SQUIDs and SQUID-microscopy

Klaus Hasselbach

outline

- Basic principles of SQUIDs
- Applications of SQUIDs
- SQUID microscopy

Basic principles of SQUIDs

- Flux quantization in superconducting Ring
- DC and AC Josephson effect

Realization of SQUIDs

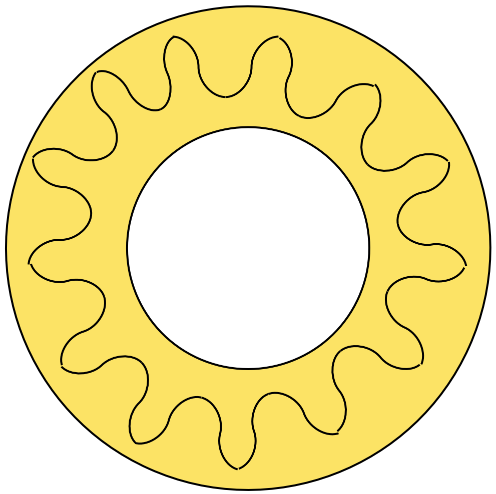
Flux quantization in superconducting Ring

$$\psi = \rho_s^{1/2}\exp(i\varphi(r)) = \psi = \rho_s^{1/2}\exp(i\vec{p}\vec{r}/\hbar)$$

$$\vec{p} = \vec{p}_{kin} + \vec{p}_{pot} = 2m\vec{v}_s - 2|e|\vec{A}$$

$$\vec{j}_s = -2|e|\rho_s\vec{v}_s$$

$$\vec{p} = -(m/|e|\rho_s) - 2|e|\vec{A}$$



Rigid phase:
total phase change must be single valued

$$\Delta\varphi = \oint(\vec{p}/\hbar)\cdot d\vec{l} = \frac{m}{|e|\rho_s\hbar}\oint\vec{j}_s\cdot d\vec{l} - \frac{2|e|}{\hbar}\oint\vec{A}\cdot d\vec{l} = 2\pi n$$

$$\phi' = (m/2\rho_s e^2)\oint\vec{j}_s\cdot d\vec{l} + \phi = n(2\pi)\hbar/(2|e|) = n\phi_0$$

Flux quantization in superconducting Ring

$$\phi' = (m/2\rho_s e^2)\oint \vec{j}_s \cdot d\vec{l} + \phi = n(2\pi)\hbar/(2|e|) = n\phi_0$$

=0 in bulk sc as J_s= 0 in bulk

$$\phi' = \phi = n\phi_0$$

$$\Phi_0 = h/2e = 2.07 \cdot 10^{-15}\,Tm^2$$

Flux(oid) quantization
Deaver and Fairbanks (PRL **7**, 43 (1961)) Doll and Naebauer (PRL **7**, 51 (1961))

Experiment proof of flux quantization

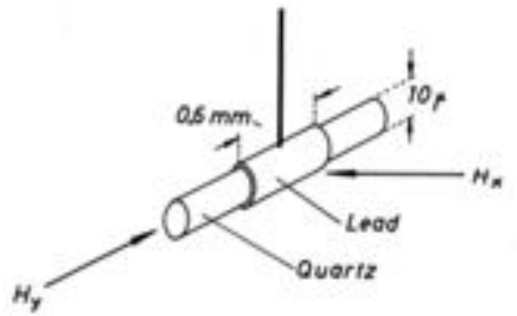


FIG. 1. Schematic diagram of the sample with the directions of the applied field H_y to be frozen in, and the measuring field H_x.

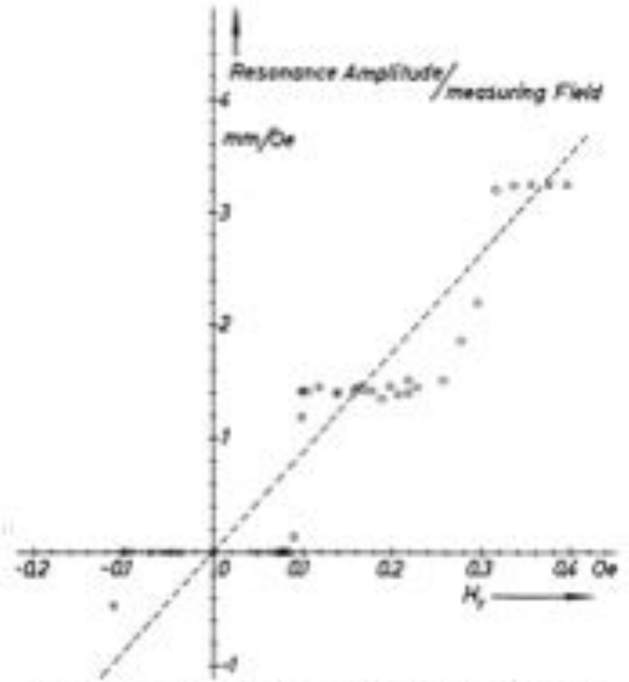
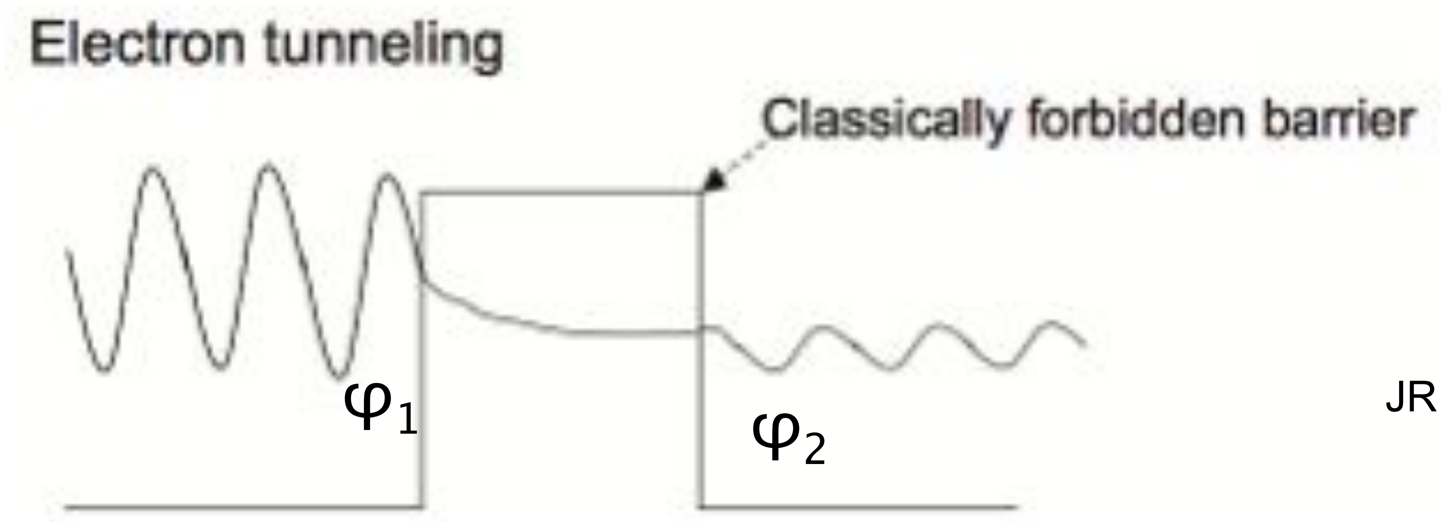


FIG. 2. Resonance amplitude divided by measuring field H_x as a function of the applied field H_y. The ordinate is proportional to the frozen-in flux. ×– First run; o– second run.

Torsional oscillator

Doll and Näbauer (PRL **7**, 51 (1961))
Torsional oscillator
Deaver and Fairbanks (PRL **7**, 43 (1961))
Magnetometry of tin coated copper wire

Josephson junction



JR Kirtley

Josephson tunneling- transfer of Cooper pairs rather than single electrons

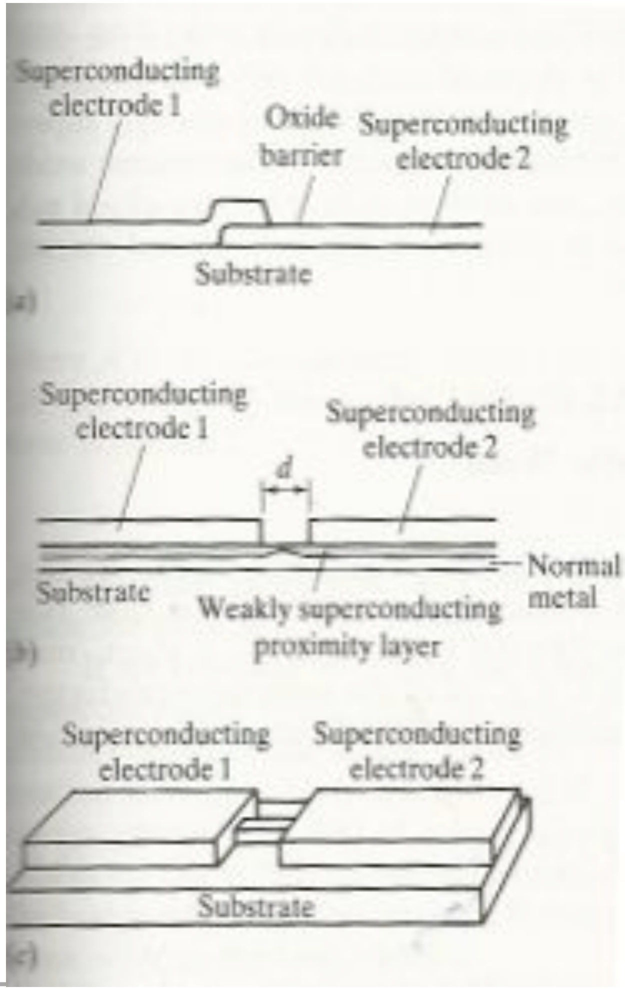
B.D. Josephson (PRL **1**, 251(1962))

$$I_s = I_0 \sin\varphi$$

$$V = \frac{\hbar}{2e}\frac{d\varphi}{dt}$$

I_s -Cooper pair current across junction
I_0 -Junction critical current
φ −difference in pair phases across junction

Josephson Junctions



Tunnel barrier

SNS Junction

Micro Bridge junction

M. Tinkham

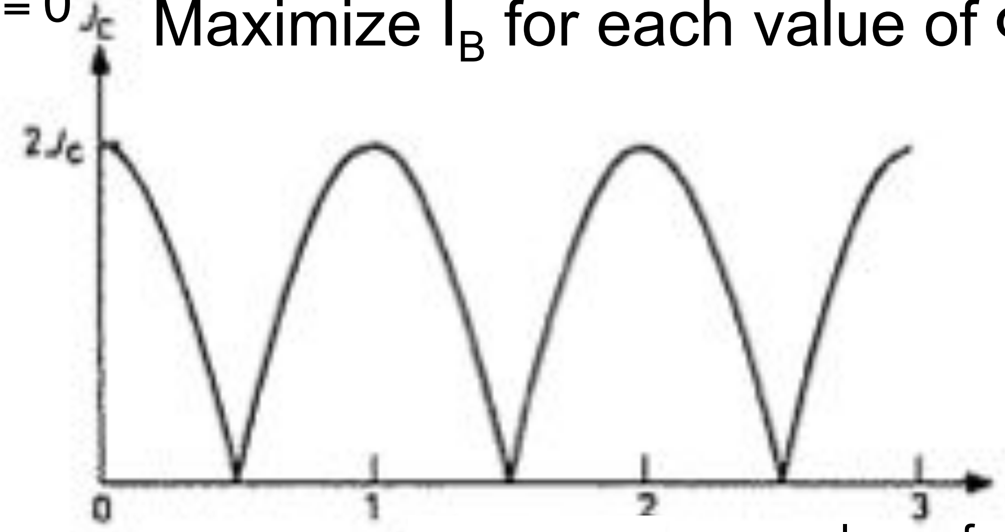
DC-SQUID

I_1, I_2 – critical current of junctions
L_1, L_2 - inductances of arms of SQUID loops

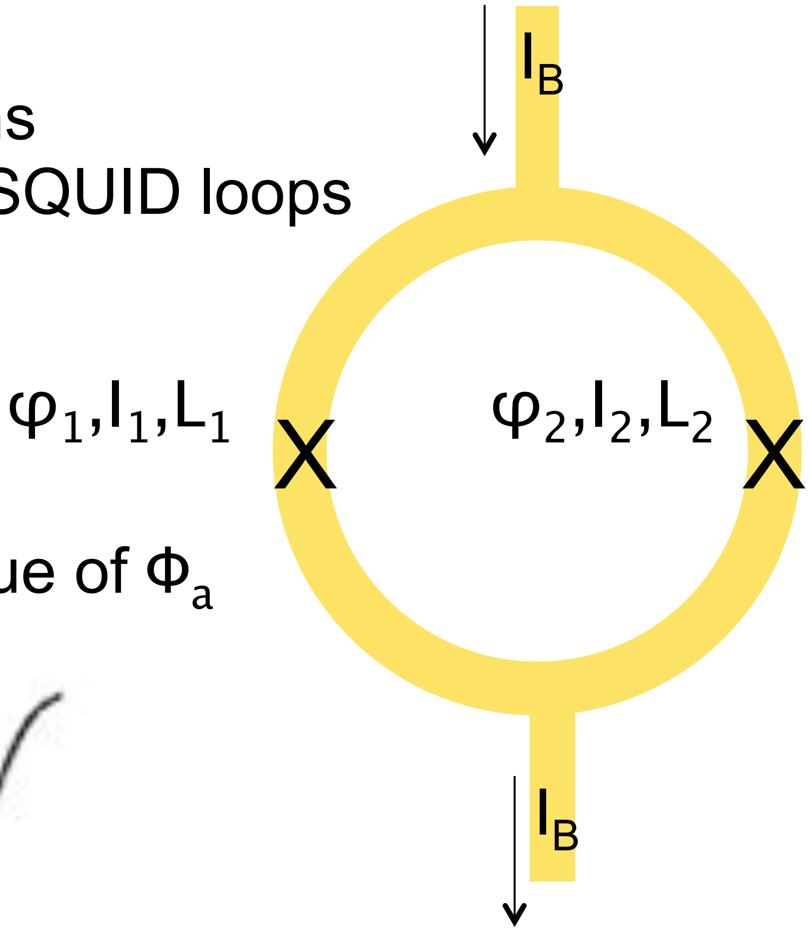
$$I_B = I_1 \sin(\varphi_1) + I_2 \sin(\varphi_2)$$

$$2\pi n = \varphi 2 - \varphi 1 + \frac{2\pi}{\Phi_0}(\Phi_a + L_2 I_2 - L_1 I_1)$$

