PROGRESS IN NEAR-FIELD MICROWAVE MICROSCOPY OF SUPERCONDUCTING MATERIALS

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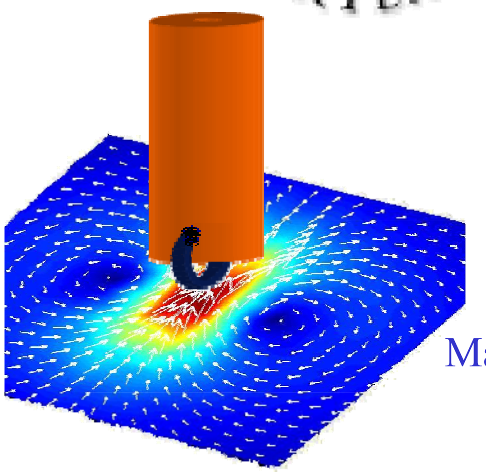
19 February, 2010



Funding from
Department of Energy
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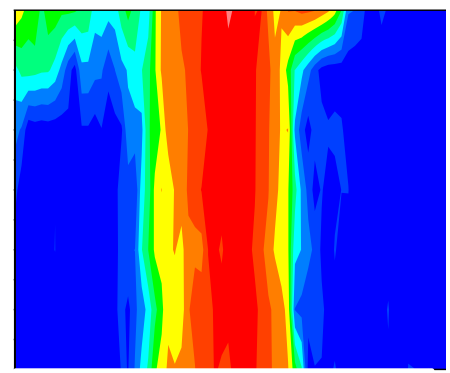


6th SRF Materials Workshop
NHMFL, Tallahassee, Florida

APPROACH

GOAL: To establish links between microscopic defects and the ultimate RF performance of Nb at cryogenic temperatures

APPROACH: Work with the SRF community to develop well-characterized defects and subject them to 2 forms of microscopy:

Near-Field Microwave Microscopy

Laser Scanning Microscopy

NEAR-FIELD MICROWAVE MICROSCOPY

The Idea

1) Stimulate Nb with a concentrated and intense RF magnetic field

2) Drive the material into nonlinearity (nonlinear Meissner effect)

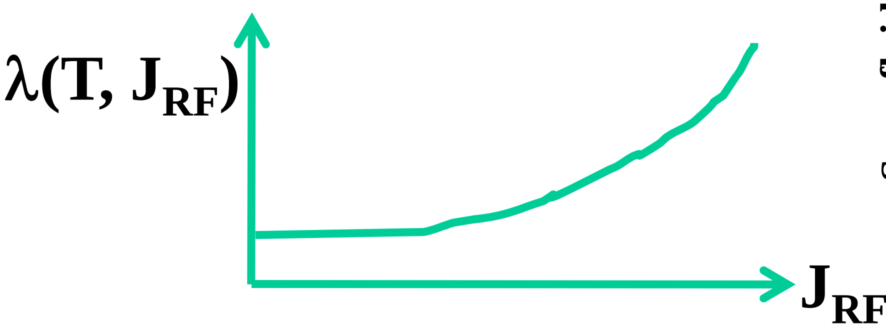
Why the NLME? It is very sensitive to defects…

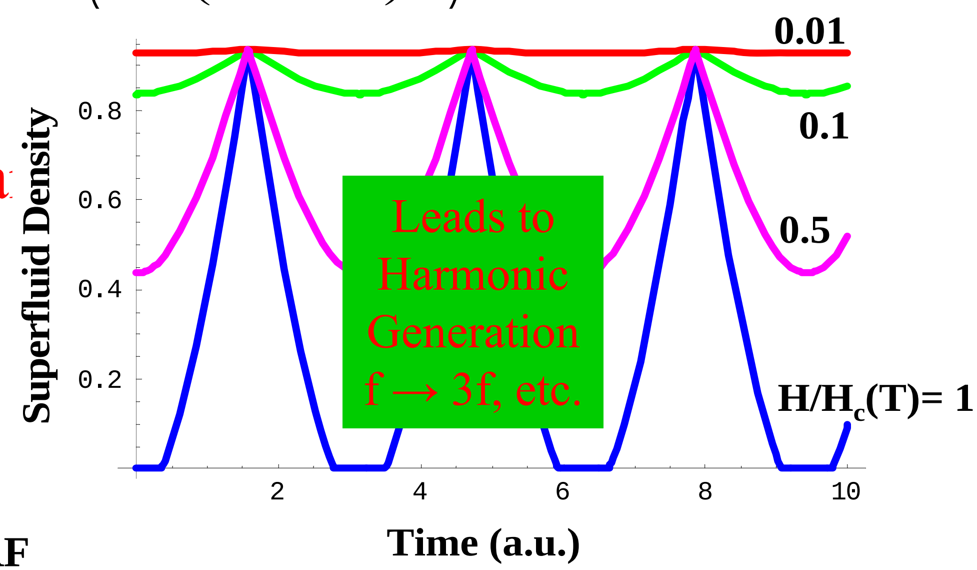
3) Measure the characteristic field scale for nonlinearity: J_{NL}

$$\lambda^2(T, J_{RF}) \approx \lambda^2(T,0)\left(1 + \left(\frac{J_{RF}}{J_{NL}(T)}\right)^2\right)$$

4) Map out $J_{NL}(x,y)$

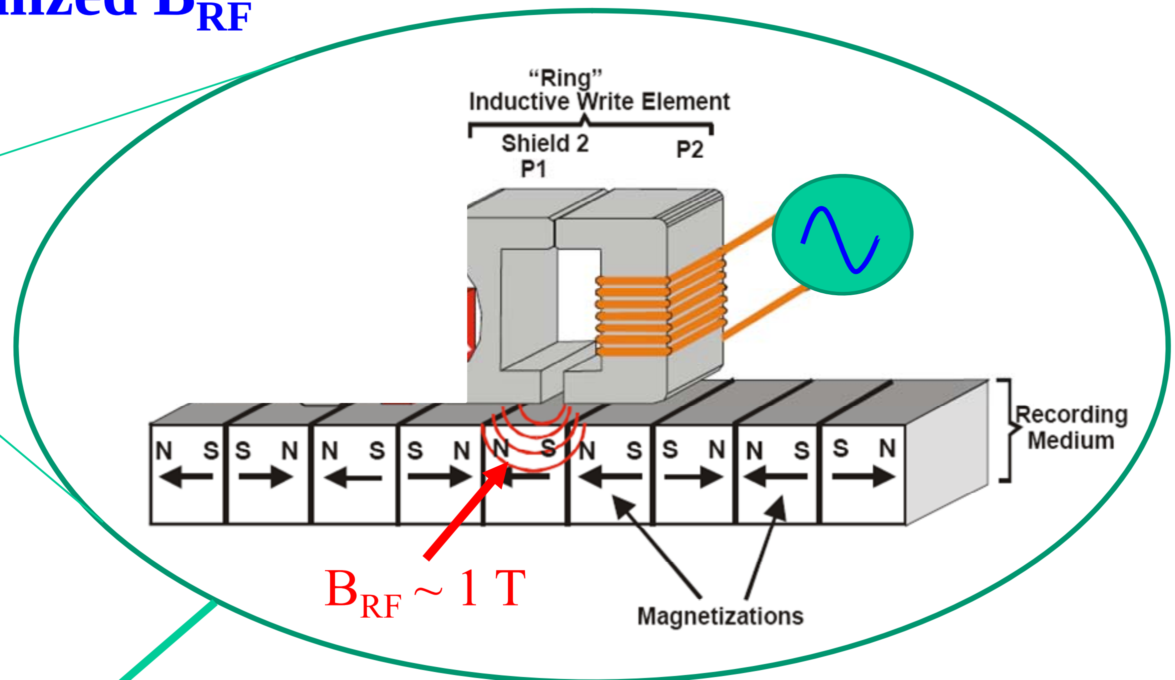
5) Relate $J_{NL}(x,y)$ maps to ca

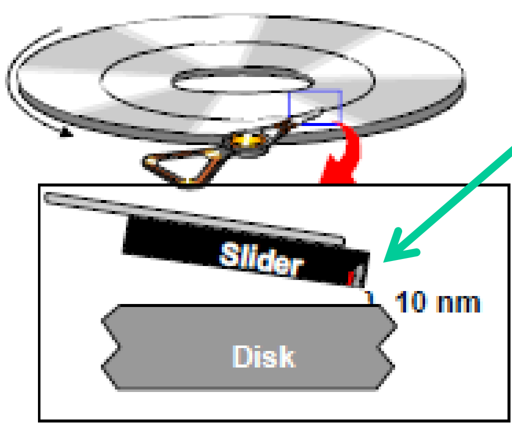




How to Generate Strong RF Magnetic Fields?

Magnetic recording heads provide strong and localized B_{RF}

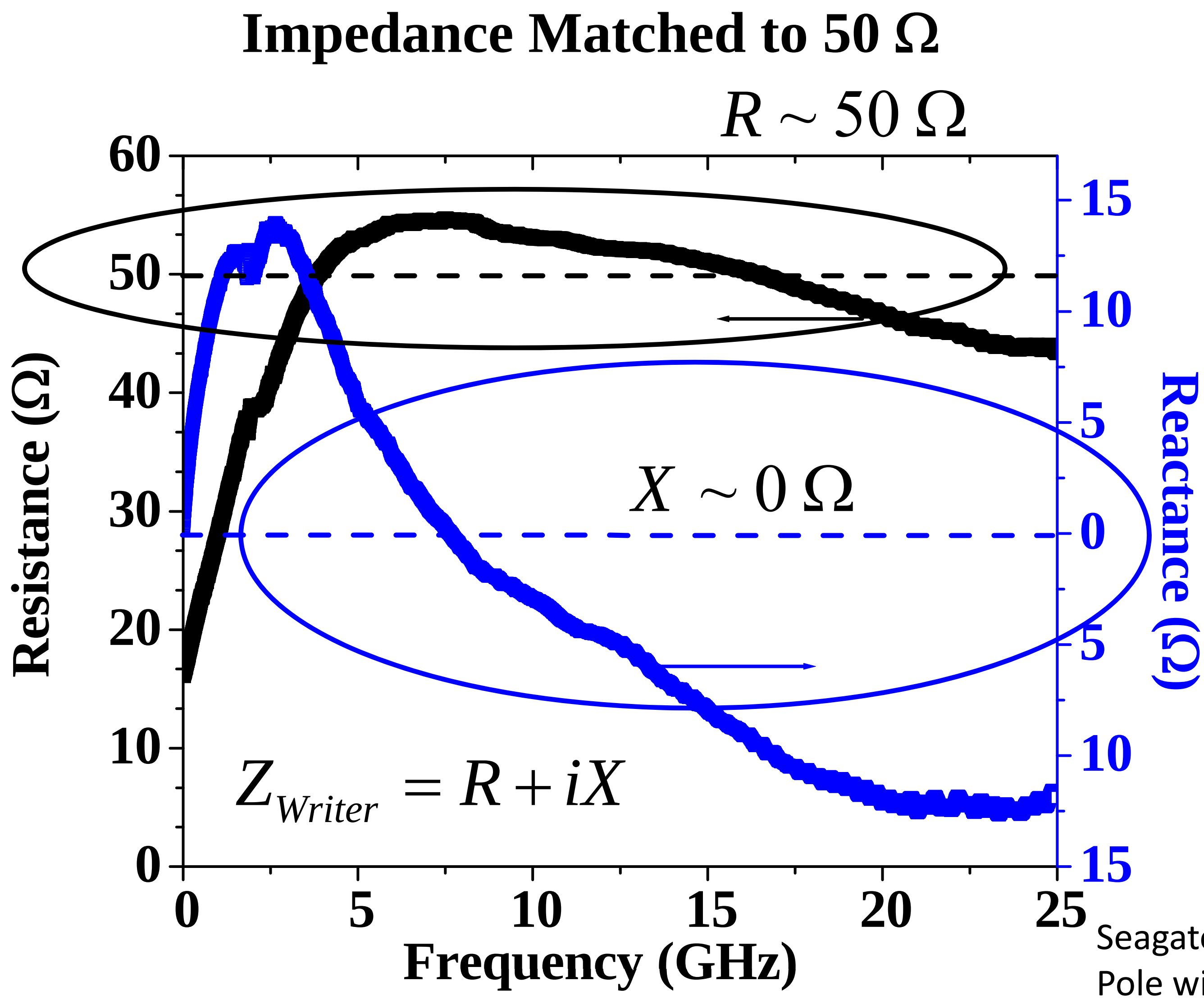




$B_{RF} \sim 1$ Tesla

Lateral size ~ 100 nm

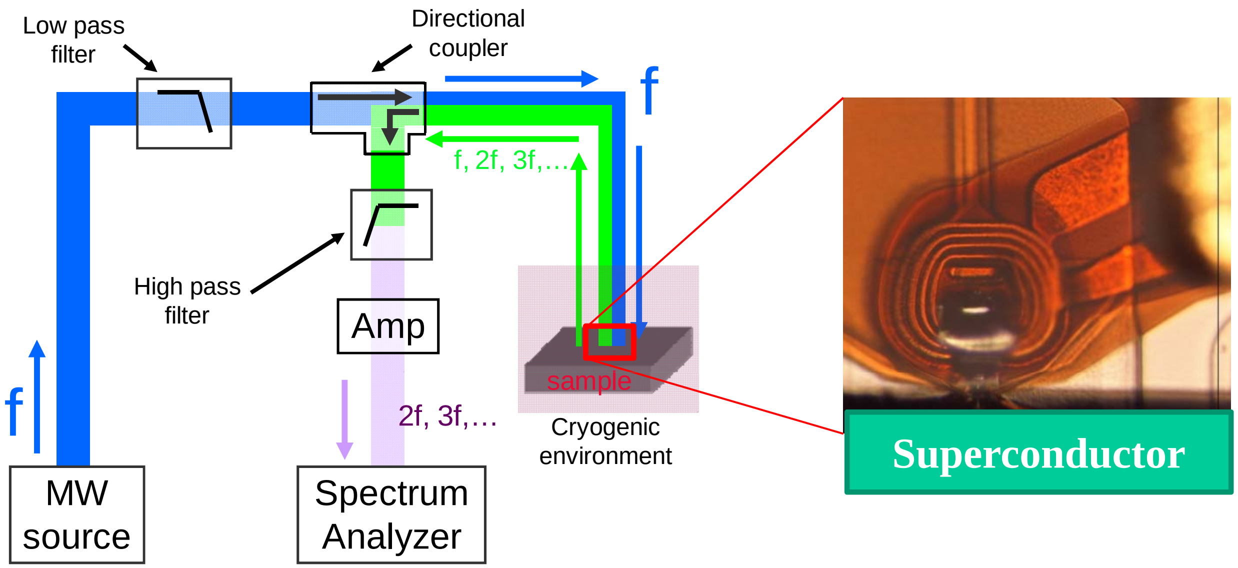
Measured Input Impedance of Write Head



Seagate Longitudinal Head
Pole width ~ 200 nm
Pole gap ~ 100 nm
Pole thickness ~ 1 μm
Coil turns 6 ~ 8

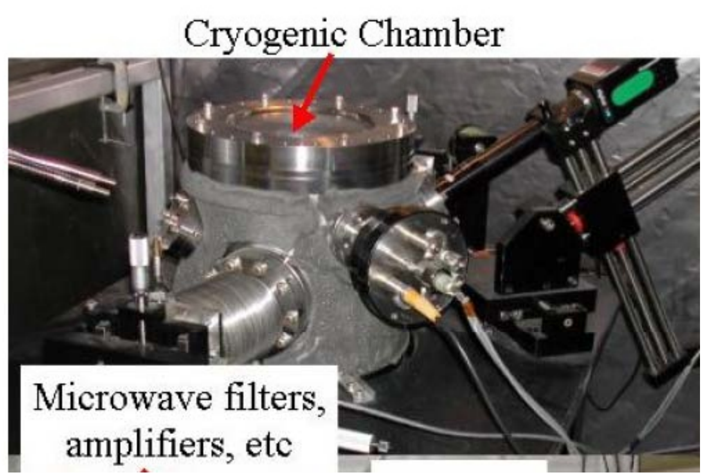
Next Generation Experiment

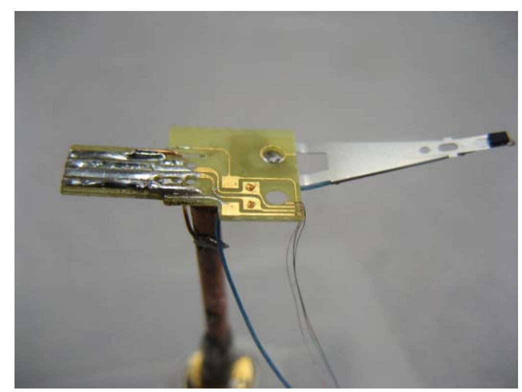
We need higher B_{RF} and strongly localized field distributions



