Microscopic Investigation Of Materials Limitations of Superconducting RF Cavities

aka

RF Local Magnetometry

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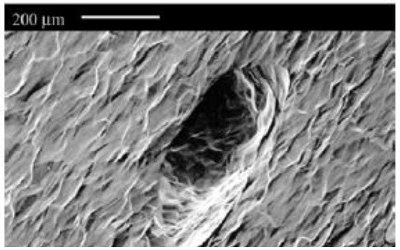
TTC 2020

This work is funded by US Department of Energy High Energy Physics program grant # DESC0017931 and the Maryland Quantum Materials Center

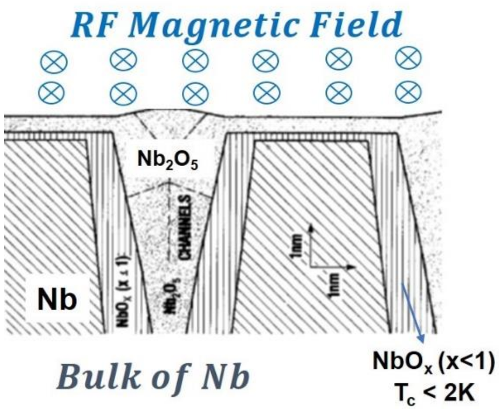
Outline:

1. What is the issue?
2. How Magnetic Microwave Microscopy works?
3. What did we measure?
5. What is the origin of this data?
6. Where do we plan to go with this?

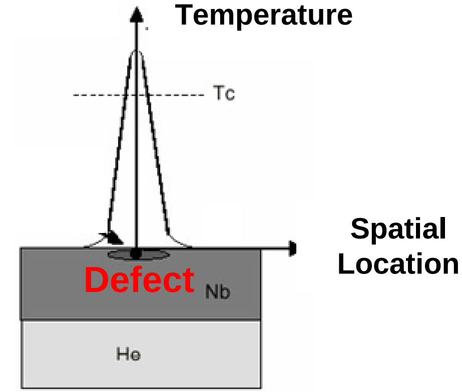
Defects/Processes limiting SRF Performance



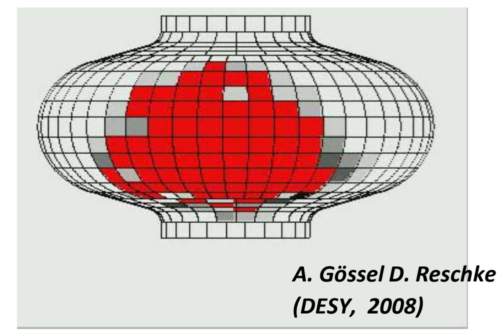
500 x 200 µm pit



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



Cavity Temperature Map



A high resolution near-field magnetic-field microscope can identify those defects and relate which defects results in the breakdown of the cavities is needed

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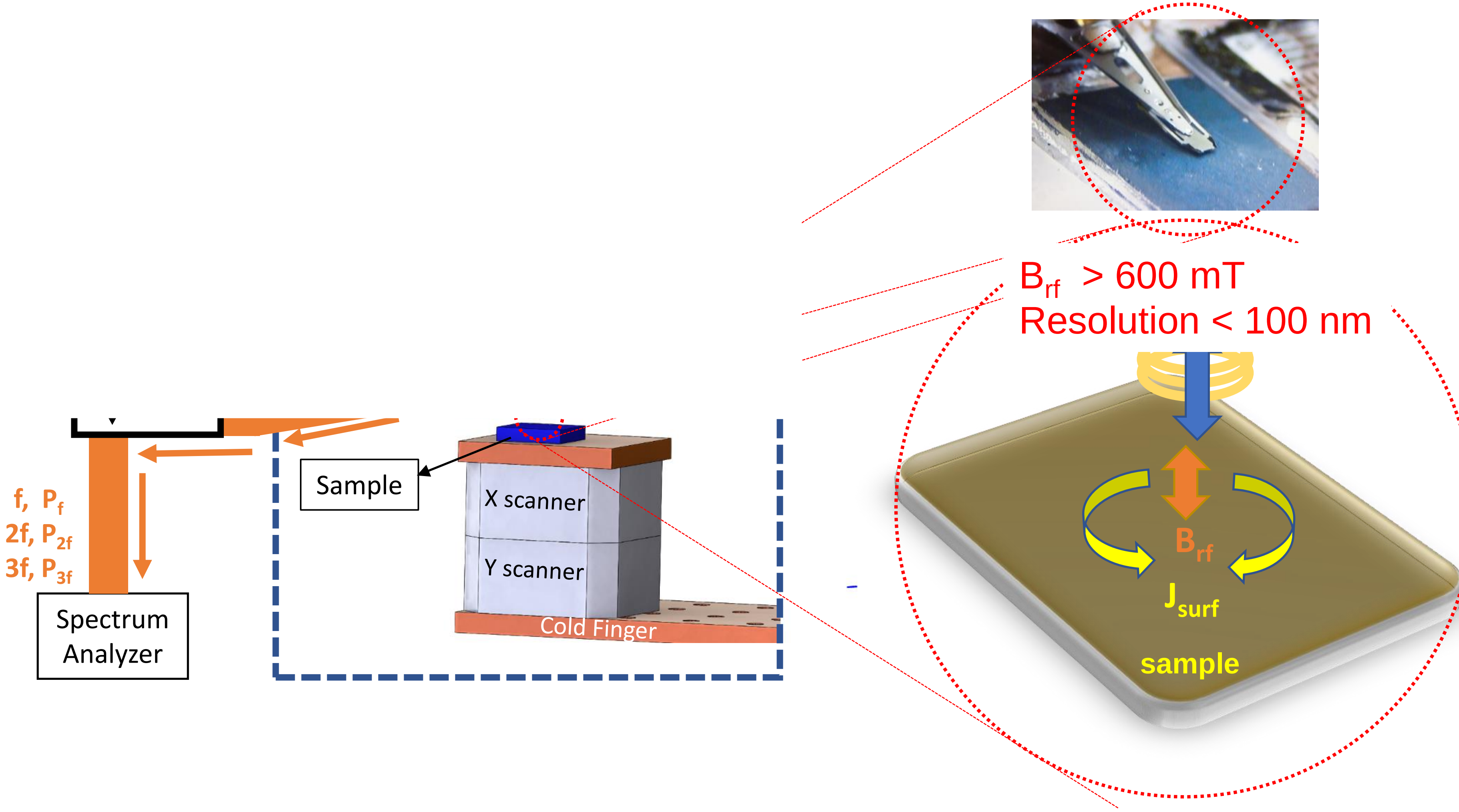
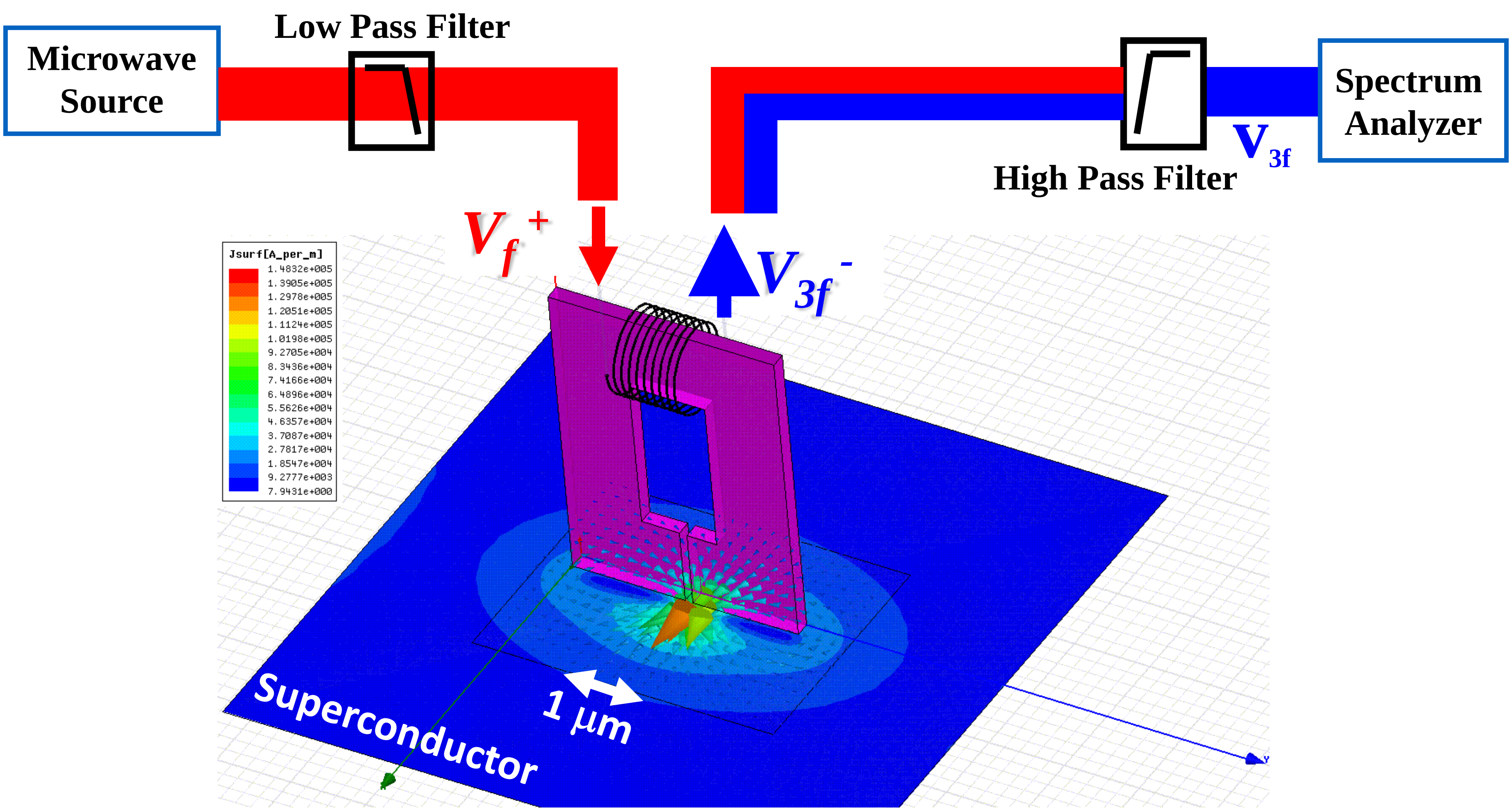
Near-Field B_{rf} Microscope



Objective: Identify microscopic defects that cause breakdown of SRF cavities

Method:

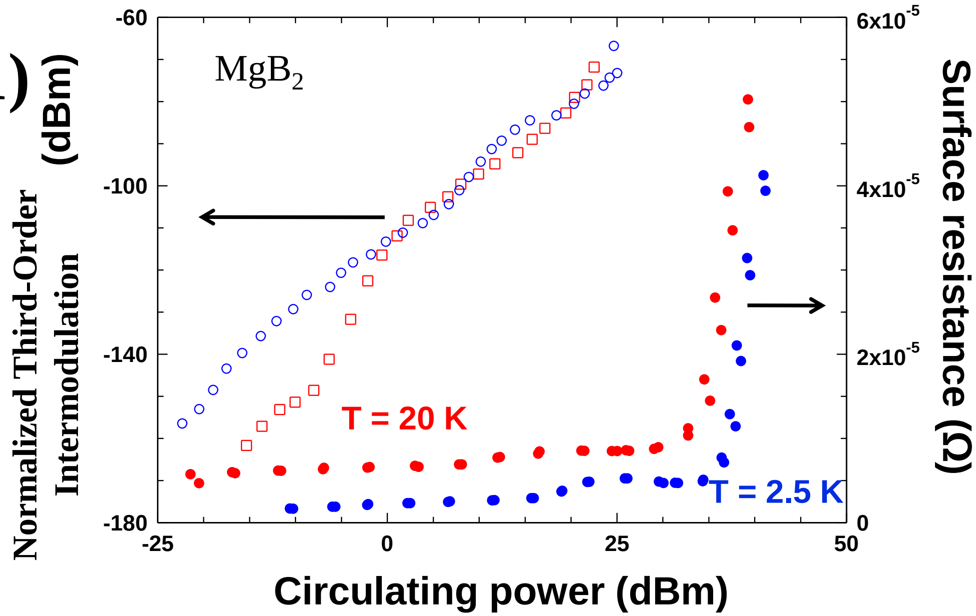
1) **Examine coupons with intense, localized B_{RF} in the superconducting state**
2) **Measure locally-produced harmonic generation from defects**
3) **Scan the probe and image the response**



T. Tai, *et al*. IEEE Trans. Appl. Supercond. 21, 2615 (2011); 23, 7100104 (2013)

Why Harmonics?

1)



D. E. Oates, Y. D. Agassi, B. H. Moeckly,
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 17, NO. 2, JUNE 2007

comparison to SRF conditions

	SRF Cavity	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**

2) **Each defect type will have different nonlinear signature**

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

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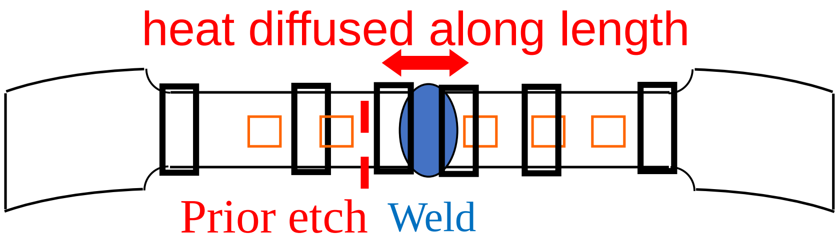
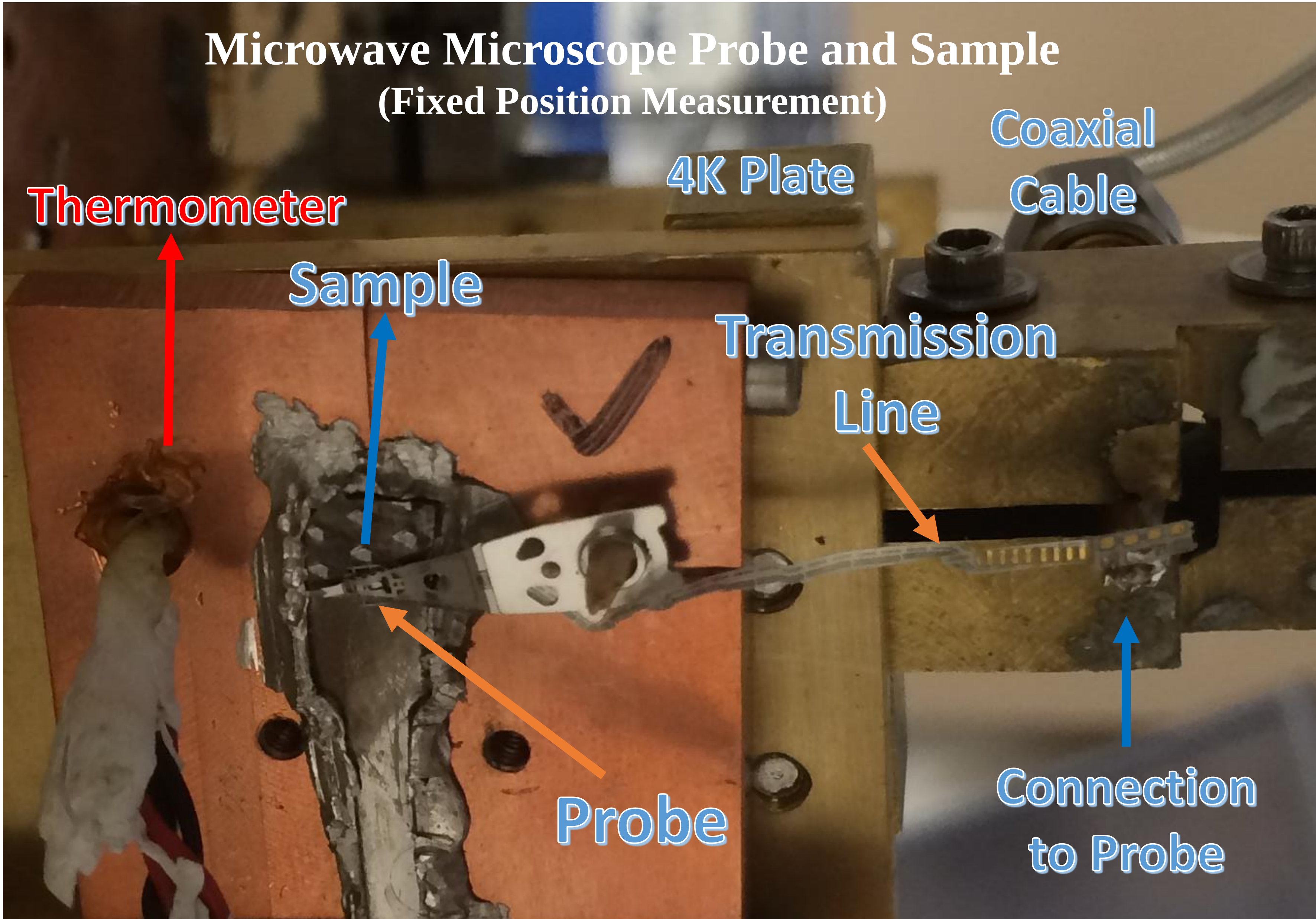
Bulk Nb Sample



