Scanning Hall Probe Microscopy Analysis of Critical Current Density in Superconducting Materials

Samuel Warren[1,2], Zeyu Wu[3], Kohei Higashikawa[3], Takanobu Kiss[3]

[1]*Department of Chemistry, Yale University, New Haven, CT, USA*
[2]*Nakatani RIES Program and Department of Electrical and Computer Engineering, Rice University, Houston, TX, USA*
[3]*Department of Electrical Engineering, Kyushu University, Motooka, Fukuoka, Japan*

Realistic applications for superconductors abound in the realms of electronics, mechanics, and power transport. However, superconductivity relies on the microscopic properties of a material to provide the macroscopic benefits of zero resistance and incredibly high current loads. The production of superconducting wires or tapes requires that the microscopic structures of the material are carefully controlled so that current density is maximized. While the transport current density can be easily measured through four-probe testing or other simpler means, to gain an understanding of the localized critical current density or its distribution these methods prove inadequate or impractical. It is imperative that this data is obtained so that the microscopic structures that seem to limit or improve critical current can be identified and removed or replicated. The use of Hall probe microscopy allowed for the rapid analysis of current density within several superconducting samples through the measurement of their produced magnetic fields. In addition, by inducing current within the superconducting samples, the measured current densities were the critical values at the specified magnetic field strength and temperature. The inverse problem of Biot-Savart law, converting the magnetic field data into a current distribution, has been solved with a sheet current approximation in order to calculate the critical current density distribution solely from the perpendicular component of the 2-D magnetic field emitted from the sample.

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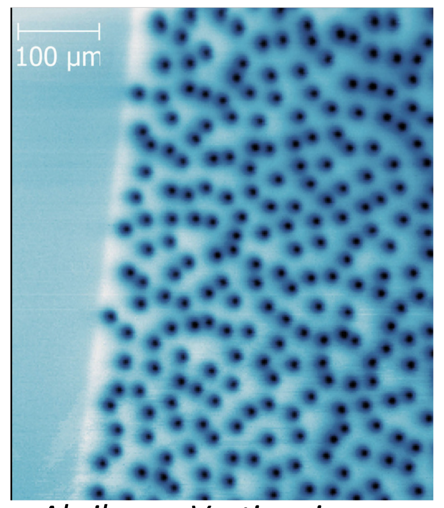
Contact: Samuel Warren- samuel.warren@yale.edu

Improving Current Density Analysis

The mass production of superconducting wires and tapes will require the ability to produce:

- Kilometers of superconducting material
- Microscopic structures which generate superconductivity

However, the 4-probe method that is traditionally used to measure superconductors' performance has no spatial resolution



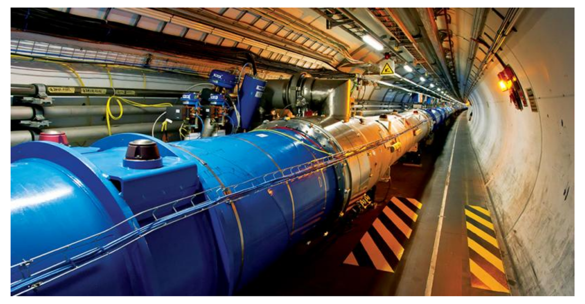
Abrikosov Vortices in a Type-II Superconductor[1]

Hall probe microscopy can rapidly provide high resolution critical current density (J_c) distribution images and data for large samples of superconducting material to allow for the identification of performance limiting obstacles

Current Technologies

The 4-probe method can provide a measurement of the transport J_c

- This is a measurement of the maximum current density between two points
- This measurement cannot determine the location between those two points where the current is limited



36000 Tons of NbTi wire are used in the Large Hadron Collider at CERN[2]

Niobium Titanium is one of the most widely used superconducting materials:

- However, there is still room to increase its critical current (I_c) by optimizing processing
- Internal current distribution data can be used to identify the current limiting or enhancing mechanisms

Microscopy Designed Around Basic Physics

Hall Probe Microscopy relies on two basic physics concepts:

- The Hall Effect
- Magnetic Induction

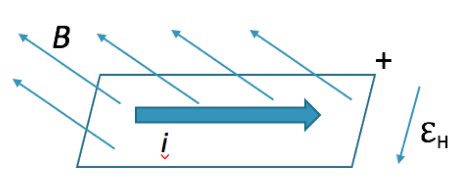
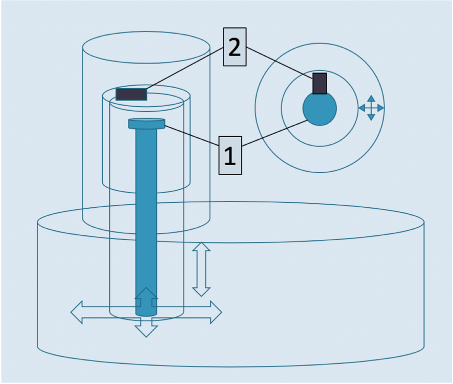


