Origins of the SQUID

Arnold H. Silver

Josephson Half-Centennial Symposium

Cambridge University

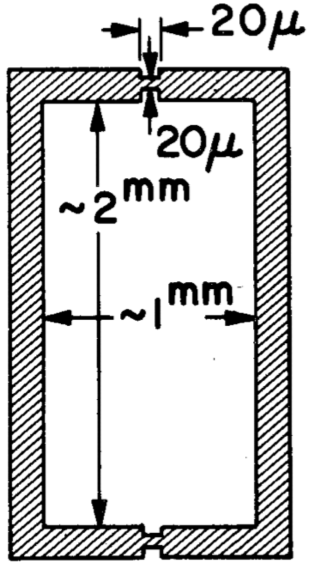
June 23, 2012

Historical Context

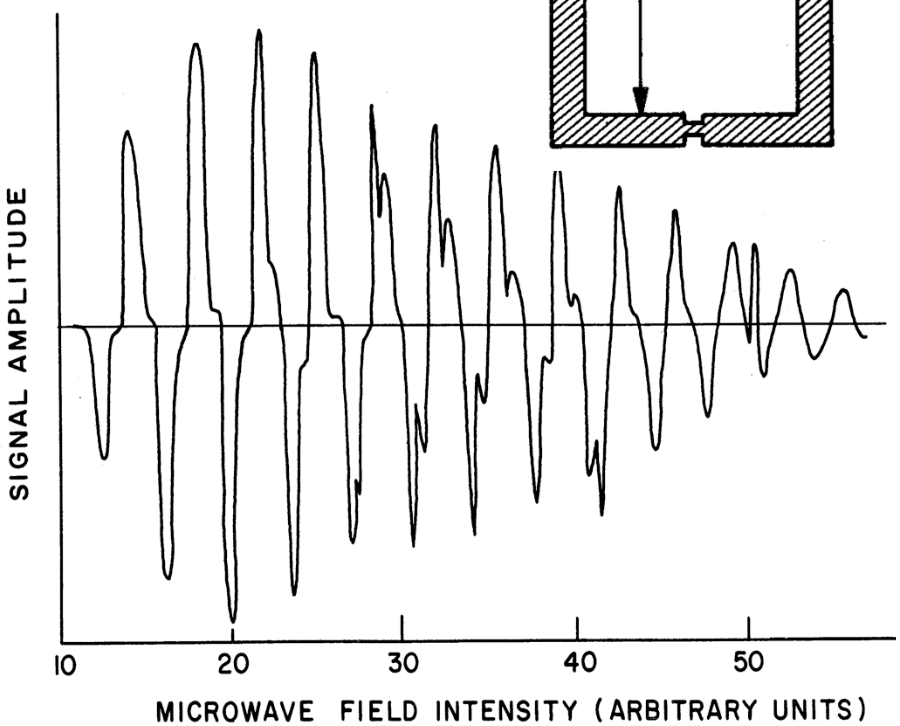
- **Phase One - Lambe, Silver, Jaklevic, Mercereau**
  - Precursor microwave observations by John Lambe
  - First thin-film, two-Josephson junction macroscopic quantum interference
  - Additional thin-film quantum interference experiments
- **Phase Two – Silver, Zimmerman**
  - Evolution of point contacts and bulk SQUIDs
  - SQUID flux model
  - dc, rf, and R SQUIDs
  - Linearized SQUID magnetometer
  - Demonstration of SQUID properties
- **Continuously hectic activity from 1963 through 1968**


PERIODIC CHART OF THE ATOMS
The Atoms Grouped According to the Number of Outer (Valence) Electrons

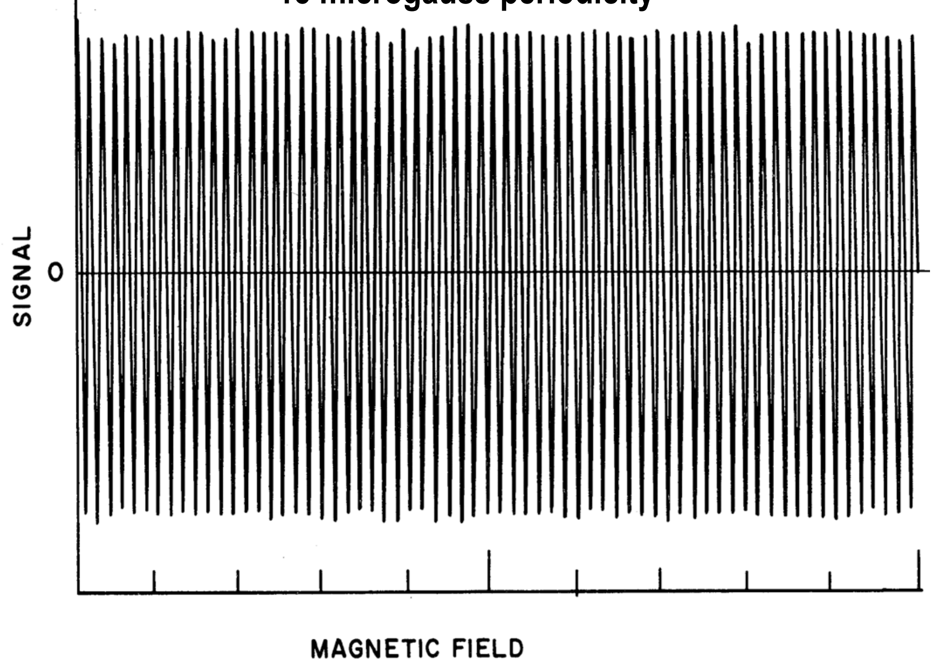
Periodic Microwave Signals (1963)



Published in mid-1964
in Physics Letters



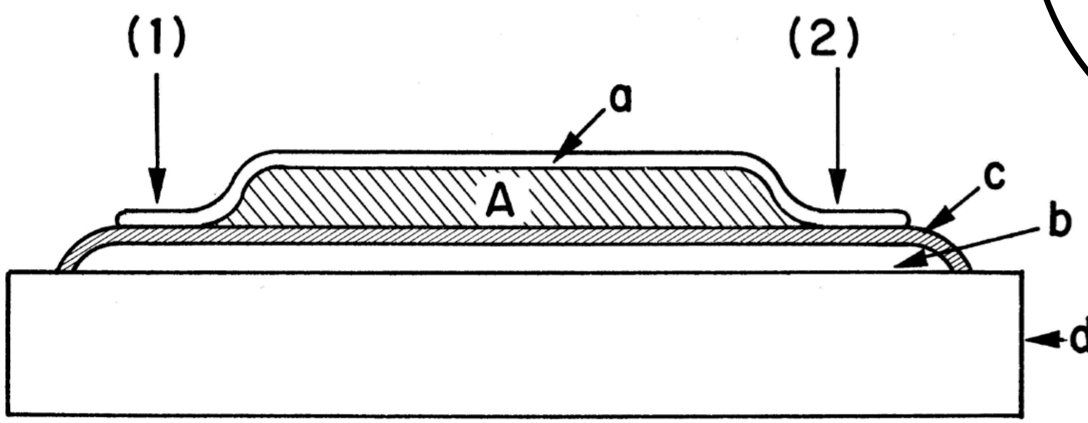
15 microgauss periodicity



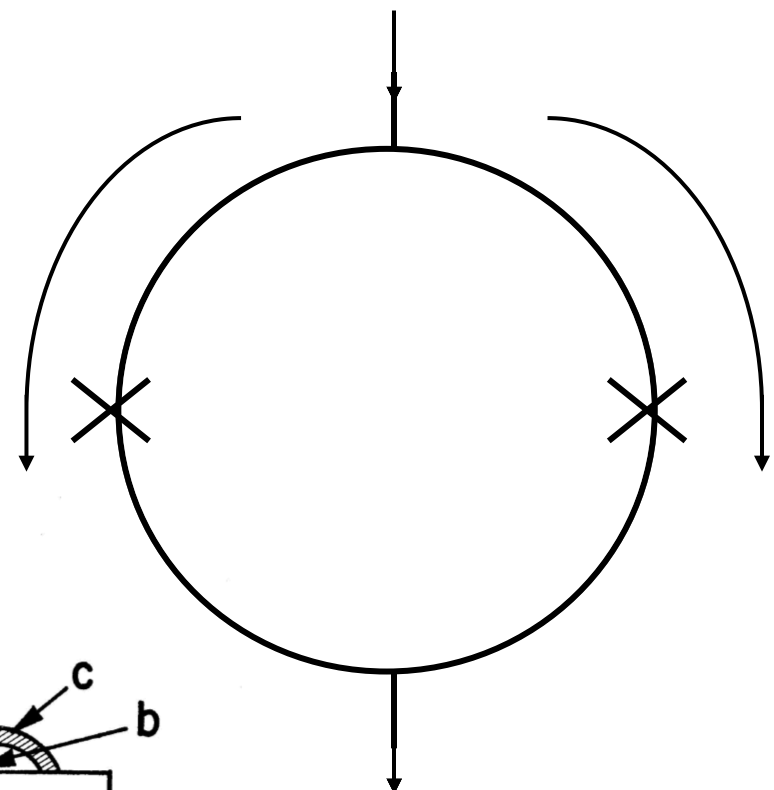
Ford Scientific Lab (Circa 1964)

