CENTRE NATIONAL
DE LA RECHERCHE
SCIENTIFIQUE

Quantum dynamics of a DC SQUID

UNIVERSITE JOSEPH FOURIER
SCIENCES. TECHNOLOGIE. MEDECINE
GRENOBLE 1

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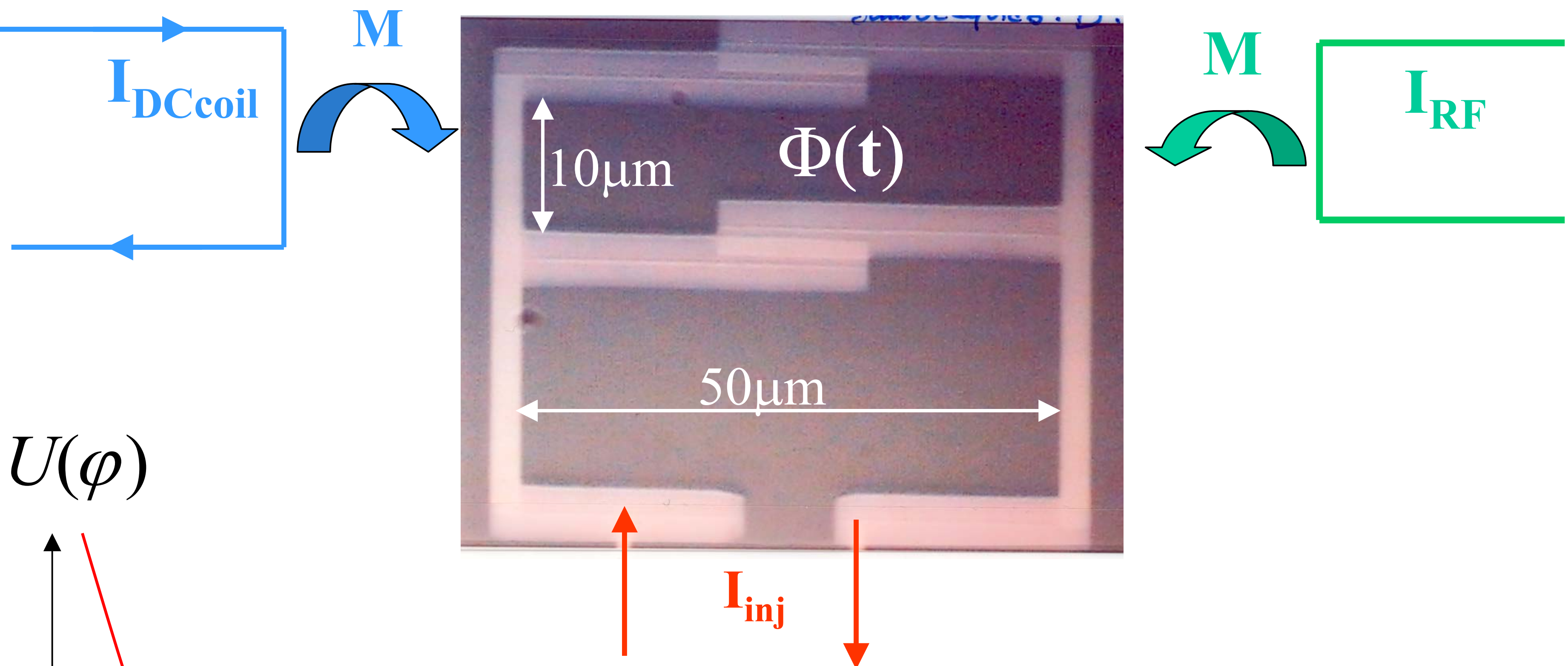
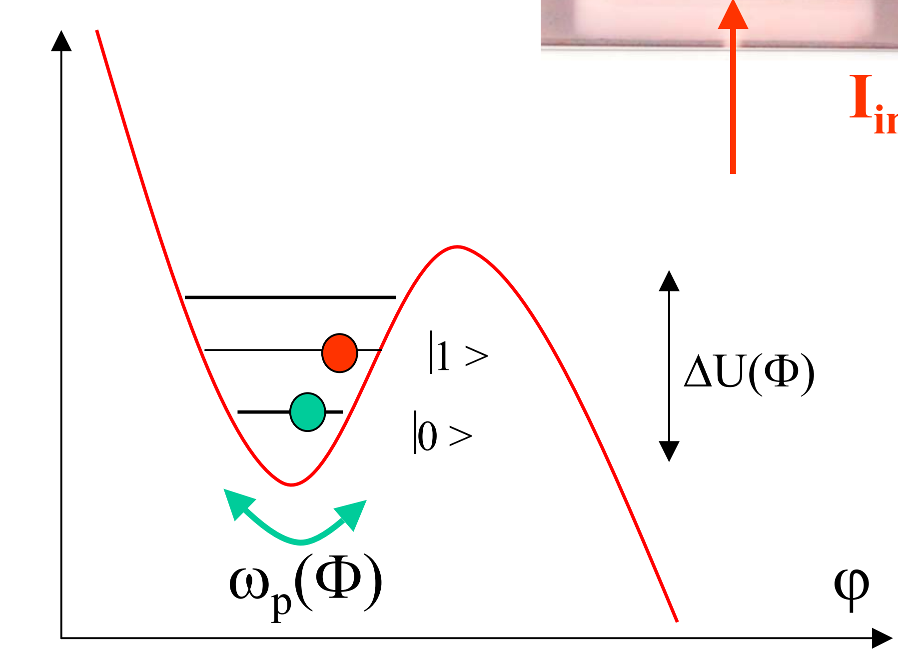
Outline

- Quantum dynamics of a DC SQUID
- Experimental set-up
- MQT in a SQUID
- RF pulse measurement
- Nanopulse measurement

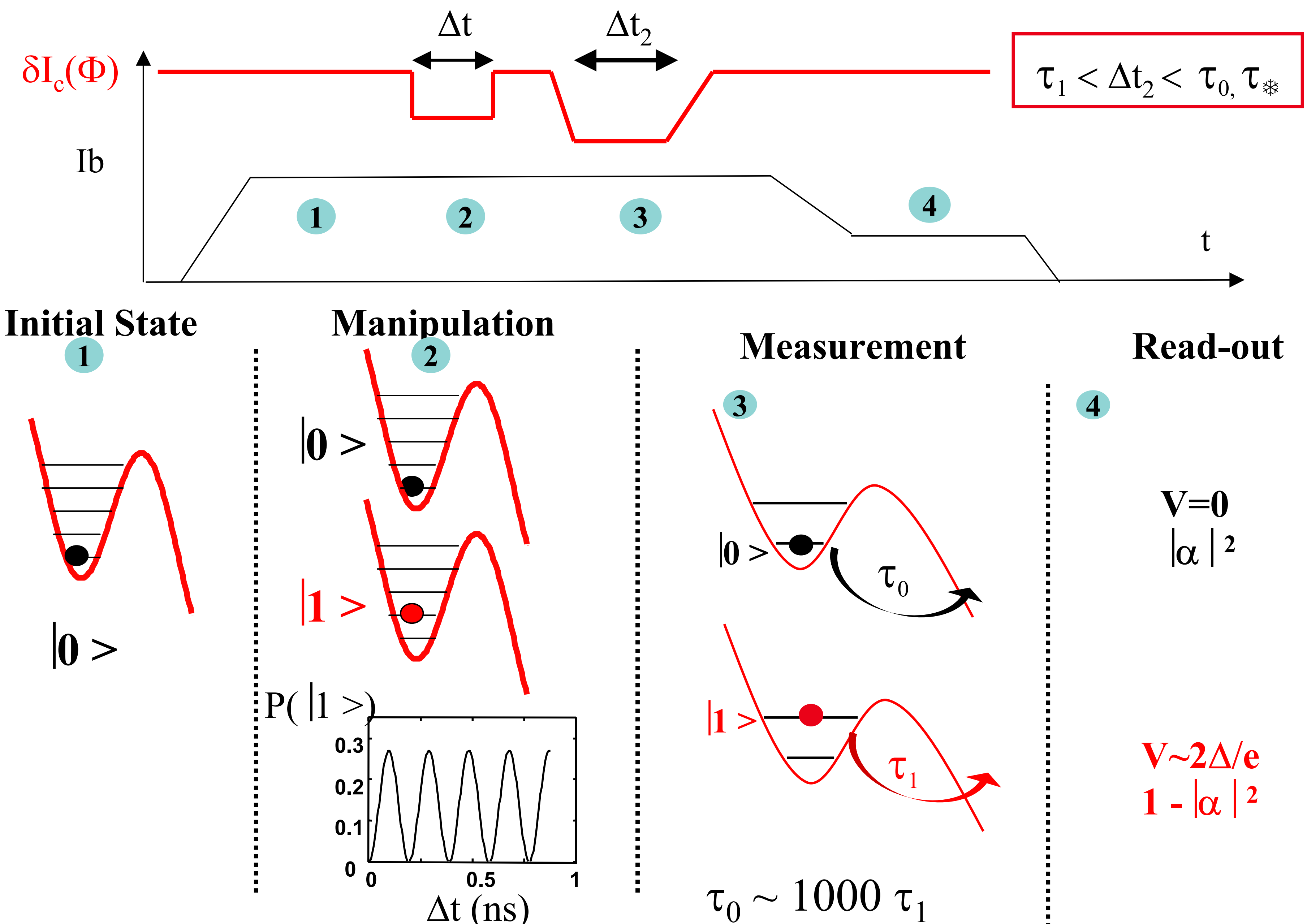
SQUID : a controllable quantum oscillator





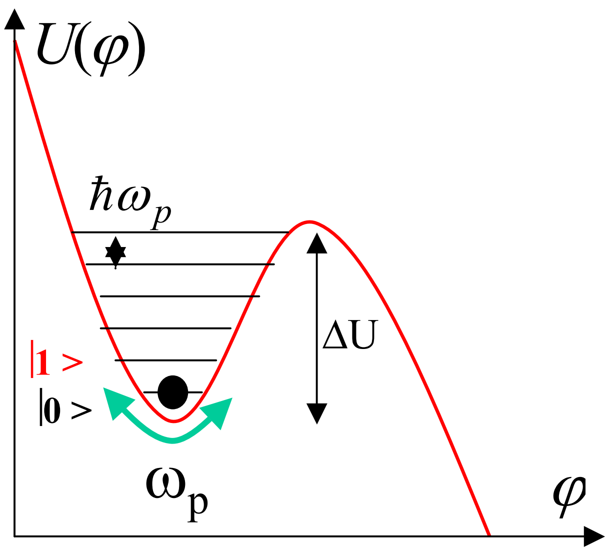
$$H = \hbar\omega_p(P^2 + X^2) - \sigma\hbar\omega_p X^3 + \lambda(t)\hbar\omega_p X$$

Typical experiment



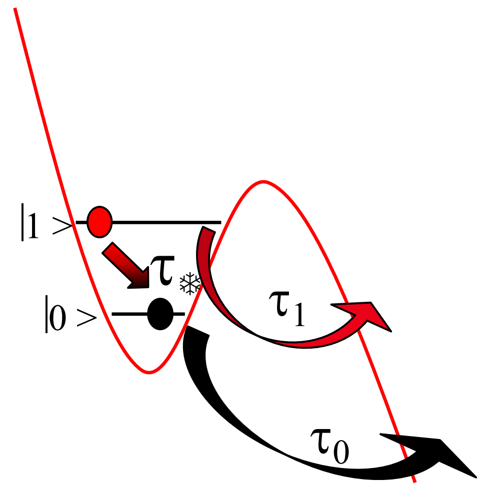
SQUID : a controllable and mesurable resonator