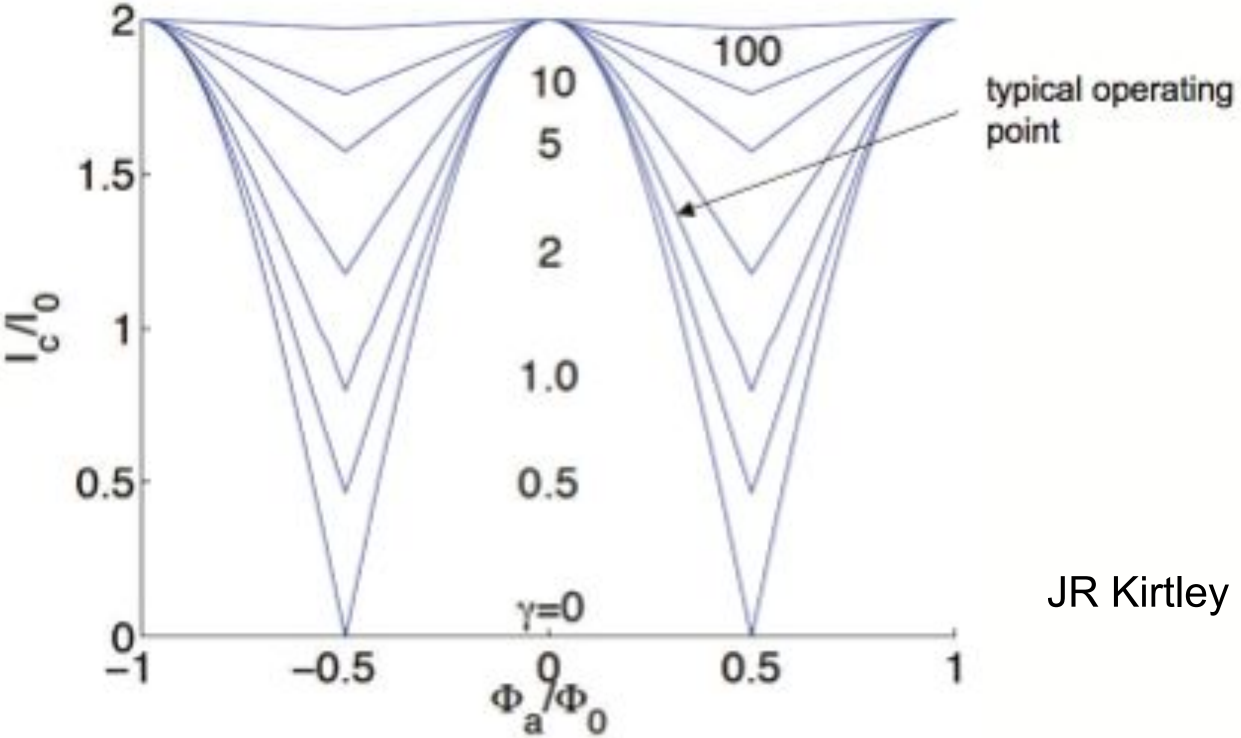
$n = 0$ Maximize I_B for each value of Φ_a



Φ_a/Φ_0



Design considerations



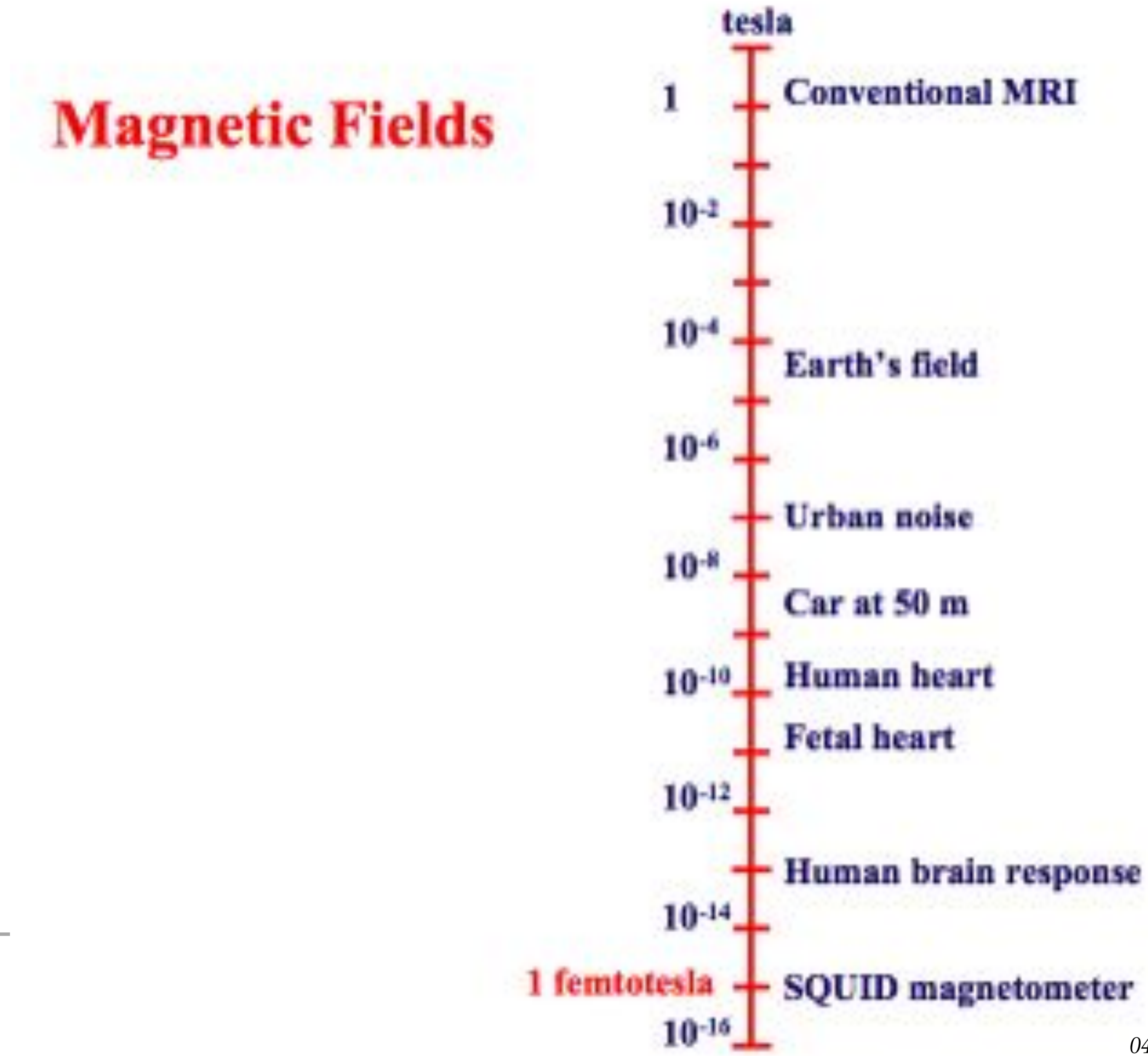
JR Kirtley

$$\gamma \equiv \frac{2\pi L I_o}{\Phi_o}$$

SQUID size (≈inductance L) not too small

I_c sufficient big compared to thermal noise

Magnetic field scales



J. Clarke

Operation of SQUID

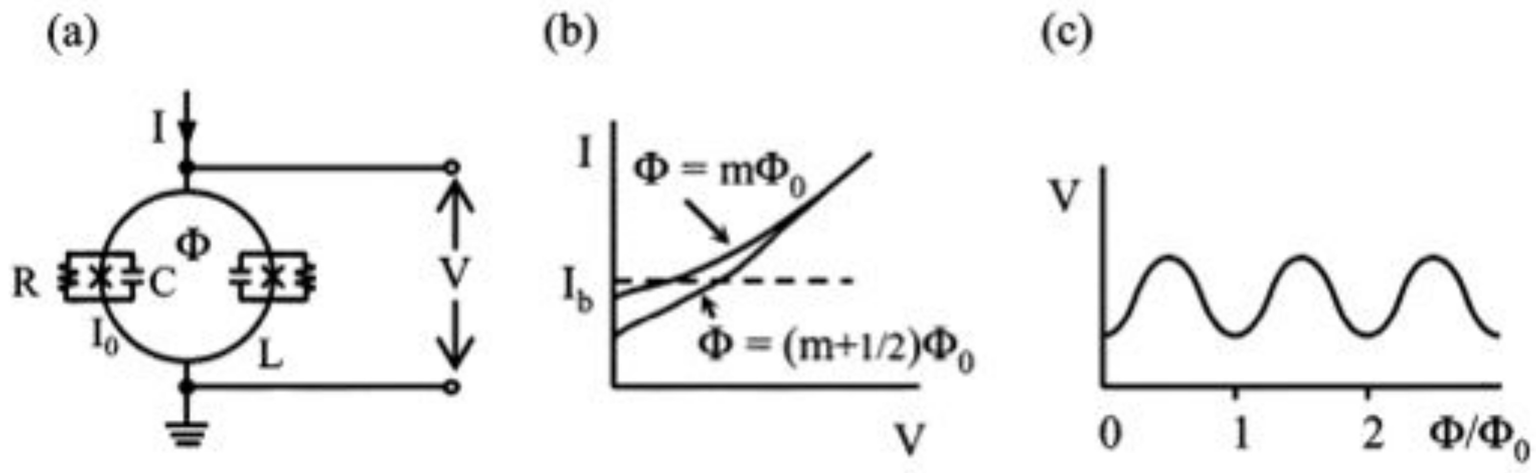


Fig. 1. DC SQUID. (a) Schematic. (b) *I–V* characteristic. (c) V versus Φ/Φ_0 at constant bias current I_b.

R. Kleiner

Noise in DC SQUID

- Nyquist noise of shunt resistor
- Spectral density of flux noise

$$S_{\phi}(f) \approx 16 k_B T L^2 / R$$

- L=200 pH, R= 6 Ohm T=4.2 K

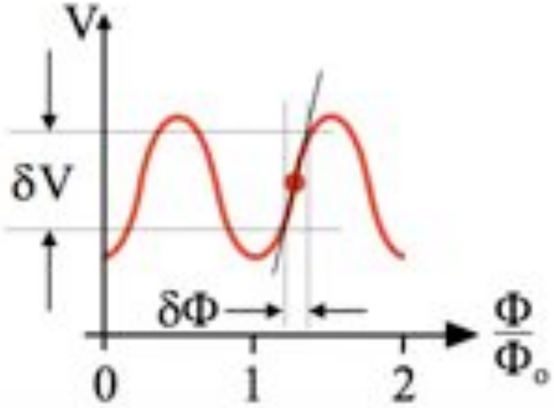
$$S_{\phi}^{1/2}(f) \approx 1.2 \cdot 10^{-6} \phi_0 / \sqrt{Hz}$$

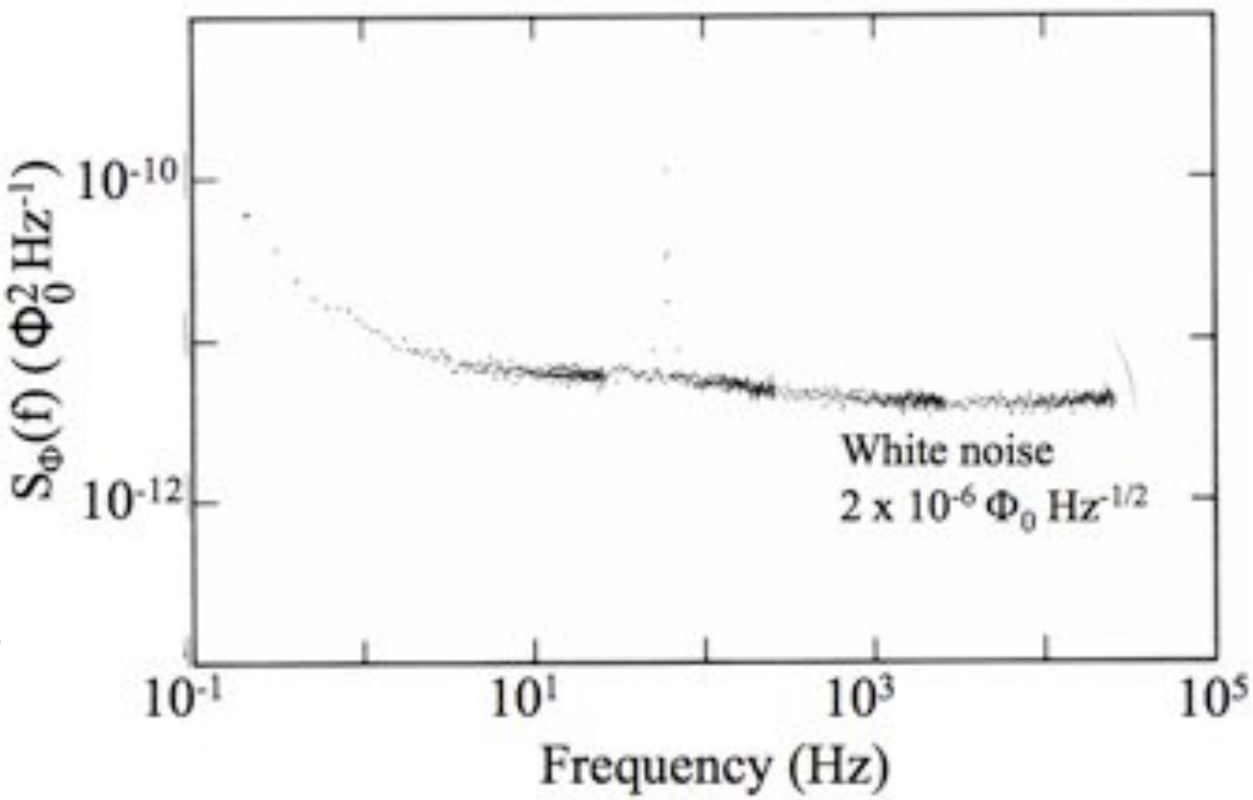
- Noise energy

$$\varepsilon(f) = S_{\phi}(f) / 2L \approx 10^{-32} JHz^{-1} \approx 100\hbar$$

C. Tesche, J Clarke 1977

Flux noise in the SQUID





J. Clarke

Applications of SQUIDs

- Magnetometer
  - Geophysics
  - Medical research
- Non destructive testing
- Current amplifier

How is the SQUID coupled to the world?