First Two-Junction Macroscopic Thin Film *Interferometer*

- Microscope slide substrates
- Stainless steel shim masks
- Formvar insulating aperture "A"
- Sn thin films

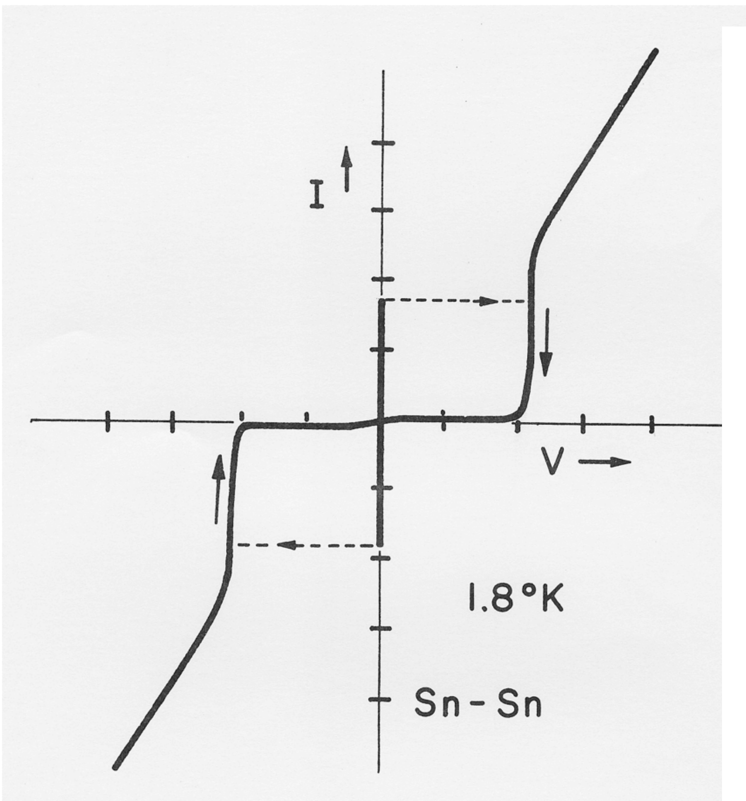


Tin thin film macroscopic quantum interferometer with two Josephson tunnel junctions (1) and (2)

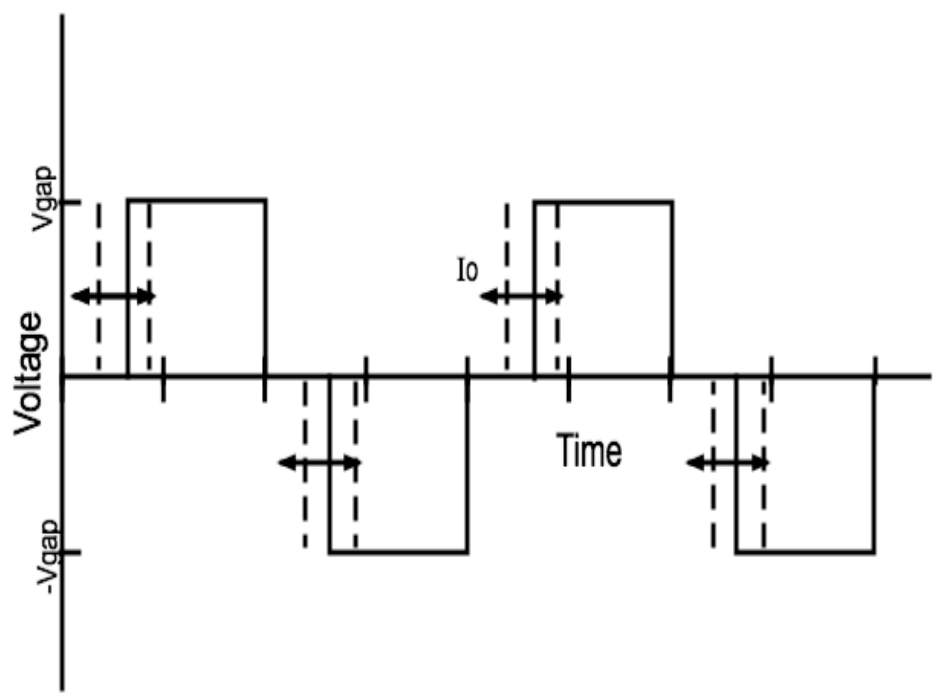


Josephson Tunnel Junction

- Hysteretic I-V characteristic
- Requires current cycling



- Sinusoidal current source
- Synchronous detector DC voltage linear in critical current



PHYSICAL REVIEW LETTERS

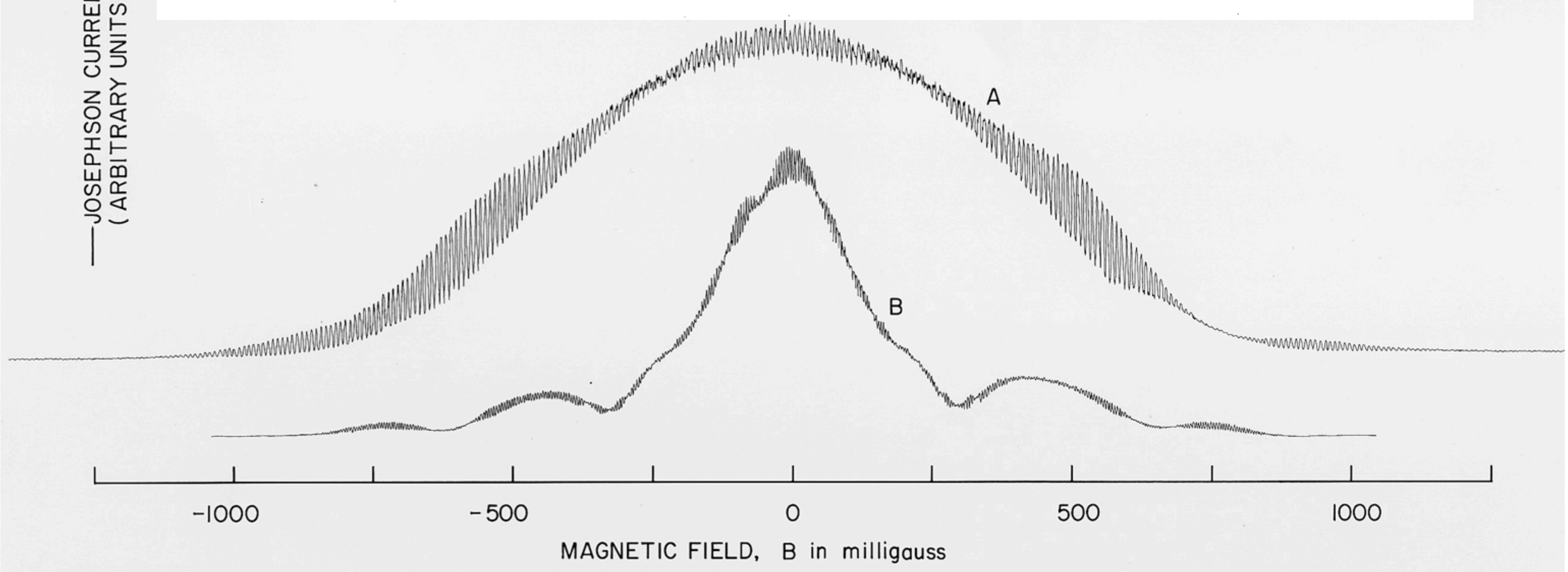
VOLUME 12 — 17 FEBRUARY 1964 — NUMBER 7

QUANTUM INTERFERENCE EFFECTS IN JOSEPHSON TUNNELING

R. C. Jaklevic, John Lambe, A. H. Silver, and J. E. Mercereau

Ford Scientific Laboratories, Dearborn, Michigan

(Received 16 January 1964)

