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School of Electrical Engineering

A new Method to Measure Critical Current Density of HTC Superconductor Bulk
&
Short Review of Ongoing Experimental Works on SQUID based NDE and VSM

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Outline

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- Superconductivity

- A new method to measure critical current density of HTC superconductor Bulk
  - Current methods
  - New method
    1. Theory
    2. Experimental

- Nondestructive evaluation system based on SQUID sensor (NDE)
  - A brief review on Josephsone junction
  - A brief review on rf SQUID
  - SQUID NDE simulation and results

- Vibrating Sample Magnetometer system based on SQUIS sensor (VSM)

Superconductivity

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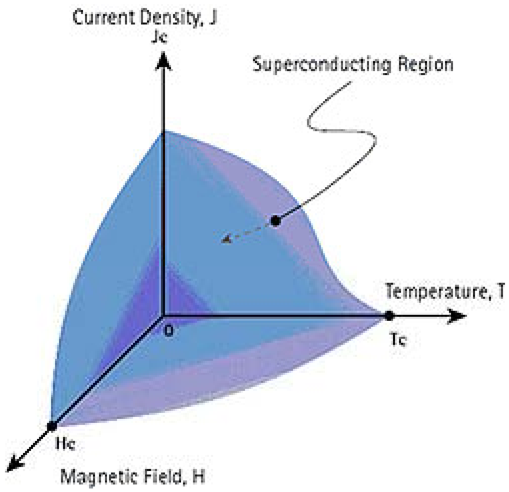
- Superconductor : below its critical temperature T_c
- ✓ Perfect diamagnetism
- ✓ Zero DC electrical resistance



- Critical current
  Critical temperature
  Critical magnetic field

- Energy gap

J_c Measurement

- **Critical current:**

  The maximum current that a superconductor can carry at a particular temperature with zero resistivity

- J_c: An important parameter for characterizing a superconductor

✓ DC transport method

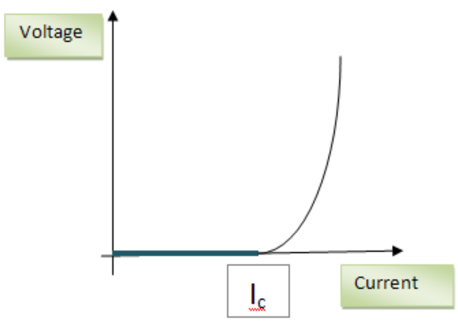
  Increasing current

  Recording voltage

  V-I characteristic

  Critical current

  Critical current density



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Current methods

- **Lock- in**

  A DC. bias current is applied to the superconductor specimen

  Low amplitude AC. Current

  Lock-in amplifier measures the resulting voltage

- **Pulse method**

  To reduce current contact heating

  Current pulse is applied to the specimen while the voltage is monitored

- **Magnetization**

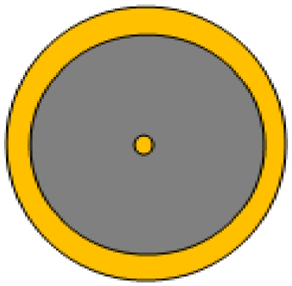
  A convenient method

  Based on the Bean critical state model

  A mathematical relationship between a superconductor's magnetic behavior and its I_c

New method to measure critical current density of SC. Bulk (Theory)

- Based On V-I characterization
  - No magnetic field
- Applying current into small zone
  - Circular cross section
  - Au Sputtering for electrodes
- Pulse current source
  - To reduce heat generation

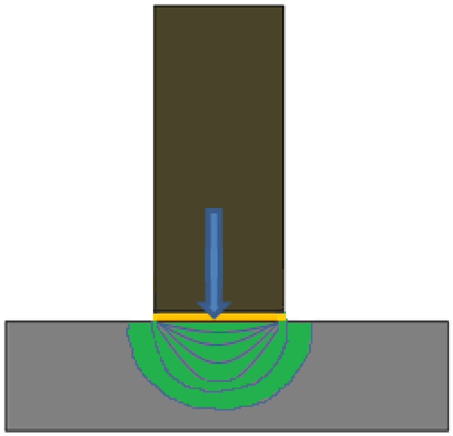


New method to measure critical current density of SC. Bulk (Theory)

- Current distribution

✓ Lower current
Lower penetration
Elliptical distribution

✓ Higher current
Higher penetration
Semispherical distribution



Normal zones development

New method to measure critical current density of SC. Bulk (Theory)

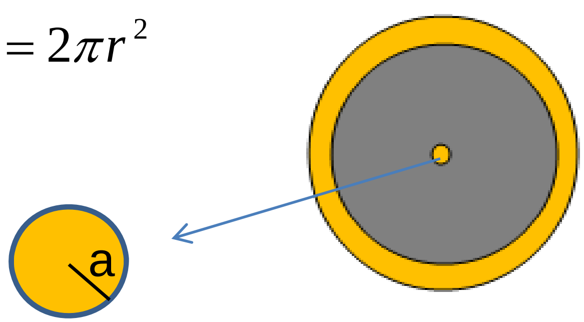
$$V = -\int E.dl \qquad J = \frac{E}{\rho} \quad \longrightarrow \quad V = -\int J\rho.dl \qquad J = \frac{I}{A}$$

$$\longrightarrow \quad V = -\rho \int \frac{I}{A}.dl$$

- ✓ Oblate spheroid surface area: $A_{Oblate}(r) = \frac{\pi}{\sqrt{a^2 - r^2}} \left[2a^2\sqrt{a^2 - r^2} + ar^2 \ln\left(\frac{a + \sqrt{a^2 - r^2}}{a - \sqrt{a^2 - r^2}} \right) \right]$
- ✓ Semispherical area: $A_{spherical} = 2\pi r^2$

