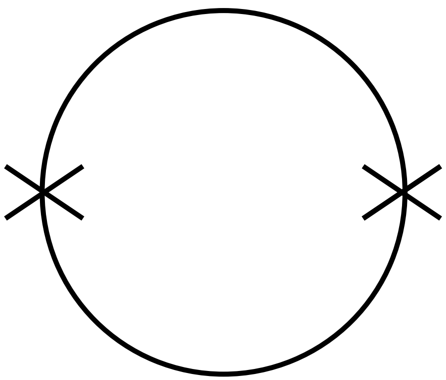
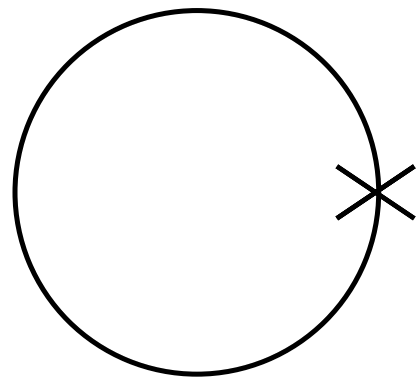
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), September 2019.
Distinguished presentation 1-SQ-D-1 given at ISEC, 28 July-1 August 2019, Riverside, USA.

The History of SQUIDs

Superconducting **Qu**antum **I**nterference **D**evice





Arnold H. Silver

Monday July 29, 2019: 2 PM
ISEC 2019
Riverside, CA, USA

Post-WWII Innovations

- Microwave oven (1946)
- Magnetic resonance (1946) Nobel Prize (1952). Led to MRI
- Transistor (1947) Nobel Prize (1956). Enabled digital computers, etc
- Instant photography (Polaroid 1948)
- Holography (1951). Nobel Prize (1971)
- Maser (1953)
- Artificial satellites (Sputnik 1957) Eventually led to GPS, comsats, etc.
- BCS Theory (1957) Nobel Prize (1972)
- Laser (1960) Enabled CDs, DVDs, optical memory, etc.
- Xerography (1960) Led to copiers, laser printers, etc.
- Observation of the flux quantum (1961)
- Tunneling in superconductors (1960). Nobel Prize (1973)
- Josephson effect (1962) Nobel Prize (1973). Led to SQUIDs, voltage standard, superconductor electronics
- SQUID (1963)
- Cosmic background radiation (1964) Nobel Prize (1978)

SQUID Is Based on Earlier Research

Year	Authors	Description
1950	F. London	Electrodynamics of superconductors
1957	J. Bardeen, L. Cooper, & J.R. Schrieffer	Cooper pairs Microscopic theory of superconductors
1961	I. Giaever	Observation of tunneling in superconductors
1961	B.S. Deaver & W.M. Fairbank M. Doll & M. Neubauer	Direct observation of the flux quantum $\Phi_0 = h/2e$
1962	M.H. Cohen, J.C. Phillips, & L.M. Falicov	Microscopic theory of tunneling in superconductors
1962	W.A. Little & R.D. Parks	Free energy of the flux quantum
1962	B.D. Josephson	Theory of supercurrent tunneling
1963	P.W. Anderson	Interpretation of Josephson effect
1963	P.W. Anderson & J.M. Rowell	Experimental confirmation of Josephson tunneling

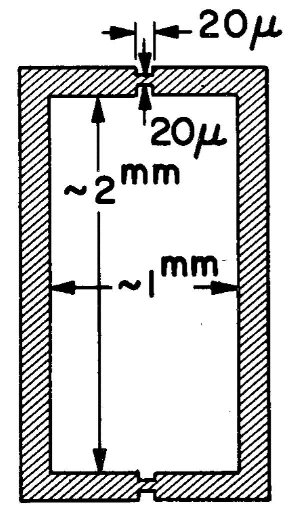
Early Technology of the 1960's?

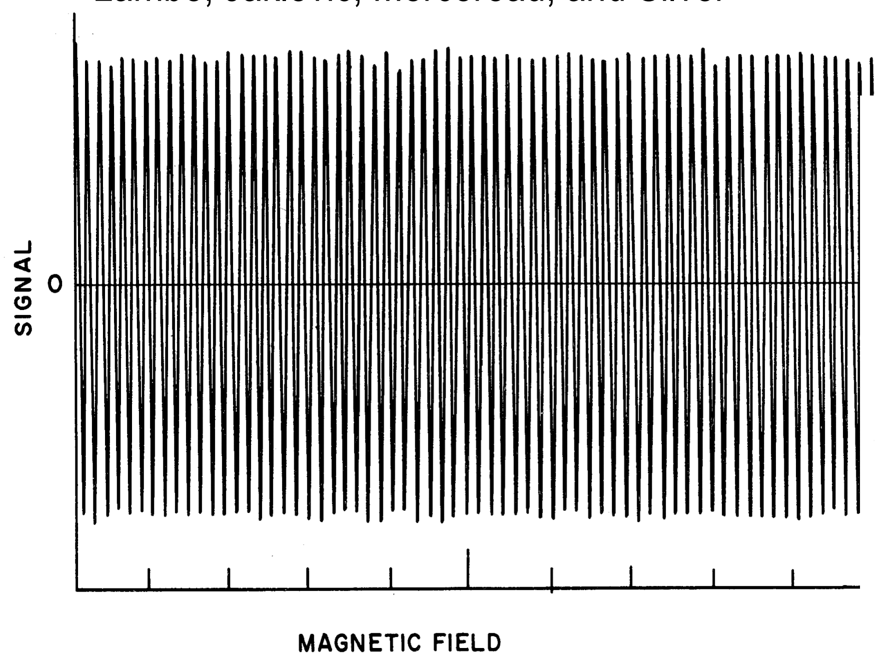
- Mostly analog, vacuum-tube electronics
  - Few equipment suppliers
  - Oscillators
  - Oscilloscopes
  - Polaroid cameras
  - Strip-chart and X-Y recorders
- Source of LHe an issue
- Glass LHe dewars with LN2 glass jacket dewars
- Manuscripts
  - Hand written
  - Literally "cut and paste" typewriter editing
  - "Carbon" copies
  - Limited availability of the new Xerox copiers
  - Hand-plotting on graph paper
  - Traced on vellum for presentations and publications
- Presentations like this used 3" x 4" photographic glass slides