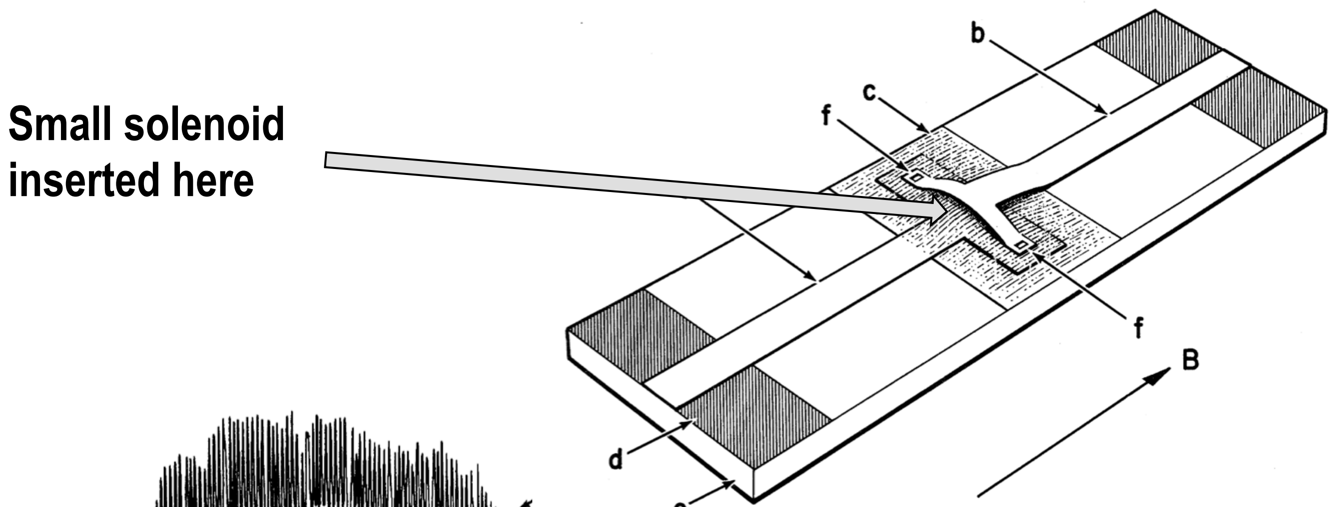


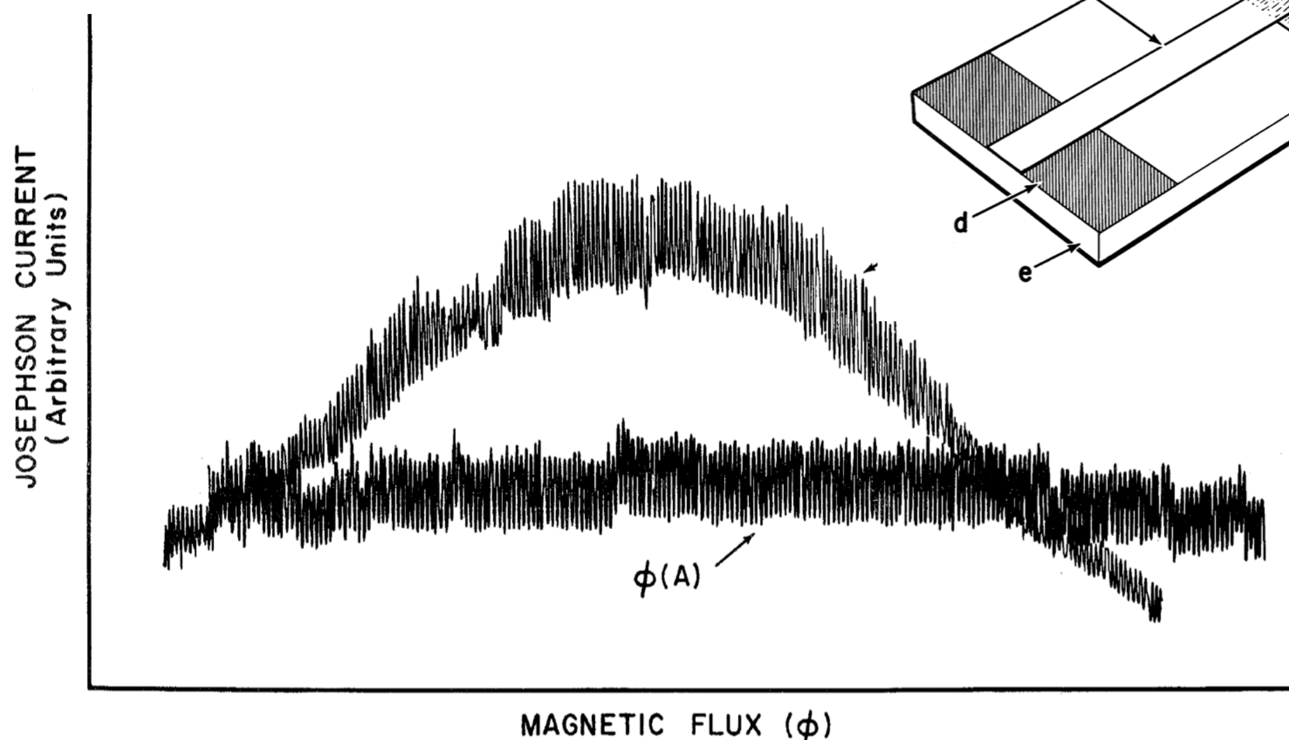
VOLUME 12, NUMBER 11 PHYSICAL REVIEW LETTERS 16 MARCH 1964

QUANTUM INTERFERENCE FROM A STATIC VECTOR POTENTIAL IN A FIELD-FREE REGION

R. C. Jaklevic, J. J. Lambe, A. H. Silver, and J. E. Mercereau
Scientific Laboratory, Ford Motor Company, Dearborn, Michigan

(Received 18 February 1964)





A. Silver, Cambridge University 2012

Other Tunnel Junction Measurements

- **Josephson junction kinetic inductance.**
  L_J *vs.* I/I_C was measured at 30 MHz using an RF transformer and RF voltmeter. This was achieved by applying flux to the junction to vary I_C at a small fixed current I.

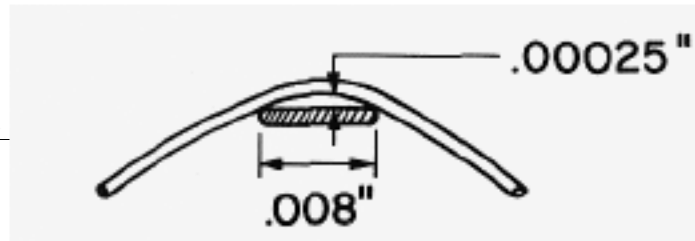
- **deBroglie wavelength**
  Experiment used current in a film thinner than the London penetration length to generate phase shifts along the film. This was a good way to measure the temperature dependence of the London penetration length.

