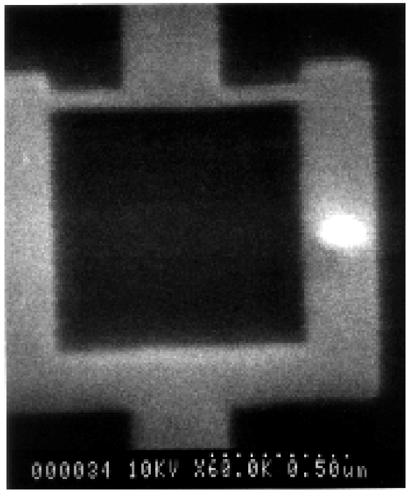
Nanomagnetometry



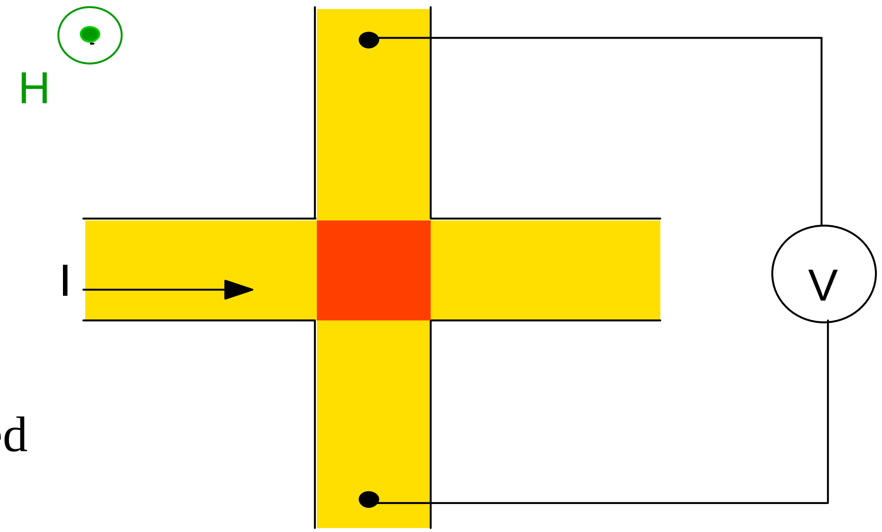
W. Wernsdorfer, E. Bonet Orozco and B. Barbara
Lab L. Néel - CNRS, Grenoble, France
A. Benoit
CRTBT - CNRS , Grenoble, France
D. Mailly
L2M, Bagneux, Paris, France
and a lot of collaborators

Different techniques

- Torque balance [Morrish 1956]
  - "Rotation method" [Knowles 1978]
  - Vibrating sample magnetometer $10^7\ \mu_B$ [Richter 1989]
  - Lorentz microscopy $10^7\ \mu_B$ [Salling 1991]
  - MFM $10^7\ \mu_B$ [Chang 1993, Ledermann 1994]
  - Hall sensor $10^6\ \mu_B$ [Kent 1994]
  - Micro - SQUID $10^4\ \mu_B$ [Wernsdorfer 1995]
  - Transport measurements $10^4\ \mu_B$ [Giordano 1995]

…

2D Hall probes



Principle: Deviation of electrons induced by a magnetic field (Lorentz force)

Semi-conductor heterostructure : GaAs - GaAlAs (à 4K)

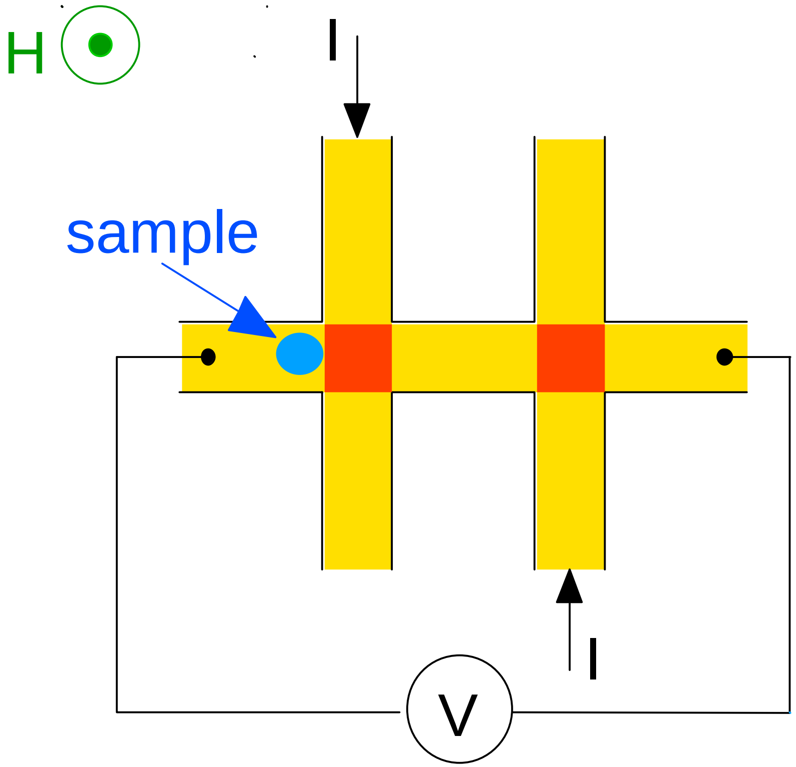
electron density : n = 3 10^{11} cm^{-2}

mobility : 800 000 $cm^2V^{-1}s^{-1}$

Hall resistant : 2000 □/T

resistance : 20 □ at 4K and 2000 □ at 300K

2D Hall bridge



A.D. Kent, D.D. Awschalom et al.,
JAP, 76, 6656 (1994)
sensitivity of $10^6\ \mu_B$

A.K. Geim et al. APL, 71 (16), (1997)

Luise Theil Hansen,
<theil@meyer.fys.ku.dk>
sensitivity of $10^4\ \mu_B$

Electric transport measurements

Magnetoresistance

K. Hong, N. Giordano, JMMM, 151, 396 (1995)
depinning of a domain wall in an isolated Ni wires

F. Coppinger et al., PRL 75, 3513 (1995)
Single domain switching of small ErAs clusters investigated using telegraph noise spectroscopy

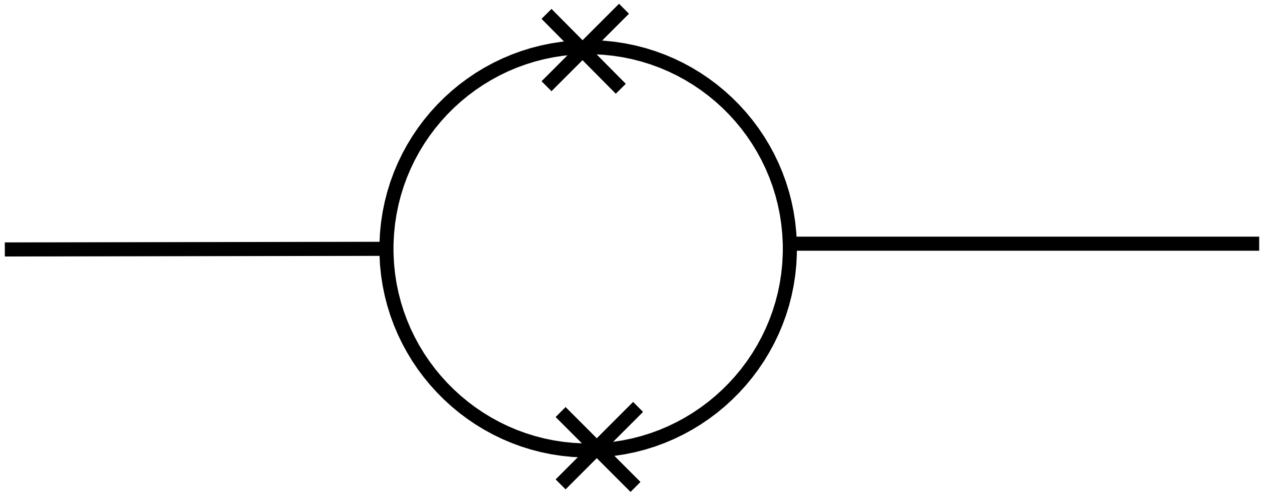
Giant magnetoresistance

V. Gros, A. Fert et al.
Co/Cu/Co structures

Spin-dependent tunneling with Coulomb blockade

L.F. Schelp, A. Fert et al., PRB, 56. R5747 (1997)
$Co/Al_2O_3/Co$ tunnel junctions with cobalt clusters in the Al_2O_3 layer

Superconducting Quantum Interference Device (SQUID)



Different types of Josephson junctions :

