Steve Remillard
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Nonlinear Materials and Devices

Studies Using Superconductive Thin Films

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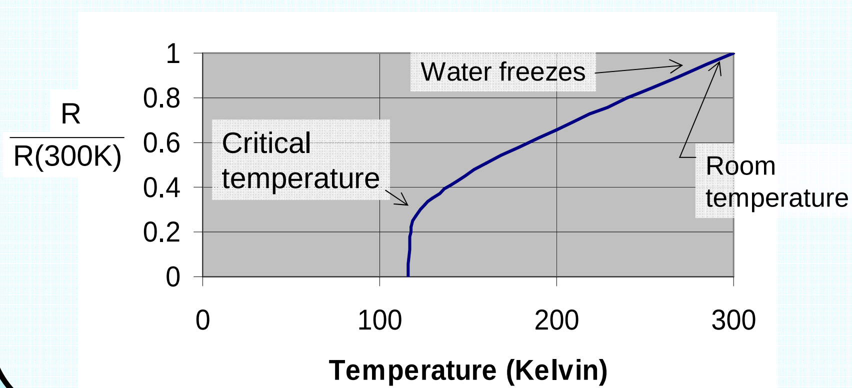
What is a Superconductor?

…Resistance suddenly drops to zero below a certain temperature called the C*ritical Temperature,* T_C.



Superconductors have zero resistance below the critical temperature.

Outline

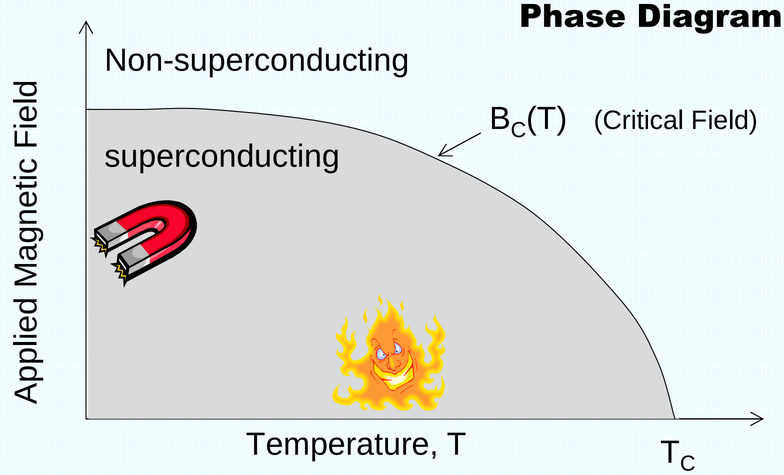
I. Every branch of physics is used in the description & study of superconductors

II. Fluxons: A thermal, magnetic and quantum conspiracy

III. Fluxons in superconductive devices: High frequency nonlinearities

Thermodynamics

Phase Diagram



Superconductivity occurs below T_C and B_C.

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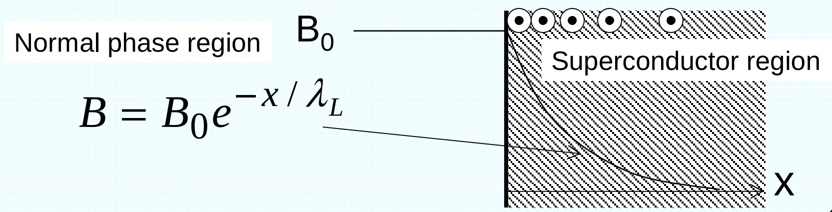
5

Electromagnetics

- Meissner Effect: Superconductors expel all B-field.
- Magnetic induction field only penetrates a short distance (London penetration depth, λ_L)



$$B = B_0 e^{-x/\lambda_L}$$

Magnetic field drops to zero in a superconductor.

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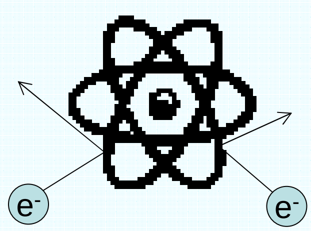
6

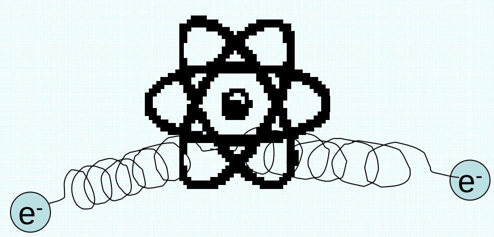
Quantum Mechanics

- 1956: Cooper postulated e^--e^- attraction via lattice vibrations called phonons.

Phonon scattering causes resistance in a normal metal.