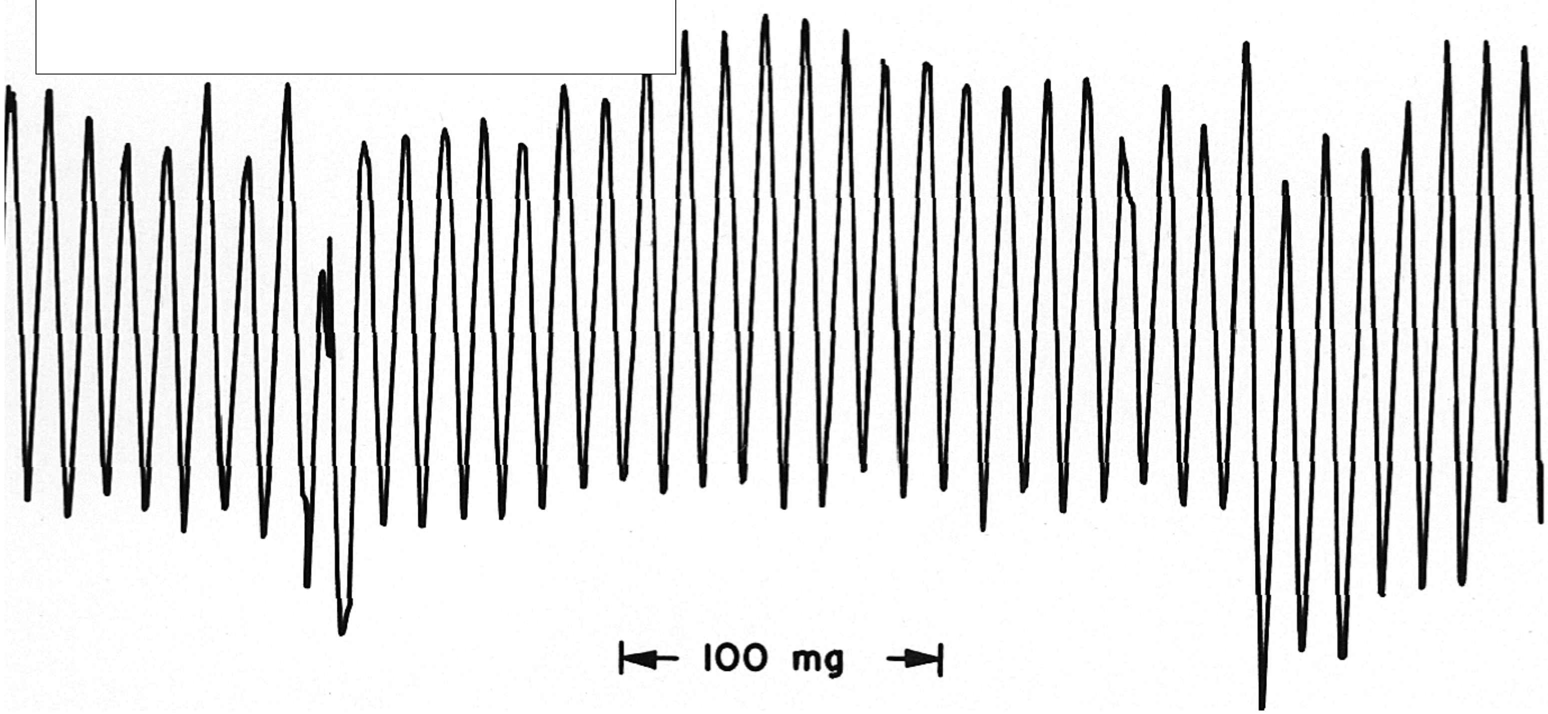
Volume 10, number 1 PHYSICS LETTERS 15 May 1964