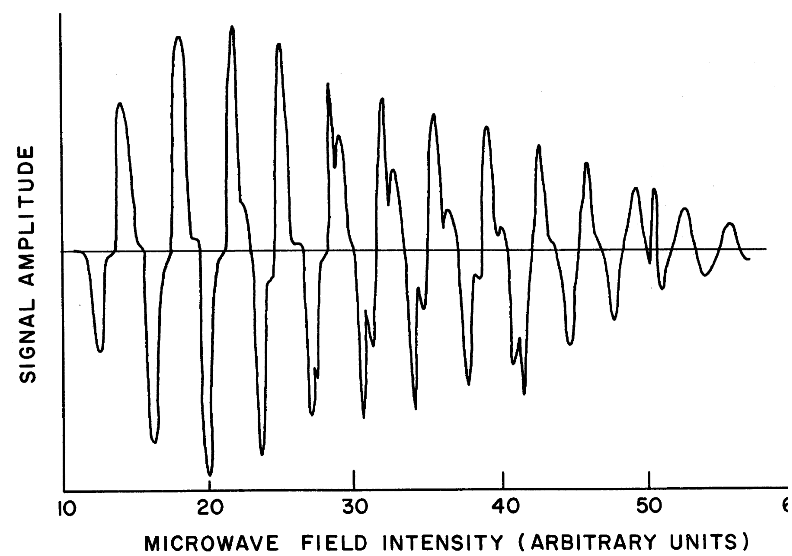
Ford Research Team

Phase One: Thin Film Devices 1963-64

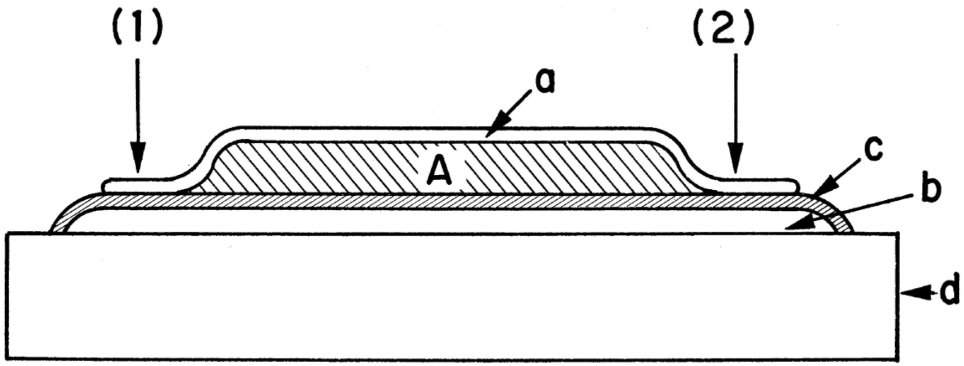
- Started with Lambe's observation of anomalous microwave signals during ENDOR experiments
  - LHe cryostat in a large electromagnet
  - Ultra-low power X-band heterodyne spectrometer
- *Periodic* in magnetic field *and* in microwave power
- Temperature dependent
- Attributed to indium solder contacts and flux quantization
- Lambe, Jaklevic, Mercereau, and Silver





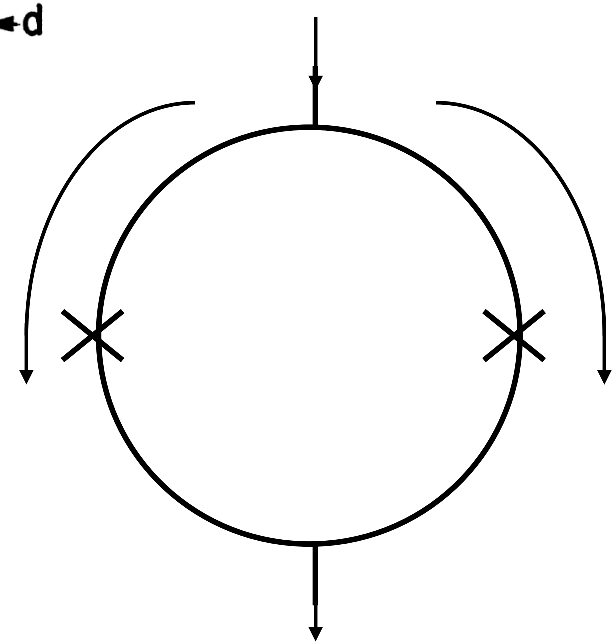


First Thin-Film Tunnel-Junction "Interferometer"

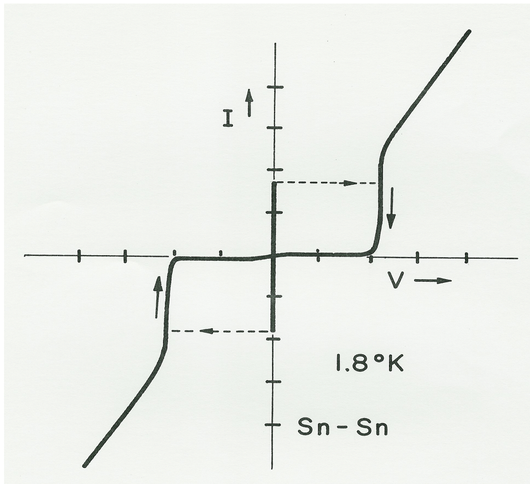


December 23,1963

- Fabricated by Robert Jaklevic
- Microscope slide substrates
- Stainless-steel shim shadow masks
- Formvar insulating aperture "A"
- Sn thin films

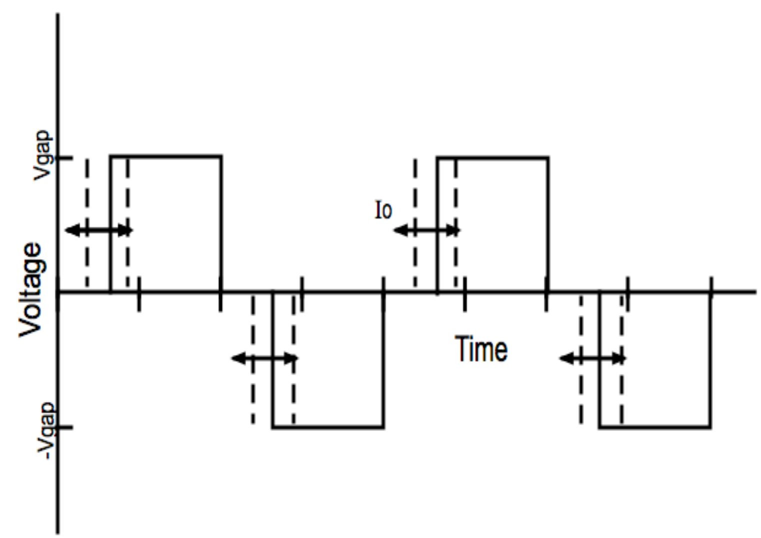


Task Was to Measure and Record Josephson Critical Current vs. Magnetic Field



- Hysteretic I-V characteristic on oscilloscope required current cycling
- Low resolution measurement on oscilloscope
- Background magnetic noise interference

