

From Weak Links to Quantum Coherence:
A Focused Ion Beam Perspective on
Superconducting Tunneling Phenomena

Jay LeFebvre

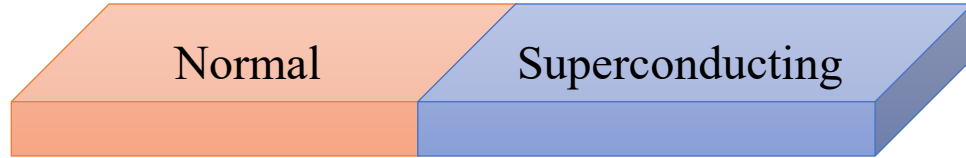
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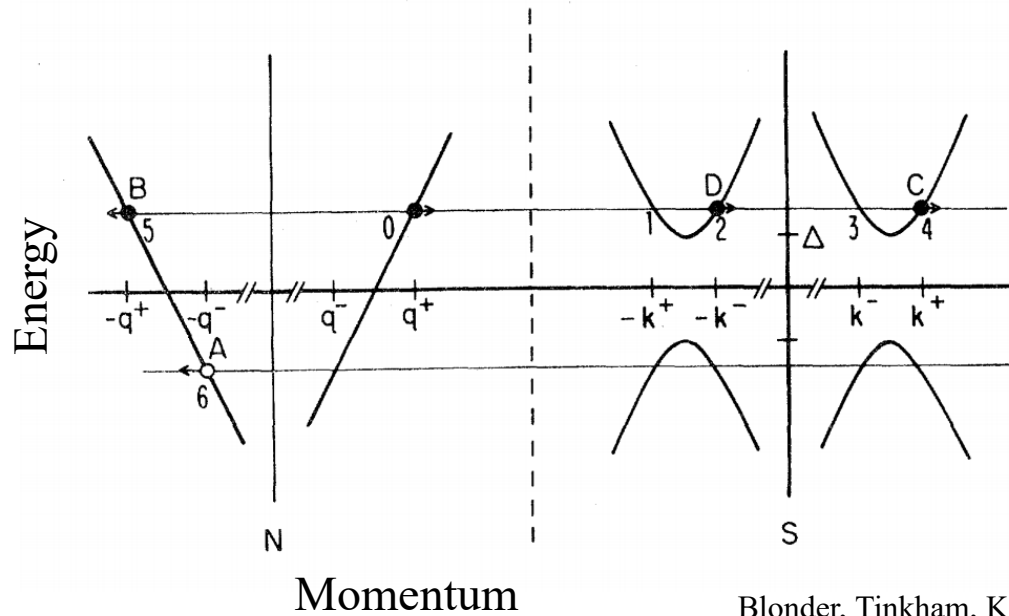
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- Tunneling in Superconducting Junctions
 - Quasiparticle Tunneling
 - Josephson Effect
- Focused Ion Beam Junctions in Cuprates
- Superconducting Analysis via Focused Ion Beam Microscopy
- Summary

Quasiparticle Tunneling in Normal-Superconducting Junctions



Z defined as barrier height
or resistivity in the normal state

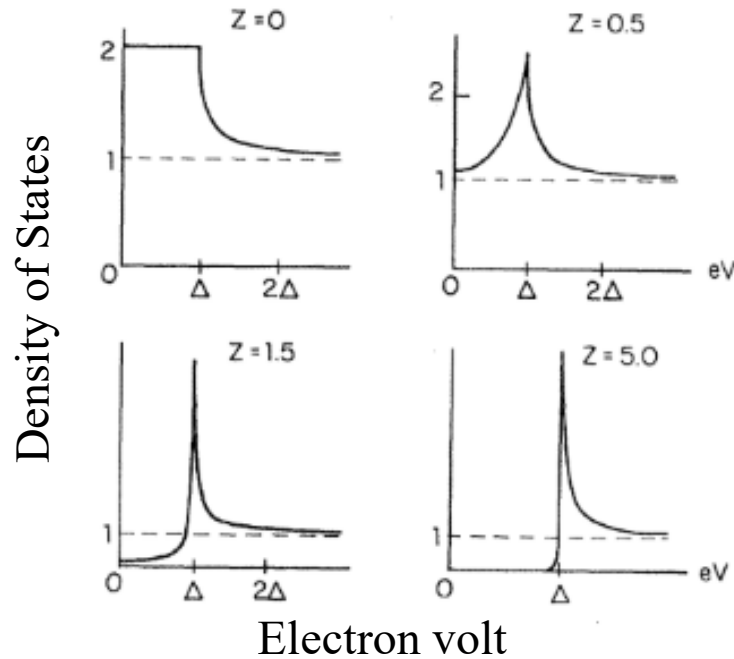
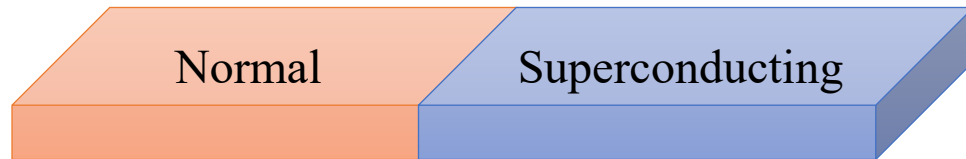


Possible quasiparticle tunneling events:

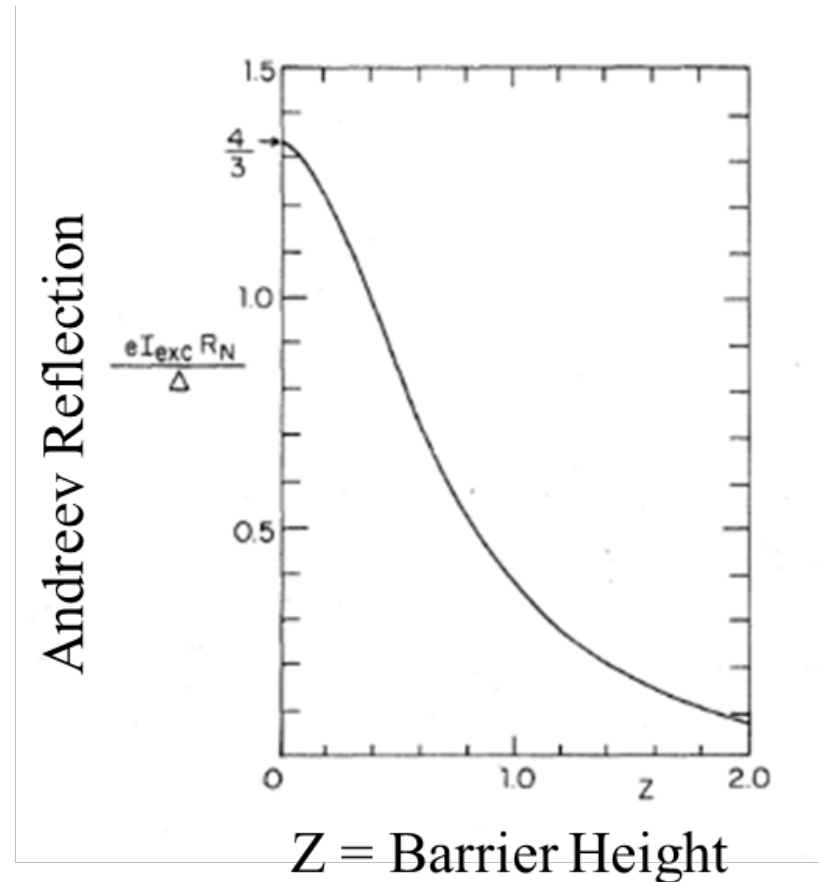
	Tunneling Type	Example
A	Andreev Reflection	$q^+ \rightarrow -q + k^+$
B	Ordinary reflection	$q^+ \rightarrow -q^+$
C	Ordinary Transmission	$q^+ \rightarrow k^+$
D	Transmission across Fermi surface	$q^+ \rightarrow -k^-$

Blonder, Tinkham, Klapwijk. "Transition from metallic to tunneling regimes in superconducting microconstrictions: Excess current, charge imbalance, and supercurrent conversion." *Physical Review B* 25.7 (1982): 4515.