r : penetration depth

a: radius of central electrode



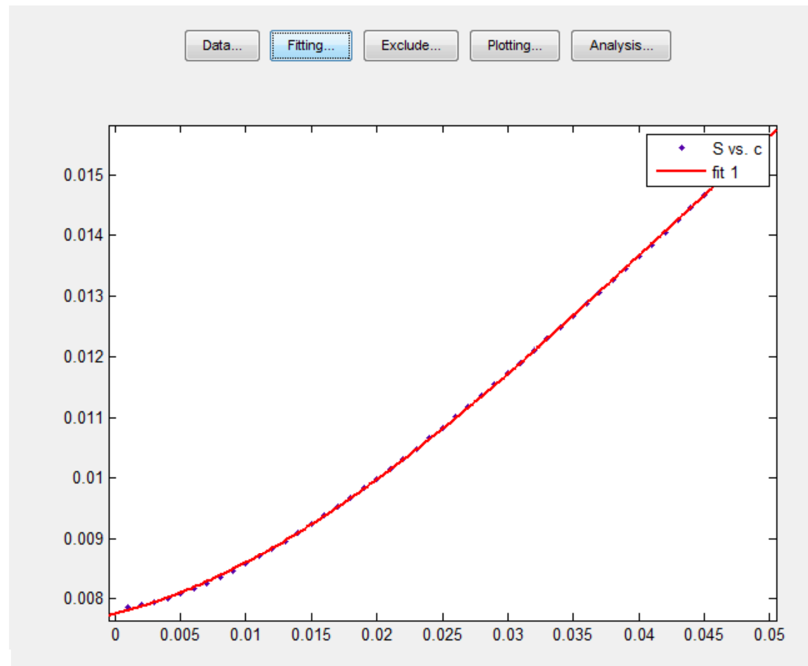
New method to measure critical current density of SC. Bulk (Theory)

- Elliptical zone (a=0.05 cm) :

$$S(r) = .5r^{1.38} + .0077$$

$$S(r) = \frac{I}{J} \longrightarrow r = 2\sqrt[1.38]{\frac{I}{J} - 0.0077}$$

$$S(r) = -26.83r^{3} + 3.43r^{2} + .053r + .0077$$



New method to measure critical current density of SC. Bulk (Theory)

- Elliptical zone:

$$V = \rho I \int_0^r \frac{dr}{S(r)}$$

$$V = \rho I [5.2 \arctan(0.3 + 24.4r) - 1.28 \ln(0.15 - r)$$
$$+.64 \ln(r^2 + .025r + .0018) + 0.1008]$$

$$r = 2\sqrt[1.38]{\frac{I}{J_c} - 0.0077}$$

- By substituting penetration depth in voltage equation : V-I curve

New method to measure critical current density of SC. Bulk (Theory)

- Elliptical zone:

$$r = 2\sqrt[1.38]{\frac{I}{J_c} - 0.007}$$

I> .0077J_c ⟶ Voltage

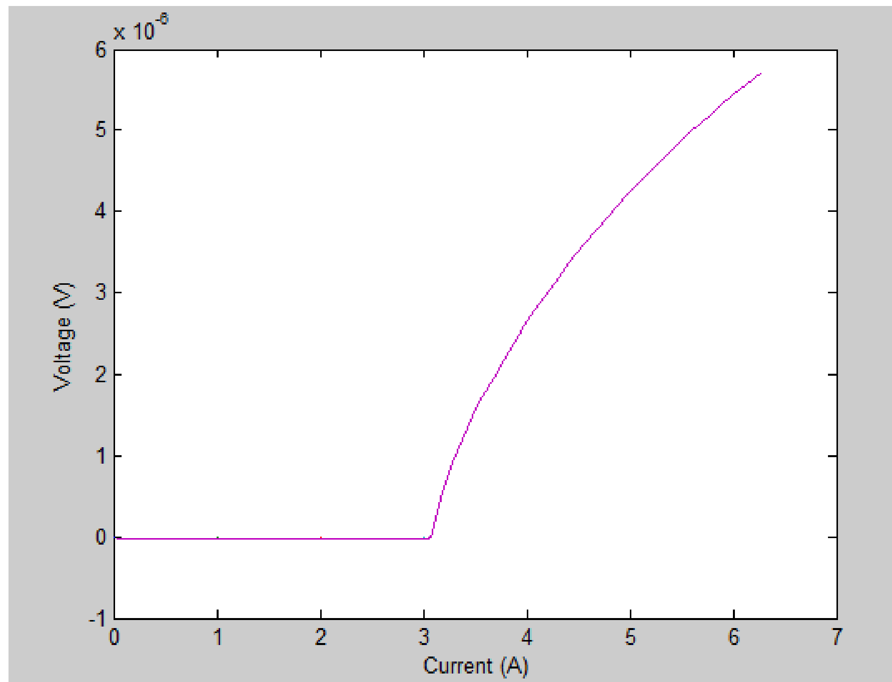
✓ There is a specific value for current

J_c=400 A/cm^2

a= .05 cm

$$\rho = 1.7 * 10^{-6} \ \Omega cm$$

$$V = \rho I\,[5.2\arctan(0.3 + 24.4r) - 1.28\ln(0.15 - r) + .64\ln(r^2 + .025r + .0018) + 0.1008]$$



Current bounds=[3.08 - 6.28] (A)

New method to measure critical current density of SC. Bulk (Theory)

- Elliptical zone:

❖ J_c=400 (A/cm2) , a=.05 cm :

I > 0.0077*Jc → Voltage

I > (coefficient, depended to radius of central electrode)* J_c

✓ Increasing current

✓ First positive voltage

✓ Using the relationship

✓ Getting the critical current density

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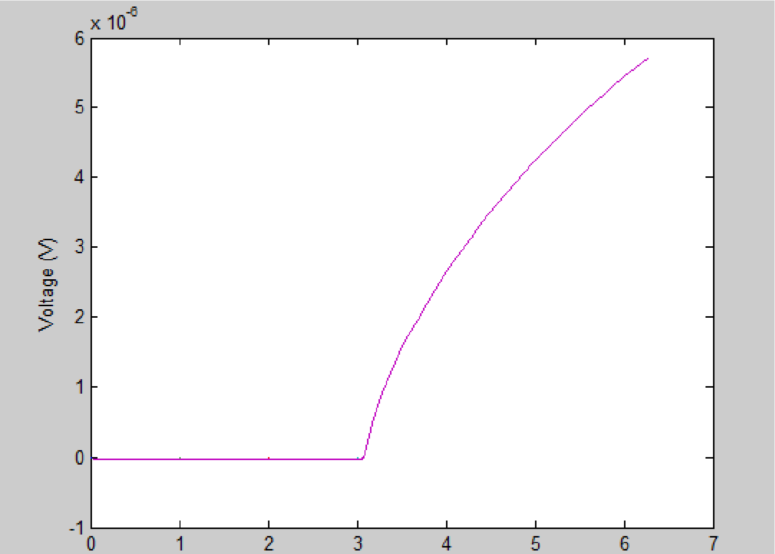