Electronics readout

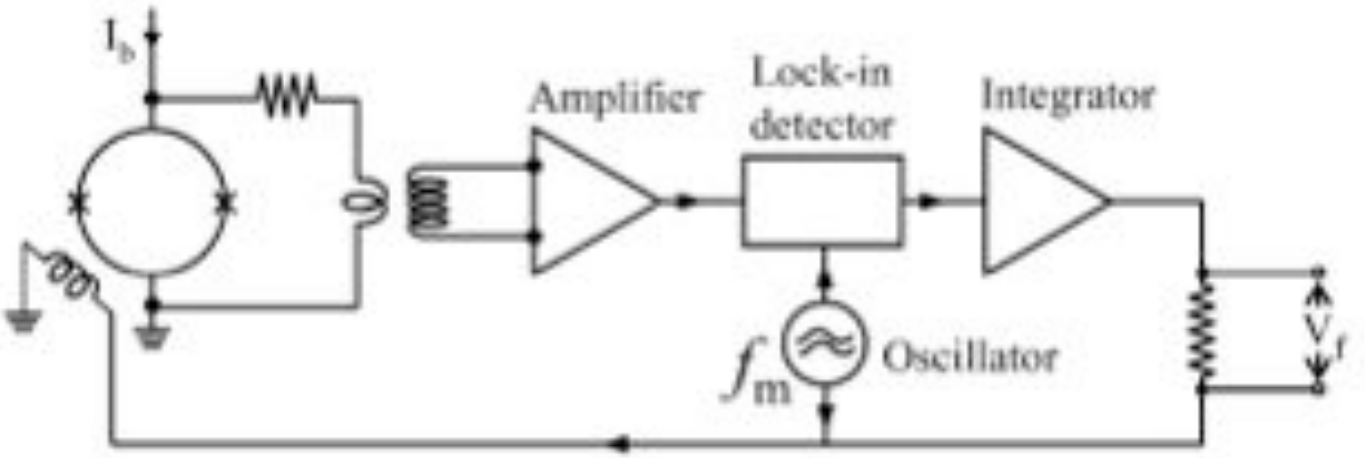


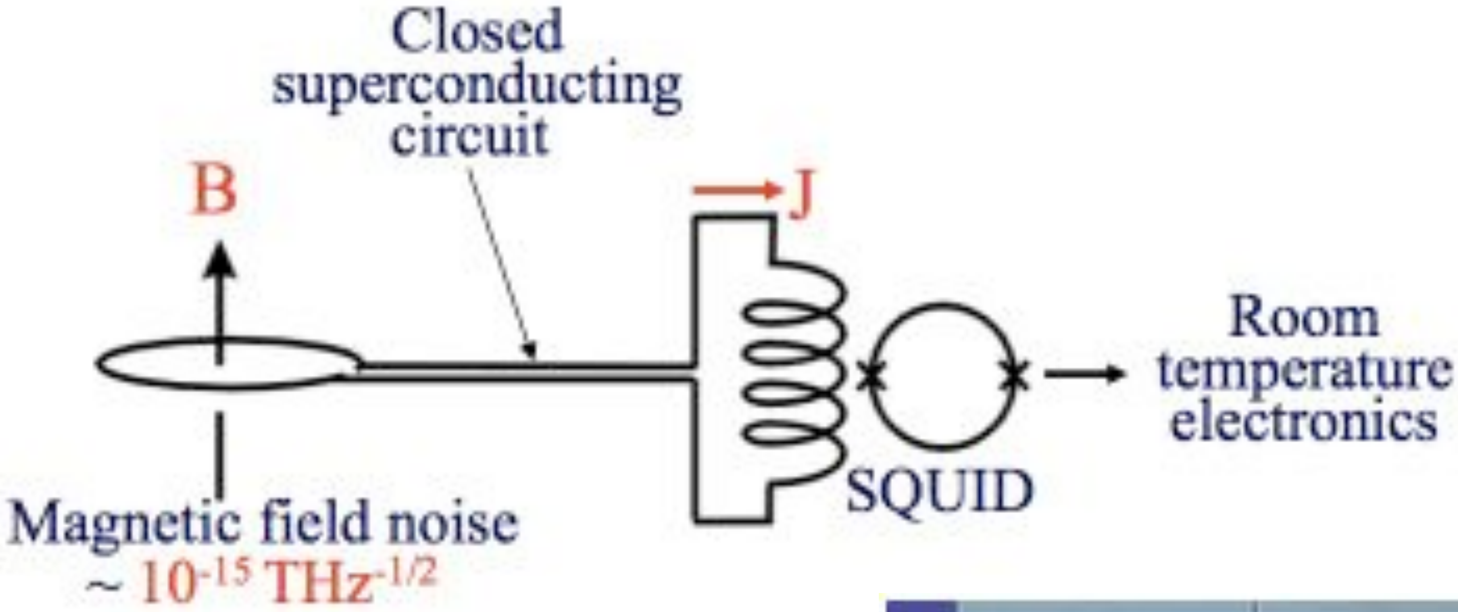
Fig. 4. FLL for operation of a dc SQUID.

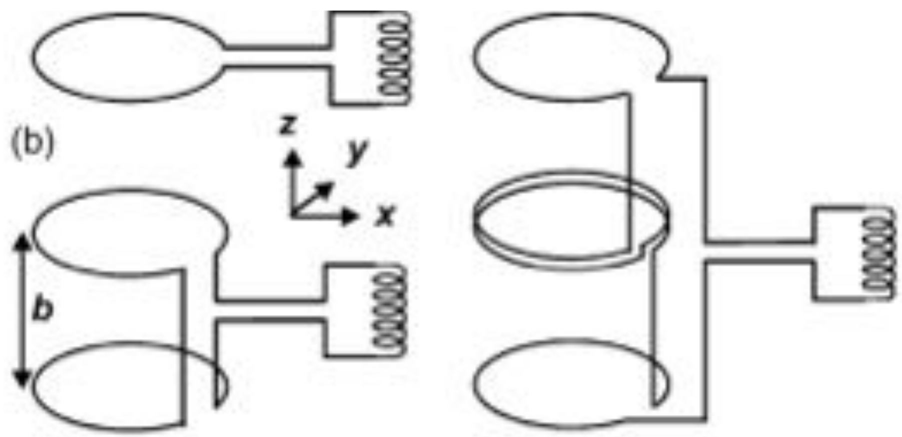
R Kleiner

The SQUID is part of a feed-back loop,
maintaining it at given Flux
-> allows to measure important fields

Transformer gradiometer…

J. Clarke





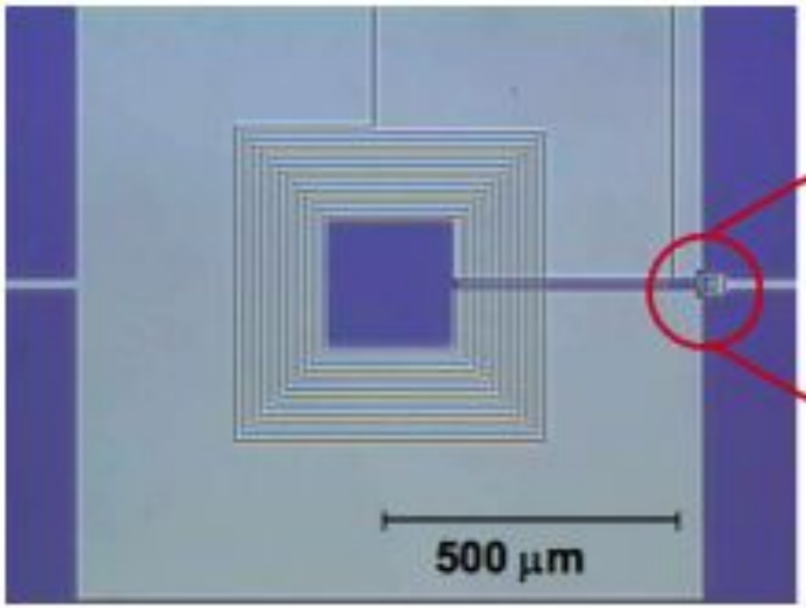


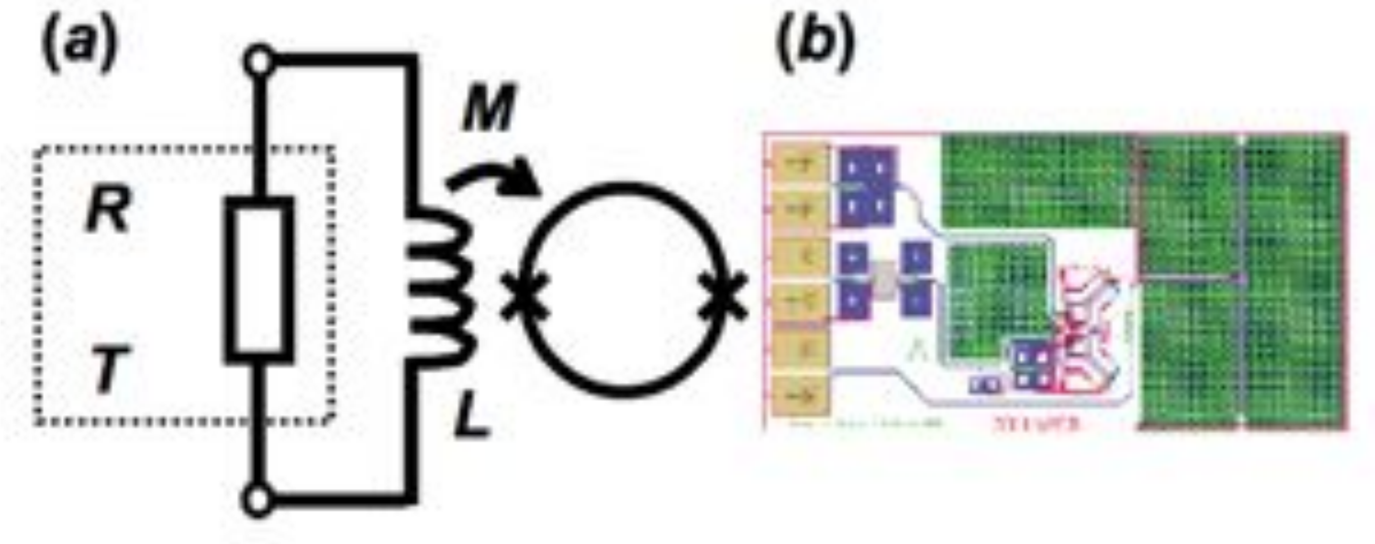
Fig. 5. Superconducting, wire-wound flux transformers. (a) Magnetometer. (b) First-derivative, axial gradiometer.

