Quantum coherence in a superconducting flux qubit

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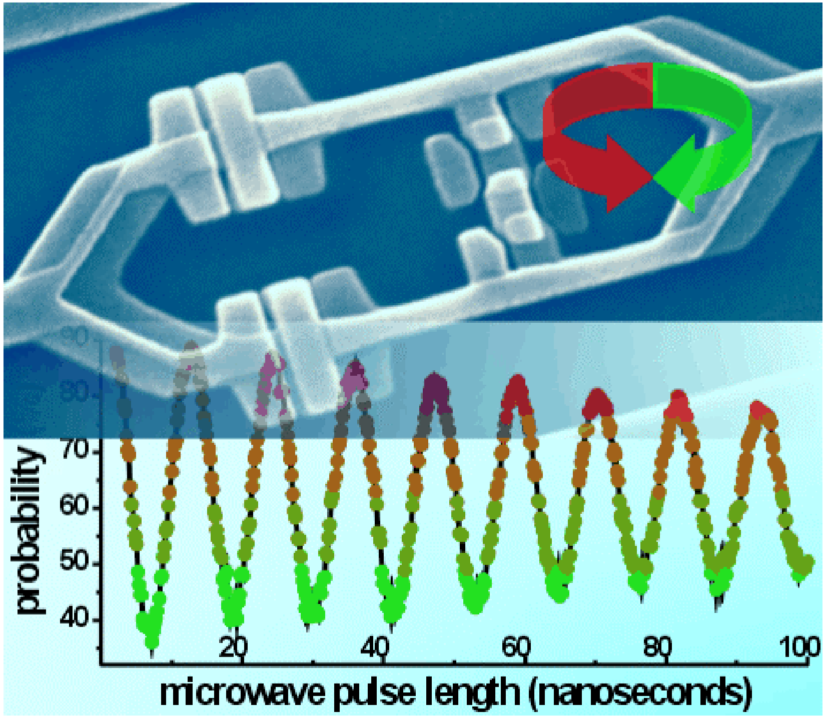

Collaborators

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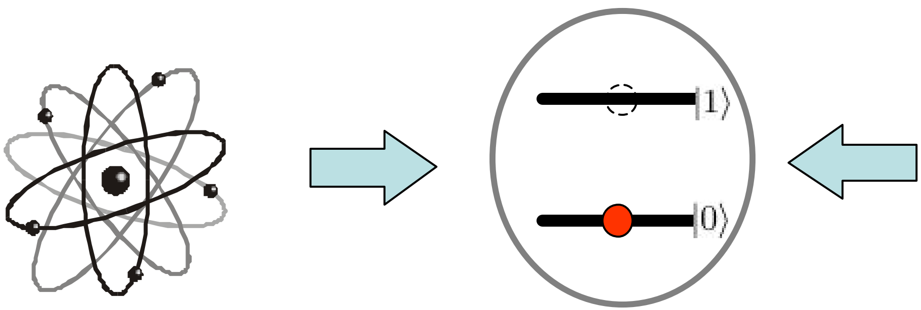
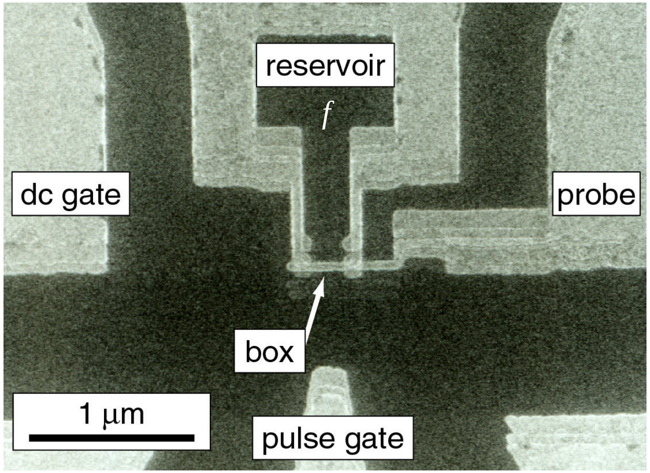
Discussions with
<u>CEA Saclay</u>
Daniel Esteve   Abdel Aassime
Denis Vion   Cristian Urbina

