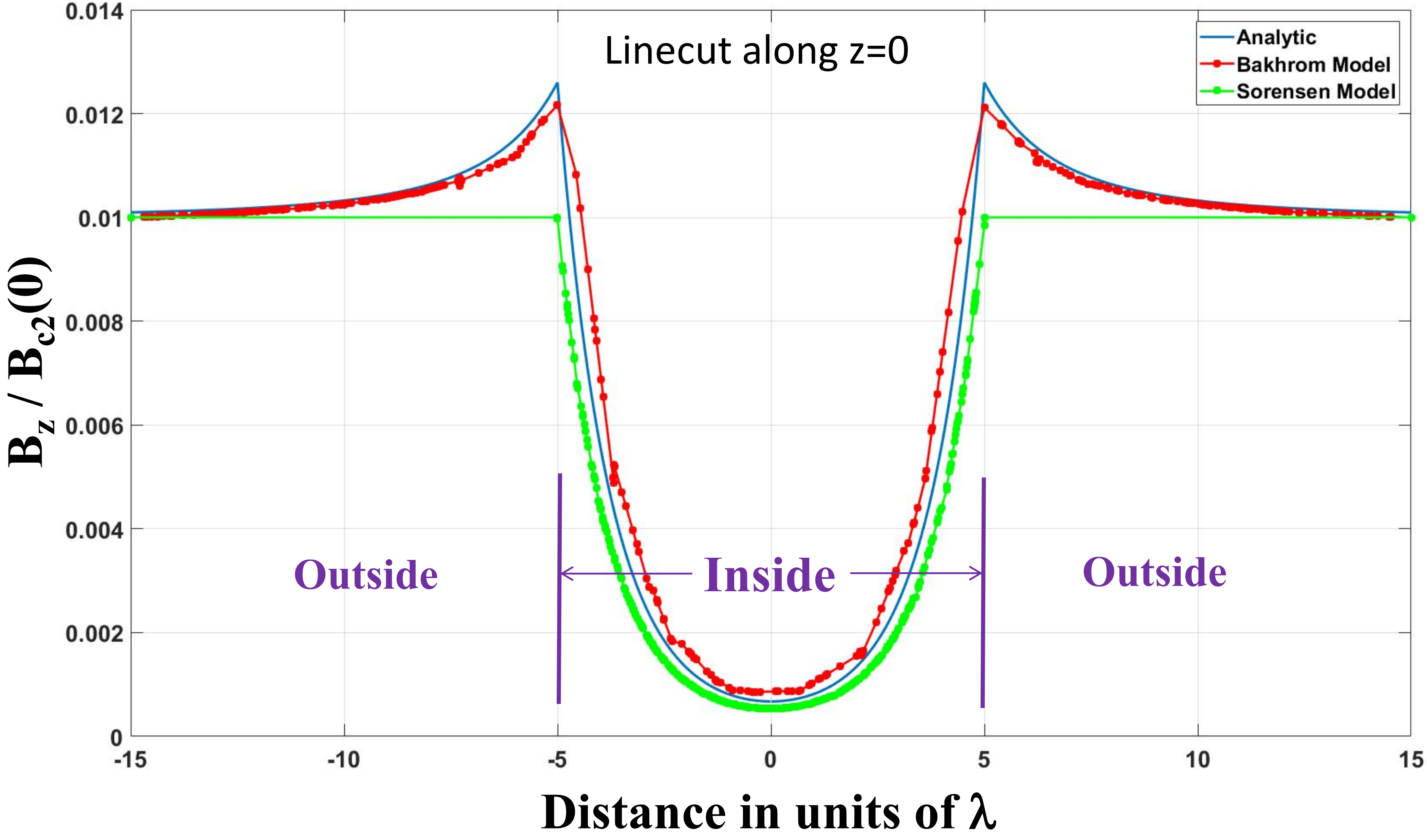
Sphere Radius = 5λ

κ = 1, T = 0;