Noise thermometry

J. Engert et al. PTB

$$S\phi(f,T) = \frac{4k_b T M^2}{R(1+(f/f_c)^2)}$$

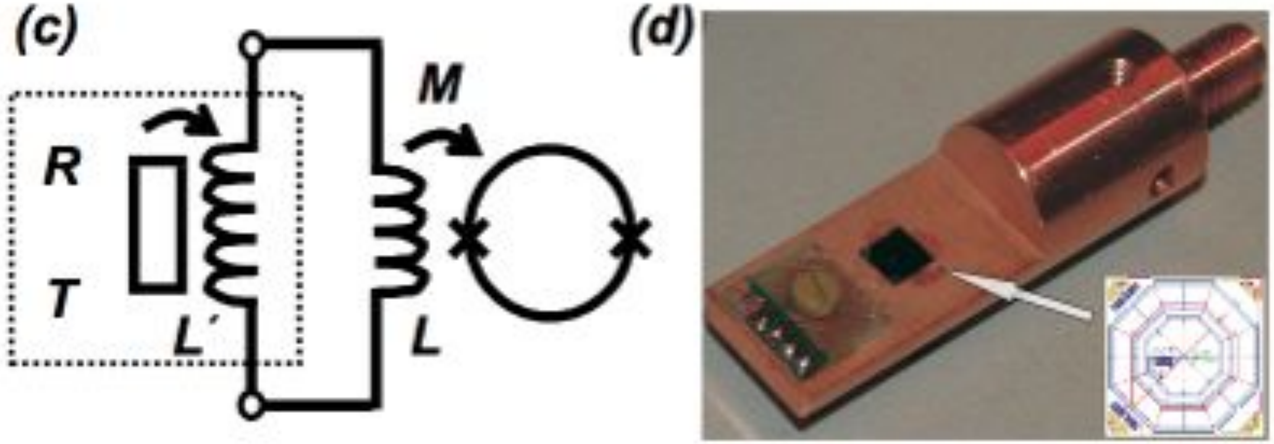
$f_c = R/2\pi L$



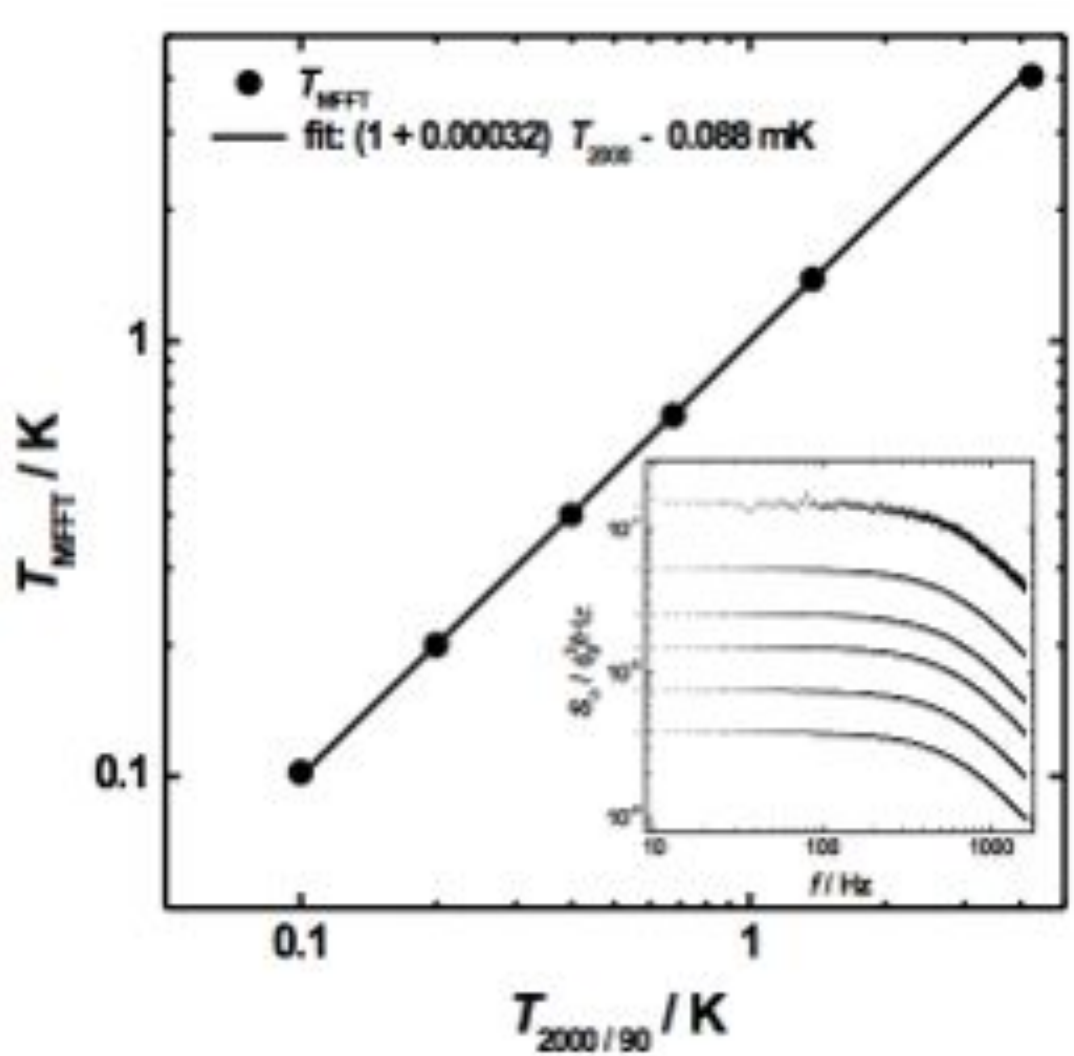
Pd resistor in the circuit of 1 mOhm (green)

Measure the fluctuating currents in a piece of copper (thermal magnetic flux noise) -> better thermalization of electrons.

$$S\phi(f,T) = \frac{4k_b T M^2}{R(1+(f/f_c)^{2a})^b}$$



Noise thermometry



Nano-SQUID

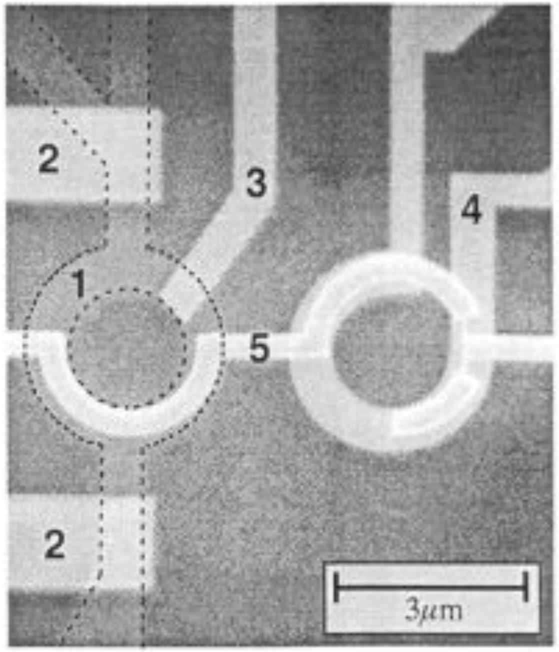


FIG. 1. Electron micrograph of the experimental device. On the left is the ring etched in GaAs 2DEG (labeled 1) (the dashed line has been added because of the poor contrast) with the two gates, (2) and (3). On the right is the calibration coil (4). On the top is the first level of the SQUID fabrication (5) with the two microbridge junctions on the right. The picture has been taken before the second level of the SQUID fabrication.

Mailly PRL 1993

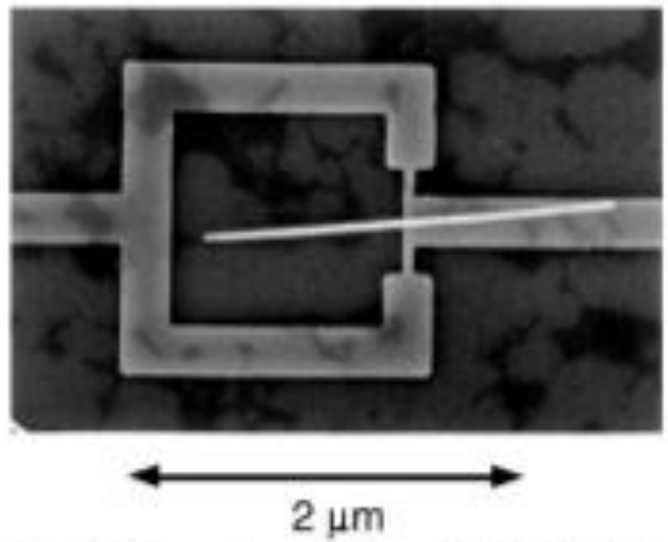
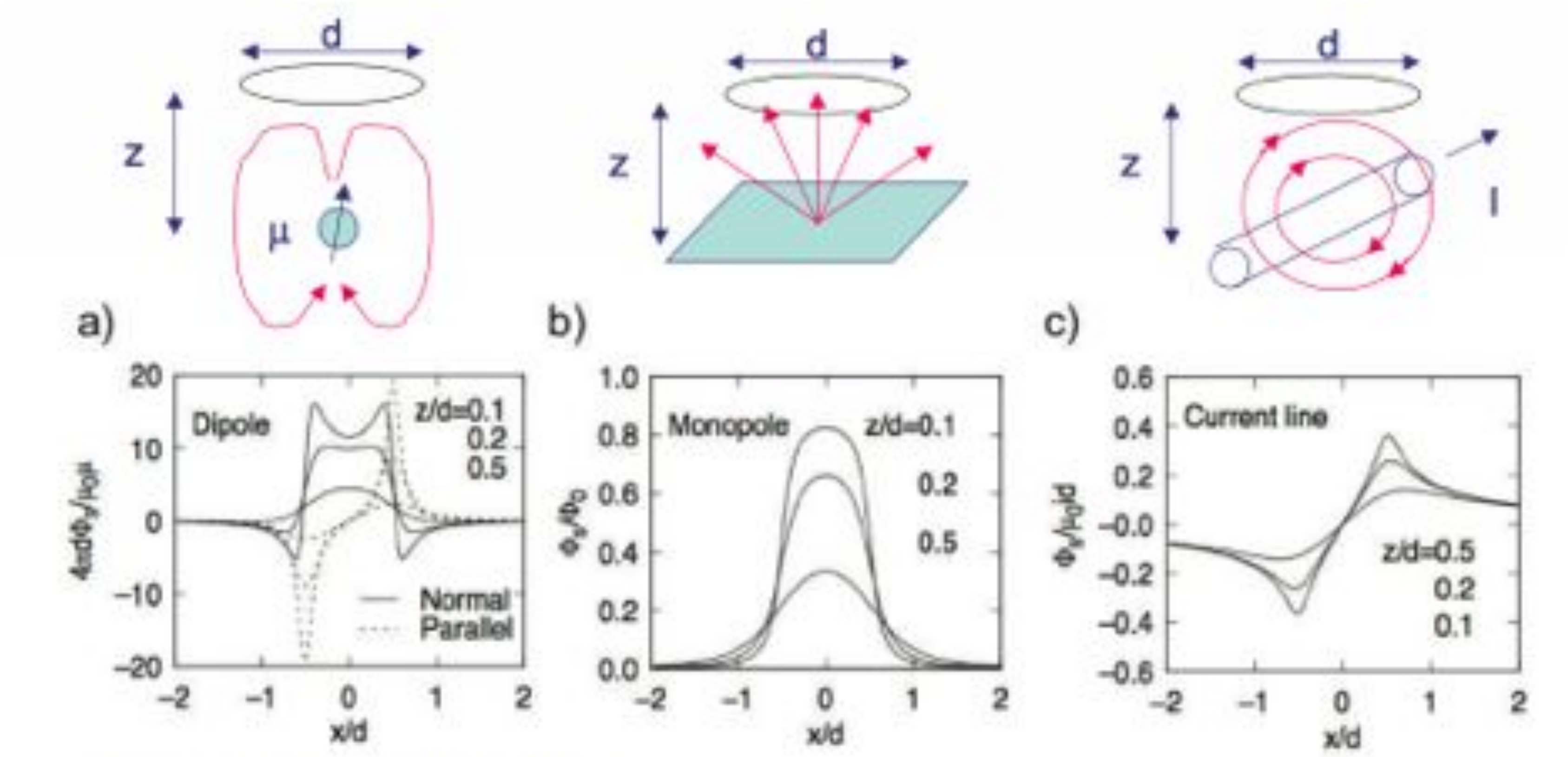


FIG. 1. Scanning electron micrograph (JEOL 6300) of a microbridge dc SQUID and a Ni wire of diameter of 65 ± 4 nm.

Wernsdorfer PRL 1996

SQUID Microscopy



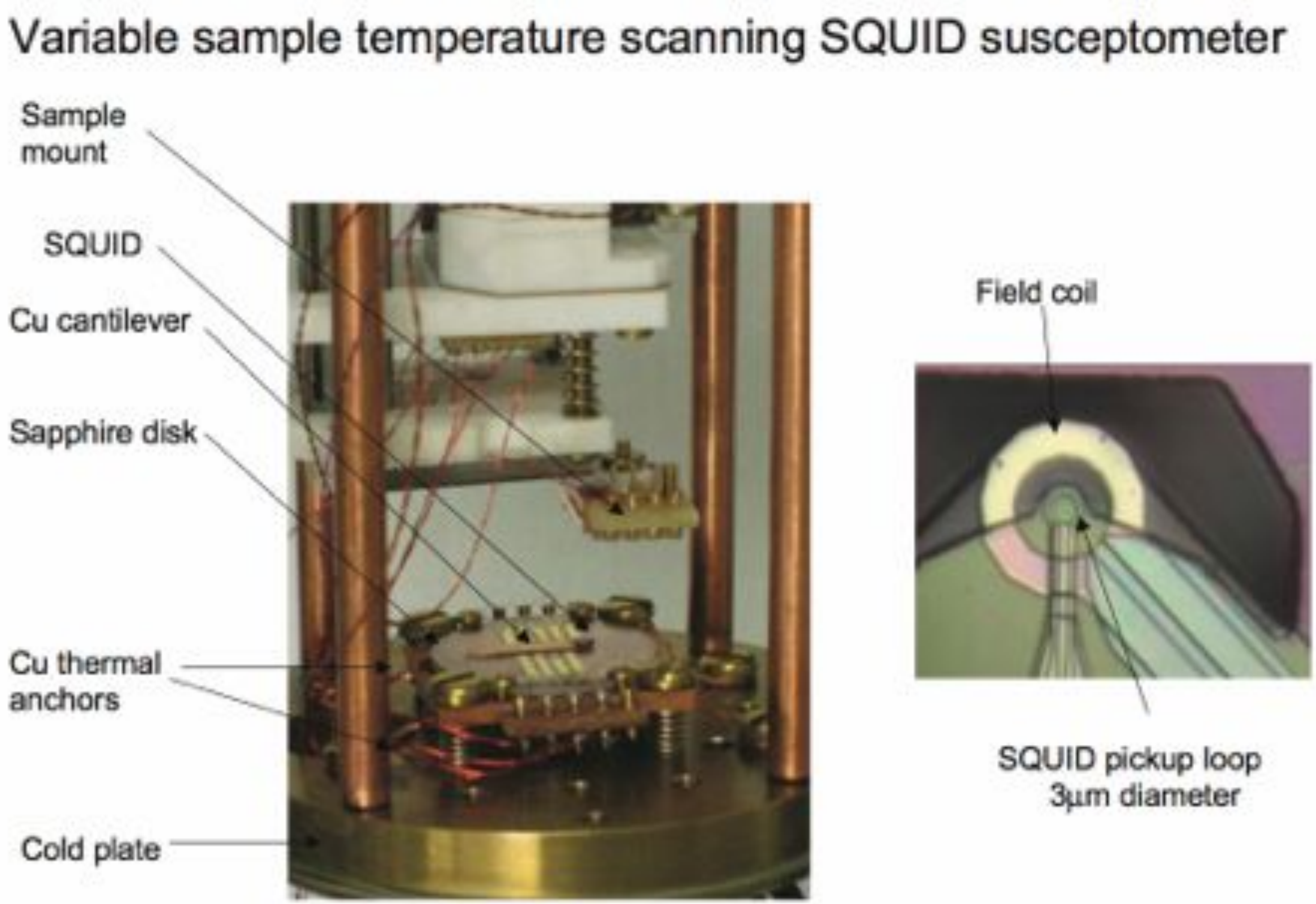
If SQUID noise = $10^{-6}\,\Phi_0/Hz^{1/2}$