- Sinusoidal current source produced voltage train of variable-width square waves
- Synchronous detector (Lock-In amplifier) generated DC voltage linear in critical current
- Automatic X-Y recording



PHYSICAL REVIEW LETTERS

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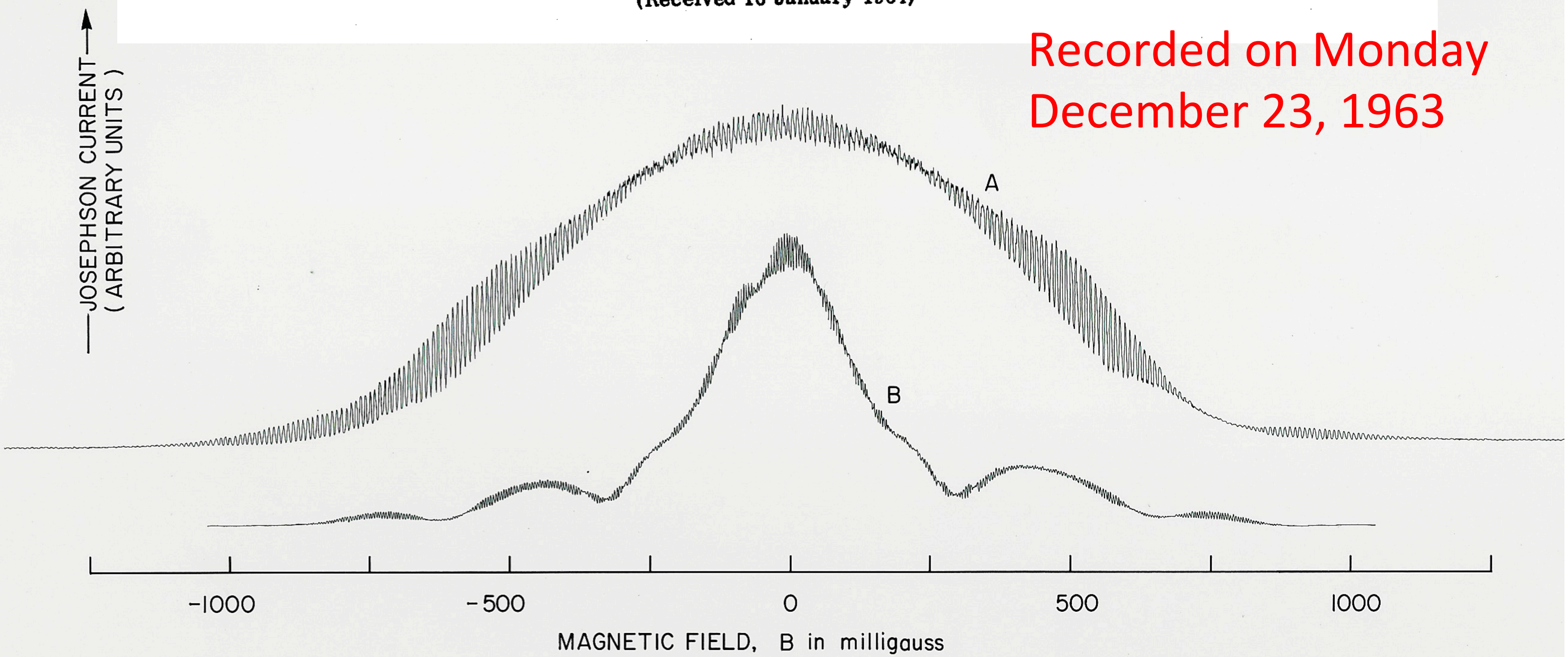
QUANTUM INTERFERENCE EFFECTS IN JOSEPHSON TUNNELING

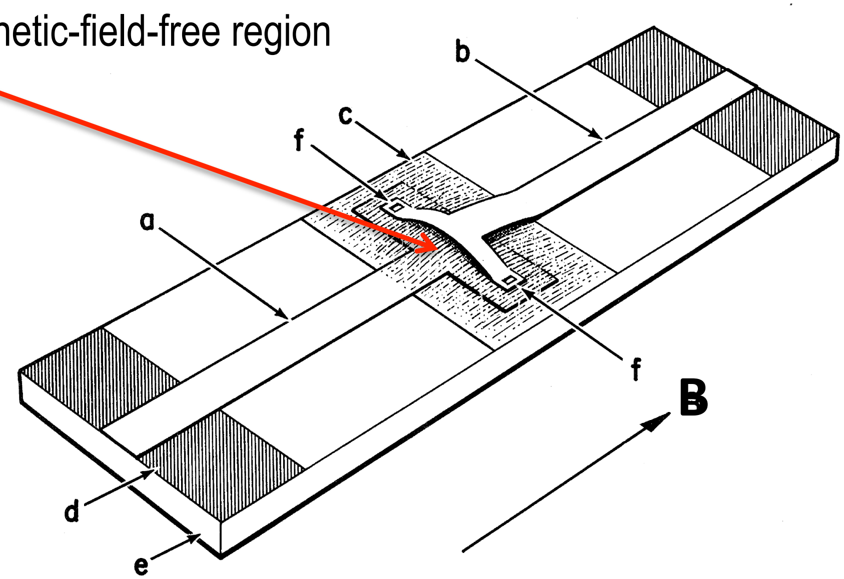
R. C. Jaklevic, John Lambe, A. H. Silver, and J. E. Mercereau
Ford Scientific Laboratories, Dearborn, Michigan
(Received 16 January 1964)

