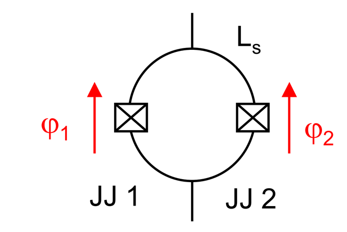
Journées J3N Réseau National en Nanosciences et en Nanotechnologies
6 au 8 novembre 2006

Quantum dynamics in superconducting nano-cuiruits

The SQUID: a tunable anharmonic oscillator

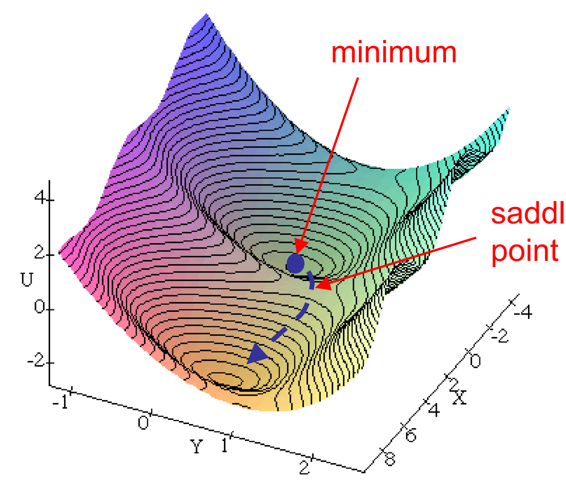
The DC-SQUID:

- 2 Josephson junctions (JJ) (capacitance C_0, critical current I_0)
- coupled by a superconducting loop (inductance L_s)

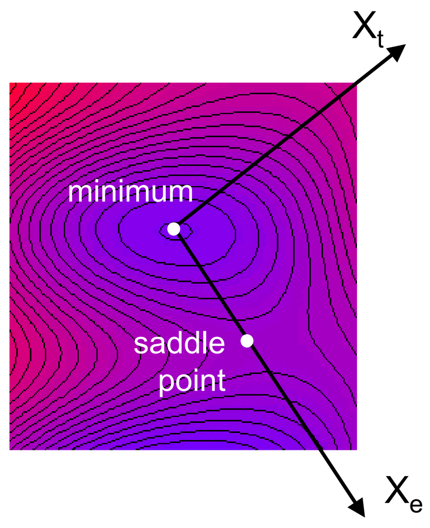


⇨ 2 degrees of freedom φ_1 and φ_2

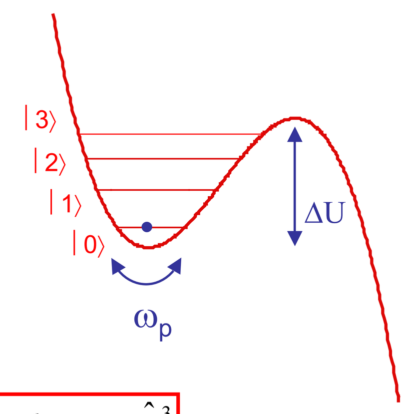
A fictitious particle (mass m) moving in a 2D potential U(X,Y)