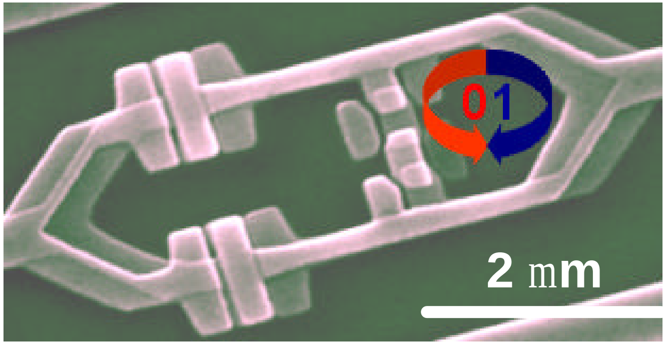
Motivation

- Coherent control of an artificial two-level system in solid-state device
- Understanding the mechanism of decoherence



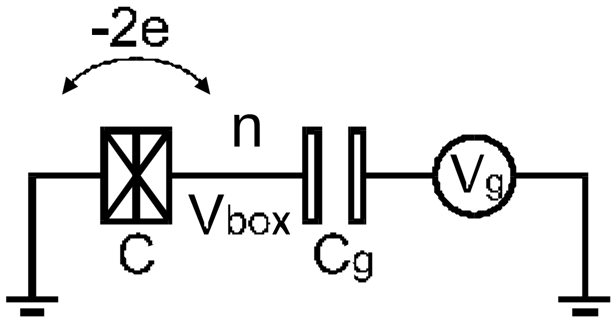
$$\alpha|0\rangle + \beta|1\rangle$$

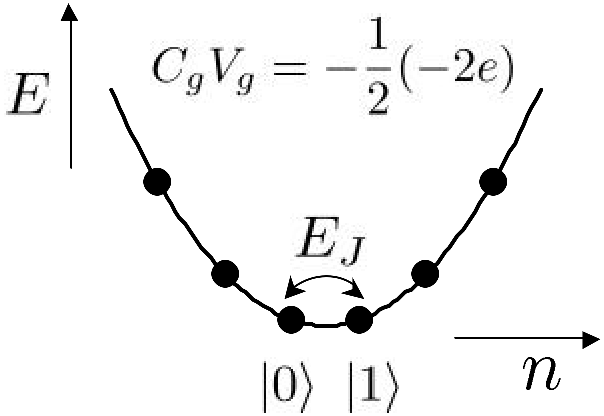




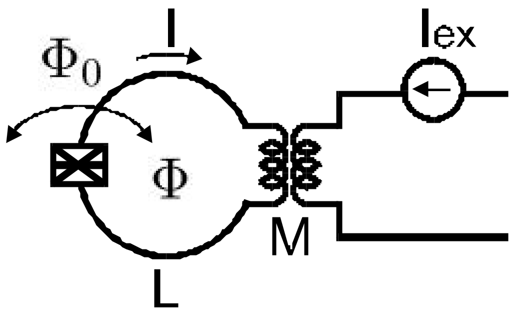
Charge qubit and flux (phase) qubit

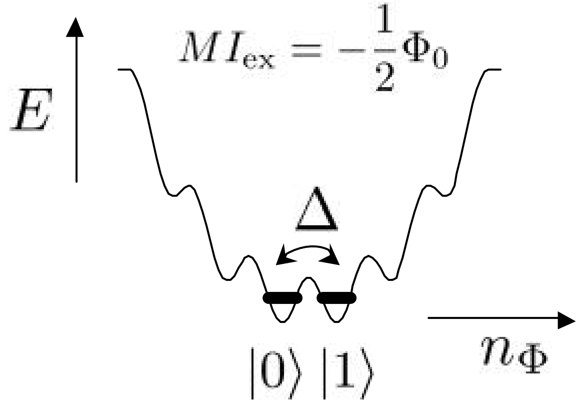
Cooper-pair box $E_J \ll E_C$





RF-SQUID $E_J \gg E_C$



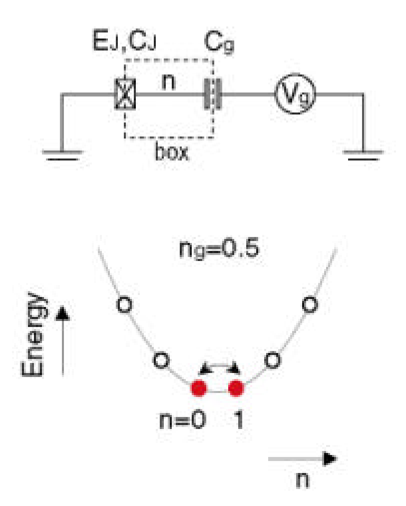


Variety of Josephson-junction qubits