Quasiparticle Tunneling in Normal-Superconducting Junctions

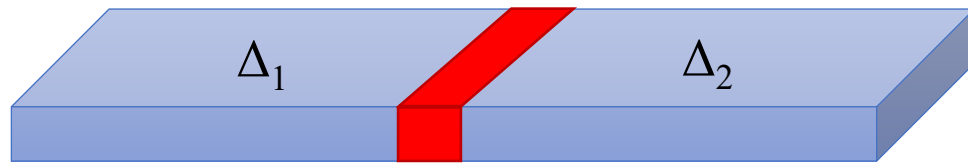


For $T=0$

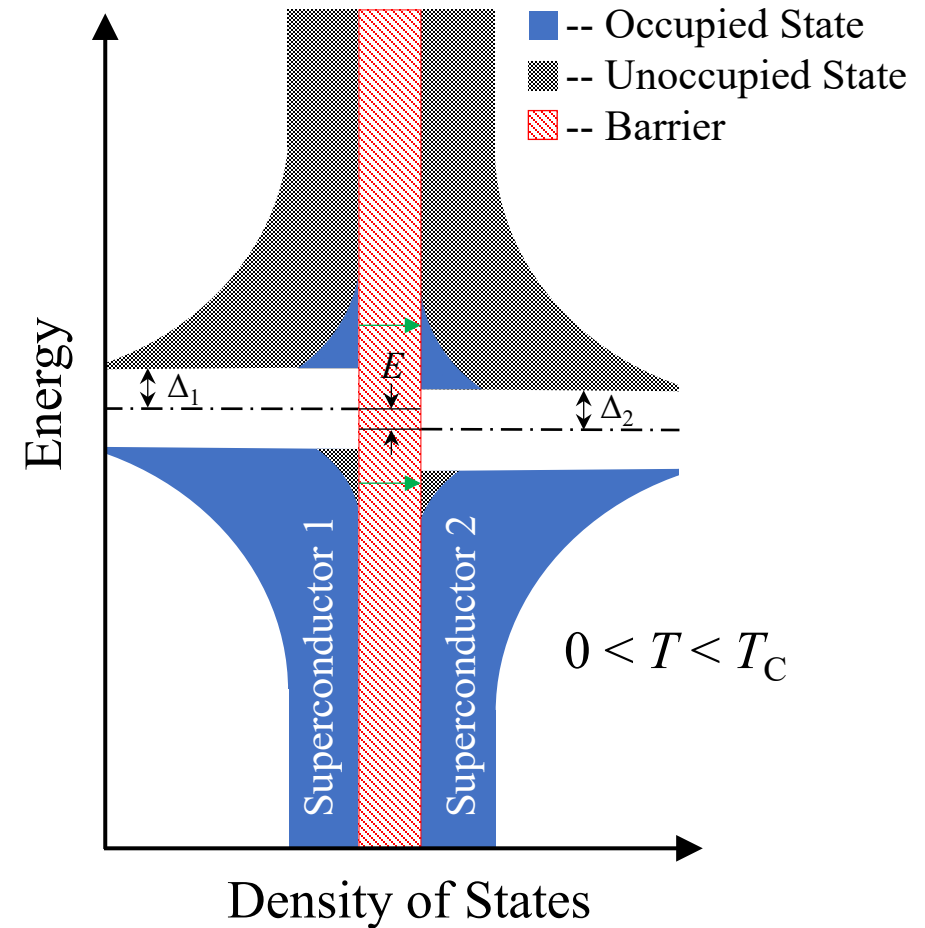
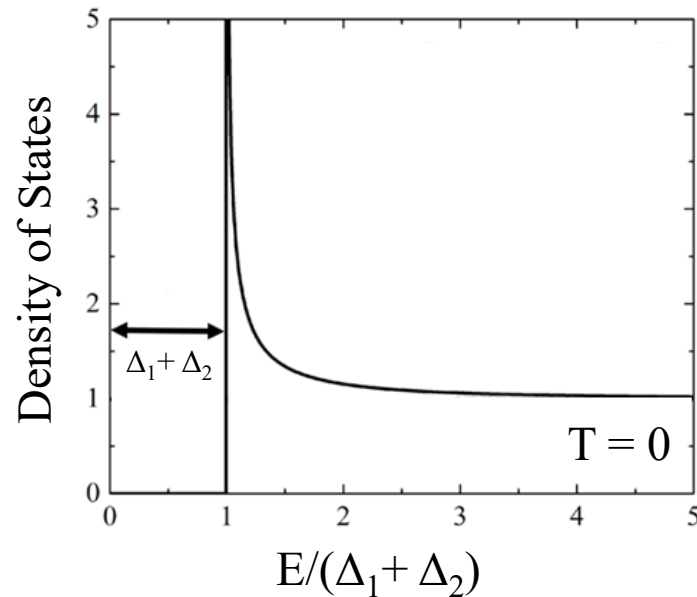


Blonder, Tinkham, Klapwijk. "Transition from metallic to tunneling regimes in superconducting microconstrictions: Excess current, charge imbalance, and supercurrent conversion." *Physical Review B* 25.7 (1982): 4515.

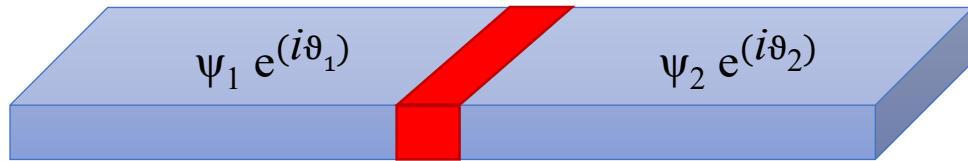
Quasiparticle Tunneling in Superconducting Junctions



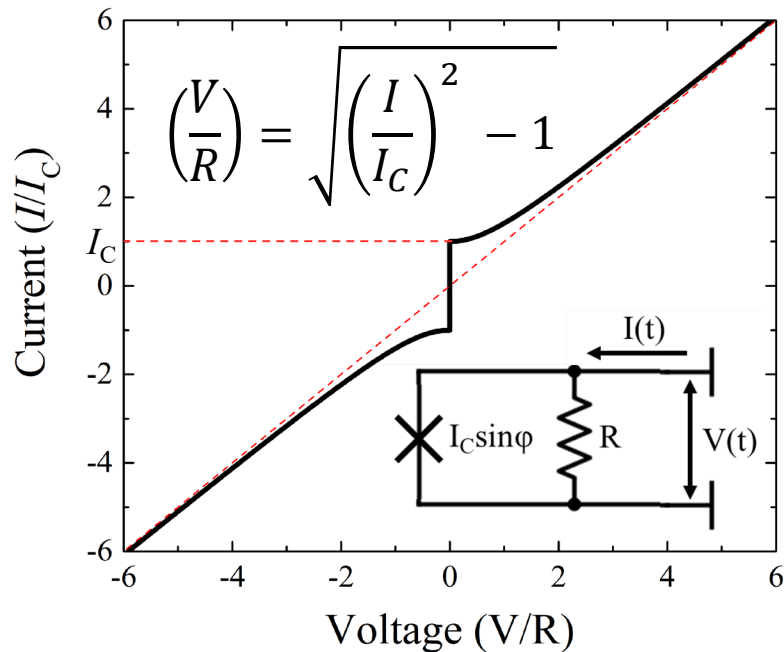
Superconductor – Barrier – Superconductor



Josephson Tunneling



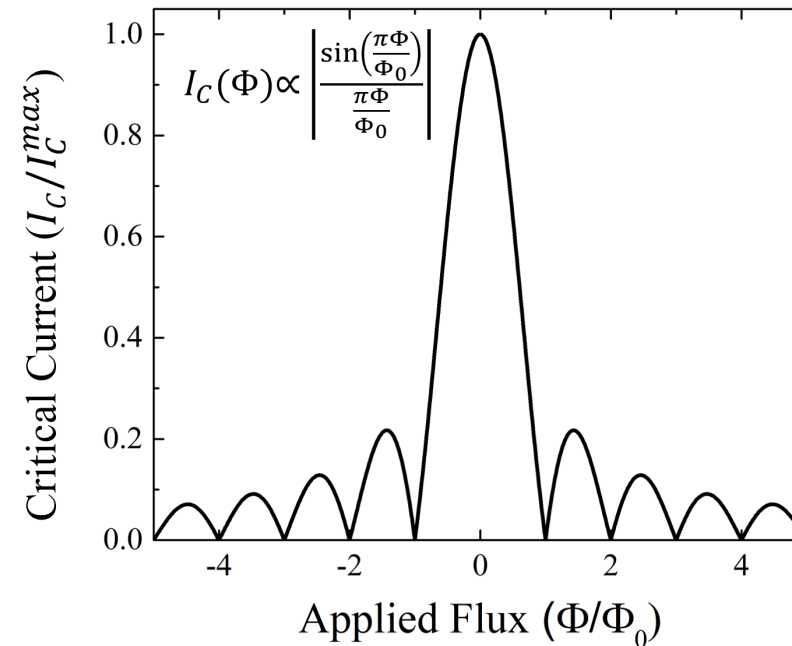
Superconductor – Barrier – Superconductor