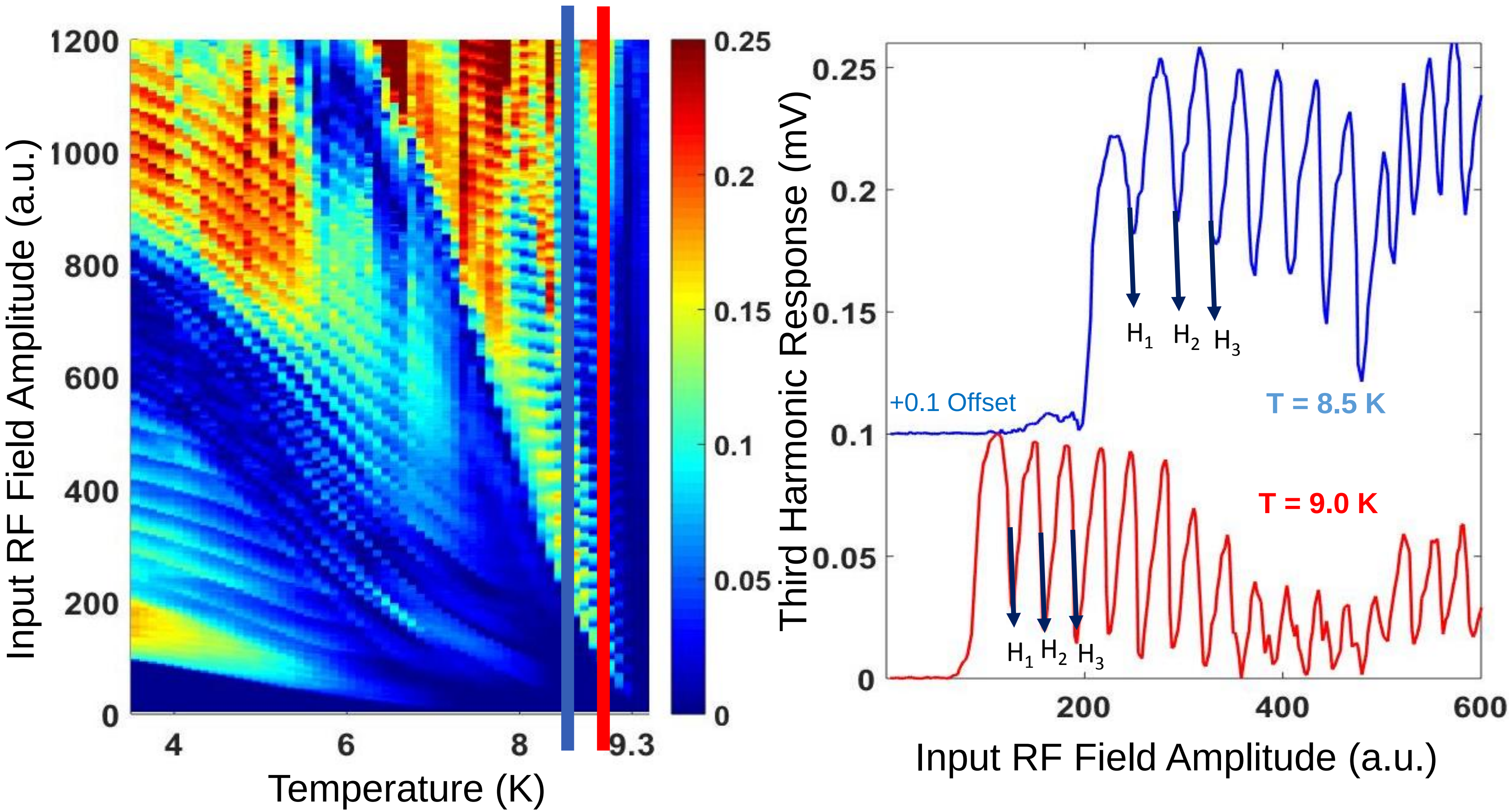
Deformed (ϵ ~ 0.4) single crystals pulled apart, Etched for 10 min then welded back together

Sample prepared by Tom Bieler's group

MICHIGAN STATE UNIVERSITY


Microwave Microscope Probe and Sample
(Fixed Position Measurement)
Coaxial Cable
4K Plate
Thermometer
Sample
Transmission Line
Probe
Connection to Probe

Bulk Nb Data: Periodicity in Harmonic Response

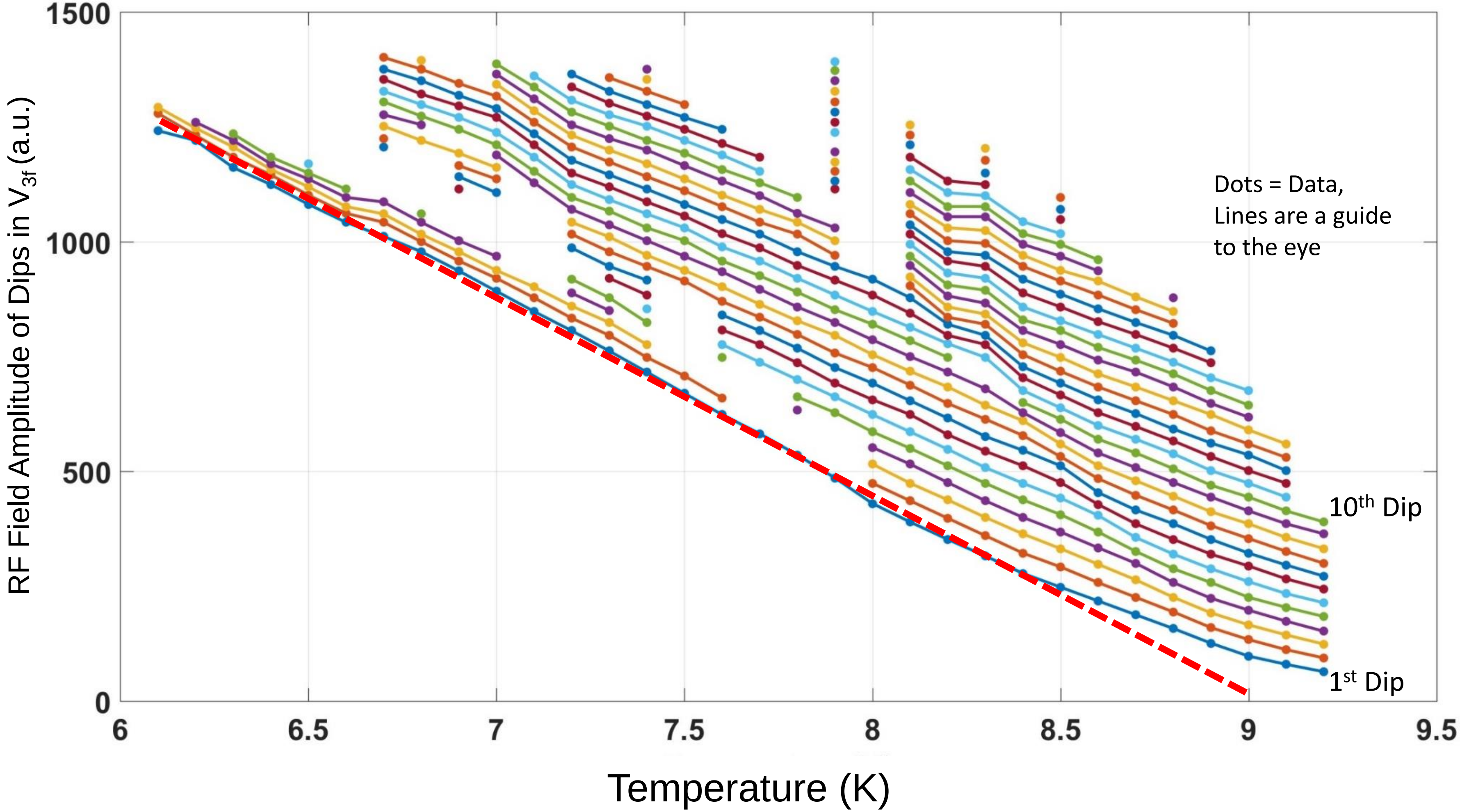


f = 4.38 GHz

Probe background nonlinearity subtracted

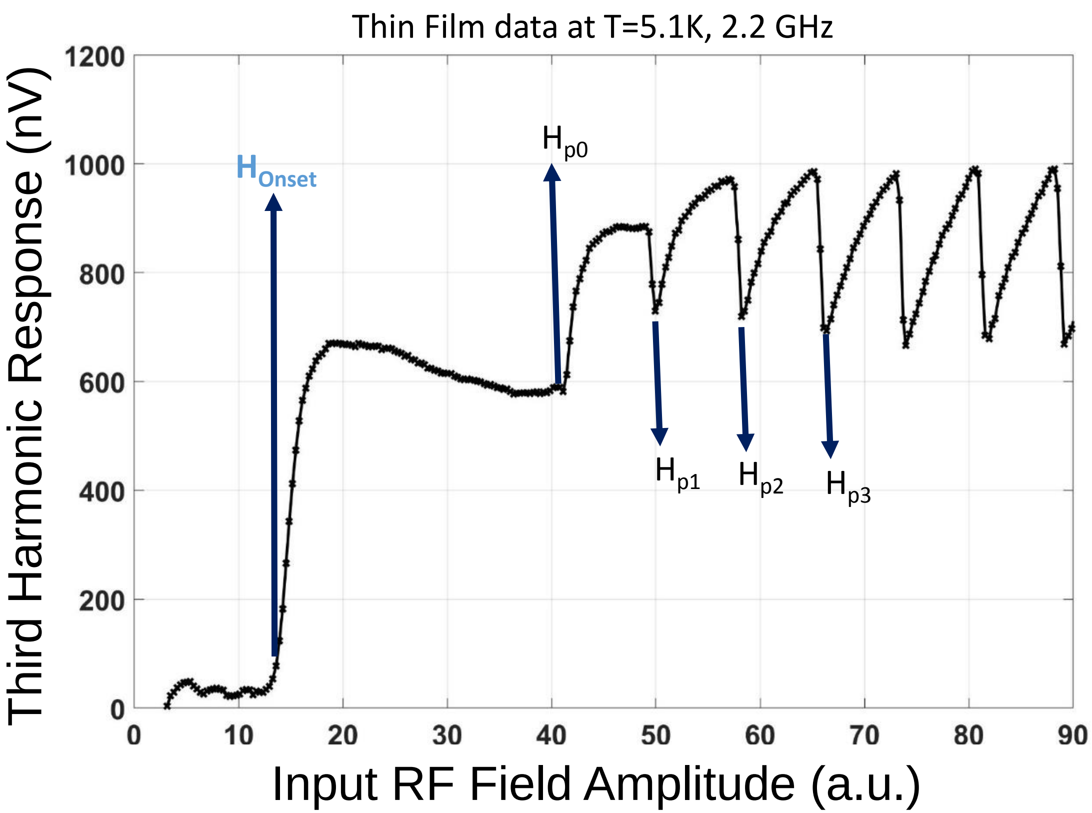
RF Amplitude scale estimate:
11.4 μT/(arb. units) for weak link #1