Simplification: from 2D to 1D



Dynamics along the escape direction (X_e): a tunable artificial atom



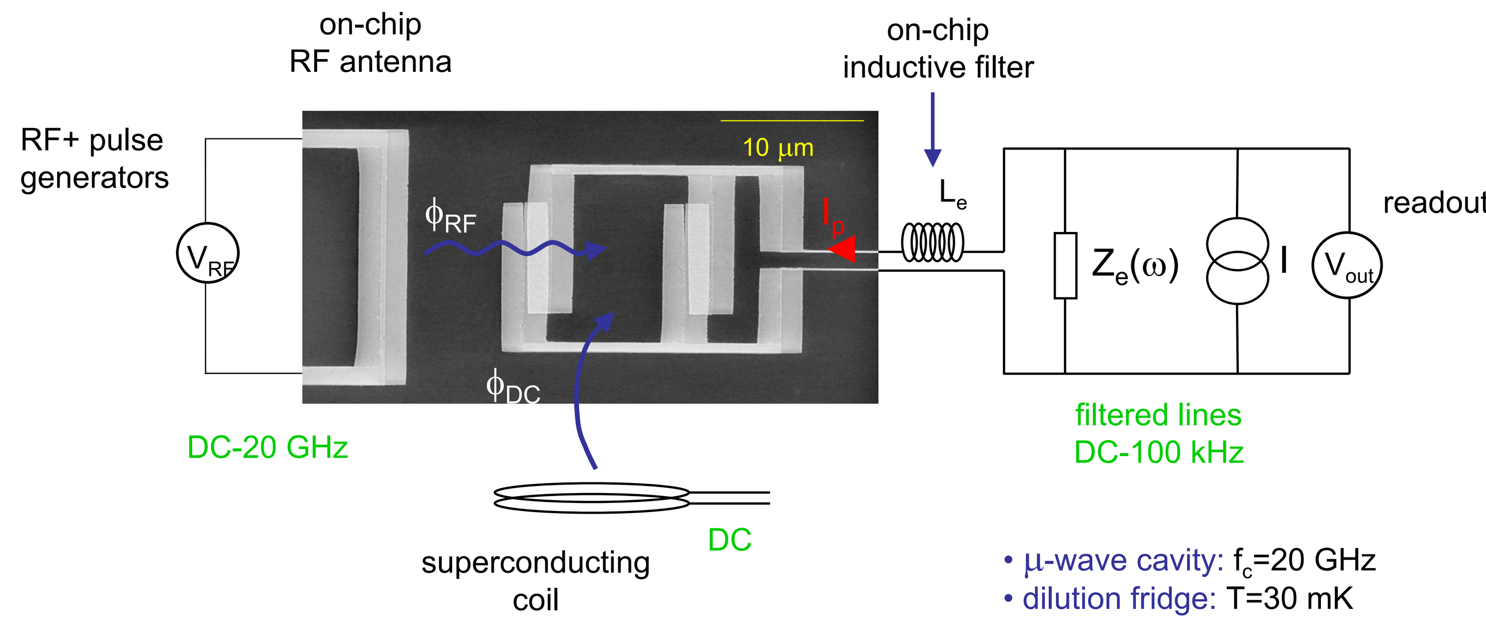
$$\hat{H}_e = \hbar\omega_p \cdot \left(\hat{P}^2 + \hat{X}^2\right) - \hbar\omega_p\sigma \cdot \hat{X}^3$$

Dynamics along X_e and X_t:
⇨ weakly coupled

Characteristics of the atom
- number of levels
- levels spacing

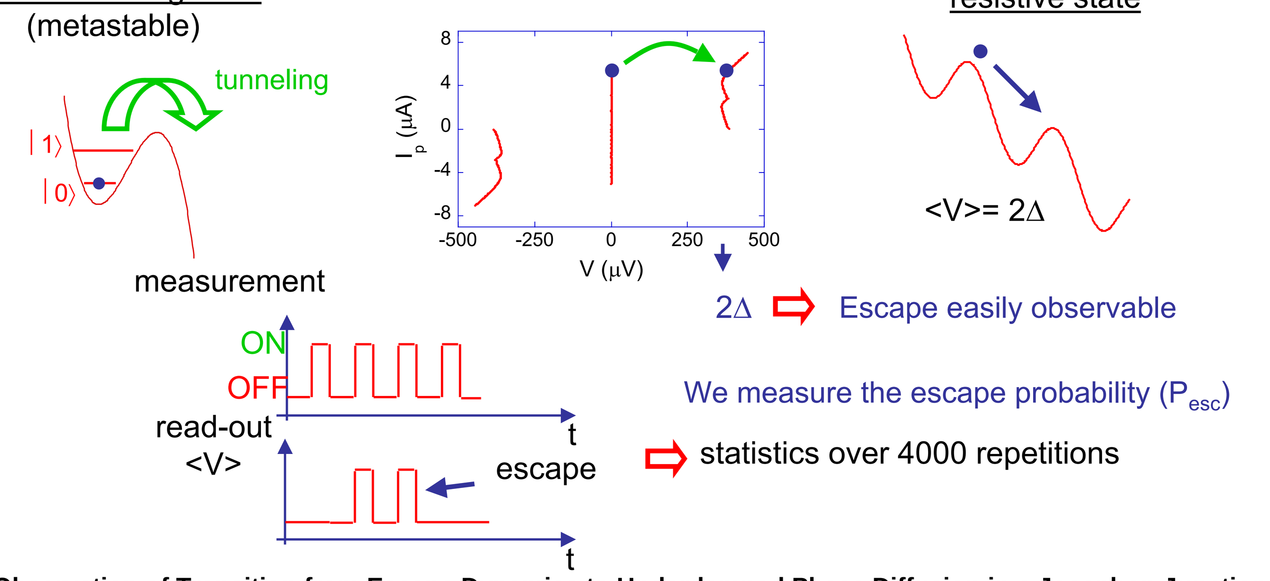
⇨ experimentally controlled by I_p and ϕ_{DC}