Illustration of the Hall Effect



1. Sample Table; 2. Hall Probe

Using the Hall Probe allows for instantaneous collection of magnetic field data

Large changes in the external magnetic field guarantees that the measured current is the critical current

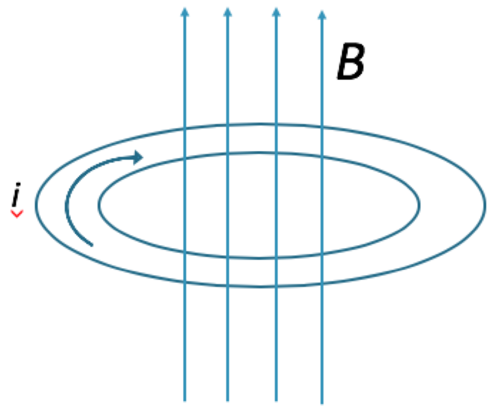


Illustration of current induction

Biot-Savart Law: J→B[3,4]

$$B_z(r) = \frac{\mu_0}{4\pi}\int_{-d/2}^{d/2}\iint_{-\infty}^{\infty}\frac{J_x(x',y',z')(y-y')-(x-x')J_y(x',y',z')}{[(x-x')^2+(y-y')^2+(z-z')^2]^{3/2}}dx'dy'dz'$$

Using Convolution Theorem

$$b_z(k_x,k_y,z) = \int_{-d/2}^{d/2} i\frac{\mu_0}{2}e^{-k(z-z')}\left(\frac{k_y}{k}j_x(k_x,k_y) - \frac{k_x}{k}j_y(k_x,k_y)\right)dz'$$

Inverse Biot-Savart Problem: B→J

$$j_x(k_x,k_y,z) = -\frac{2i}{\mu_0}\frac{e^{kz}}{1-e^{-kd}}k_y b_z(k_x,k_y,z)$$

$$j_y(k_x,k_y,z) = \frac{2i}{\mu_0}\frac{e^{kz}}{1-e^{-kd}}k_x b_z(k_x,k_y,z)$$

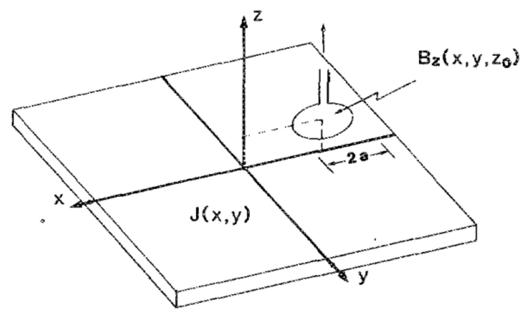
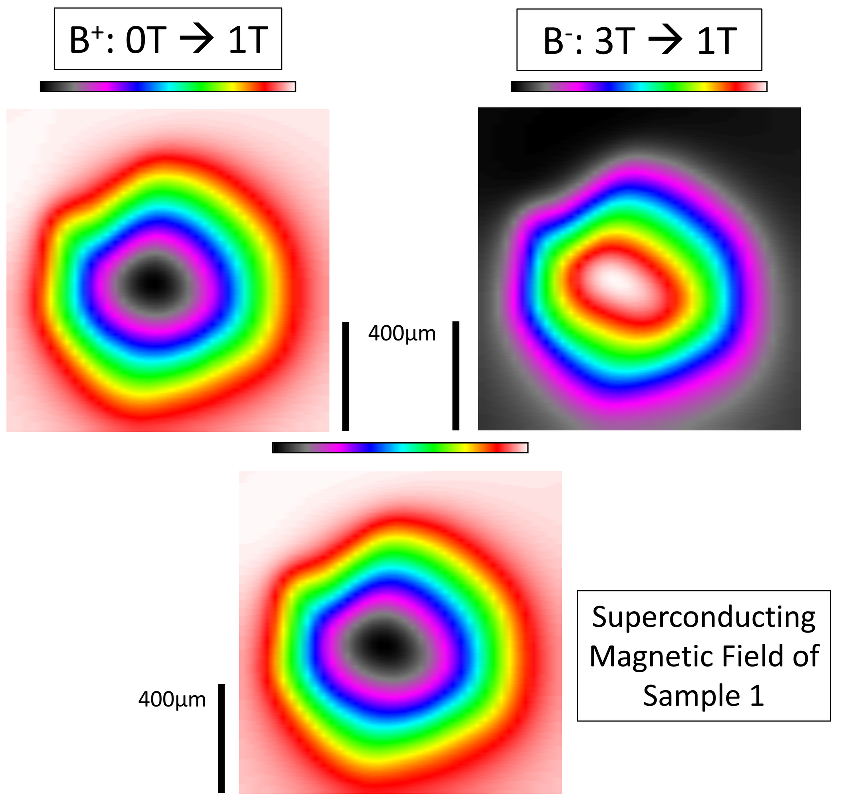