New method to measure critical current density of SC. Bulk (Theory)

- Semispherical zone:

$$a = .05(cm)$$

$$\rho = 1.7*10^{-6}(\Omega cm)$$

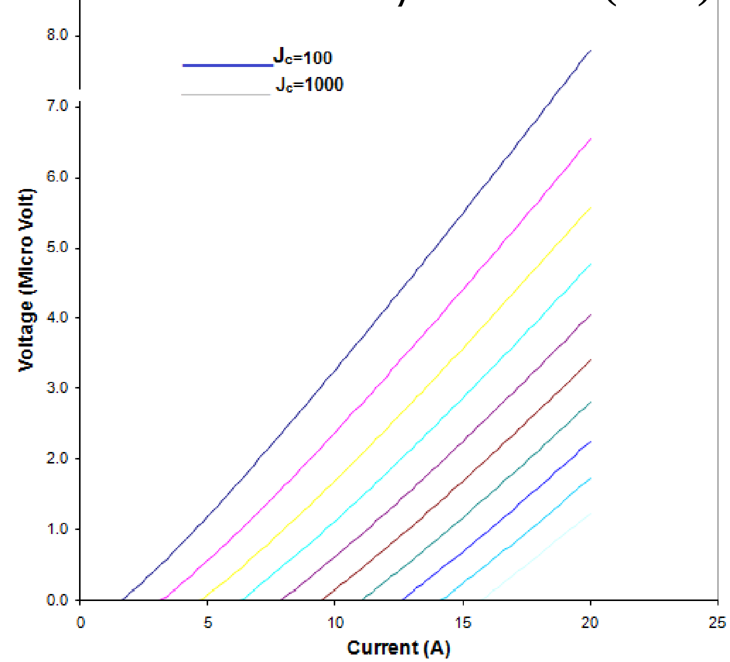
$$J = \frac{I}{2\pi r^2}$$

$$V = \frac{\rho}{2\pi}\left(\sqrt{2\pi JI} - \frac{I}{a}\right)$$

$$R = \frac{dV}{dI} = \frac{\rho}{2\pi}\left(\sqrt{\frac{\pi J}{2I}} - \frac{1}{a}\right)$$

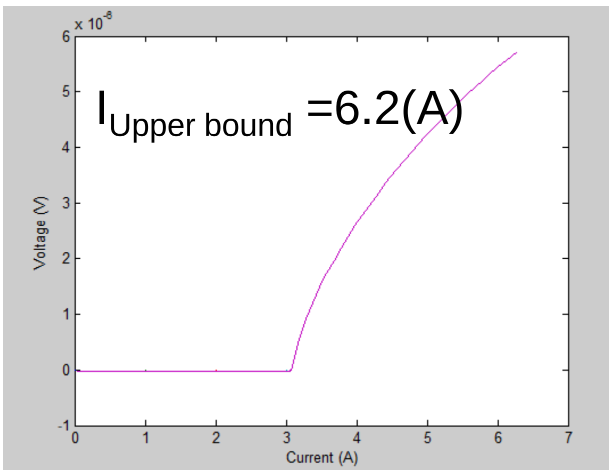
$$R = \rho\int_a^r \frac{dr}{2\pi r^2} = \frac{\rho}{2\pi}\left(\frac{1}{a} - \frac{1}{r}\right)$$

penetration depth: $r = \dfrac{a\rho}{\rho - 2\pi aR}$



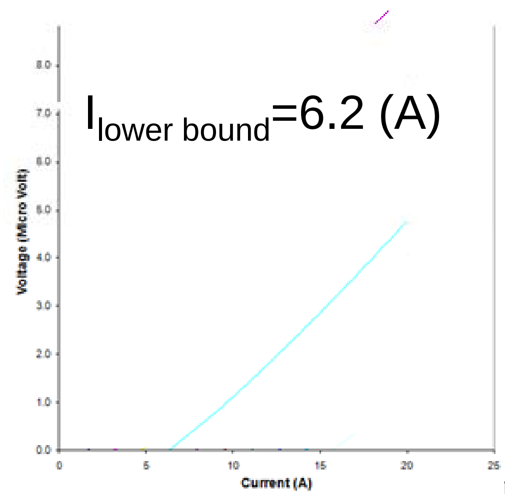
New method to measure critical current density of SC. Bulk (Theory)

Elliptical zone+ Semispherical zone : (Assuming J_c=400 (A/cm^2) and a=0.05 (cm))



Elliptical

$$V = \rho I [5.2 \arctan(0.3 + 24.4r) - 1.28 \ln(0.15 - r) + .64 \ln(r^2 + .025r + .0018) + 0.1008]$$