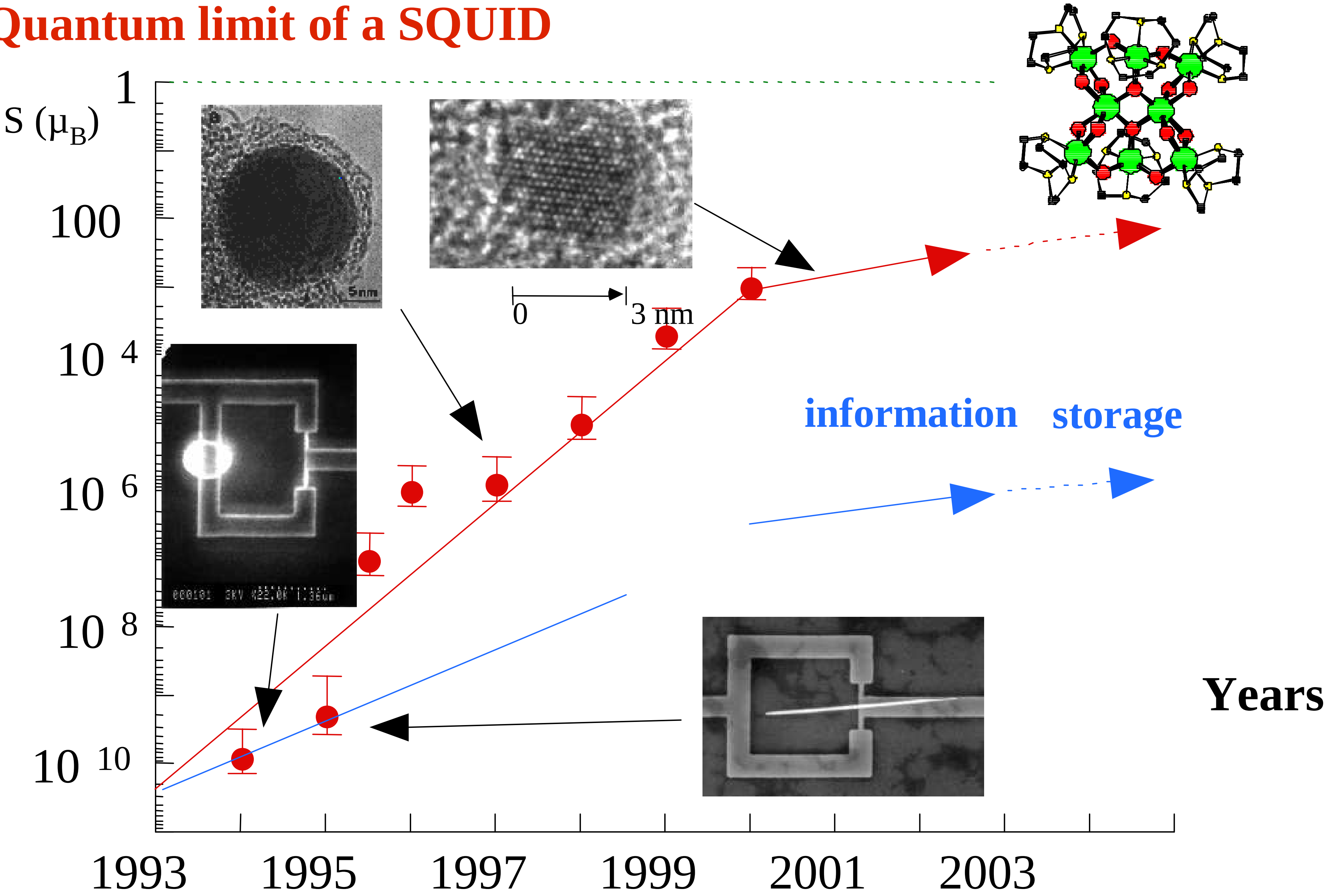
- point junctions
- tunnel junctions
- micro bridge junctions

Theoretical limit : 1 μ_B !!!

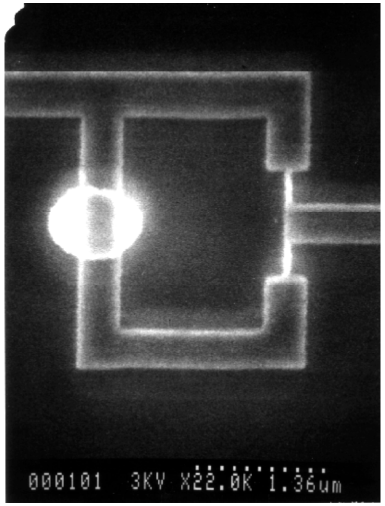
with a coupling factor of $4*10^7$ μ_B/Φ_0

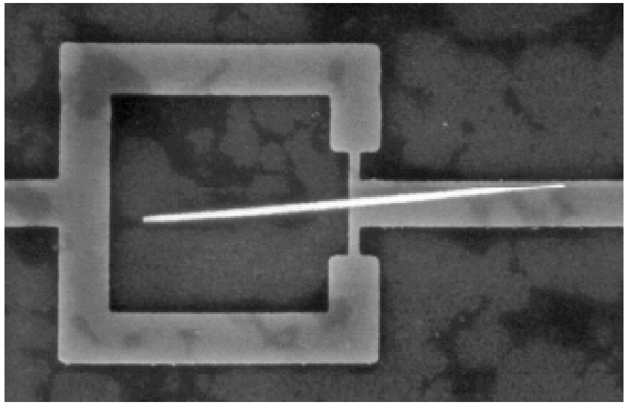
Roadmap of the micro-SQUID technique

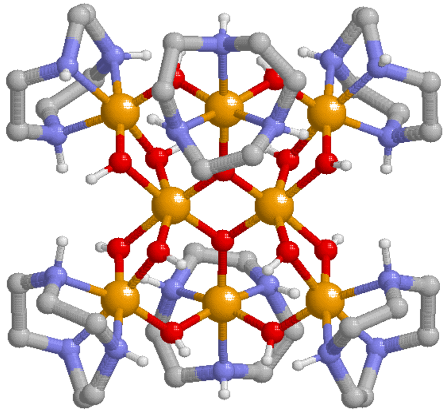
Quantum limit of a SQUID

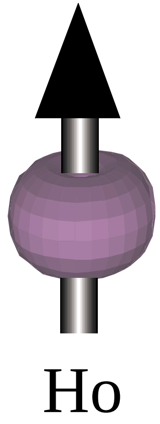


Studied nanostructures



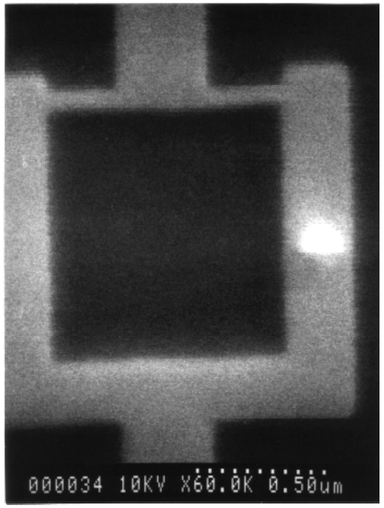


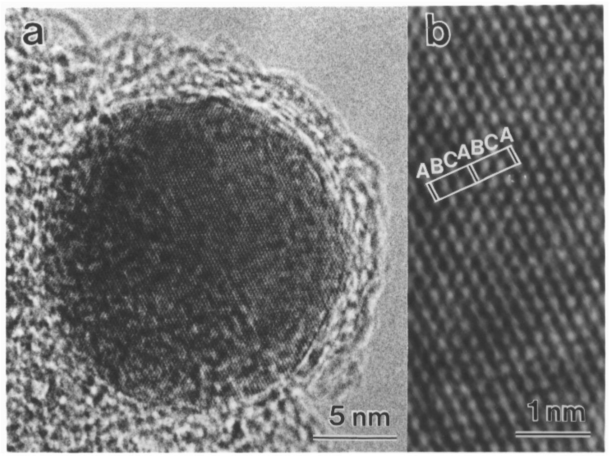


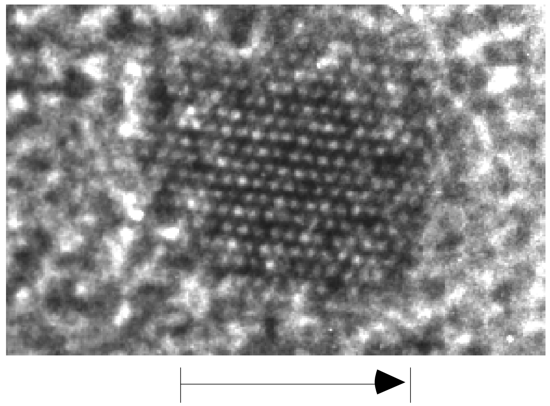


submicron particles	wires	nanoparticles	clusters	molecular clusters	individual spins

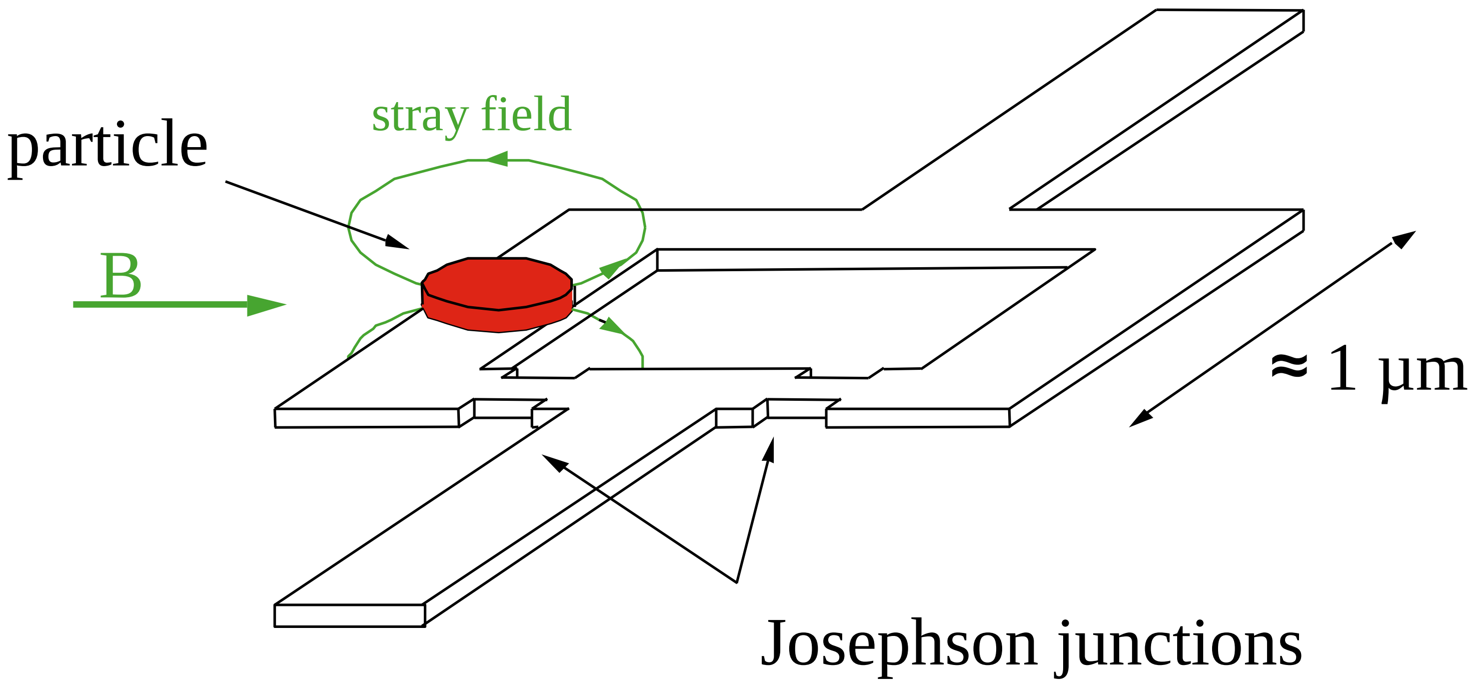
S = 10^{20} 10^{10} 10^{8} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2} 10 1