$N_{min} \cong 200$ electron spins/$Hz^{1/2}$ $\Phi_{min} \cong 10^{-6}\,\Phi_0/Hz^{1/2}$ $I_{min} \cong 4\times10^{-9}\,A/Hz^{1/2}$

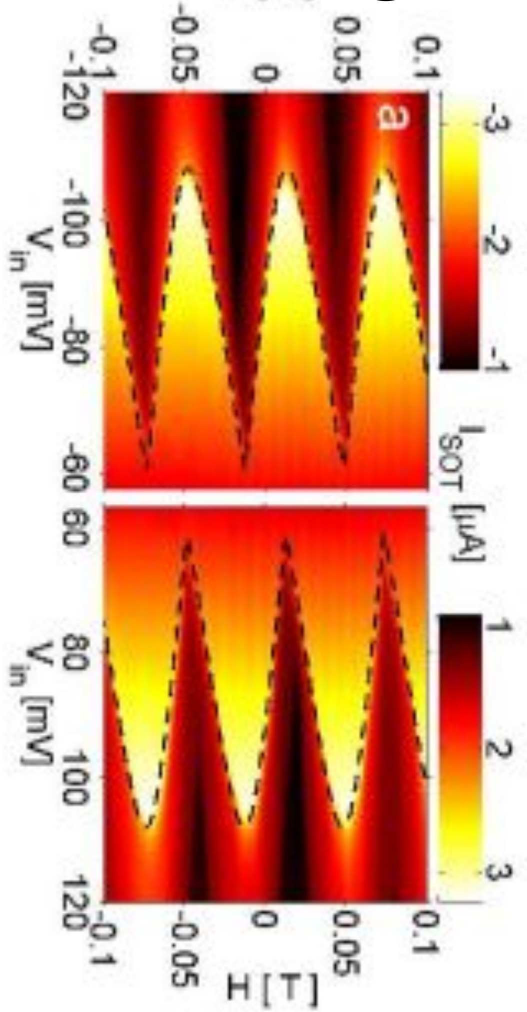
Sensitivity and spatial resolution depend on size of pickup area and spacing to sample

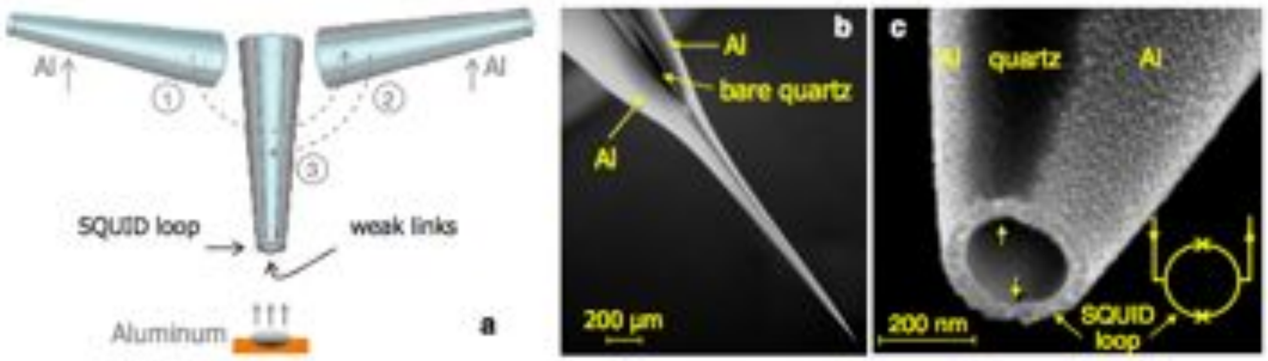
JR Kirtley

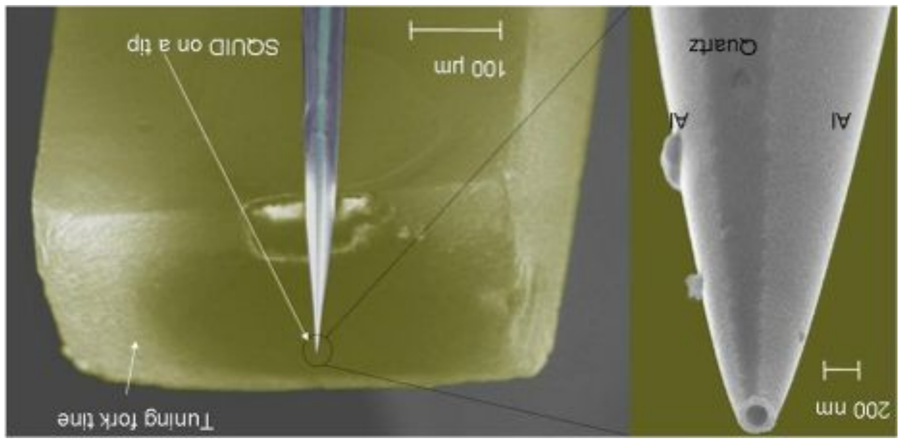
Stanford IBM J.R. Kirtley



Weizmann SQUID on Tip

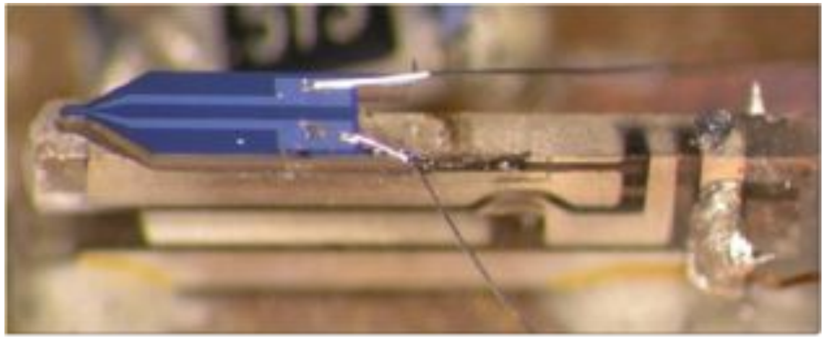






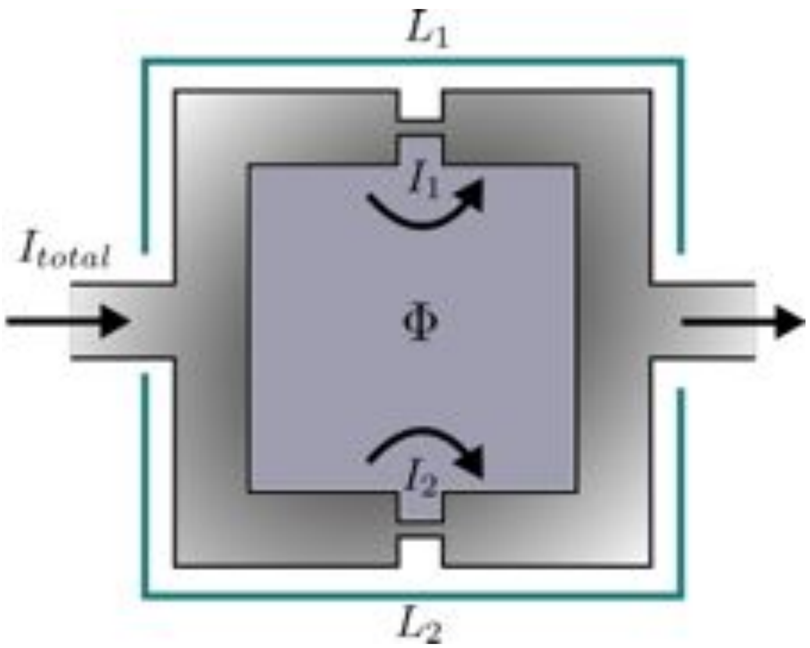
Grenoble NanoSQUID microscope

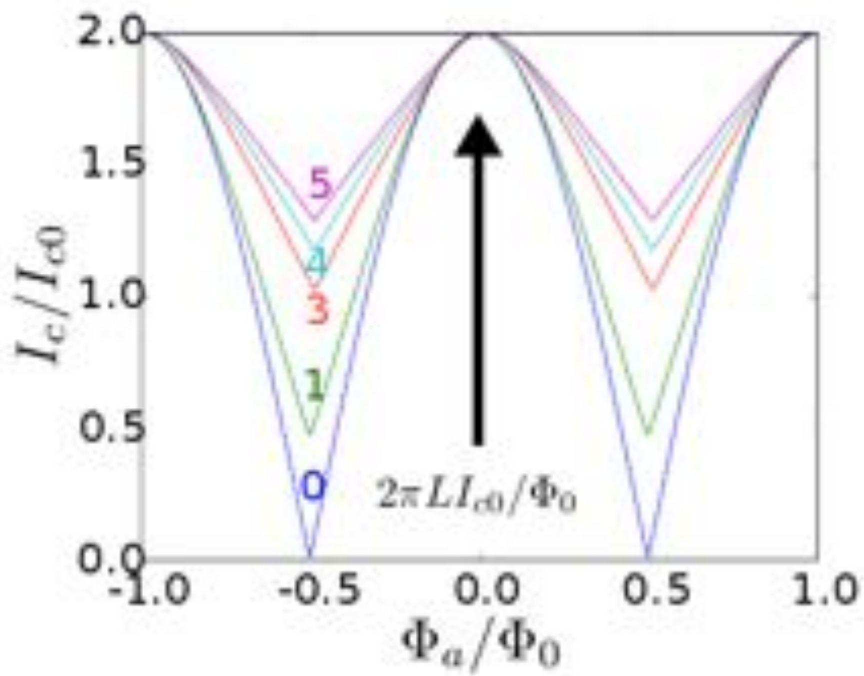
- Former PhD students:
  - C. Veauvy, V.O. Dolocan, D. Hykel
- Present PhD
  - Z.S. Wang
- PostDoc
  - D. Hazra



- Technical support:
  - T. Crozes, T. Fournier, G. Garde, J. Minet, P. Carecchio, O. Exshaw, M. Grollier
- Collaborations:
  - K. Schuster IRAM, J.R. Kirtley,…..

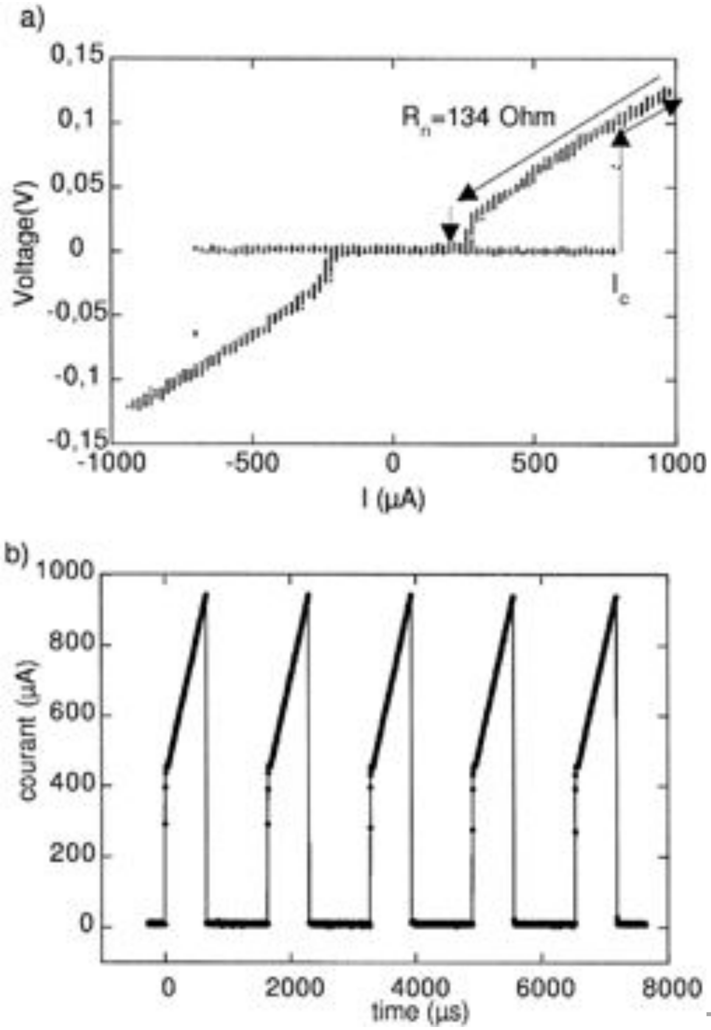
SQUID





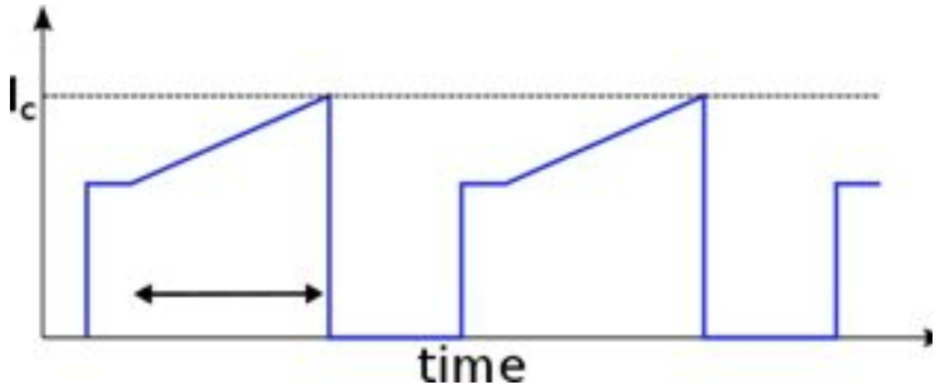
Flux penetrating the SQUID loop modulates the critical current