If carriers pair up through phonons, then there is no scattering, ∴no resistance.



Cooper pairs, charge -2e and mass 2m, are lossless carriers.

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7

Classical Mechanics

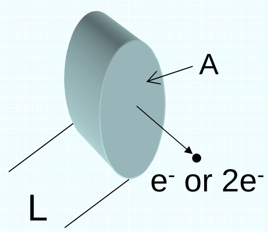
Derive the electrical conductivity.

Newton's 2nd law

$$F = ma = -eE - m\frac{v}{\tau}$$

Ohm's Law

$$\frac{I}{A} = \sigma E = -en_s v_s - en_n v_n$$



Use $E = E_0 e^{j\omega t}$ [$\omega = 2\pi f$]

$$\sigma = \sigma_n(T) + j\frac{1}{\omega\mu_0\lambda_L^2}$$

The AC electrical conductivity of a superconductor is finite.

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8

Part I Summary

1. Superconductivity occurs below T_C and B_C.
2. Superconductors expel magnetic fields, except within a region that drops off as λ_L.
3. Electrons form pairs in superconductors and can travel without meeting any resistance.
4. The resistance of a superconductor is not zero for AC current.

Outline

I. Every branch of physics is used in the description & study of superconductors

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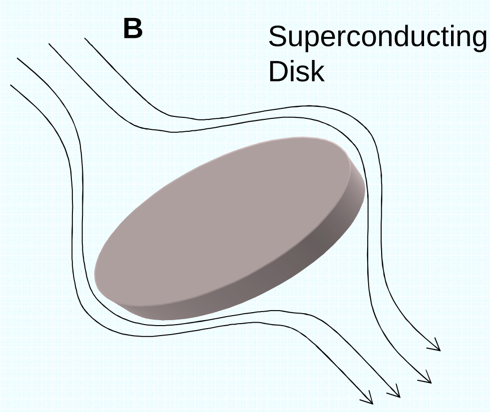
III. Fluxons in superconductive devices: High frequency nonlinearities

Type 2 Flux Entry

So you cannot have magnetic field inside of a superconductor.



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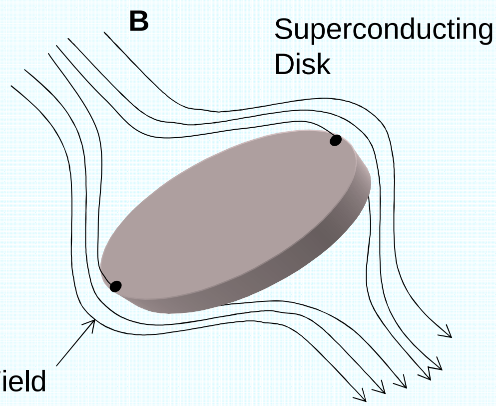
Type 2 Flux Entry

$B=B_C$ can occur at the edge even though the applied $B<B_C$



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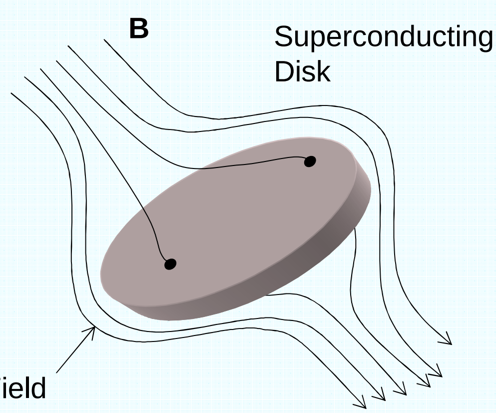

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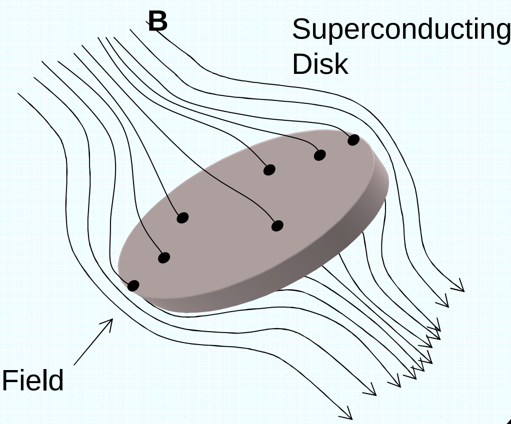

Magnetic field will enter the superconductor in bundles called “Fluxons”.