Micro-SQUID magnetometry



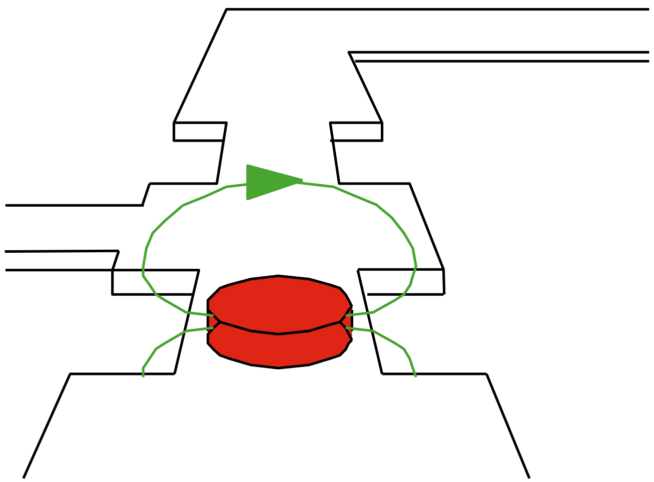
- **fabricated by electron beam lithography**

  (D. Mailly, LPM, Paris)

- **sensitivity : 10 $^{-4}$ Φo**

  ≈ $10^2 - 10^3\ \mu_B$, i.e. (2 nm)^3 of Co

  ≈ $10^{-18} - 10^{-17}$ emu



SQUID details

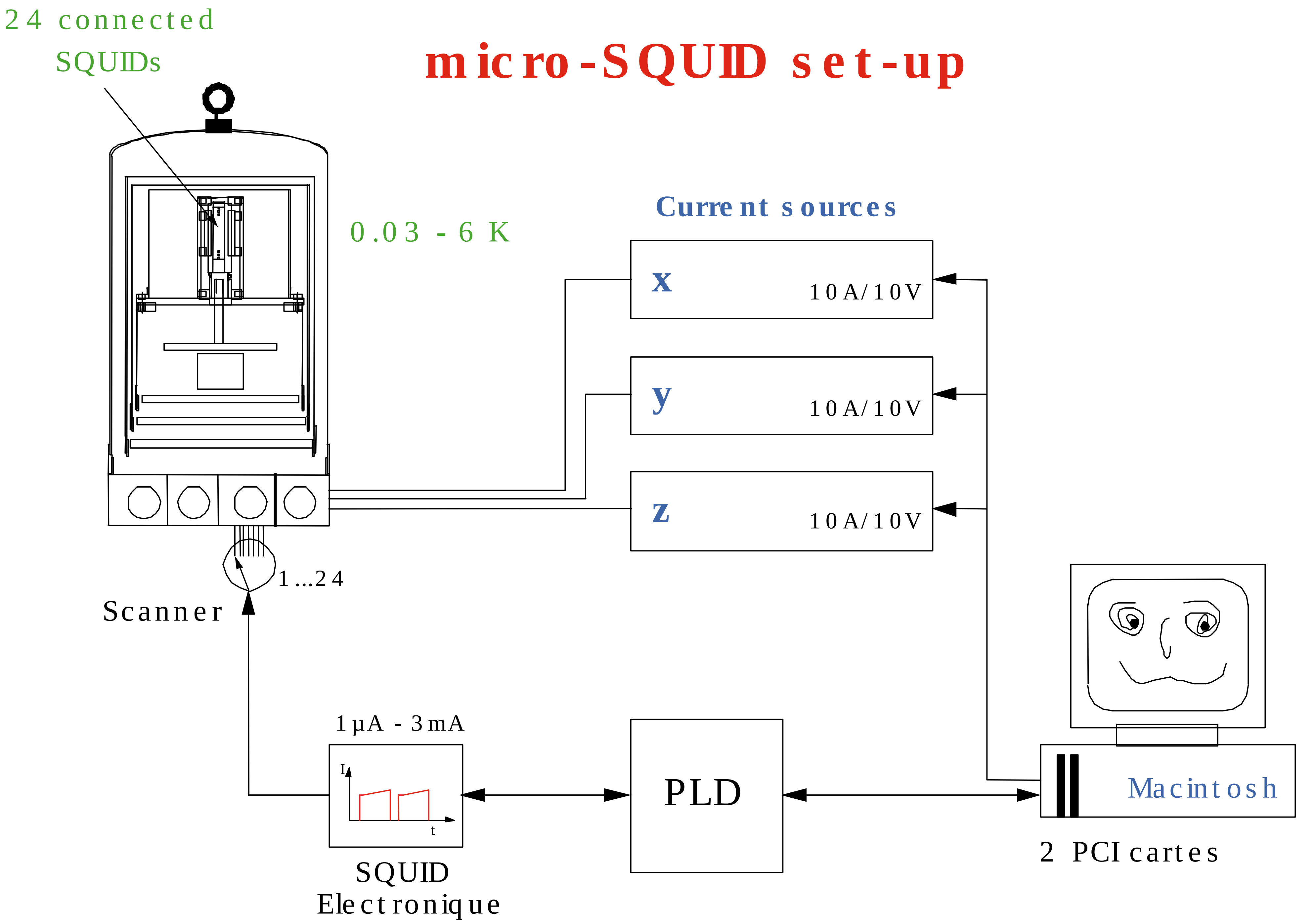
- fabricated by electron beam lithography
  D. Mailly, L2M - CNRS, Bagneux
- dimension : 1 - 2 µm
- material : Nb
- temperature : < 7K
- direct coupling with the SQUID
- sensitivity : $10^{-4}\,\Phi_o$