Hysteretic Nano-SQUID

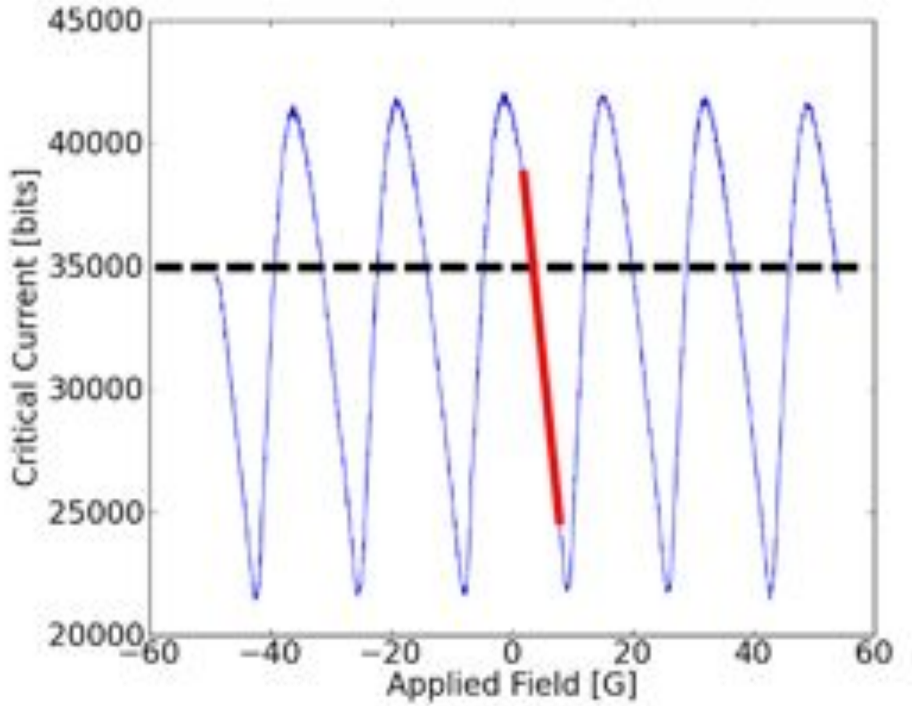


K. Hasselbach et al.
Physica C 332(2000)140–147

Critical current measurement



Field range ± 100 G

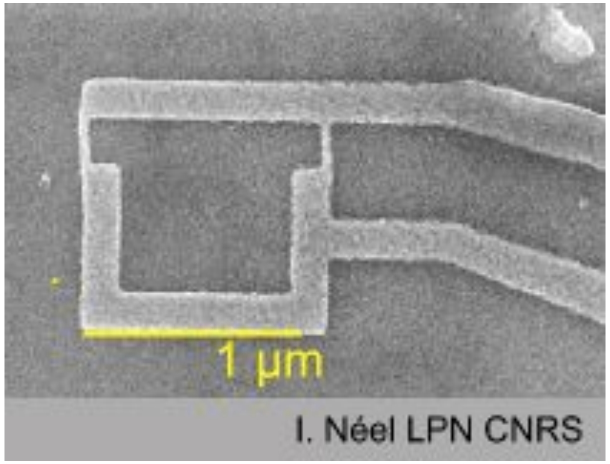


Magnetic sensitivity

$1.2\cdot 10^{4}\Phi_0/\sqrt{Hz}$

$2\cdot 10^{-3}G/\sqrt{Hz}$

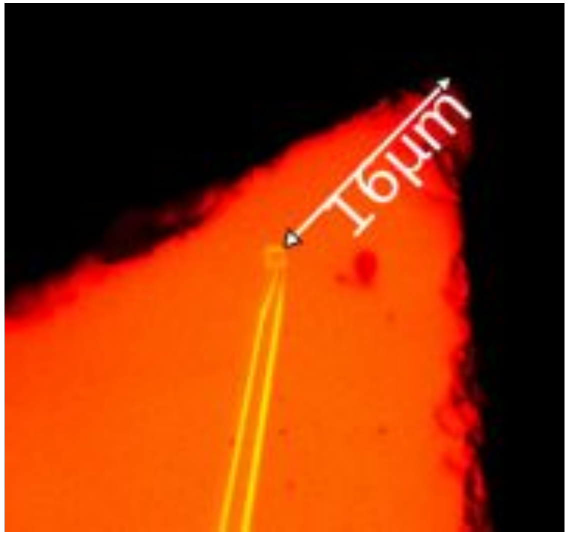
SQUID tip first generation



Aluminium

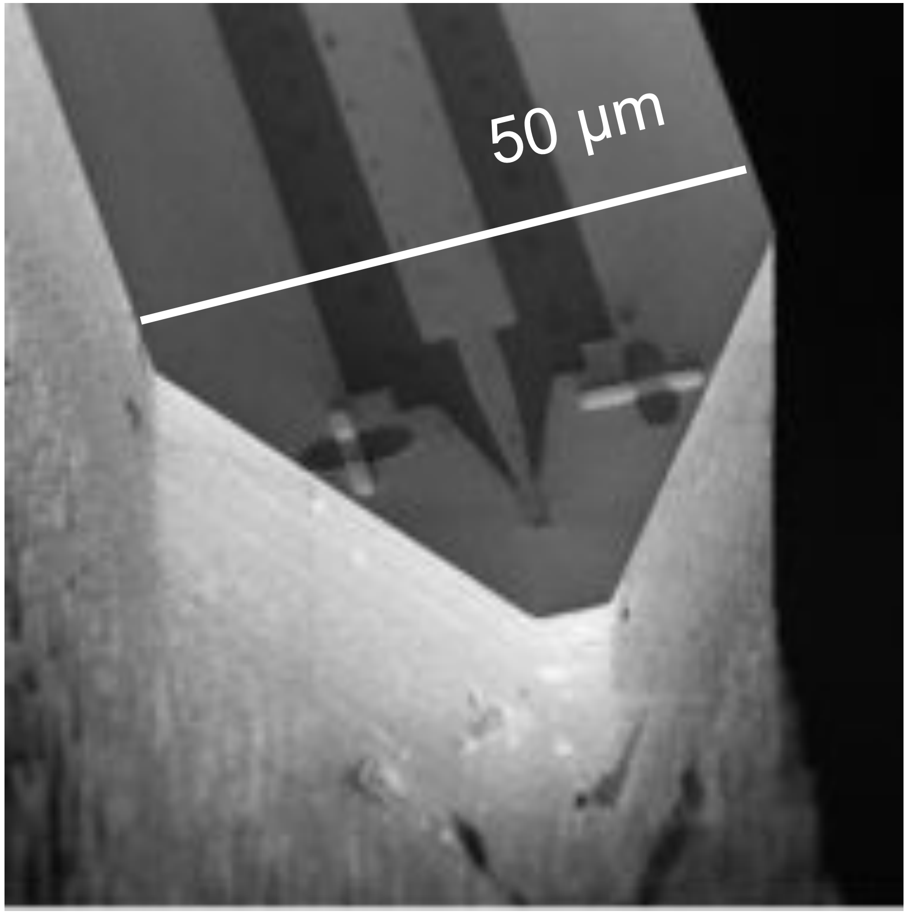
0.6 µm / 1.1 µm diameter

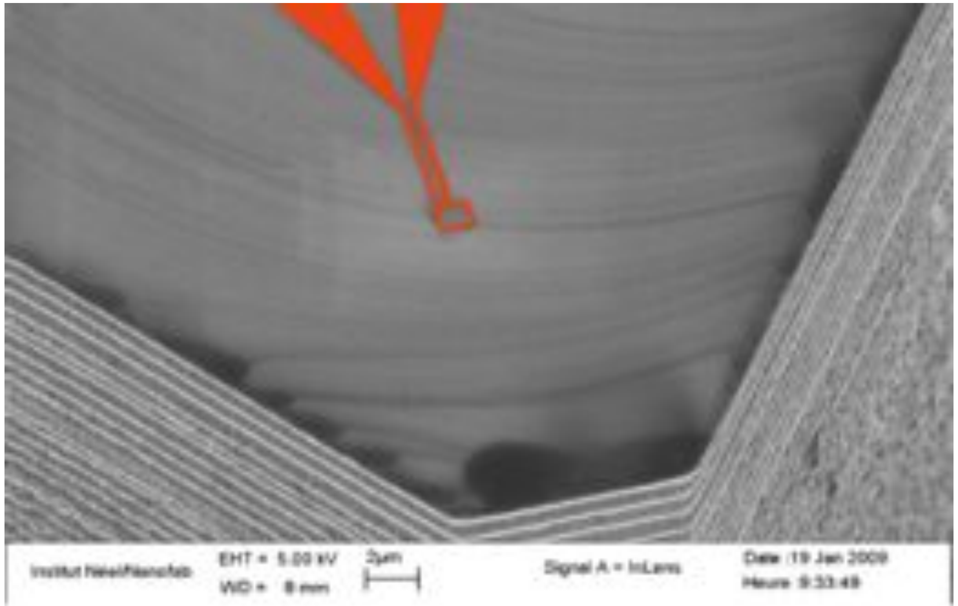
To minimize the distance between SQUID and sample we cut the wafer



T. Crozes (IN)
D. Mailly (LPN)
Y. Gamberini

SQUID tip second generation

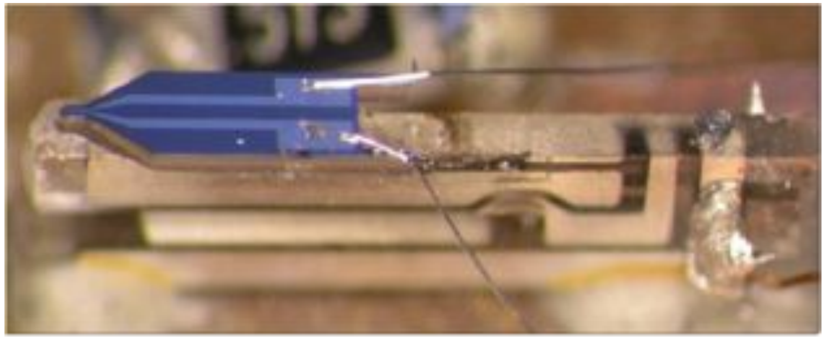




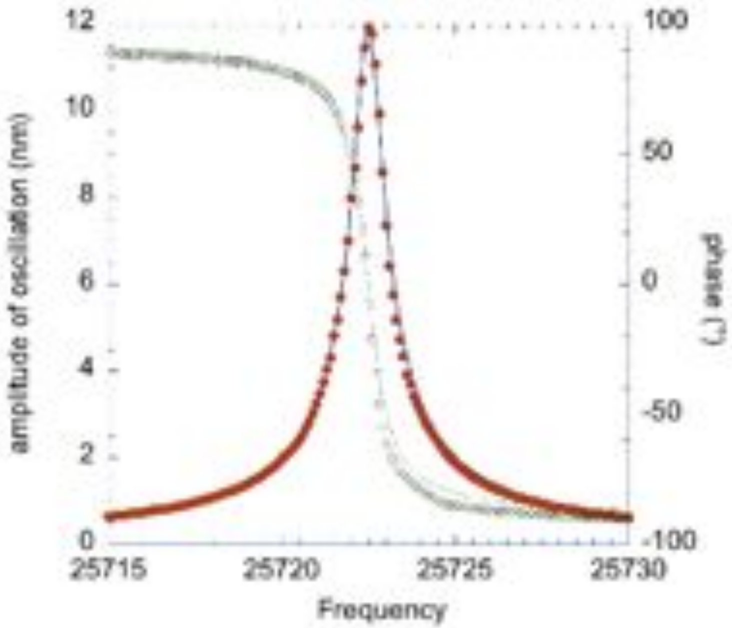
Deep Si etching allows for better edge SQUID alignment