Semispherical

$$V = \frac{\rho}{2\pi}\left(\sqrt{2\pi J I} - \frac{I}{a}\right)$$

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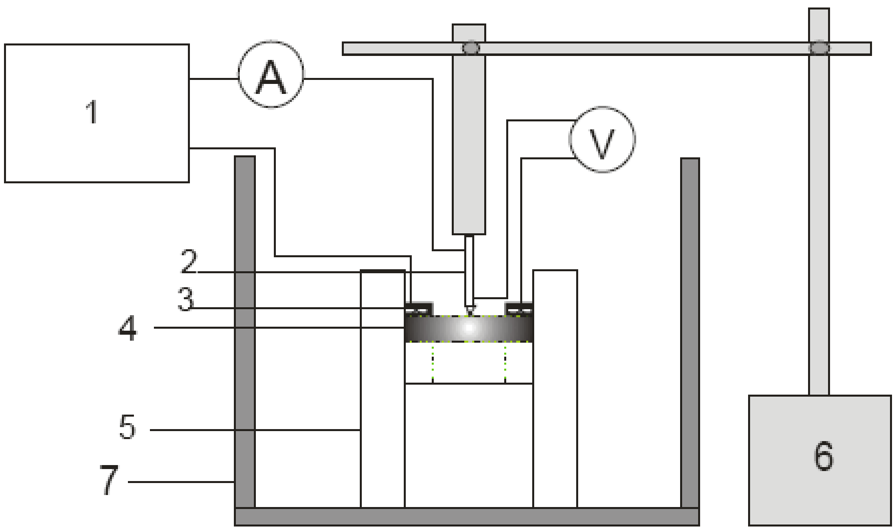
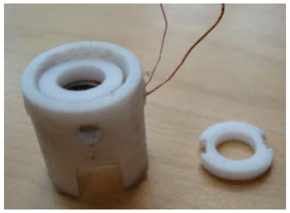
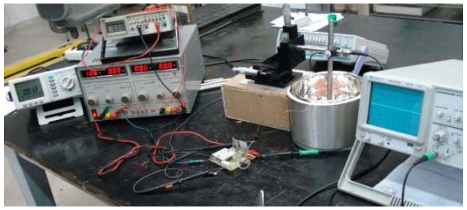
New method to measure critical current density of SC. Bulk (Experimental)



1- Electronic circuit
2- Needle
3- Electrode (Au-silver paste-copper)
4- YBCO
5- Holder
6- Micrometer
7- Dewar for liquid Nitrogen





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New method to measure critical current density of SC. Bulk (Experimental)

- ✓ **YBCO superconductor bulk** (Diffusion fabrication process)

  Diameter of bulk =1.4 (cm)

  Thickness of bulk=0.25(cm)

  $\rho = 1.7 * 10^{-6} (\Omega cm)$

  T_c=92 (K)

- ✓ **Electronic circuits**:

  - Current source (differential pair)

    Pulsive current , T=25 (ms) , t_{on}=5 (ms) (considering heat generation and heat capacity of bulk)

  - Other measuring equipments

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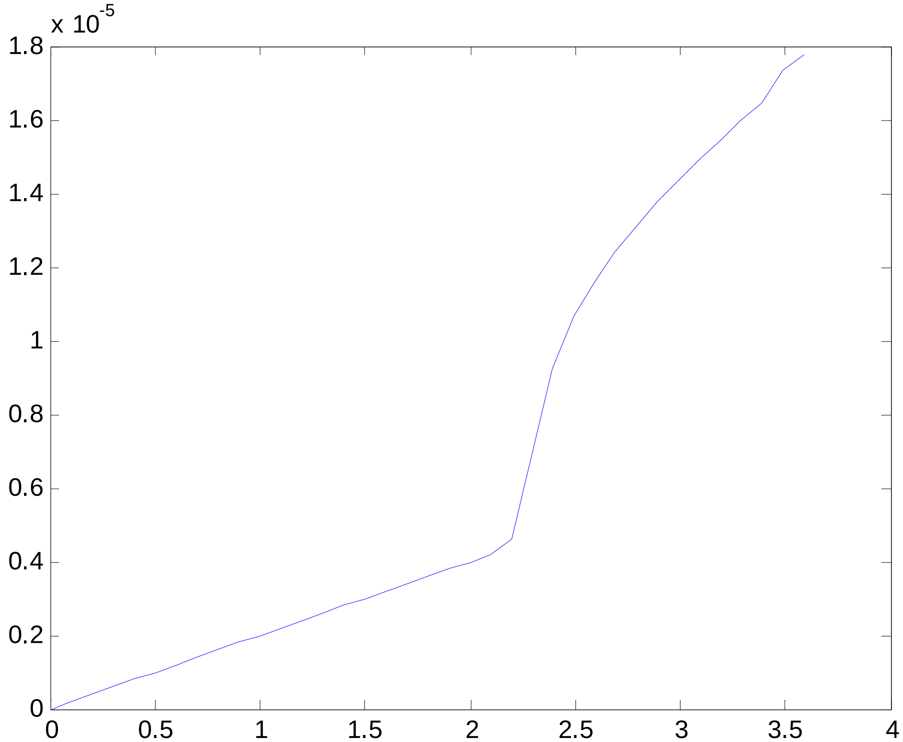
New method to measure critical current density of SC. Bulk (Experimental)

$Voltage\,(V)$



$Current\,(Amp)$

There is a positive voltage at i>0

- Crack and flaw on the surface

$$J_c = 310 (Amp / cm^2)$$

New method to measure critical current density of SC. Bulk (Experimental)

$$\frac{\partial V}{\partial I} = 1.7\times10^{-6}\, i \left(\frac{0.64\left(\frac{0.00724638}{\left(-0.0077+\frac{i}{j}\right)^{0.275362} j} + \frac{5.7971\left(-0.0077+\frac{i}{j}\right)^{0.449275}}{j} \right)}{0.0018 + 0.01\left(-0.0077+\frac{i}{j}\right)^{0.724638} + 4\left(-0.0077+\frac{i}{j}\right)^{1.44928}} + \right.$$

$$\frac{183.884}{\left(1+\left(0.3+48.8\left(-0.0077+\frac{i}{j}\right)^{0.724638}\right)^{2}\right)\left(-0.0077+\frac{i}{j}\right)^{0.275362} j} +$$

$$\left. \frac{1.85507}{\left(0.15-2\left(-0.0077+\frac{i}{j}\right)^{0.724638}\right)\left(-0.0077+\frac{i}{j}\right)^{0.275362} j} \right) +$$

$$1.7\times10^{-6}\left(0.1008 + 5.2\,\mathrm{ArcTan}\left[0.3+48.8\left(-0.0077+\frac{i}{j}\right)^{0.724638}\right] - \right.$$

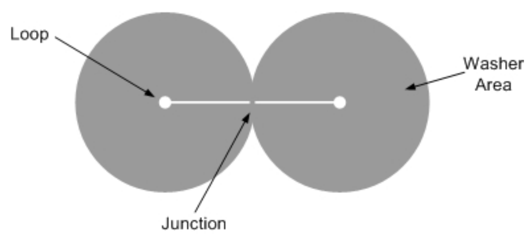
$$1.28\,\mathrm{Log}\left[0.15-2\left(-0.0077+\frac{i}{j}\right)^{0.724638}\right] +$$

$$\left. 0.64\,\mathrm{Log}\left[0.0018+0.01\left(-0.0077+\frac{i}{j}\right)^{0.724638} + 4\left(-0.0077+\frac{i}{j}\right)^{1.44928}\right]\right)$$