$\Rightarrow$ $\approx 10^{4}\,\mu_B$ i.e. $(6nm)^3$ of Co

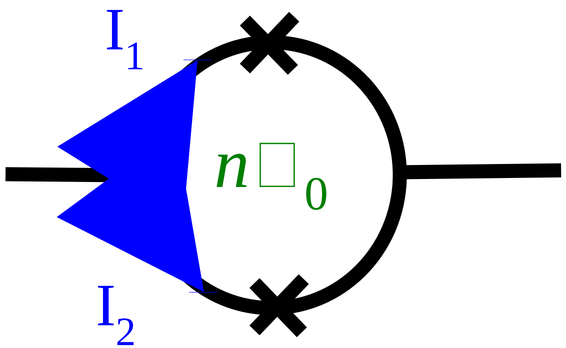
$\Rightarrow$ $\approx 10^{-16}$ emu

conventional SQUID : 10^{-7} emu

micro-SQUID set-up



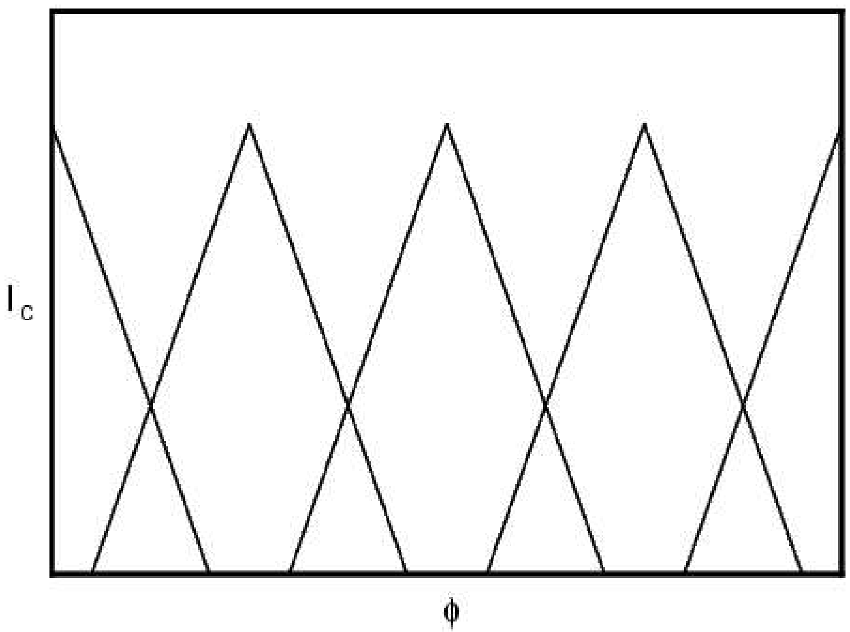
Naïve theory

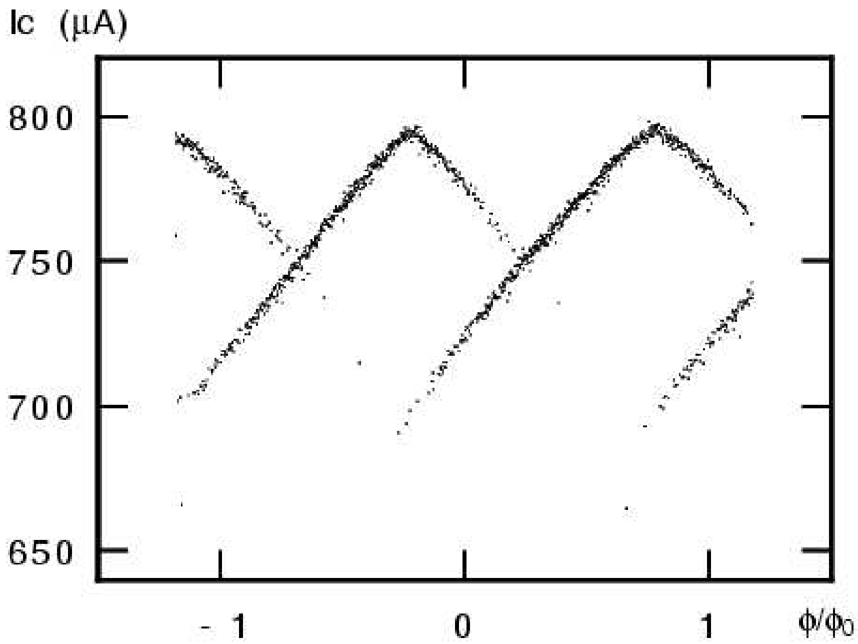


$$n\Phi_0 = \Phi + L_1 I_1 + L_2 I_2 \qquad \Phi_0 = \frac{h}{2e}$$

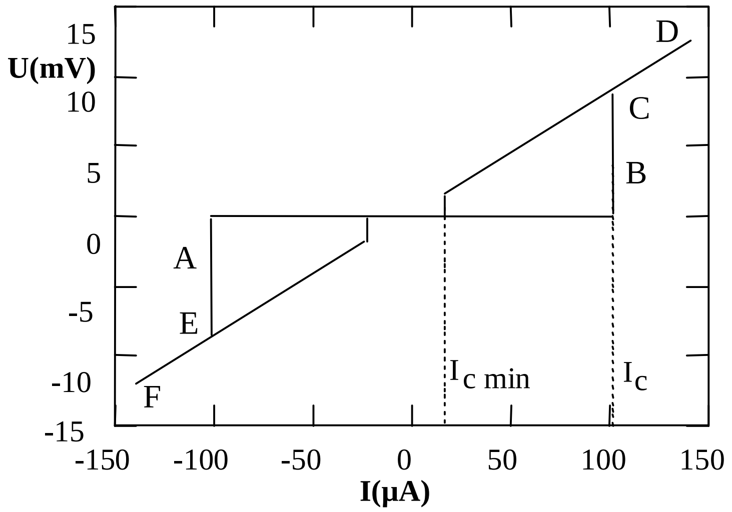
$$n\Phi_0 - \Phi = L_1 I_1 + L_2 I_2 = L_2 I + (L_1 - L_2) I_1$$

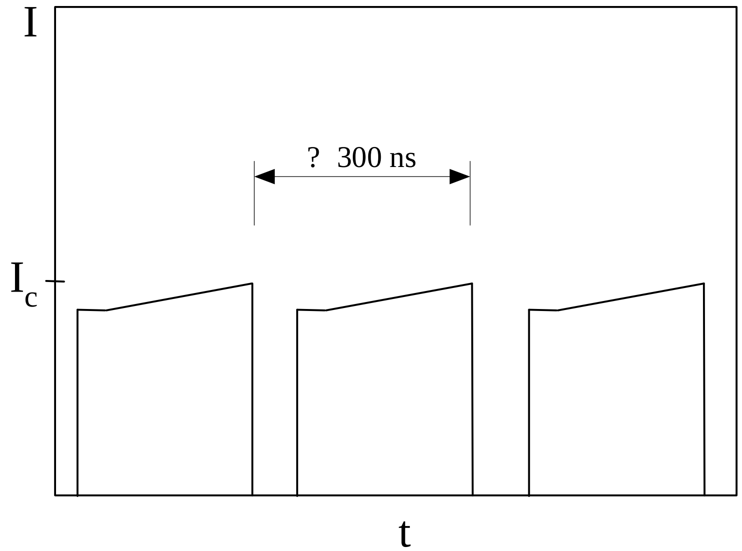
$$I < \frac{n\Phi_0 - (L_1 - L_2) I_1^{\max}}{L_1} - \frac{\Phi}{L_1}$$

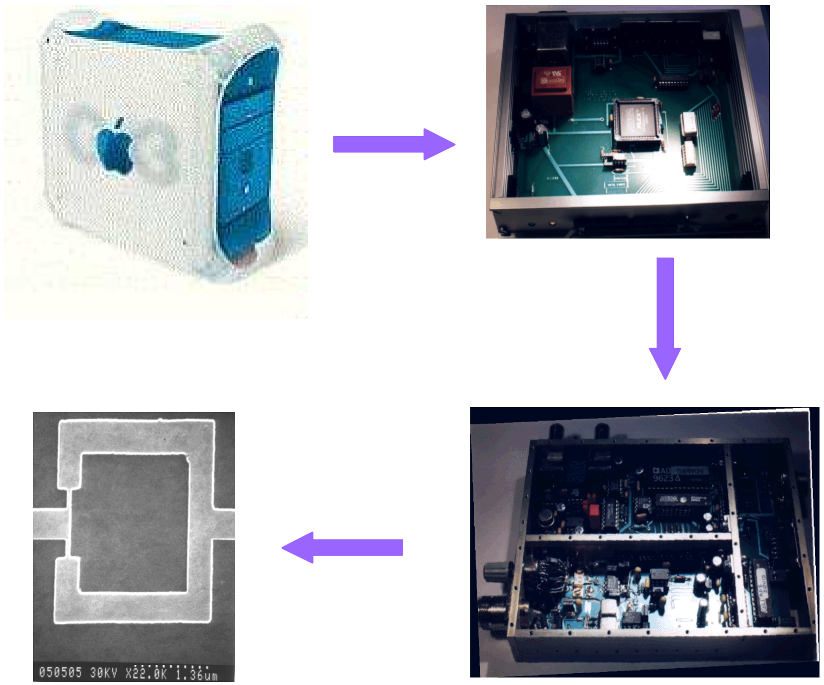


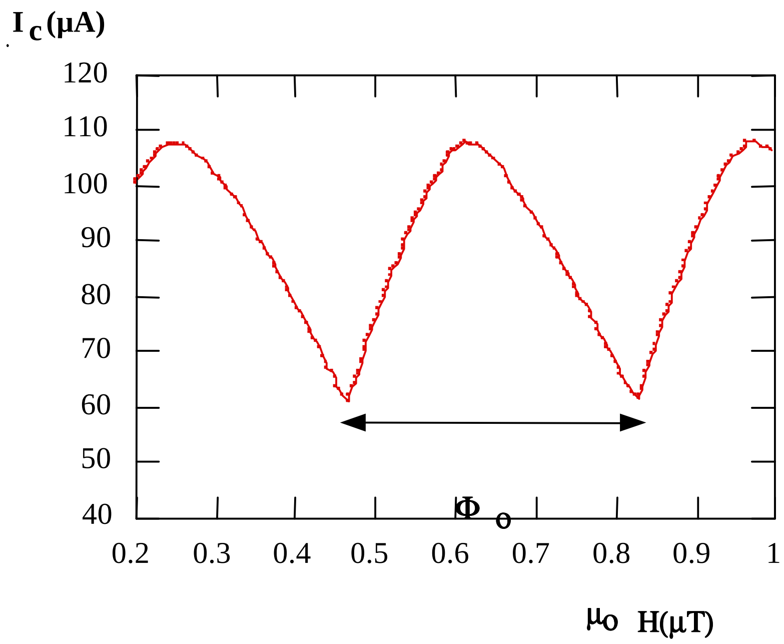


Critical current measurements

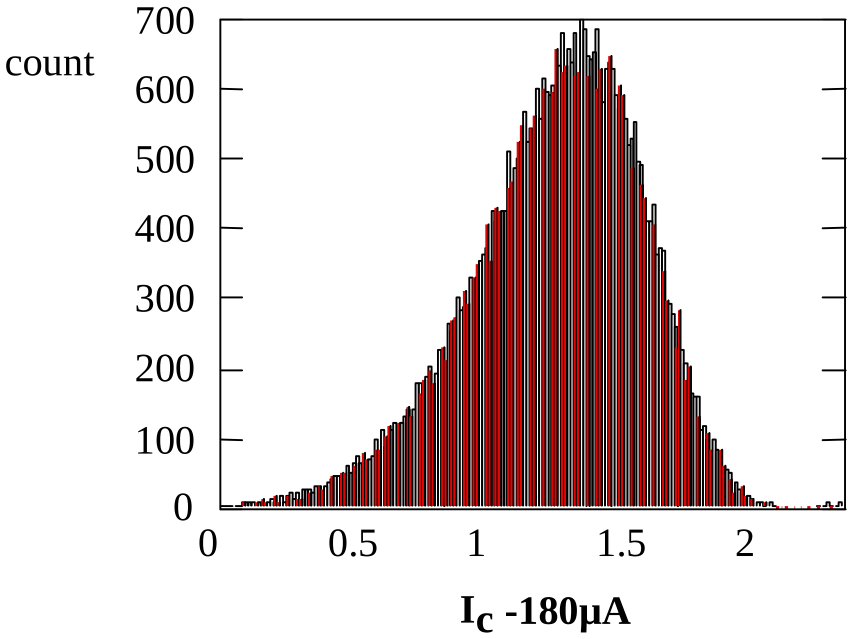








I_c statistics



Histogram of 60000 I_c measurements

- Magnetization measurement : average of N measurements of I_c

  precision increases with

- limitation of the cycling frequency of I_c measurement :