- Controllable oscillator



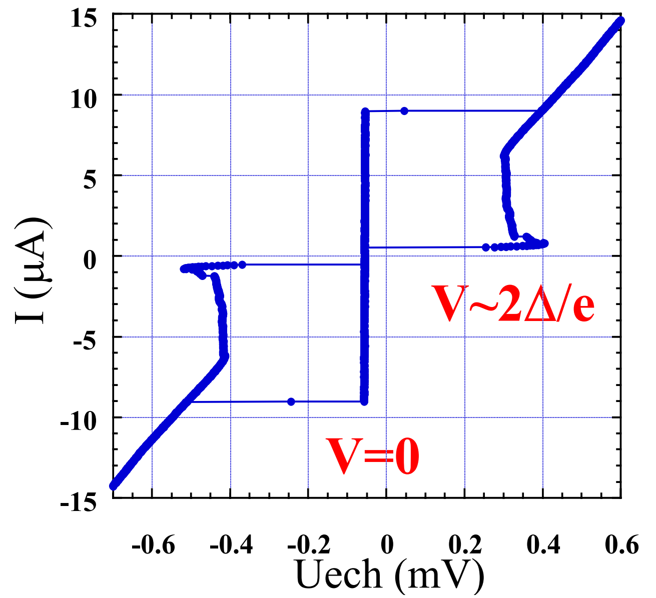
$\Delta U(\Phi(t))$
$\omega_p\,(\Phi(t))$

- Quantum measurement



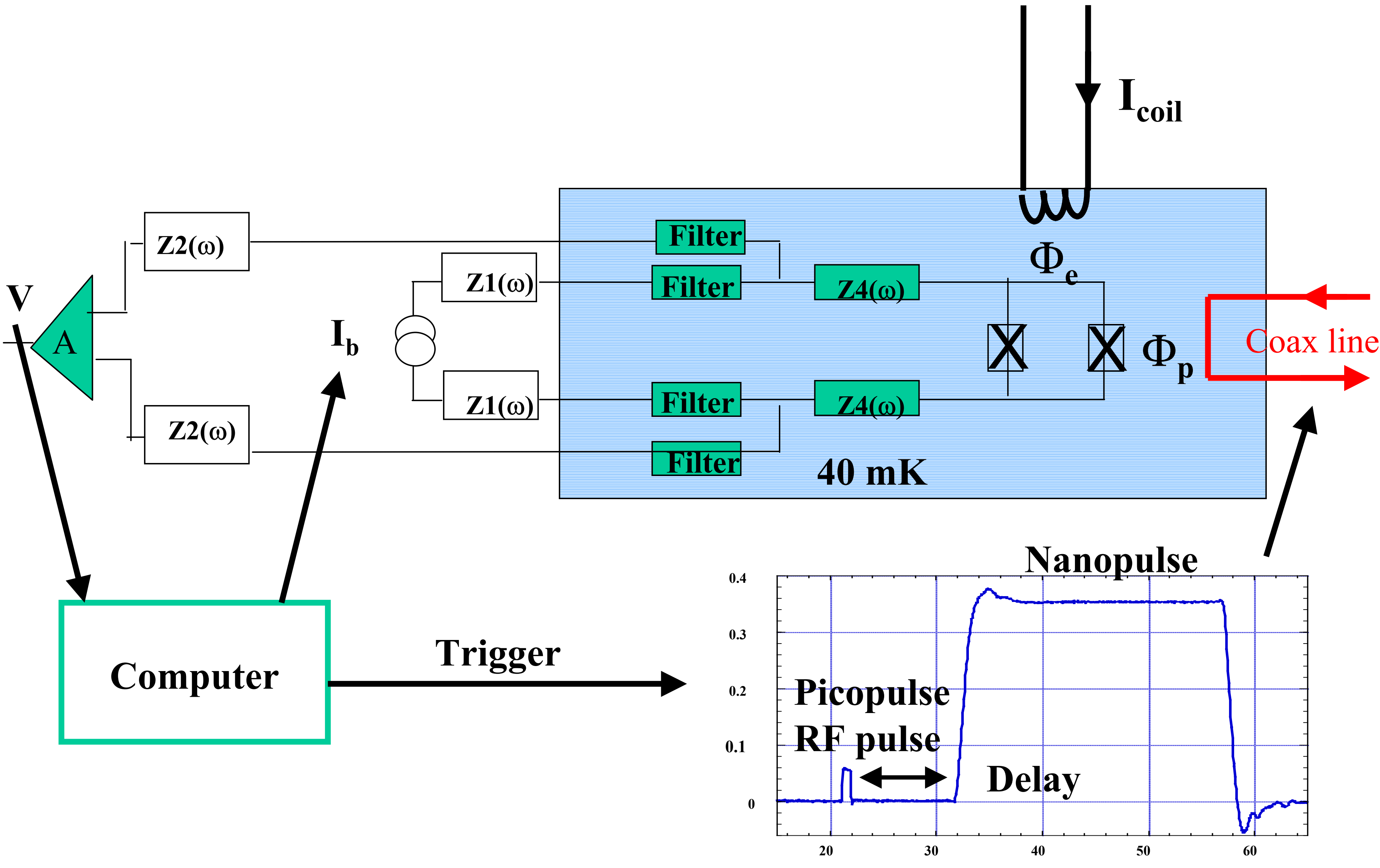
$\tau_0 = 1000\ \tau_1$
$\tau_{❄}\ \alpha\ Q$