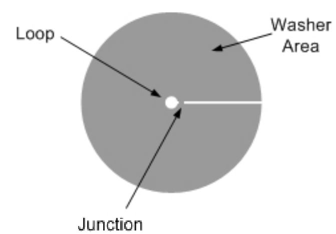
NDE system :

- ✓ Nondestructive Evaluation for Finding flaws
- ✓ Scanning surface → the place of hidden crack
- ✓ Based on SQUID sensor

- SQUID: **S**uperconducting **Qu**antum **I**nterference **D**evices
- SQUIDs are the most sensitive magnetic flux detectors introduced until now
- Using SQUIDs it is possible to detect a change in flux typically as low as $10^{-6}\ \Phi_0$ (sensitivities down to 10^{-15} T



RF SQUID gradiometer



RF SQUID magnetometer

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Brief review on Josephson junction

- Two superconductors separated by a barrier can experience tunneling of Cooper Pairs through the junction

Basic Josephson Junction Relations:

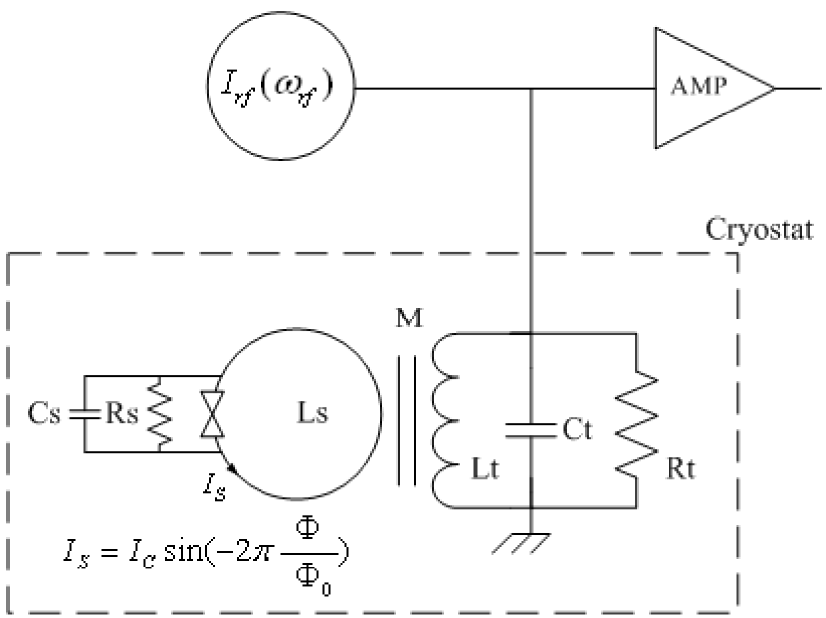
✓ DC Josephson effect : a current proportional to the phase difference of the wave functions

✓ AC Josephson effect : a Josephson junction will oscillate with a characteristic frequency which is proportional to the voltage across the junction

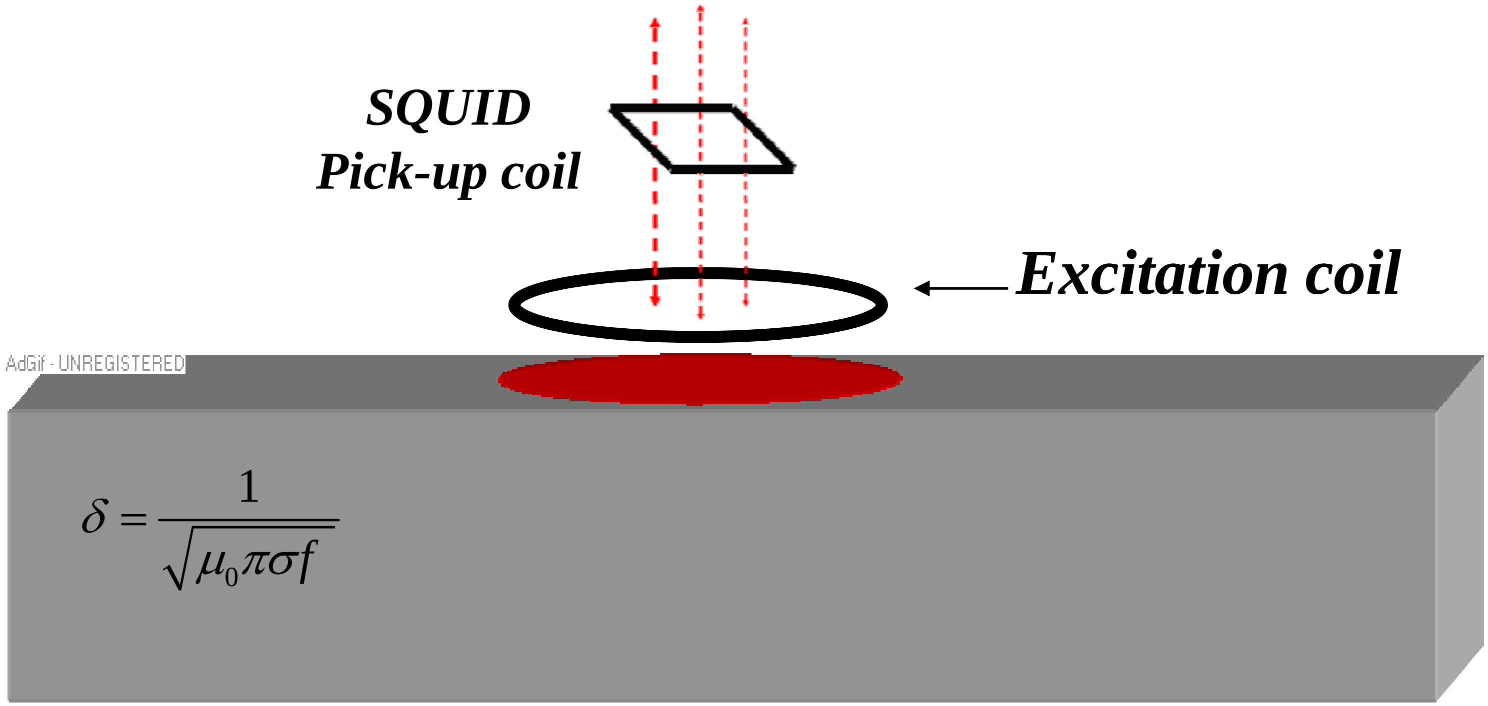
$$I = I_c Sin(\varphi) \qquad \frac{\partial \varphi}{\partial t} = \frac{2e}{\hbar} V$$