Recorded on Monday December 23, 1963



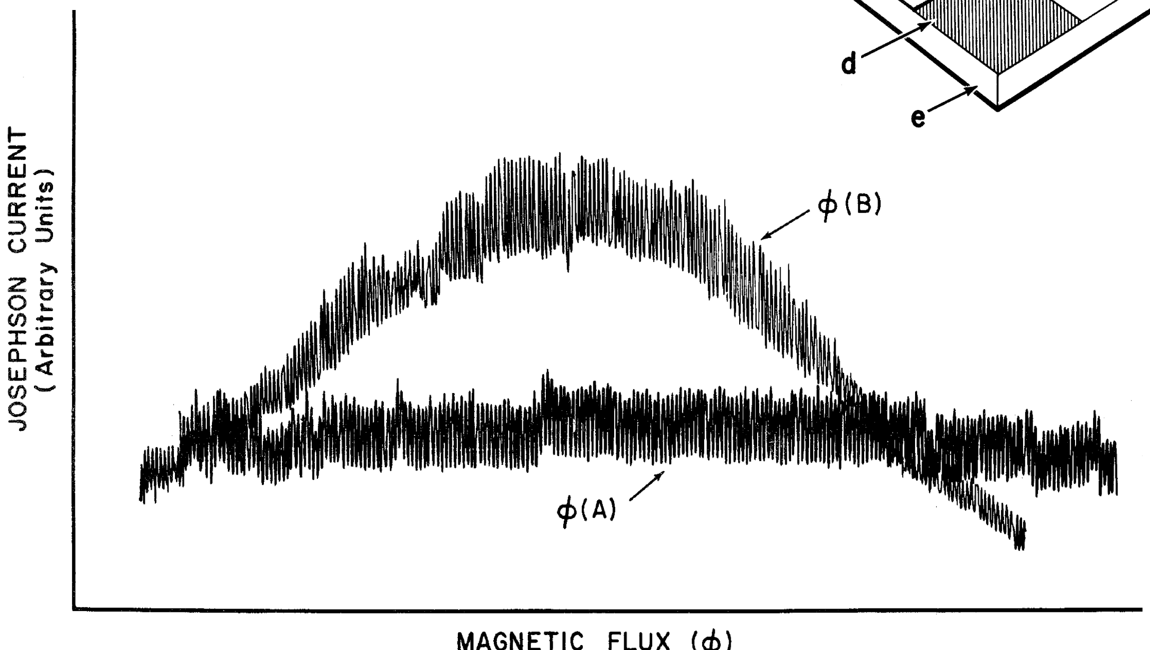
Superconducting Aharonov-Bohm Interferometer

- Influence of the vector potential in a magnetic-field-free region
- Miniature coil inserted in a small sleeve



$$B = curl A$$

$$\Phi = \oint A \bullet dl$$



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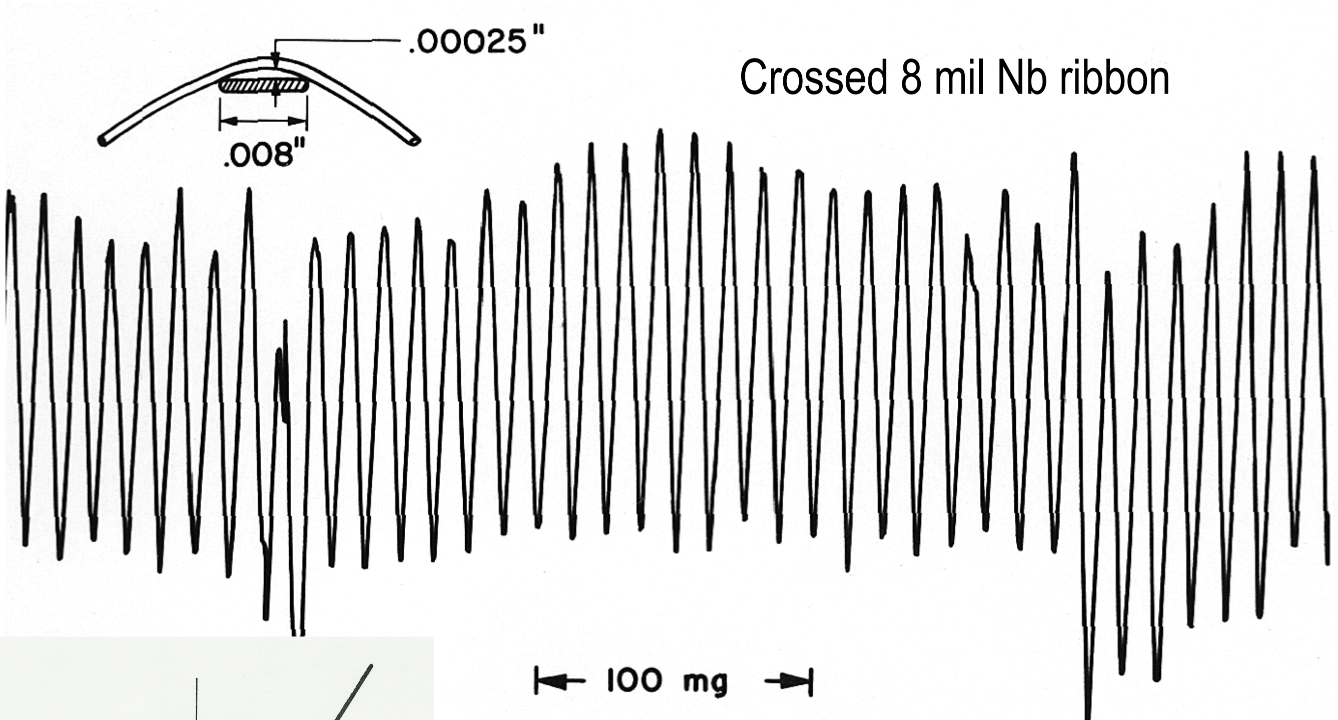
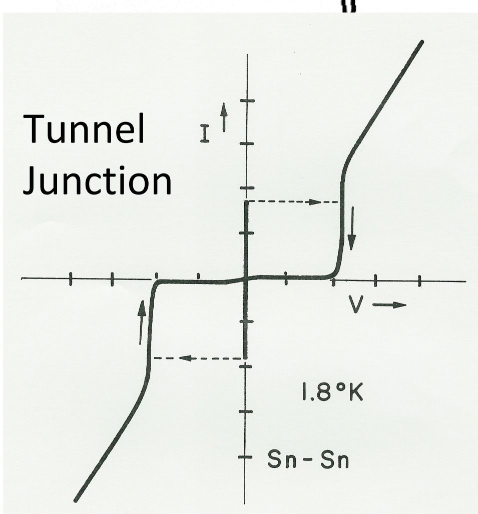
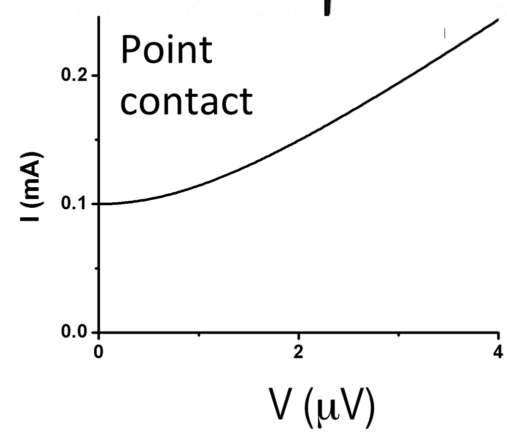
Phase 2: Nb Point-Contact Devices 1964 – 68