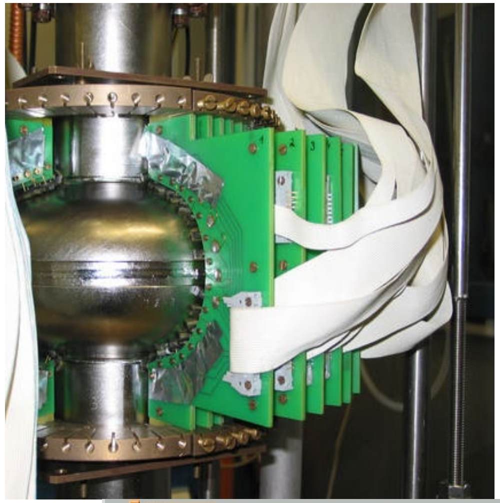
B_z applied = 0.01

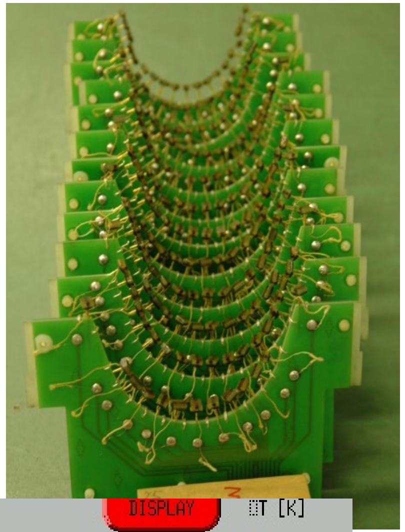


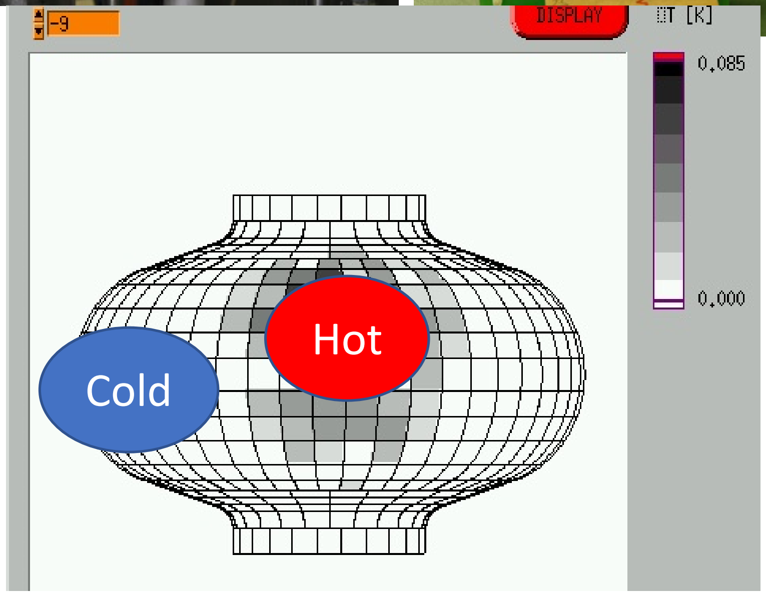
Static Magnetic Field In and Around a Superconducting Sphere