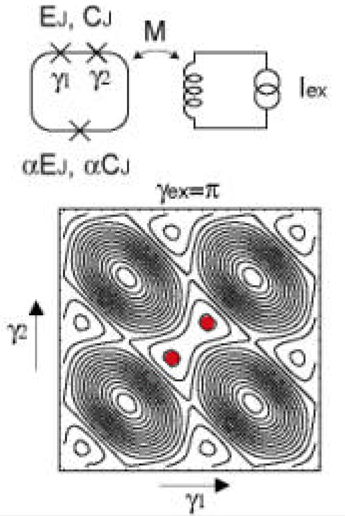
small E_J/E_C large

charge	phase (flux)	phase (flux)	phase

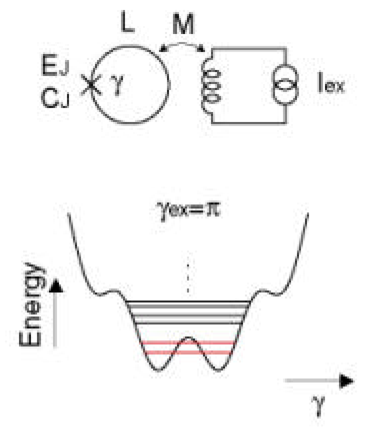
Cooper-pair box



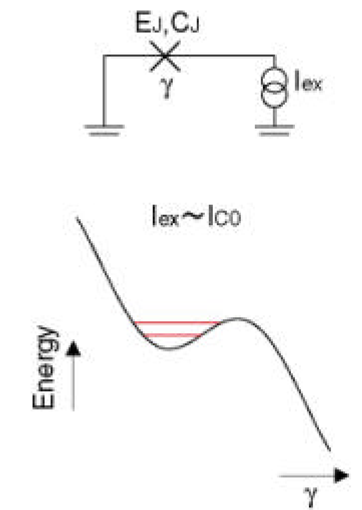
3-junction loop



RF-SQUID



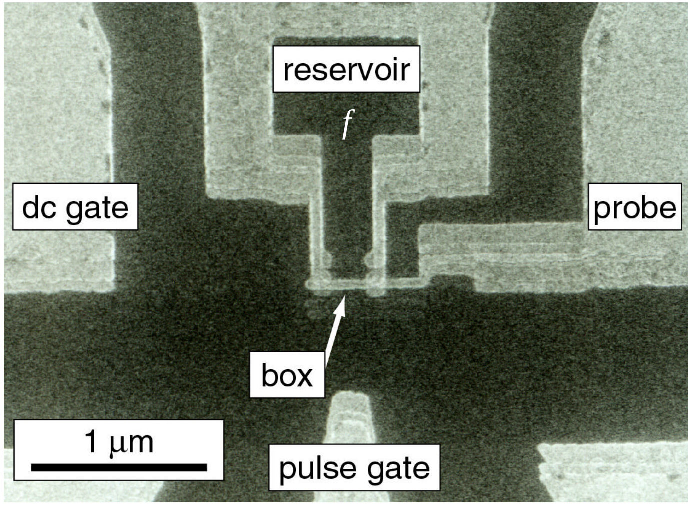
Current-biased JJ



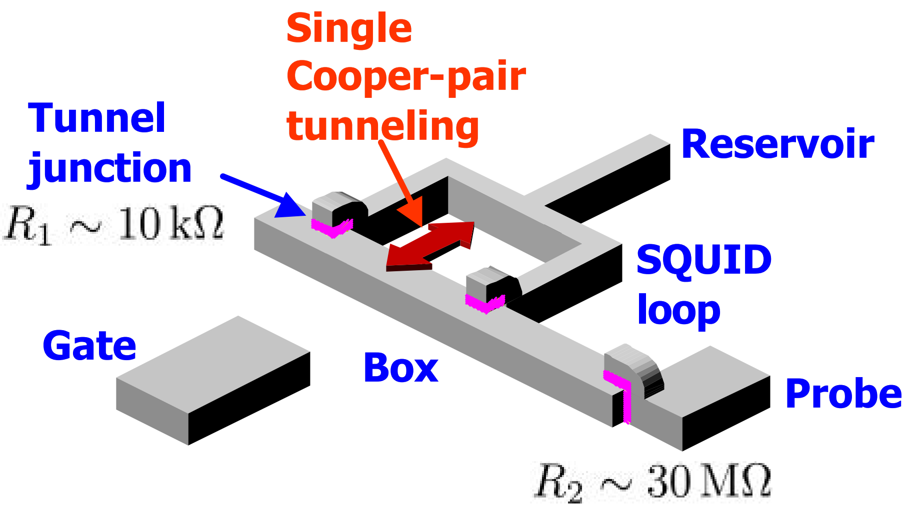
NEC Tsukuba Chalmers/Yale Saclay (large E_J/E_C)	Delft	IBM Yorktown Heights	Kansas NIST Boulder
coherent/Rabi osc. Ramsey, echo coupled qubits	Rabi osc. Ramsey, echo	coherent osc.	Rabi osc.