Brief review on RF SQUID

- The relation between externally applied flux (Φ_{ext}) and actually passing flux through the SQUID loop (Φ) implies the basis of RF SQUID operation

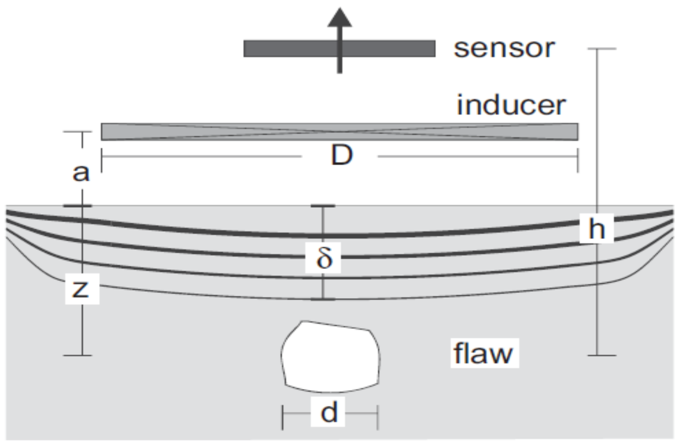


SQUID NDE

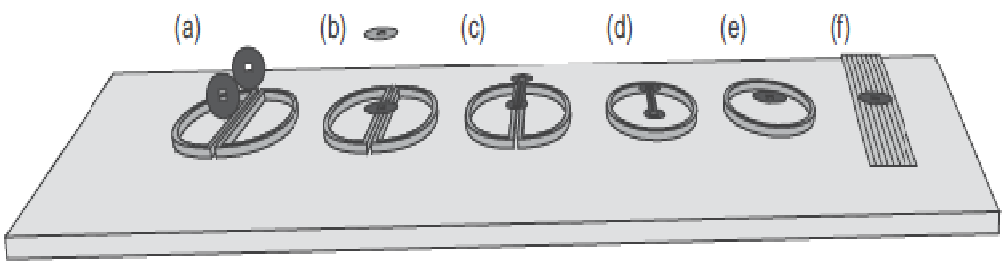


$$\delta = \frac{1}{\sqrt{\mu_0 \pi \sigma f}}$$

- SQUID NDE Parameters

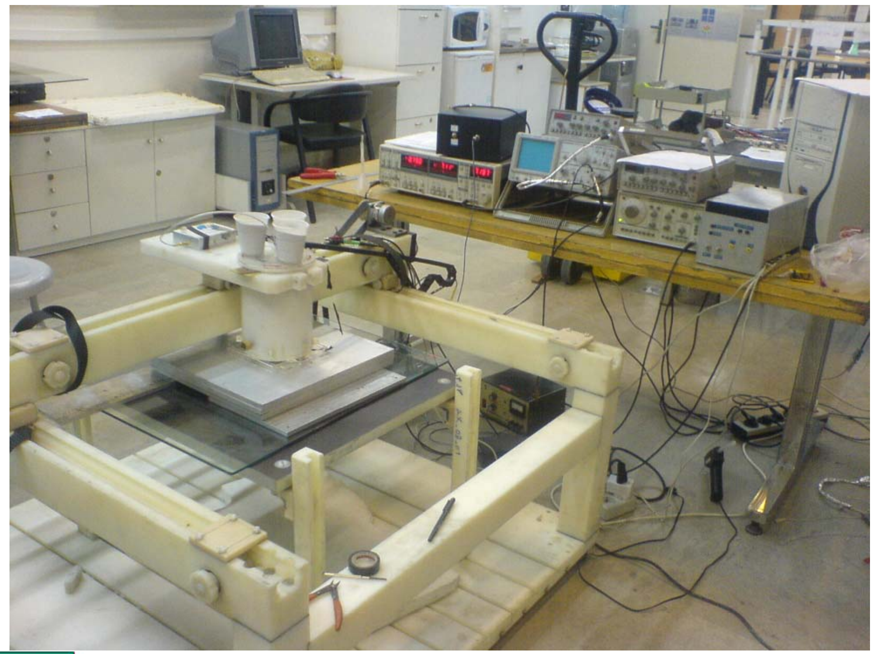


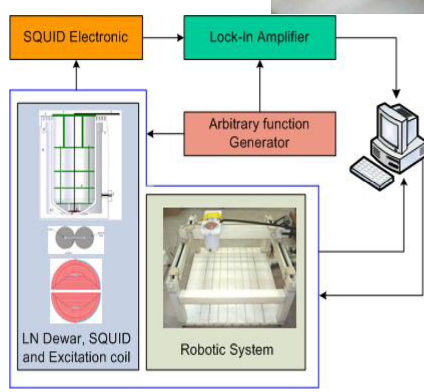
- SQUID-Excitation Coil Configuration



SQUID NDE system

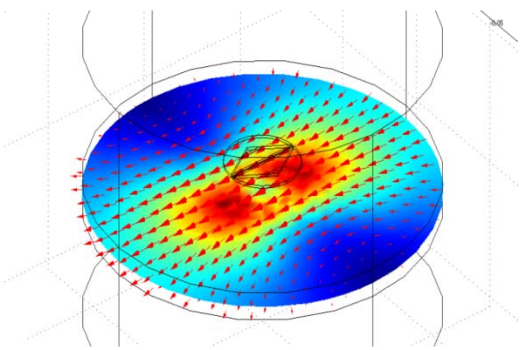
- ✓ SQUIDs
- ✓ Readout Electronics
- ✓ Cryogenics & Vacuum
- ✓ 2-D Scanning robot
- ✓ Excitation coils
- ✓ Micro-positioner
- ✓ Shielding