Schematic experimental setup



- µ-wave cavity: f_c=20 GHz
- dilution fridge: T=30 mK

Escape measurements



⇨ Escape easily observable

We measure the escape probability (P_{esc})

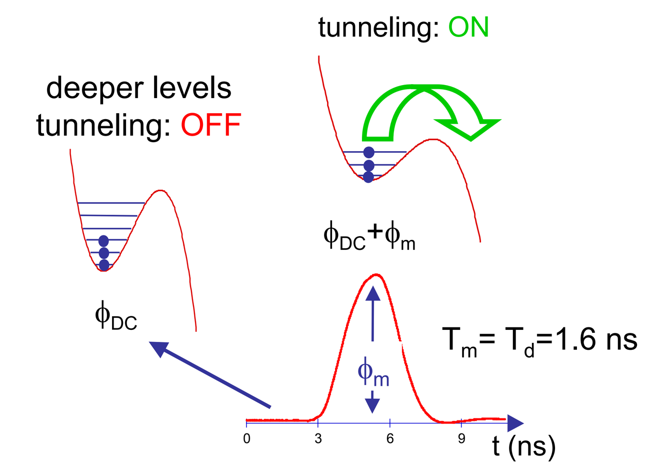
⇨ statistics over 4000 repetitions

Observation of Transition from Escape Dynamics to Underdamped Phase Diffusion in a Josephson Junction
J. M. Kivioja, T. E. Nieminen, J. Claudon, O. Buisson, F.W.J. Hekking, and J.P. Pekola *PRL* **94** 247002 (2005)

Measuring the quantum state of the SQUID

Adiabatic measurement technique

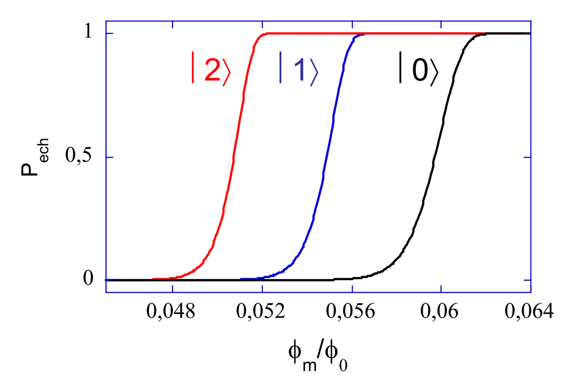
GOAL: measurement of the energy levels population
⇨ short DC flux pulses

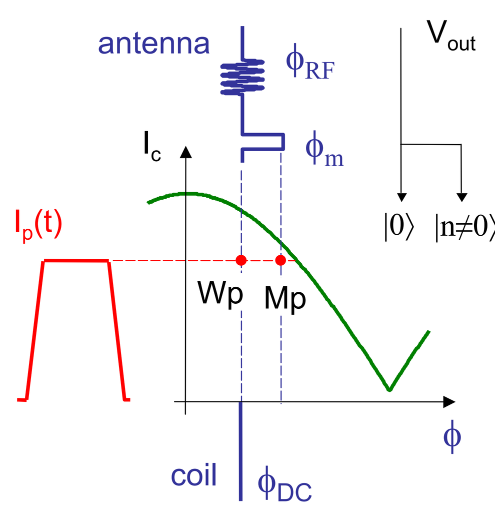


Constraints:
- adiabatic pulse
- faster than relaxation processes

⇨ fast measurement: 5 ns

Contrast (theory)