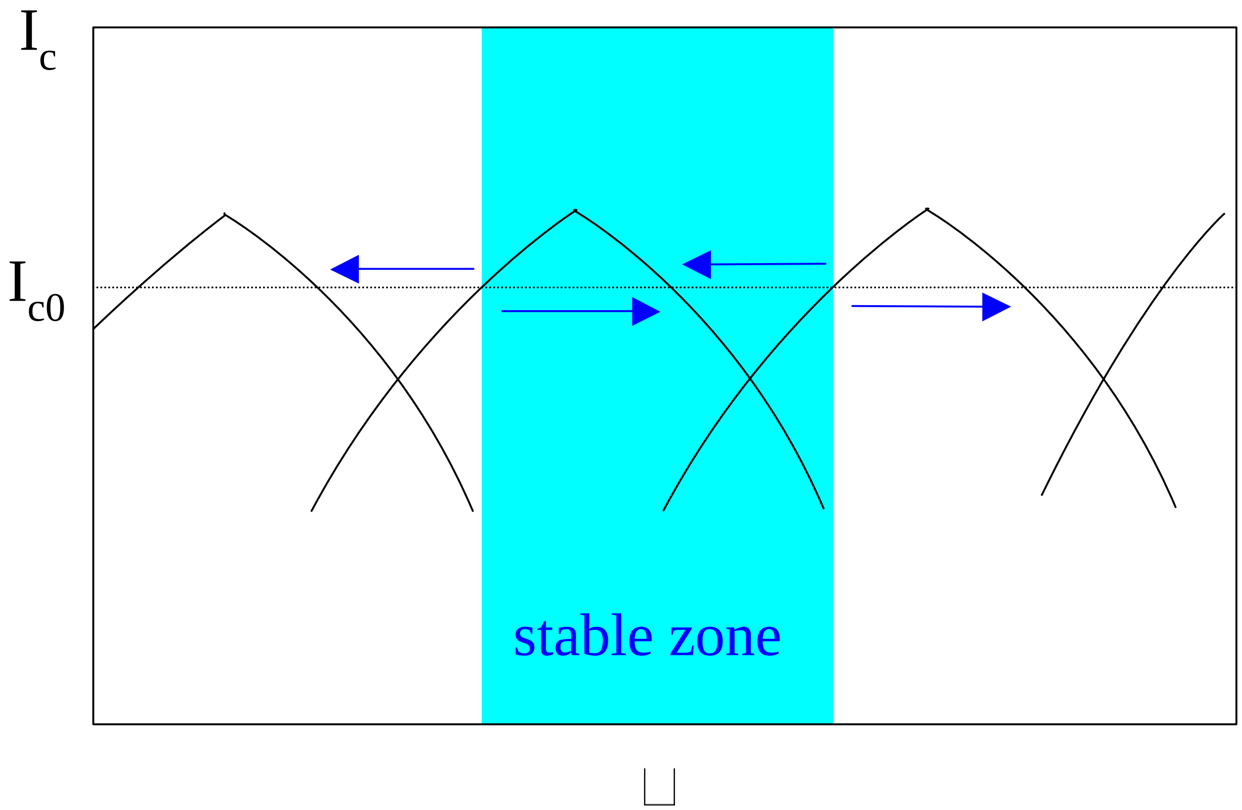
  length of the current ramp ≈ 100 µs
  cooling of SQUID ≈ 1 µs

- sensitivity :

  10000 measurements per second :

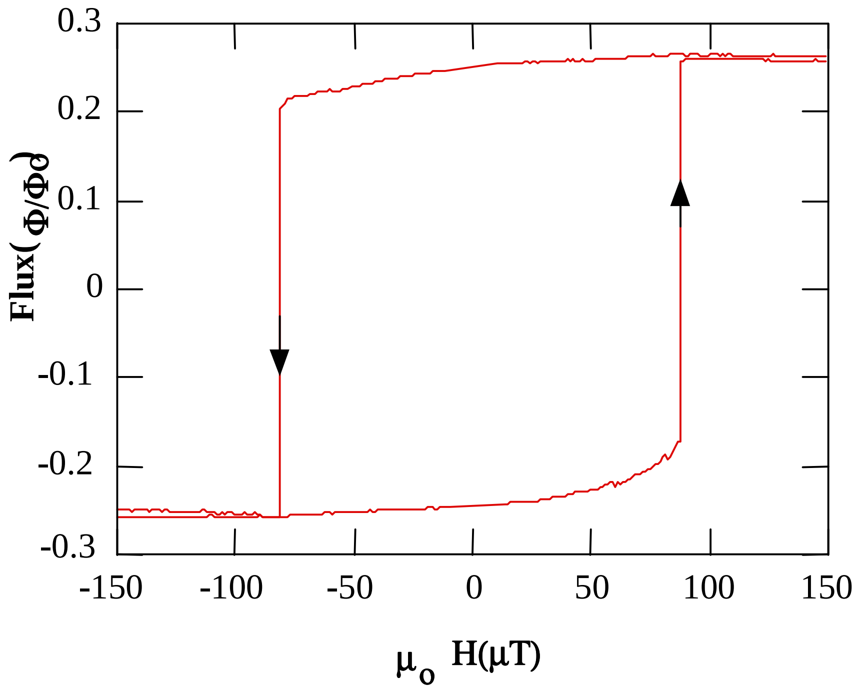
Ex. : our sensitivity : 10^4 μ_B
≈ cluster of Co of 5 nm in diameter

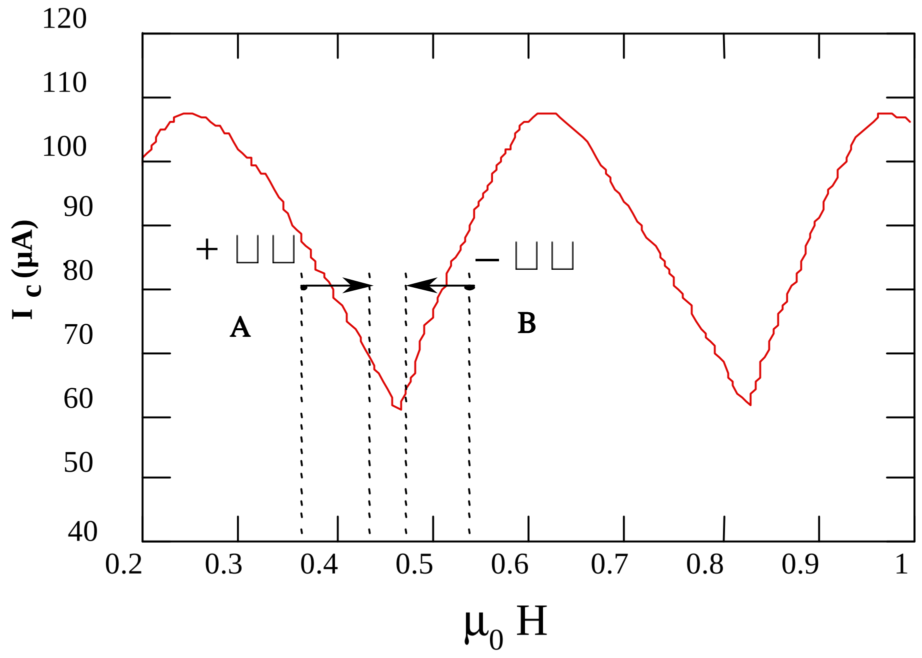
Feedback mode



- measure I_c continuously
- if $I_c > I_{c0}$, apply positive external flux
- if $I_c < I_{c0}$, apply negative external flux
- ⇒ external flux compensates sample's fux

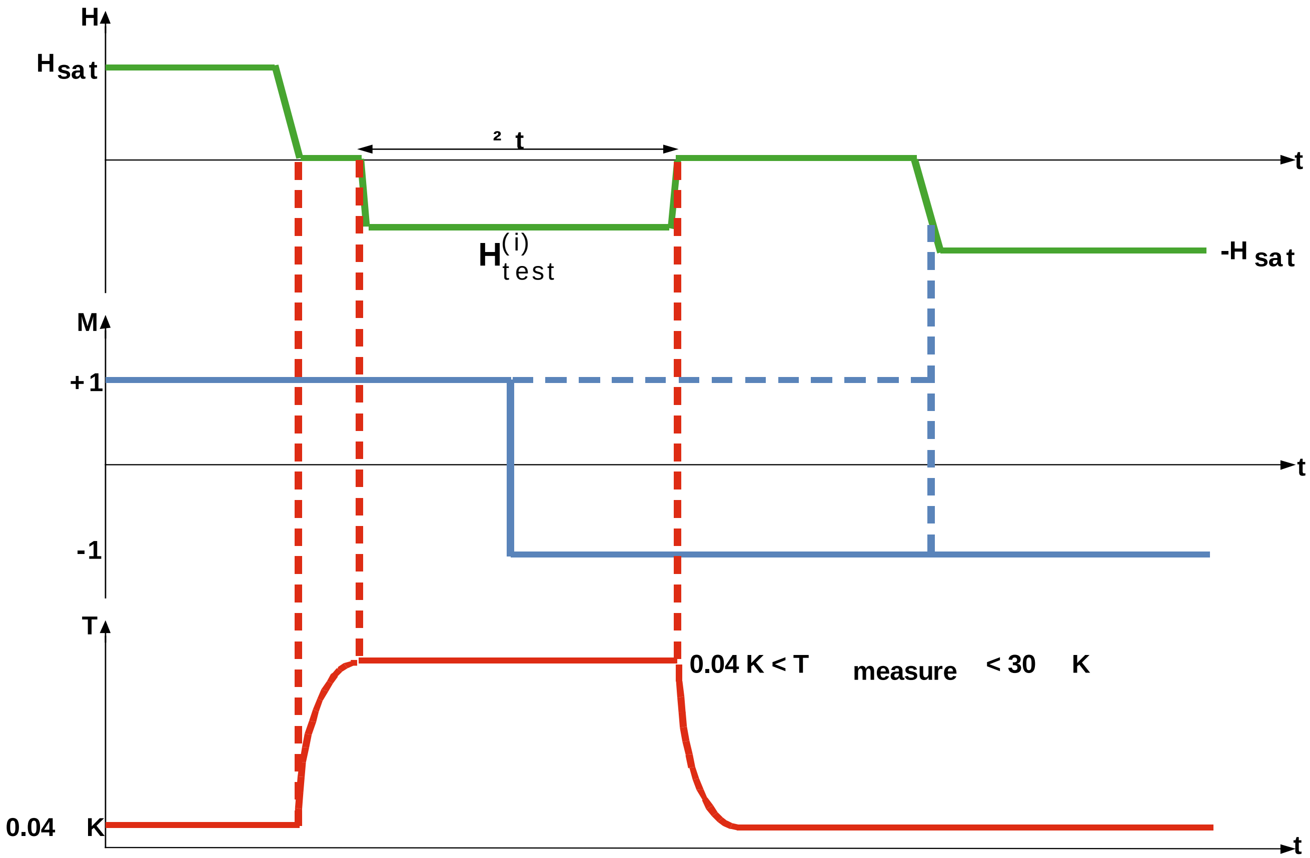
Jump detection: “cold mode”