Josephson Equations:

$$I = I_C \sin \varphi \quad V = \frac{\hbar}{2e} \frac{\partial \varphi}{\partial t}$$

$$\varphi \equiv \vartheta_1 - \vartheta_2$$

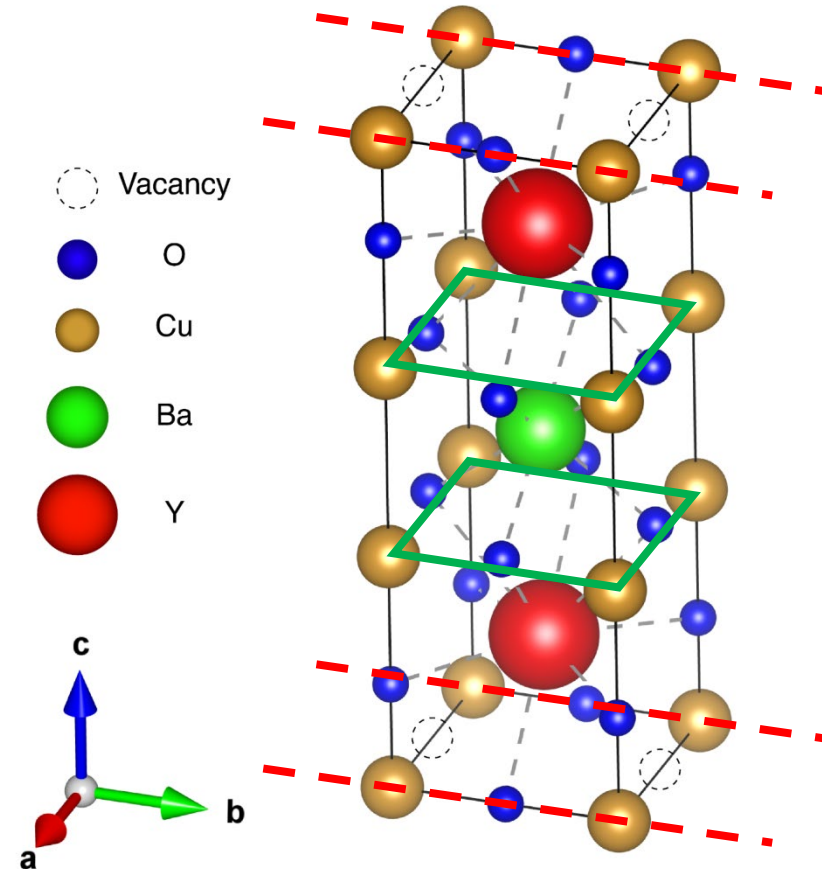


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- Tunneling in Superconducting Junctions
- Focused Ion Beam Junctions in Cuprates
 - YBCO
 - Focused Ion Beam (FIB) Microscopy
 - FIB Fabricated Junctions
- Superconducting Analysis via Focused Ion Beam Microscopy
- Summary

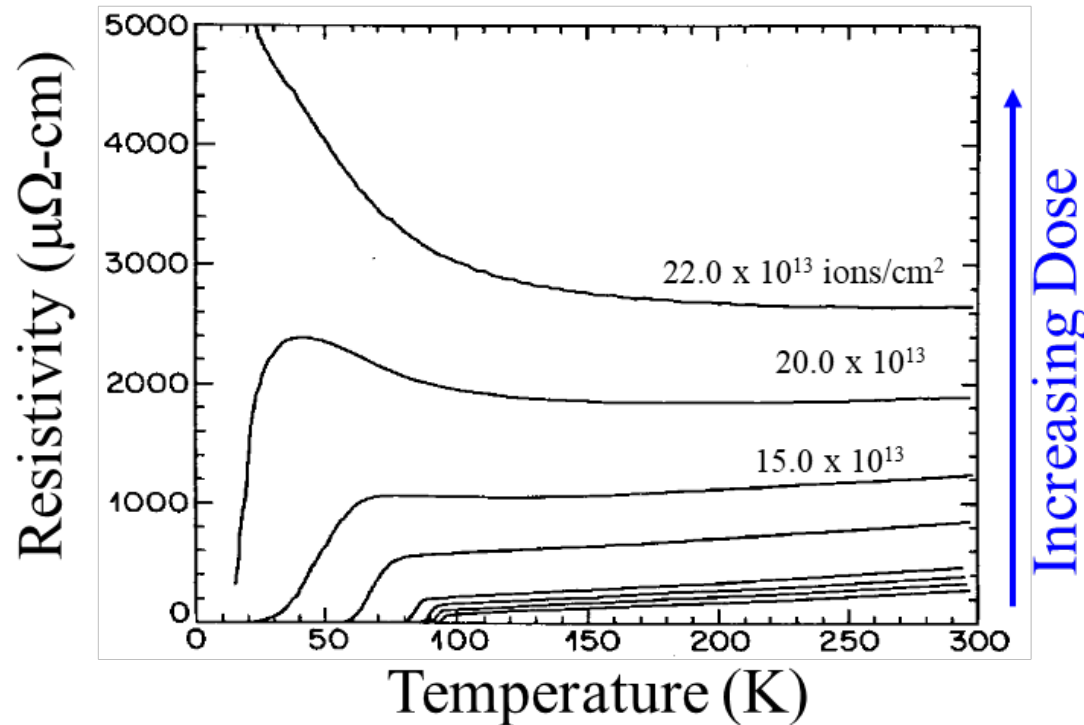
Yttrium Barium Copper Oxide (YBCO)

- Orthorhombic perovskite unit cell
- Ceramic material
- Anisotropic resistivity:
 - $\rho_a \approx 2\rho_b$
 - $\rho_c > 10 \rho_b$
- Anisotropic critical current density:
 - $j_c^a > j_c^b$
- Anisotropic Penetration Depth:
 - $\lambda_a > \lambda_b$

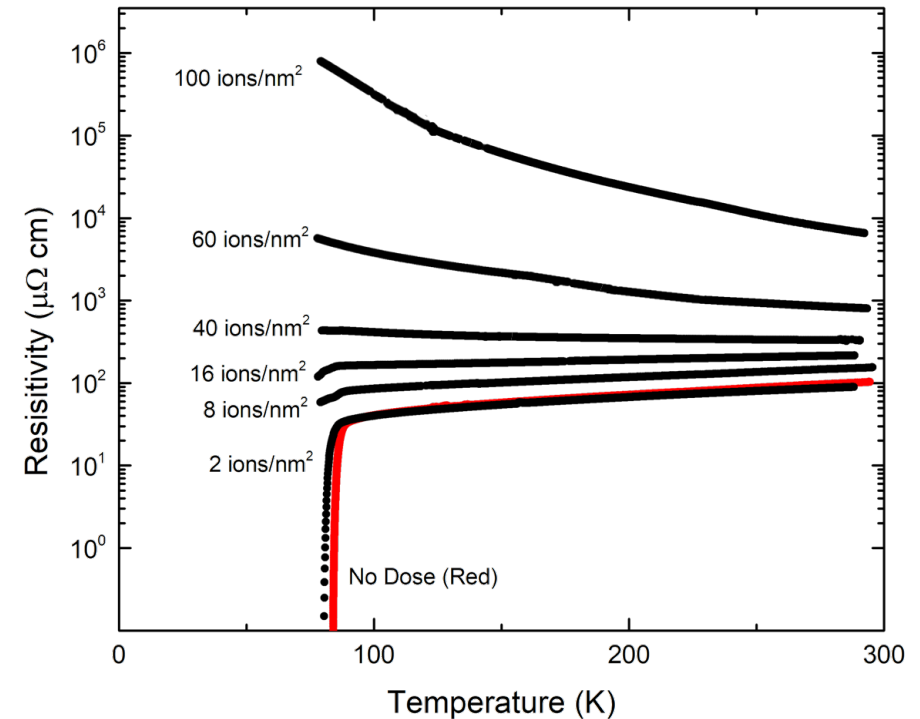


Ion Irradiation Effect on YBCO

1 MeV Ne⁺ Ions,
(0.0, 0.1, 2.5, 4.0, 10, 15, 20, 22 x 10¹³ ions/cm²)

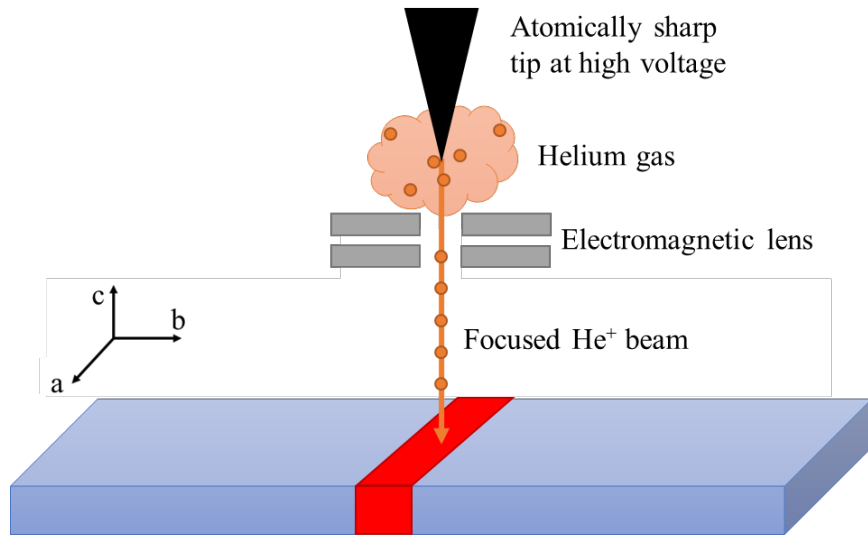


35 keV He⁺ Ions,
(0.0, 2.0, 8.0, 16, 40, 60, 100 x 10¹⁴ ions/cm²)