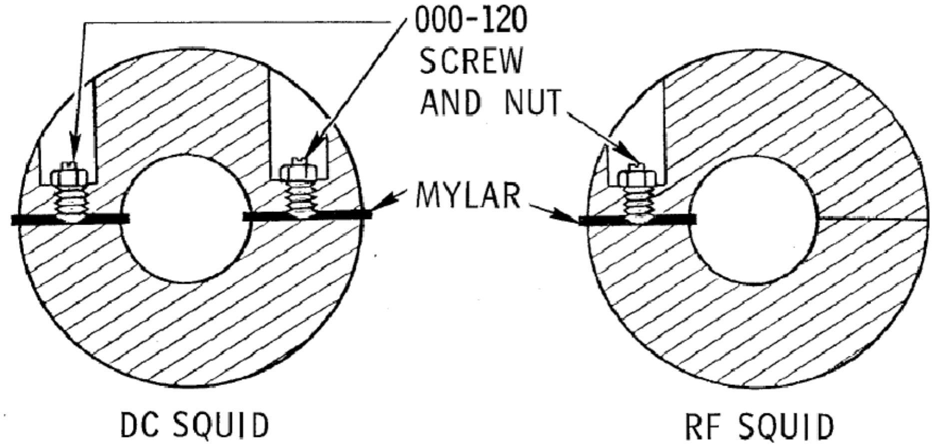


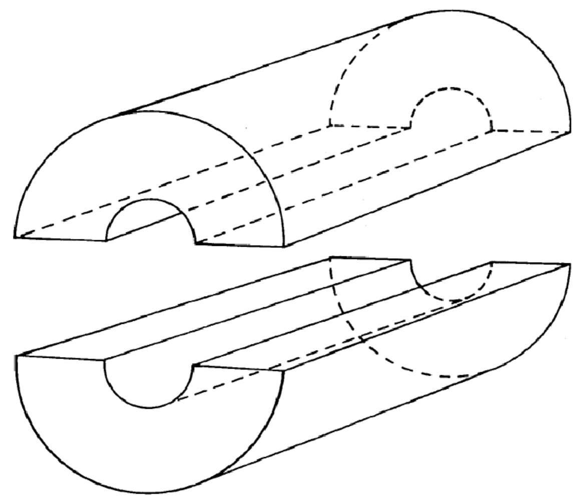




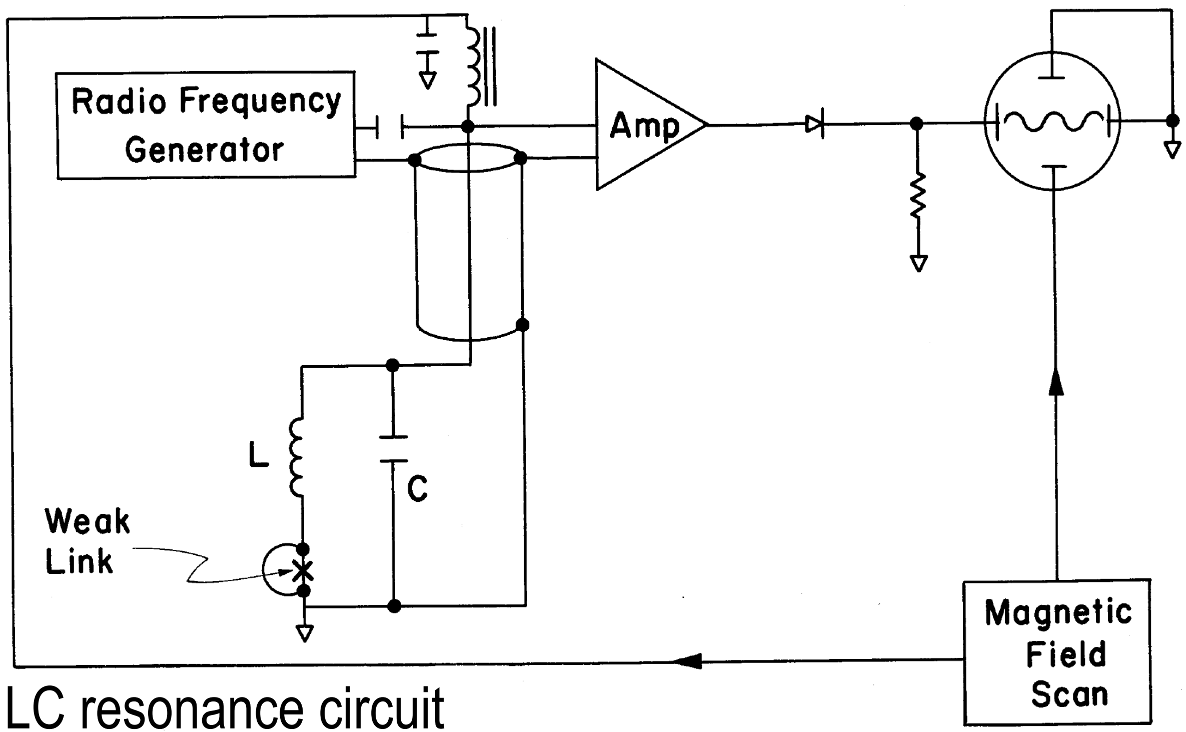
Niobium Point Contact SQUIDs

- SQUIDs machined from bulk Nb
- Pointed 000-120 Nb screws
- Screws were adjustable in-situ with long wrench
- Devices were sealed in stainless steel tubing with He gas
- Moved to RF measurement
- Silver and Zimmerman