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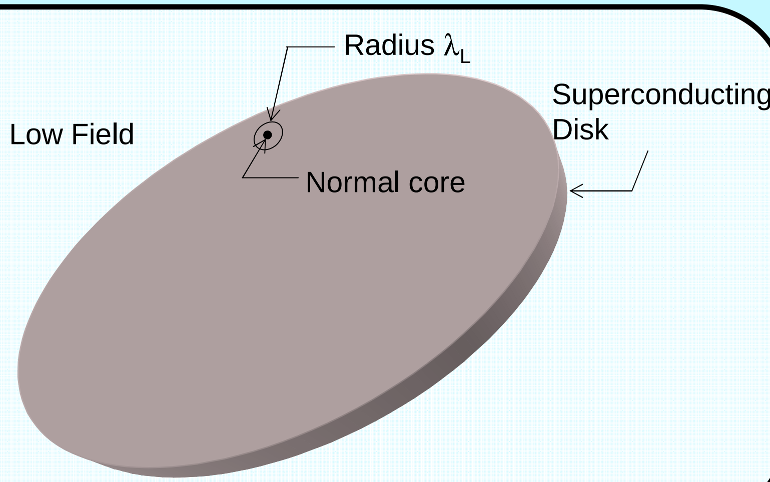
Anatomy of a Fluxon



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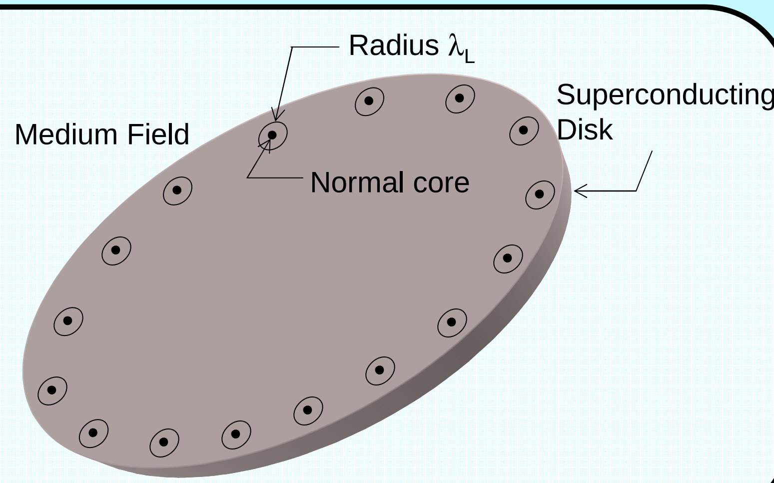

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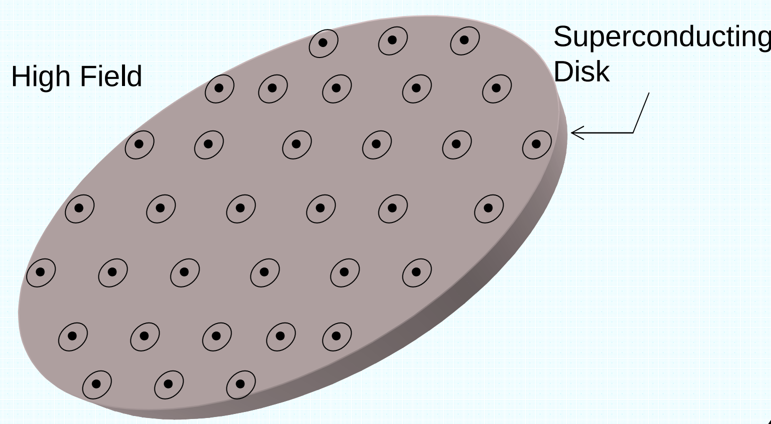
Anatomy of a Fluxon



A Fluxon is a “tube” of field with radius λ_L and a normal core.

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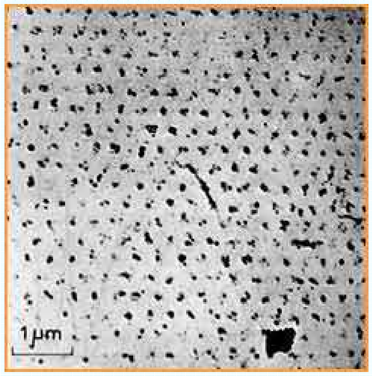
Flux Lattice

17

Observation



$$Flux = \iint \vec{B} \cdot \hat{n} dA = B \cdot \text{Area}$$

Magnetic field penetrates a superconductor in fluxons of quantity:
Φ=h/2e
=2.07x10^{-15} Weber.

U. Essmann and H. Traüble,
Physics Letters,
v. 24A, p.526, 1967.

Fluxons fill up a superconductor in high field.