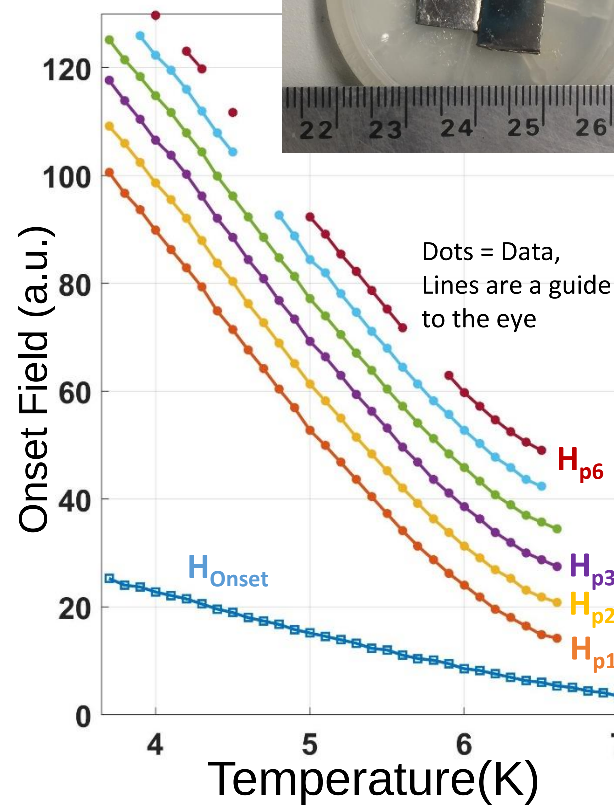
Bulk Nb Data: Closer look at Dips

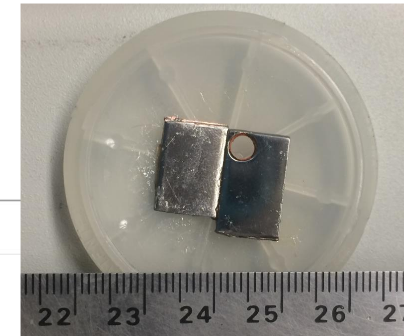


Nb Film on Copper samples from CERN

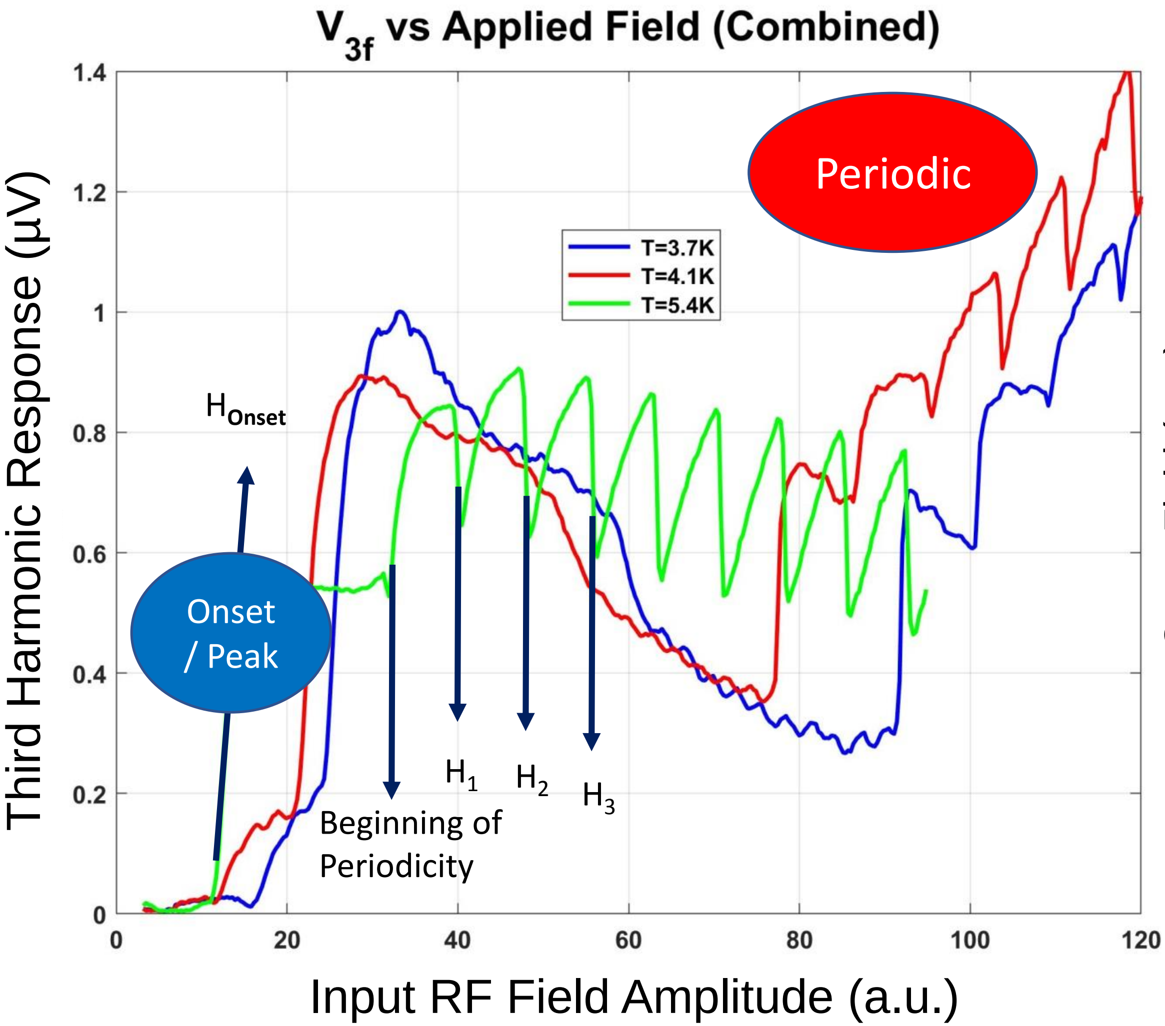
- Deposited by high-power impulse magnetron sputtering (HIPIMS)
- Highly Granular (grain size around 10 nm)
- 1 μm Nb / Cu