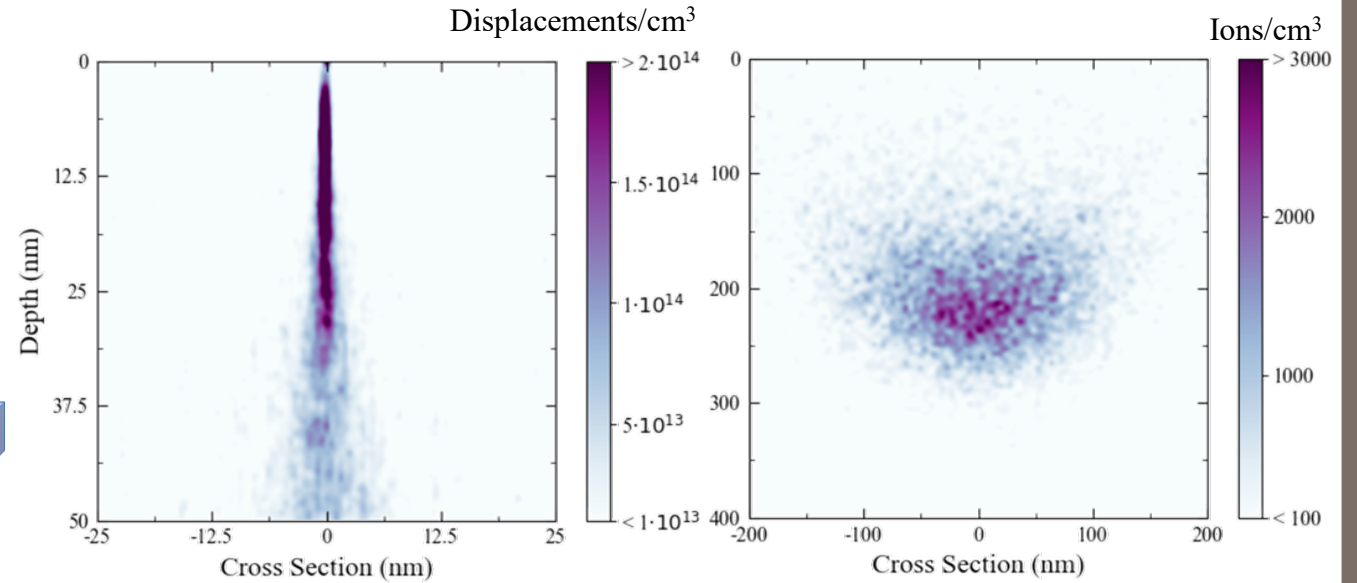


Valles Jr, J. M., et al. "Ion-beam-induced metal-insulator transition in YBa₂Cu₃O_{7- δ} : A mobility edge." *Physical Review B* 39, no. 16 (1989): 11599.

Focused Helium Ion Microscope

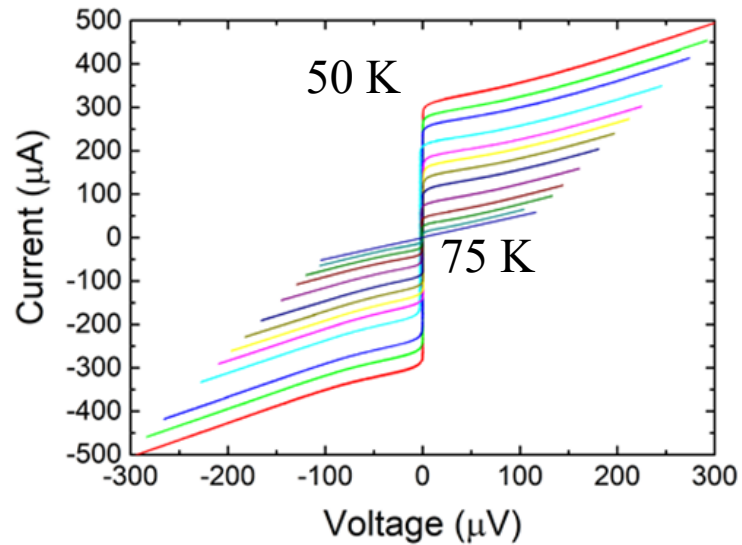


Superconductor – Ion Irradiated – Superconductor



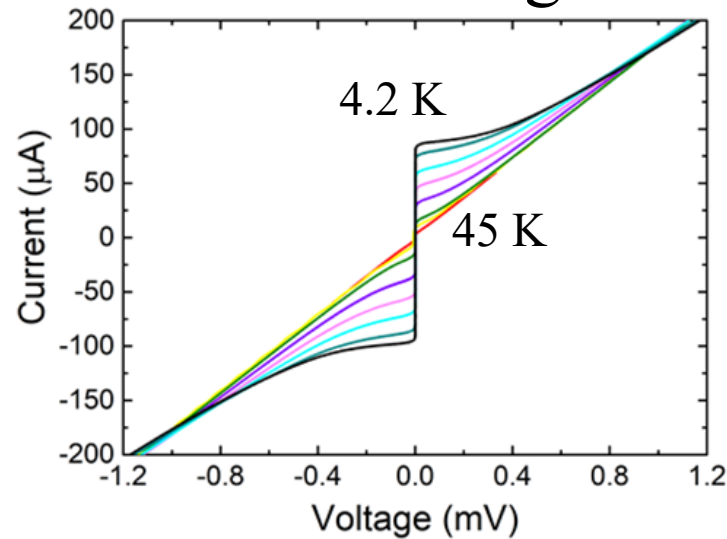
Metal to Insulator Transition in Josephson Junctions