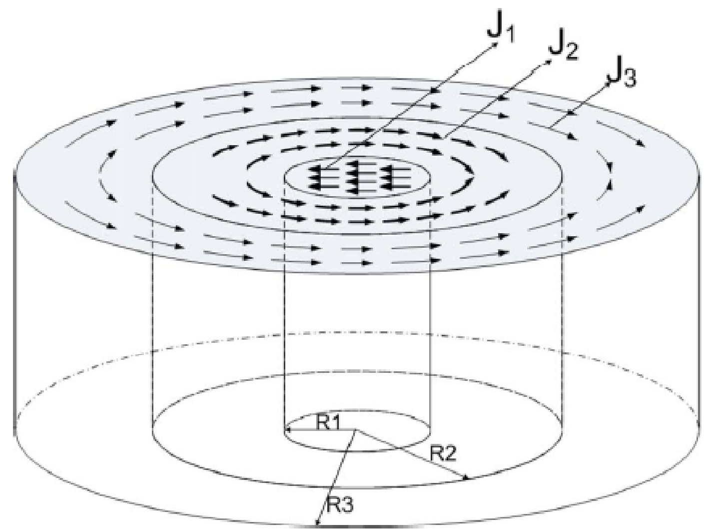


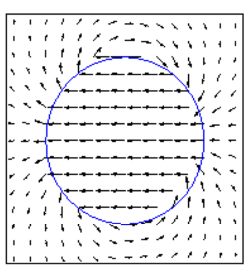


- FEM Simulation of SQUID NDE

✓ Flaw modeling

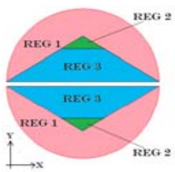


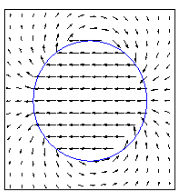


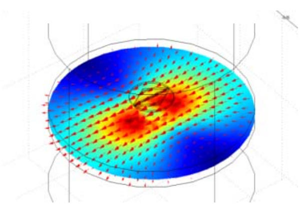


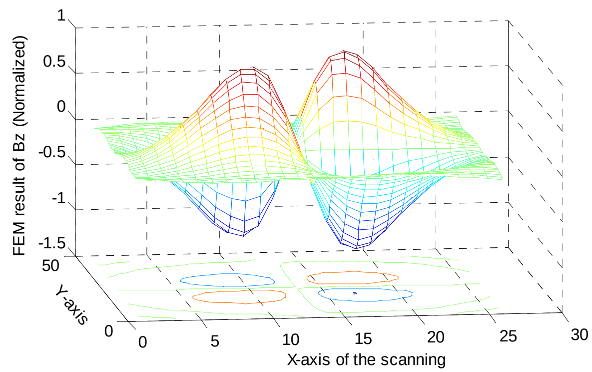
$$J_2 = \frac{1}{R_2 - R_1} \int_{R_1}^{R_2} J_{field} .dr$$

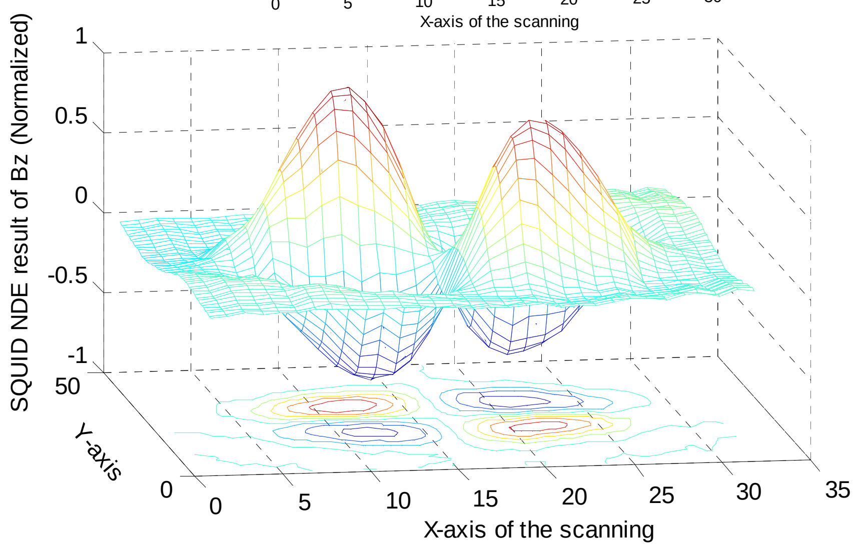
- SQUID NDE result











Flaw: single hole

f=40 (Hz)

h= 2 (cm)

VSM…?

- Operates on Faraday's law:
- ✓ Change in magnetic field → electric field

VSM : measuring magnetic behavior of magnetic materials

- How VSM works…?
- ✓ Sample in magnetic field
- ✓ Alignment of magnetic domain
- ✓ Magnetic dipole moment:

  create magnetic field around sample

  (Magnetic Stray Field)
- ✓ Vibration of sample

  Voltage

  Sensing by set of pick-up coils → SQUID sensor

…How VSM works

- The strength of the constant magnetic field is set
- The sample begins to vibrate
- The signal received from probe, translated into a value for the magnetic moment of the sample
- Change in magnetic field, no data during transition
- New magnetic field value, new translated data from probes
- The constant magnetic field varies over a given range
- Generation of a plot of magnetization (M) versus magnetic field strength (H)