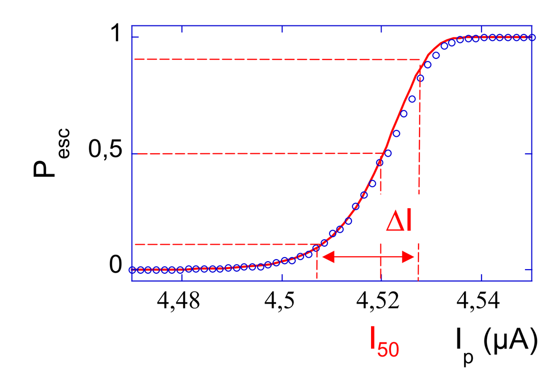
Sketch of quantum experiments

Wp = Working point
Mp = Measuring point

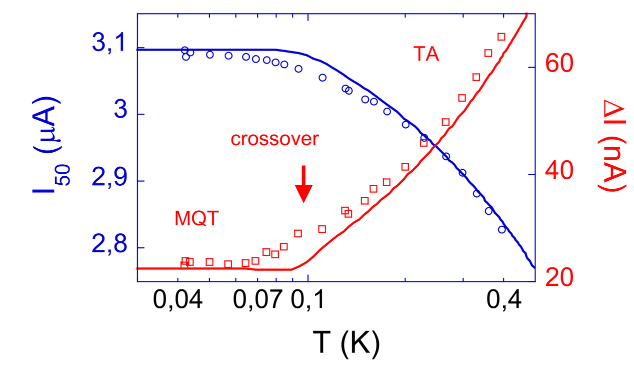
One-Shot Quantum Measurement Using a Hysteretic dc SQUID
O. Buisson, F. Balestro, J. P. Pekola, and F. W. J. Hekking *PRL* **90** 238304 (2003)

Escape of the ground state

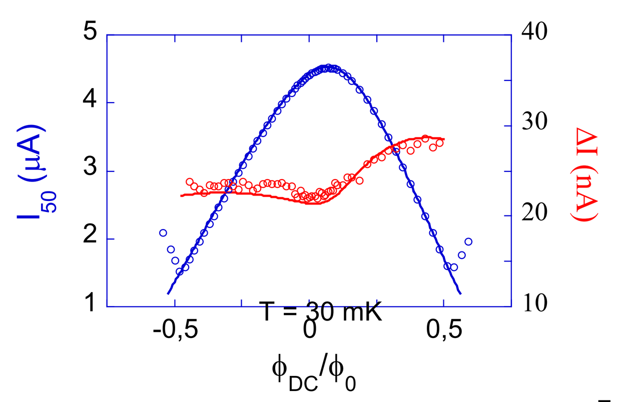
Escape induced by slow current pulses (I_p 50 µs)



Temperature dependance of the escape process



DC flux dependance



2 escape regimes:
- quantum tunneling (MQT)
- thermal activation (TA)

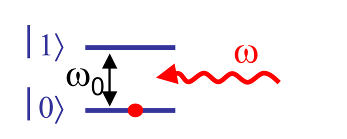
ΔI = f(T) At low temperature, the SQUID lies in the ground state at all fluxes.

I_{50} = f(ϕ_{DC}) Characterization of the SQUID 's parameters

I_0 = 2.33 µA   b= 0.6
C_0= 0.46 pF   η= -0.26

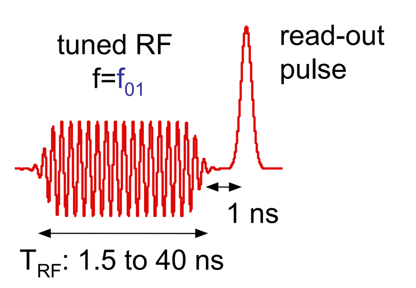
Evidence of two-dimensional MQT of a current-biased dc-SQUID
F. Balestro, J. Claudon, J. P. Pekola, and O. Buisson *PRL* **91** 158301 (2003)