Illustration of scanning a superconducting sample

Measured Magnetic Data and Analysis for NbTi Wire Samples



Superconducting Magnetic Field of Sample 1

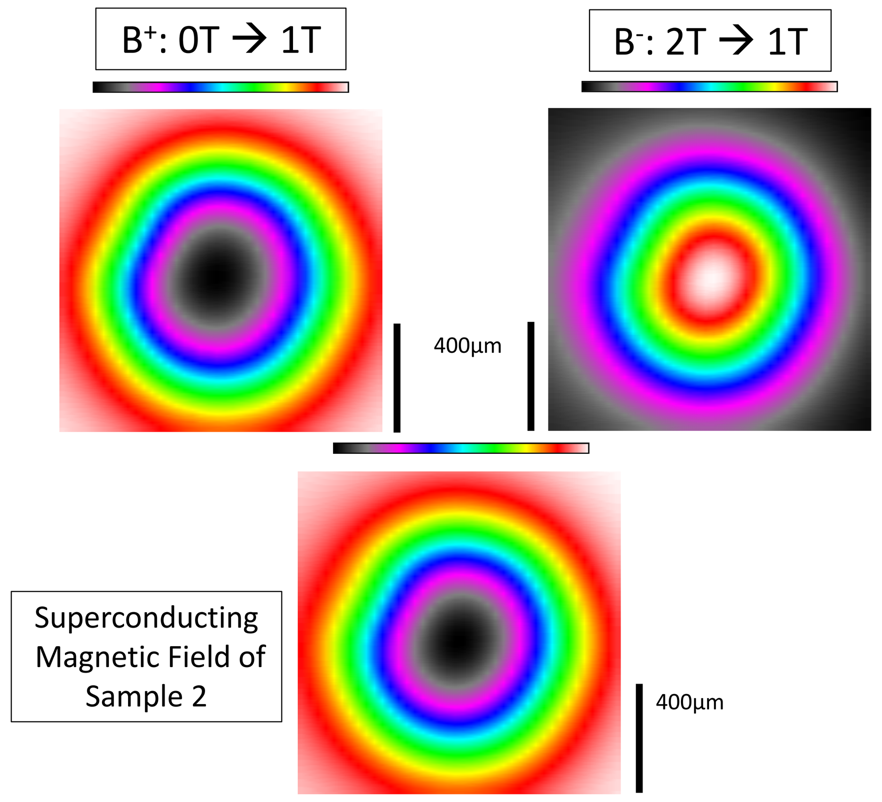
Magnetic Fields B_z For NbTi Wires

$B^+=B-B_s$

$B^-=B+B_s$

$$\frac{(B^- - B^+)}{2}=B_s$$

Resolution
dx=30μm
dy=4μm



Superconducting Magnetic Field of Sample 2

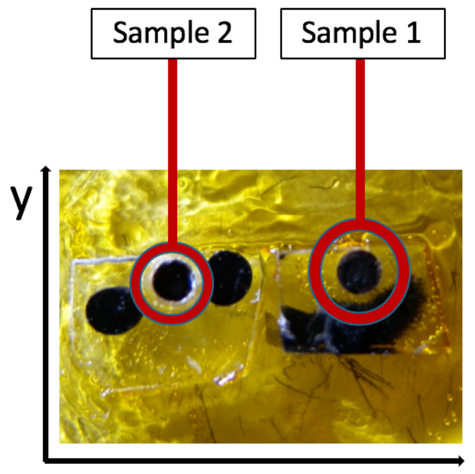
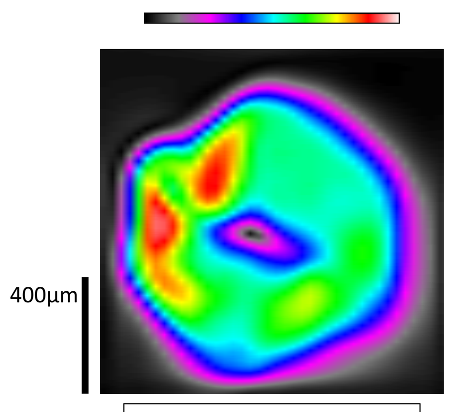