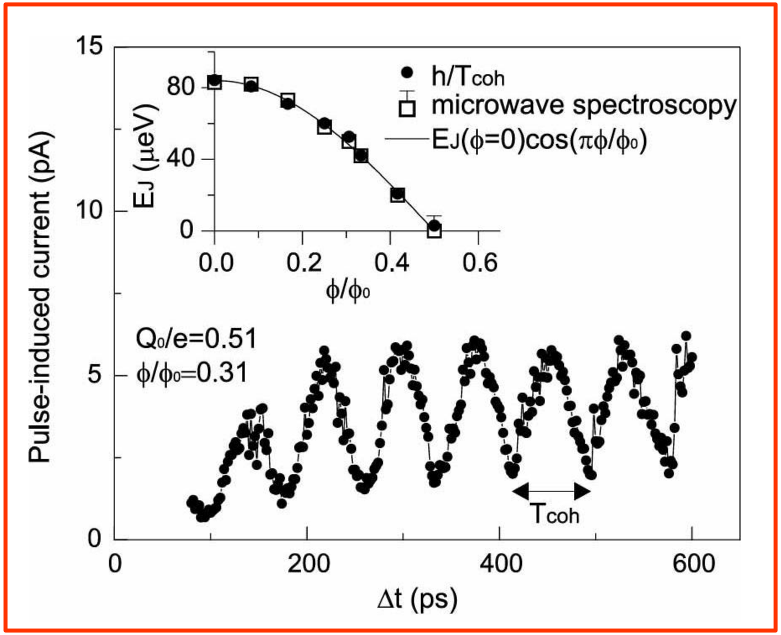
Cooper-pair box: a charge qubit

$E_J/E_C \sim 0.3$



- sensitive to charge fluctuations
- decoherence time ~ ns