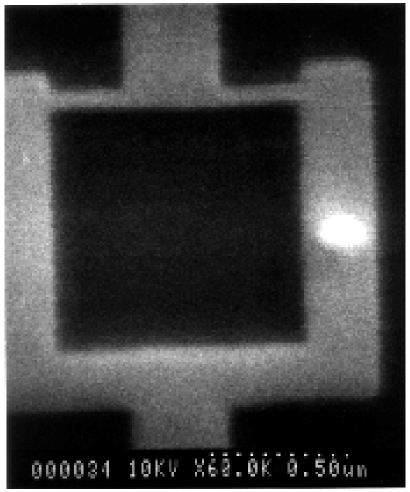
- SQUID polarized below the critical current
- magnetization jump SQUID transition
- the SQUID heats only **after** the magnetization jump

Blind mode



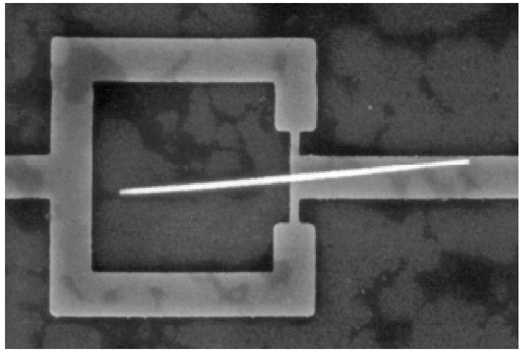
- apply a test field, we may (or may not) have reversal
- measure after the fact with a second field
- ⇒ field out of plane, high T, microwaves...