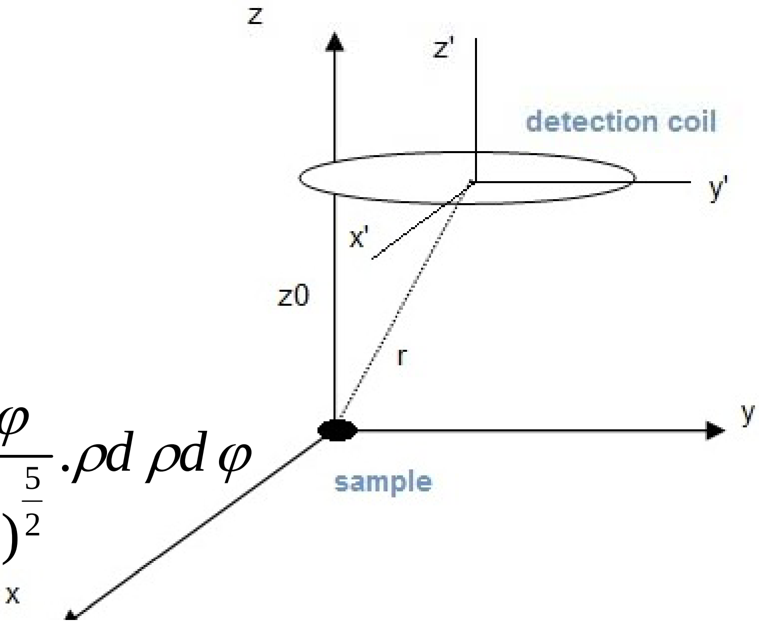
Magnetic field of dipole

$$B = \frac{\mu_0 m}{4\pi r^3}(\hat{r}\, 2\cos\theta + \hat{\theta}\sin\theta)$$

$$\phi = \int \vec{B}.d\vec{A}$$

$$\phi = \frac{\mu_0 m}{4\pi}\iint_A \frac{2z_0{}^2 - \rho^2 - \sigma^2 + 2\rho\sigma\cos\varphi}{(\rho^2 + z_0{}^2 + \sigma^2 - 2\rho\sigma\cos\varphi)^{\frac{5}{2}}}.\rho d\,\rho d\,\varphi$$

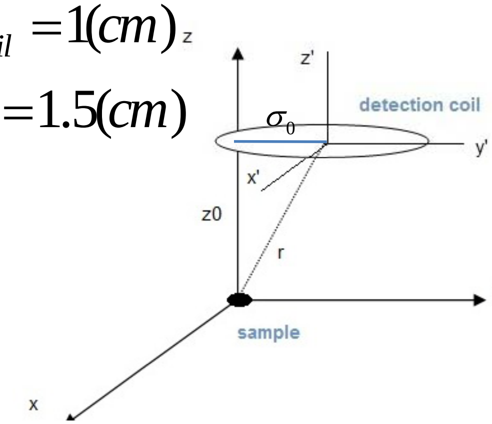
$$V = -\frac{d\phi}{dt}$$

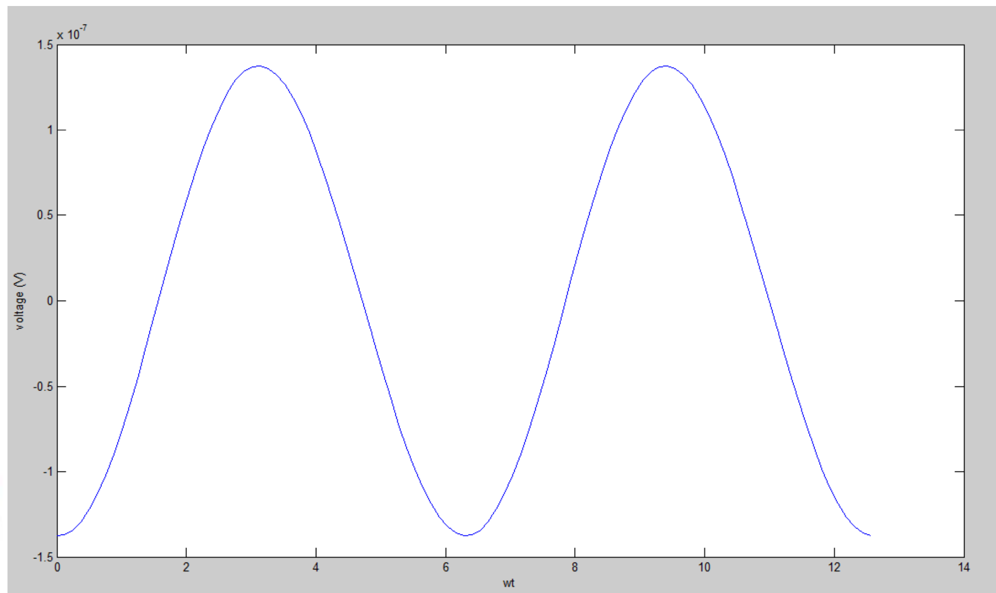


By solving integral → Voltage

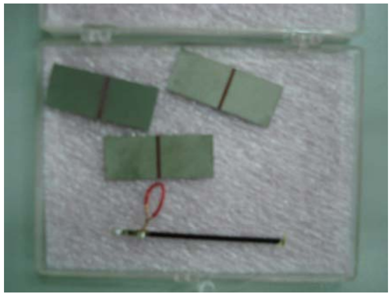
$$\sigma = \sigma_0 + \sigma_1 \sin \omega t$$

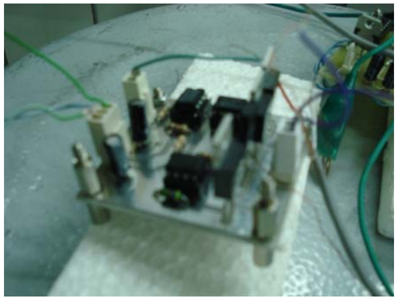
$$\sigma_0 = .9(cm)$$
$$\sigma_1 = 250(\mu m)$$
$$R_{coil} = 1(cm)$$
$$Z_0 = 1.5(cm)$$





- VSM experimental





- ✓ Piezoelectric
- ✓ Electromagnet(Up to 1.7 Tesla)
- ✓ Detection coil
- ✓ Band pass filter
- ✓ Lock in amplifier
- ✓ Function generator
- ✓ Current amplifier
- ✓ Other electronic instruments

Summary

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- A new method to measure critical current density of HTC superconductor Bulk has been introduced. Theoretical and experimental data surveyed.
- By SQUID sensor, Nondestructive Evaluation system(NDE) for finding hidden cracks is one of sensitive system.
- We could characterize magnetic property of materials by SQUID base VSM system

Thank you!