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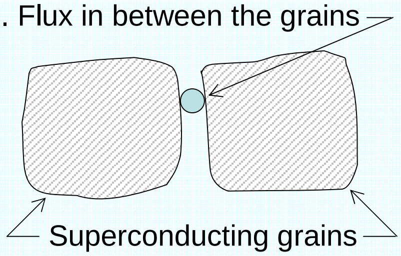
Fluxon Dissipation

18

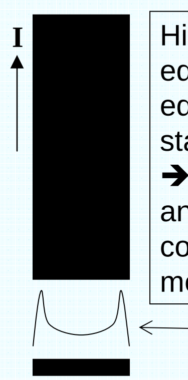
Two ways fluxons affect conductivity

1. Flux in between the grains



Reduces the ability of cooper pairs to tunnel across the boundary

2. Flux at the edge of the film



High current at the edge forces the edges out of the SC state.
➔Electrical width, and hence the conductance, is modulated.

The electrical conductivity changes in a magnetic field (or a current).

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19

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20

High Frequency What?

Ohm's Law $V = I \cdot R$ V is *linear* in current

"Nonlinear Ohm's Law" $V = I \cdot R(I)$ V is *nonlinear* in current

AC current: $I = I_0 \cos(\omega t)$

In the nonlinear case, V does not simply vary as $\cos(\omega t)$

Nonlinearity usually grows with frequency.
Microwave frequencies: 0.1-100 GHz.

Nonlinear materials have current dependent resistivity.

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Harmonic Distortion

21

Let's expand **V(I)** in a Taylor series

$$V(I) = V(0) + \left.\frac{dV}{dI}\right|_{I=0} I + \left.\frac{d^2V}{dI^2}\right|_{I=0} \frac{I^2}{2!} + \cdots$$

Use $I = I_0 \cos(\omega t)$ for the current:

$$V(I) = V(0) + \left.\frac{dV}{dI}\right|_{I=0} I_0 \cos\omega t + \frac{1}{2}\left.\frac{d^2V}{dI^2}\right|_{I=0} I_0^2 \cos^2\omega t + \cdots$$

The 2[nd] order term is: $V_2 = \frac{1}{4}\left.\frac{d^2V}{dI^2}\right|_{I=0} I_0^2 (1 + \cos 2\omega t)$ — 2ω!!!

The material's nonlinearity produces its own response signal at 2ω.

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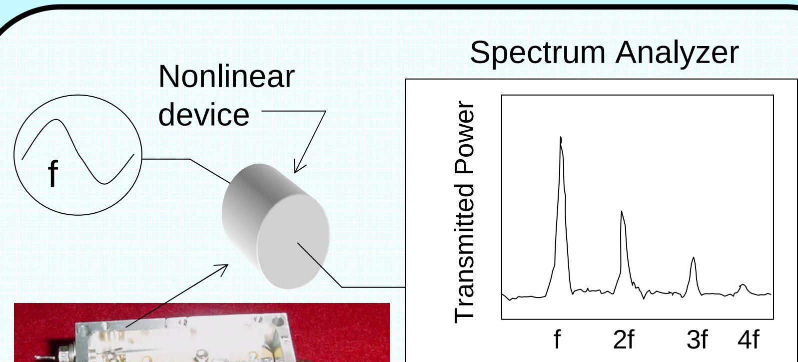
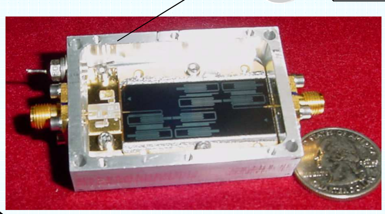
Seeing Nonlinearity

22





A real superconducting device

Nonlinearity is seen by viewing output with a spectrum analyzer.

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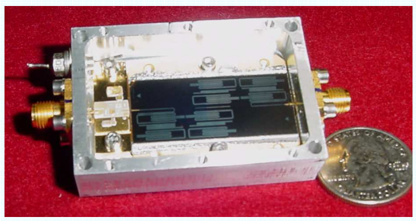
Two Forms of Superconductor