QUANTUM EFFECTS IN TYPE II SUPERCONDUCTORS

J. E. ZIMMERMAN and A. H. SILVER
Scientific Laboratory, Ford Motor Company, Dearborn, Michigan

Received 29 April 1964



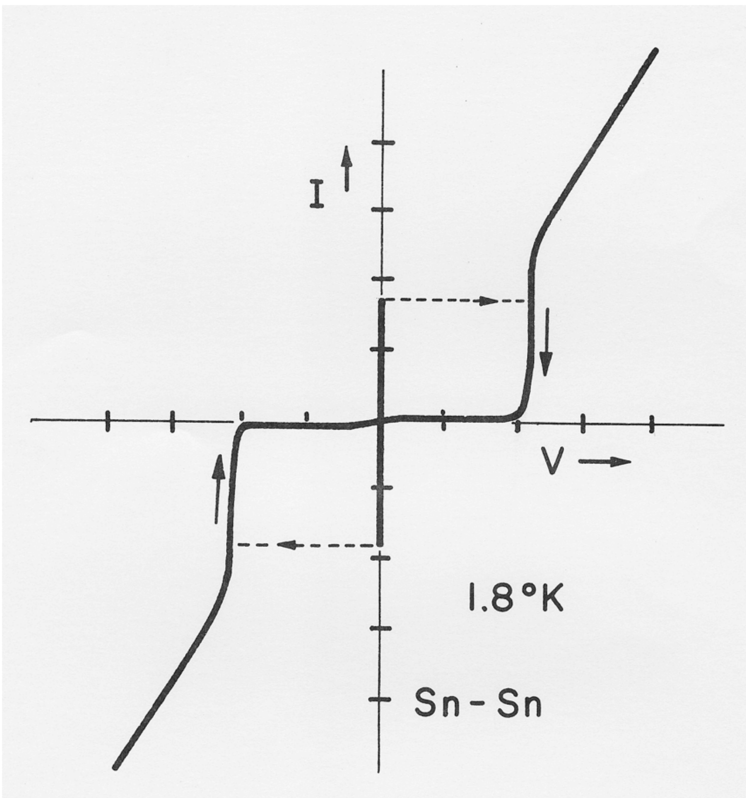


Junction Comparisons

Josephson tunnel junction

Hysteretic

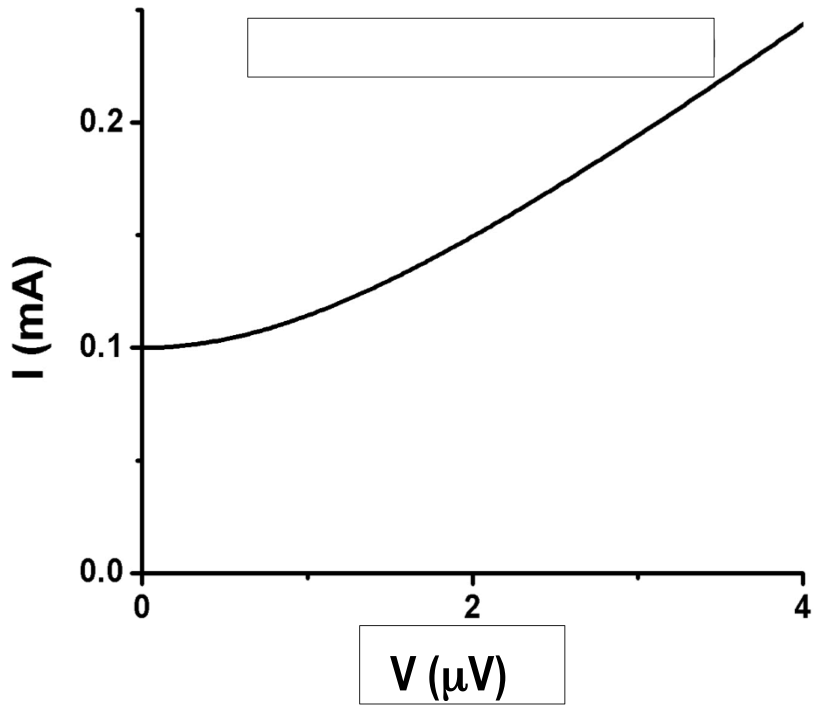
Required current cycling



Point contact junction

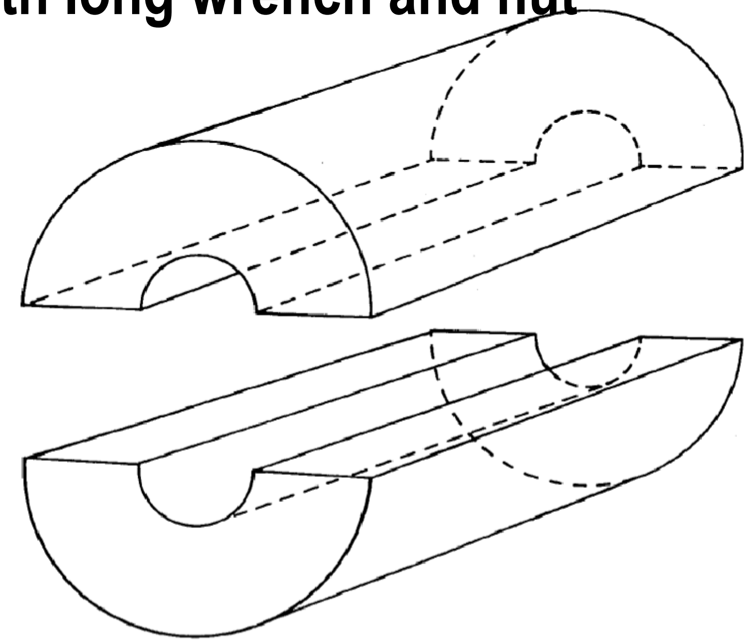
Single valued

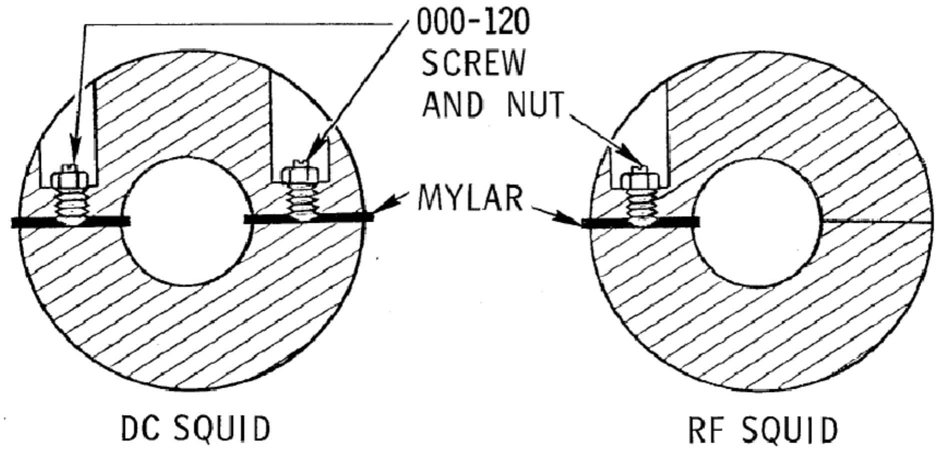
Microvolt signals



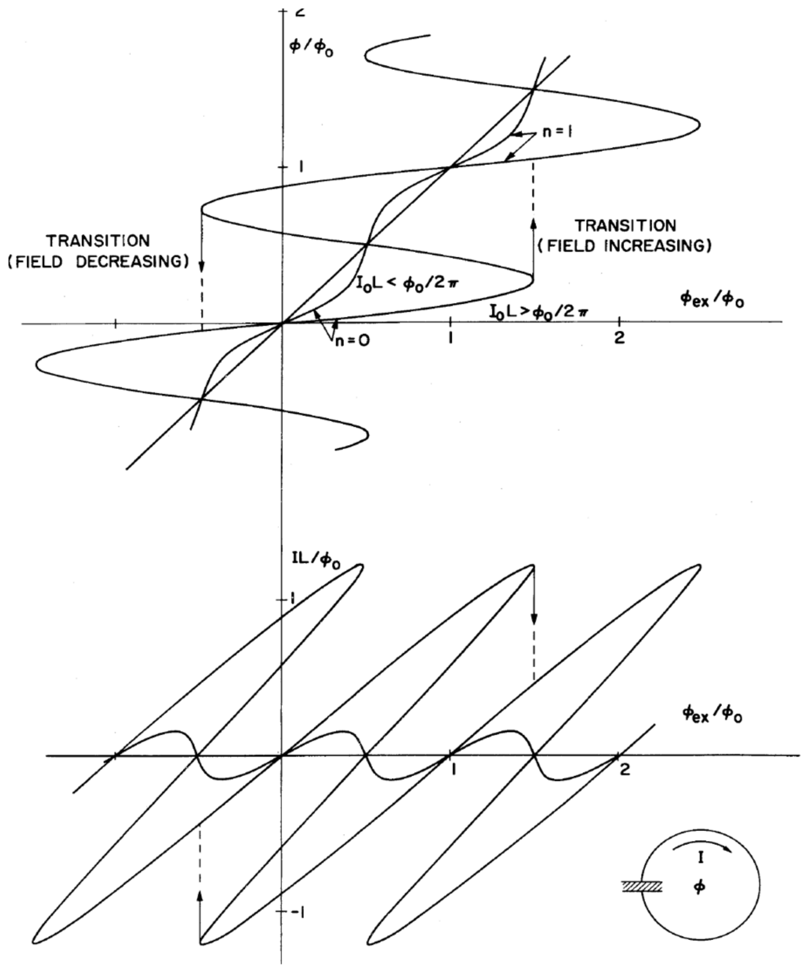
Point Contact SQUIDs in Bulk Niobium

- SQUIDs were machined from bulk Nb
- Pointed 000-120 Nb screws
- Screws were adjustable in LHe with long wrench and nut