- 2 experimental states Read-out

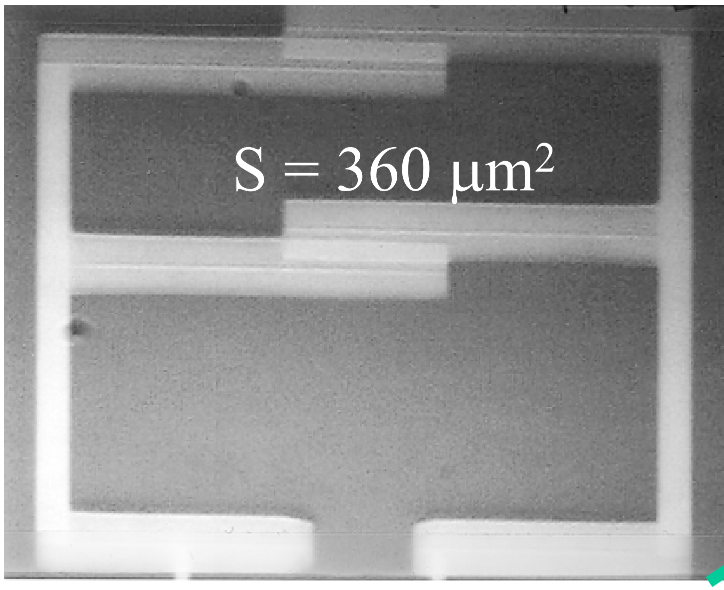


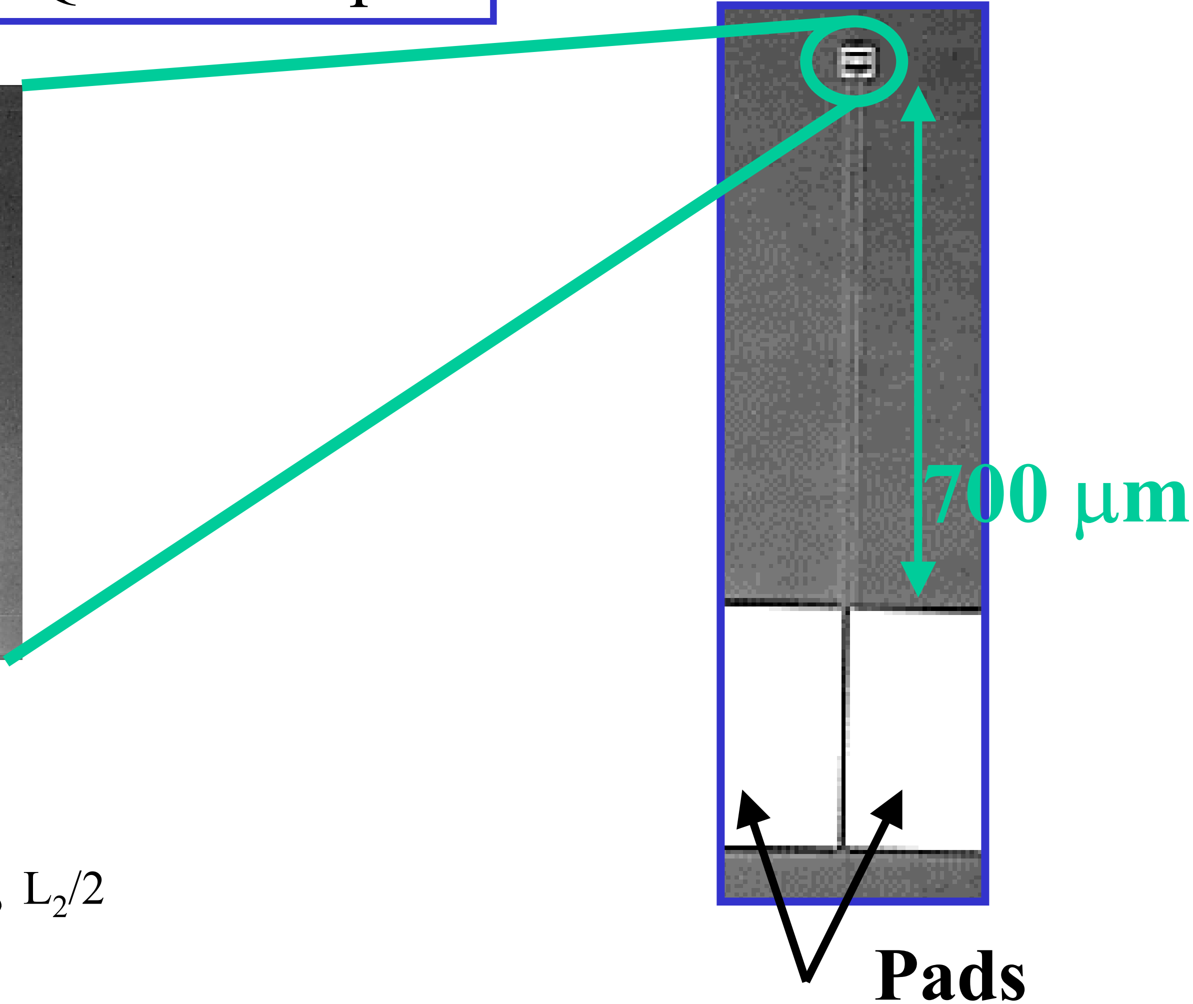
$\Delta V \approx 400\ \mu V$

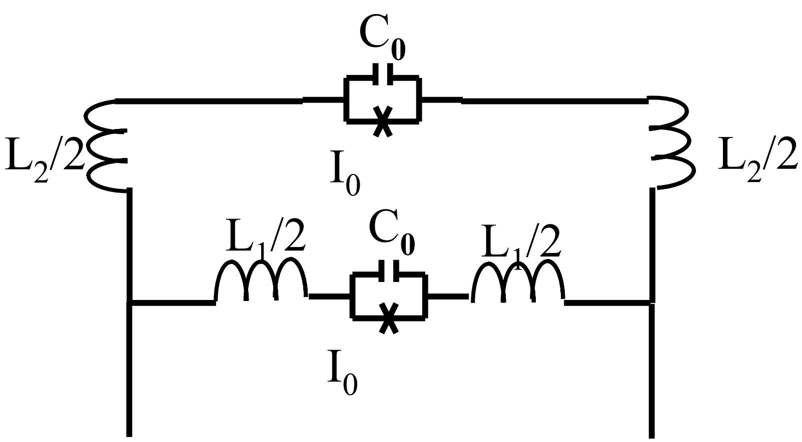
Actual experimental set-up



SQUID samples







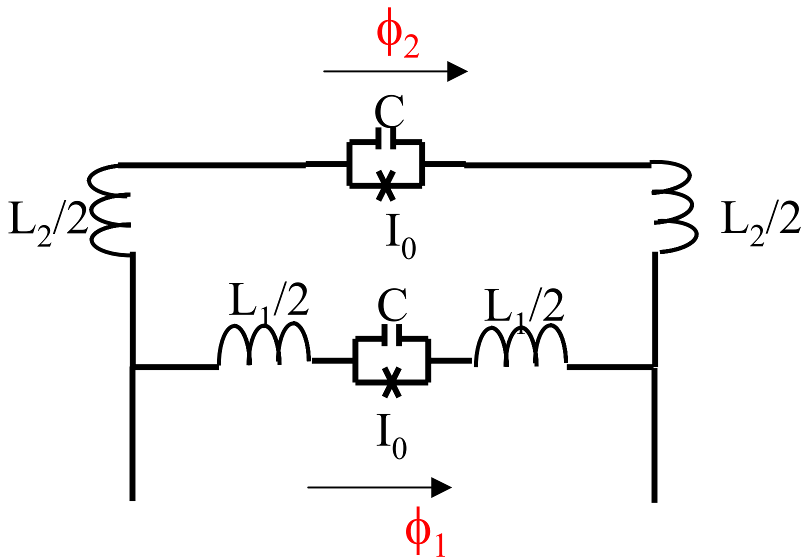
$L_1 = 90pH$, $L_2 = 154pH$

$L_{squid} = L_1 + L_2$

Kinetic inductance

$$L_K = 2\mu_0 \lambda_{eff}^2 \frac{l}{ew} \approx 2nH$$

2D potential of the SQUID

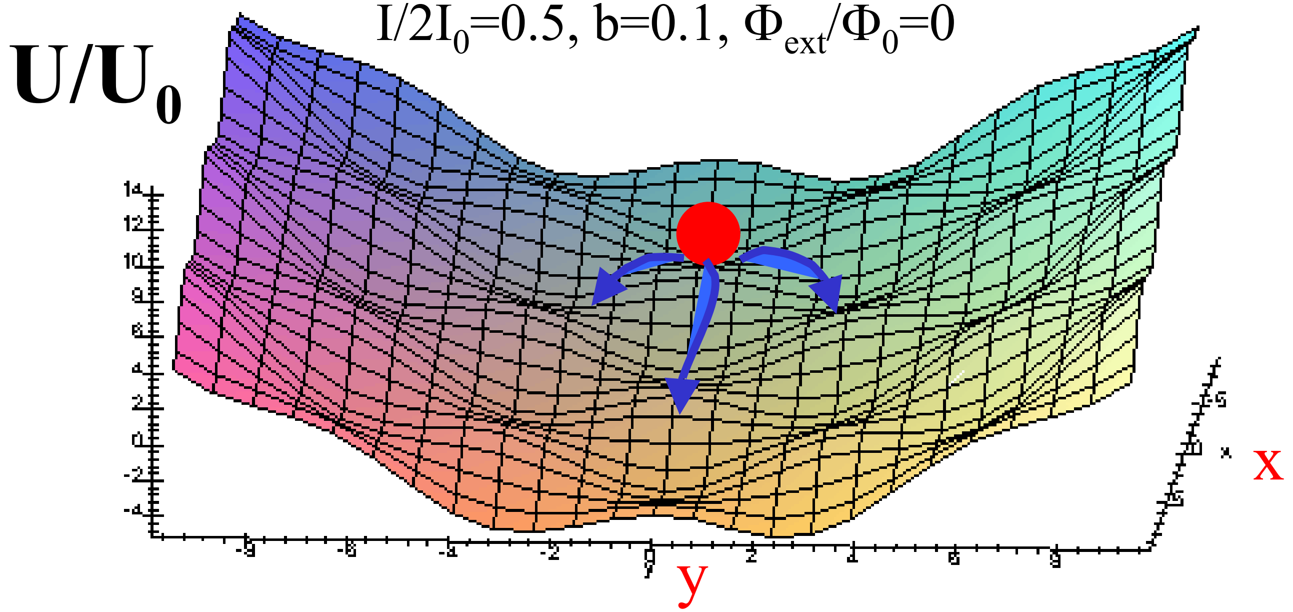


$\mathbf{x}=(\phi_1+\phi_2)/2$

$\mathbf{y}=(\phi_1-\phi_2)/2$

$b=\Phi_0/(2\pi I_0 L_{squid})$

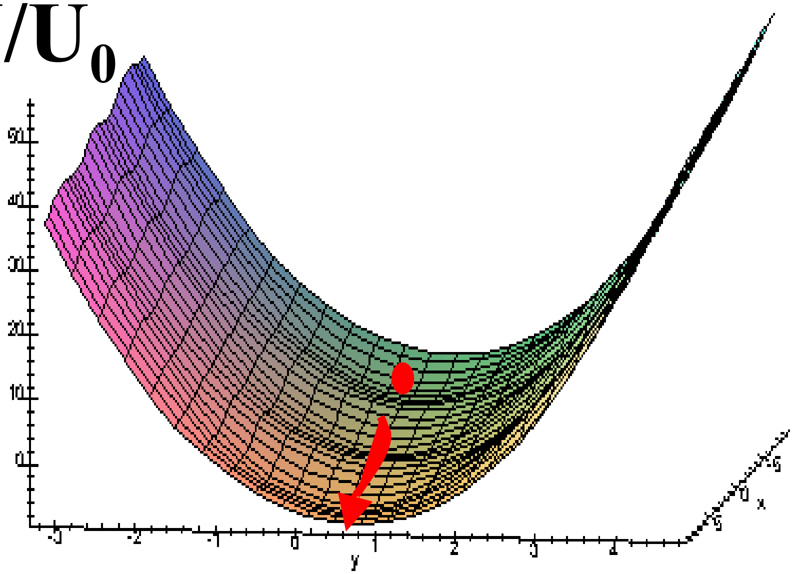
$I/2I_0=0.5,\ b=0.1,\ \Phi_{ext}/\Phi_0=0$