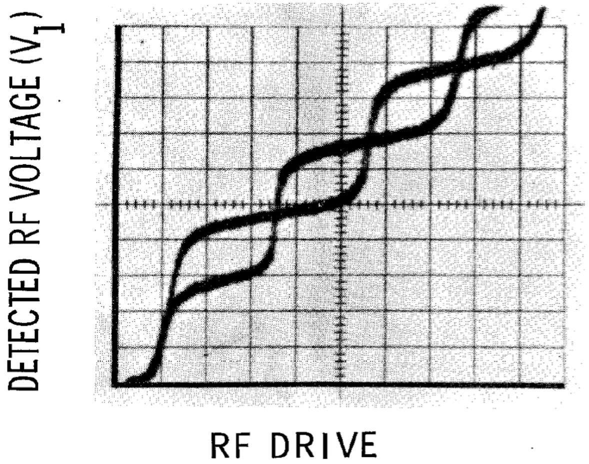


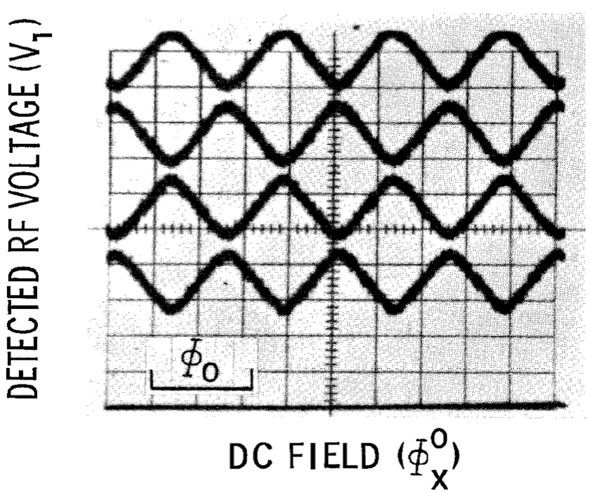
Typical RF SQUID Measurement System



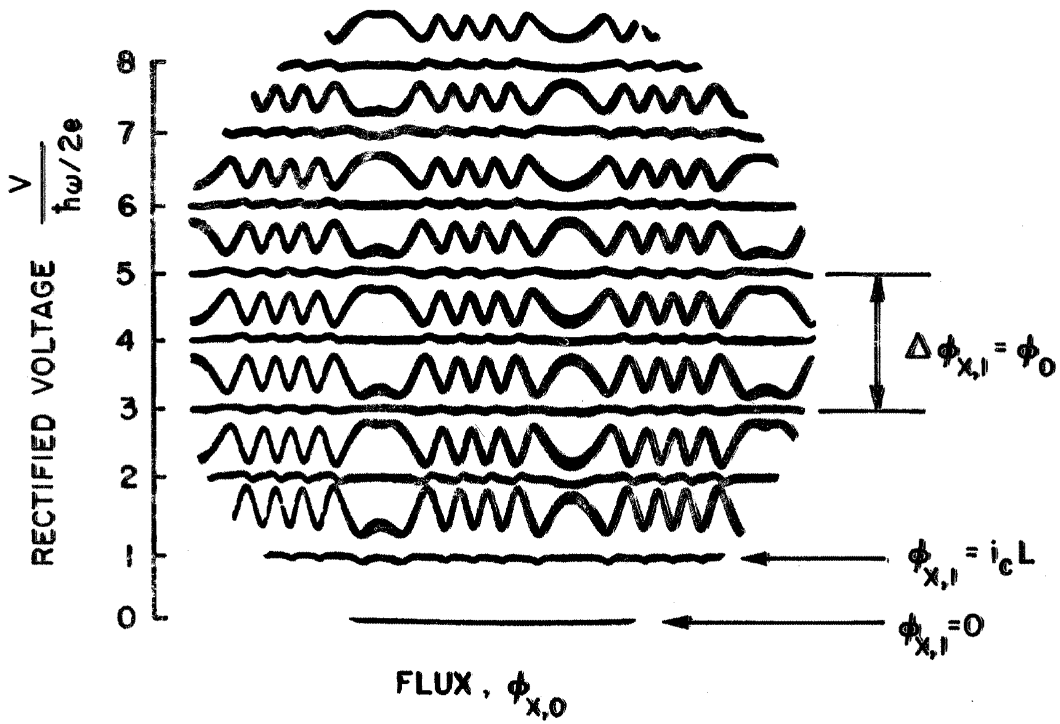
- Gain of Q from LC resonance circuit
- Wideband response
- Single cable connection to SQUID
- Homodyne detection provides both amplitude and phase information

RF SQUID Multiple Exposure Data





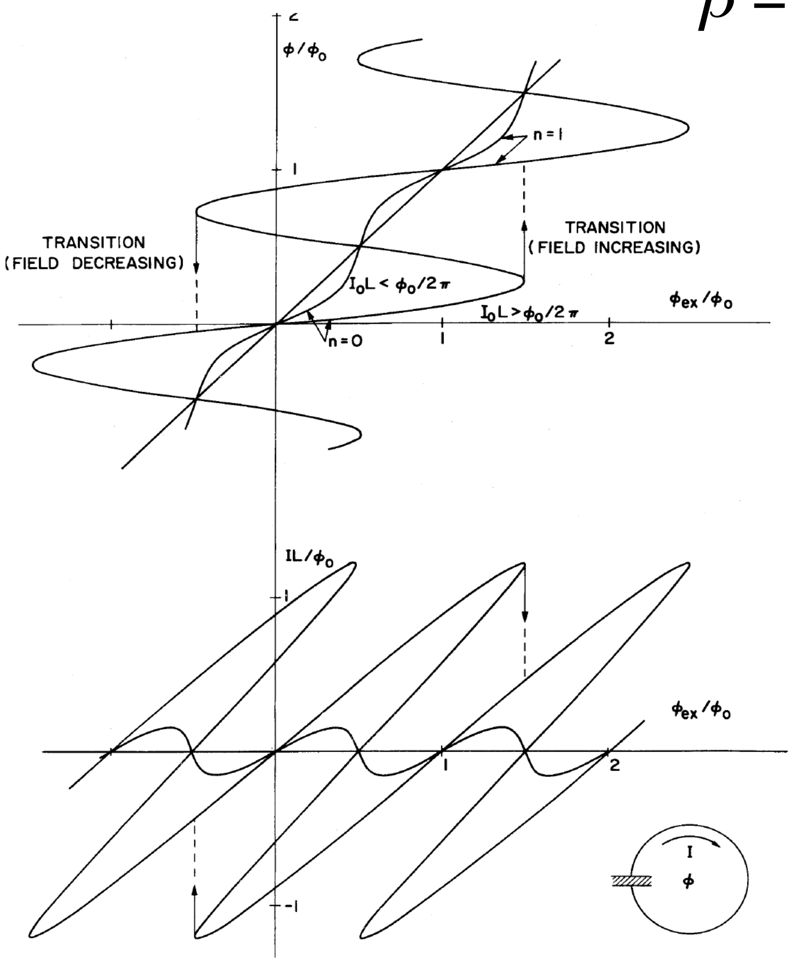
Composite Data Provides Quantitative Calibration