Josephson Junction SQUID
Quantized Flux States and Transitions



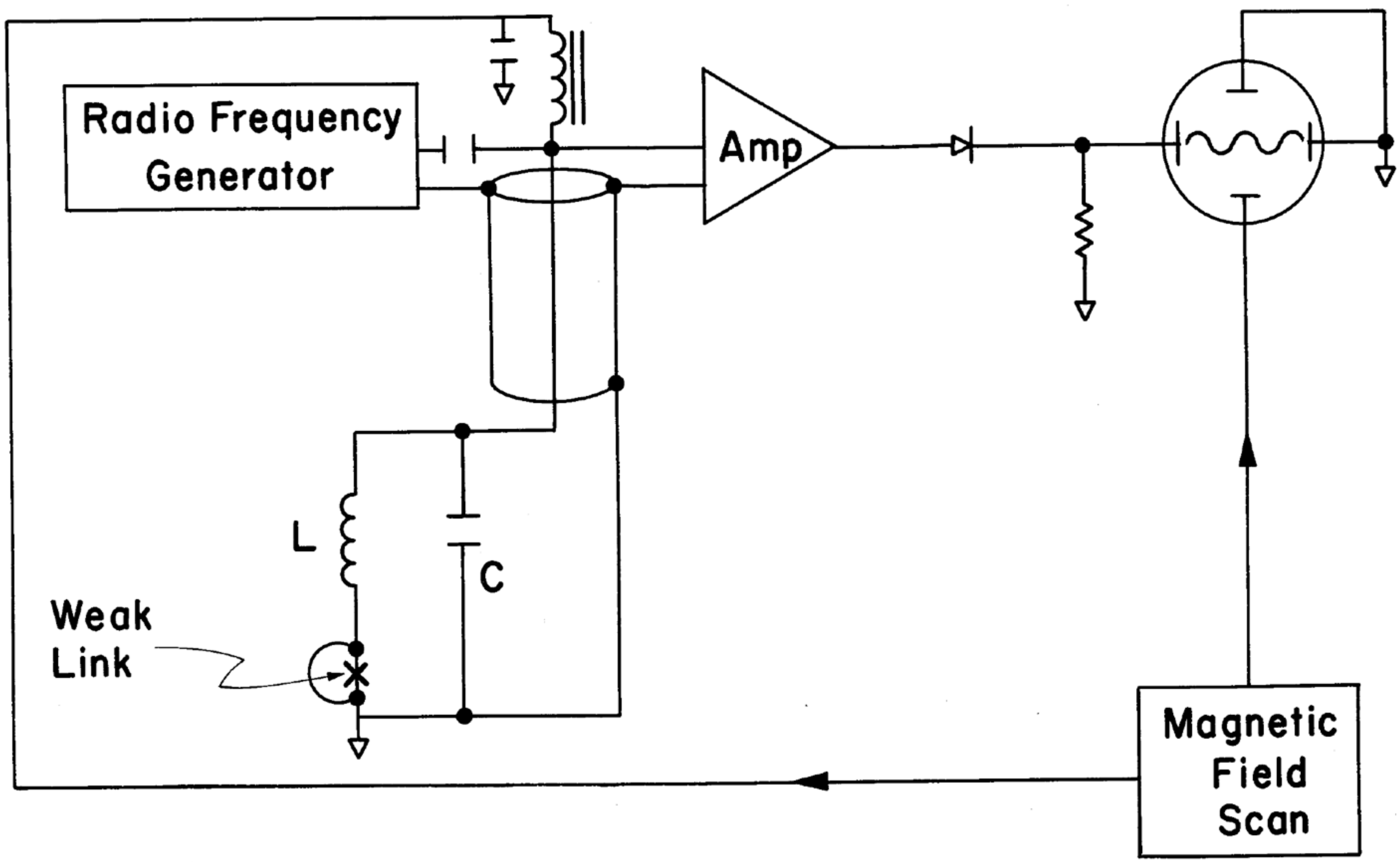
$$\beta = \frac{2\pi L I_C}{\Phi_0}$$

Single valued for $\beta \leq 1$

Multiple-valued for $\beta > 1$

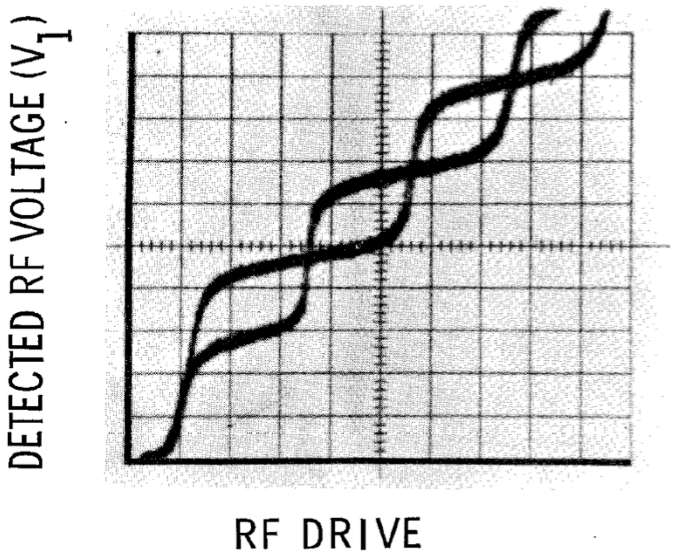
For $\beta \leq 1$ **there is an inflection point where** $\phi = \phi_a = \Phi_0/2$ **and** $I = 0$**.**