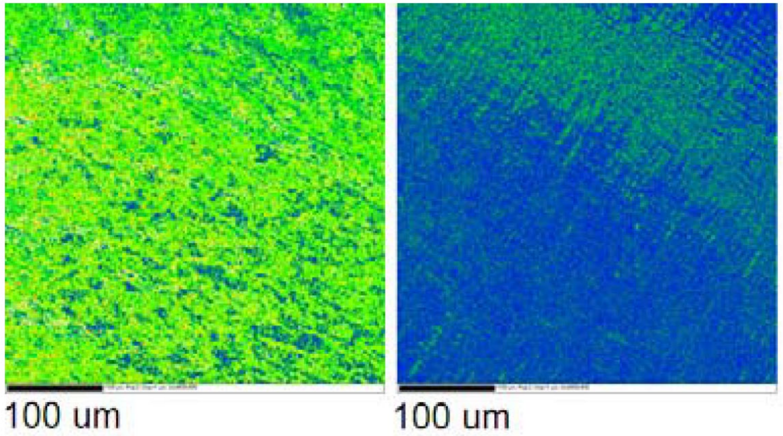


“Hot” and “Cold” Comparison

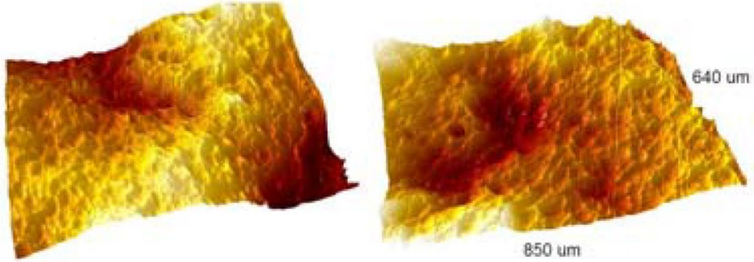






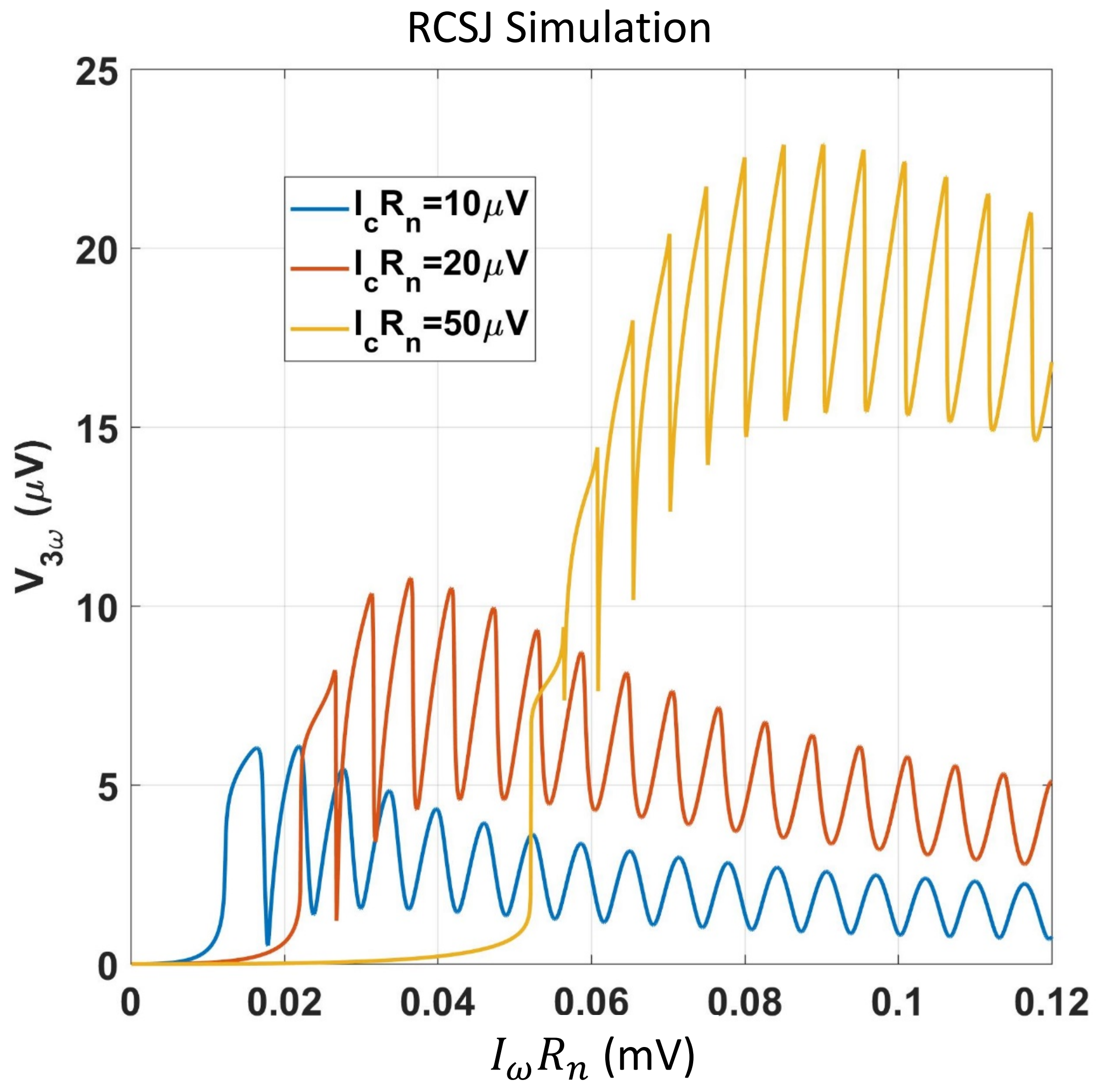


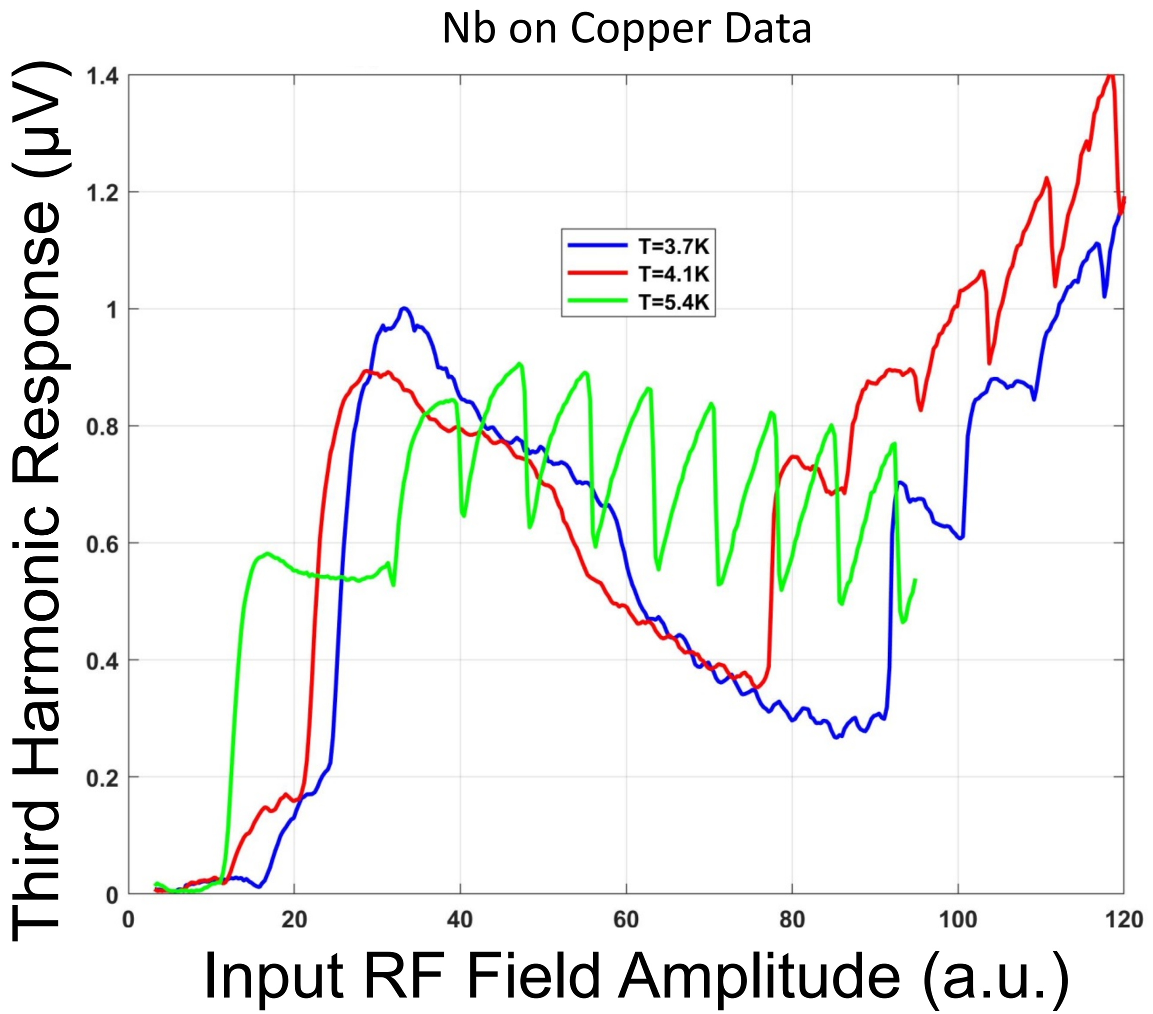
(EBSD) Local misorientation maps for “hot” (left) and “cold” (right) regions. Green color corresponds to 2◦ mis-orientation, blue - 0◦.



Optical profilometry 3-D images (850 µm × 640 µm) of the hot (left) and cold (right) samples.

A. Romanenk† , G. Eremeev, D. Meidlinger, H. Padamsee “Studies of the high field anomalous losses in small and large grain niobium cavities“, Proceedings of SRF2007, Peking Univ., Beijing, China