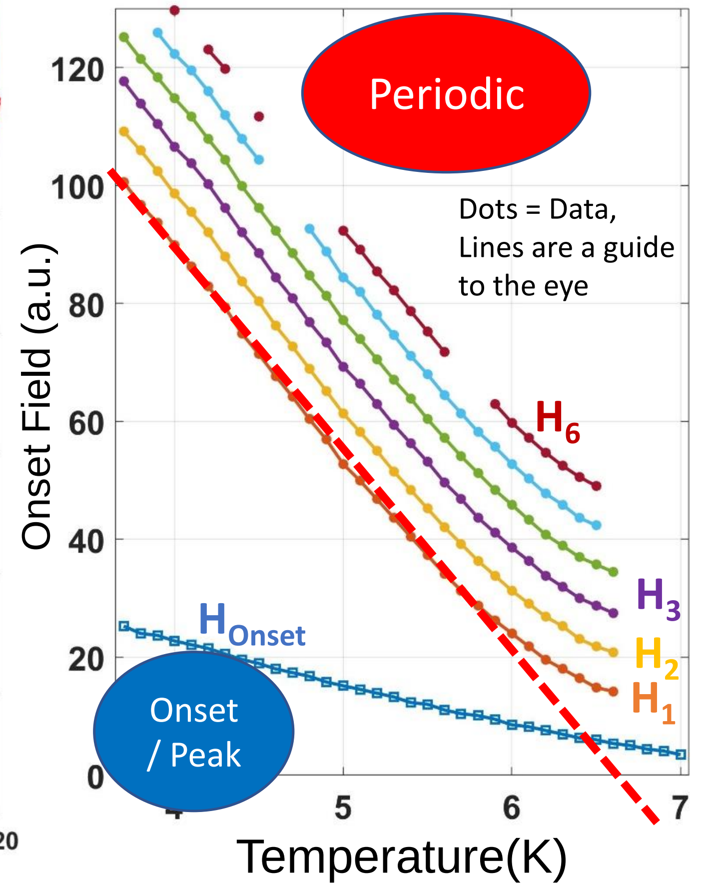






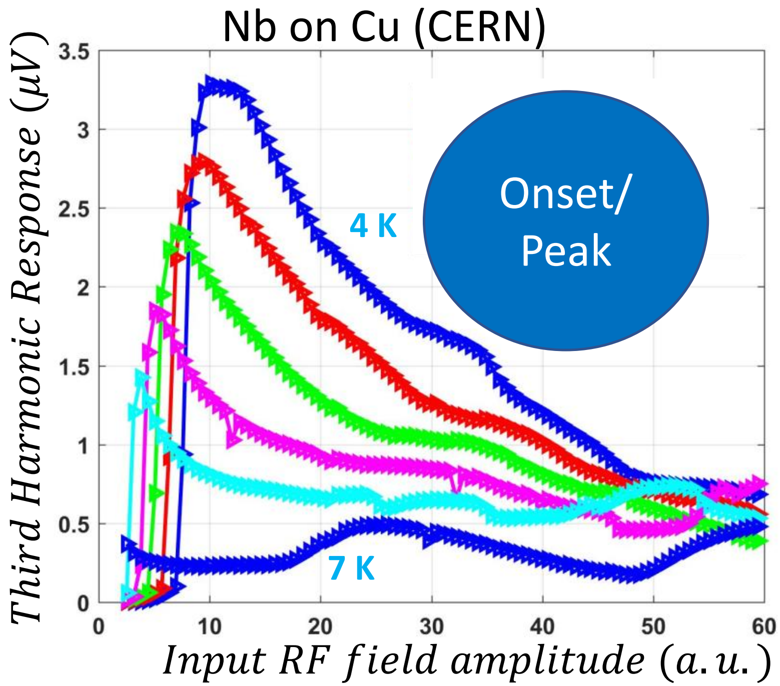
Nb on Copper samples from CERN

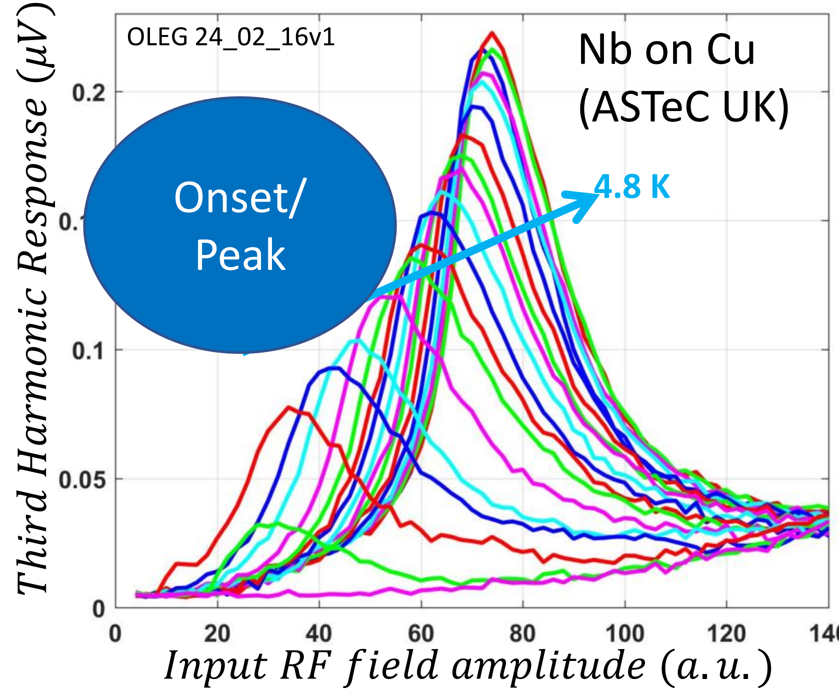


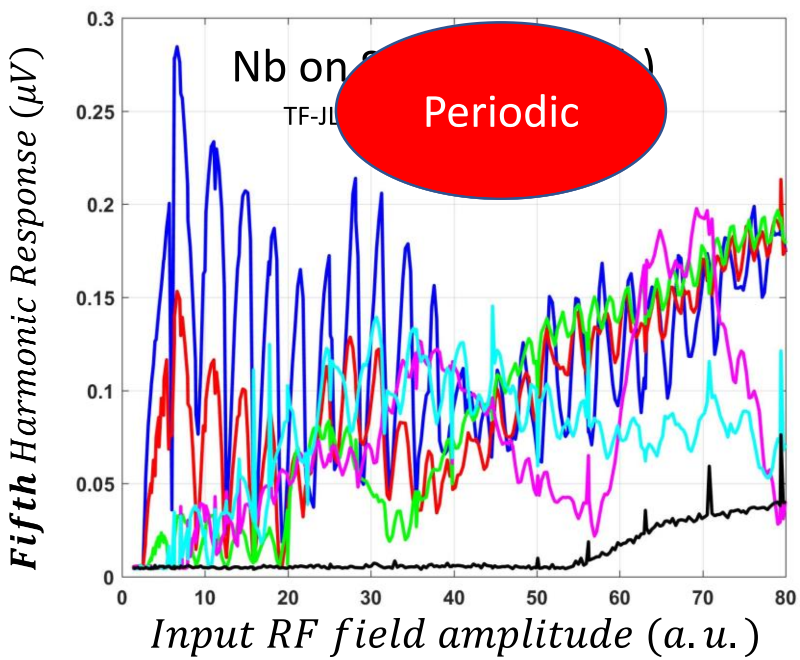


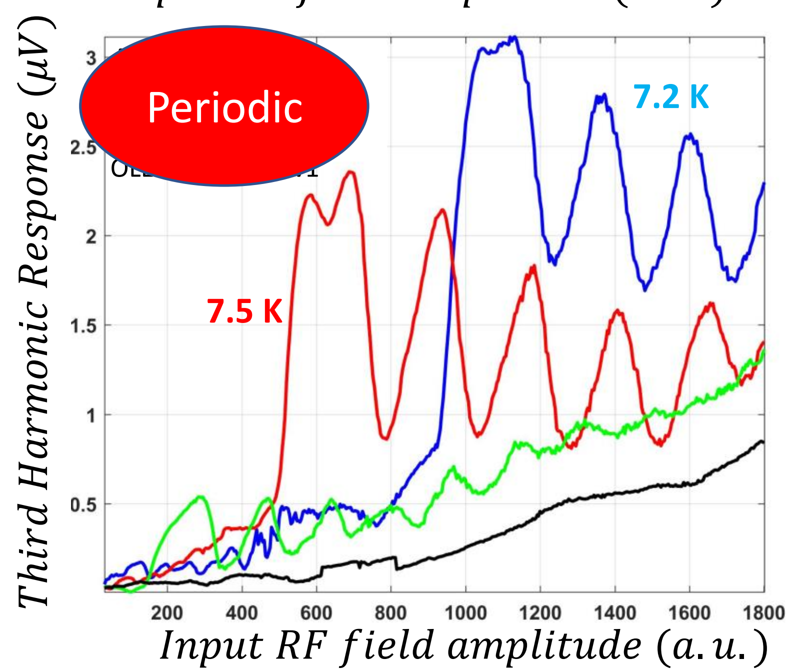
f = 2.2 GHz

Similar Results Seen on Other Film Samples

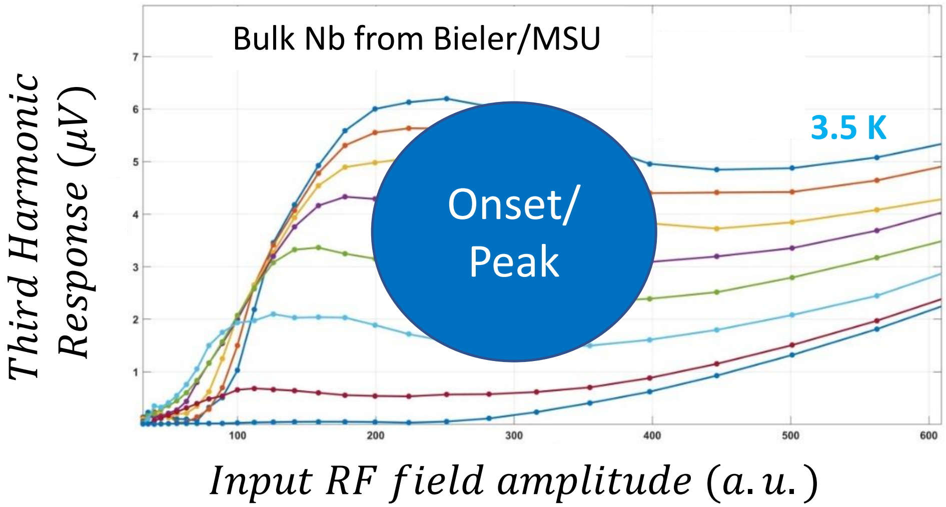


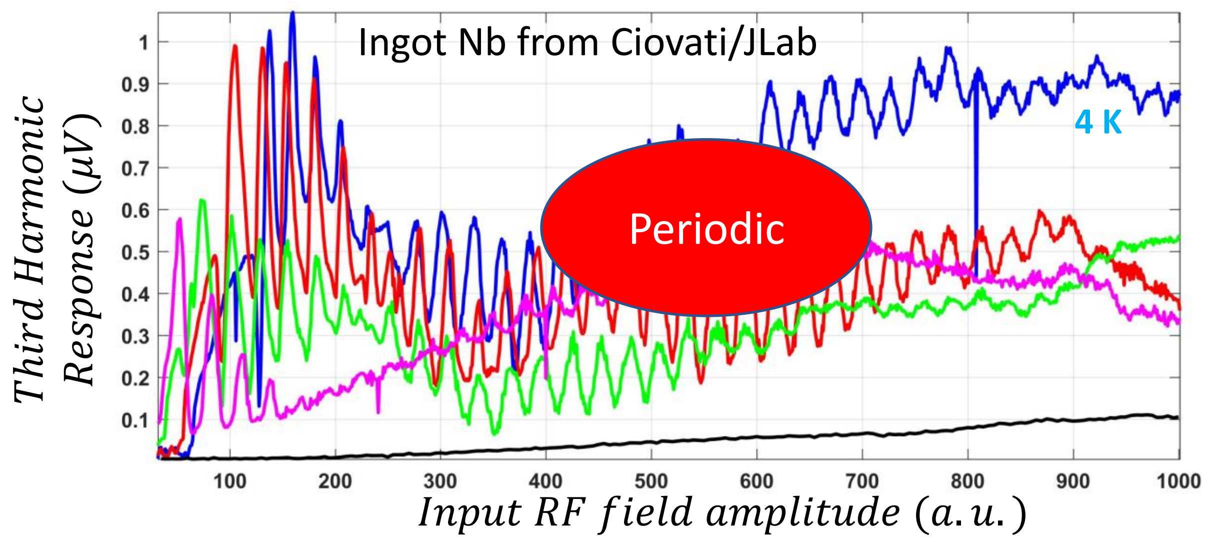






Similar Results Seen on Bulk Samples





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

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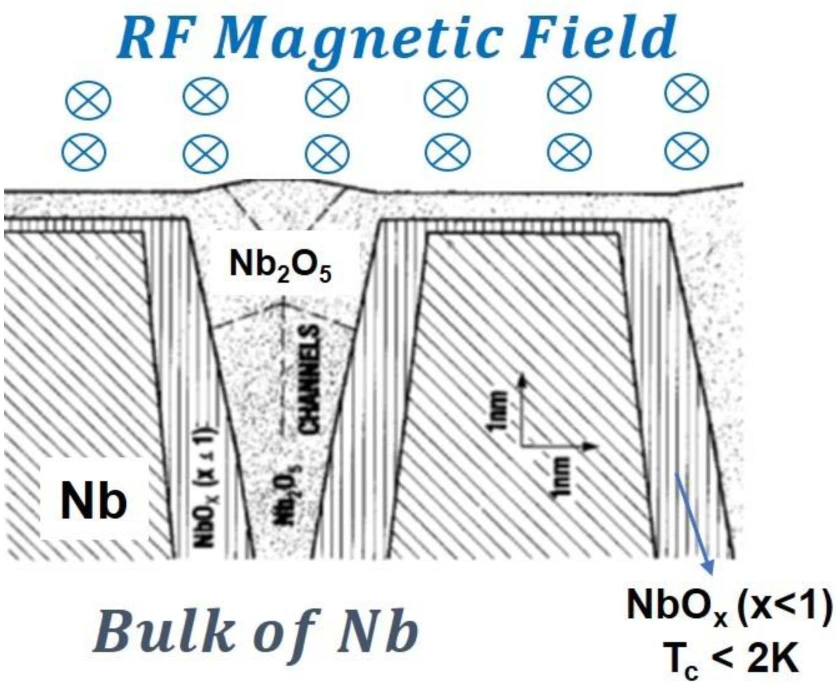
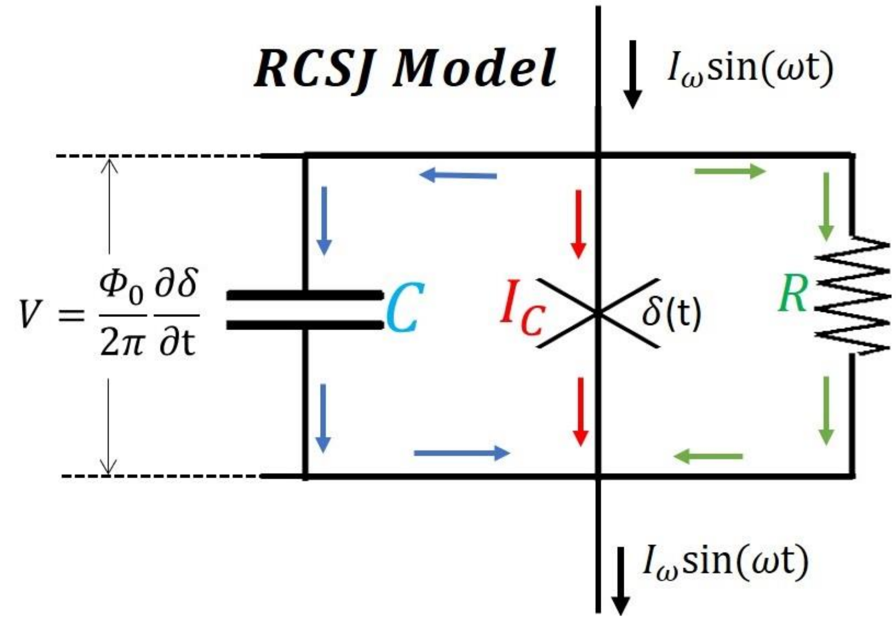
Current Driven Resistively and Capacitively Shunted Josephson Junctions (RCSJ) model



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



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

L. M. Xie, J. Wosik, and J. C. Wolfe, **" Nonlinear microwave absorption in weak-link Josephson junctions,"** Phys. Rev. B 54, 15494 (1996).

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

Example Solution to the RCSJ Model and Fit

Solution to the RCSJ Model

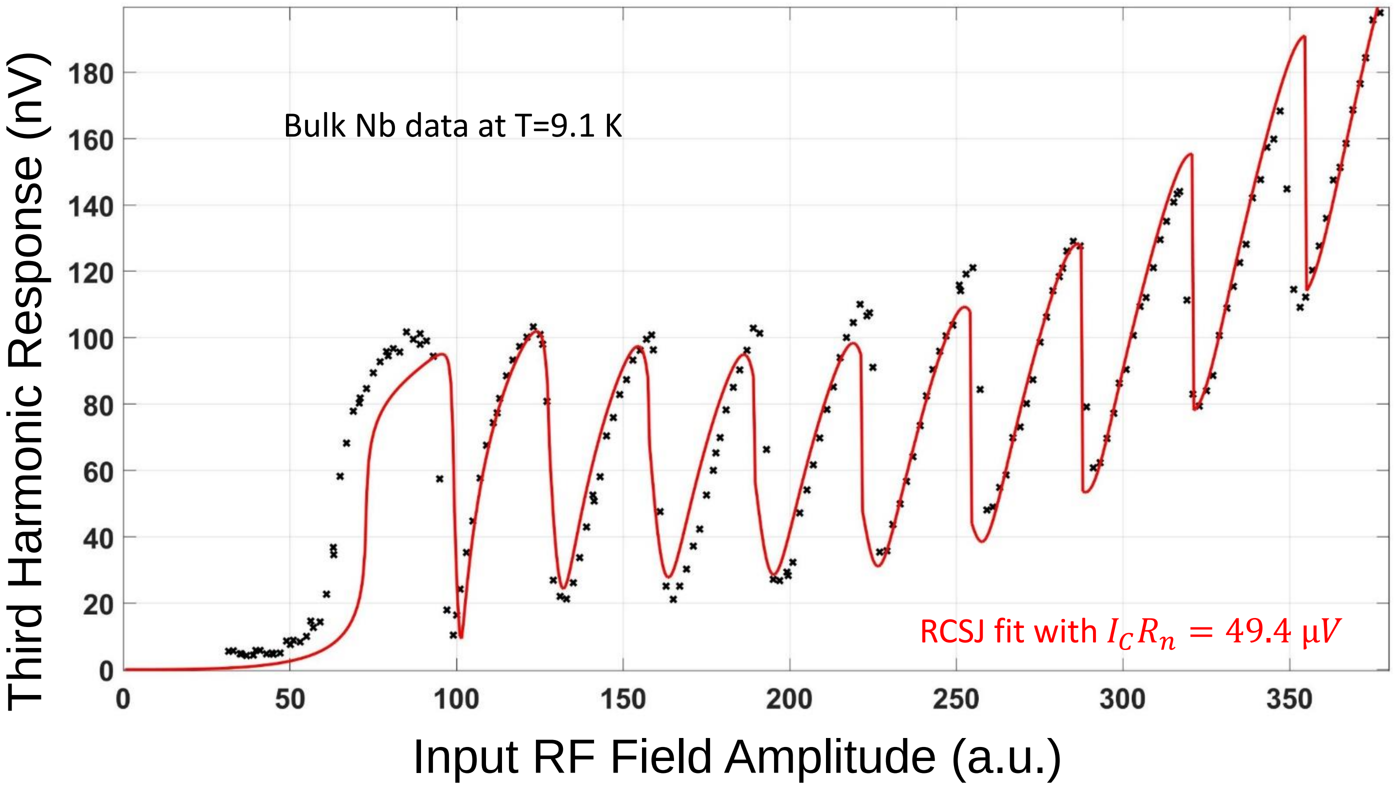
$$\frac{\Phi_0 C}{2\pi}\frac{\partial^2\delta}{\partial t^2} + I_C \sin\delta + \frac{\Phi_0}{2\pi R_n}\frac{\partial\delta}{\partial t} = I_\omega \sin(\omega t)$$

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

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

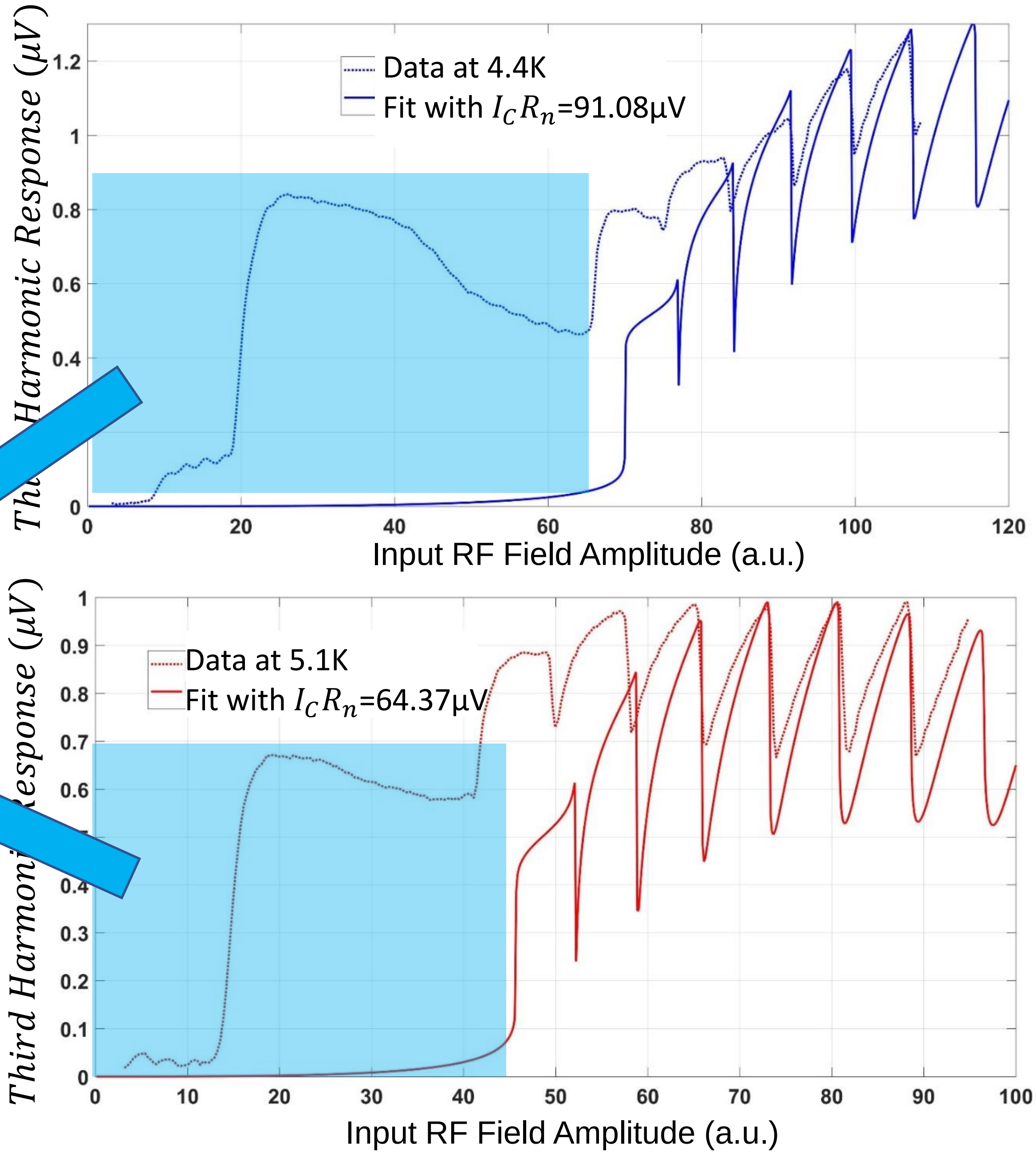
$I_C R_n$ - Fitting Parameter
$I_\omega R_n$ - ScalingFactor * Input RF Field Amplitude (a.u.)

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



Additional (Non-Periodic) Feature in the Data

Nb on Cu Data measured at f = 2.2 GHz



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

Other Sources of Nonlinear Response

TDGL Equations:

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

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

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]

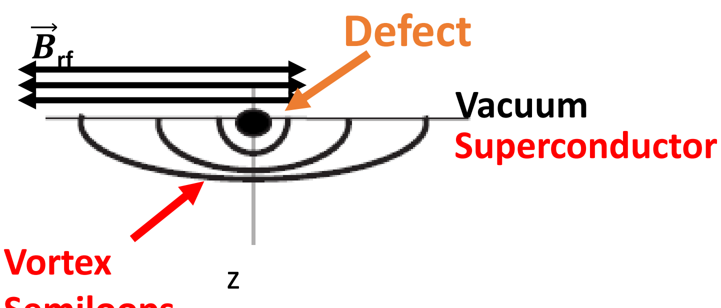
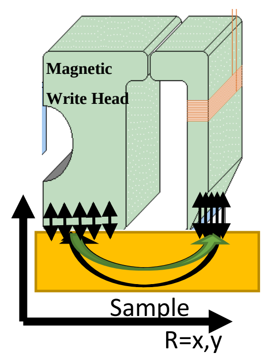
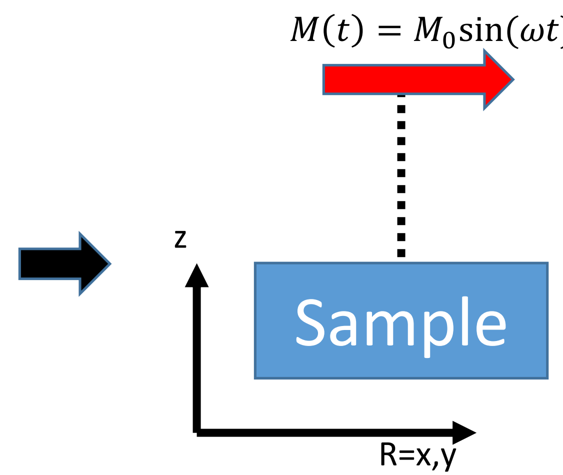


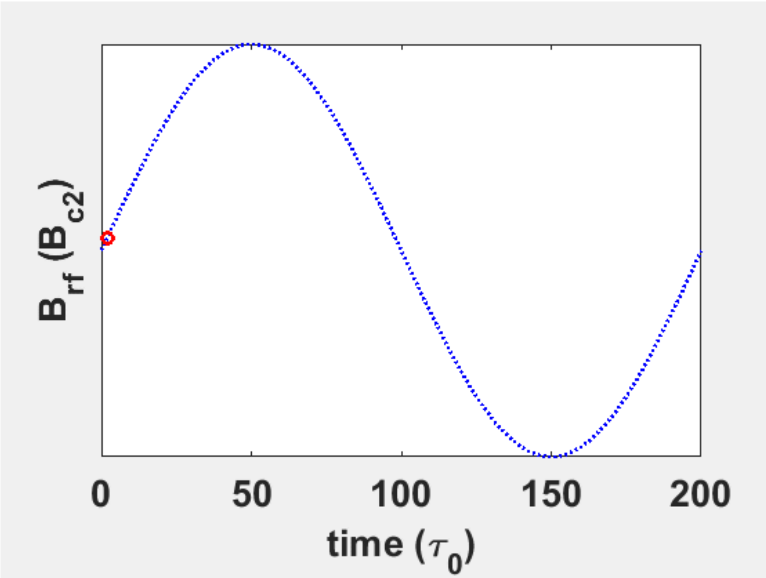
FIG. 2. Snapshots of an expanding vortex semiloop emerging from a surface defect (black dot). The quicker expansion of the loop