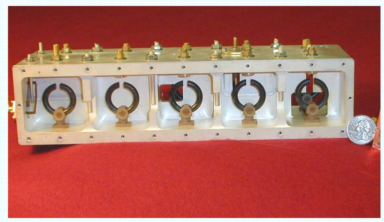
23

Thin Film
- Small size
- High quality crystal
- 2-Dimensional

Thick Film
- Large size
- Granular polycrystal
- 3-Dimensional

Both devices have identical electrical characteristics





2 forms of SC device: compact thin film, large thick film

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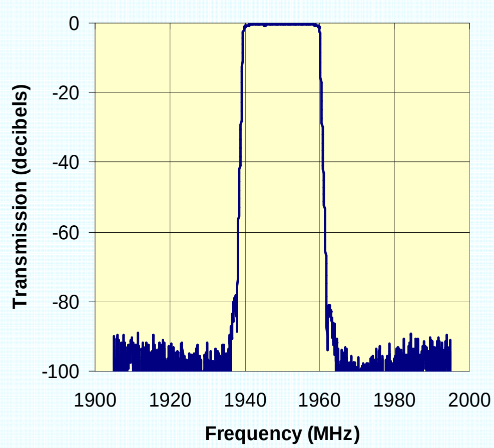
Superconducting Filters

24

compositions:
$YBa_2Cu_3O_{7-x}$
$Tl_2Ba_2CaCu_2O_8$
material forms:
granular thick films,
epitaxial thin films
device characteristics:
bandwidth, skirt slope
center frequency



Superconducting filters are the devices in these studies.

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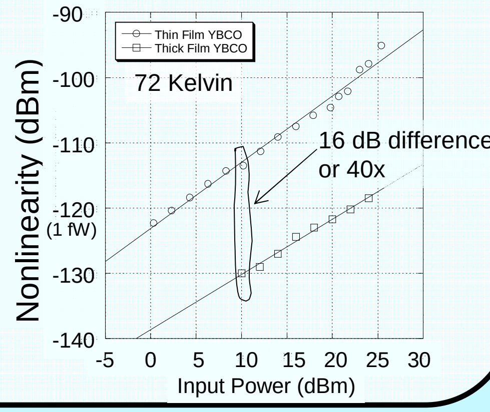
25

Measured Nonlinearity

Filter 1: $YBa_2Cu_3O_{7-x}$	thin film	5 MHz bandwidth
Filter 2: $YBa_2Cu_3O_{7-x}$	thick film	5 MHz bandwidth

The thin film filter has 15-20 dB more nonlinearity than the thick film filter…

…or 30x to 100x more.



Higher quality thin film superconductor is more nonlinear.

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26

What Do We Expect?

Film Type	"Peak Current" (per cm²)	Dominant Cause of NL	Nucleation Current* (/cm²)
1. Thick Film	2.7×10^3 A	Flux nucleation in grain boundary	$I_n \approx 750$ A
2. Thin Film	9.3×10^7 A	Flux nucleation at the film edge	$I_n \approx 5 \times 10^6$ A

***define nucleation current:** the current level where fluxons first form, or nucleate, in the superconductor.

Current is ~34,000x higher in thin film structures, but thick films are ~6,600x more sensitive to current.

Thin films have more current than thick films, but are less sensitive.

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What Do We Expect?

27

Estimate the relative nonlinearity

$$P_{\text{thin rel to thick}} = 20Log_{10}\left(\frac{\text{Percentage of nucleation current in thin film}}{\text{Percentage of nucleation current in thick film}}\right)$$

$$= 20Log_{10}\left(\frac{I_{thin}}{I_{n,thin}} \Big/ \frac{I_{thick}}{I_{n,thick}}\right)$$

From rough estimate, expect 14 dB more nonlinearity in thin film.

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What Do We Expect?

28

Estimate the relative nonlinearity

$$P_{\text{thin rel to thick}} = 20Log_{10}\left(\frac{\text{Percentage of nucleation current in thin film}}{\text{Percentage of nucleation current in thick film}}\right)$$

$$= 20Log_{10}\left(\frac{I_{thin}}{I_{n,thin}} \Big/ \frac{I_{thick}}{I_{n,thick}}\right)$$

$$\approx 20Log_{10}\left(\frac{9.3x10^{7}\,A/cm^{2}}{2.7x10^{3}\,A/cm^{2}}\frac{750\,A/cm^{2}}{5x10^{6}\,A/cm^{2}}\right)$$

$$\approx 14\,dB \text{ or } 25x$$

From rough estimate, expect 14 dB more nonlinearity in thin film.

Summary

1. Practical superconductors admit magnetic fields only in quantized bundles called fluxons.
2. These fluxons dissipate electromagnetic energy nonlinearly due to current dependent resistance.
3. Thick film superconductor devices are more sensitive to fluxons due to weak links across grain boundaries. But…
4. Thin film superconductor devices are still more nonlinear due to higher currents.

What's Next?

1. A more thorough quantification of the expected level of nonlinearity.
2. Local measurements, rather than measurements of the *average* of a device.
3. Applications: Sometimes you want nonlinearity.