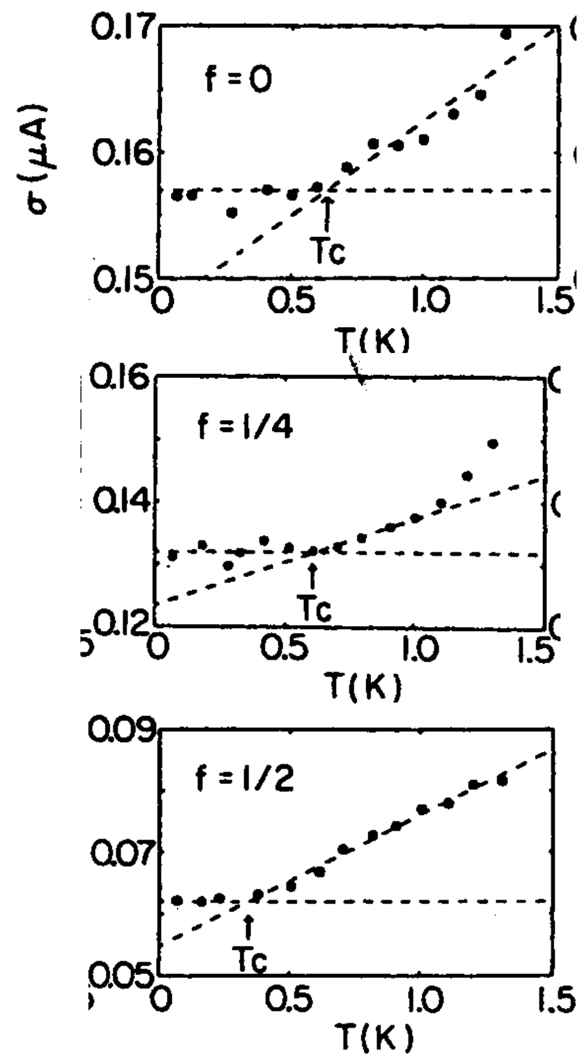


Escape in the 1D potential limit

$I/2I_0=0.5$, $b=3.3$, $\Phi_{ext}/\Phi_0=0.2$

U/U_0

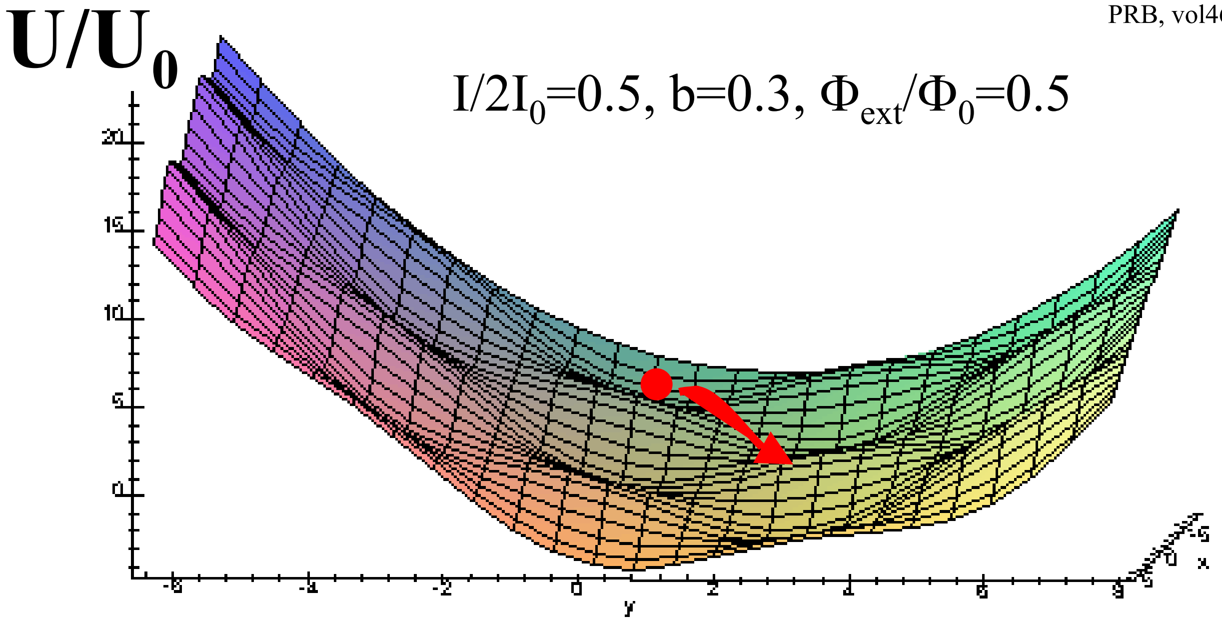


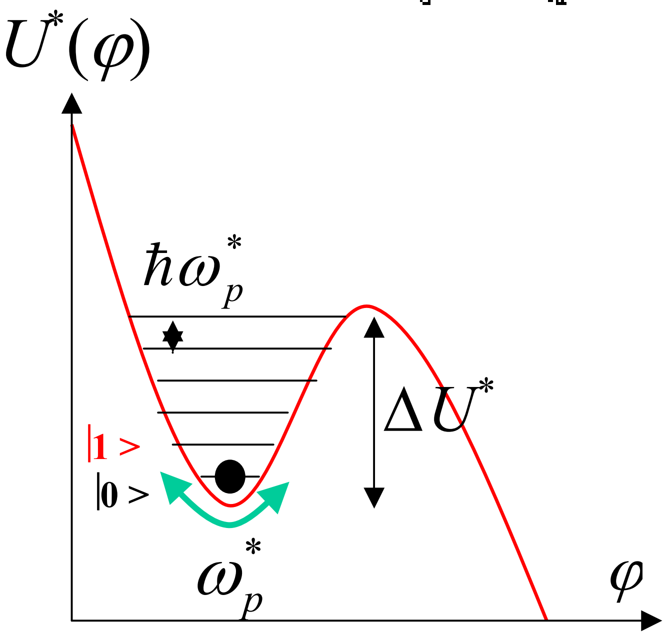


Sharifi and al.
PRL, vol61, #6, 1988, pp 742

Escape from a 2D potential

Lefevre-Seguin and al.
PRB, vol46, #9, 1992, pp 5507



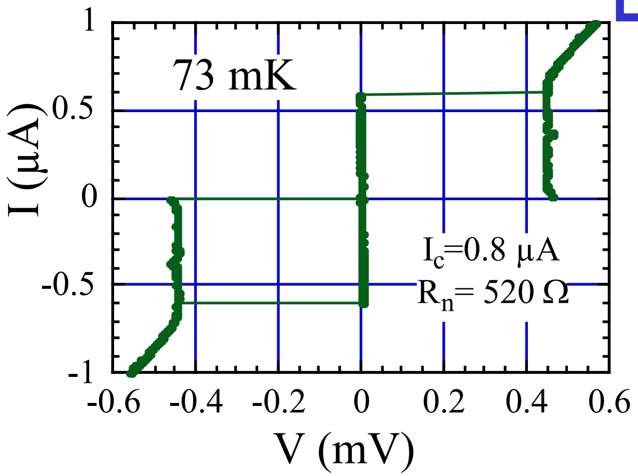


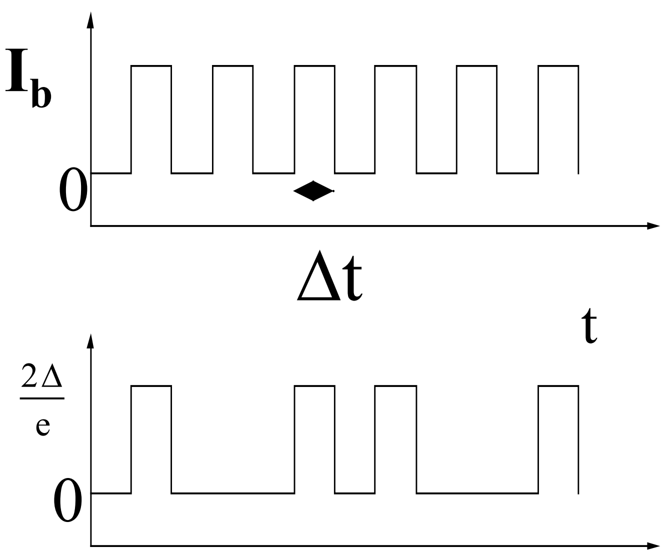
$$\omega_p^* = \omega_p(2I_0, 2C_0)\kappa_1(I_b, L_{squid}, \Phi_e)$$

$$\Delta U^* = \Delta U(2I_0)\ \kappa_2(I_b, L_{squid}, \Phi_e)$$

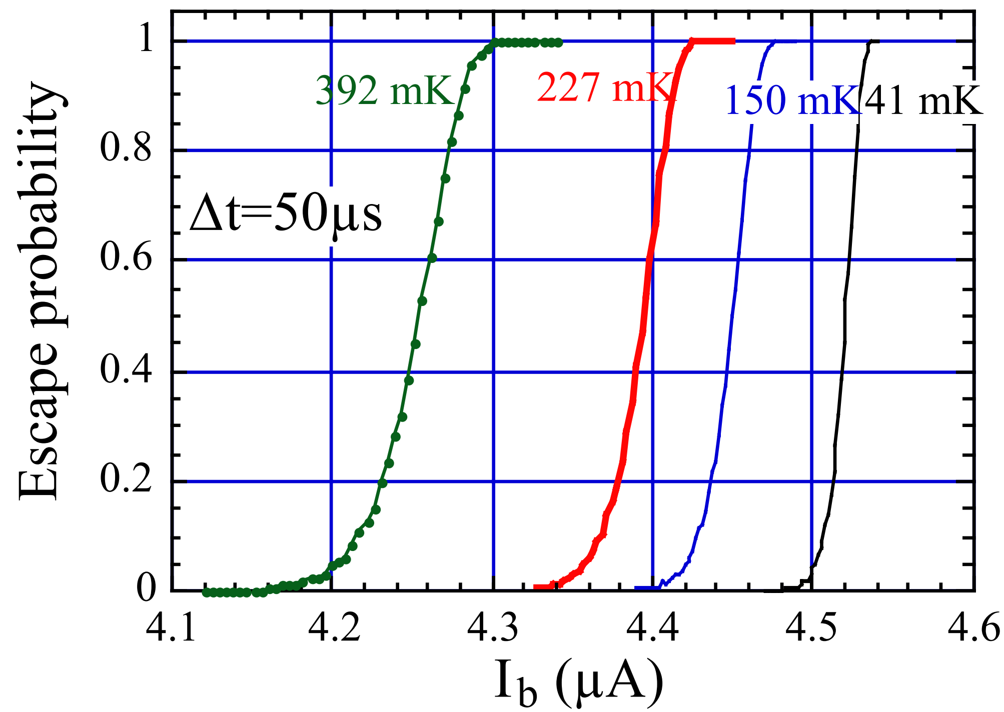
$$\Gamma_{TA}^* = \frac{\omega_w^\perp}{\omega_s^\perp}\frac{\omega_p^*}{2\pi}e^{-\frac{\Delta U^*}{kT}}$$

Histogram technic





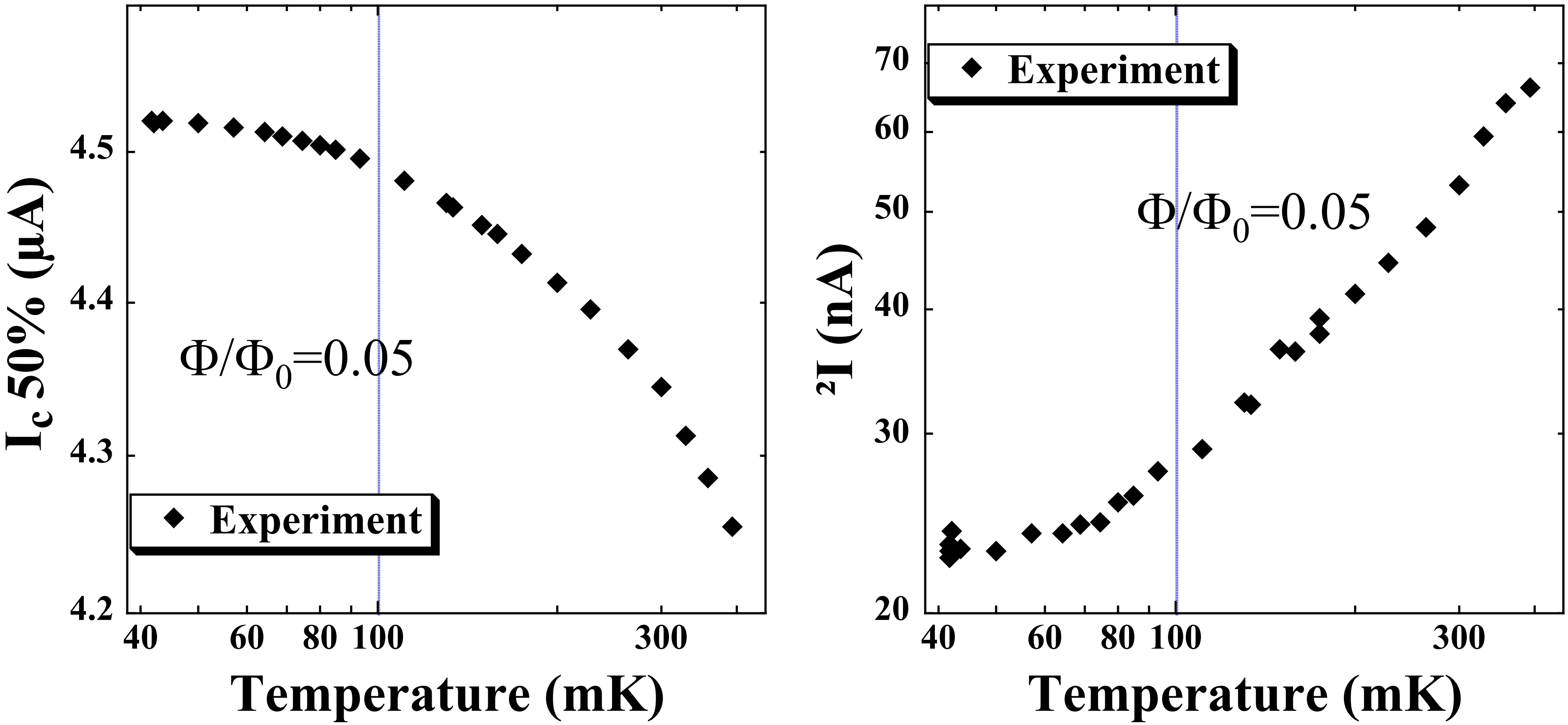
Escape probability for a current pulse I_b