Image of NbTi Wire Samples

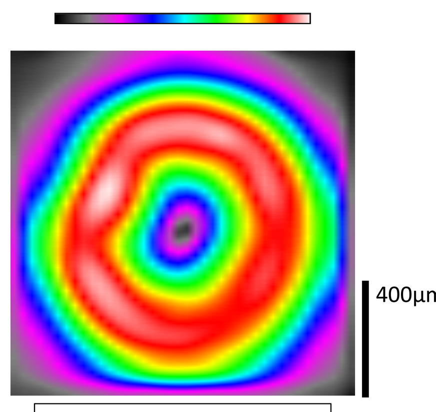
Current Distributions



Current Distribution of Sample 1

The magnetic data was analyzed using the solutions for the inverse Biot-Savart Problem

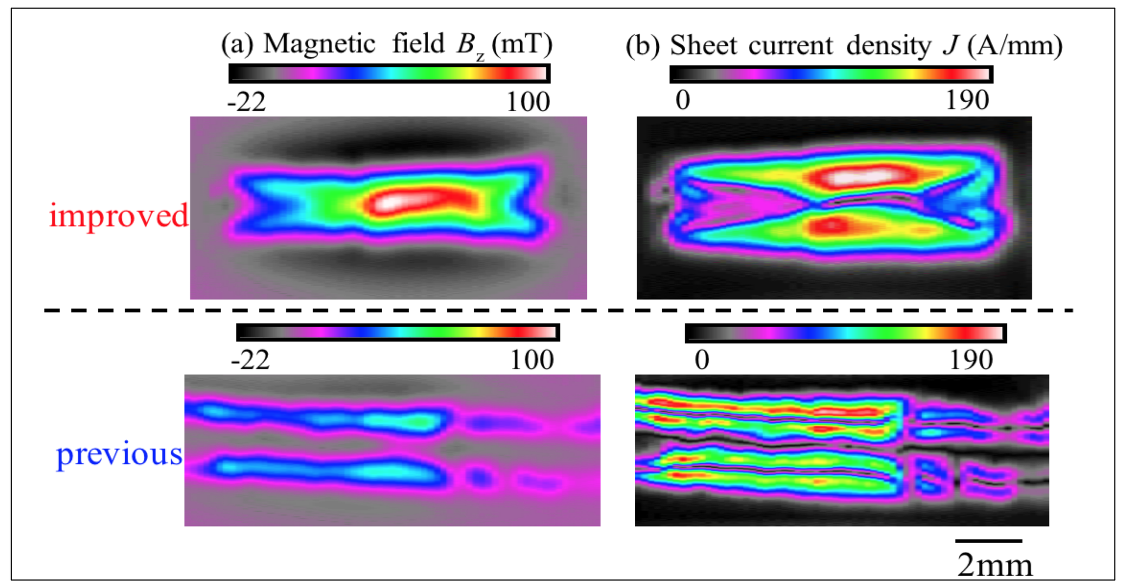
Sample 1	Sample 2
• A non-uniform J_c distribution • SEM analysis can be done on edges of high J_c regions	• Very uniform J_c distribution • Large region of high J_c



Current Distribution of Sample 2

Conclusion

- Scanning Hall Probe Microscopy (SHPM) provides high resolution J_c distribution images
- SHPM can analyze large areas rapidly
- SHPM images can be used to further our understanding of the material properties of superconductors
- SHPM images can be used to improve the manufacturing processes of superconducting tapes and wires



Current distributions for Ba/K doped Iron Arsenide samples before and after the manufacturing process was changed due to the poor quality of the former results.[5]

References

1. Image from F.S.; Pan, A.V.; Wang, X.R.; Fedoseev, S.A.; Hilgenkamp, H. *Scientific Reports*. "Analysis of low-field isotropic vortex glass containing vortex groups in $YBa_2Cu_3O_{7-x}$ thin film visualized by scanning SQUID microscopy." 5, 8677, 2015.
2. Image from CERN, https://home.cern
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5. Wu, Z.;Warren, S.;Higashikawa, K.; Huang, H.; Yao, C.; Ma, Y.; Kiss, T. "Local Characteristic of Ag Sheath (Ba, K)Fe_2As_2 Tape Fabricated by Hot-press Process Based on In-field Magnetic Microscopy," The 79th JSAP Autumn Meeting, Sept. 18-21, 2018, to be presented

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