RF Coil on slider

D. Mircea, Phys. Rev. B **80**, 144505 (2009)





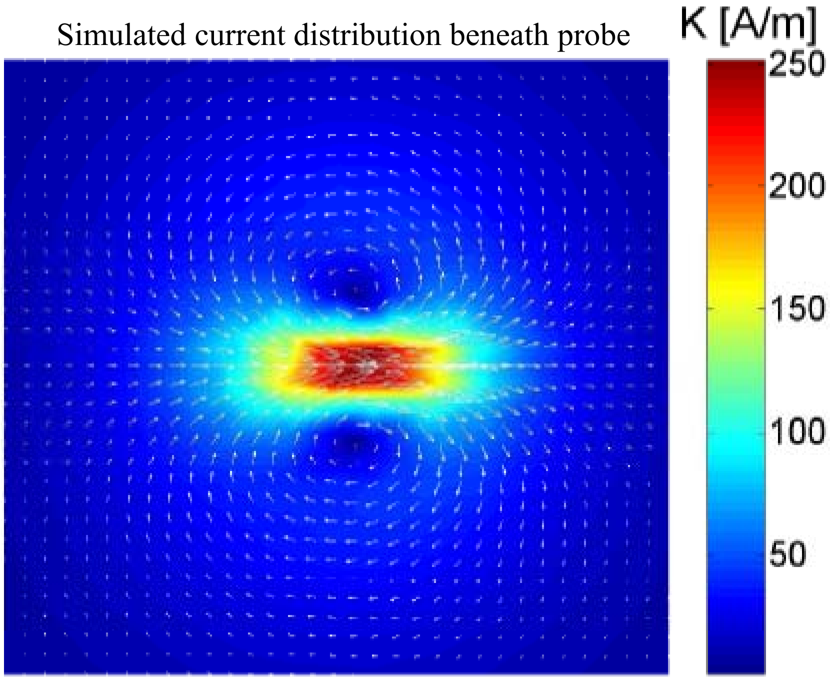
Goals: B_{RF} ~ 200 mT
Lateral size ~ 100 nm

What do We Learn About the Superconductor?

$$P_{3f} \propto \frac{\omega^2 \lambda^4(T)\Gamma^2}{J_{NL}^4(T,x)}$$

$$\lambda^2(T,J_{RF}) \approx \lambda^2(T,0)\left(1+\left(\frac{J_{RF}}{J_{NL}(T)}\right)^2\right)$$

Simulated current distribution beneath probe



$$\Gamma = \frac{\iint_S K^4\,dx\,dy}{I_{Total}} \propto K_{peak}^3$$

Current distribution geometry factor

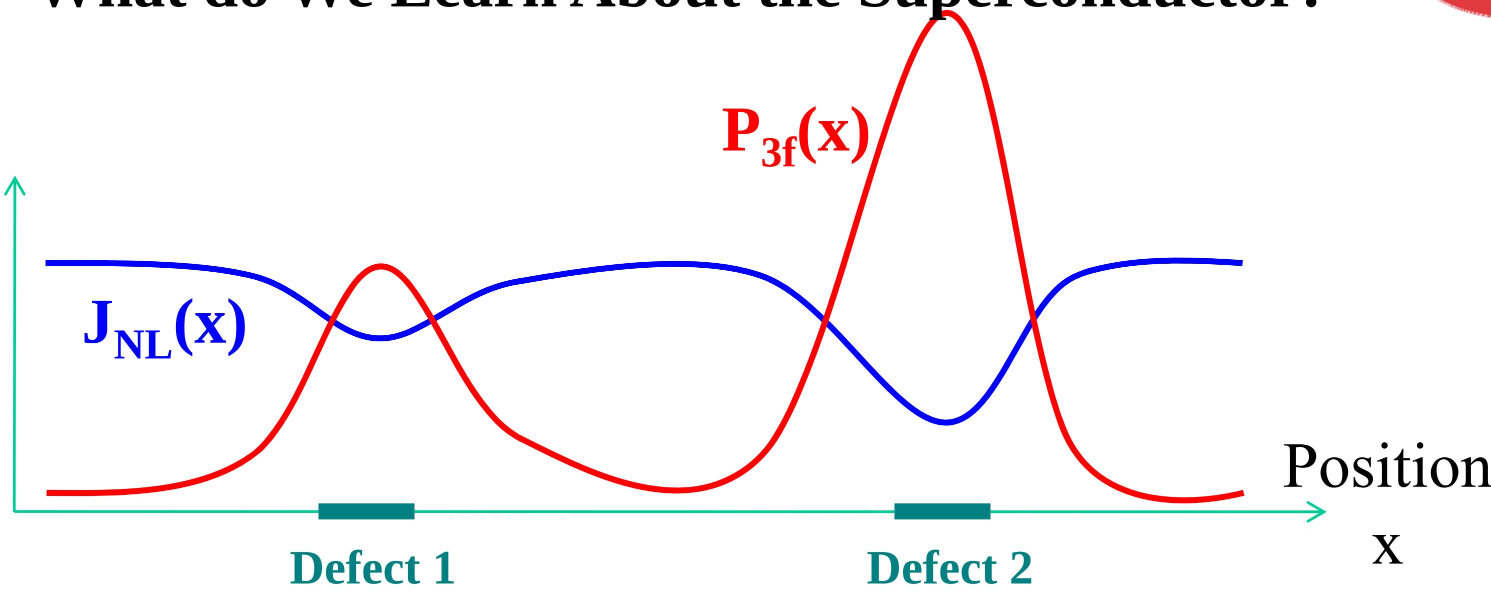
Induce high $\mu_0 K \sim 200$ mT

$K(x,y)$ sharply peaked in space

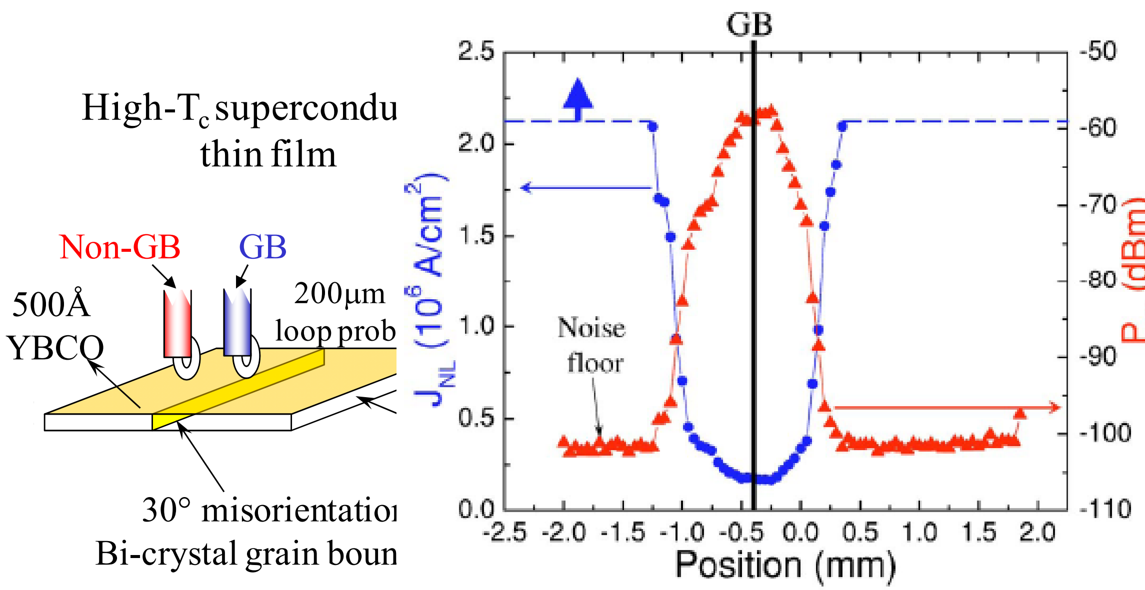
► Better spatial resolution

D. Mircea, SMA, Phys. Rev. B **80**, 144505 (2009) + references therein

What do We Learn About the Superconductor?



$$P_{3f} \propto \frac{\omega^2 \lambda^4 \Gamma^2}{J_{NL}^4(T,x)}$$



. Lee, *et al*., Phys. Rev. B **72** , 024527 (2005).

NEAR-FIELD MICROWAVE MICROSCOPY
Expected Outcome

Locally (< 1 μm) stimulate Nb surface with large (B_{RF} ~ 200 mT) RF field and induce nonlinear response

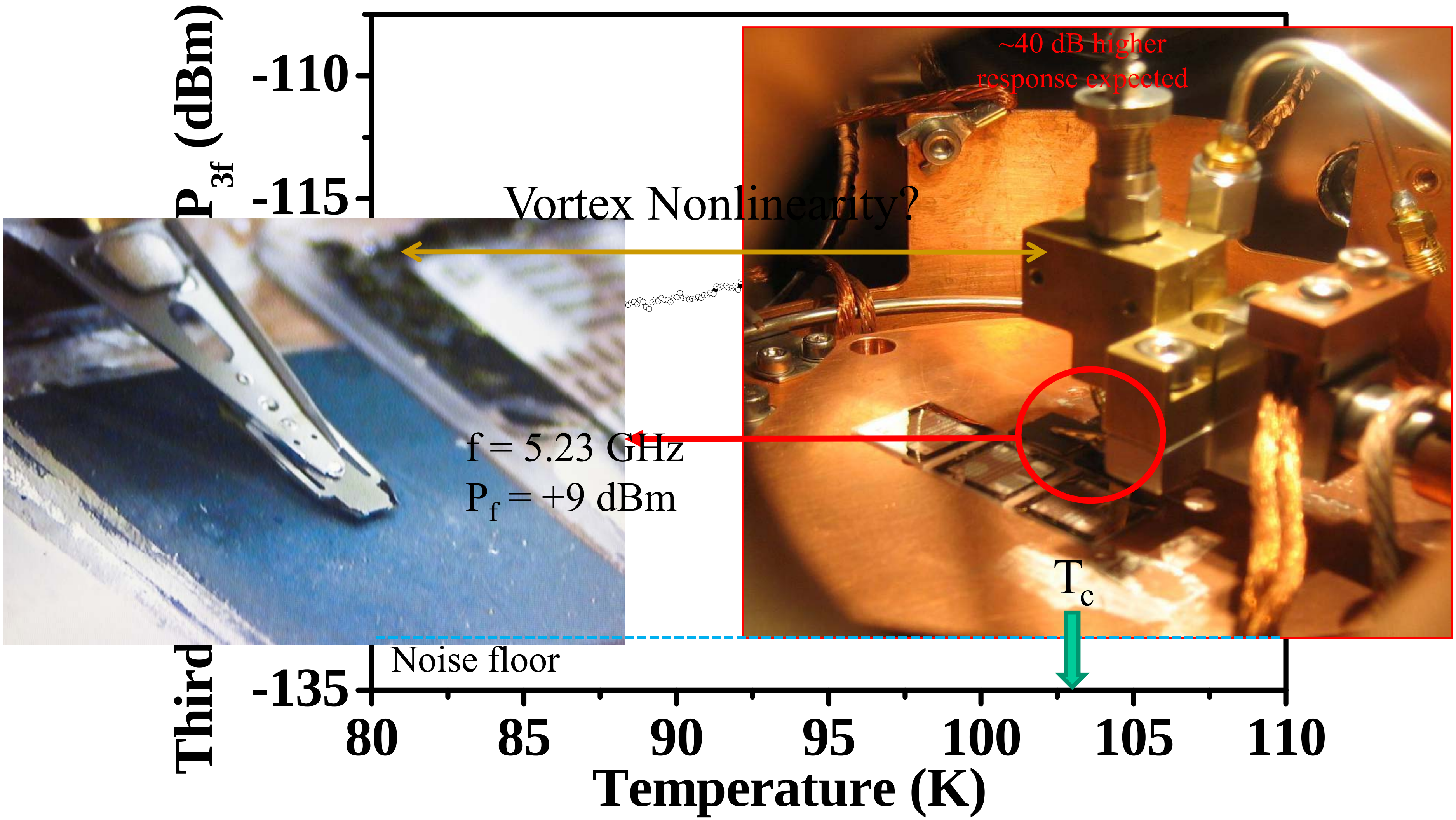
Map $J_{NL}(x,y)$ and relate to known defects

Catalog of Defects and their Superconducting RF Properties

Defect	Local RF Properties	J_{NL} (A/m^2)
Etch Pit		
E-beam Weld		
Step Edge		
Grain Boundary		
…		

Measurements on $Tl_2Ba_2CaCu_2O_8$ Film

At a fixed location



Accomplishments

Suppressed background nonlinearity (3f) from write head

Proven that heads are impedance matched

Seeing clear, reproducible signal from superconducting samples

Receiving technical assistance from the magnetic recording industry

Dragos Mircea, Sining Mao (Western Digital)
Tom Clinton (Seagate → N[th] Degree)

Unresolved Issues

Not achieving the P_{3f} response levels expected

Gap may be too far from sample: Dirt, roughness

Gap may be too close to sample: Gap+SC creates large reluctance

Stray fields from slider inducing vortices?

Next Steps

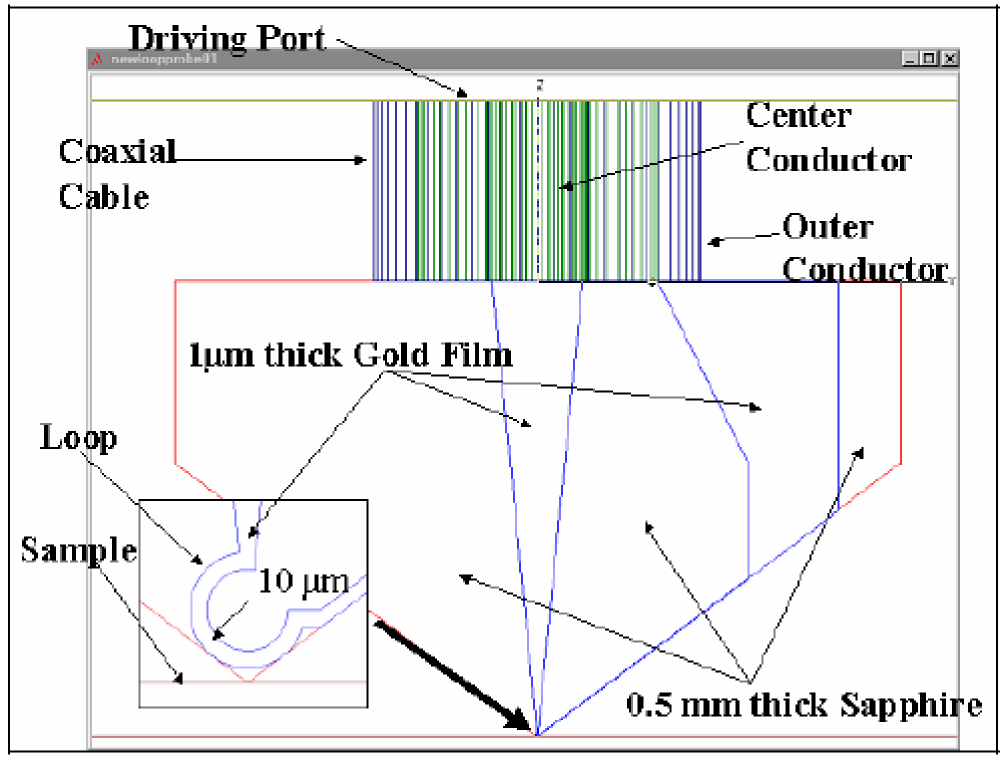
Slider gap - sample distance control, and scanning

Micro-Loops

JOURNAL OF APPLIED PHYSICS — VOLUME 87, NUMBER 4

50 T pulsed magnetic fields in microcoils

K. Mackay, M. Bonfim,[a)] D. Givord, and A. Fontaine
Laboratoire Louis Néel, CNRS, BP 166, 38042 Grenoble Cedex, France



$\Gamma = 1.3 \times 10^6\ A^3/m^2$

Original loop probes had $\Gamma \sim 10^3\ A^3/m^2$

Greg Ruchti, Senior Thesis, UMD

LASER SCANNING MICROSCOPY

Experiments in collaboration with Alexey Ustinov and Alexander Zhuravel at Uni. Karlsruhe, Germany

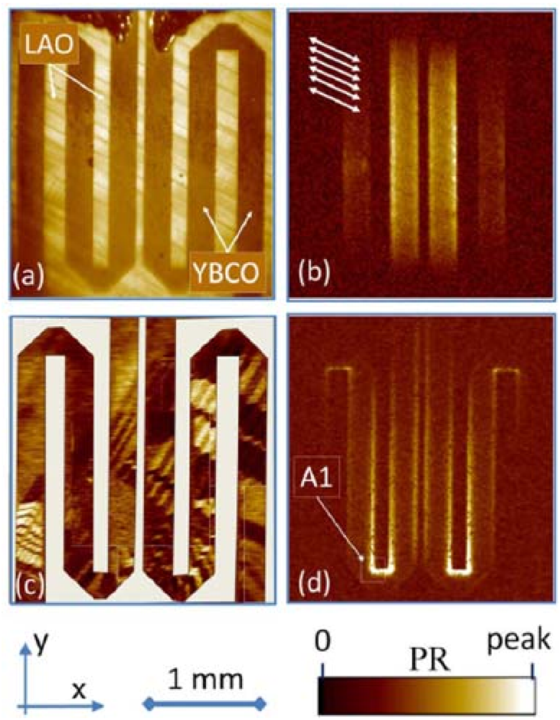
New round of experiments in March+April on bulk Nb + films