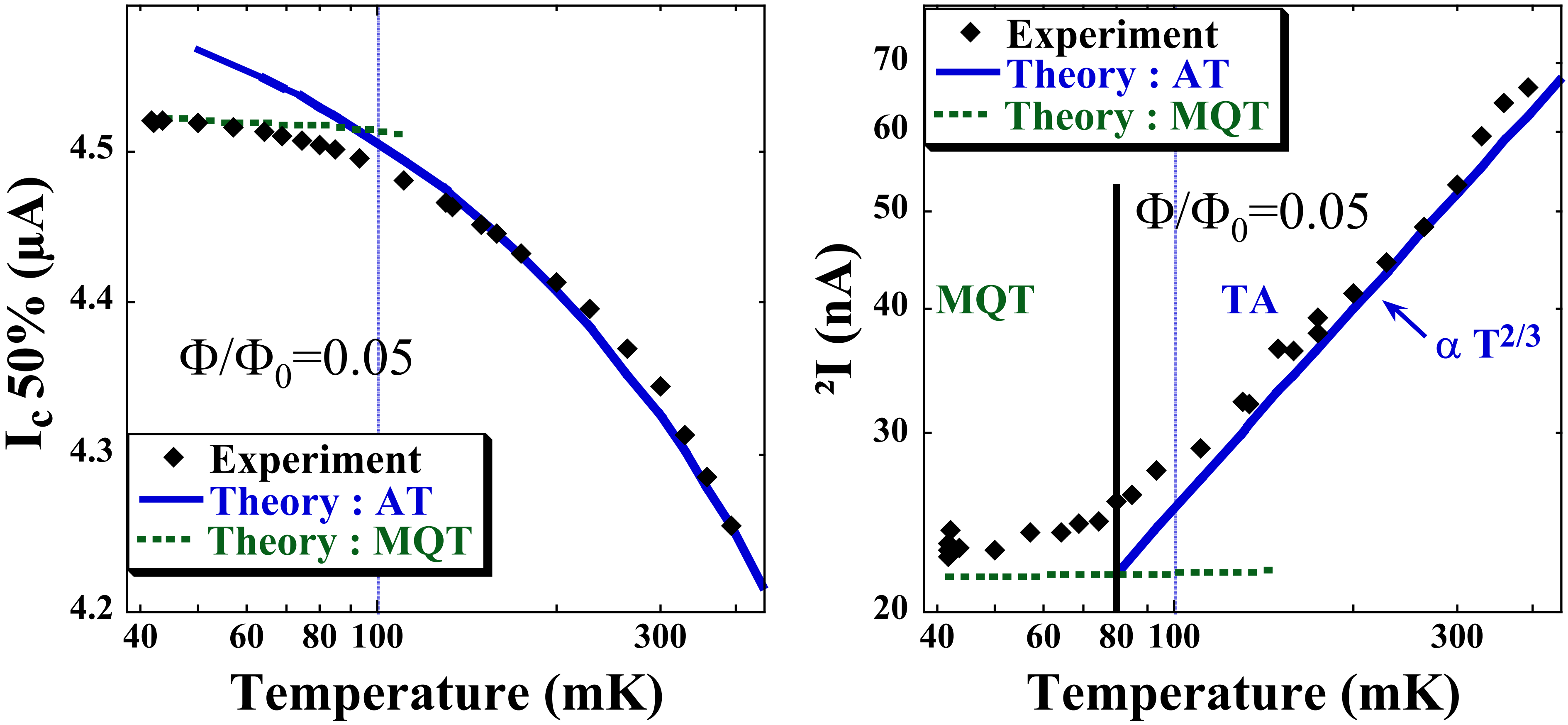
$P(\Delta t, I) = 1 - \exp(-\Delta t / \tau(I))$

τ(I): life time

MQT and TA for a SQUID close to zero flux

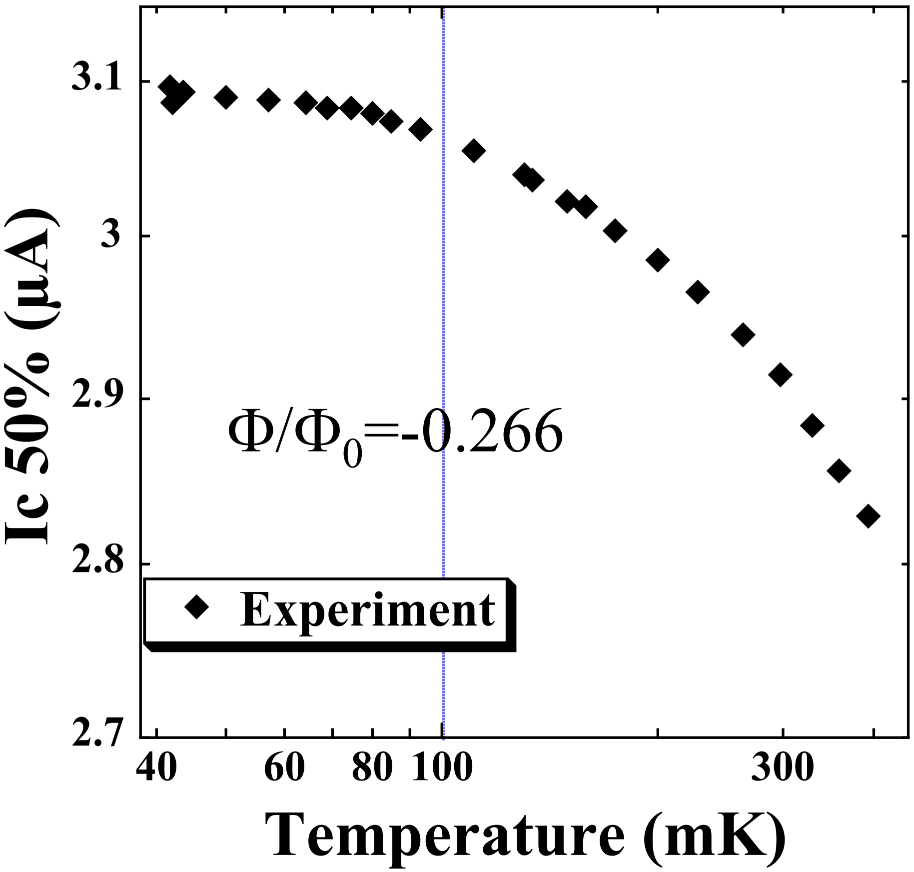


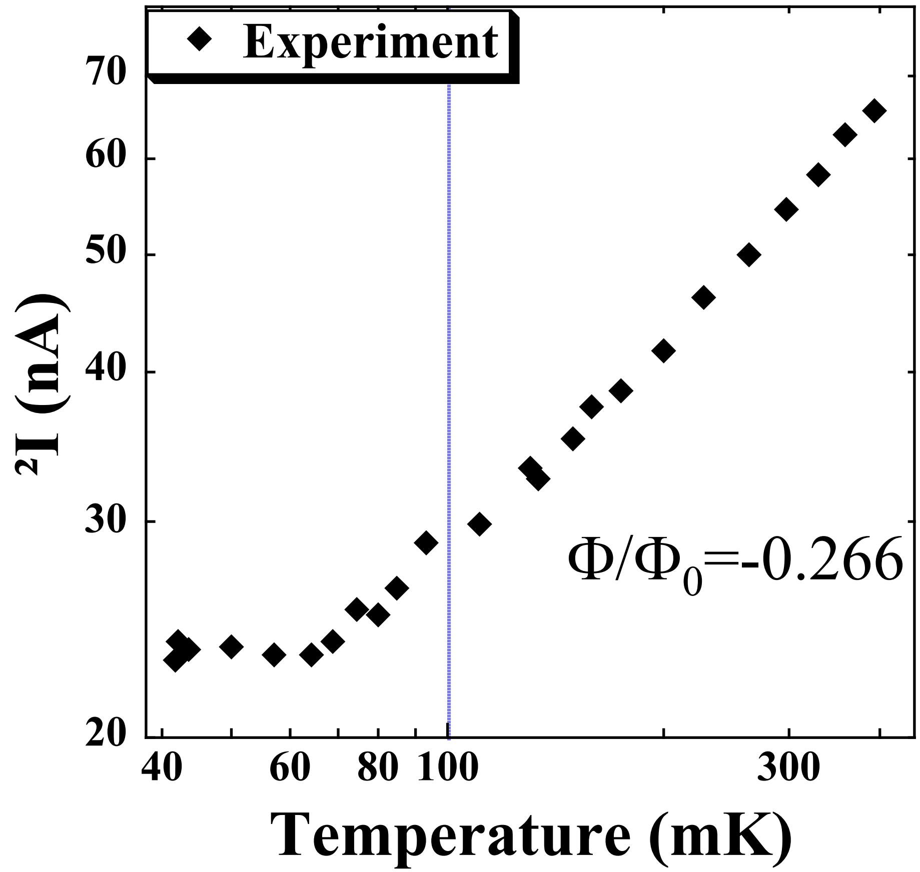
MQT and TA for a SQUID close to zero flux



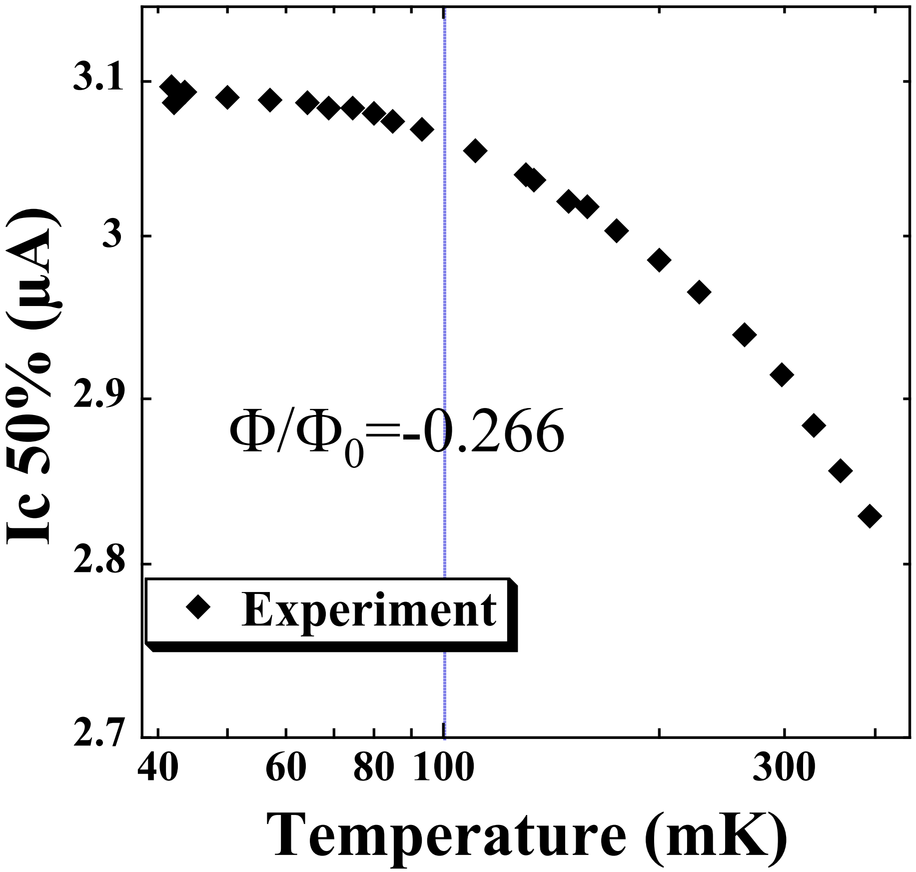
I_0 = 2.342 μA
C_0 = 0.44 pF
L_{env} = 11 nH