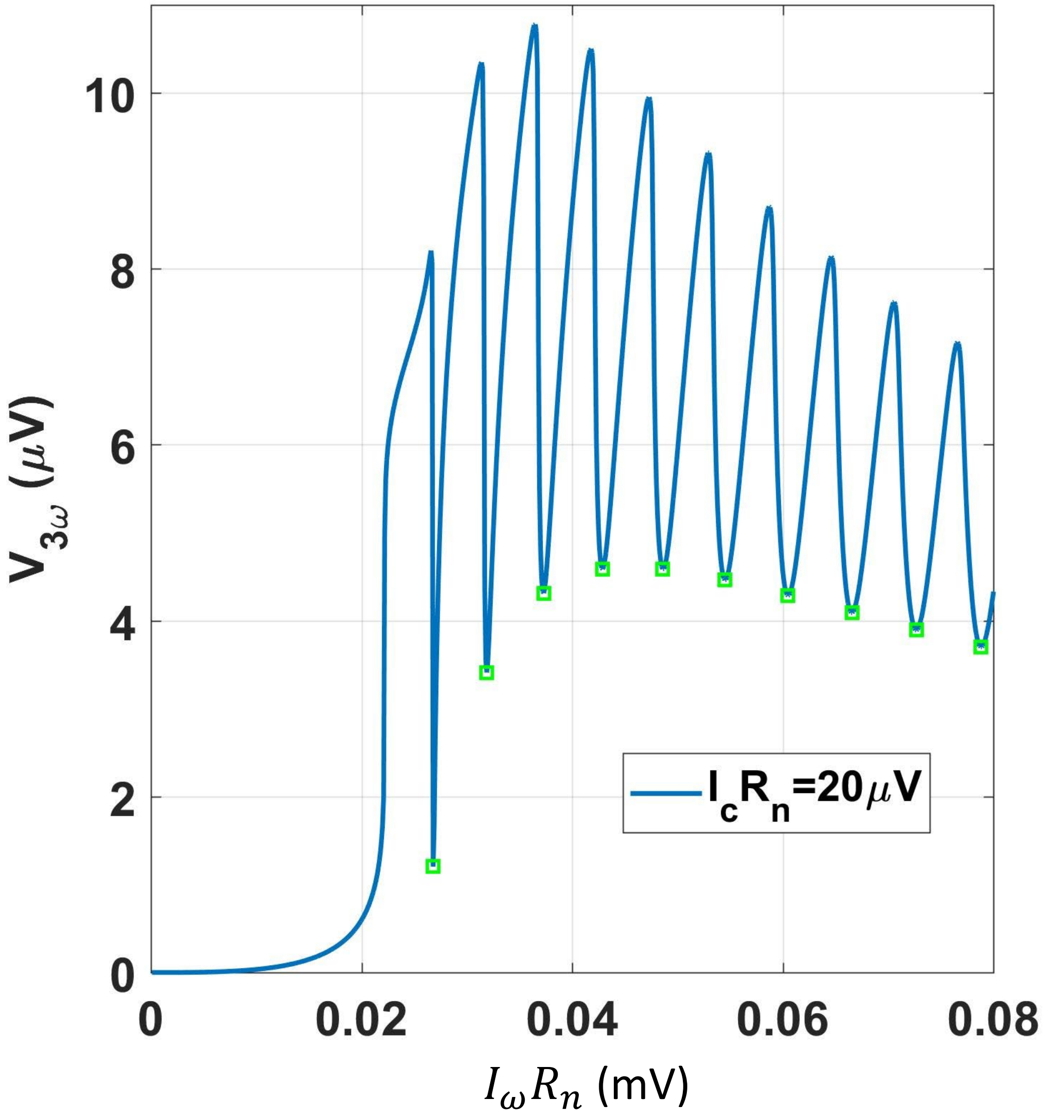
$\boldsymbol{I_\omega R_n}$(mV) = ScalingFactor * Input RF Field Amplitude (a.u.)