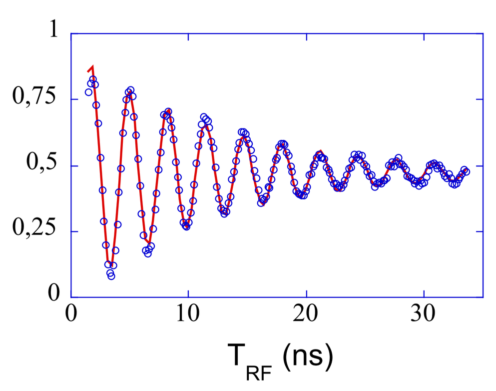
Multi-level coherent oscillations



$$\hat{H} = \hat{H}_0 + \hbar\Omega\sin(\omega t)\hat{X}$$

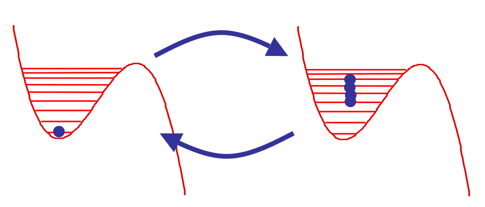
eigenstates: |0⟩ and |1⟩
coupling to RF



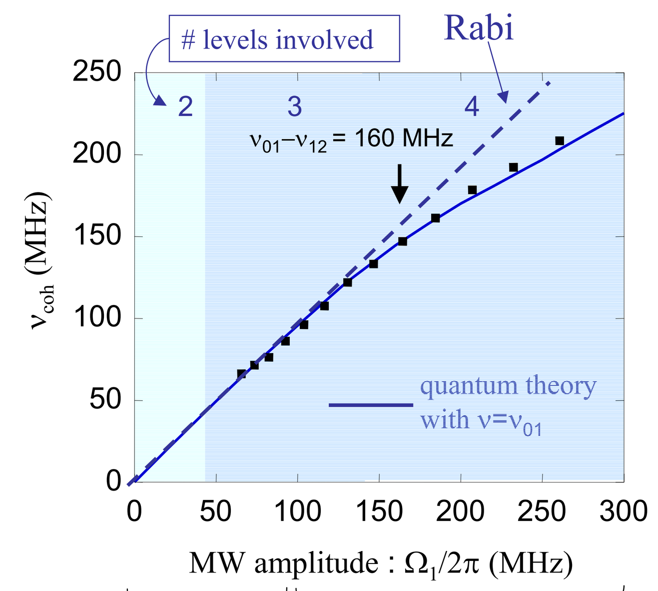


⇨ decoherene time ~14 ns

Multi-level coherent oscillations



How many levels?



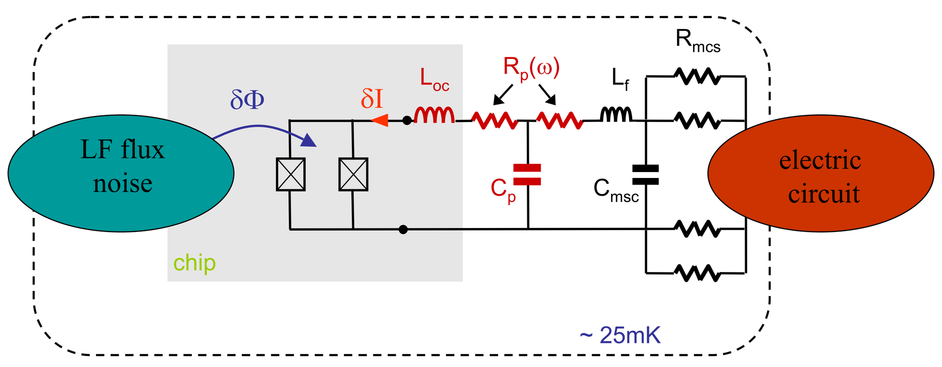
- Low excitation power : two level description
- Intermediate power : multi- level description

Cross- over condition:

Anharmonicity ⟺ MW amplitude
$\nu_{01}-\nu_{12}$ Ω_1

Coherent oscillations in a Superconducting Mutilevel Quantum System
J. Claudon, F. Balestro, F. W. J. Hekking, and O. Buisson *PRL* **93** 187003 (2004)