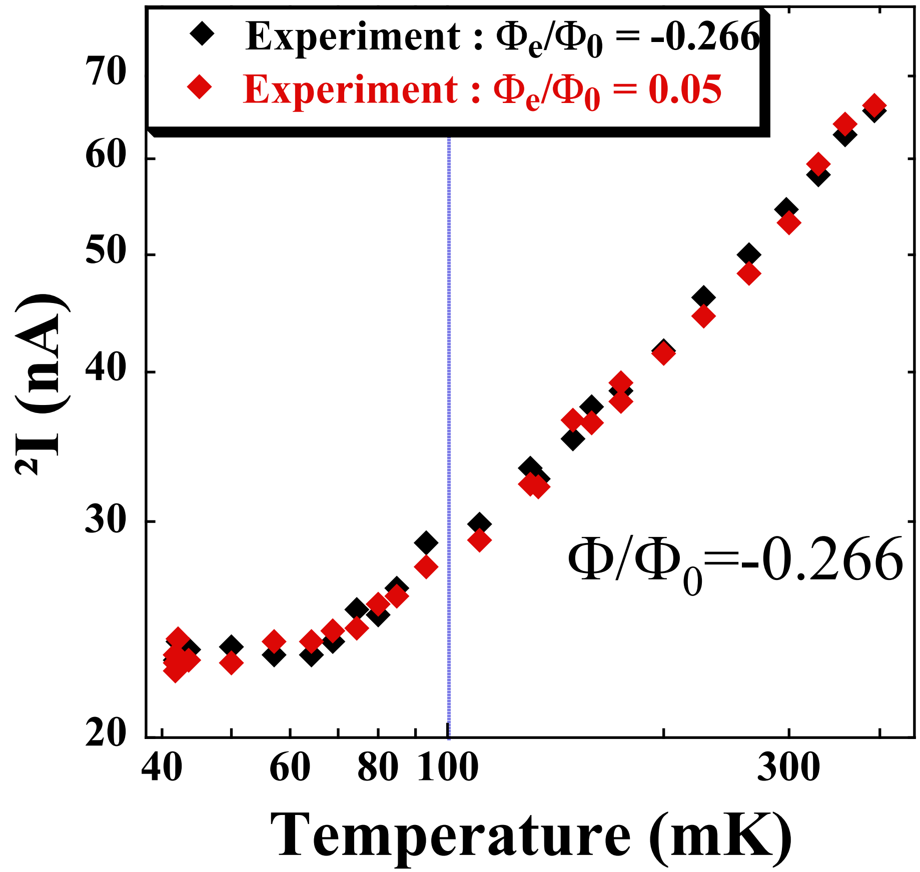
MQT and TA for a SQUID at -Φ_0 /4



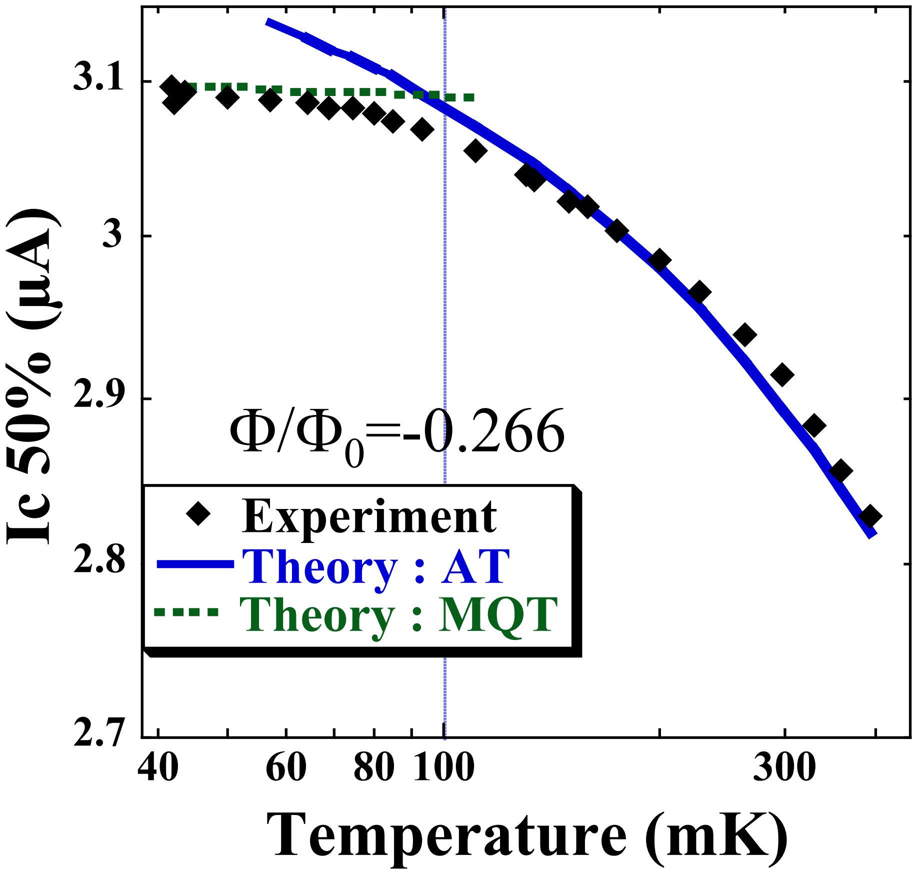


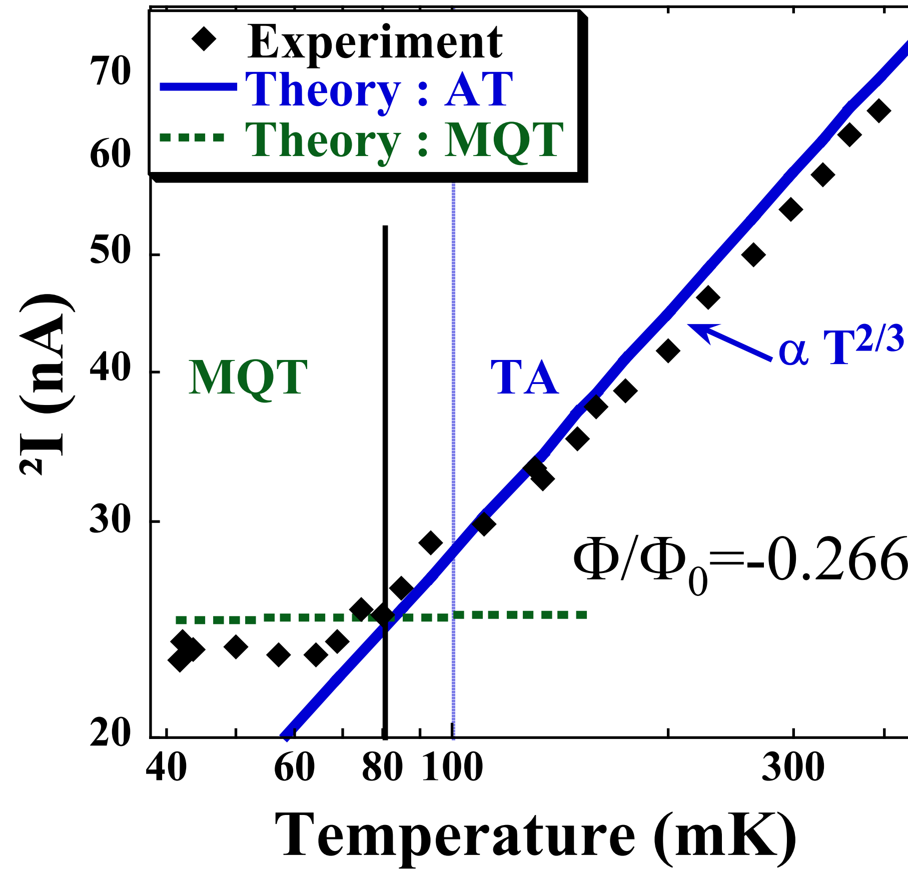
MQT and TA for a SQUID at $-\Phi_0/4$





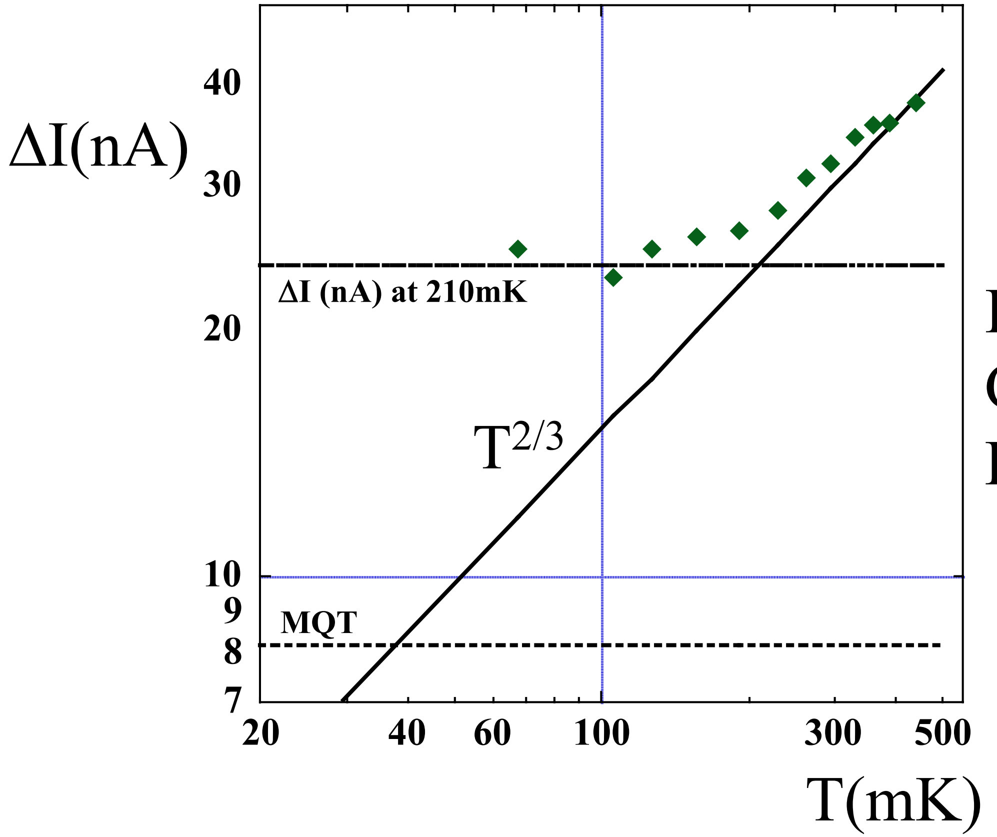
MQT and TA for a SQUID at $-\Phi_0/4$





$I_0 = 2.342\ \mu A$
$C_0 = 0.44$ pF
$L_{env} = 11$ nH

RF measurements on a SQUID



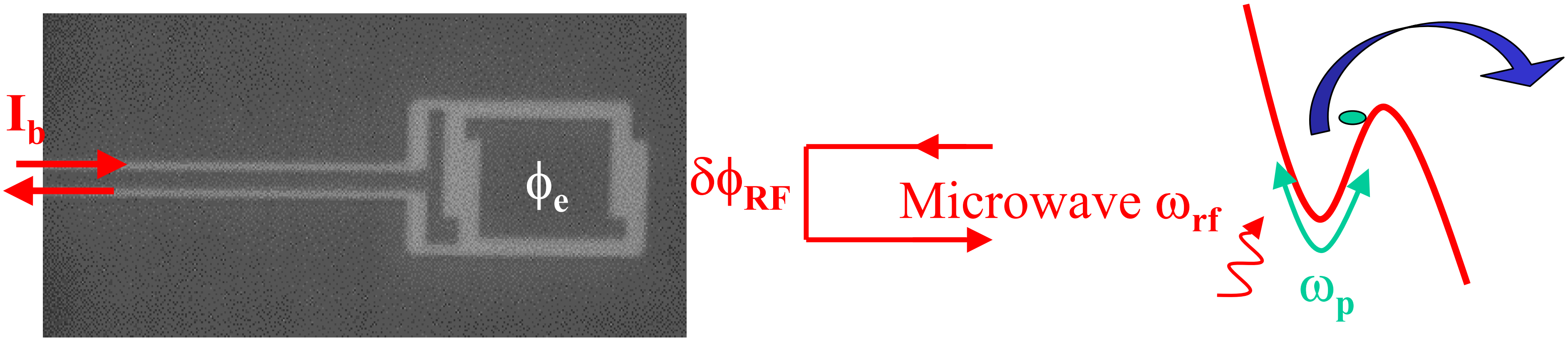
$I_c(\Phi/\Phi_0=0)=770nA$
$C_{squid}=0,65pF$
$L_{squid}=150pH$

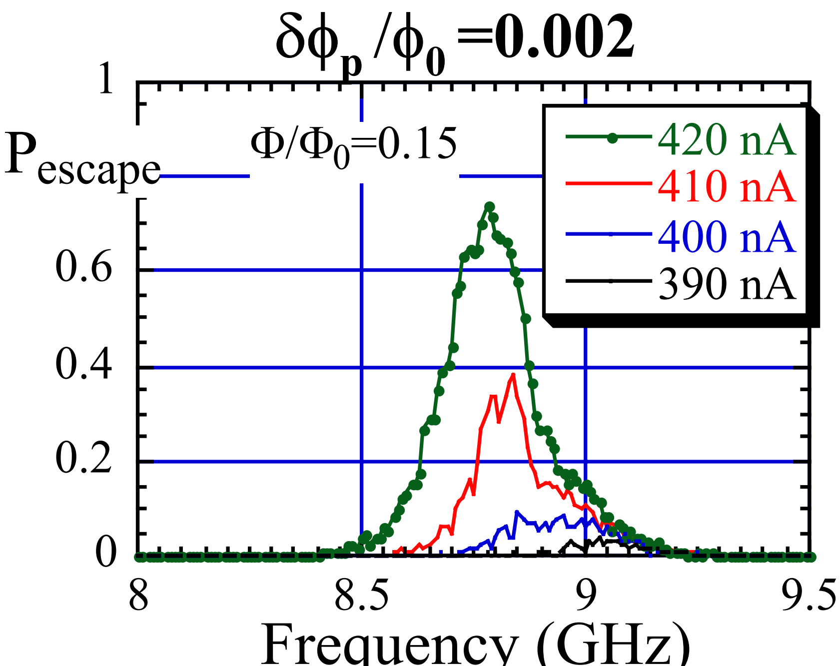
External noise?