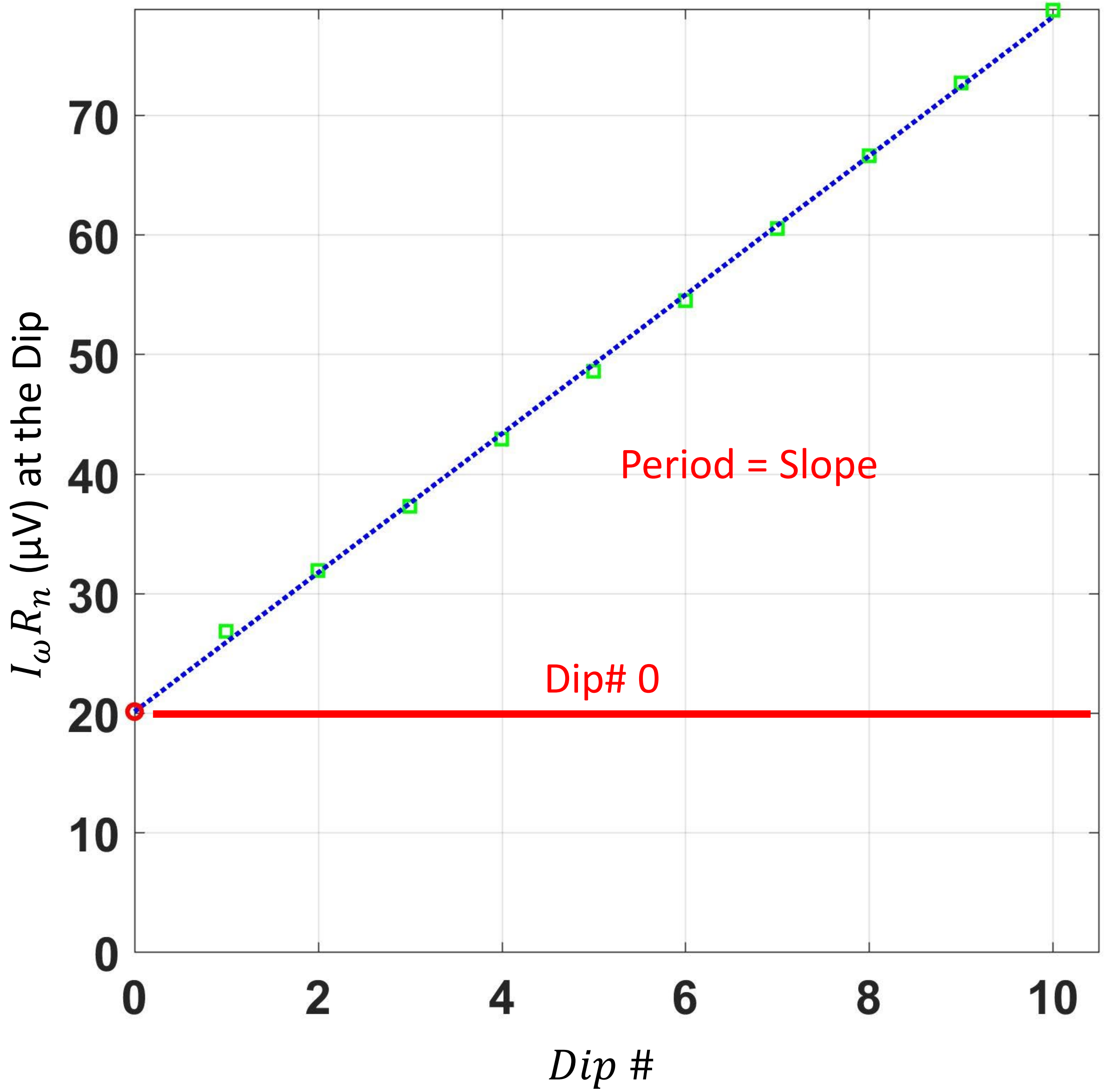
$\boldsymbol{Onset}$(mV) = ScalingFactor * Onset (a.u.)
$\boldsymbol{Period}$(mV) = ScalingFactor * Period (a.u.)
$\boldsymbol{Dip\ \#1}$(mV) = ScalingFactor * Dip #1 (a.u.)

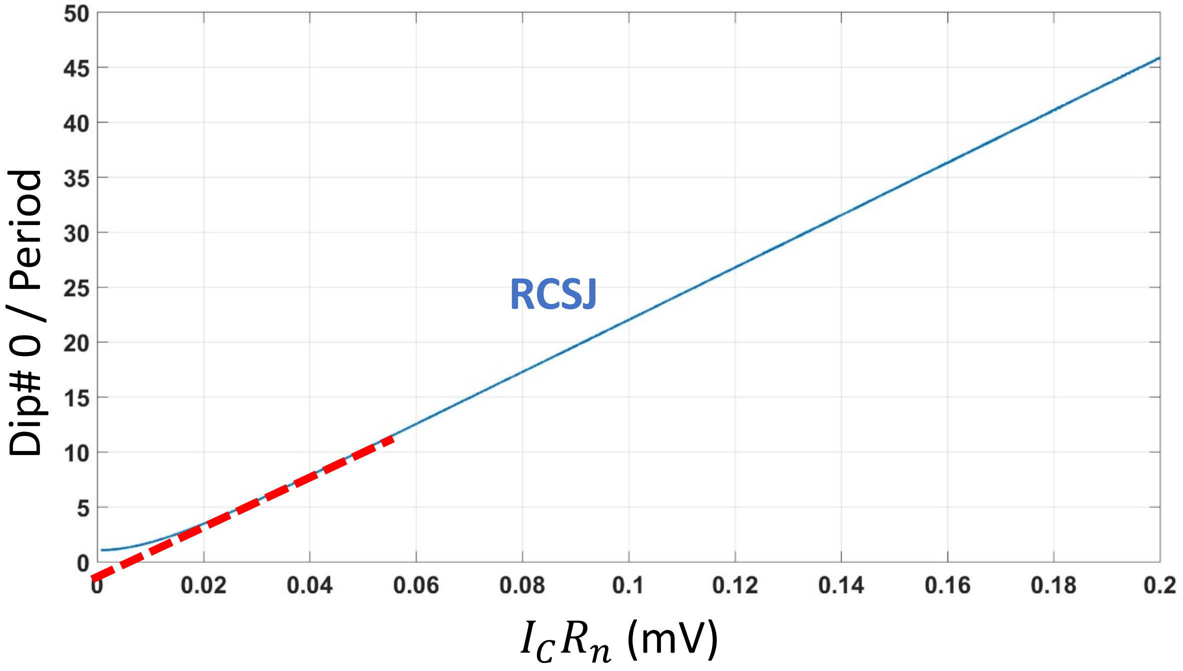
?