LASER SCANNING MICROSCOPY

Preliminary Results on $YBa_2Cu_3O_7$ Patterned Film

Reflectivity Image

DC Critical State Image ($T < T_c$, $I > I_c$)



Thermo-Electric Image (room temperature)

$J_{RF}(x,y)$ Image (5.5 GHz, $T < T_c$)

Conclusions

Near-field microwave microscopy and Laser Scanning Microscopy are quantitative measurement techniques capable of addressing important materials issues in Nb

The microscopes are flexible, simple, broadband, and have frequency-independent spatial resolution

Looking for materials collaborators with well-characterized local defects

Objectives:

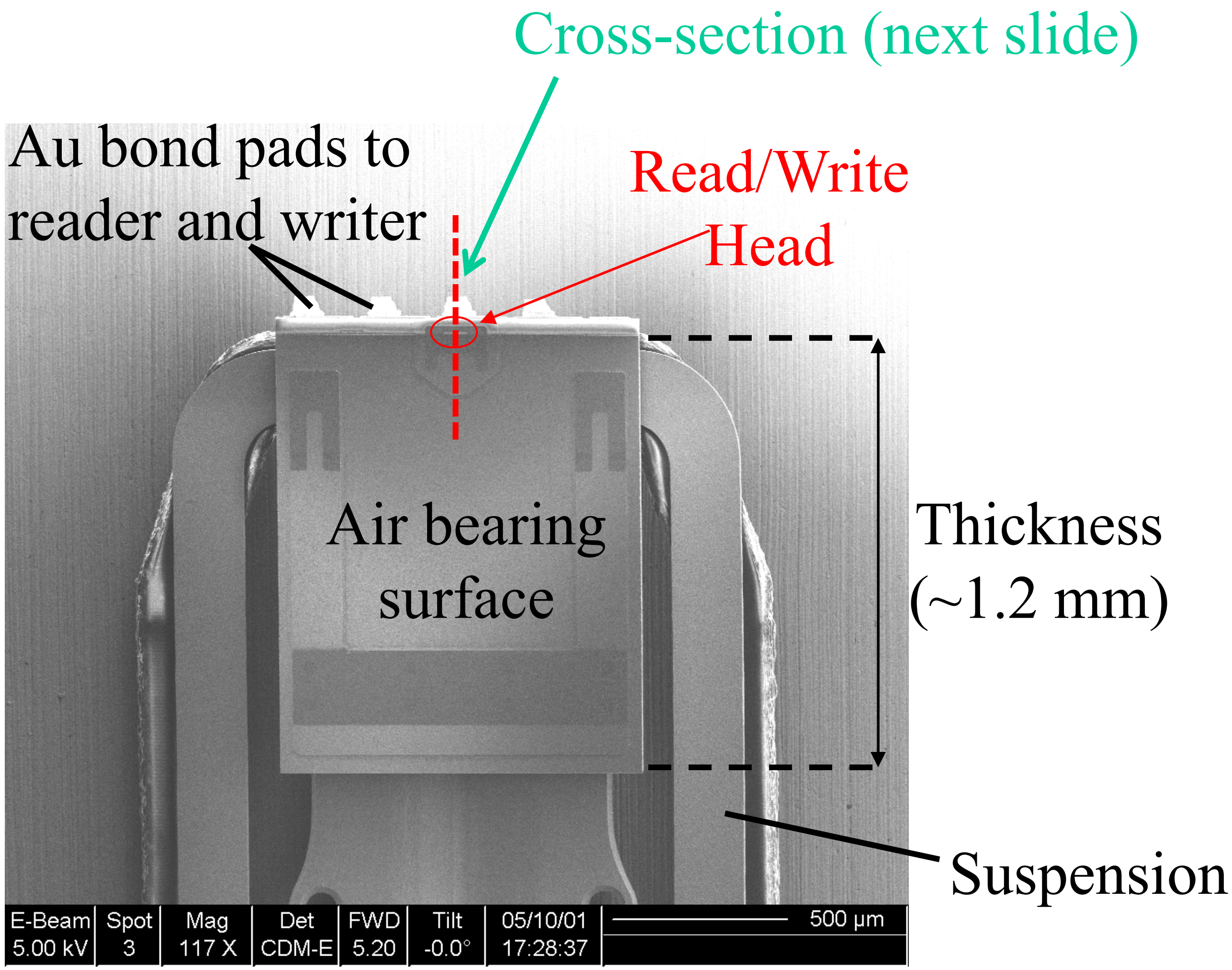
Develop B_{surf} ~ 200 mT, μm-scale probes for RF Critical Field imaging

Develop compact resonators with Nb coupon samples

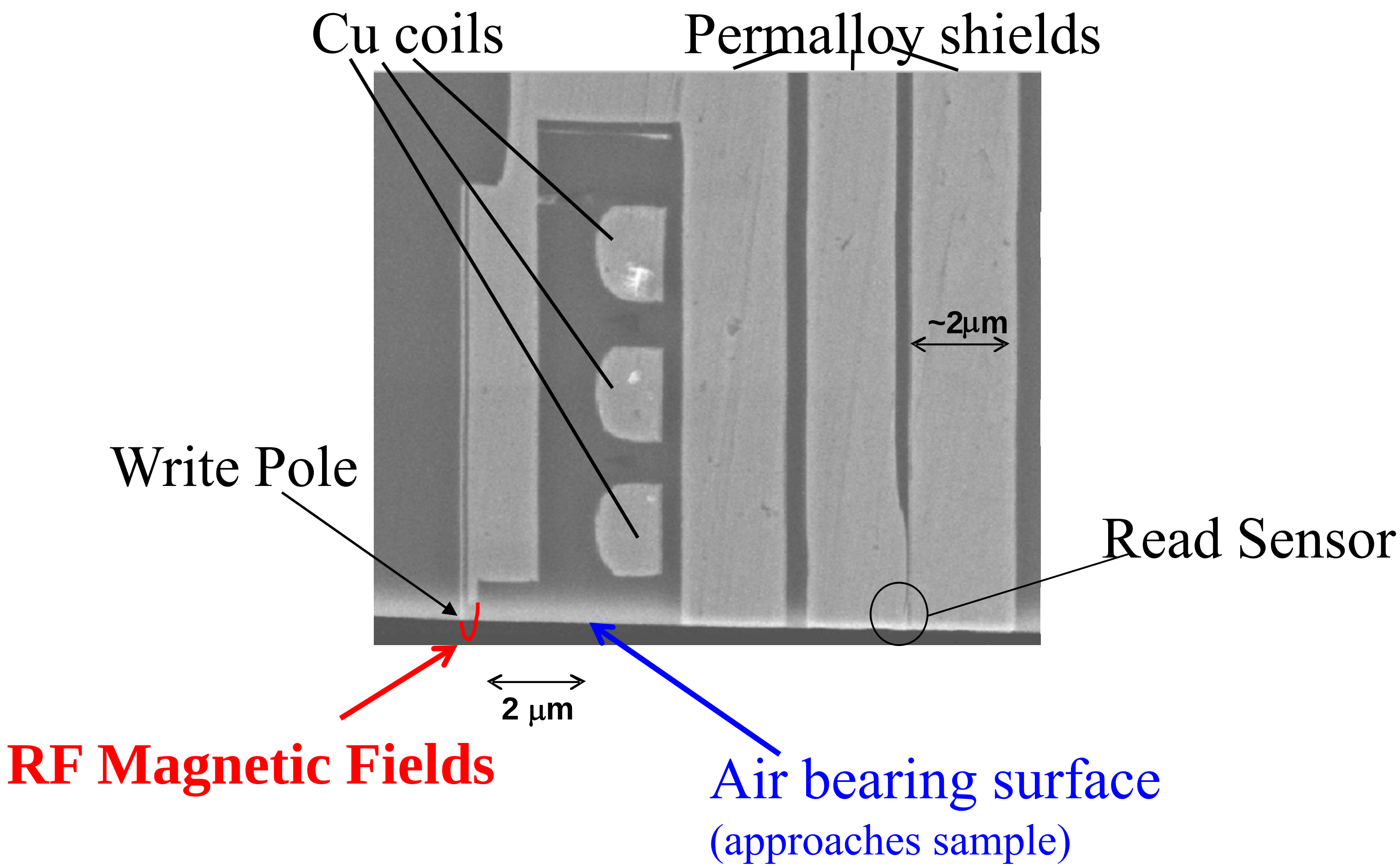
Relate local cryogenic RF properties to microstructure

http://www.cnam.umd.edu/anlage/AnlageHome.htm

Magnetic Recording Head Slider



Magnetic Recording Head Cross Section



LASER SCANNING MICROSCOPY

The Idea

1) Create a compact resonant structure involving a Nb coupon
2) While exciting on resonance, scan a focused laser spot on sample
3) Image the Photo-Thermal effects:

   $J_{RF}(x, y)$ - RF current density in A/cm^2

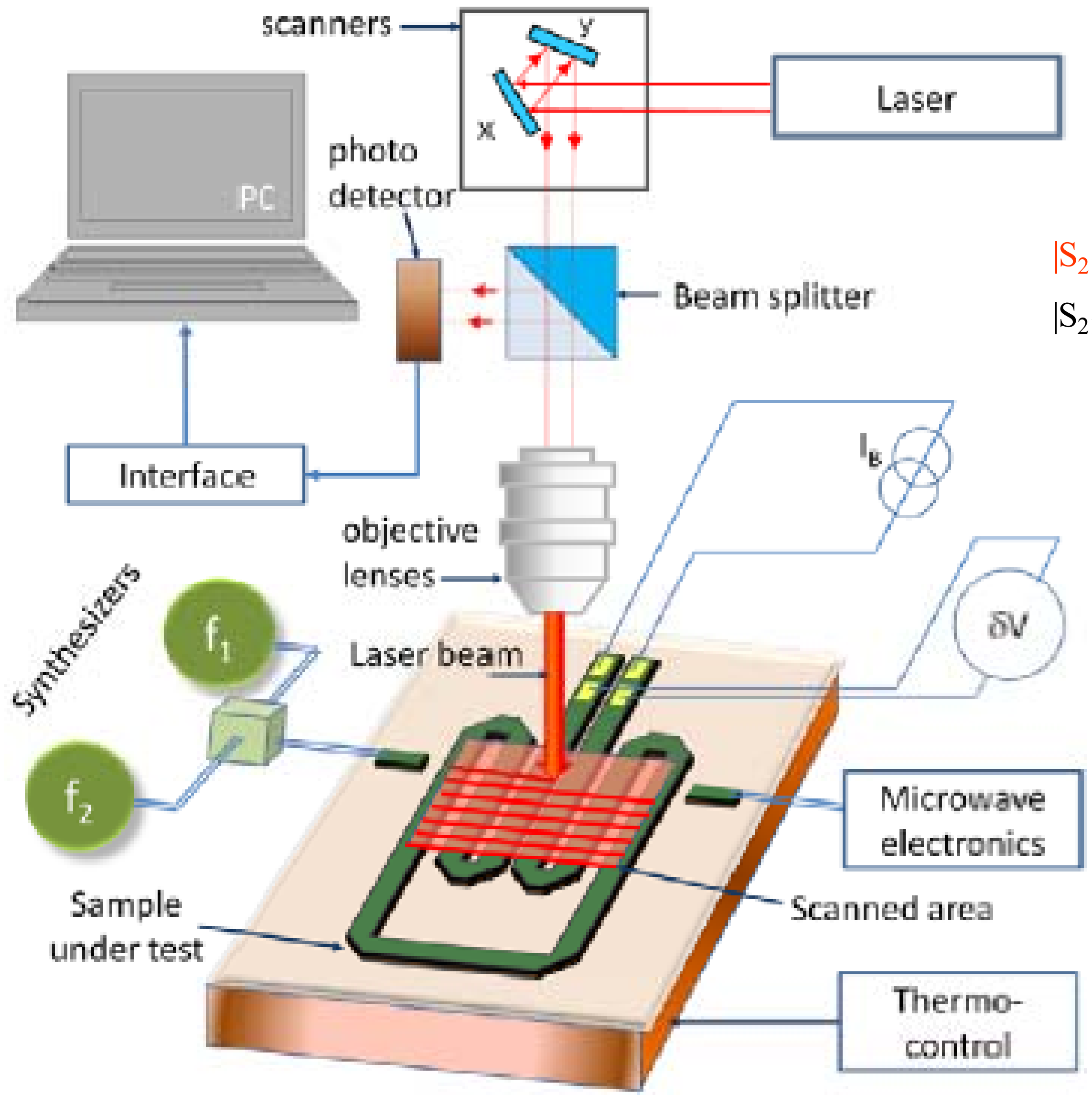
   Thermo-Electric imaging

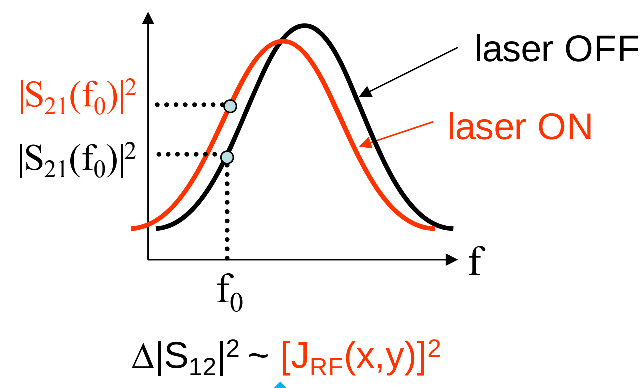
   $J_{NL}(x,y)$ – Nonlinearity current scale in A/cm^2

   RF vortex breakdown, flow, critical state

4) Relate these images to candidate defects

LASER SCANNING MICROSCOPY
Preliminary Results





LASER SCANNING MICROSCOPY

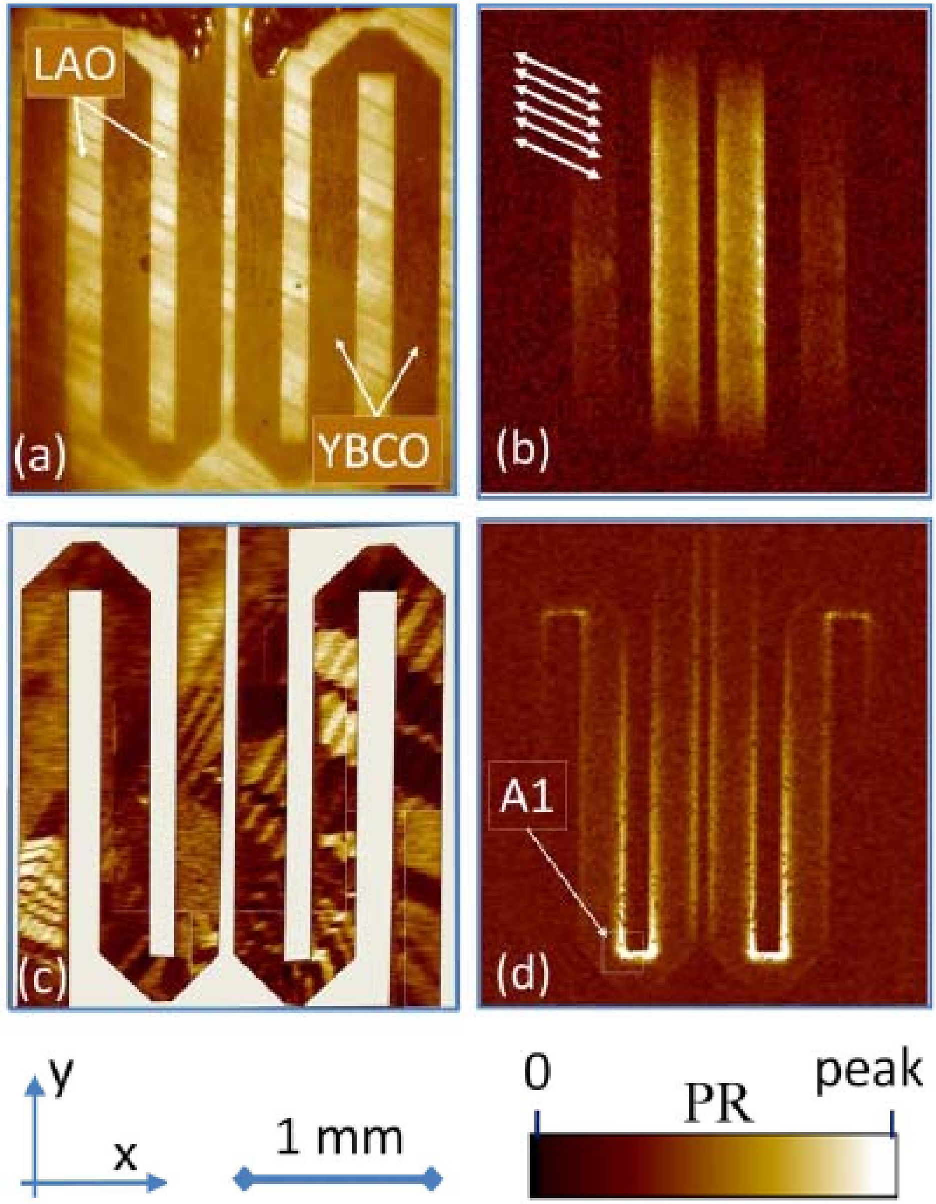
Preliminary Results on $YBa_2Cu_3O_7$ Patterned Film