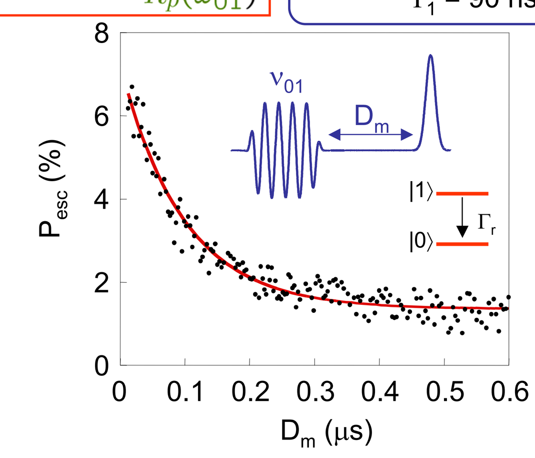
Decoherence processes



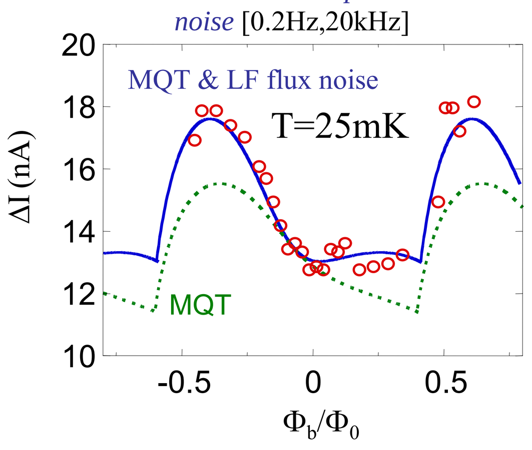
- HF fluctuations from electric circuit —— quantum fluctuation dissipation theorem ⟶ $S_I(\omega)$ (long correlation time ~30ns)
- LF flux noise —— MQT analysis ⟶ $\sqrt{\langle\delta\Phi^2\rangle} = 5.5 \times 10^{-4}\ \Phi_0$

$$T_1 \approx 2C_0\frac{L_{oc}^2}{R_p(\omega_{01})}\omega_{01}^2$$

solid line ∝ $\exp(-D_m/T_1)$
T_1 = 90 ns

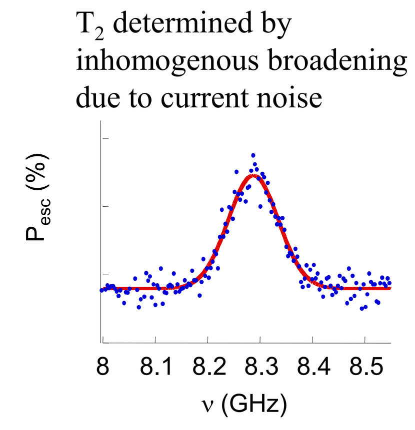


ΔI measurements : a probe to LF noise [0.2Hz,20kHz]



- no significant LF current noise $\sqrt{\langle\delta I^2\rangle} < 1$ nA (fit uncertainty)
- yes LF flux noise $\sqrt{\langle\delta\Phi^2\rangle} = 5.5 * 10^{-4}\ \Phi_0$

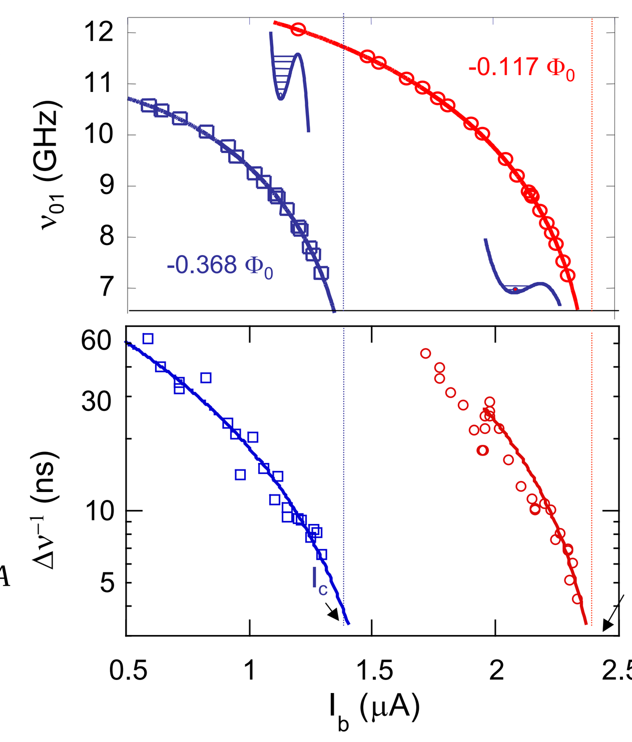
T_2 determined by inhomogenous broadening due to current noise



$$\Delta\nu \propto \frac{\partial\omega_{01}}{\partial I}\sqrt{\langle\delta I^2\rangle}$$

with $\sqrt{\langle\delta I^2\rangle} = \sqrt{\frac{kT}{L_{OC}}} \approx 6nA$

No free parameter



Decoherence processes in a current biased dc SQUID
J. Claudon, A. Fay, L. P. Lévy, and O. Buisson, *PRB* **73**, 180502 (2006)

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