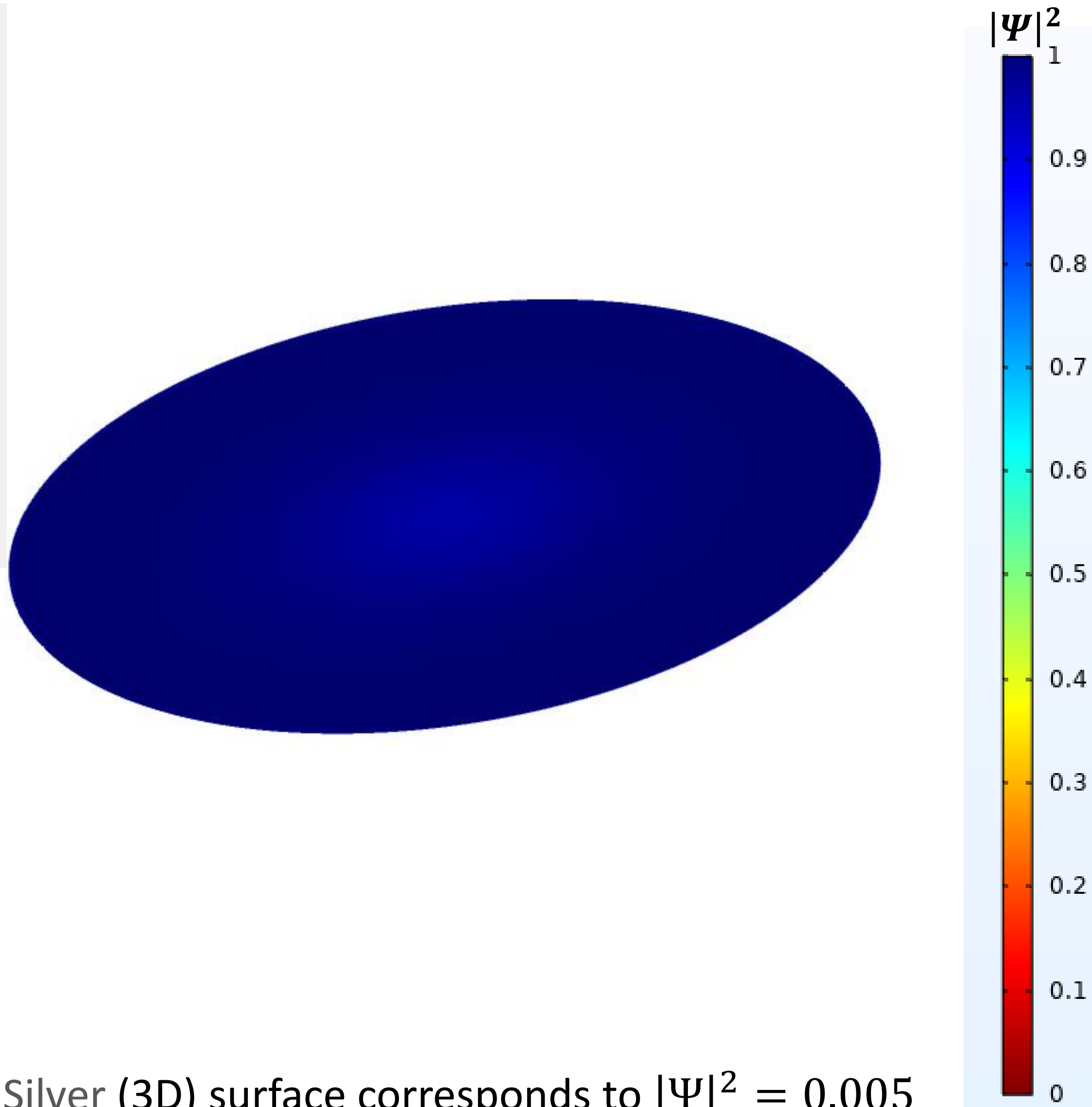




B. Oripov, SMA, arXiv:1909.02714

Horizontal RF Dipole Above Superconductor





H_{dipole} = 8 λ   κ = 1

B_{dipole} = 0.75 B_{c2} η = 1

Period = 200 τ_0 T = 0

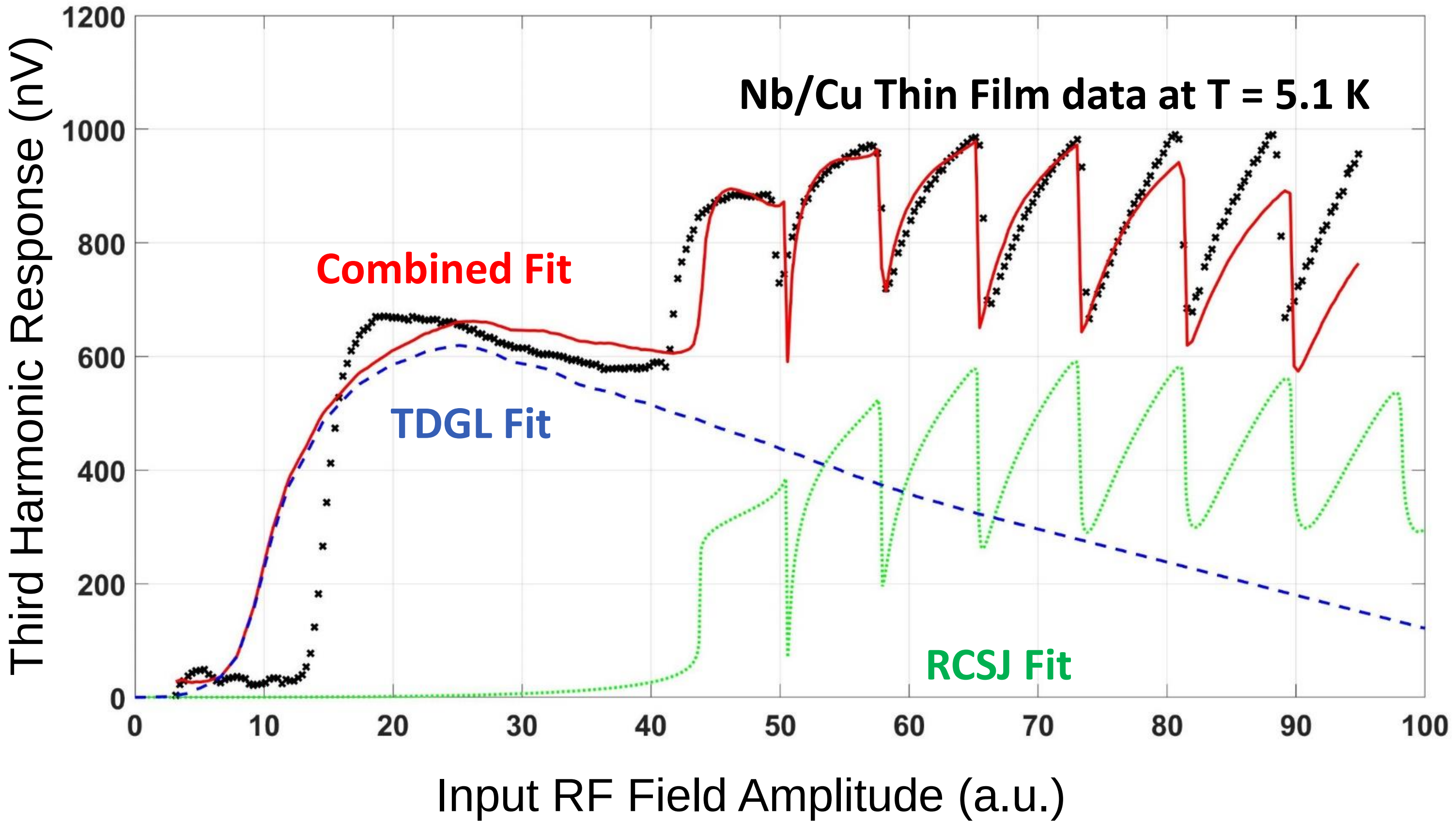
Frequency ≈ 5 GHz   NO DEFECTS

NO DC Magnetic Field

Silver (3D) surface corresponds to $|\Psi|^2 = 0.005$

B. Oripov, SMA, arXiv:1909.02714

Comparing TDGL with Data



B. Oripov, *et al.*, Phys. Rev. Applied **11**, 064030 (2019)

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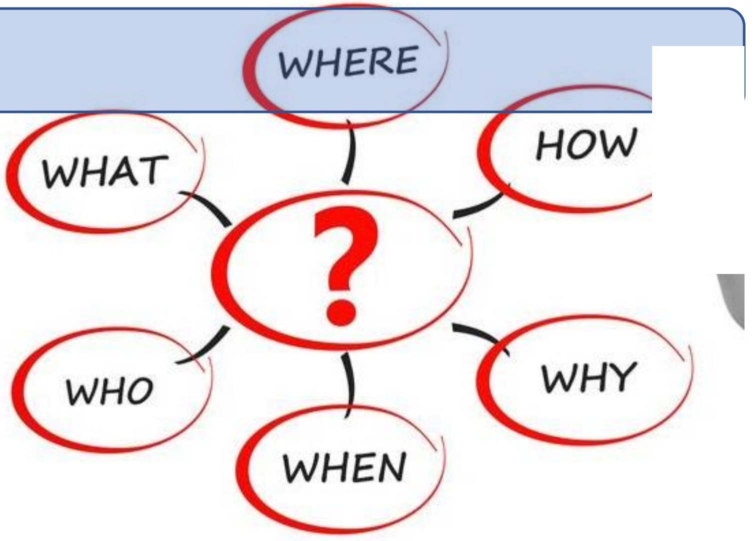
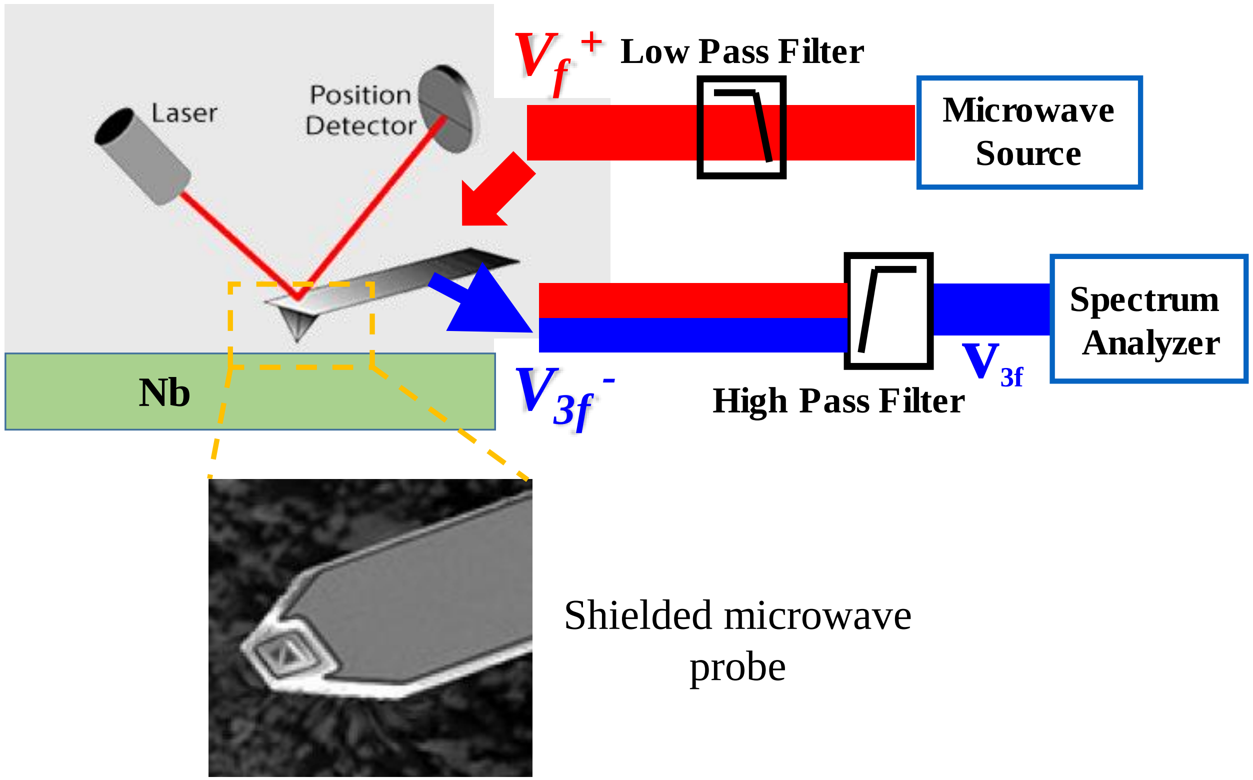


Atomic Force Microscopy (AFM) Based Microwave Microscope



Scanned Nonlinear response imaging

Correlate $P_{3f}(x, y)$ images with topography, surface potential, etc.

Thermal Properties of Nb Coatings and Interfaces

Supercond. Sci. Technol. **29** (2016) 015004 (12pp)

doi:10.1088/0953-2048/29/1/015004

Thermal contact resistance at the Nb/Cu interface as a limiting factor for sputtered thin film RF superconducting cavities

V Palmieri[1] and R Vaglio[2]

Proposal:

Measure thermo-reflectance of Nb/Cu coatings to deduce the thermal boundary resistance $R_{Nb/Cu}$

Expected outcome:

Determination of:

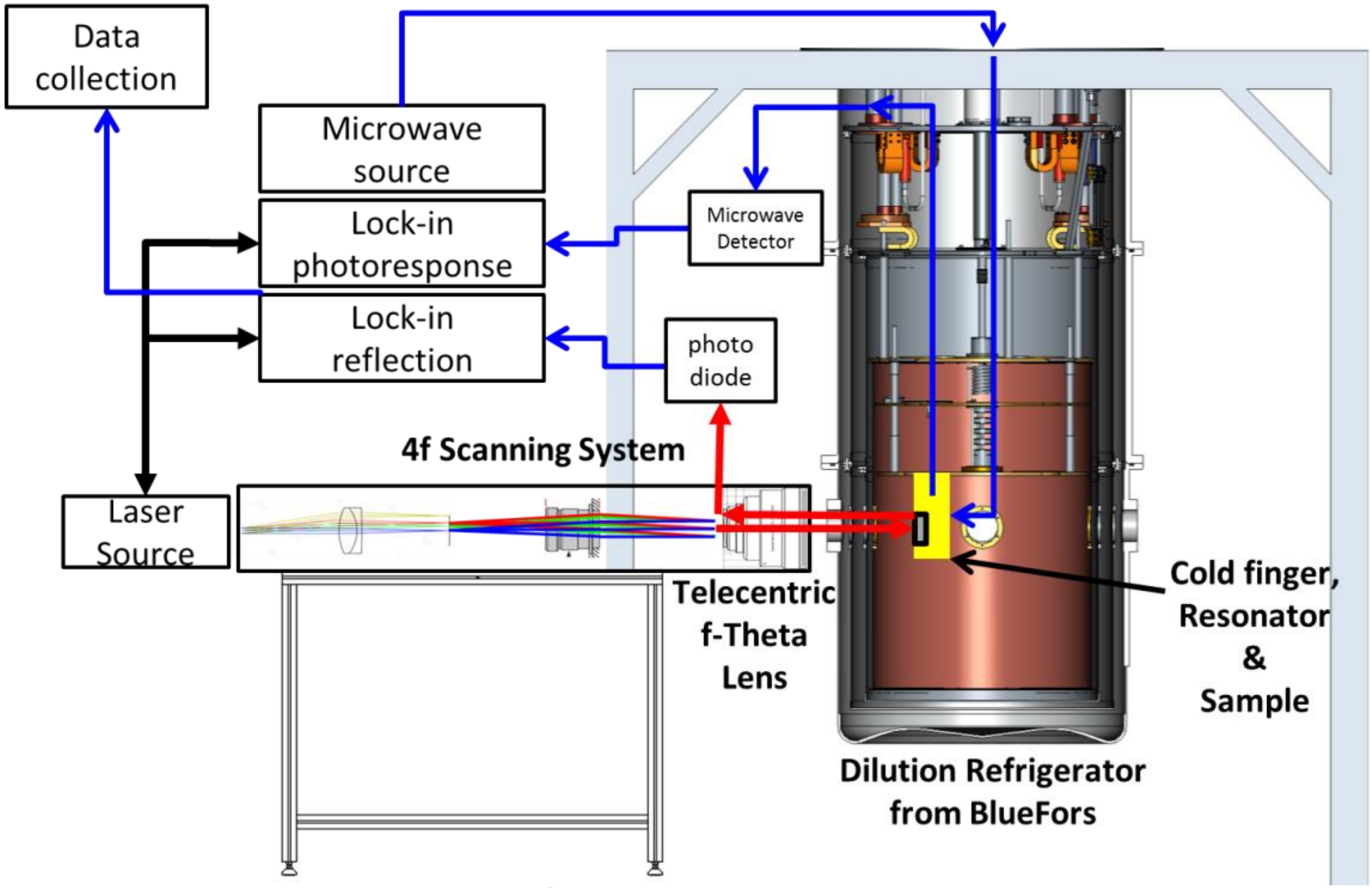
Film thermal diffusivity $\alpha_{film} = \frac{\kappa}{(\rho C)}$