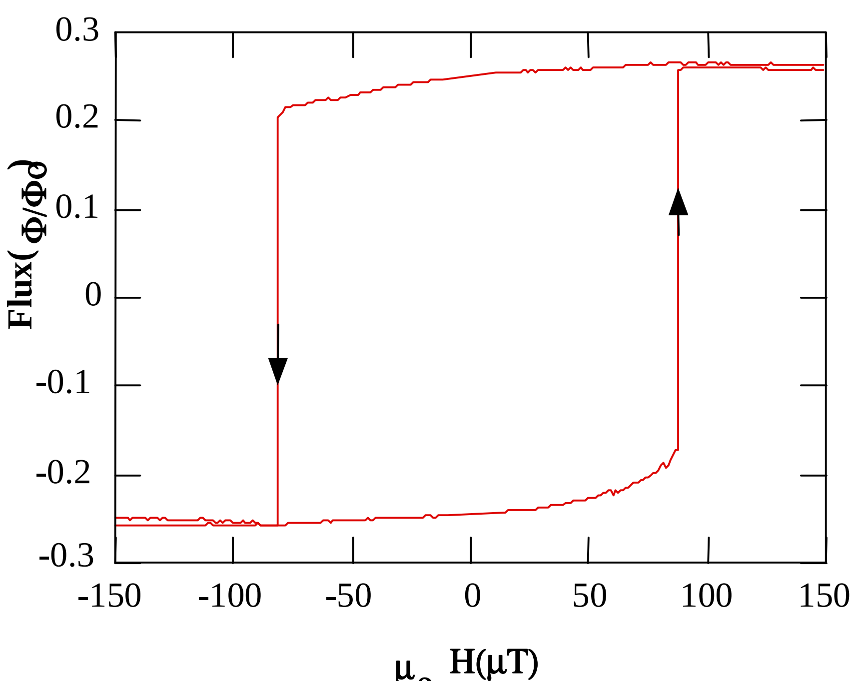
Ex: “large” particles

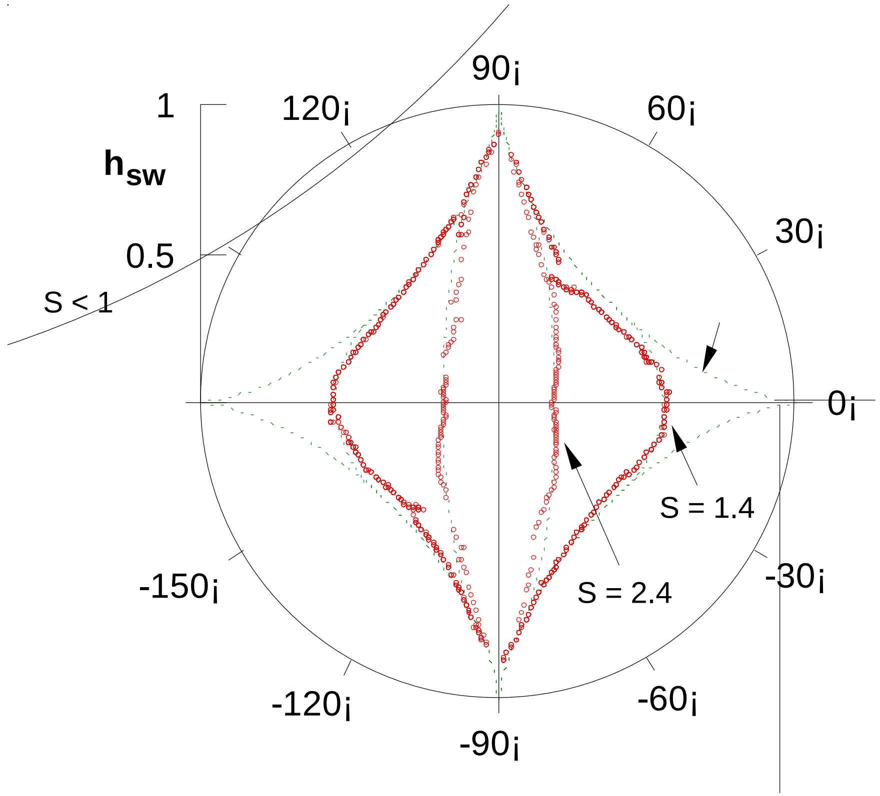


Co particle:
70 nm x 50 nm x 25nm

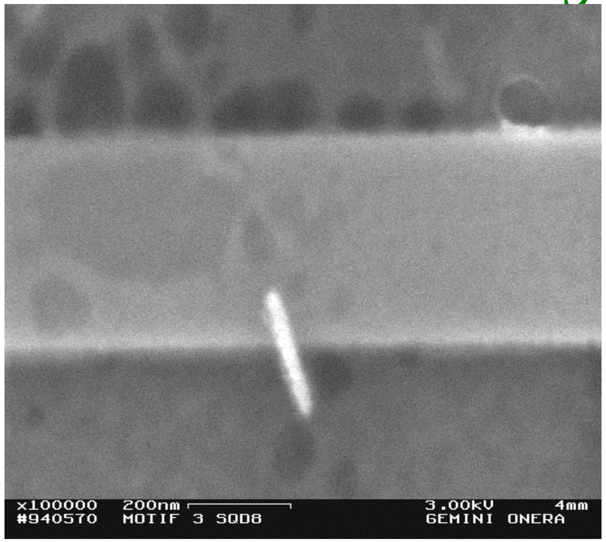
Ni wires:
(40-100) nm x (4-5) µm





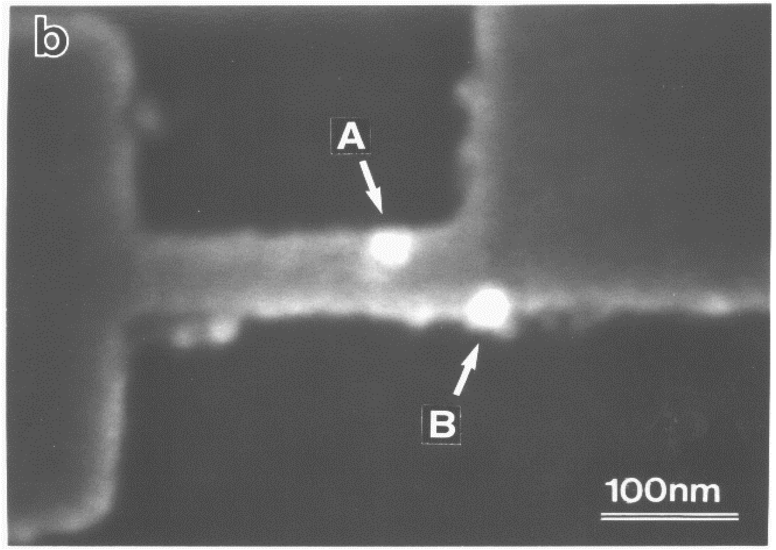


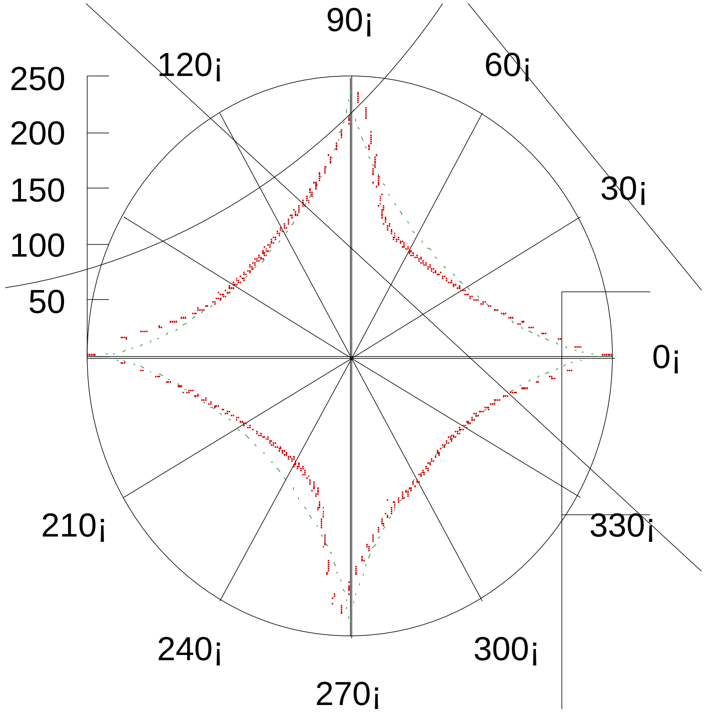
Smaller systems

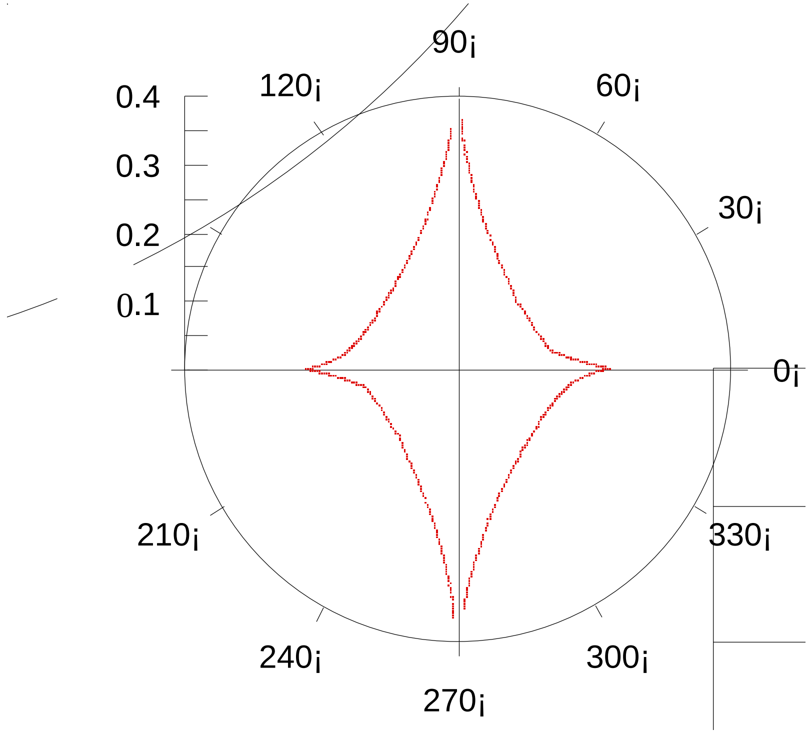


FeS particle:
length 200 nm,
diameter 20 nm

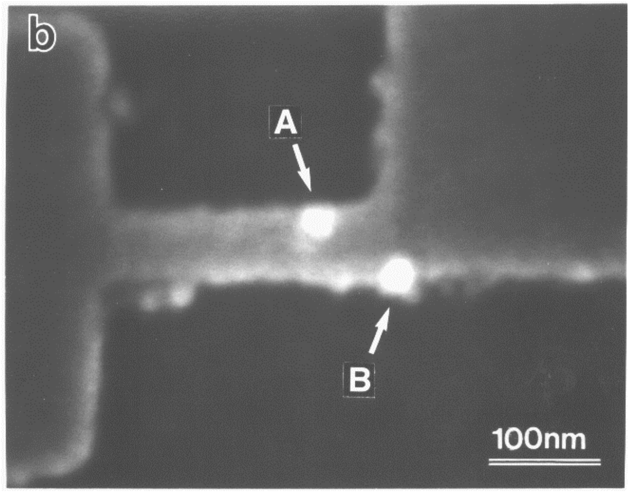
Co nanoparticles:
diameter 20 nm

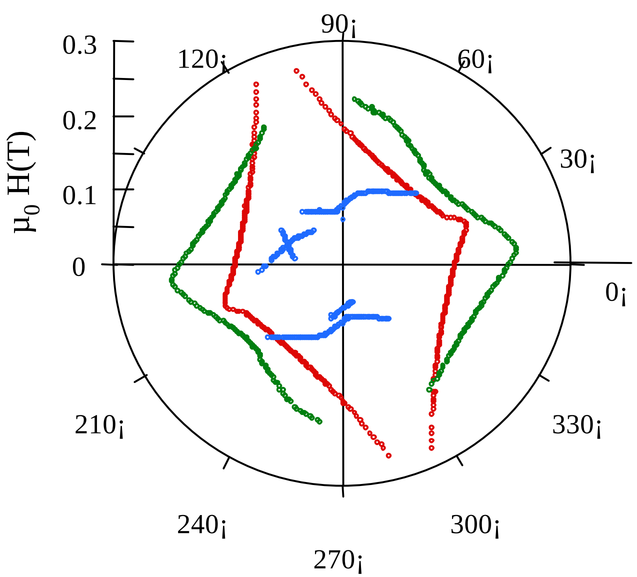


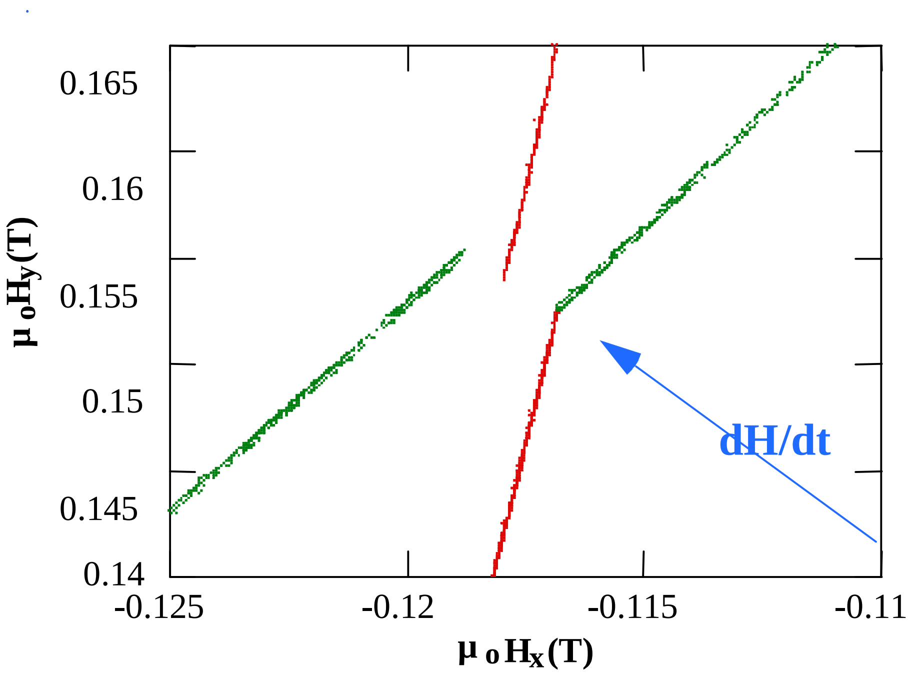




Coupling between nanoparticles



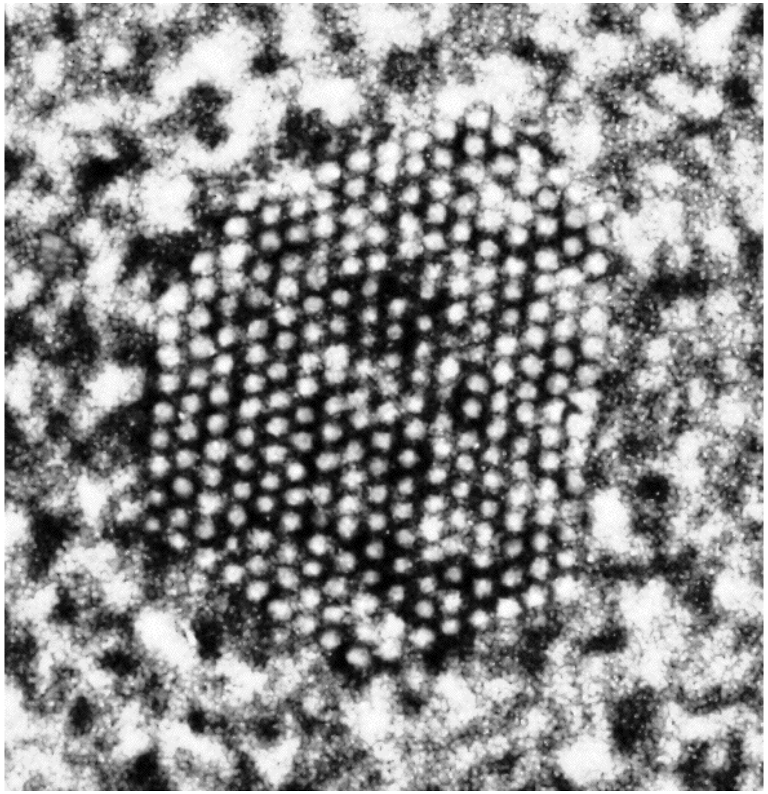




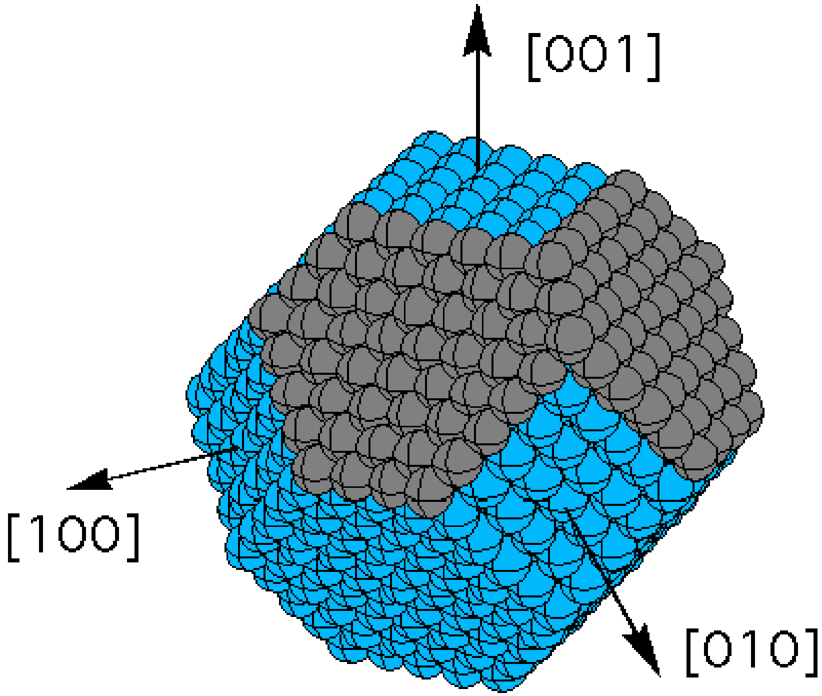
3 nm cobalt cluster

DPM - Villeurbanne: LASER vaporization and inert gas condensation source