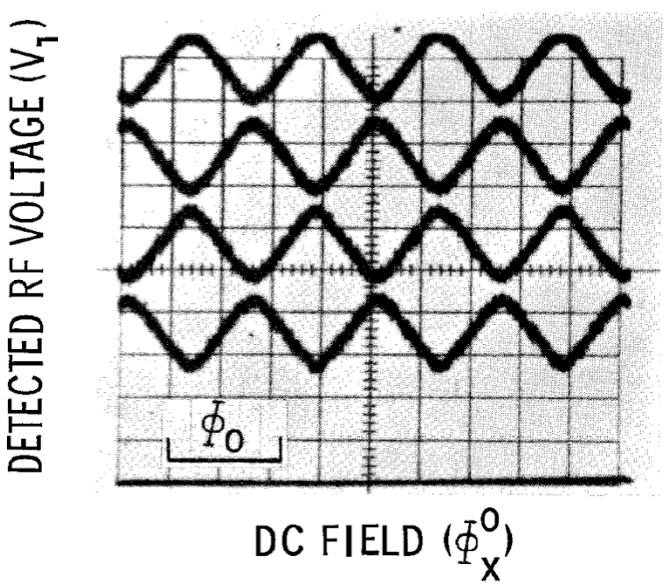
Typical RF SQUID Measurement

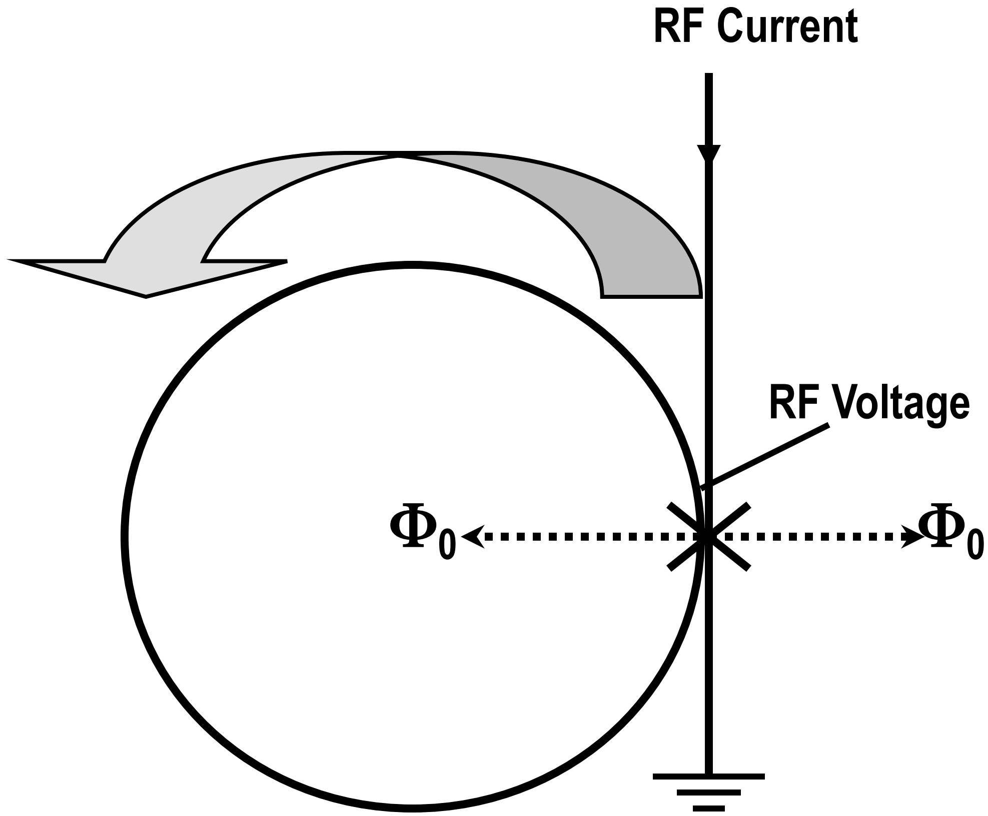


RF SQUID Response

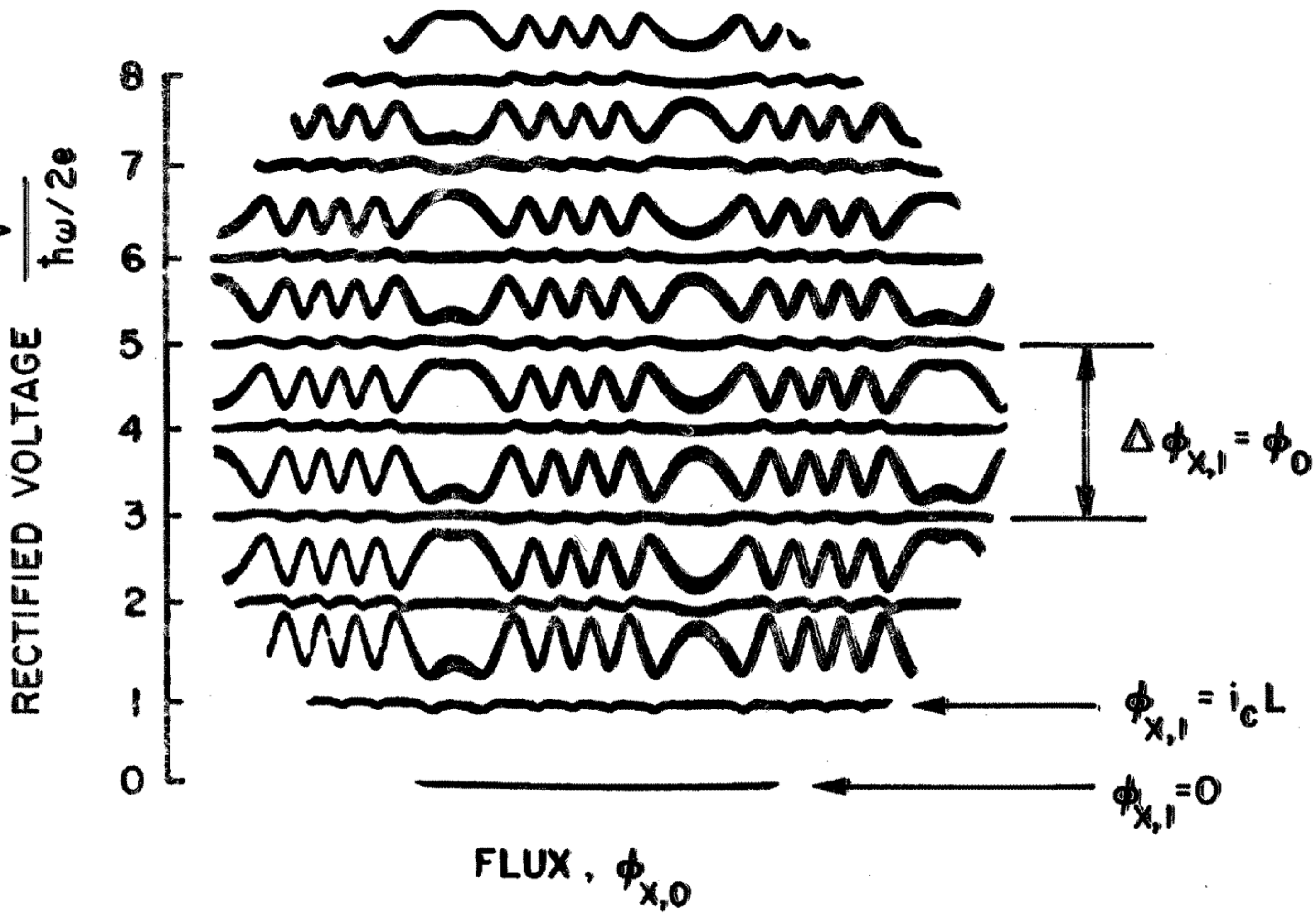
Mimics Microwave Observations



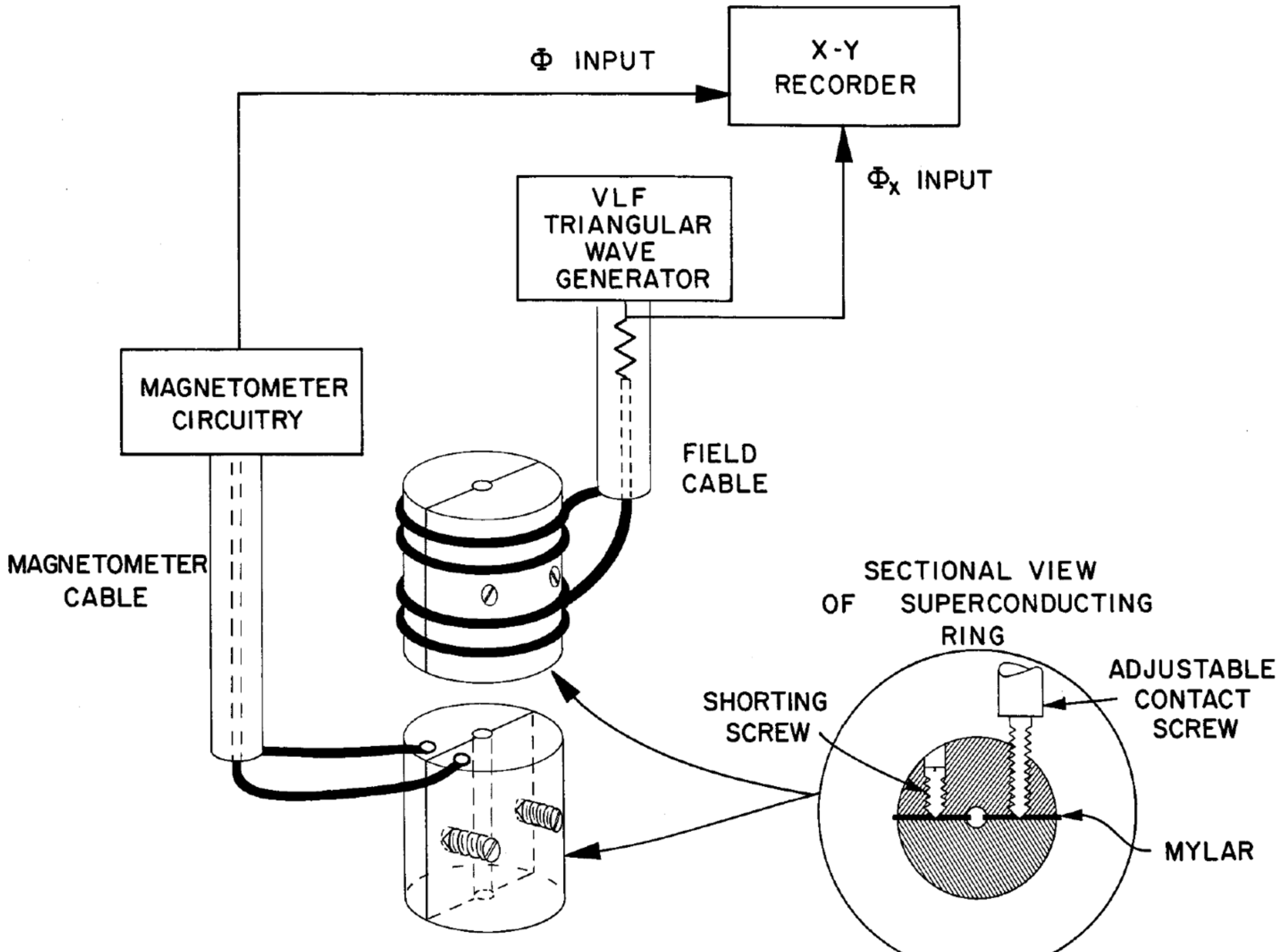




Quantitative Diagnostics With RF SQUID

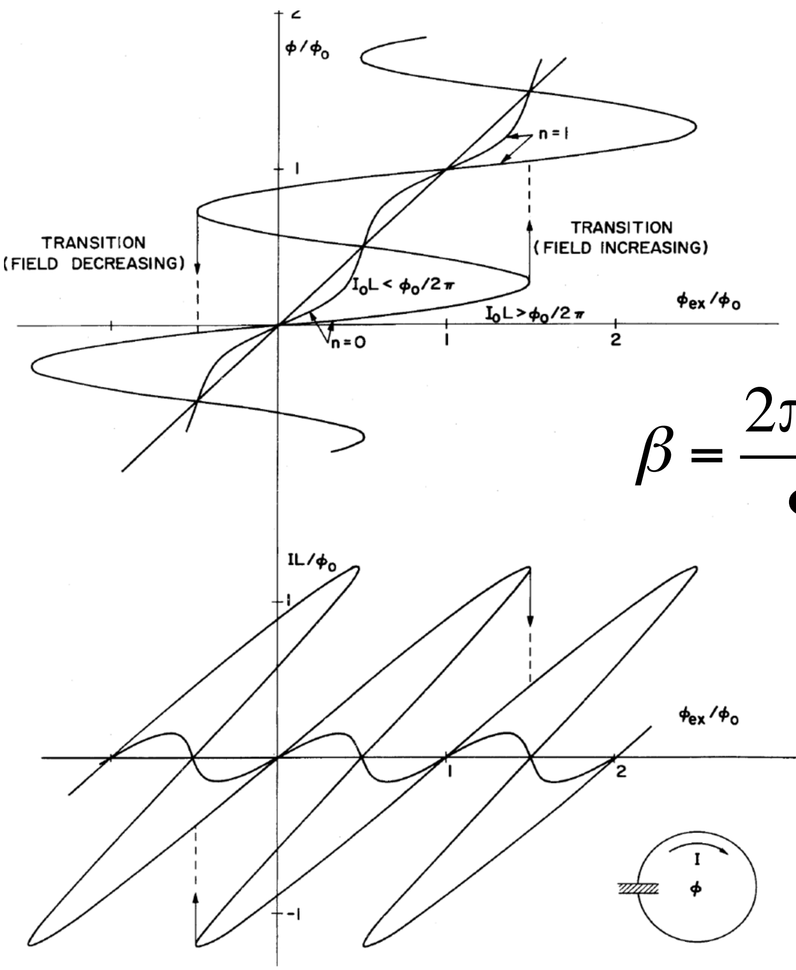


RF SQUID Measured With Linearized RF SQUID Magnetometer



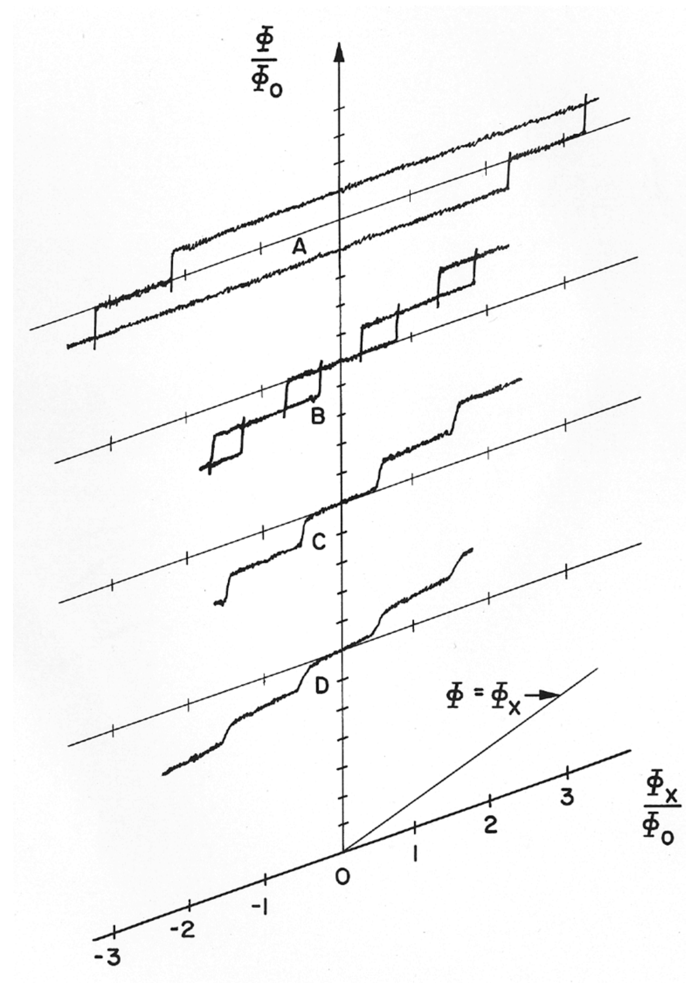
SQUID Quantized States and Transitions

Theory

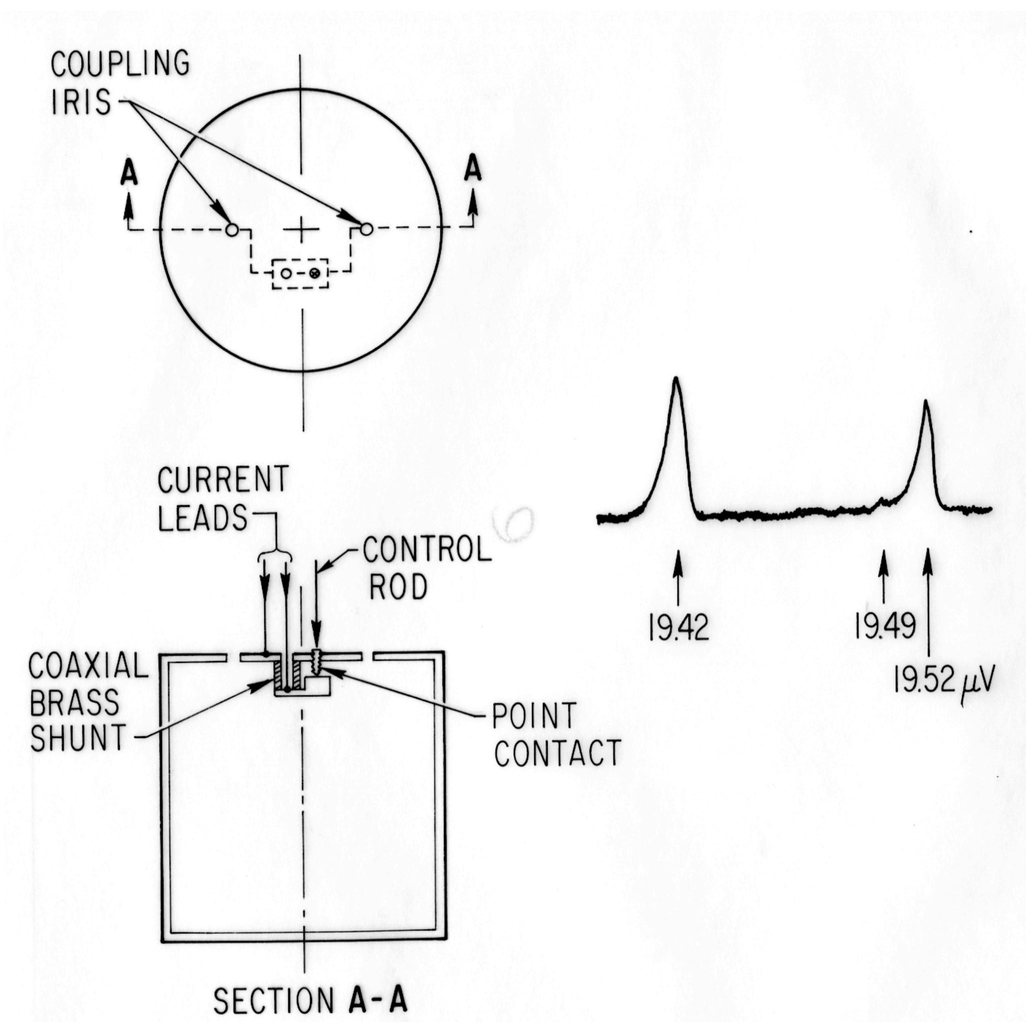


$$\beta = \frac{2\pi L I_C}{\Phi_0}$$

Measurement

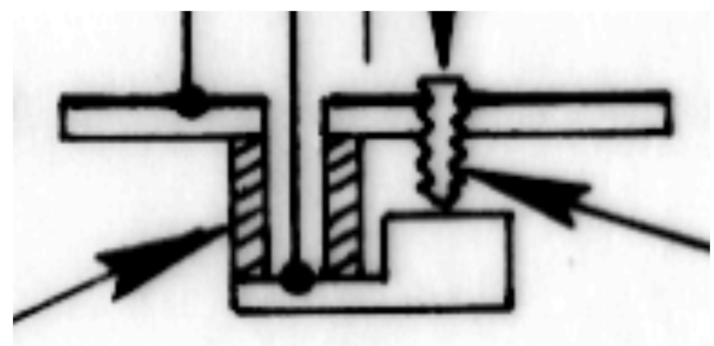


Resistive R-SQUID Oscillator



- **Micro-ohm resistance**
- **X-band, 10 GHz, cavity**
- **Josephson ac effect**

$$V = \Phi_0 f$$



SQUID Evolution Summary

Ford Motor Company Scientific Laboratory

- Spurious microwave observations in Si:P
- First 2-junction interferometer (DC SQUID)
- Vector potential experiment
- deBroglie wavelength experiment
- Crossed wires DC SQUID
- "Point contact" DC SQUID
- London moment measurement
- "Point contact" RF SQUID
- Flux quantum model
- Resistive RF SQUID
- SQUID microwave oscillator
- SQUID oscillator-detector
- SQUID noise thermometer

1963 1964 1965 1966 1967 1968

First Magnetocardiogram MCG
@ MIT Magnet Lab
Zimmerman, Cohen, Edelsack