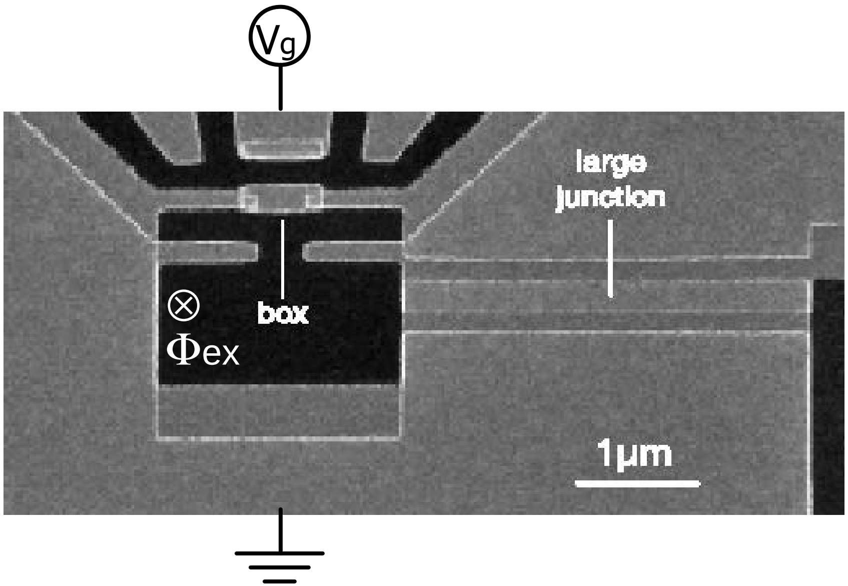


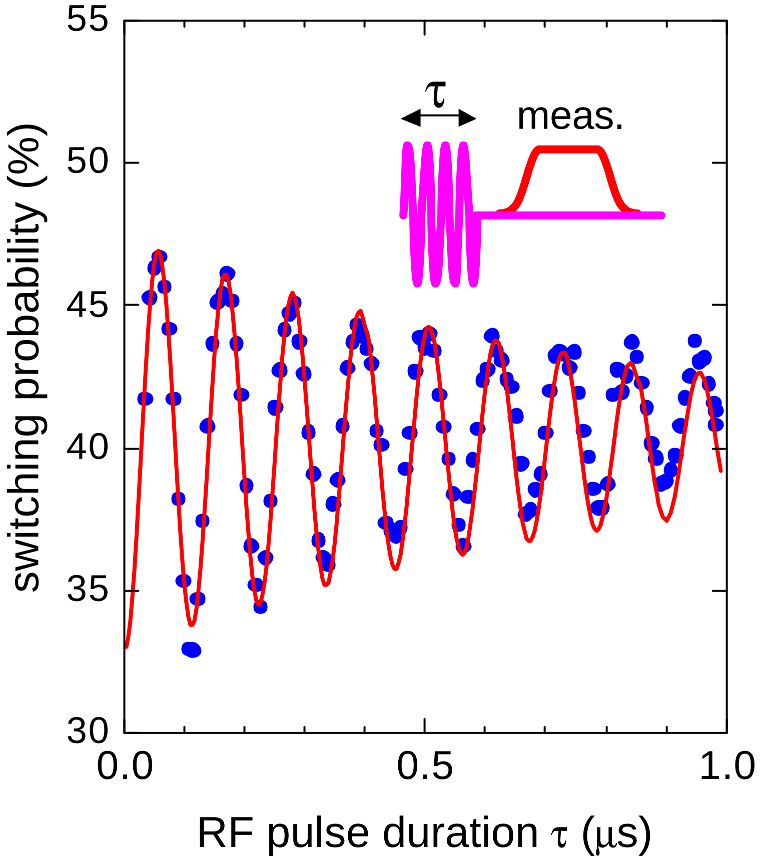


NEC

Nakamura et al. Nature 398 786 (1999)

Rabi oscillations in "Quantronium"