S-Metal-S



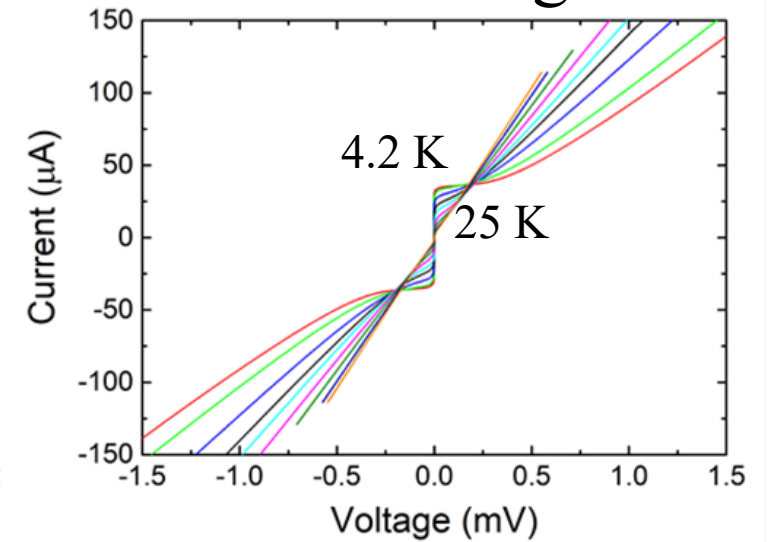
-64% change in R
over 25 K

S-Tunneling-S



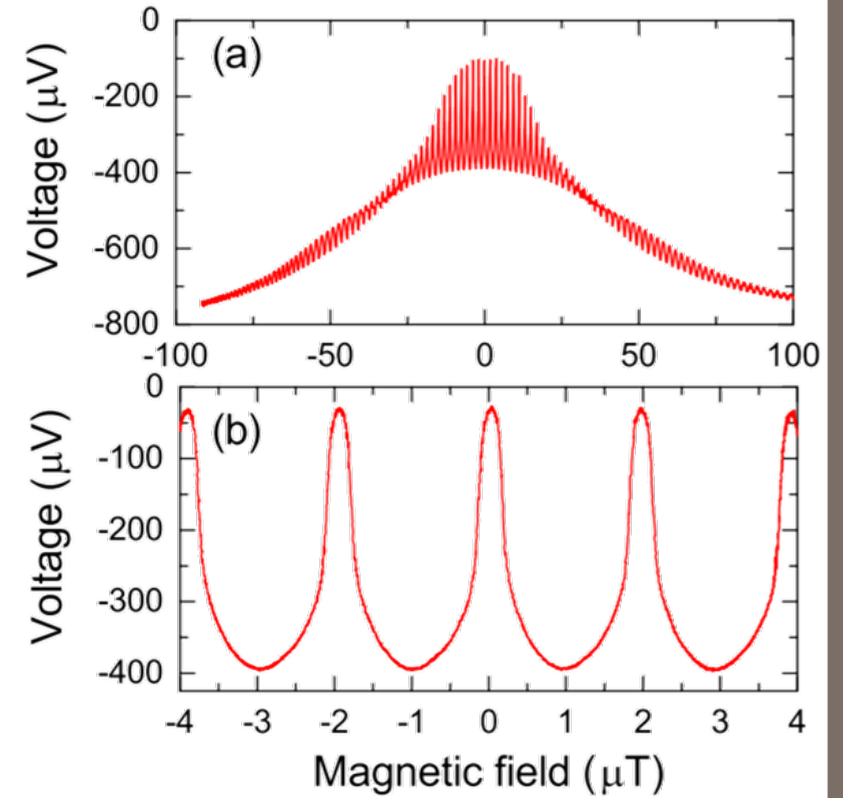
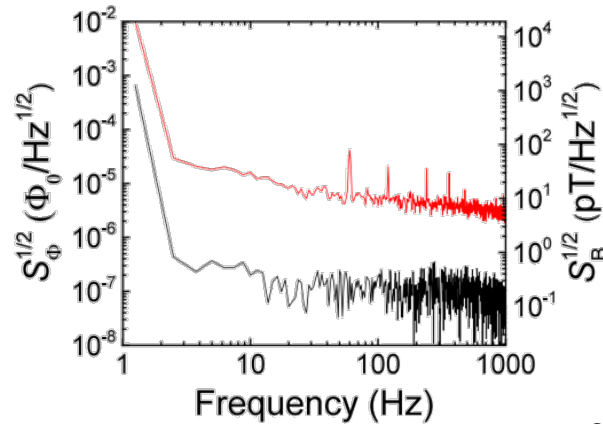
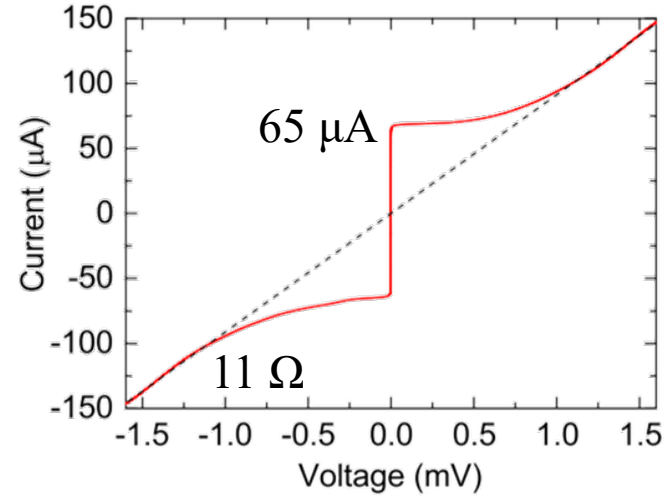
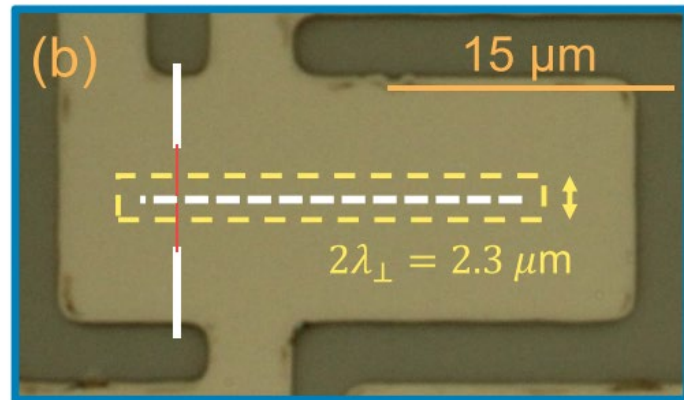
6.7% change in R
over 25 K

S-Insulating-S



50% change in R
over 20 K

Direct-inject Washer NanoSlit SQUID

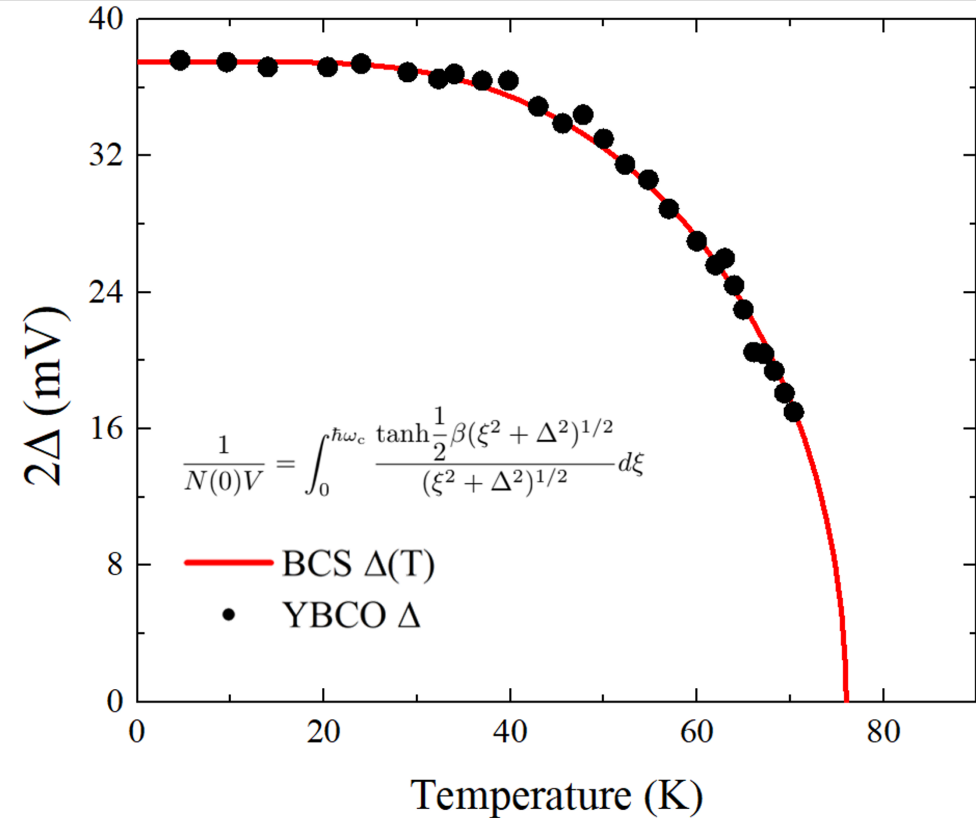
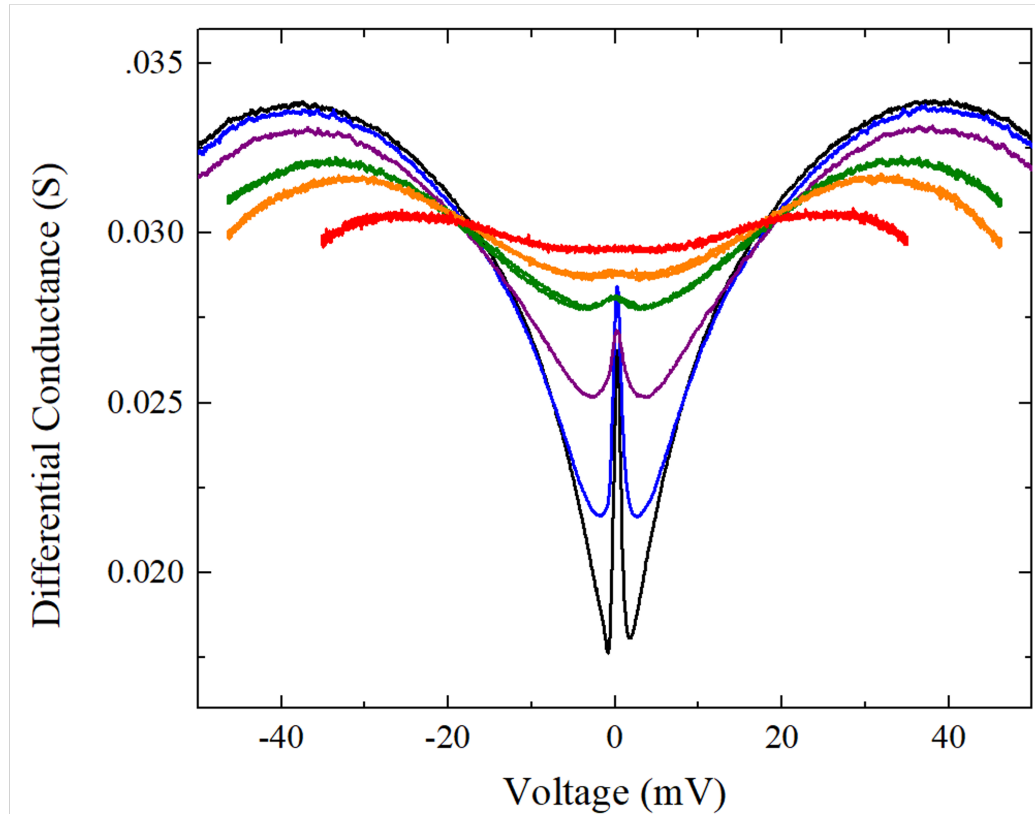


Cho, Ethan Y., et al. "Direct-coupled micro-magnetometer with Y-Ba-Cu-O nano-slit SQUID fabricated with a focused helium ion beam." *Applied physics letters* 113.16 (2018): 162602.