T. Crozes (Neel),
A. Barbier, K. Schuster (IRAM)

Squid Force Microscopy



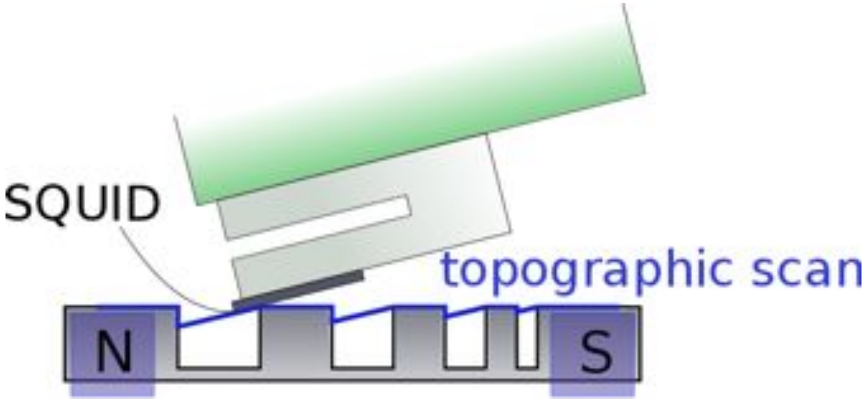
2 mm



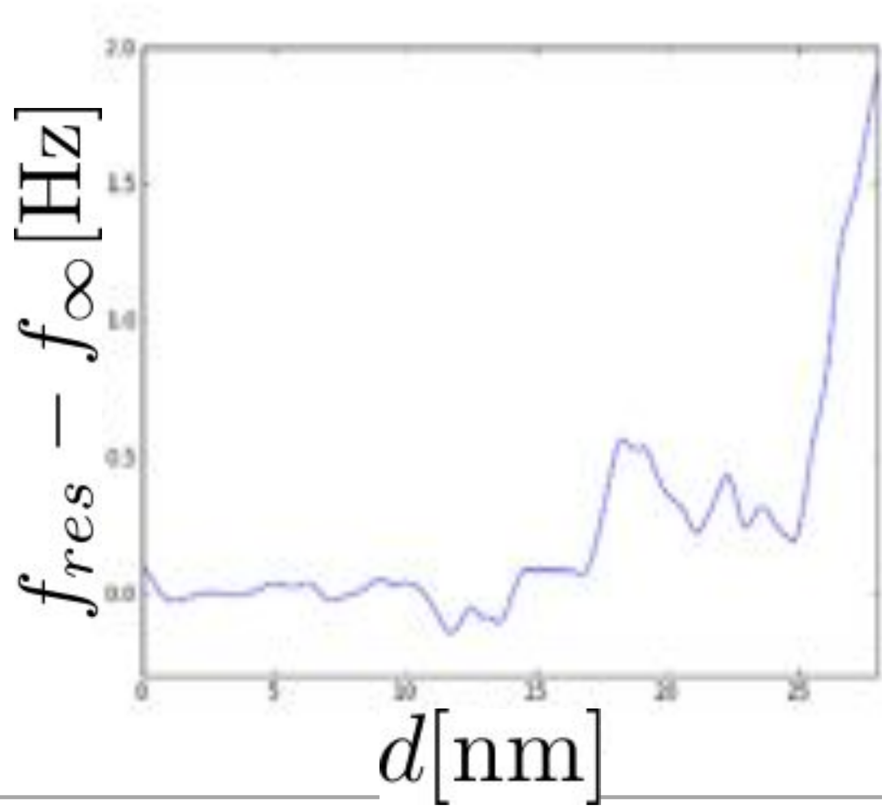
Quartz tuning fork-> Distance Control

Review of Scientific Instruments C. Veauvy et al. **73** 3825 2002

AFM Principle

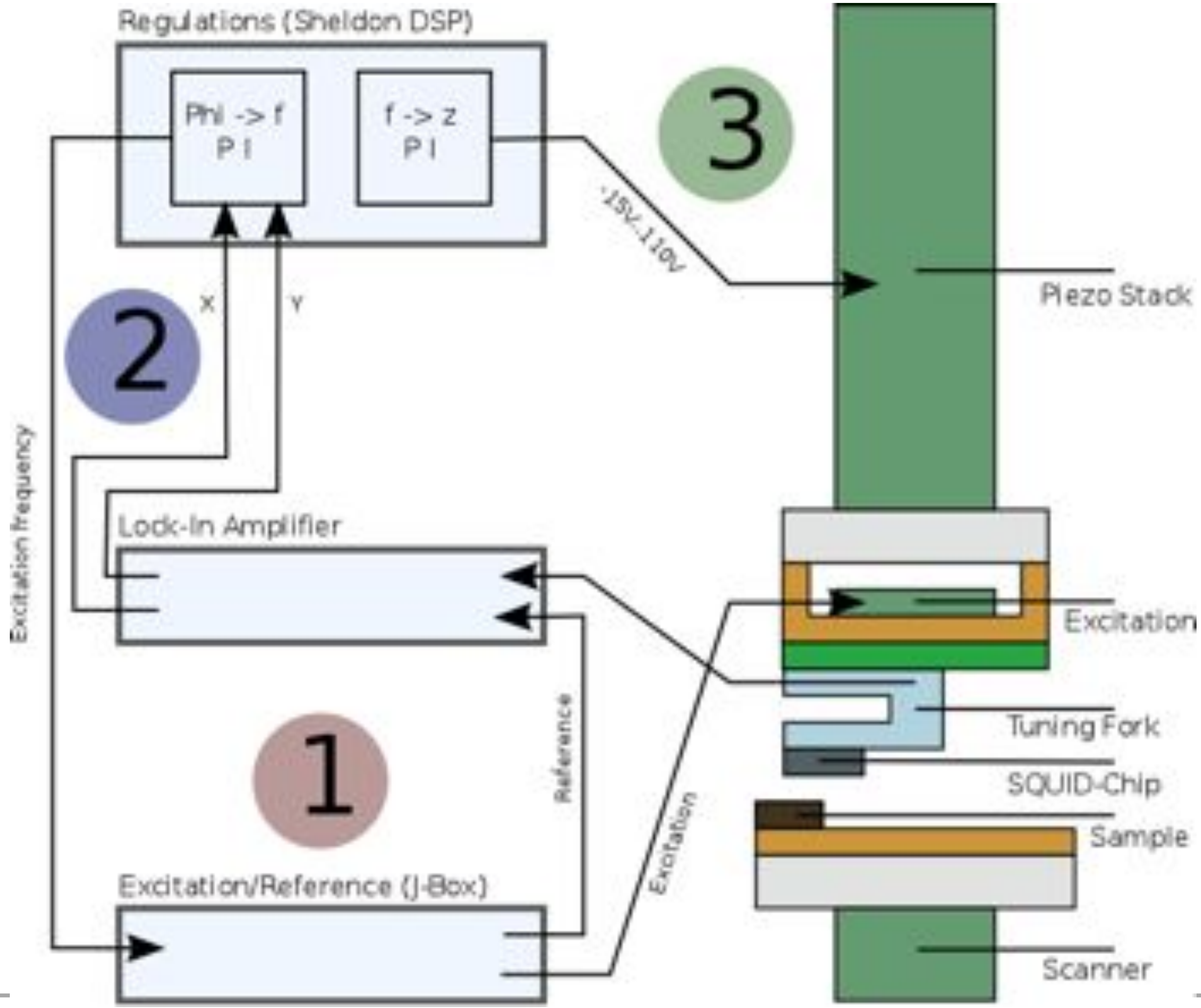


TF is a force sensor



Its resonance frequency
increases with
decreasing tip sample distance

AFM Electronic

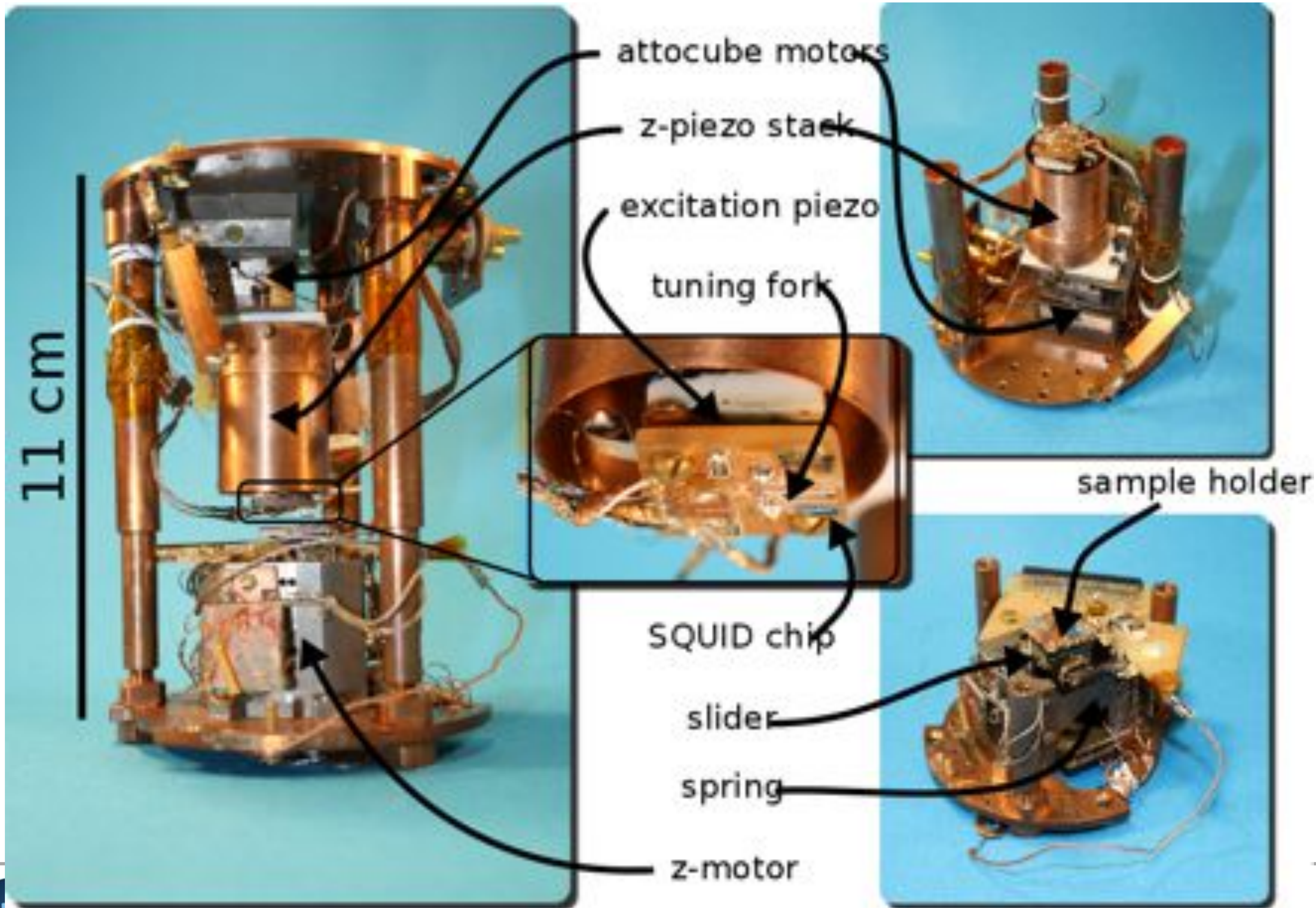


DSP contains

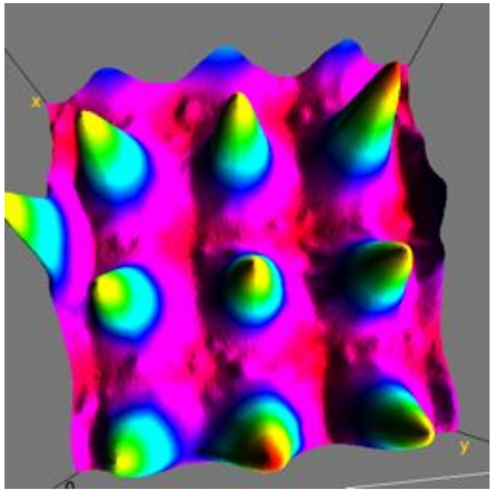
Two PI in series

10 kHz bandwidth

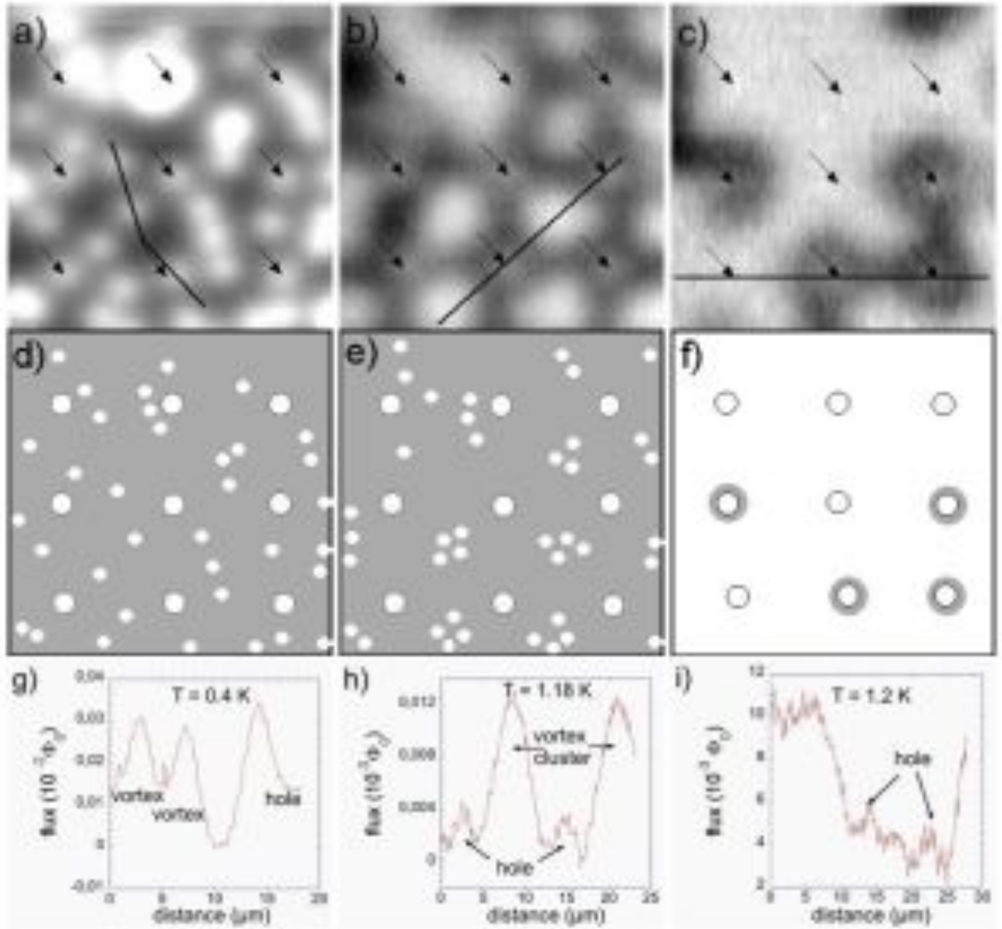
Microscope


attocube motors
z-piezo stack
excitation piezo
tuning fork
11 cm
sample holder
SQUID chip
slider
spring
z-motor