Reflectivity Image

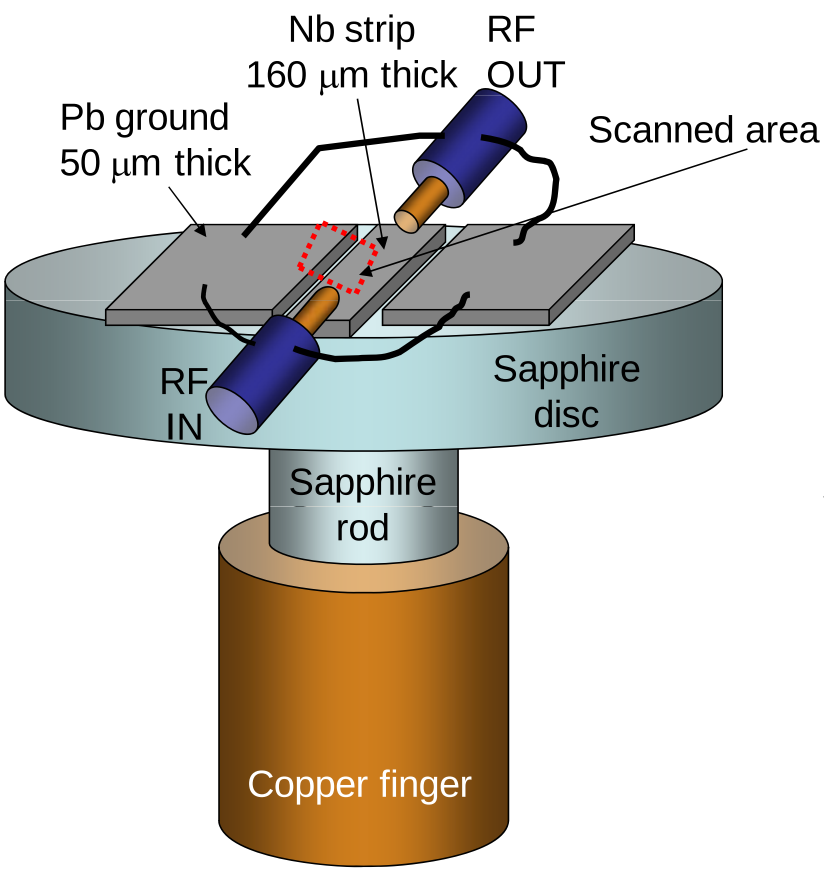
DC Critical State Image ($T < T_c$, $I > I_c$)

Thermo-Electric Image (room temperature)

$J_{RF}(x,y)$ Image (5.5 GHz, $T < T_c$)



LASER SCANNING MICROSCOPY
Preliminary Results



RF Defect Imaging in bulk Nb

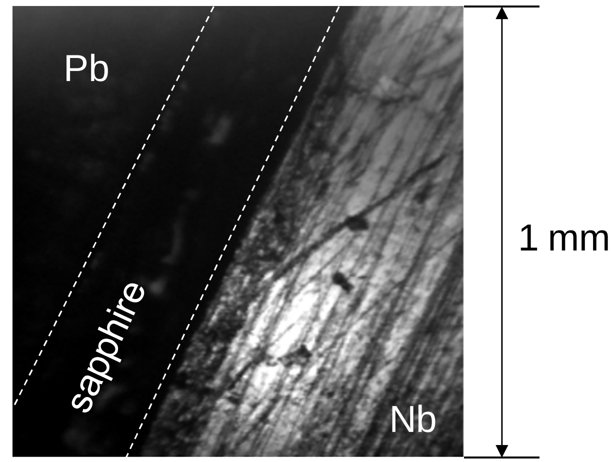
F = 3.5 GHz

T = 4.3 K

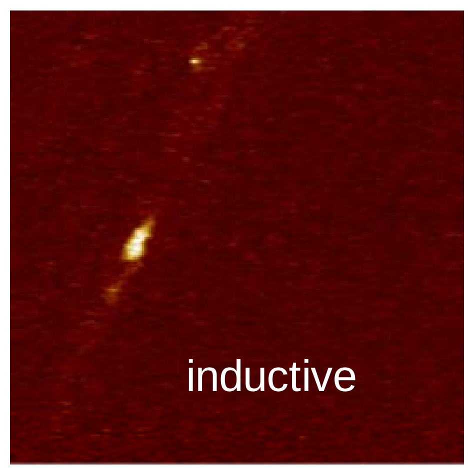
P_{IN} = -15 dBm

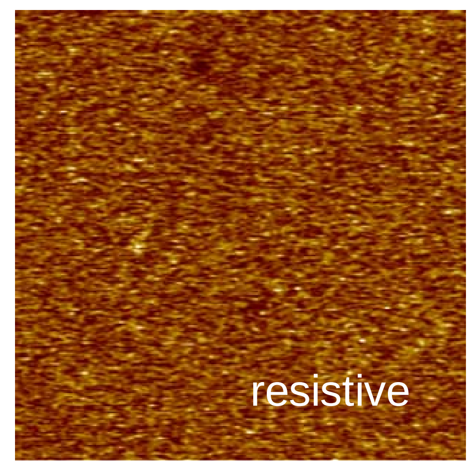
P_{laser} = 1 mW

reflectivity



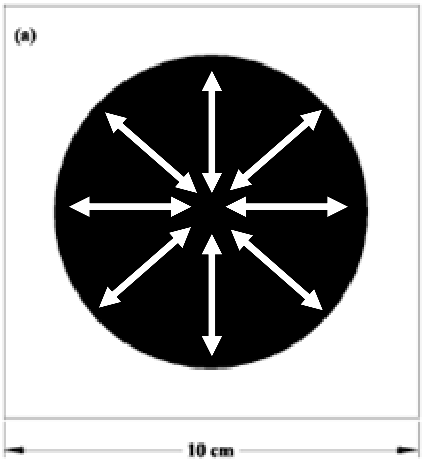
At another location, there is a different kind of defect:



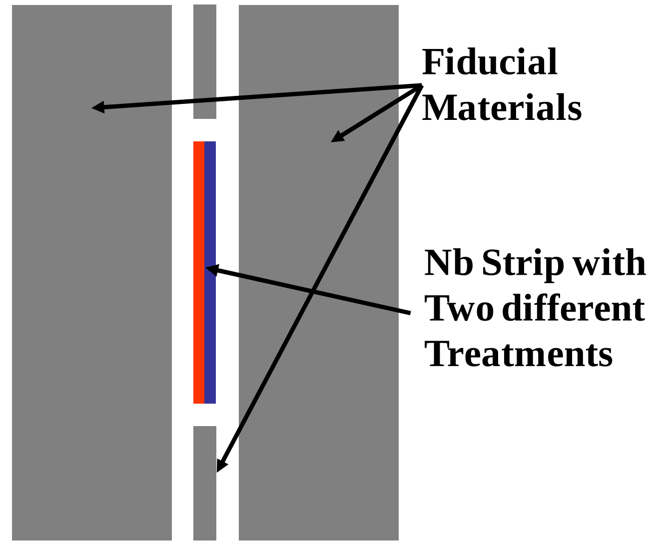


LASER SCANNING MICROSCOPY
Expected Outcome

TM_{010} Resonant Mode Current Distribution



Candidate Resonant Structures



Bulk Nb "Short Sample" structures to measure RF breakdown fields and relate to defects and surface processing

Measure RF breakdown fields in SC / Ins / SC / Ins … multilayer samples
Gurevich, Appl. Phys. Lett. (2006)

Image variations in the thermal healing length to better understand the role of heat dissipation in RF performance

$$\ell_{thermal} = \sqrt{k / c\rho_m f_{Mod}}$$

PLANS FOR THE FUTURE

Project Timetable

Year	RF B-Field Microscope	Laser Scanning Microscope
1	Develop B_{RF} ~ 200 mT probe Prelim. measurement of RF critical fields	Image film + bulk Nb samples from JLab and MSU. Design UMD LSM.
2	Image 1^{st}-generation "short sample" Nb RF critical field maps	Build/test UMD LSM Image Nb samples, thermal healing length, Seebeck coefficient
3	Image 2^{nd} and 3^{rd}-generation Nb "short samples"	Operate UMD LSM. Continue above measurements

Laser Scanning Microscope Collaborators:

Dr. Alexander Zhuravel, B. I. Verkin Inst. of Low Temperature Physics
Kharkiv, Ukraine

Prof. Dr. Alexey Ustinov, University of Karlsruhe, Germany

We seek representative samples containing well-characterized defects and/or surface treatments

Acknowledgements

Collaborators

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R. Ramesh
J. Melngailis

Graduate Students

David Steinhauer
Atif Imtiaz
Sheng-Chiang Lee
Wensheng Hu
Ashfaq Thanawalla
Sangjin Hyun (Seoul Nat. Univ.)
Dragos Mircea
Young-noh Yoon
Yi Qi

Undergraduate Students

C. P. Vlahacos
Sudeep Dutta
Jonah Kanner
Greg Ruchti
Akshat Prasad

Post-Docs

Johan Feenstra
Andrew Schwartz
C. Canedy
A. Stanishevsky
Alexander Tselev

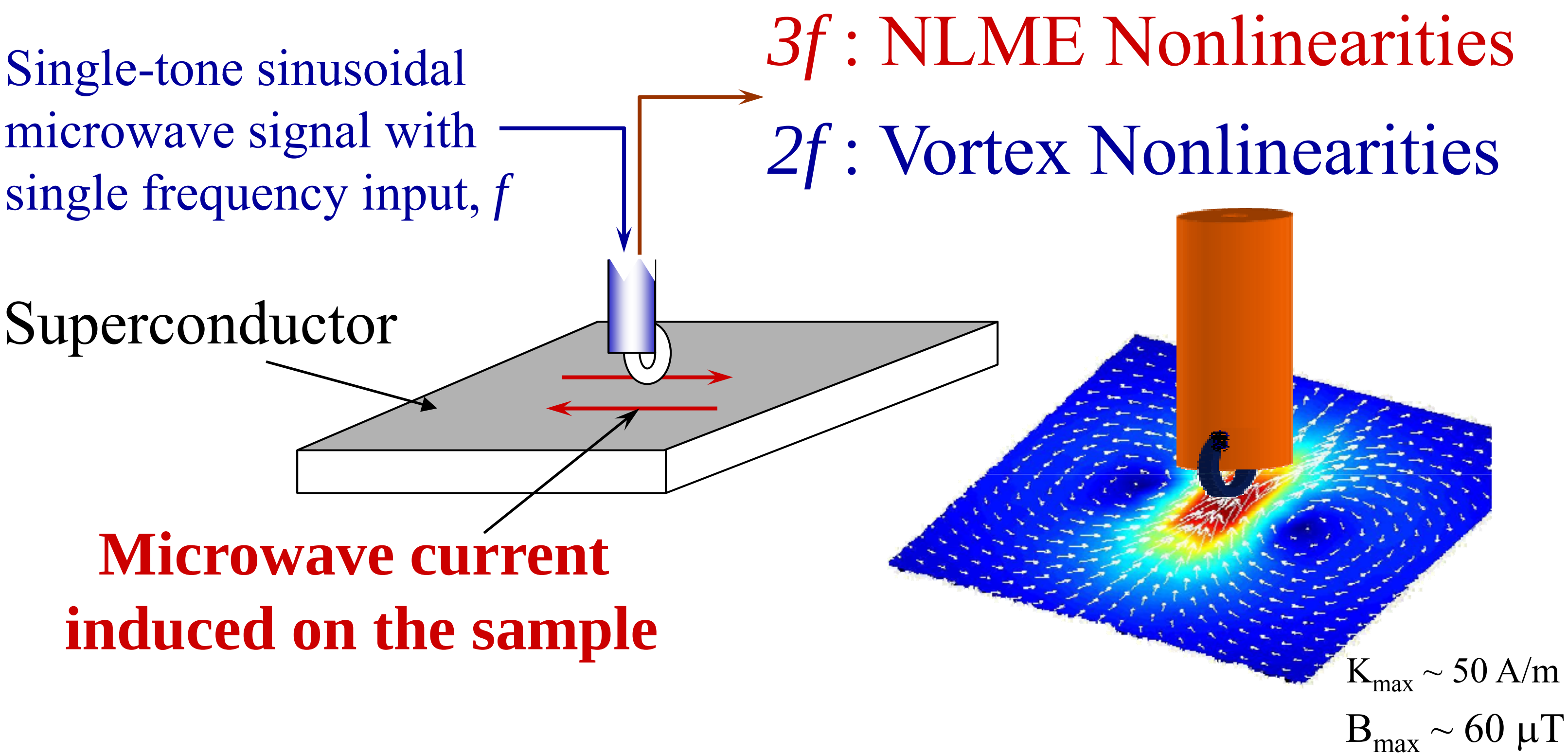
NSF REU Students

Nadia Fomin (Georgetown)
Eric Wang (UC Berkeley)
Tom Hartman (Princeton)

Industrial Collaborators

Hans Christen (Neocera)
Vladimir Talanov (Neocera → SSM)
Robert Hammond (STI)
Andrew Schwartz (Neocera)
Steve Remillard (Agile Devices)

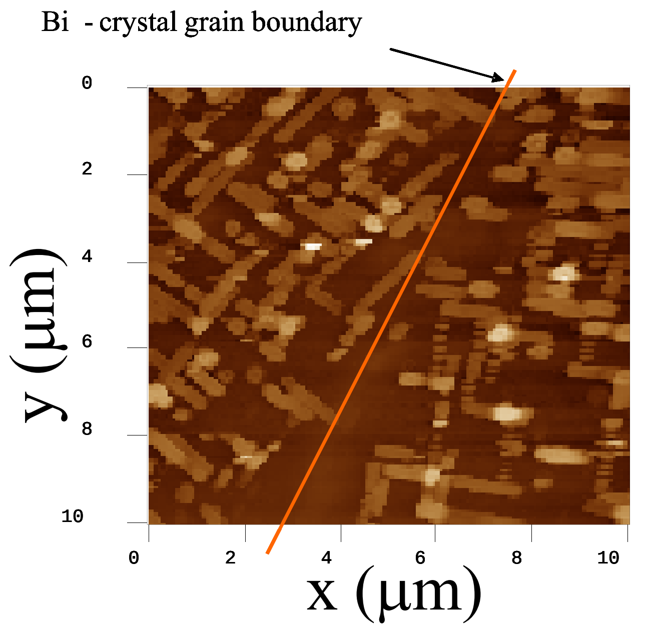
NEAR-FIELD MICROWAVE MICROSCOPY
Preliminary Results



Create a sample with well-characterized defects and probe them with localized RF currents in the superconducting state

Nonlinear Response Image of Known Defect

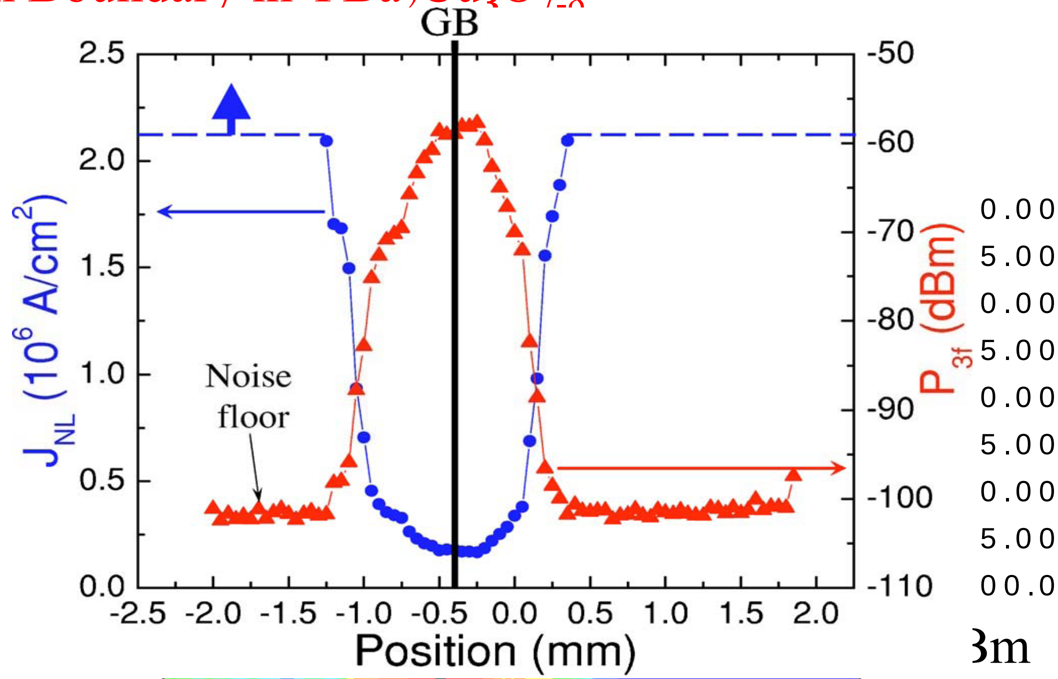
Bi-Crystal Grain Boundary in $YBa_2Cu_3O_{7-\delta}$