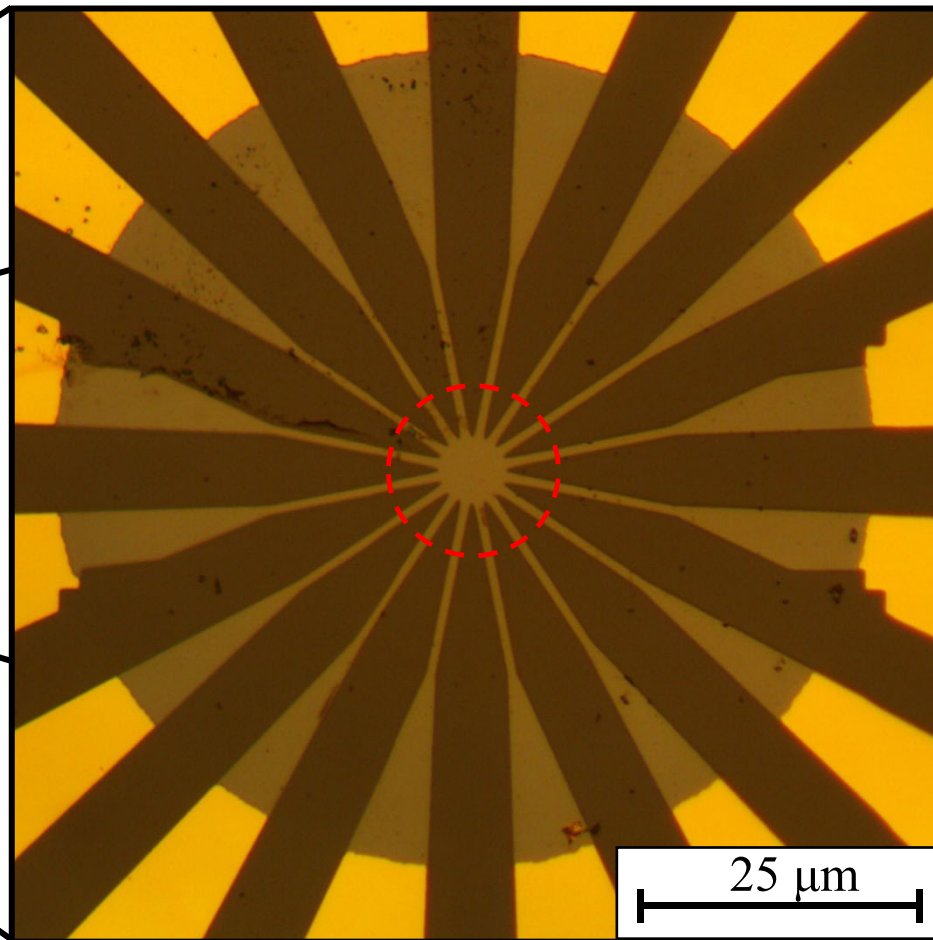
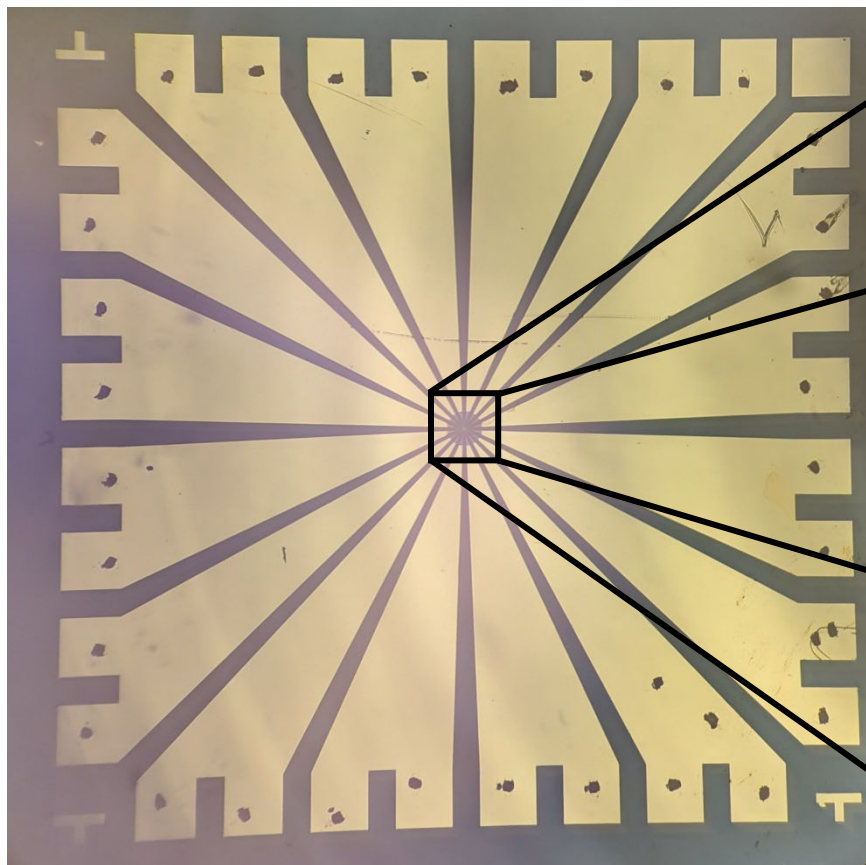
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- Tunneling in Superconducting Junctions
- Focused Ion Beam Junctions in Cuprates
- **Superconducting Analysis via Focused Ion Beam Microscopy**
 - **Determine Superconducting Order Parameter**
 - **Qualify Order Parameter Anisotropy**
- Summary

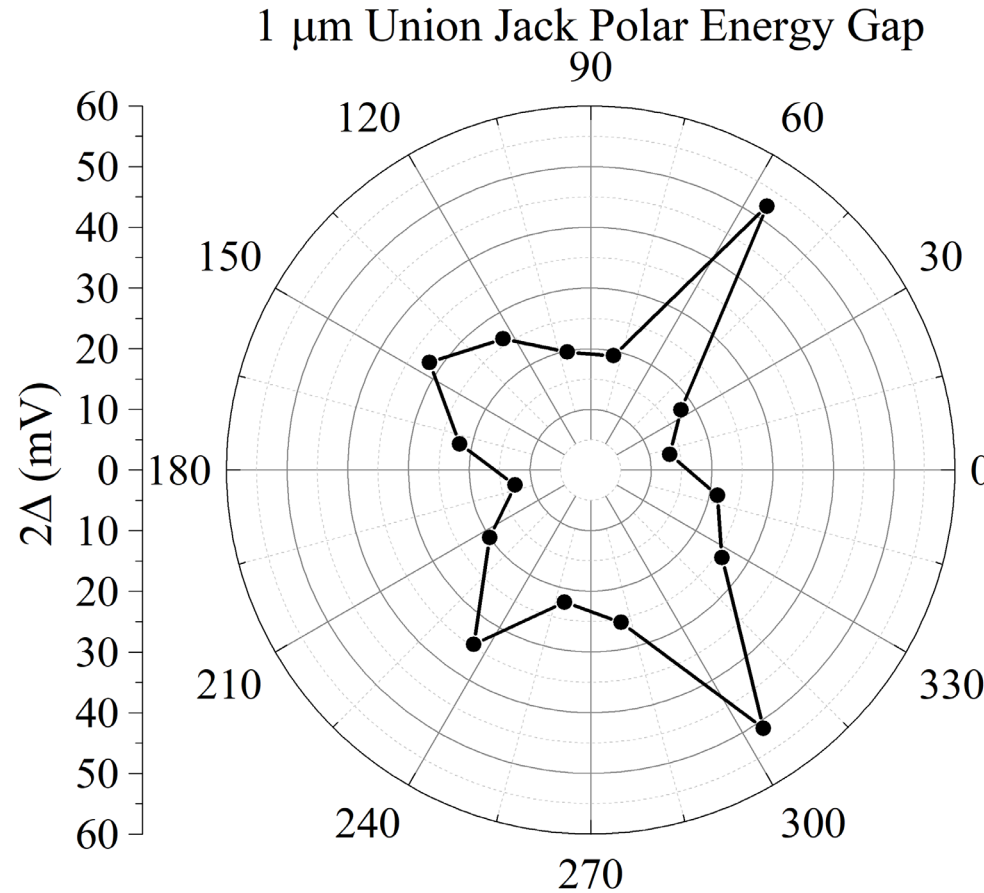
Order Parameter Measurement



- -- Indicates irradiated lines
- -- Gold ■ -- YBCO ■ -- Substrate



Angular Dependence Measurement



$$G \equiv \Delta / (K_B T_C)$$

$$G_{\text{BCS}} = 1.8$$

4 μm :