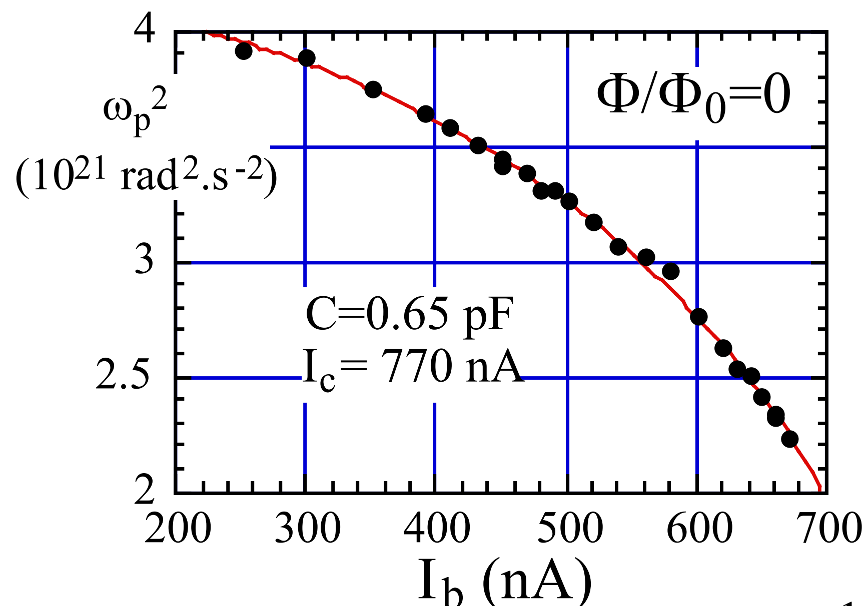
- I_c too small
- from the coaxial line
- thermal heating from the coaxial line

→ Definition of an effective temperature : $T_{eff}=210mK$

Resonant activation in a SQUID



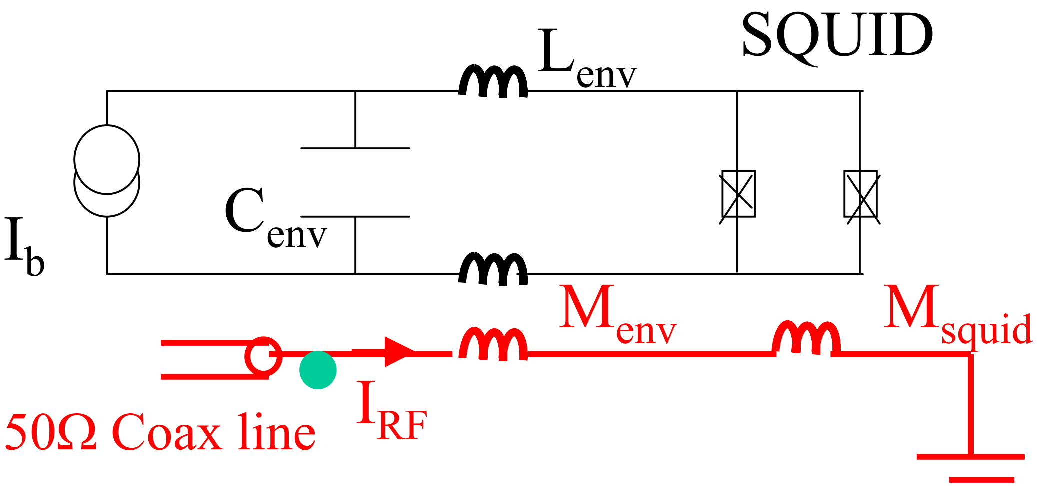




Fit law : $\omega_p \propto \sqrt{\frac{I_c}{C}}\ \left(1-\left(\frac{I}{I_c}\right)^2\right)^{\frac{1}{4}}$

Q ~ 40?

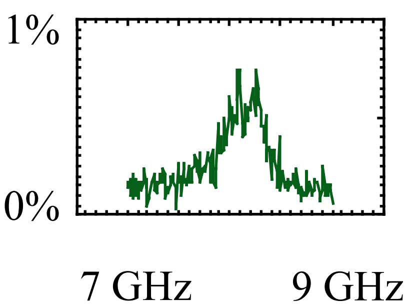
Classical and linear model



$I_c(\Phi/\Phi_0=0)=770nA$
$C_{squid}=0,65pF$
$M_{squid}=0,46pH$

$M_{env}=2,3pH$
$L_{env}=3,3nH$
$C_{env}=86pF$

For $I_{RF}= 0.5\mu A$



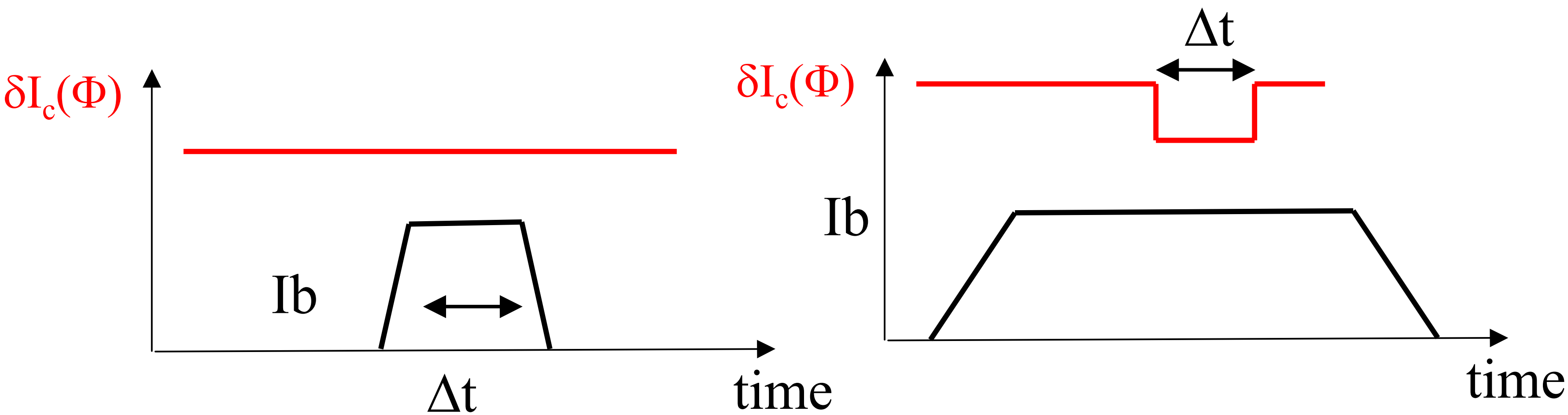
Energie : $E \propto \frac{\Phi_0 I_c}{2\pi}(\delta\varphi_{max})^2$

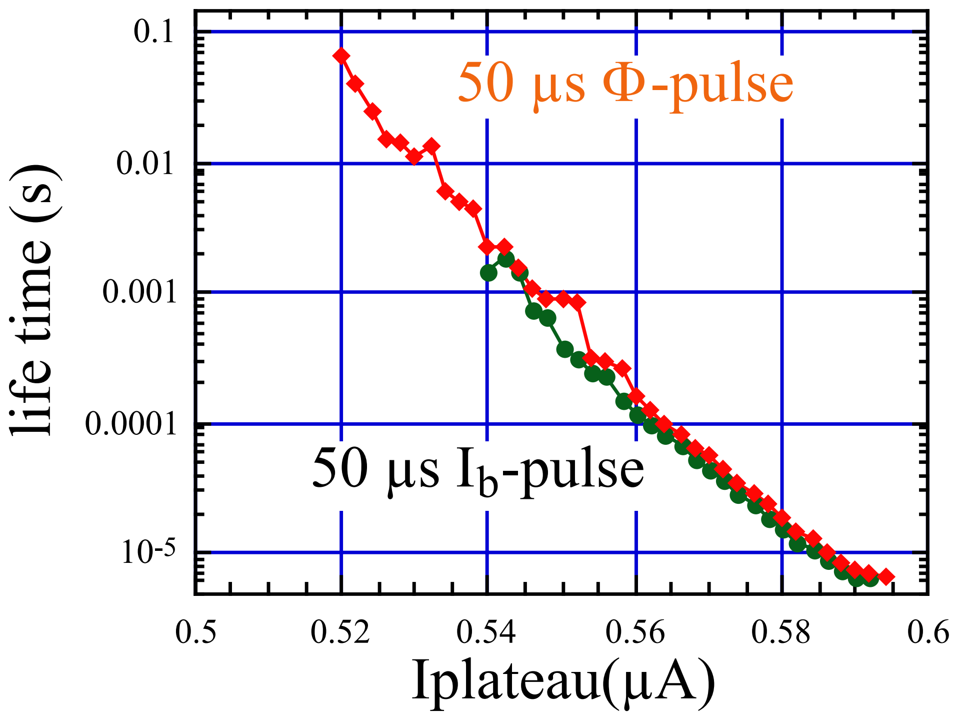
$\langle N \rangle = E/\hbar\omega_p \approx 0.015$ for Q~16

Very sensitive detection !!

But $\langle N \rangle_{therm}$ ~0,15!