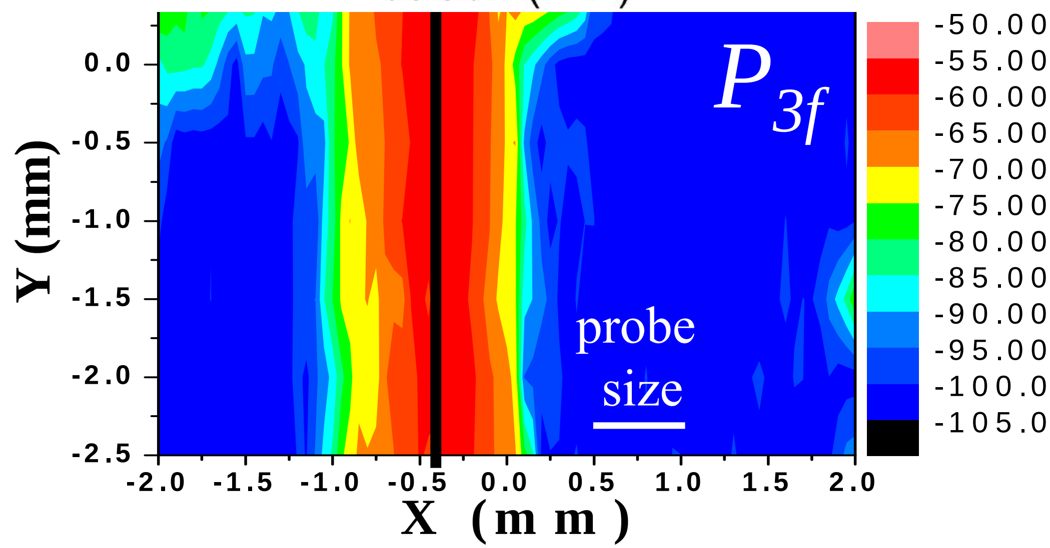


STM image of Bi-Crystal Grain Boundary in $YBa_2Cu_3O_7$

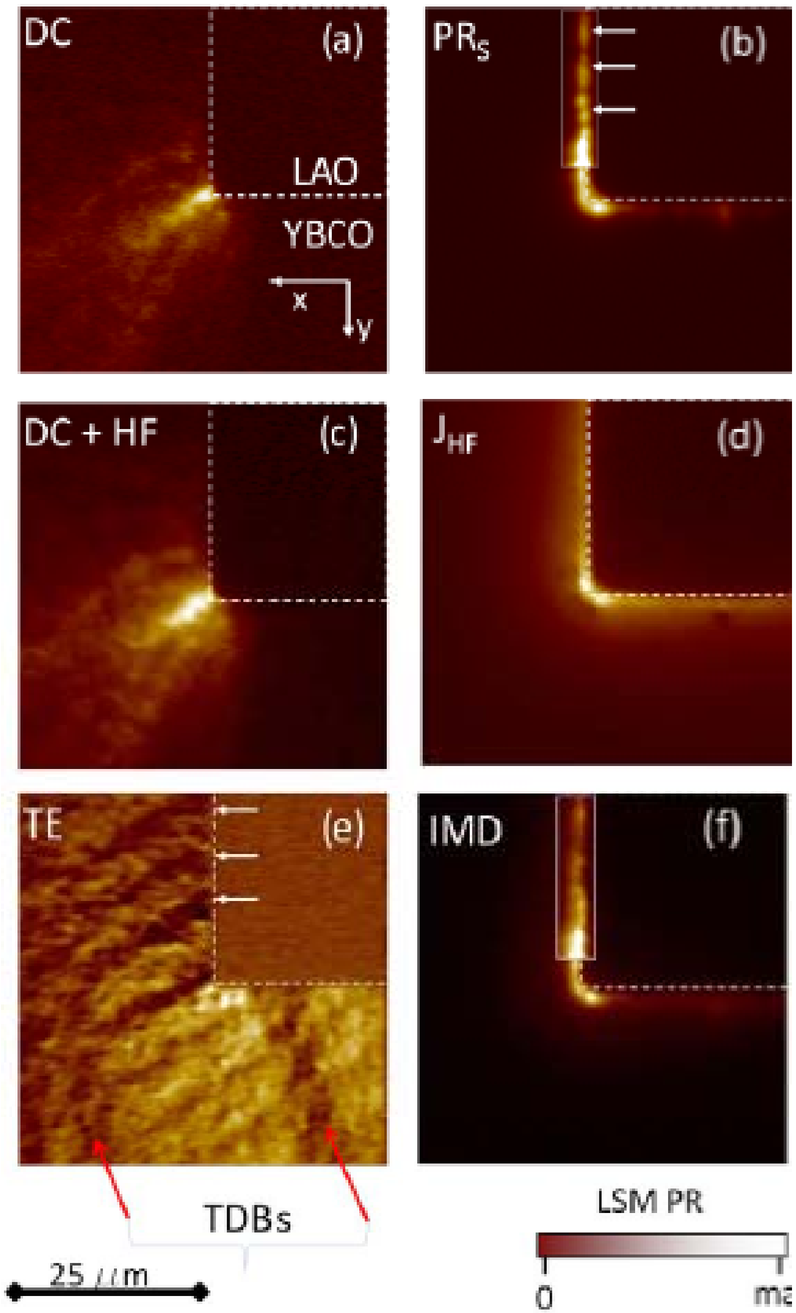
T = 60 K

f = 6.5 GHz





S.-C. Lee, *et al.*, Phys. Rev. B **72** , 024527 (2005)

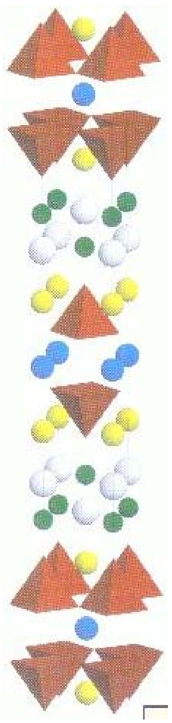

DC
(a)
LAO
YBCO
x
y
PRS
(b)
DC + HF
(c)
JHF
(d)
TE
(e)
IMD
(f)
TDBs
25 μm
LSM PR
0

Why Develop a Microwave <u>Microscope</u>?

Many cutting-edge materials in condensed matter physics have complicated crystal structures and morphologies

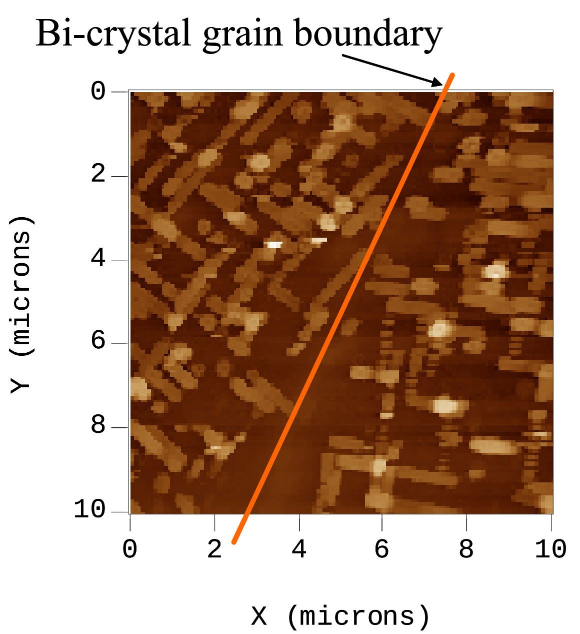
Extrinsic defects influence, or even define, physical properties:

grain boundaries (μm), twin domain boundaries (nm-μm), cracks (μm), competing phases (μm), stacking faults (nm),…

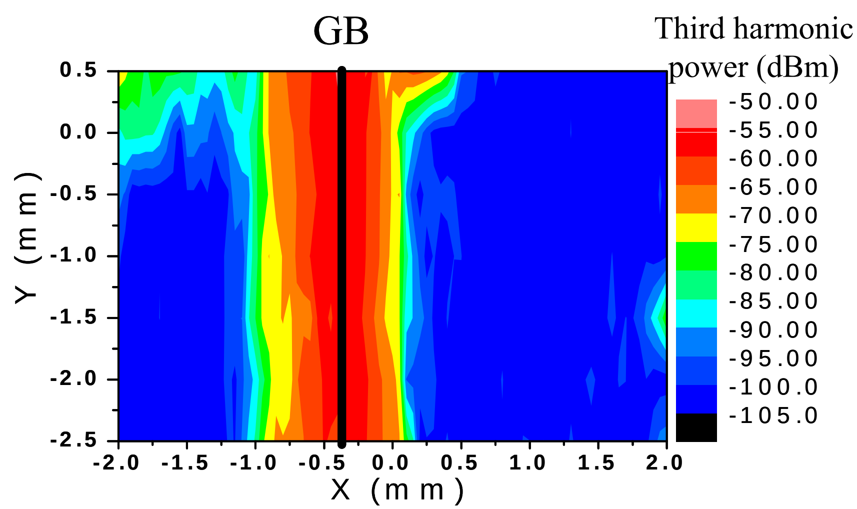


$Tl_2Ba_2CaCu_2O_8$

High-T_c superconductor thin film

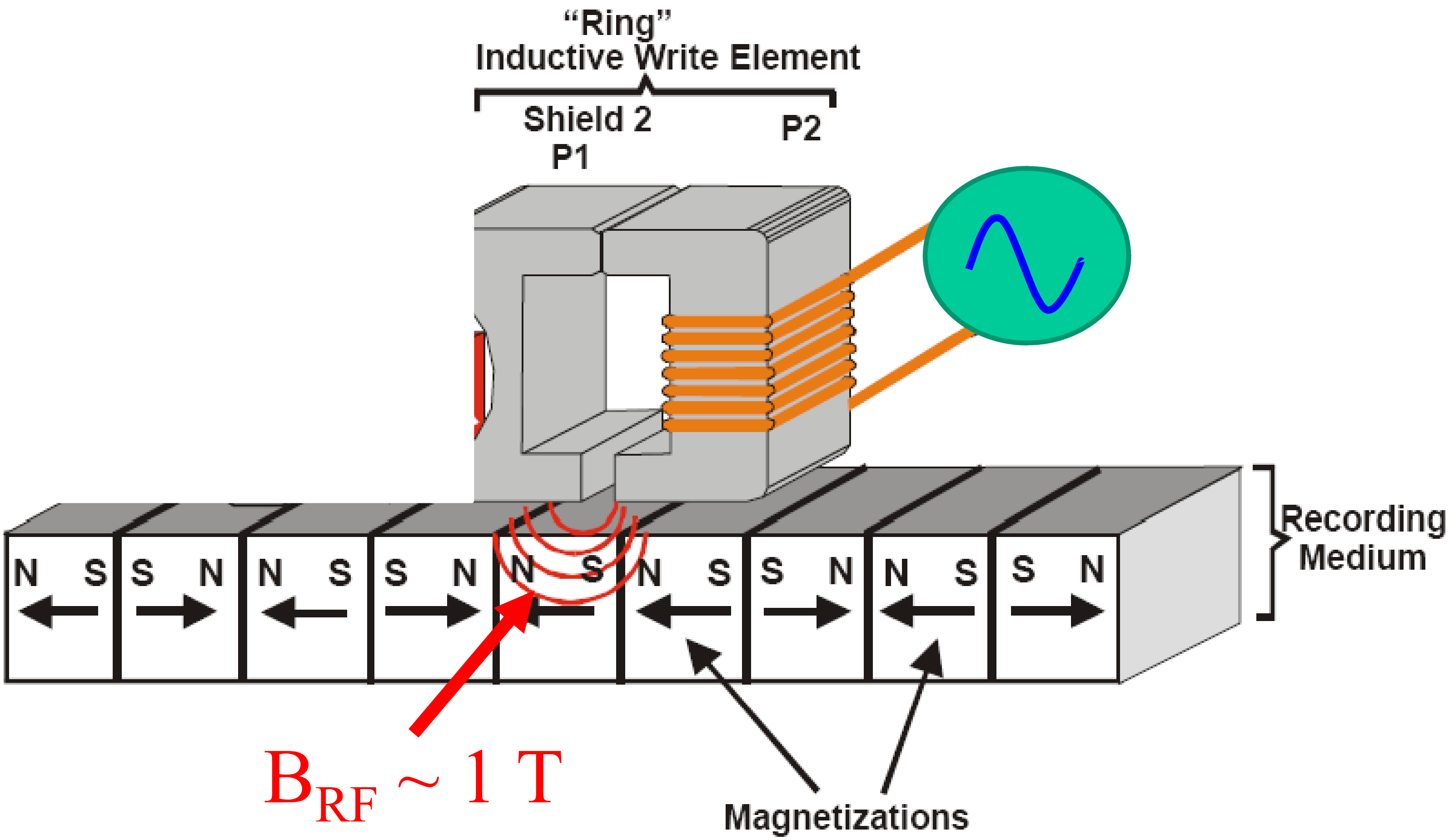


Microwave nonlinearity image
T = 60 K, 6.5 GHz



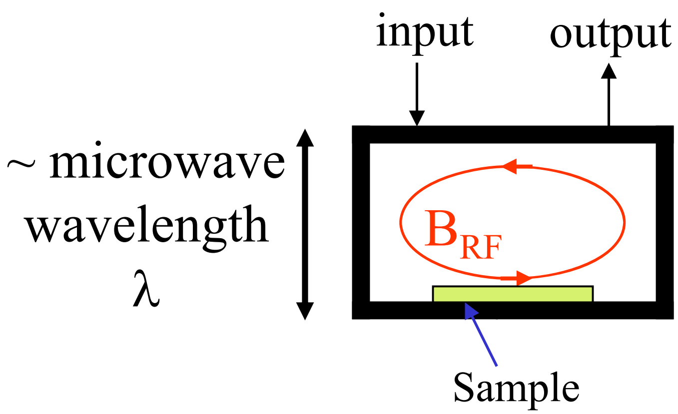
$J_\omega \rightarrow J_{3\omega}$ Nonlinearity

S.-C. Lee, *et al.*, Phys. Rev. B **72** , 024527 (2005).