$$\Delta_{\text{avg}} = 24.5 \pm 2.3 \text{ mV}$$

$$G_{4 \mu\text{m}} = 3.5$$

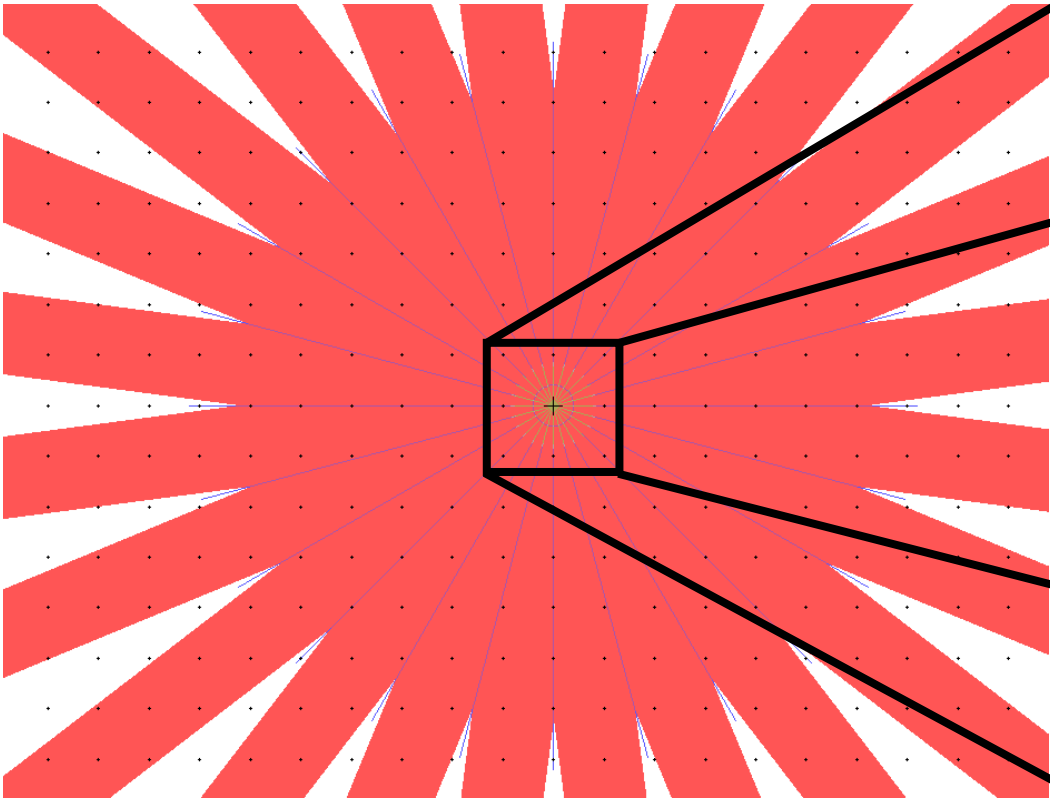
1 μm :