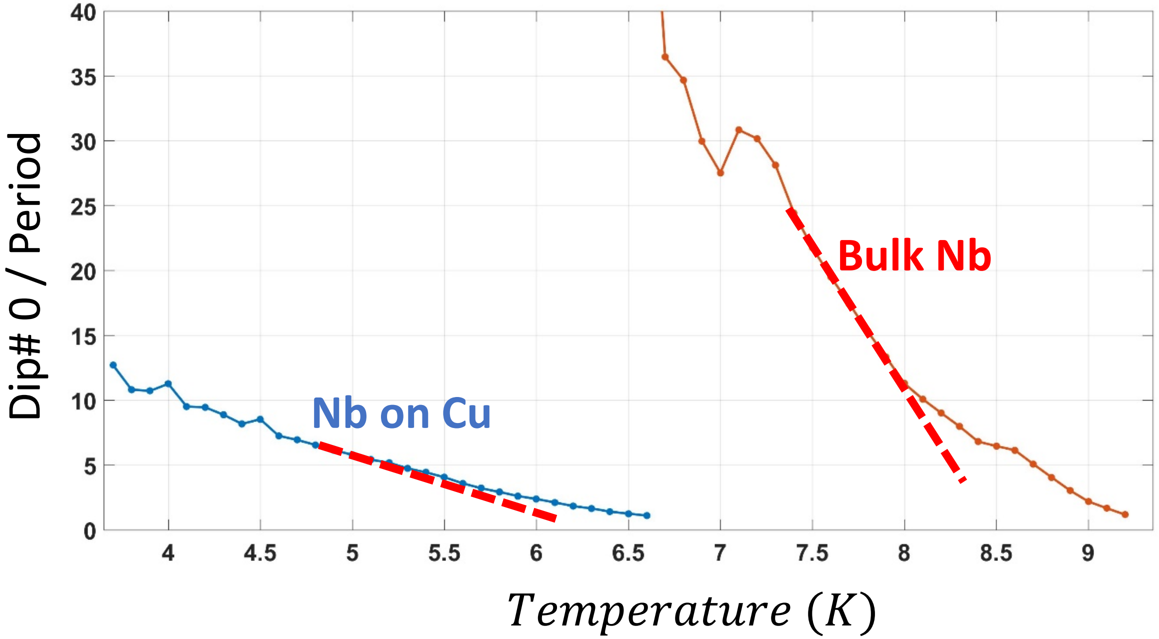
$$\frac{\text{Dip\# 0}}{\boldsymbol{Period}}$$

$$\begin{pmatrix} RCSJ\ Simulation\ at\ a\ given\ I_cR_n \\ Or\ Nb\ Data\ at\ a\ given\ Temperature \end{pmatrix}$$