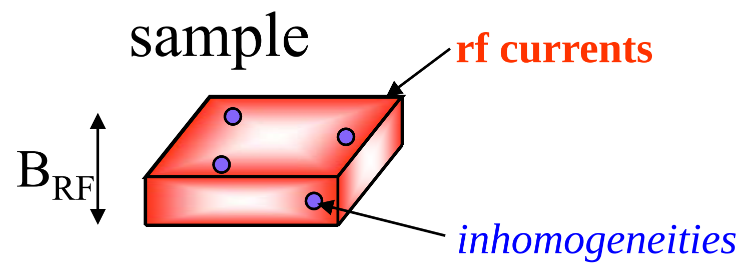


"Ring"
Inductive Write Element
Shield 2
P2
P1
Recording Medium
N S S N N S S N N S N S S N N S S N
$B_{RF} \sim 1$ T
Magnetizations

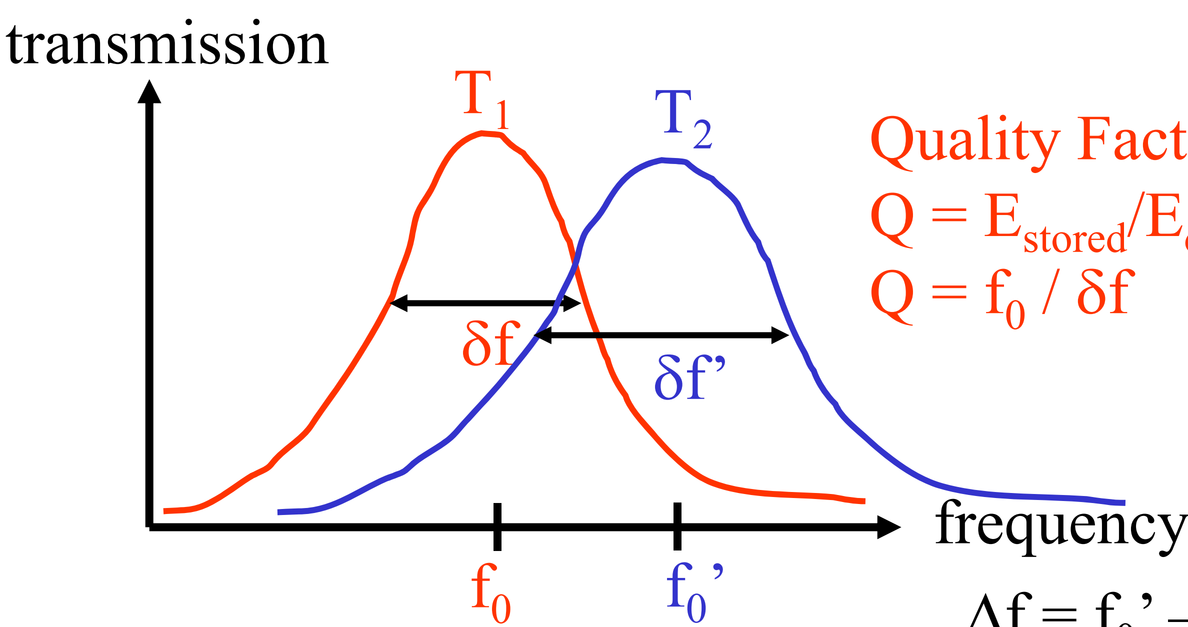
Traditional Electrodynamics Measurements Miss the Important Details



Microwave Resonator



These measurements average the properties over the entire sample



Quality Factor

$Q = E_{stored}/E_{dissip.}$

$Q = f_0 / \delta f$

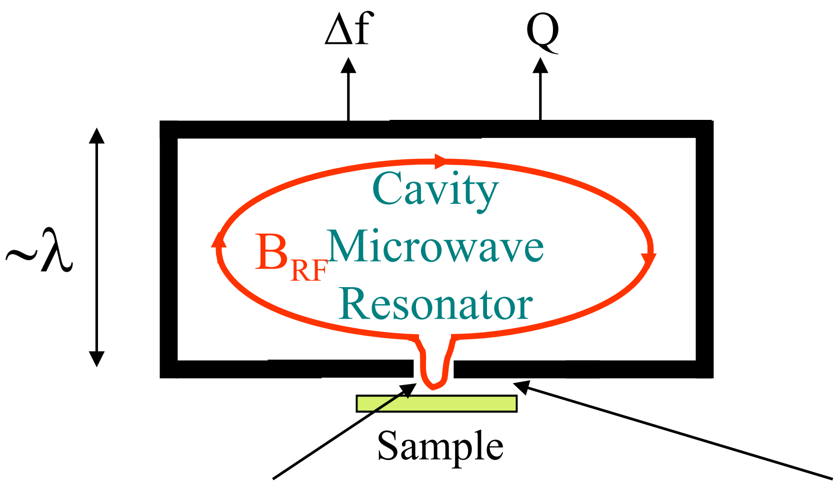
$$\Delta f = f_0' - f_0 \propto \Delta(\text{Stored Energy})$$

$$\Delta(1/2Q) \propto \Delta(\text{Dissipated Energy})$$

Near Field Microscopy

Breaking the “wavelength barrier”

“Aperture-Based”

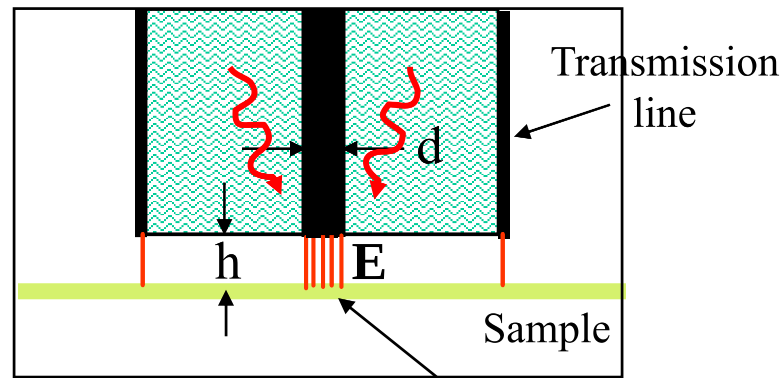


Aperture size and aperture/sample separation much less than microwave wavelength λ

Evanescent waves

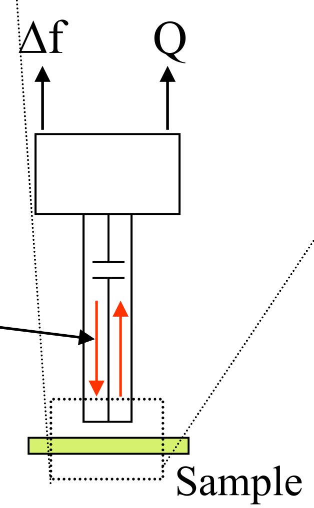
Frait (59)
Soohoo (62)
Bhagat (95)
} FMR imaging
Ash+Nichols (72)
Davidov (96)

“Aperture-Less”



Field-concentrating feature (d) and feature/sample separation (h) much less than microwave wavelength λ

Coaxial Cable Microwave Resonator

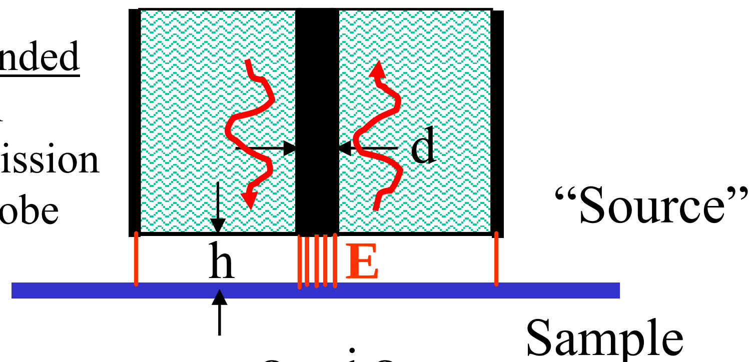


Bosisio (70)
Tabib-Azar (93)
Cho (95)
UMD (96)
Xiang (96)
…

Basic Contrast Mechanisms

Electric Field Probe

Open-ended Coaxial Transmission Line Probe



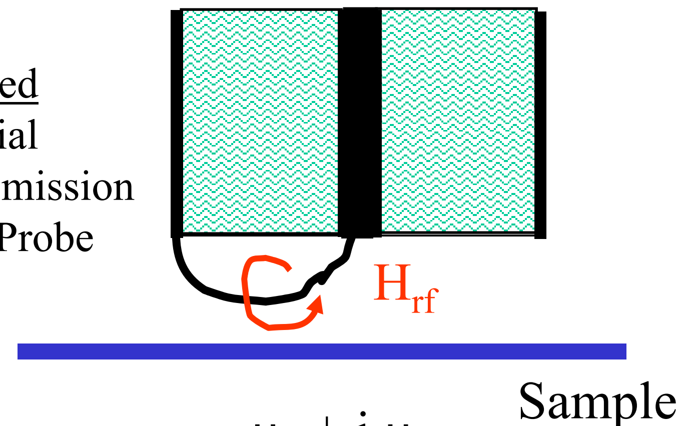
ε_1 - i ε_2

σ, ρ/t

$R_s + i\, X_s$

Magnetic Field Probe

Shorted Coaxial Transmission Line Probe



$\mu_1 + i\, \mu_2$

σ, ρ/t

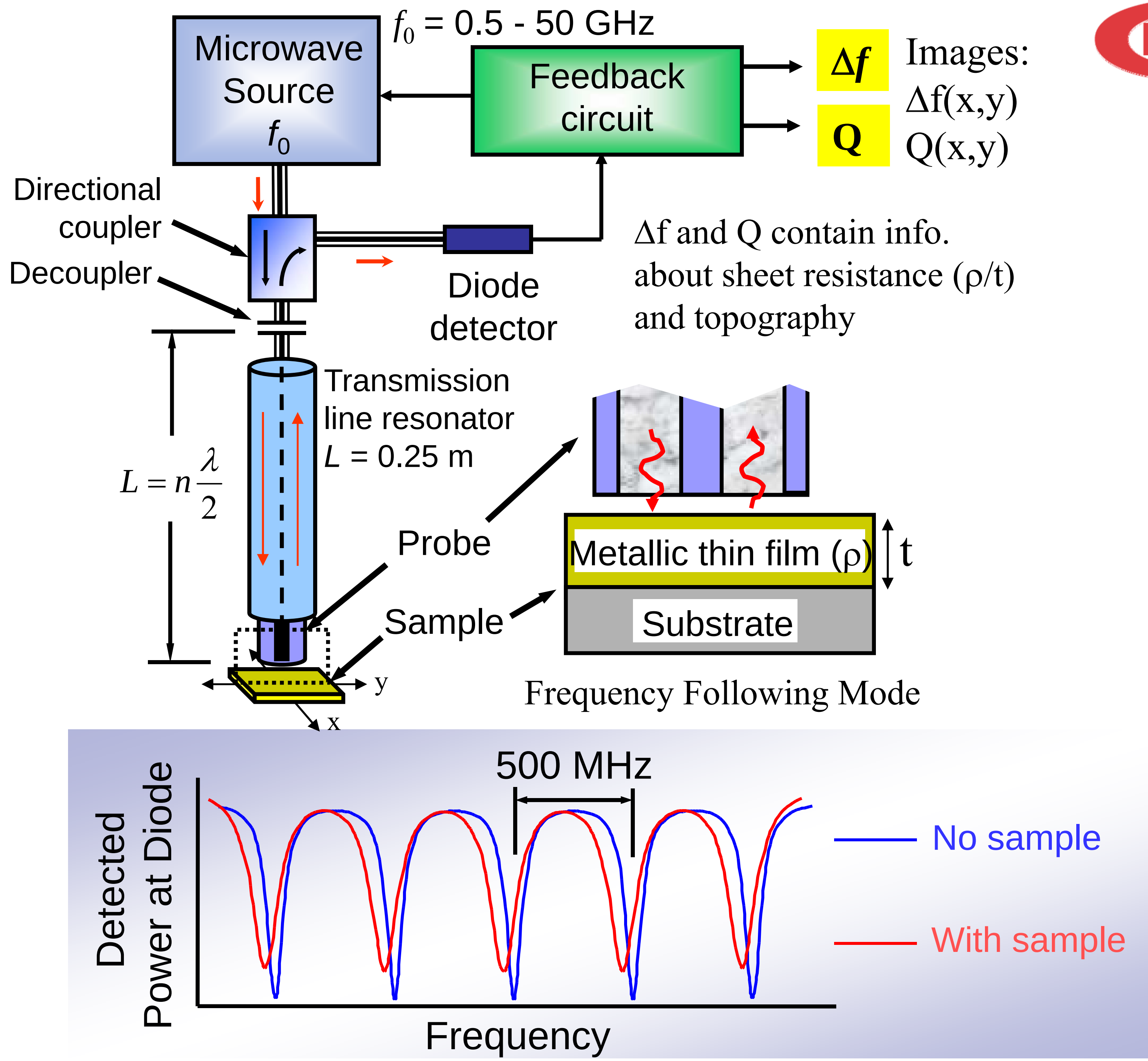
$R_s + i\, X_s$

Varying capacitance (ε_1) and inductance (μ_1) change the stored energy and resonant frequency Δf

Varying sample losses (ρ/t, $\tan\delta = \varepsilon_2/\varepsilon_1$, μ_2) change the quality factor (Q) of the microscope

$$\Delta f = f_0' - f_0 \propto \Delta(\text{Stored Energy})$$

$$\Delta(1/2Q) \propto \Delta(\text{Dissipated Energy})$$

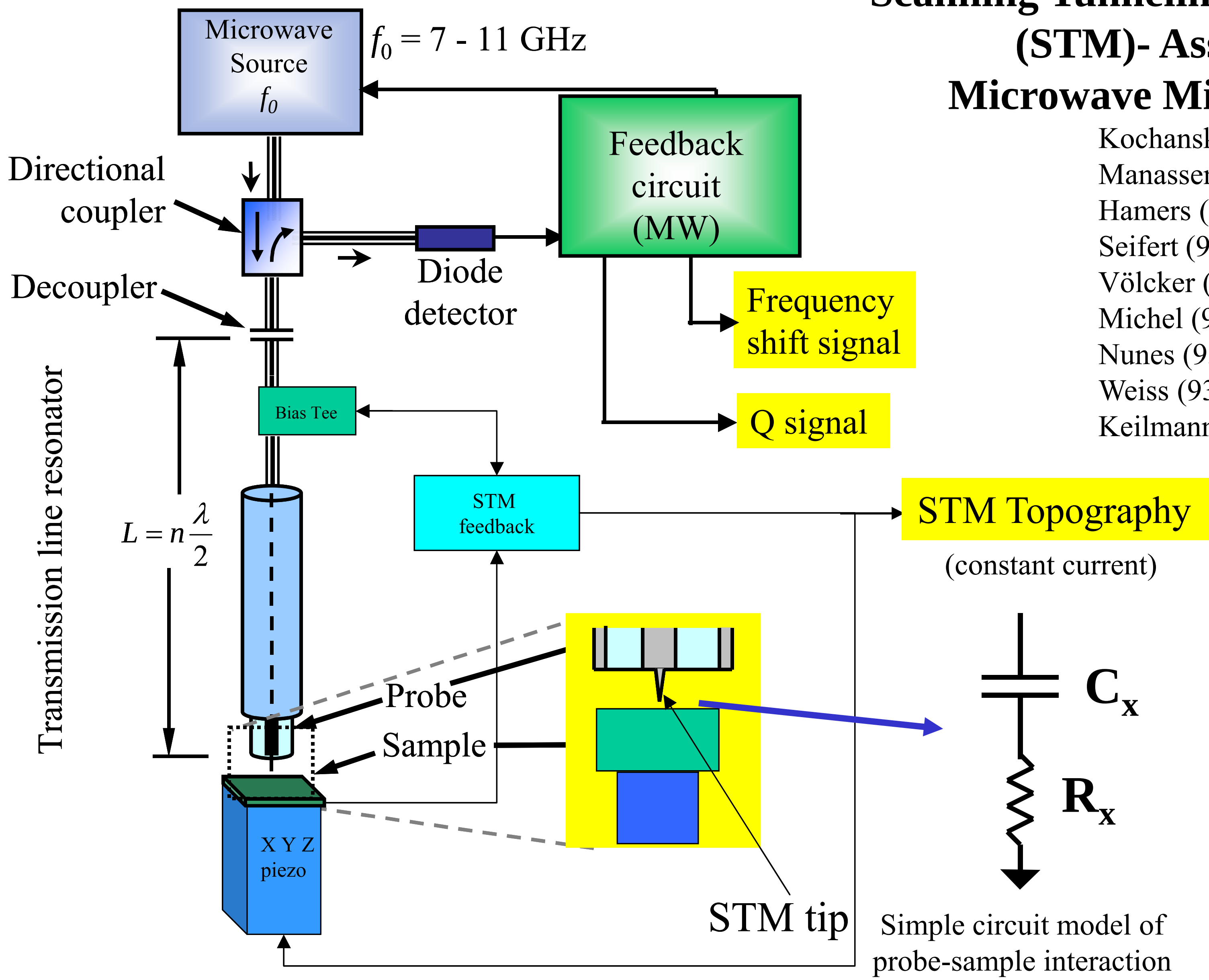


f_0 = 0.5 - 50 GHz
Microwave Source f_0
Feedback circuit
Δf
Q
Images:
Δf(x,y)
Q(x,y)
Directional coupler
Decoupler
Diode detector
Δf and Q contain info. about sheet resistance (ρ/t) and topography
Transmission line resonator
L = 0.25 m
$L = n\frac{\lambda}{2}$
Probe
Sample
Metallic thin film (ρ)
t
Substrate
y
x
Frequency Following Mode
500 MHz
Detected Power at Diode
Frequency
No sample
With sample

High Resolution Sheet Resistance Imaging

Scanning Tunneling Microscope (STM)- Assisted Microwave Microscopy

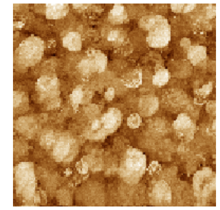
Kochanski (89)
Manassen (89)
Hamers (90)
Seifert (91)
Völcker (91)
Michel (92)
Nunes (93)
Weiss (93)
Keilmann (96)

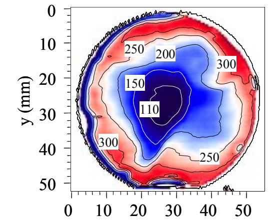


Microwave Microscope Quantitative Imaging Results

Quantitative Sheet Resistance Imaging

D. Steinhauer, *et al*. Appl. Phys. Lett. 71, 1736 (1997)
A. Imtiaz, *et al*. Ultramicroscopy. 94, 209 (2003)
A. Imtiaz, *et al*., Appl. Phys. Lett. 90, 143106 (2007)

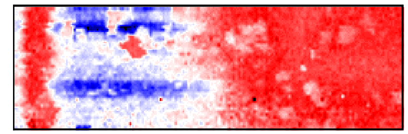




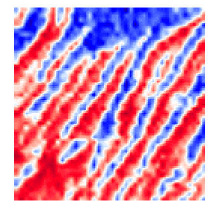
<100 nm resolution

Quantitative Imaging of Dielectric Permittivity and Tunability

D. Steinhauer, *et al*. Appl. Phys. Lett. 75, 3180 (1999)
A. Tselev, *et al*., Rev. Sci. Instrum. 78, 044701 (2007)



1 – 20 GHz
~ 1 μm res.