$$\text{Avg}_{1 \mu\text{m}} = 13 \pm 4.2 \text{ mV}$$

$$G_{1 \mu\text{m}} = 2.2$$

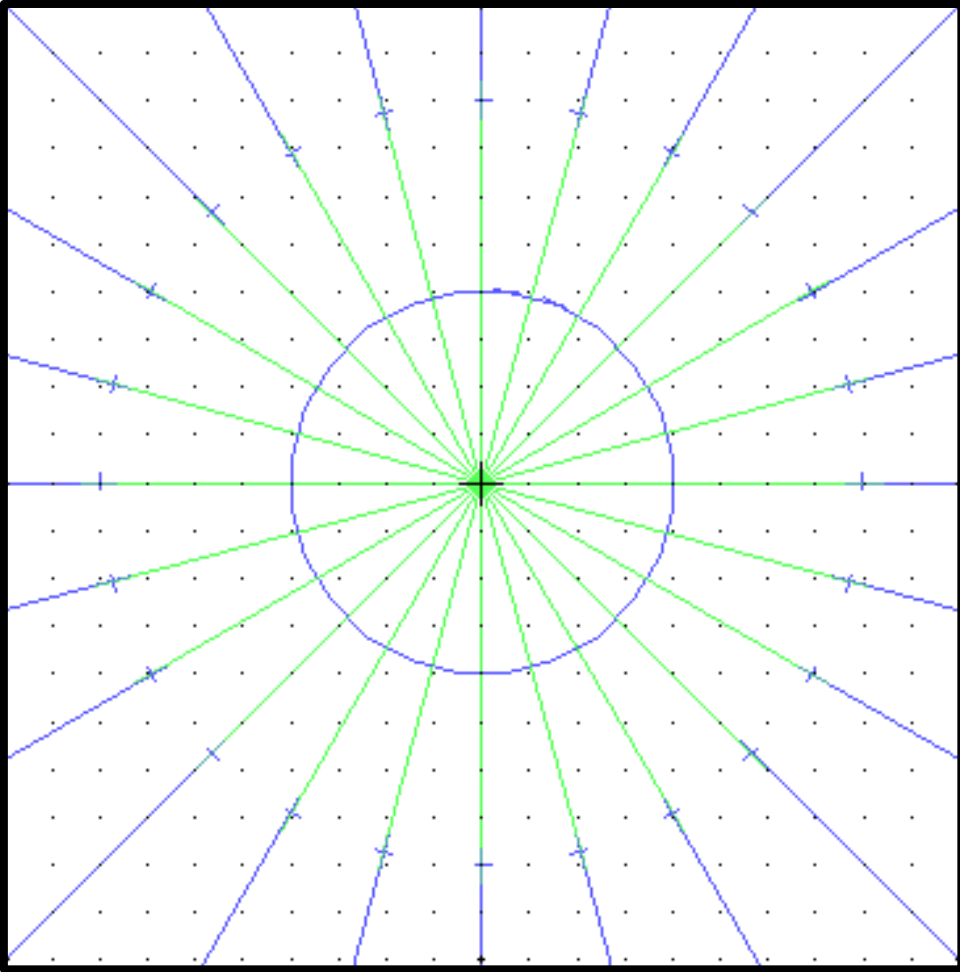
Device Geometry

■ - YBCO

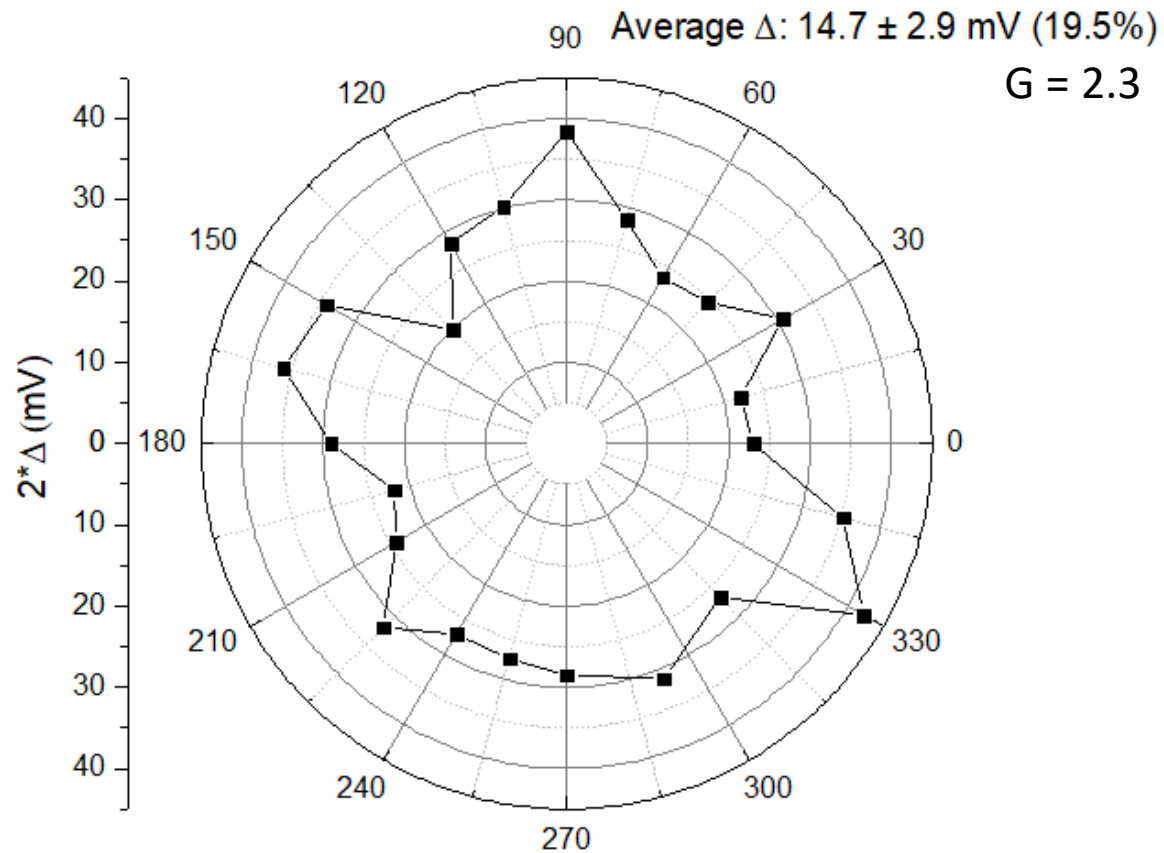


■ - Insulating Dose

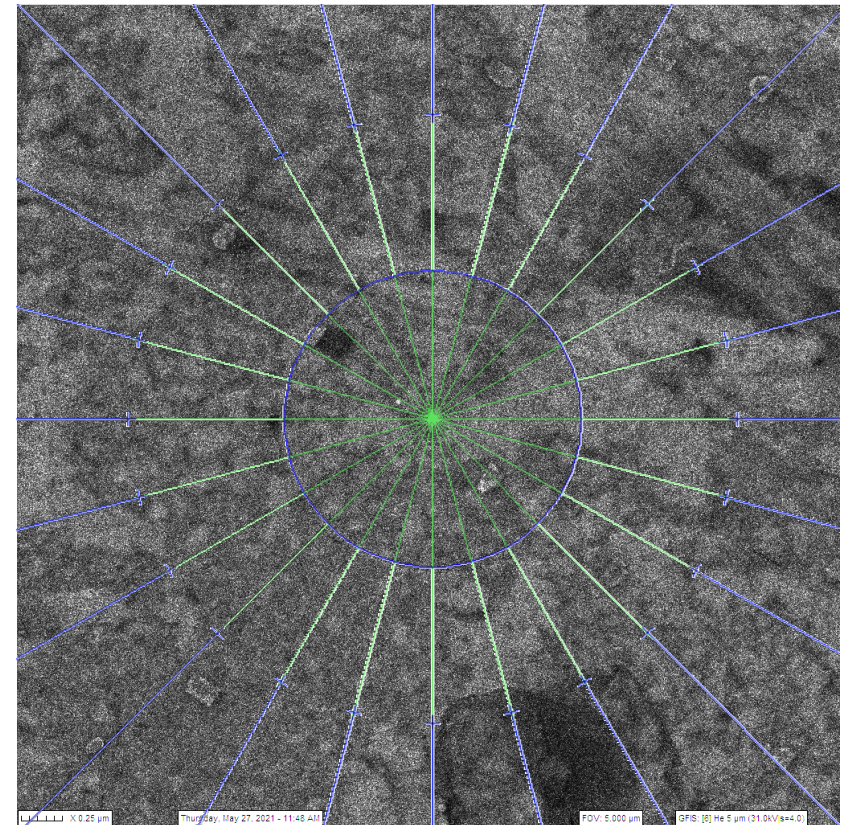
■ - Junction Dose



Angular Dependence Measurement



 - Insulating Dose  - Junction Dose

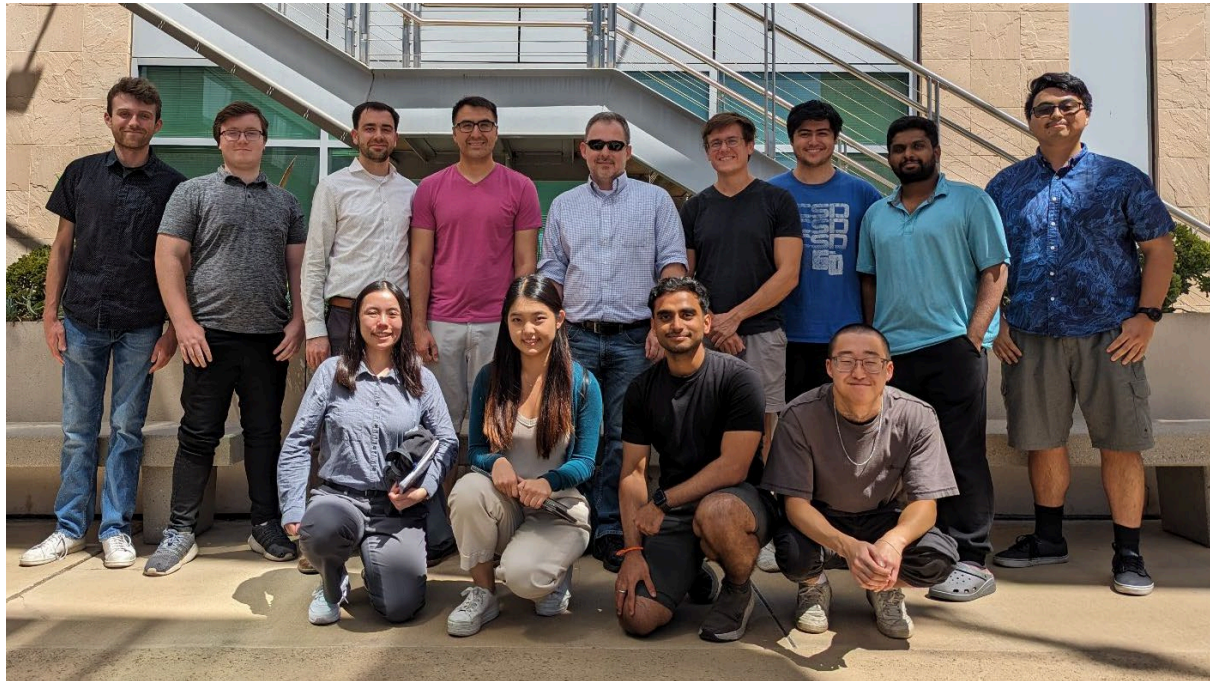


1 μ m

Summary

- Direct write interfaceless junctions with in-plane in cuprate superconductors
- Junction parameters can be tuned with ion fluence
- Measured an in plane superconducting order parameter in YBCO
 - Roughly factor of 2 difference in magnitude with node-like symmetry
- Can use this focused He ion beam fabricated junctions for superconducting tunnel analysis

Acknowledgements



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Graduate Students: Rochelle Qu, Josh Vande Berg, Sreekar Vattipalli, Adam Miller, Joseph Barrera, Nicole Chin, Adhilsha Parachikunnumal, Alex Brooks, Austin Langrehr



Relevant Publications

- LeFebvre, Jay C., Ethan Y. Cho, and Shane A. Cybart. "In-plane tunnel spectroscopy of cuprate superconductors with nano-scale Josephson junctions." *Applied Physics Letters* 123.11 (2023).
- LeFebvre, Jay C., Adhilsha Parachikunnumal, and Shane A. Cybart. "Nanofabrication of high transition temperature superconductive electronics with focused helium ion irradiation." *Journal of Vacuum Science & Technology B* 42.6 (2024).
- Cho, Ethan Y., et al. "Direct-coupled micro-magnetometer with Y-Ba-Cu-O nano-slit SQUID fabricated with a focused helium ion beam." *Applied physics letters* 113.16 (2018): 162602.
- Qu, Rochelle Y., et al. "Investigation of the Anisotropy of Y-Ba-Cu-O Thin Films With Photoemission Electron Microscopy." *IEEE Transactions on Applied Superconductivity* (2024).
- LeFebvre, Jay C., and Shane A. Cybart. "Large-Scale Focused Helium Ion Beam Lithography." *IEEE Transactions on Applied Superconductivity* 31.5 (2021): 1-4.