Substrate thermal diffusivity $\alpha_{substrate}$

Film / Substrate Thermal Boundary Resistance $R_{Nb/Cu}$

Thermal Properties of Nb Coatings and Interfaces

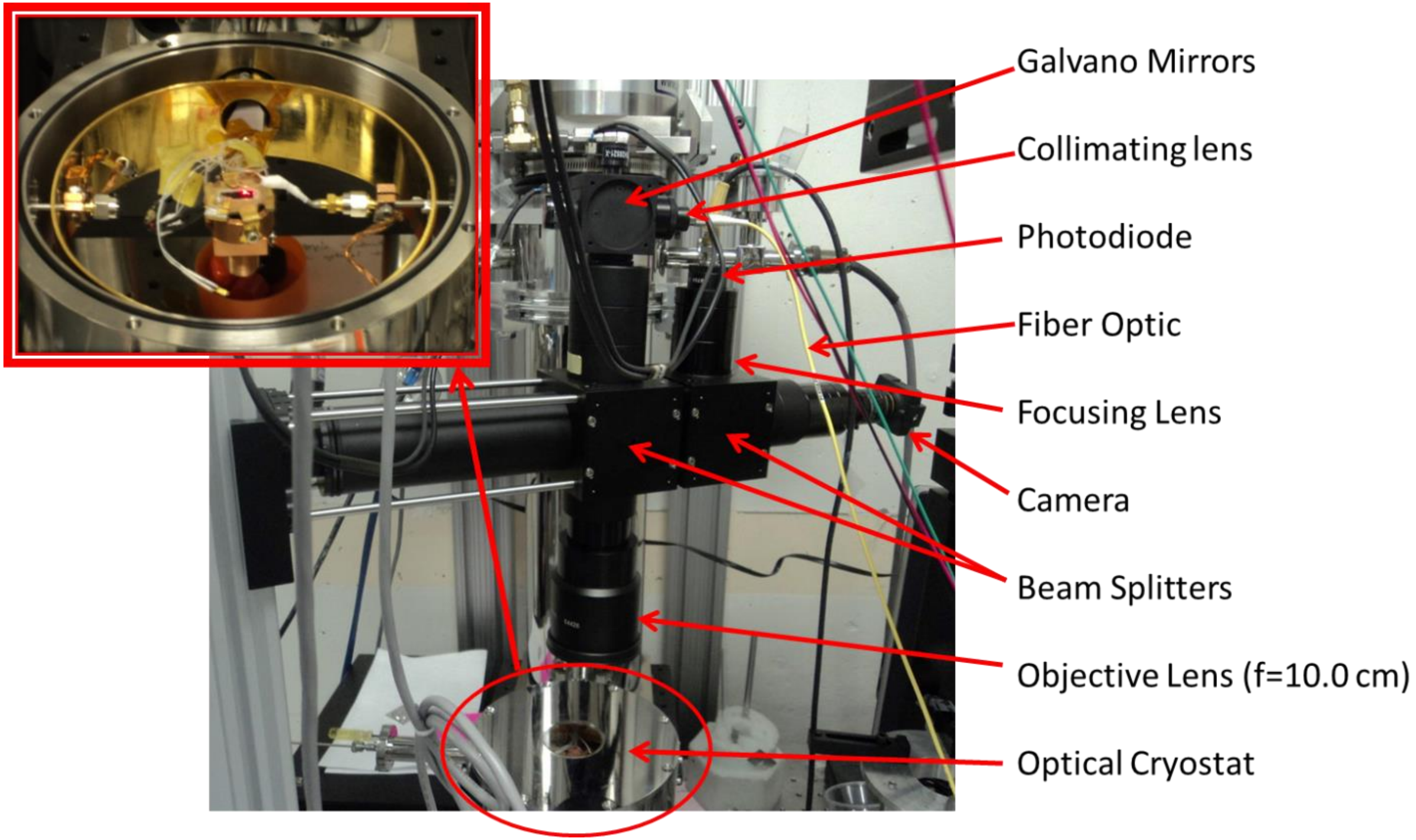
Laser Scanning Microscope #1 (Dilution Refrigerator)



S. Bae, *et al*., Rev. Sci. Instrum. 90, 043901 (2019)

Thermal Properties of Nb Coatings and Interfaces

Laser Scanning Microscope #2 (Gifford-McMahon Refrigerator)



Summary

- A microscopic probe of superconductor nonlinearity is introduced and validated
- 2 classes of Nb nonlinear response are detected and modeled
- Magnetic Microwave Microscopy can be used to extract **local T_c** and **Effective BCS Gap** at the weak-link and **local RF critical field**

Future Work

- TDGL Simulations of probe / sample interactions (arXiv:1909.02714)
- Raster Scanning over known defect while imaging onset field
- Measurement of multilayer samples
- Quantitative boundary resistance measurements of coatings
- Residual resistance measurements of SRF cavities to 60 mK

This work is funded by US Department of Energy High Energy Physics program grant # DESC0017931 and the Maryland Quantum Materials Center

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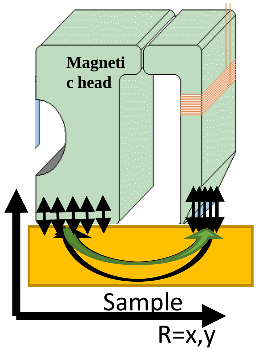
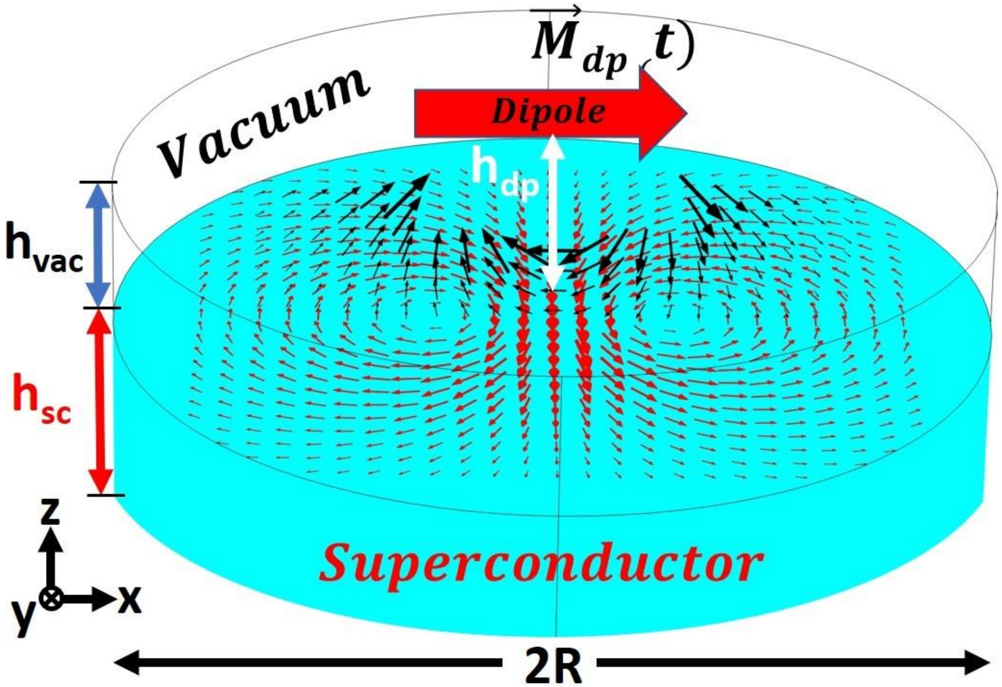
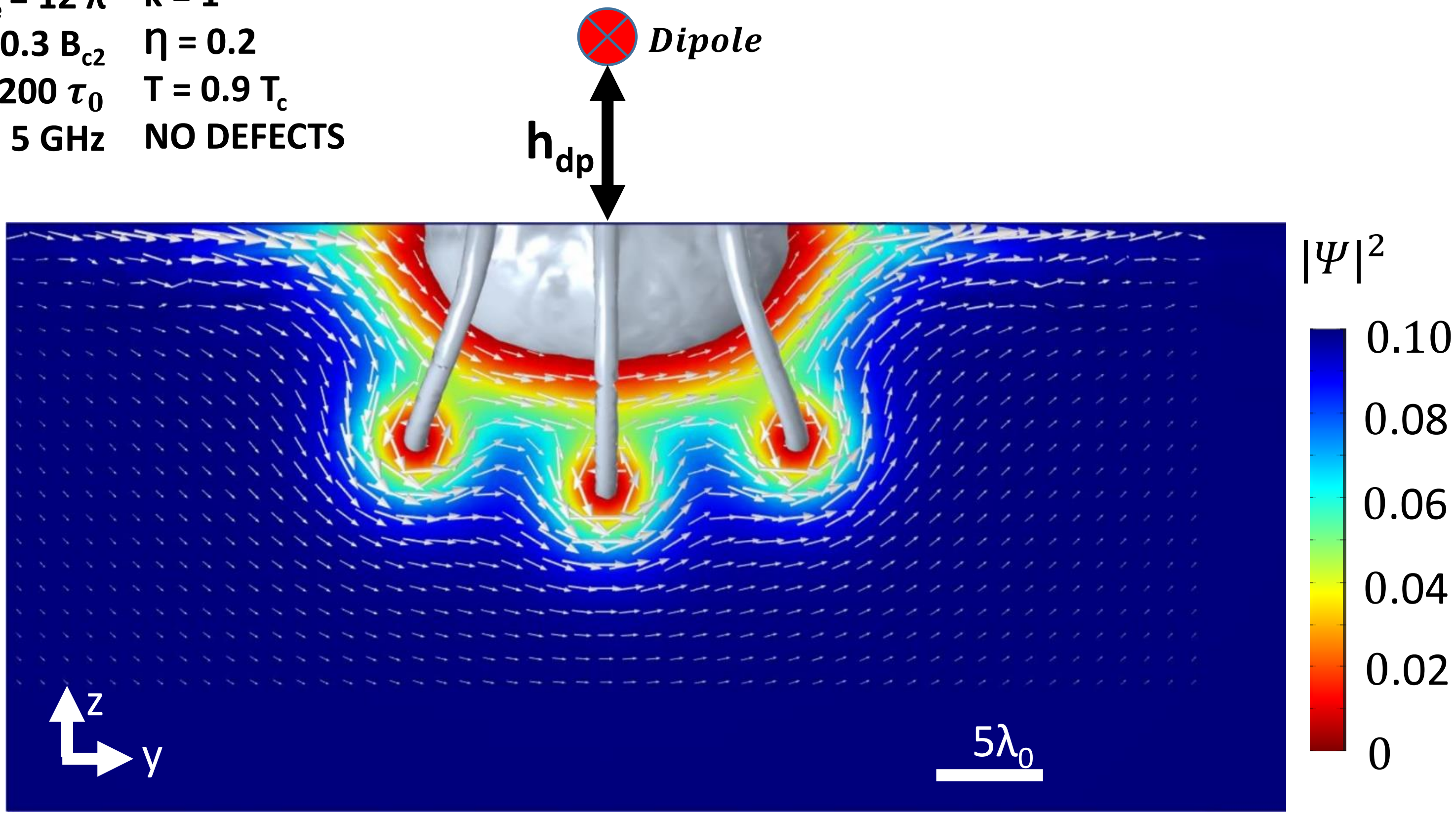
TDGL simulation setup





Screening currents

$H_{dipole} = 12\ \lambda$ κ = 1
$B_{dipole} = 0.3\ B_{c2}$ η = 0.2
Period = 200 τ_0 T = 0.9 T_c
Frequency ≈ 5 GHz NO DEFECTS



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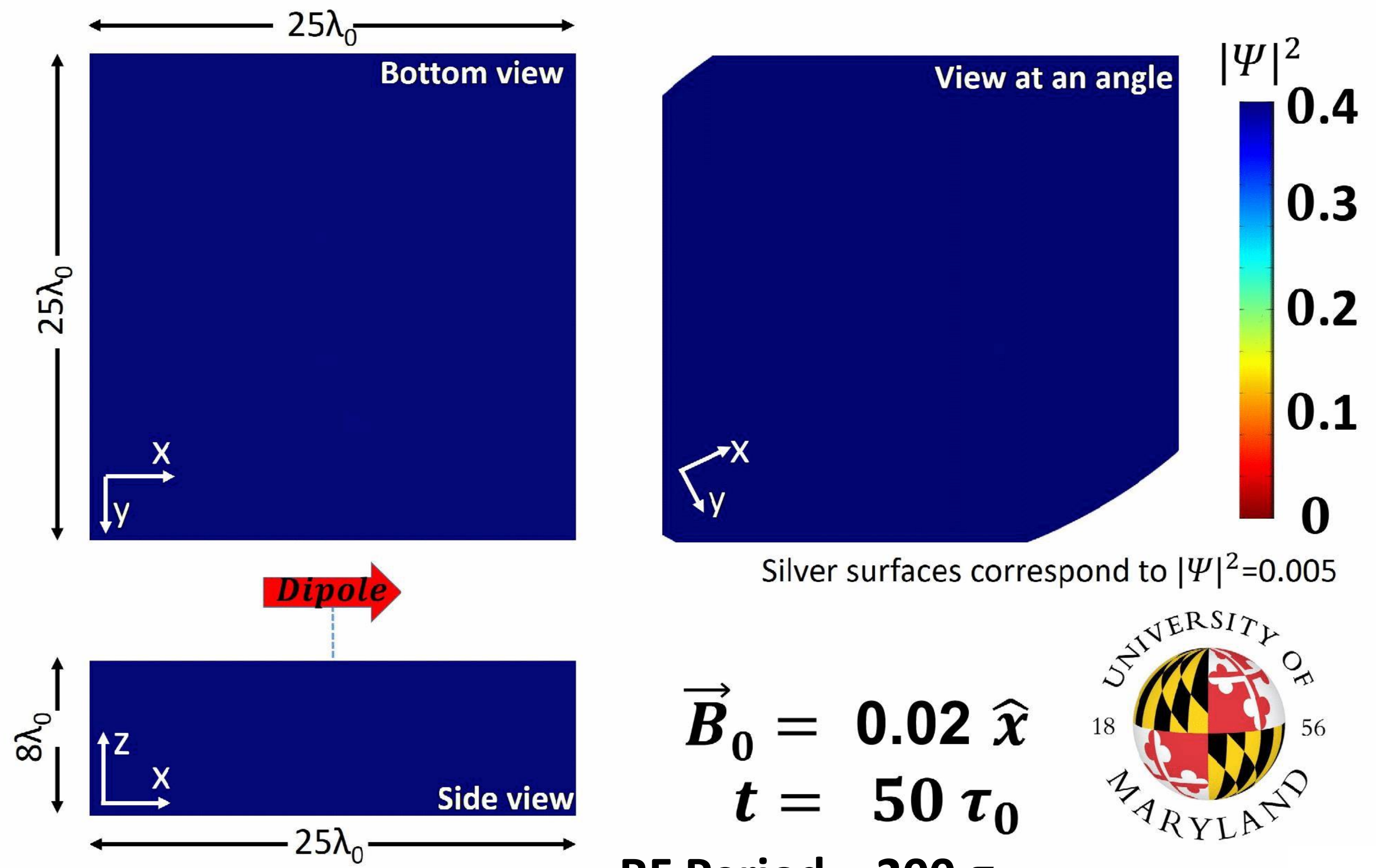
The evolution of vortex semiloops with rf field amplitude