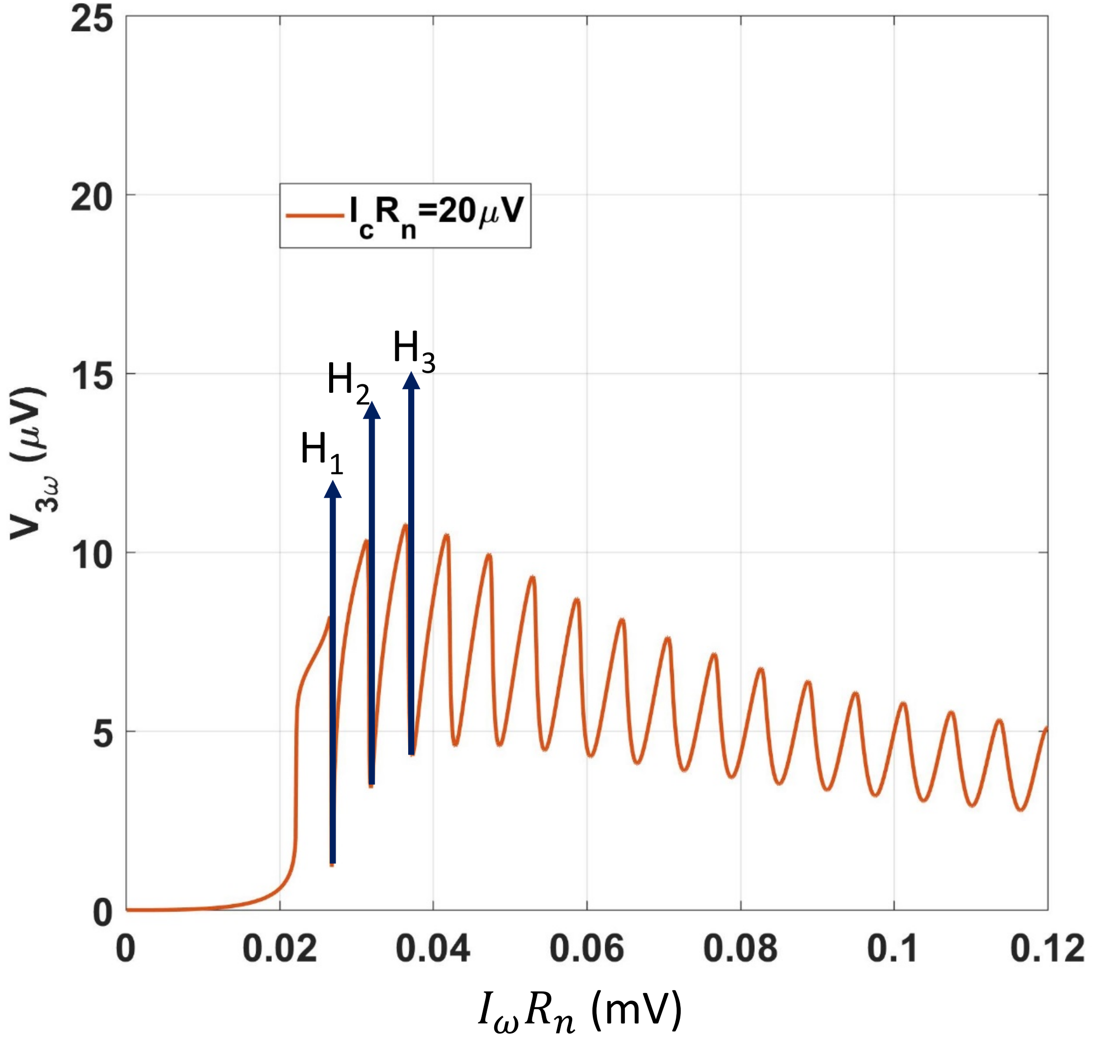




1) Taka Data at T
2) Determine Dip# 0 / Period
3) Find Matching $I_C R_n$

$I_C R_n$ (T)

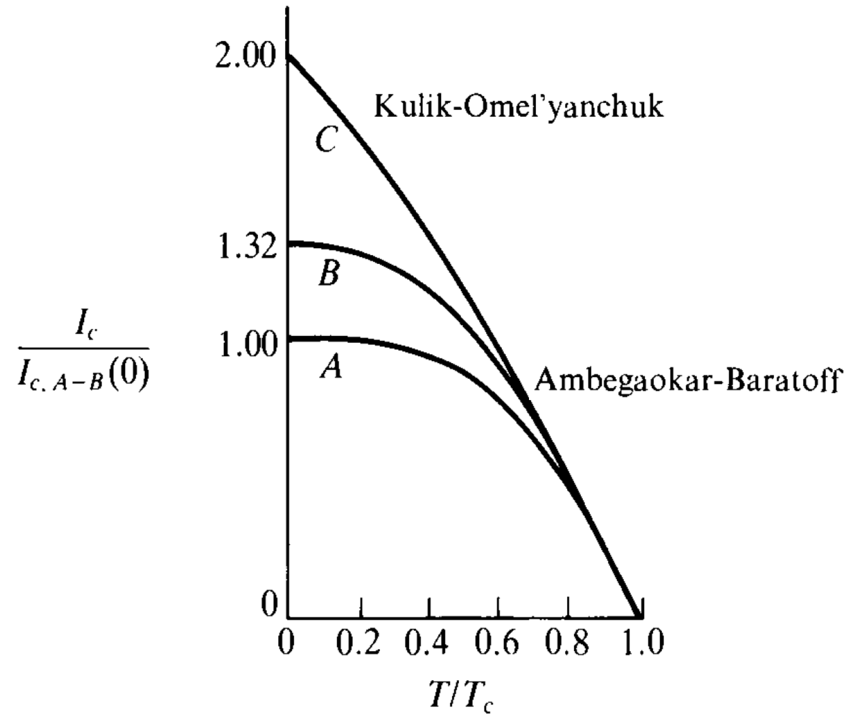
RCSJ Simulation



Getting Δ from Junction

SIS Junction Assumed:

$$I_C R_n = \frac{\pi\Delta}{2e}\tanh(\frac{\Delta}{2k_B T})$$ Ambegaokar-Baratoff



Solve for Δ