Low Energy Cluster Beam Deposition regime



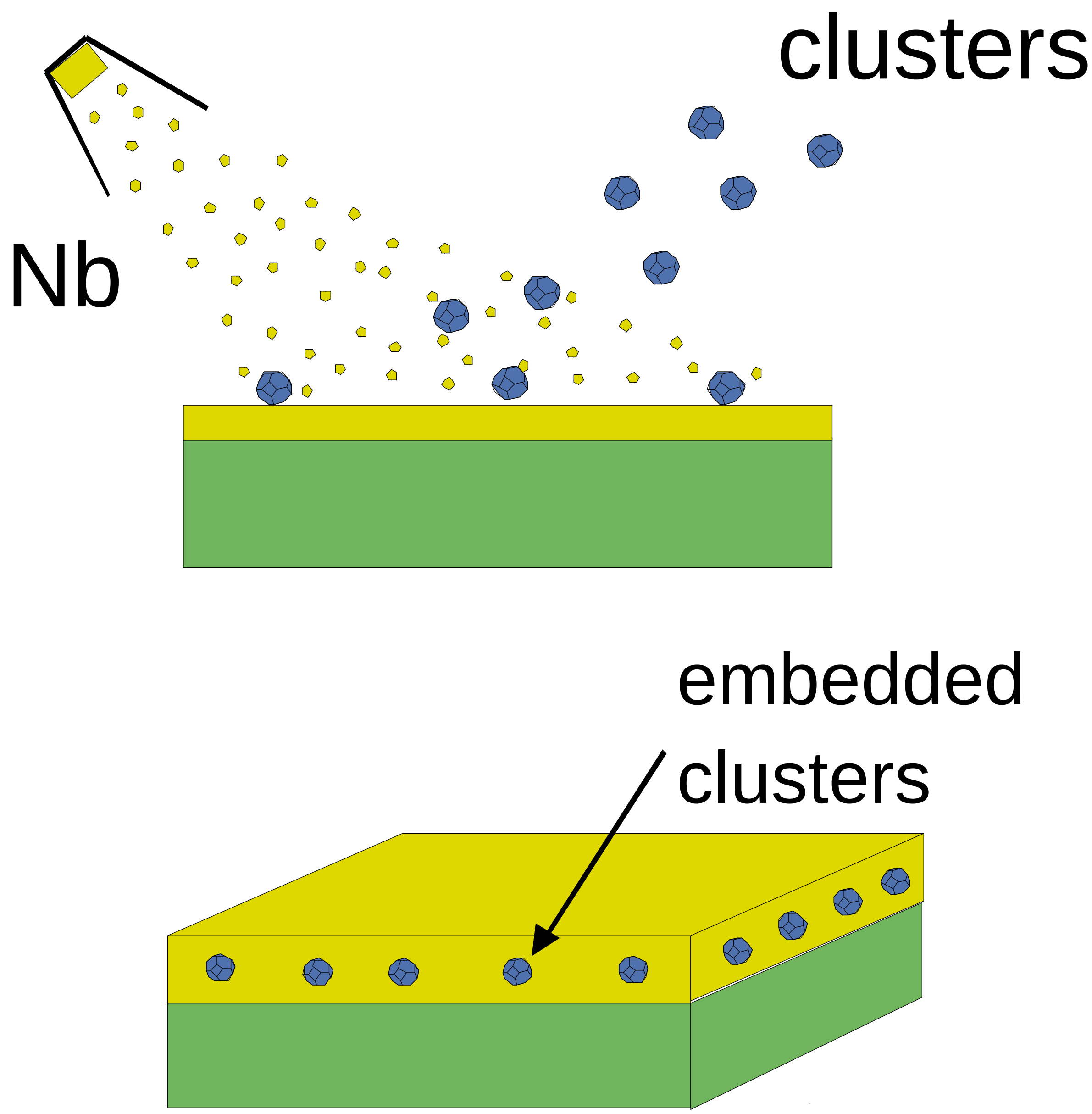
HRTEL along a [110] direction
fcc - structure, faceting



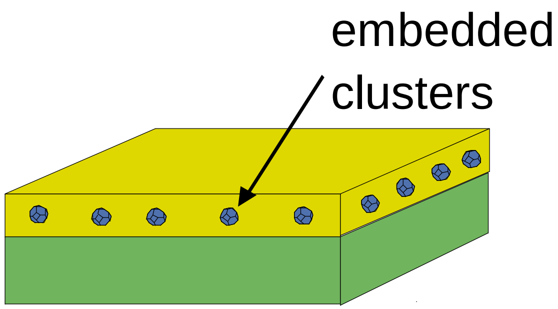
blue: 1289-atoms truncated octahedron
grey: added atomes, total of 1388 atomes

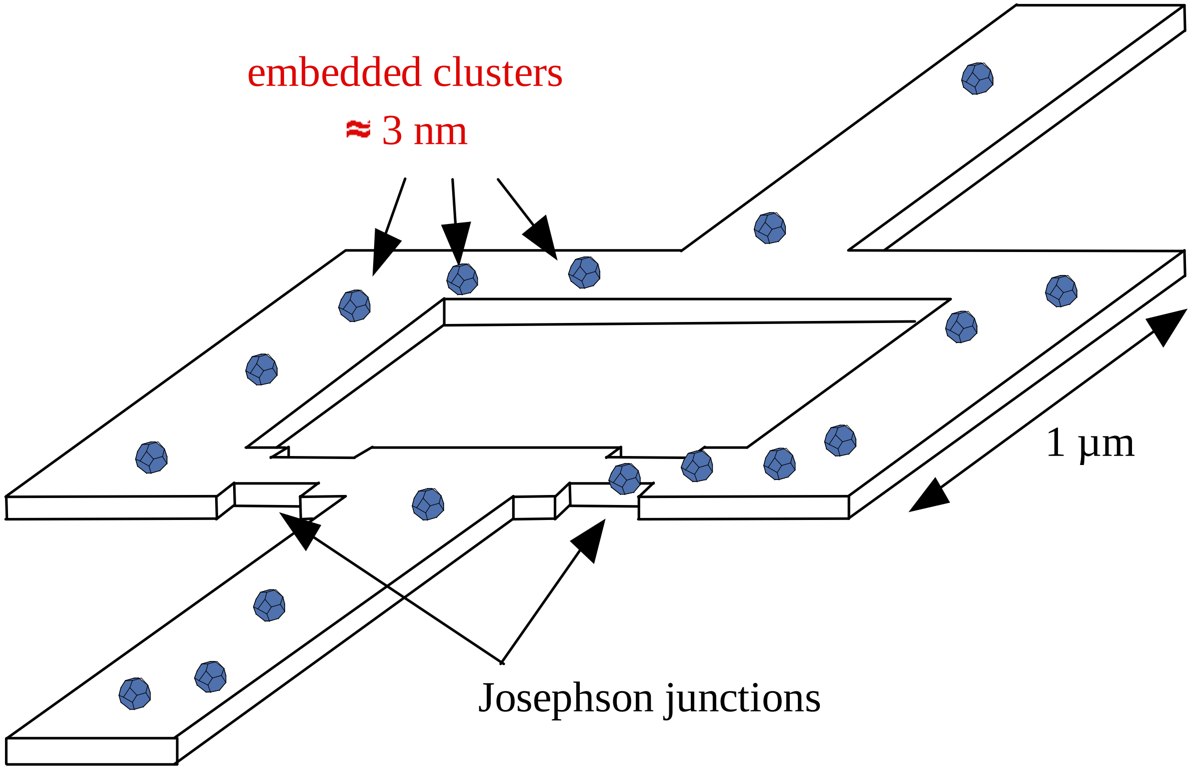
Ideal case: truncated octagedron with 1289 or 2406 atoms for diameters of 3.1 or 3.8 nm

Low energy cluster beam deposition



Micro-SQUID magnetometry





SQUID is fabricated by electron beam lithography

D. Mailly, LPN-CNRS

sensitivity : ≈ **10^2 - 10^3 μ_B** i.e. $(2\ nm)^3$ of Co

i.e. ≈ 10^{-18} - 10^{-17} emu

clusters in Nb - matrix

M. Jamet, V. Dupuis, A. Perez, DPM-CNRS, Lyon

Acknowledgment: B. Pannetier, F. Balestro, J.-P. Nozières