Current pulses and flux pulses

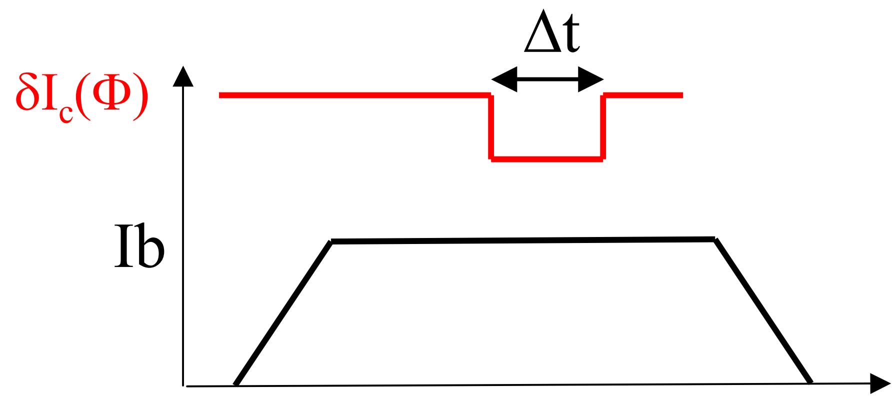




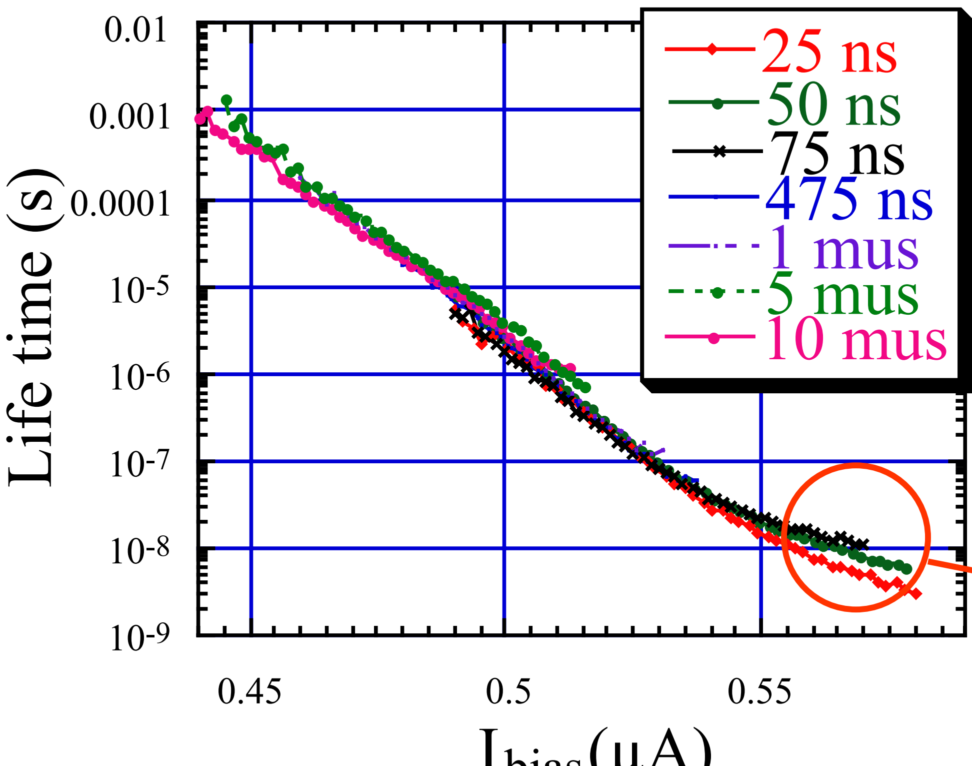
$\Phi_e/\Phi_0 = \mathbf{0.15}$

Escape can be controlled by flux pulses!

Nanopulses of flux



$\Phi_e/\Phi_0 = 0.15$
Rise time = 21ns

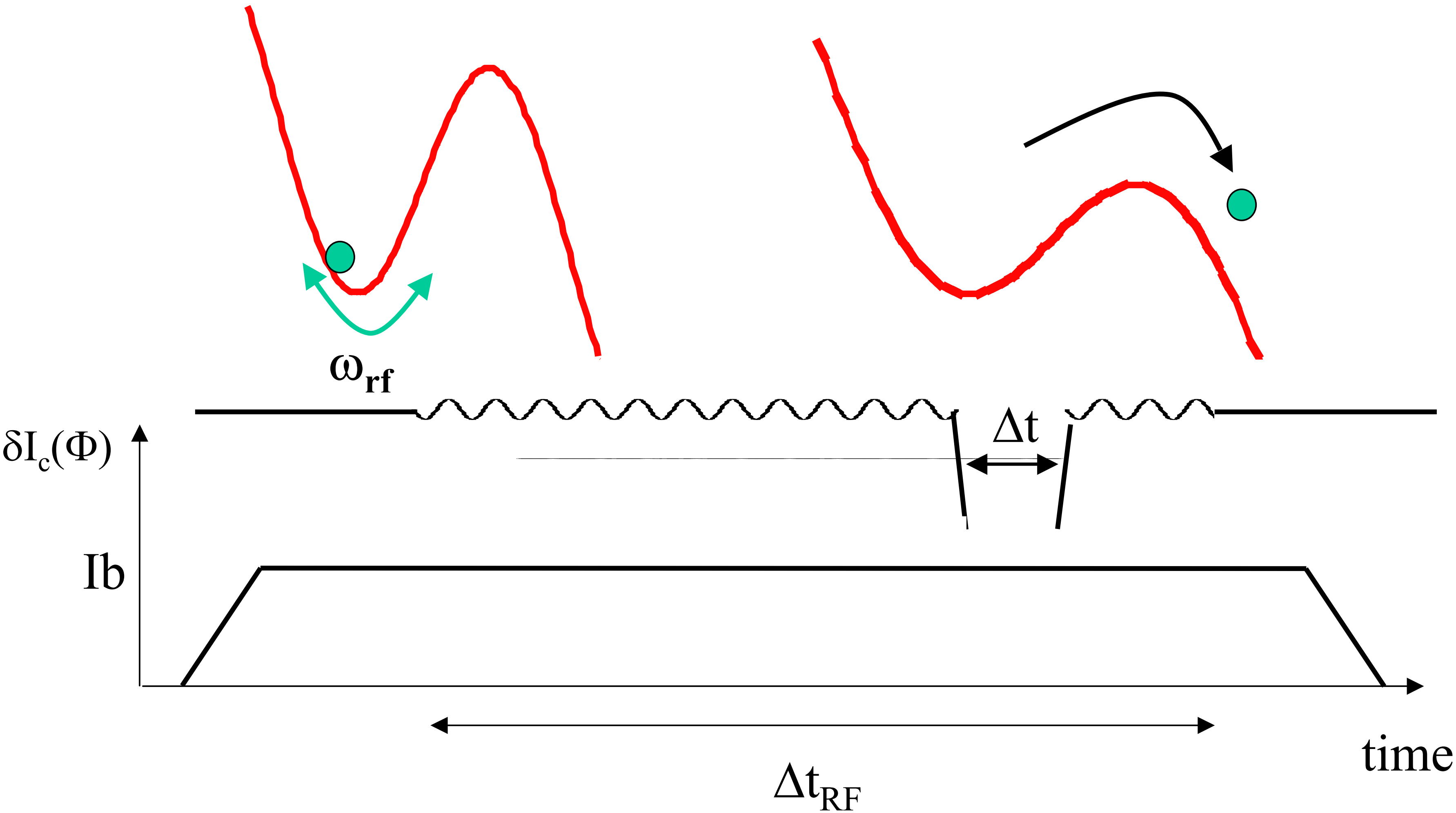


Escape probability

$$P(\Delta t, I) = 1 - \exp(-\Delta t/\tau(I))$$

10 ns life time measurement !

Adiabatic measurements

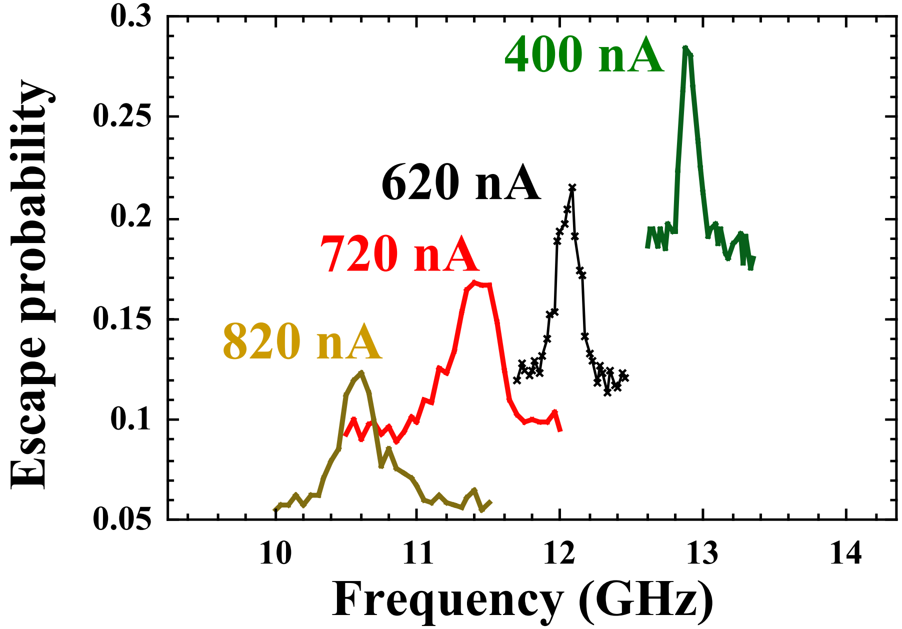


Δt_{RF} =4μs

Δt ~ 10ns ~ relaxation time

Rise and fall time of the nanopulse ~1,6ns < relaxation time

Linear measurement of the plasma frequency



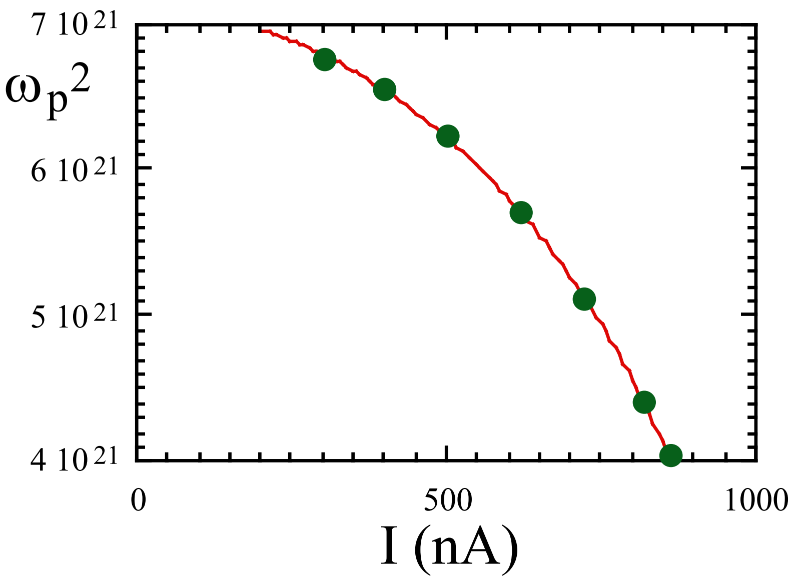
$\Phi/\Phi_0=0{,}26$

$\Delta t_{RF} = 4\mu s$

$\Delta t_{DC\text{-}pulses} = 10ns$

$T = 74mK$

$T_{eff}=150mK$



Fit law : $\omega_p \propto \sqrt{\frac{I_c}{C}}\ (1-(\frac{I}{I_c})^2)^{\frac{1}{4}}$

$I_c(\Phi/\Phi_0=0{,}26)=1047nA$

$C_{squid}=0{,}46pF$

Conclusion

Experimental set-up :

Low noise measurement

MQT for a JJ

Thermal activation with a predicted $T^{2/3}$

Observation of MQT for a particle in a two dimensional potential

Dynamics experiments :

Observation of resonant activation in the SQUID

Very short life time measurements using nanopulse

Adiabatic meausrements?

In the future :

High quality factor

Analysis of the resonant activation escape

Single excitation in the SQUID

SQUID coupled to a Cooper pair box