$$\vec{B}_0 = 0.02\ \hat{x}$$

$$t = 50\ \tau_0$$

RF Period = 200 τ_0

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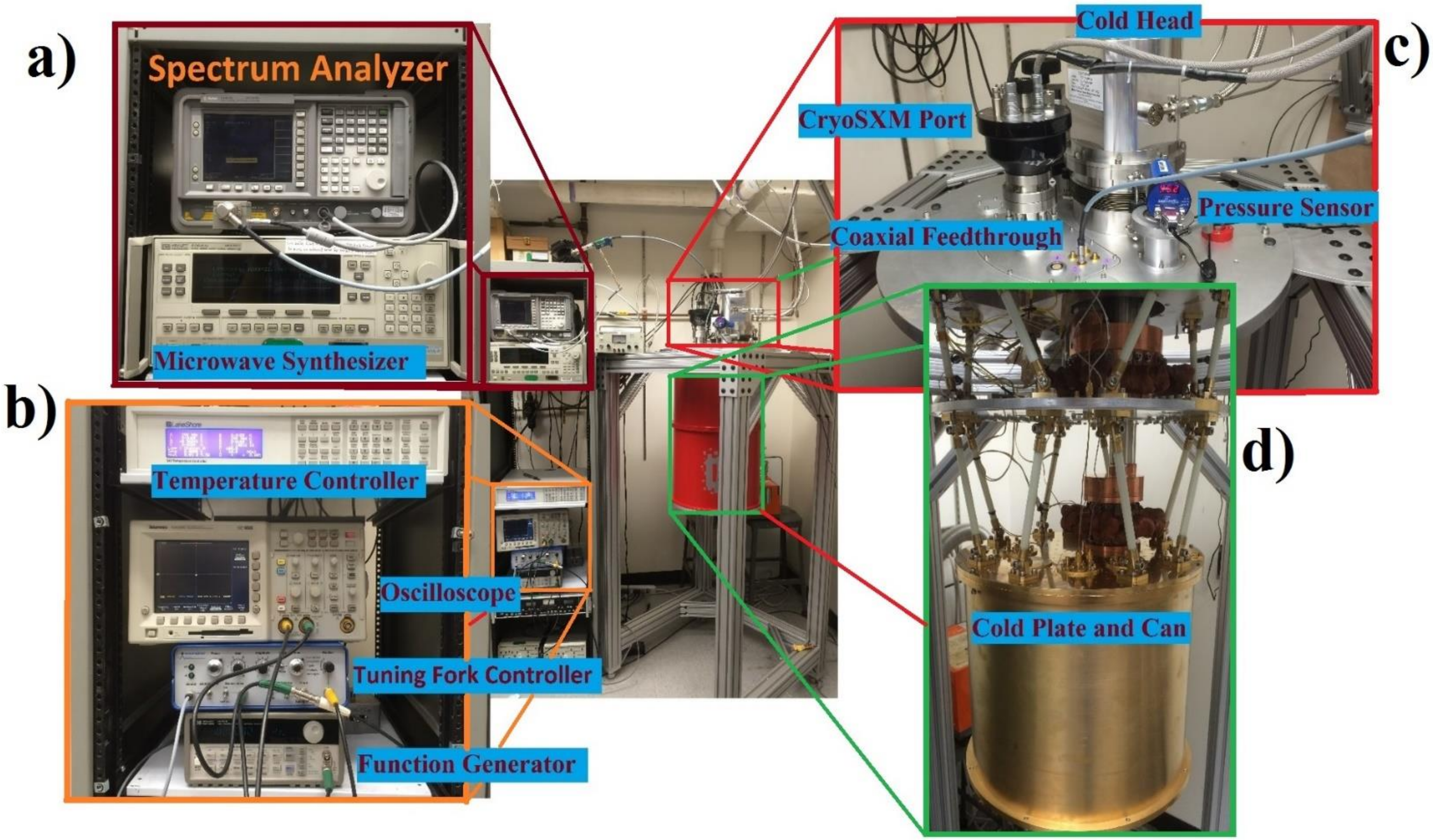
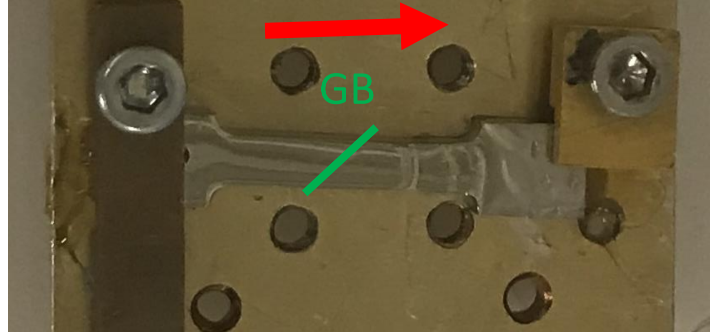
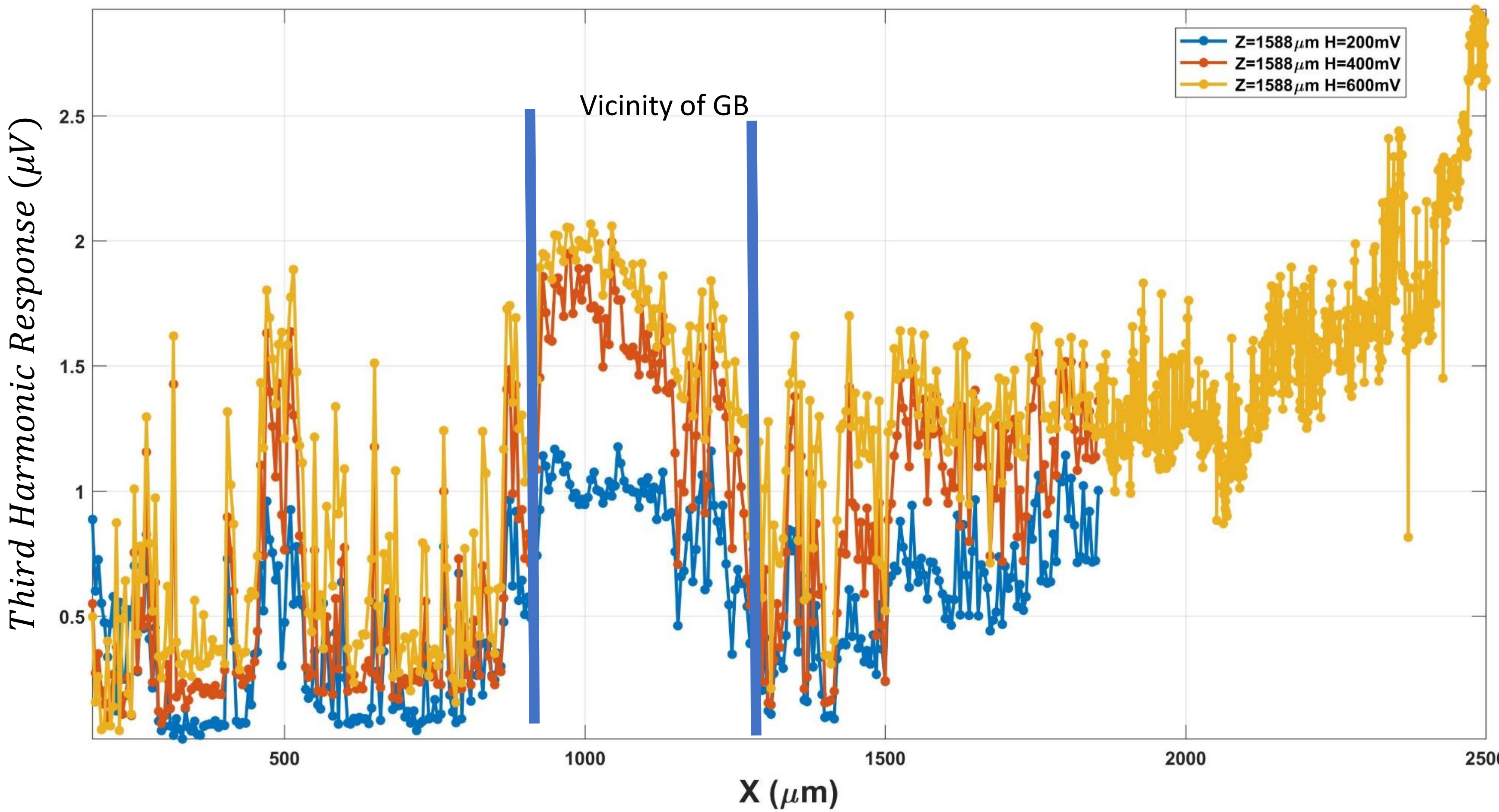

a)
Spectrum Analyzer
Microwave Synthesizer
b)
Temperature Controller
Oscilloscope
Tuning Fork Controller
Function Generator
Cold Head
c)
CryoSXM Port
Pressure Sensor
Coaxial Feedthrough
d)
Cold Plate and Can



Bulk Nb from Tom Bieler's Group

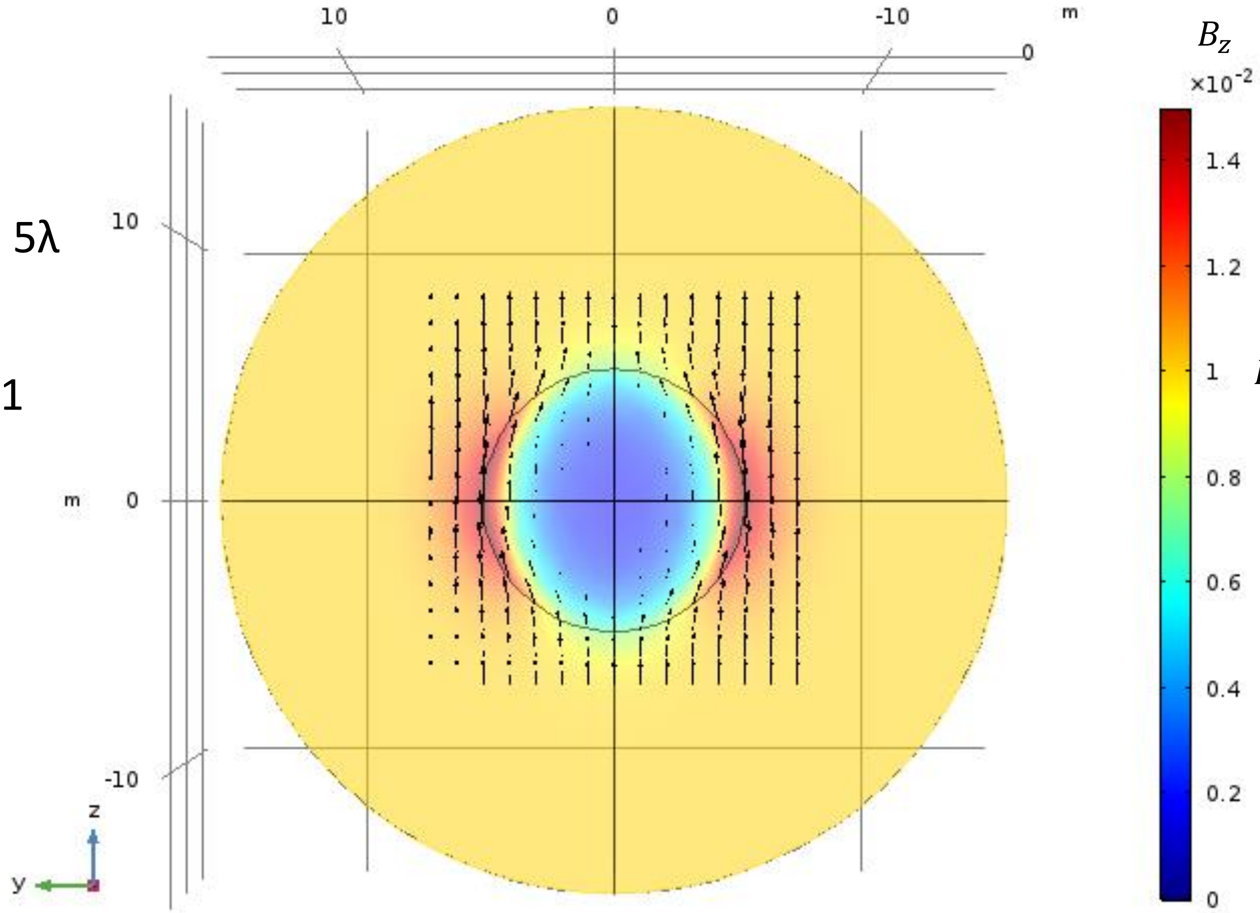


Superconducting Sphere in a Uniform Static Magnetic Field

Sphere Radius = 5λ

κ = 1, T = 0;

B_z applied = 0.01



$B_z \; applied = 0.01$

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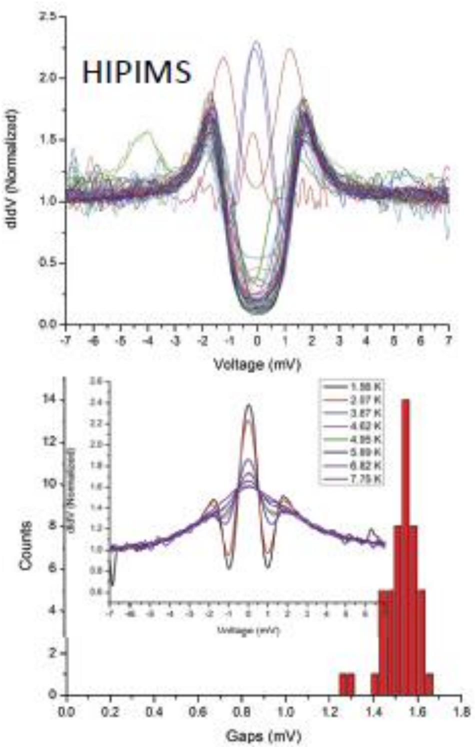
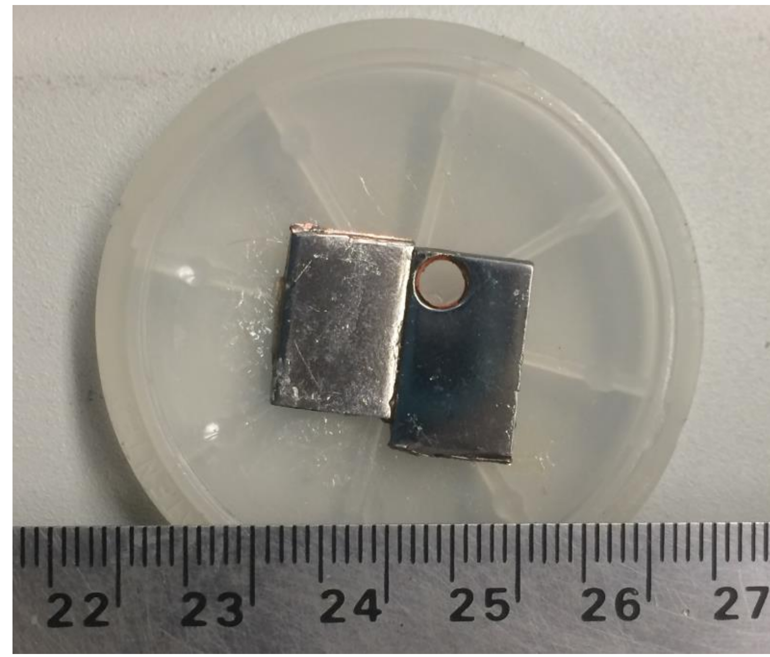
- Highly Granular (grain size around 10 nm)
- 1 μm Nb / Cu