Vortices in a perforated Al film



Flux quantization at each hole

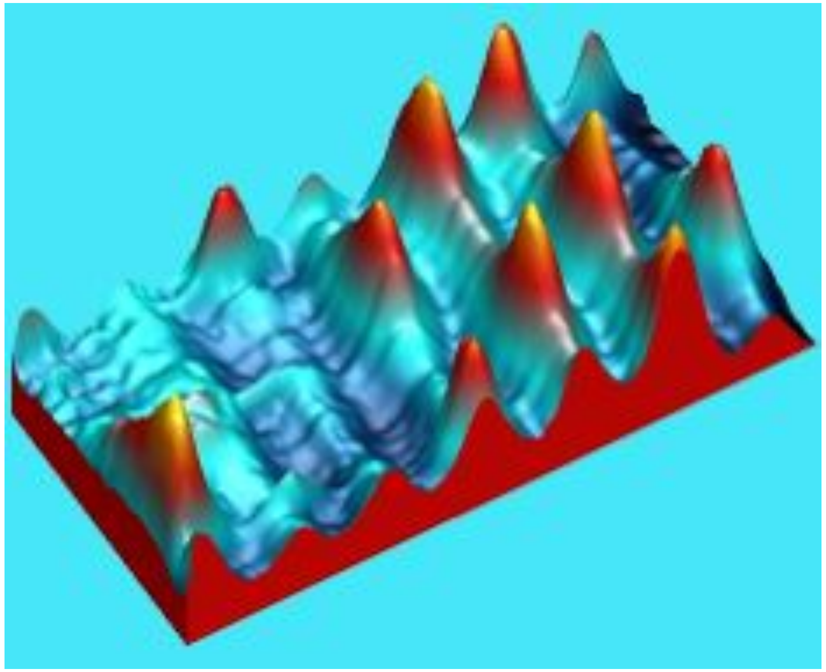


Vortex transitions: Fusion and localized SC

T=0.4K T=1.18 K T=1.2 K

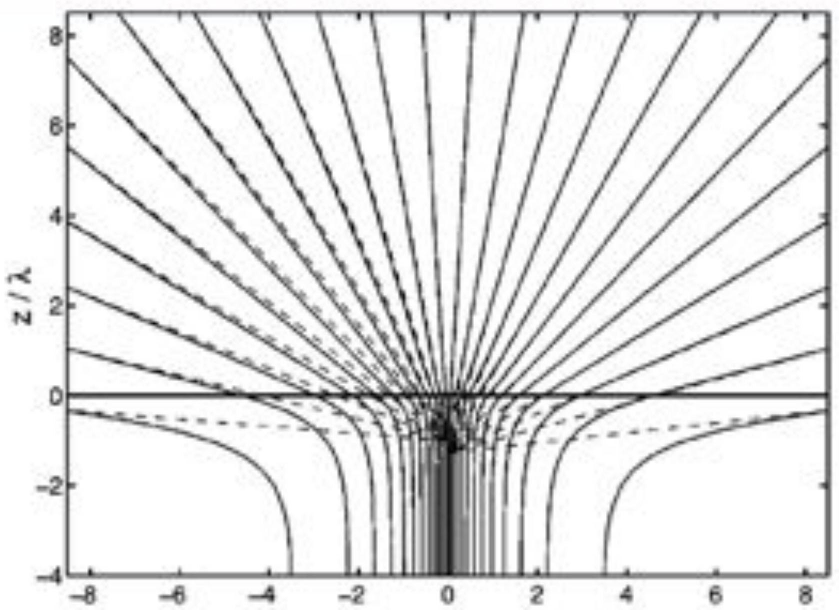
C. Veauvy, et al. Phys. Rev. B 70, 214513, (2004)

Magnetic anisotropy in the superconducting state of Sr_2RuO_4state



Crossing vortex lattices: in-plane vortex pin crossing vortices
In Sr_2RuO_4
Dolocan, V.O. et al. Phys. Rev. B **74,** 144505, 2006
Dolocan, V.O. et al. Phys. Rev. Lett **95,** 97004, 2005

Penetration depth and vortex stray field



E. H. Brandt et al. PRB, 61,6370

$$h_z = \frac{\Phi_0}{(2\pi\lambda_{ab})^2} \int d^2\vec{k} e^{i\vec{k}\cdot\vec{r}} \frac{e^{k(d/2-z)}}{\alpha\left[\alpha + k \cdot coth(\alpha d/2)\right]}$$

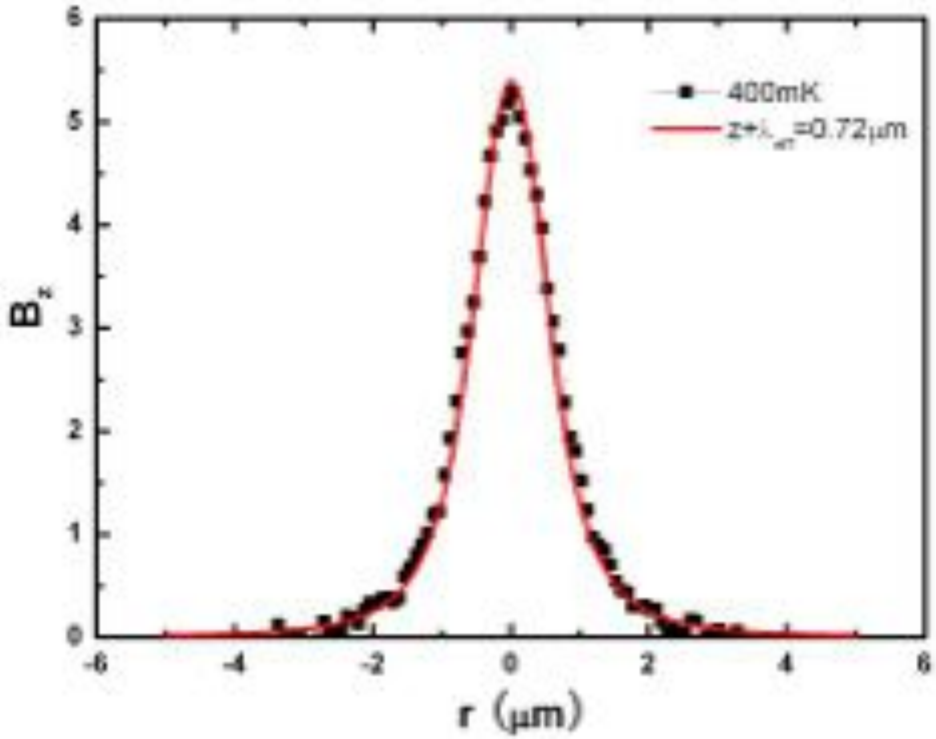
$$\vec{r} = \{x, y\}, \vec{k} = \{k_x, k_y\}, k = \sqrt{k_x^2 + k_y^2}, \quad and \quad \alpha = \sqrt{k^2 + \lambda_{ab}^{-2}}.$$

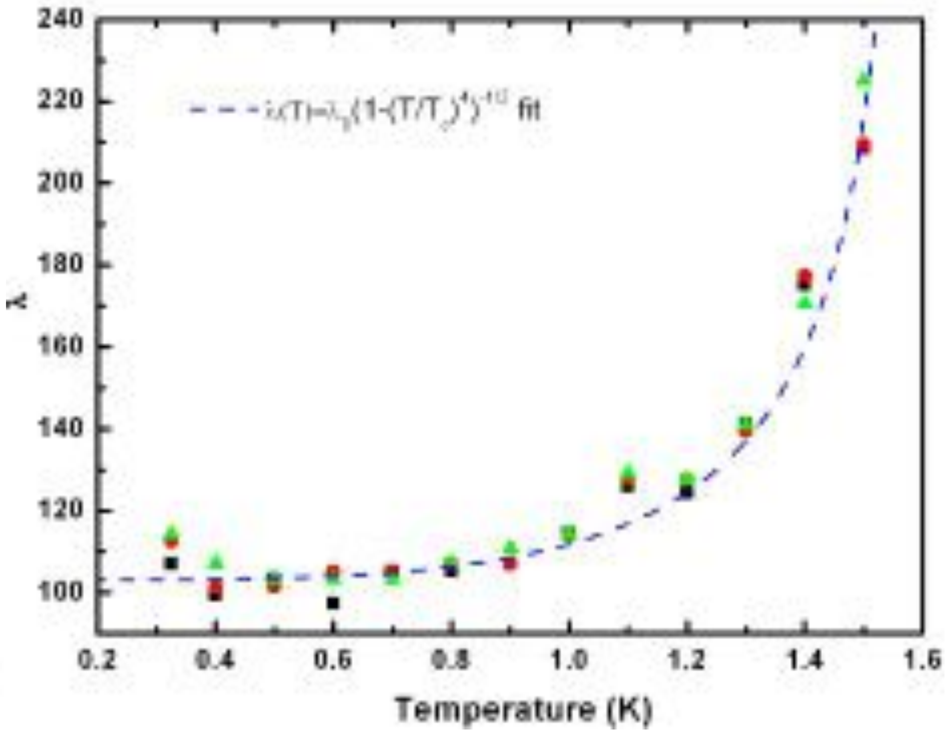
A. M. Chang et al. Appl.Phys.Lett. 61(16),1974

$$(r^2 + z^2)^{1/2} \gg \lambda \qquad h_z = \frac{\Phi_0}{2\pi} \frac{z + \lambda_{eff}}{[r^2 + (z + \lambda_{eff})^2]^{3/2}}$$

$$\lambda_{eff} = \lambda \coth(d/2\lambda)$$

Absolute value of penetration depth





z=0.45µm
λ=101nm

ZS Wang 2011

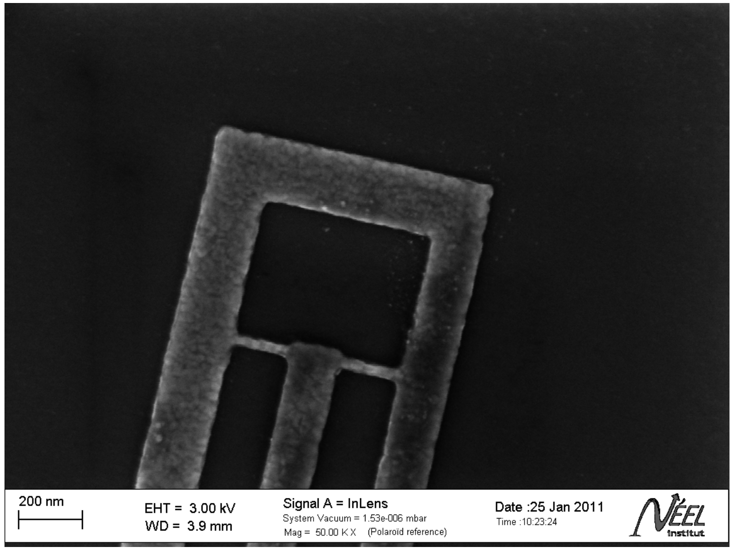
λ=103nm
T_c=1.6K

Scientific projects

- Vortex state and penetration depth (doping) in Pnictide SC
- Domain structure in superconducting Ferromagnets
- Imaging noise sources in Qbit circuits
- …….

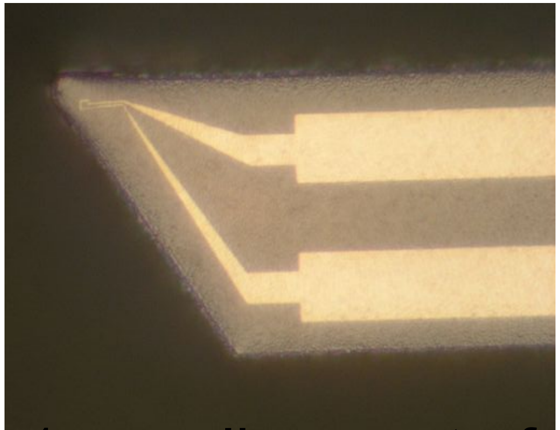
Outlook Imaging

Smaller SQUID



500 nm SQUID loop

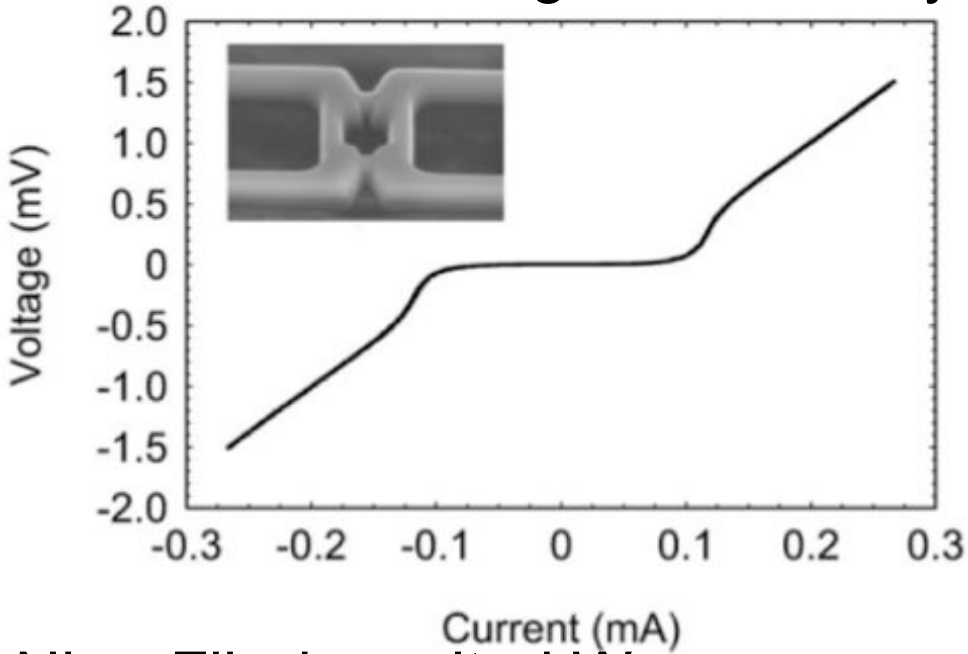
better aligned



1 µm alignment of etch
1 µm SQUID loop

Outlook Imaging

At least 10 times higher sensitivity at 4.2 K



Nb + Fib deposited W

Flux noise at 1 kHz $0.2 \cdot 10^{-7} \Phi_0 / \sqrt{Hz}$

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