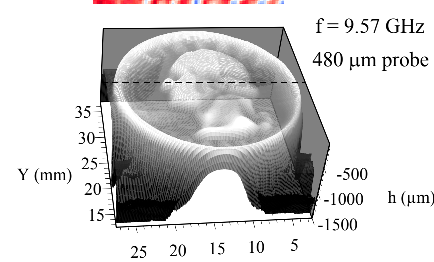
$\Delta\varepsilon_r = 2$ at $\varepsilon_r = 500$
$\Delta\varepsilon_{113} = 0.03\ V^{-1}$

Imaging of Domains in Ferroelectric Crystals

D. Steinhauer, *et al*. J. Appl. Phys. 89, 2314 (2001)

Quantitative Topographic Imaging

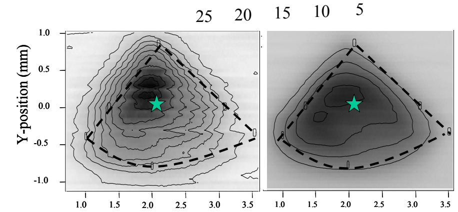
C. P. Vlahacos, *et al*. Appl. Phys. Lett. 72, 1778 (1998)



Δh = 55 nm

Magnetic Permeability Imaging

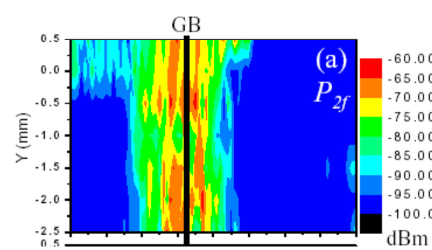
S. C. Lee, *et al*. Appl. Phys. Lett. 77, 4404 (2000)



<200 μm resolution

Meissner-State Nonlinearity Imaging in Superconductors

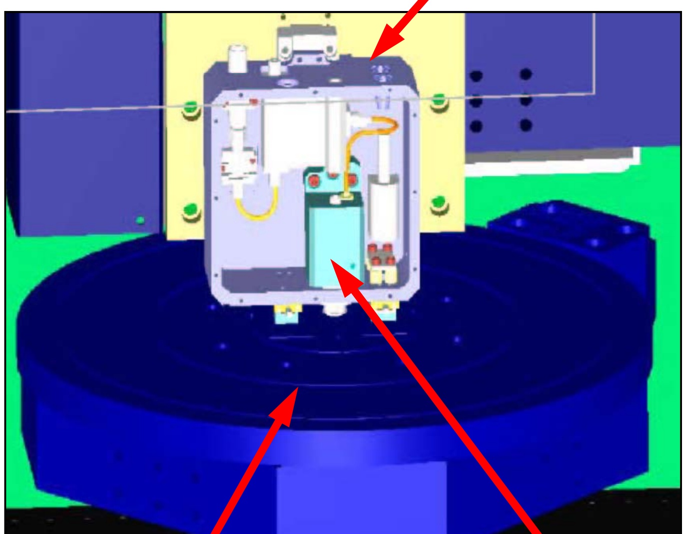
S. C. Lee, *et al*., Phys. Rev. B 71, 014507 (2005)
S. C. Lee, *et al*., Phys. Rev. B 72 , 024527 (2005)



Commercial Near-Field Microwave Microscope
Solid State Measurements 6300 NeoMetriK™

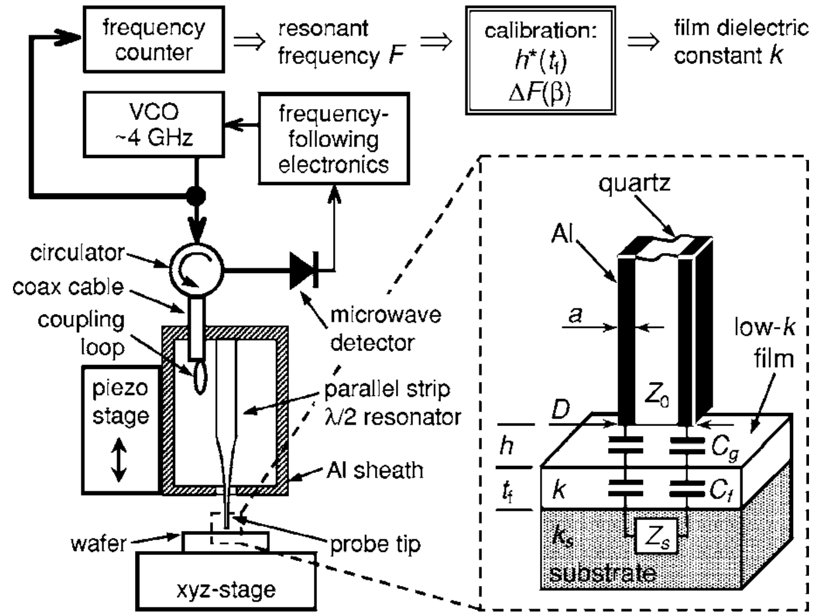
Commercial in-line dielectric metrology tool
Developed by Vladimir Talanov and Andrew Schwartz

Measurement Head
10 x 10 x 5 cm^3



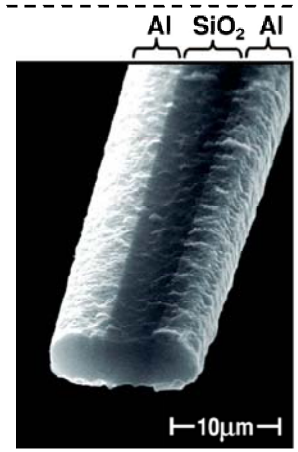
300mm wafer chuck

Probe cartridge



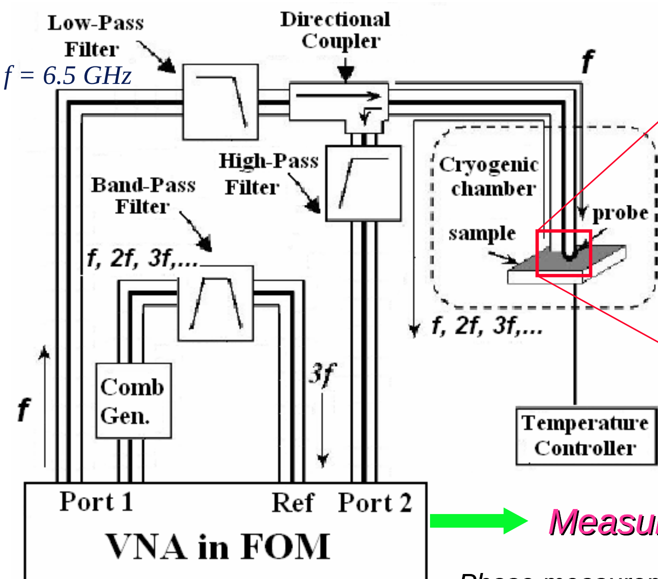
V. Talanov APL (2006)

Low-k dielectric imaging
±2% accuracy
<0.3% precision
10 μm spot size, 4 GHz

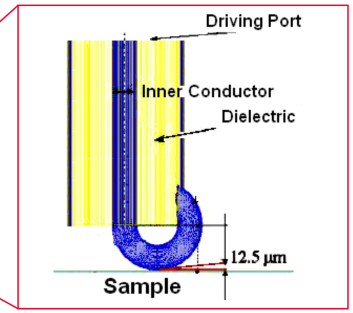


Other Forms of Quantitative Microwave Microscopy

Nonlinear Superconductor Microscopy/Spectroscopy



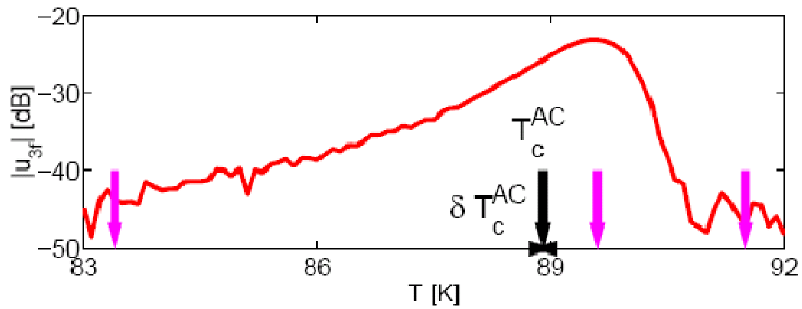
Non-Resonant!



Magnetically-shielded environment

Measures $V_{3f}^{Sample} / V_{3f}^{Ref}$

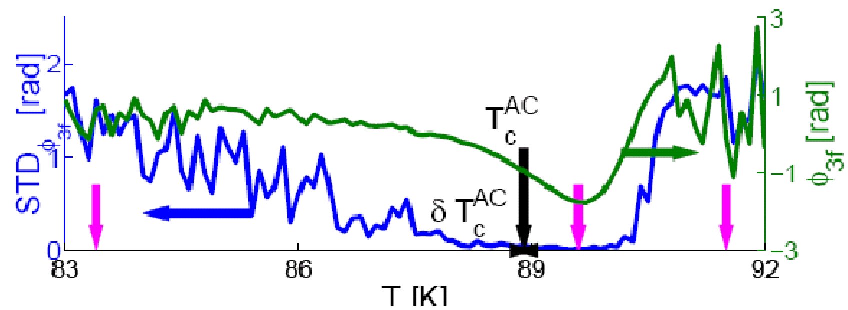
Phase measurement of 3f signal is not calibrated



$$V_{3f} = \left|V_{3f}\right| e^{i\phi_{3f}} \qquad \left|V_{3f}\right|$$

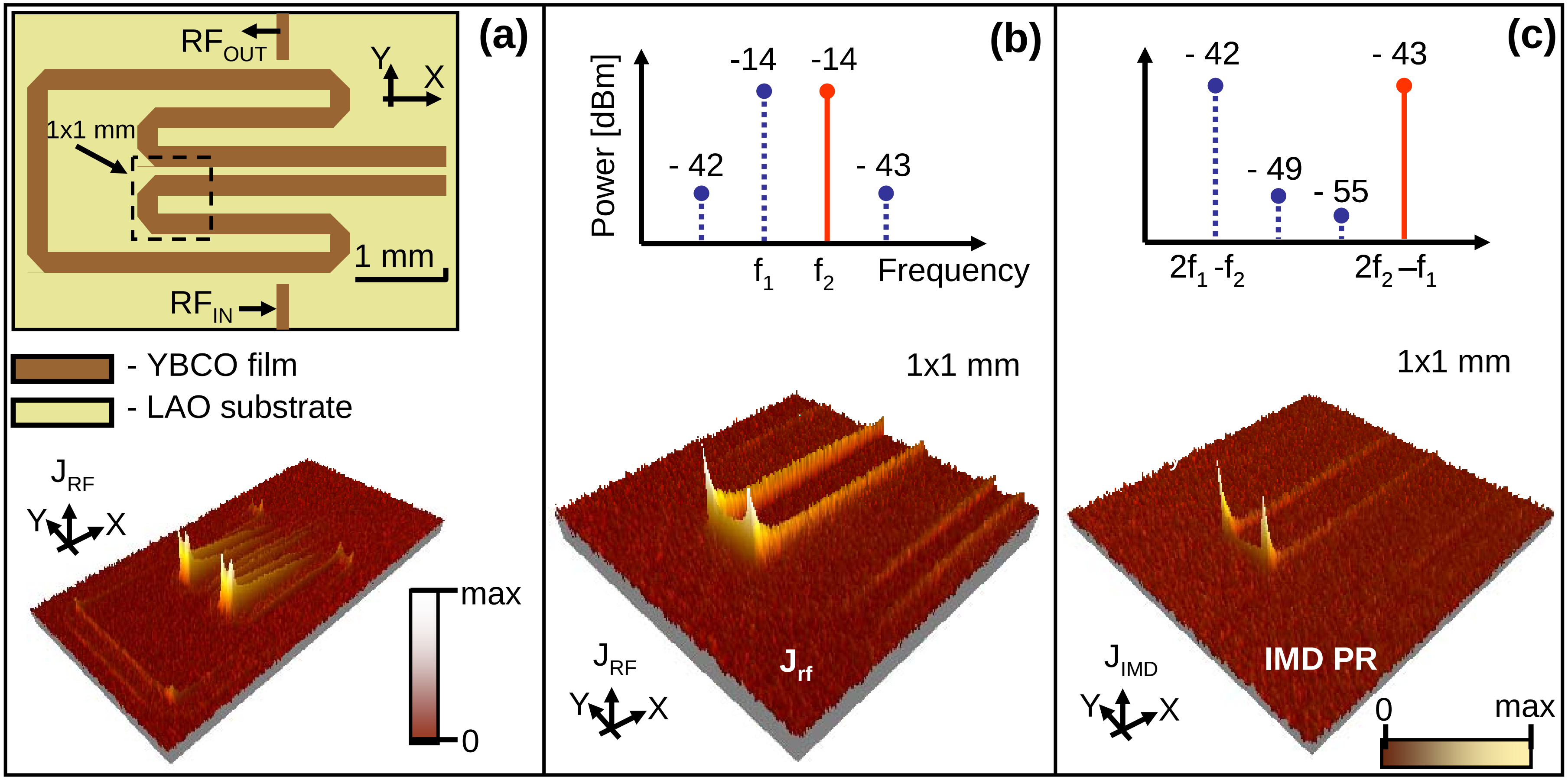
Third harmonic voltage due to the nonlinear Meissner effect near T_c in cuprates

$$\phi_{3f}$$



Other Forms of Quantitative Microwave Microscopy

Laser Scanning Microscopy (Far Field)



See, e.g. A. P. Zhuravel, *et al.*, Low Temperature Physics 32, 592 (2006)

UNIVERSITY OF MARYLAND

Spatial Resolution

Modeling and experiment support the result that spatial resolution is given by Max(d, h)

We have shown that high lateral resolution (~2.5 nm) imaging is possible

Sharp probe features (d) give rise to high lateral-wavenumber evanescent waves
Close probe/sample separation (small h) couples efficiently to evanescent waves

Other considerations:

Store and perturb energy in high-$k_{lateral}$ waves

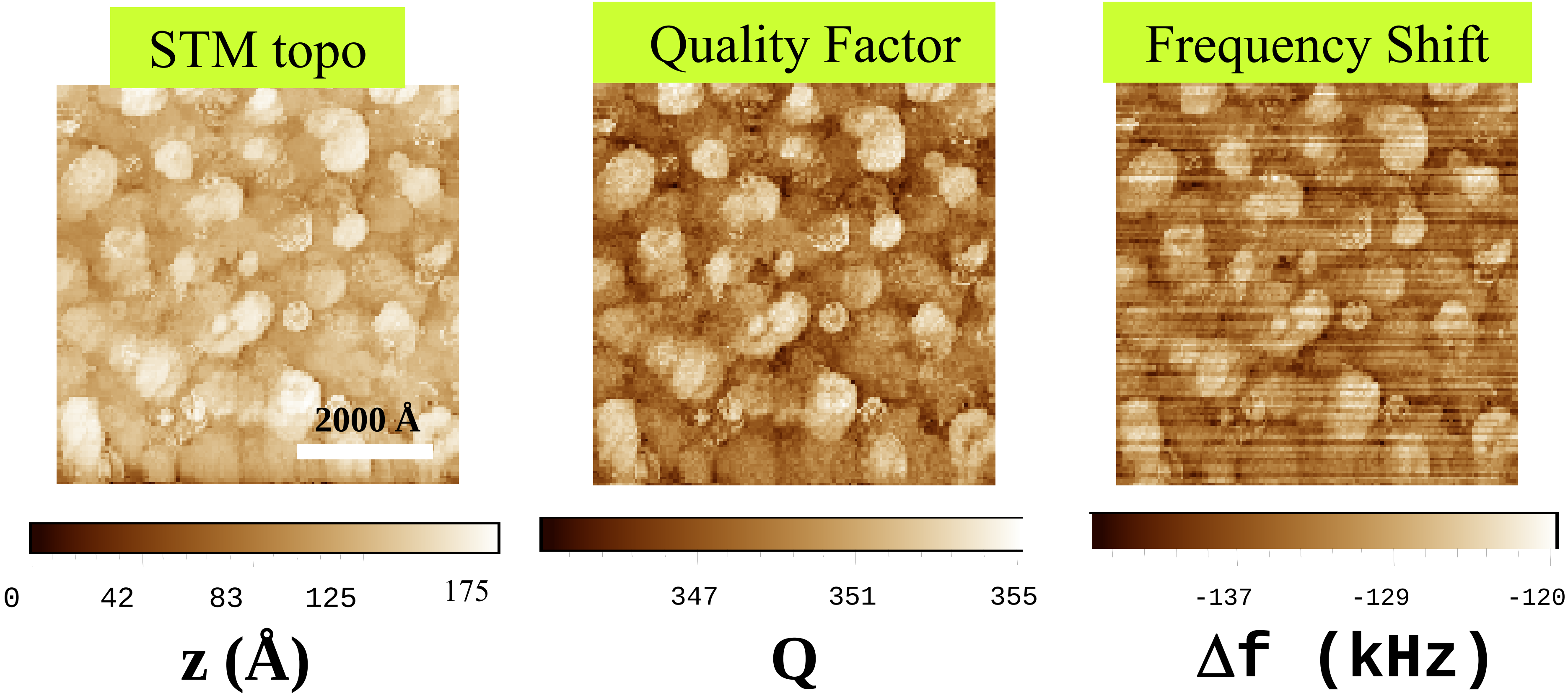
Produce contrast in Δf

$$\vec{S}_{sample} = \frac{1}{2}\vec{E}_{sample} \times \vec{H}^{*}_{sample}$$

Dissipate energy in sample

Produce contrast in Q

STM-Assisted Images of Colossal Magnetoresistive Manganite



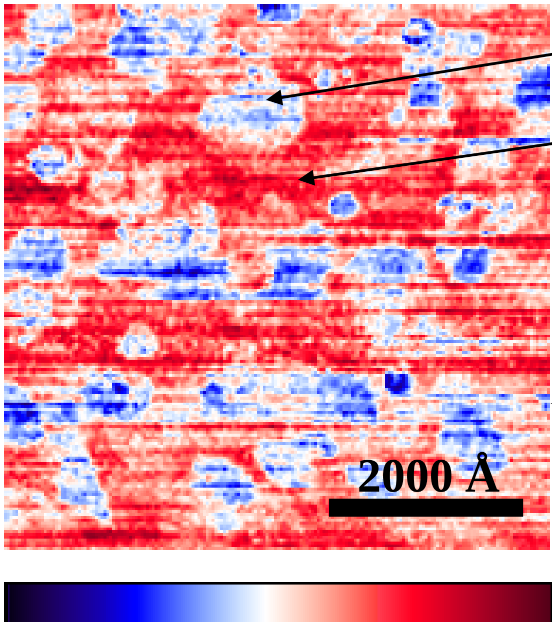
$La_{0.67}Ca_{0.33}MnO_3$
1000Å thick film
600 nm x 600 nm
$LaAlO_3$ substrate

Using methods similar to those for sheet resistance imaging on the 100 μm scale …

→ Construct R_x maps

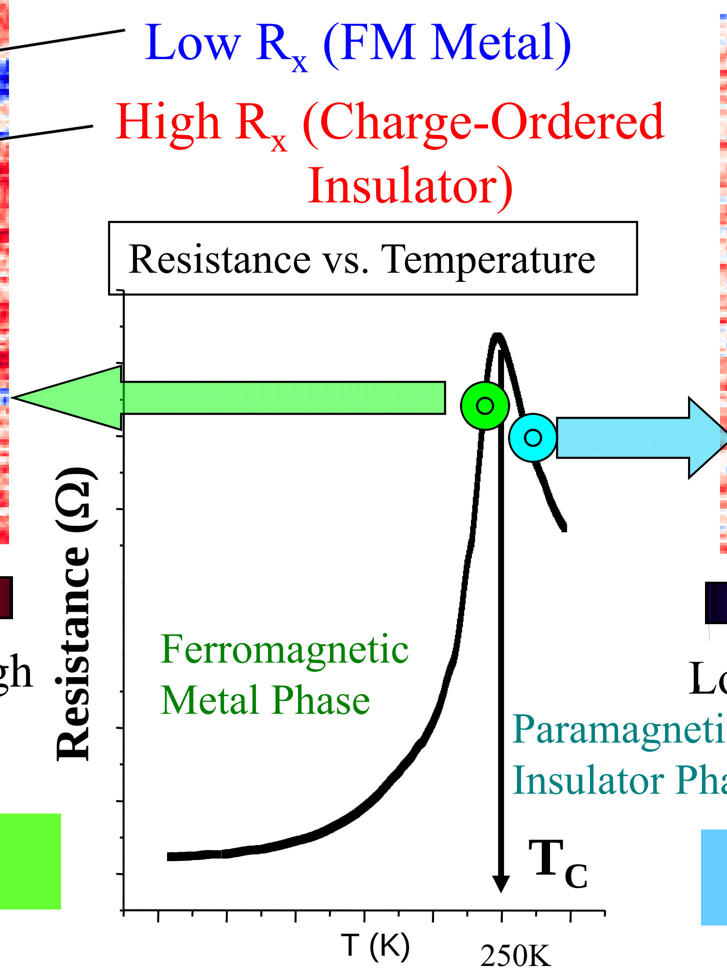
 Ultramicroscopy 94, 209-216 (2003)

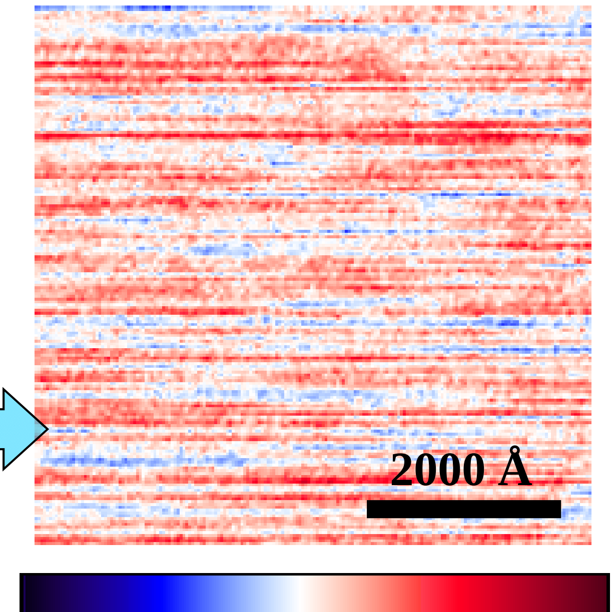
Sheet Resistance (R_x) comparison for $La_{0.67}Ca_{0.33}MnO_3$ colossal magneto-resistive sample at two different temperatures



Sheet Resistance (R_x)

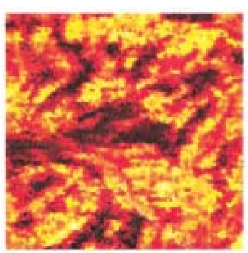
T=240K (below T_c)





Sheet Resistance (R_x)

T=272K (above T_c)

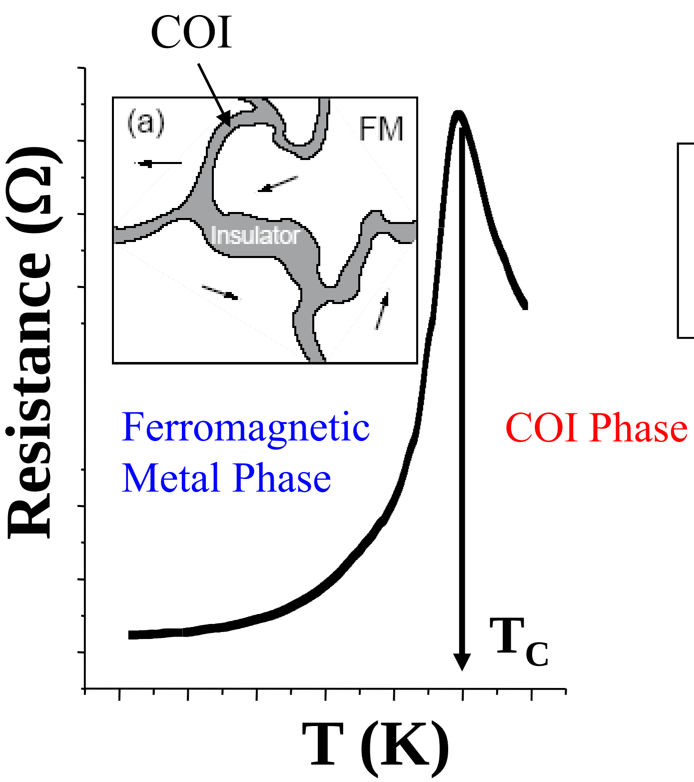


STS, 200 K
M Fäth, Science (1999)

Transport in Manganites

Percolation below T_C

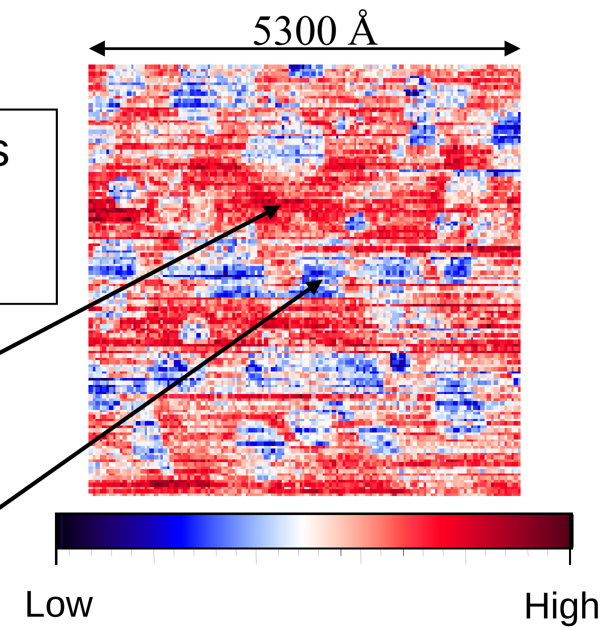
Charge-Ordered-Insulator (COI) and Ferromagnetic Metal (FM) phases have very similar energies



This data suggests spatial resolution ≤ 16 nm

High R_x inter-granular regions

Low R_x grains

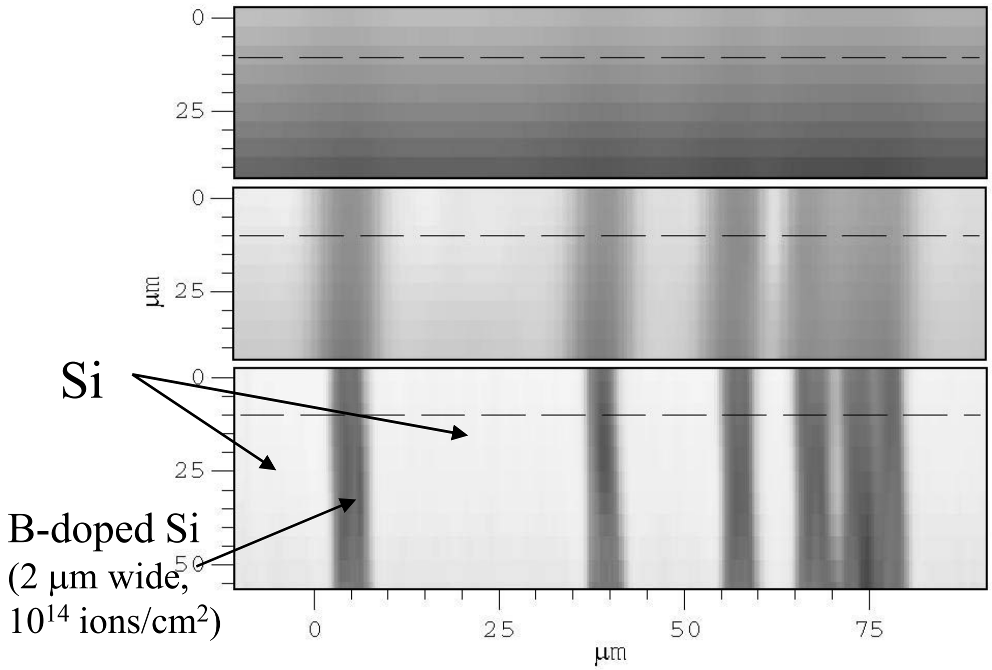


Sheet resistance $R_x = \rho/t$

$T < T_C$

New Modes of Operation
of the Microwave Microscope

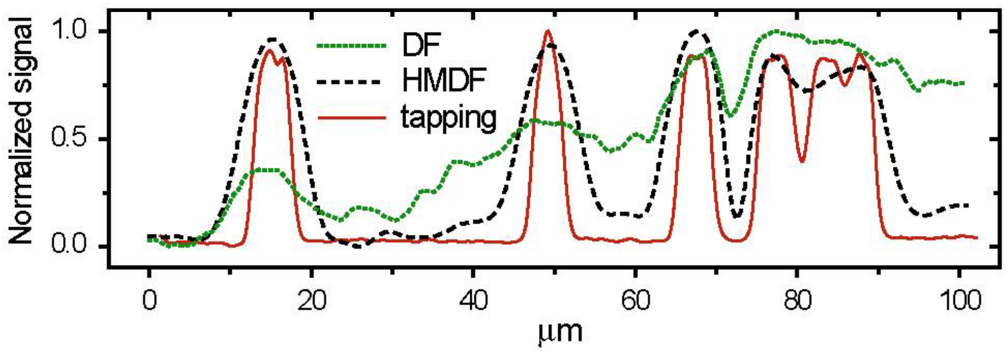
Comparison of DF with HMDF and HMDF with Tapping



Distance Following

Height-Modulated Distance Following

Height-Modulated Distance Following + Tapping



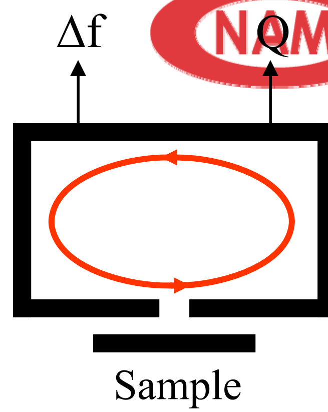
STM-tipped microwave microscope
~ 1 GHz
Room temperature

The 5 General Methods of Microwave Microscopy

cond-mat/0001075

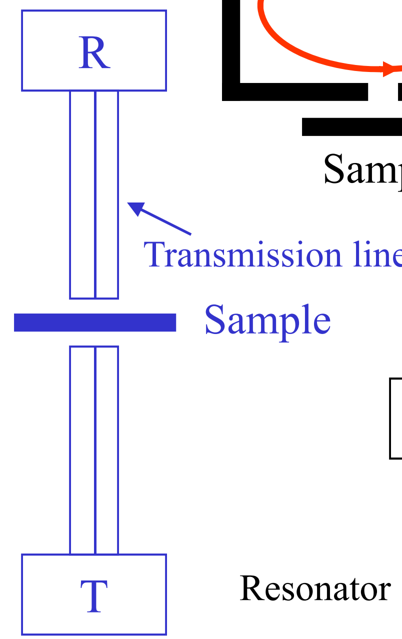
a) Cavity Resonator with evanescent coupling to sample

Used mainly for imaging FMR
Frait (1958), Soohoo (1961), Ash (1970), Bhagat (1996)



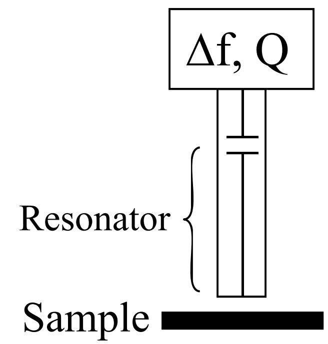
b) Non-Resonant Reflection/Transmission

Transmission line brings localized signal to sample
Bryant (1965), Stuchly (1980), Fee (1989), Keilmann (1989), Tabib-Azar (1993), Stranick (1994), Golosovsky (1996)



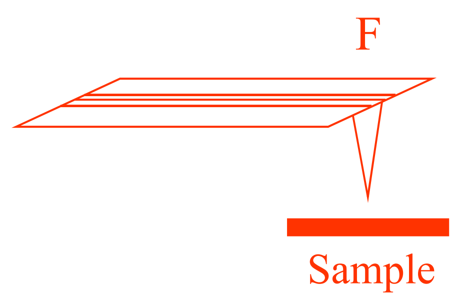
c) Perturbed Resonator with localized coupling to sample

"Field Enhancement" mechanisms employed
Bosisio (1970), Cho (1995), Xiang (1996), UMD (1996)



d) Cantilever techniques

Used mainly for imaging magnetic resonance
Manassen (1994), Zhang (1996), Rugar (1998)



e) Scanning SQUID Microscopy

rf eddy-current imaging
Black (1996)