Point Contact Spectroscopy:
- ✓ **Broadened DOS**
- ✓ **Finite 0-bias conductance (ZBC)**
- ✓ **Numerous ZBCP**



T. Junginger, SRF2015, TUPB042

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

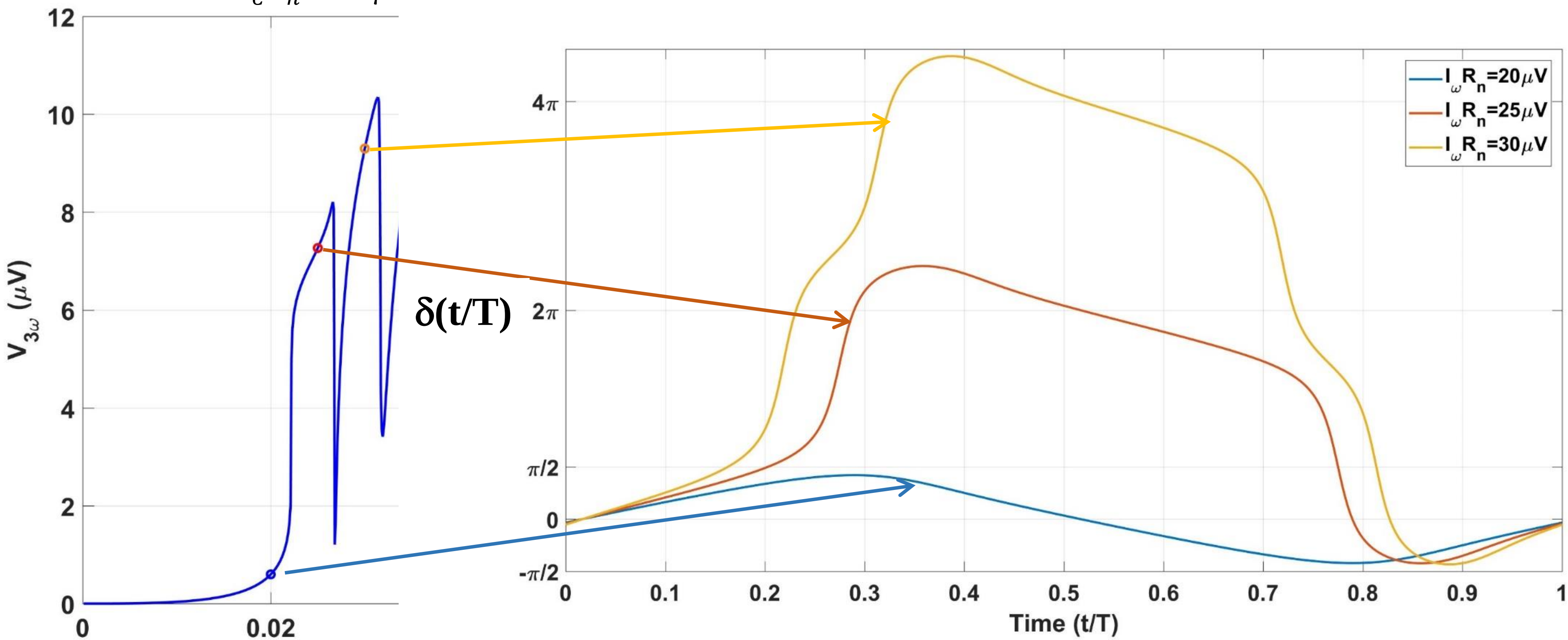
$$(I_C R_n)\sin\delta + \frac{\Phi_0}{2\pi}\frac{\partial\delta}{\partial t} = (I_\omega R_n)\sin(\omega t)$$

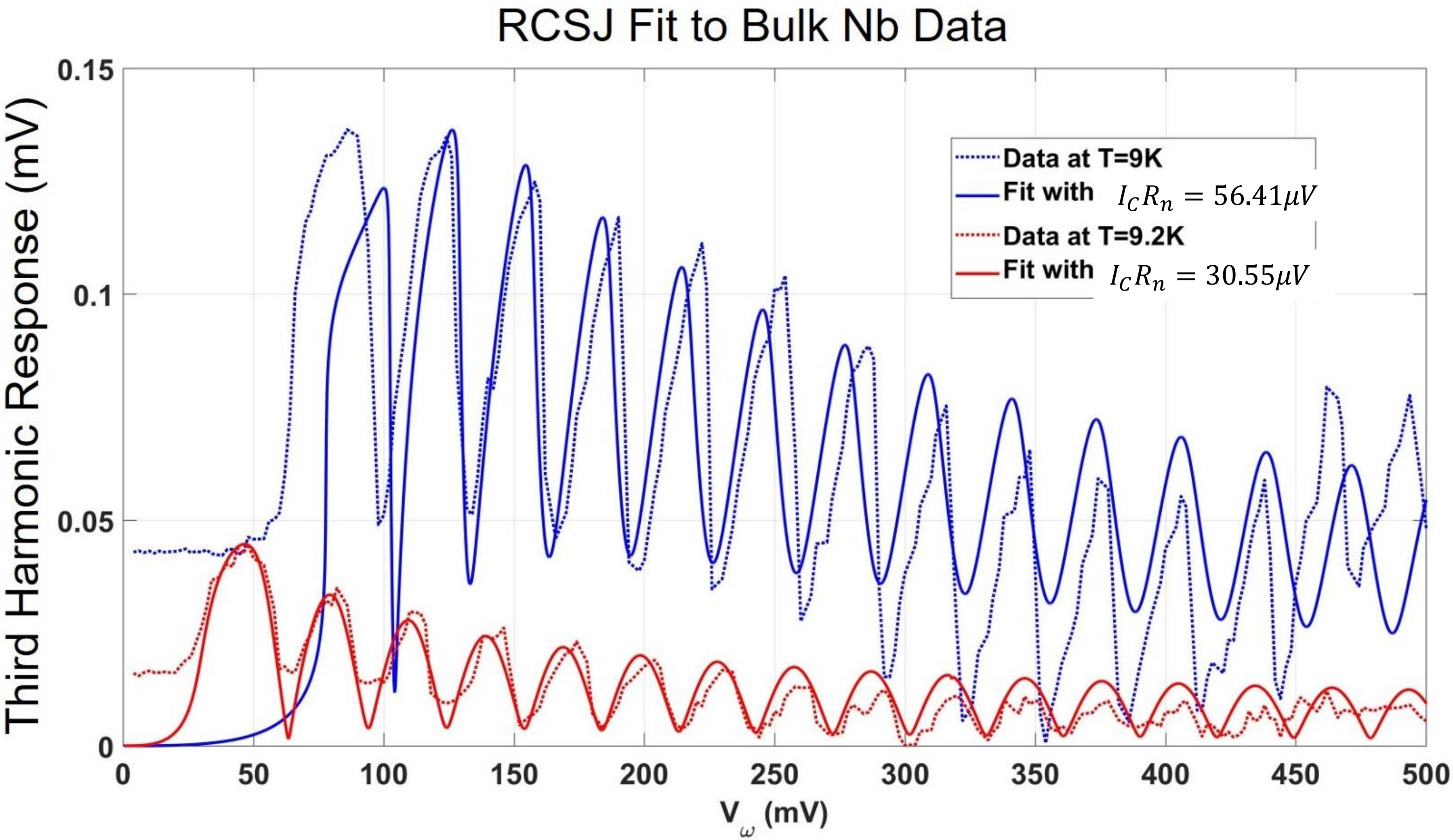
$\boldsymbol{I_C R_n}$ - Fitting Parameter
$\boldsymbol{I_\omega R_n}$- ScalingFactor * Input RF Field Amplitude (a.u.)

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

Example Solution to the RCSJ Model

For $I_C R_n = 20\mu V$

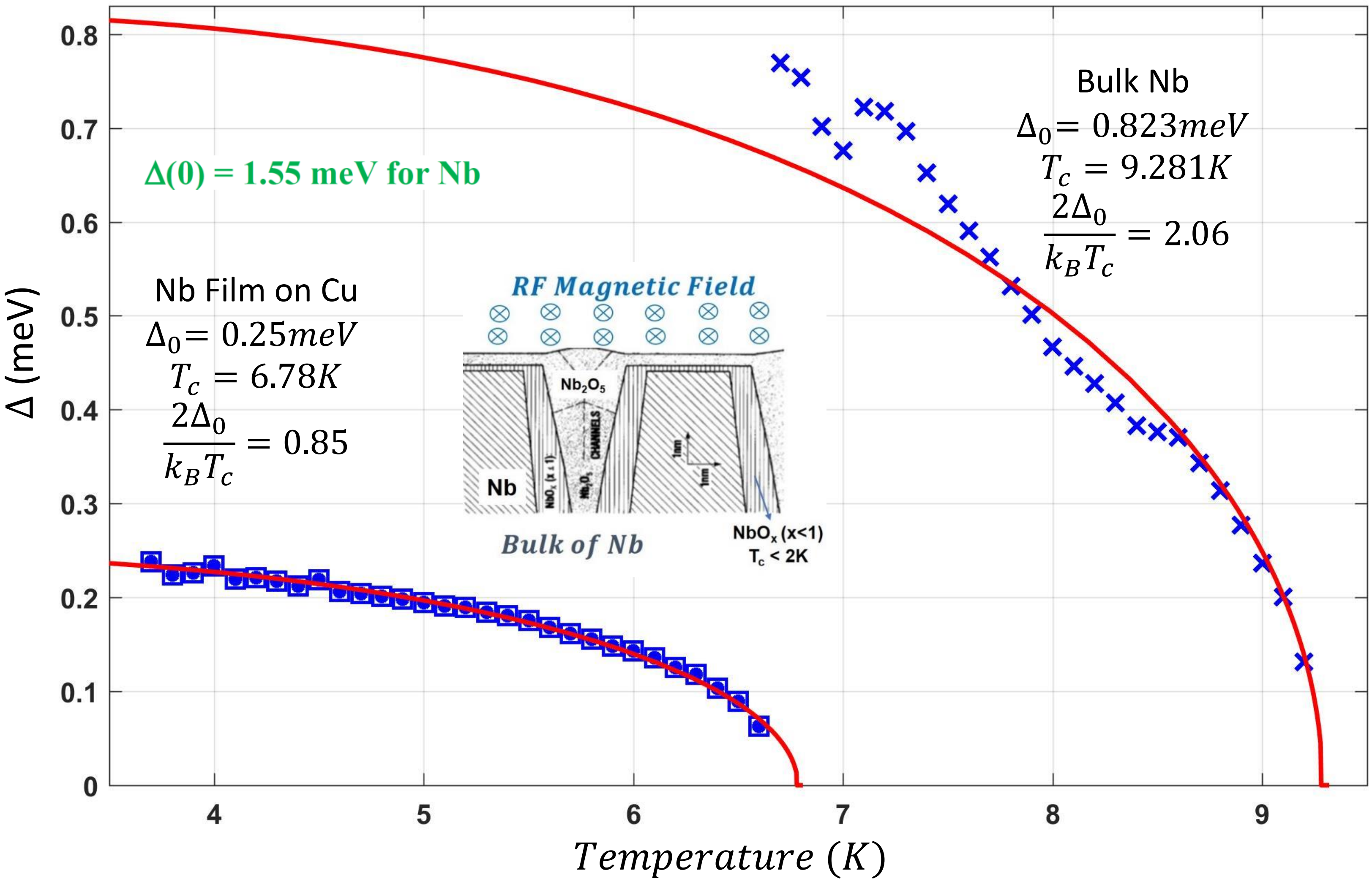



RCSJ Fit to Bulk Nb Data
Third Harmonic Response (mV)
0.15
0.1
0.05
0
0
50
100
150
200
250
300
350
400
450
500
V_ω (mV)
Data at T=9K
Fit with $I_C R_n = 56.41\mu V$
Data at T=9.2K
Fit with $I_C R_n = 30.55\mu V$

Deduced Energy Gap Temperature Dependence

Assuming AB SIS Tunneling in the JJ

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



Normalized TDGL Equations

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

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

$$\kappa = \frac{\lambda(0)}{\xi(0)}; \qquad \eta = \frac{\tau_{GL}}{\tau_0}; \qquad \vec{B} = \vec{\nabla} \times \vec{A};$$

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t}; \qquad T = \text{Temperature};$$

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

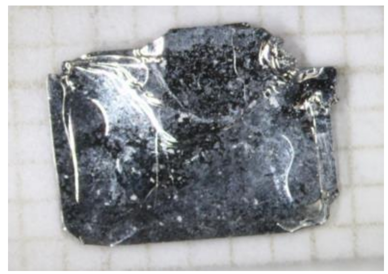
Length measured in units of $\boldsymbol{\lambda}(\mathbf{0})$

Further validation with a gap nodal superconductor

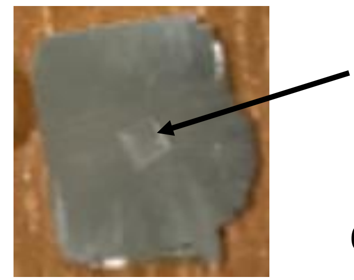
$CeCoIn_5$

T_c ~ 2.4 K

"Existing evidence of **d-wave** SC"



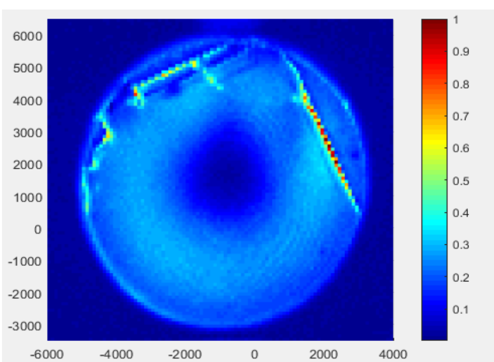
Before polishing



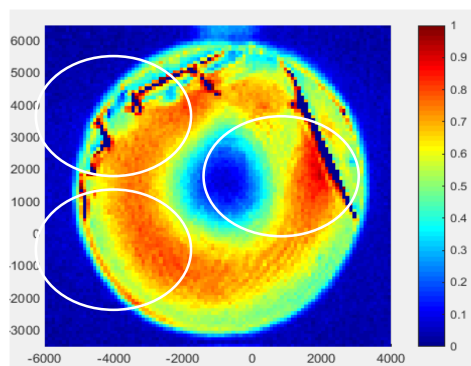
After polishing

Teflon flake

Sample from
J. Paglione
6 x 4 mm crystal



PR @ 460 mK



Replot of PR -
Cut off signal from edge

Sample size < disk

Surface impedance data [$\delta\lambda(T)$, $R_s(T)$] consistent with previously published results

UTe_2 Photoresponse Images in Rectangular Rutile Dielectric Resonator