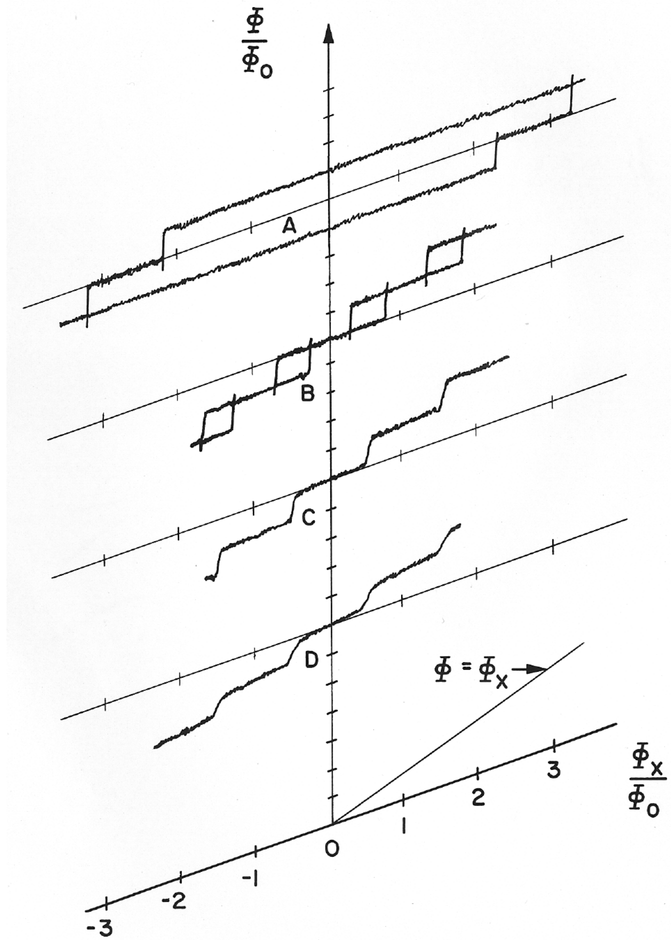
SQUID Quantized States and Transitions

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

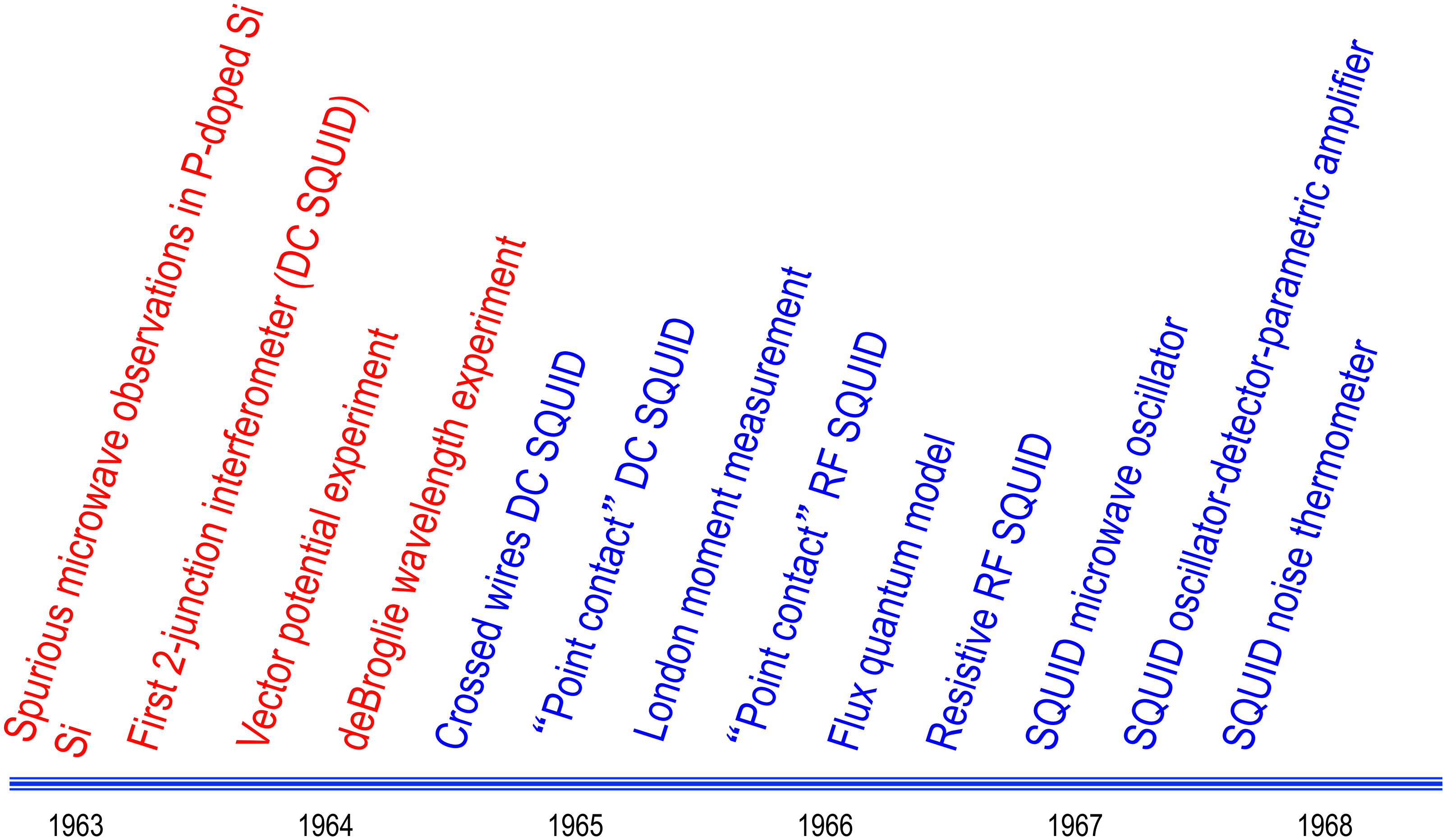
Theory



Measurement



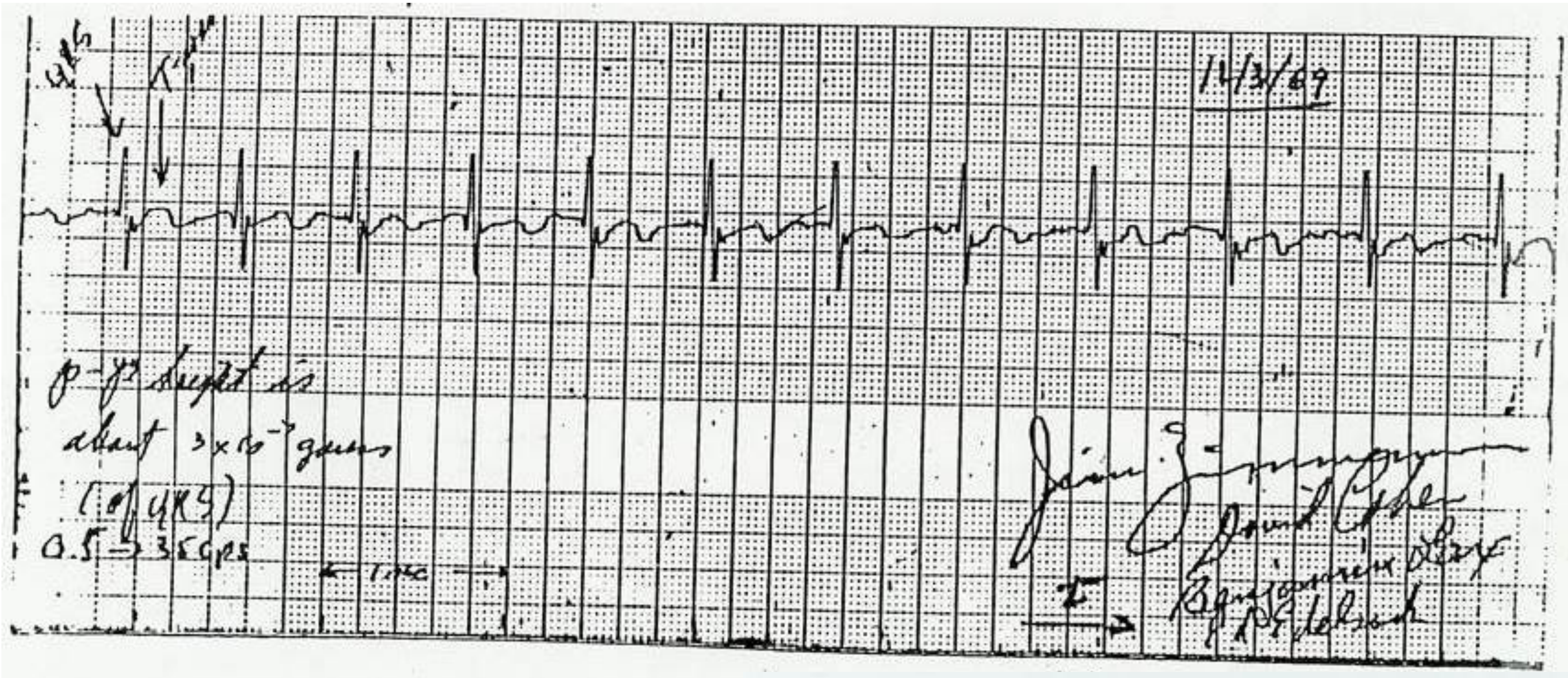
Ford SQUID Summary



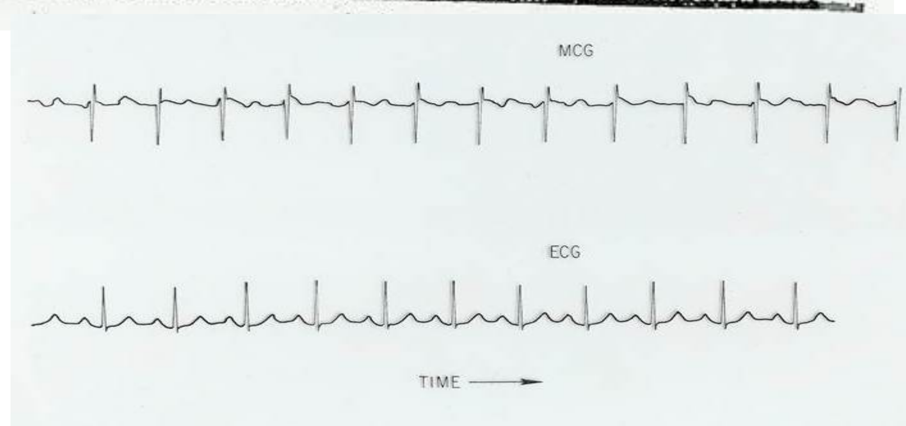
Thin-film junction devices

Bulk Nb point contact devices

First MCG: 12/1969 at National Magnet Lab, MIT



Jim Zimmerman, NBS (NIST) Boulder: test subject
David Cohen, National Magnet Lab
Benjamin Lax, National Magnet Lab
Ed Edelsack, Office of Naval Research



SQUID vs. Josephson Junction

- The Josephson junction is the critical element of a SQUID since it is the non-linear part.
- It has a small but non-linear inductance

$$L_J = \frac{\Phi_0}{2\pi i_c \cos\theta}$$

- It is difficult to match the inherent Josephson inductance, parasitic capacitance, and resistance of the Josephson junction
- The SQUID inductance provides the most effective method of coupling to the junction inductance,

$$L_{SQ} \approx L_J$$

- Flux quantization is inherent in the physics of both the junction and the SQUID loop

Notable Developments

- IBM Josephson latching logic computer project
- IC lithographic processes
- Washer SQUIDs
- Nb AlOx tunnel junction process
- Japan computer projects
- A/D converters
- SFQ circuitry
- HTS technology
- Mixed-signal electronics
- SQUID Qubits

SQUIDs have impacted at least these areas

- Sensing magnetic fields from many sources
- A/D converters
- Cryogenic imagers
- Mixed-signal electronic devices and systems
- Digital computing
- Quantum computing

RF SQUID Video Recordings