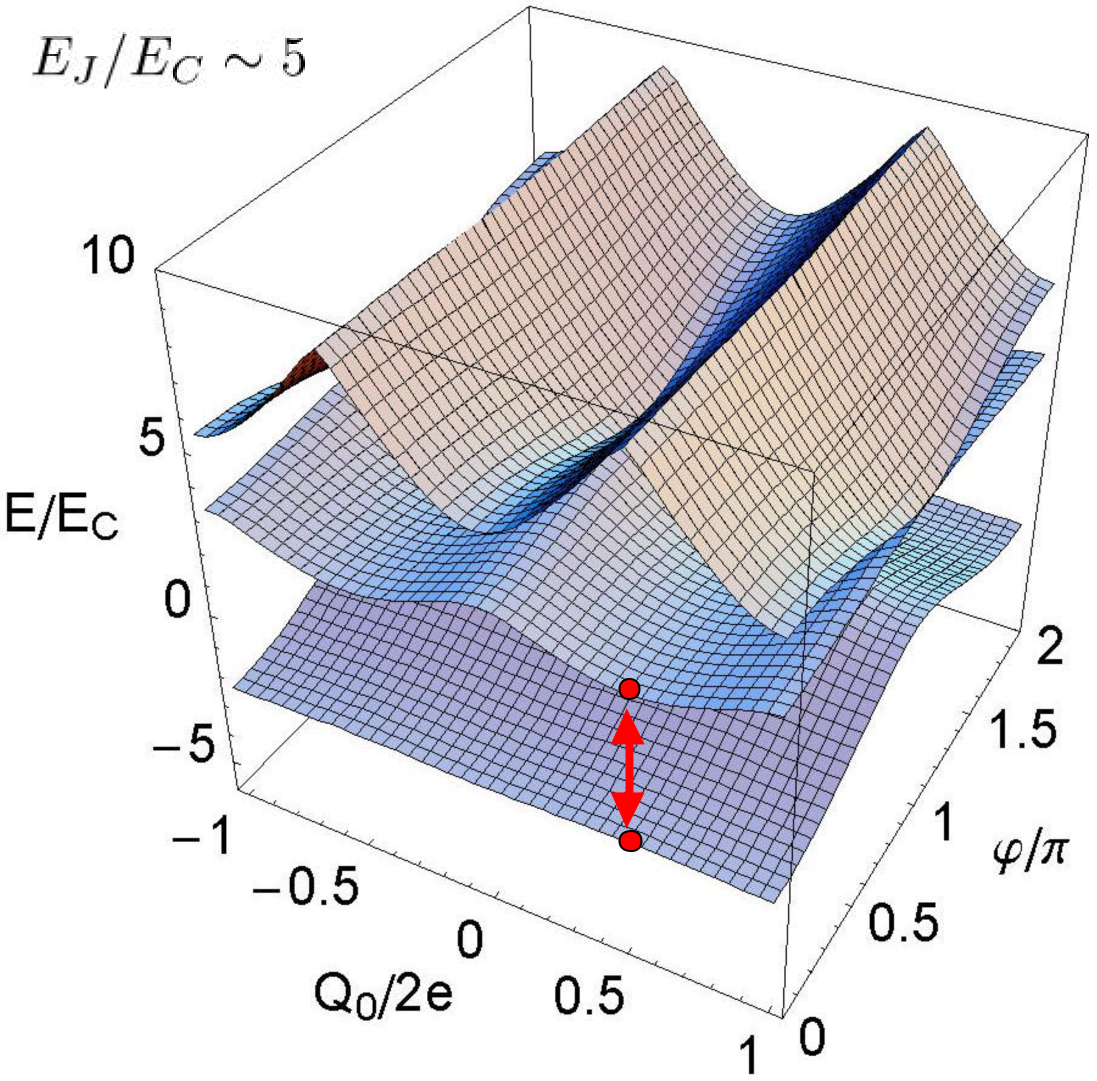


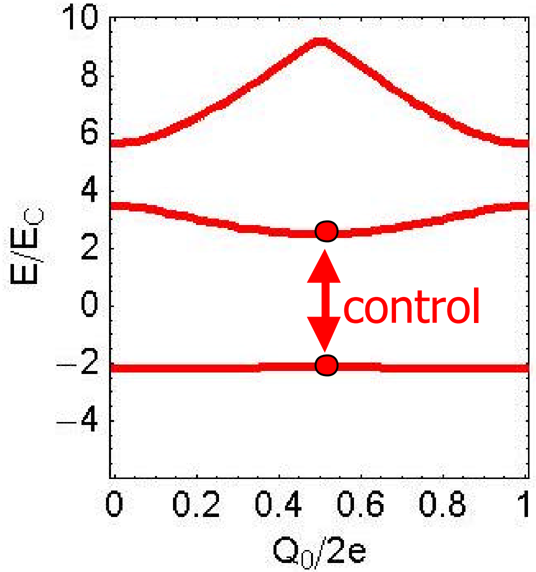
- Large $E_J/E_C \sim 5$
- Operation at optimal point
- Long decoherence time ~ 0.5 µs

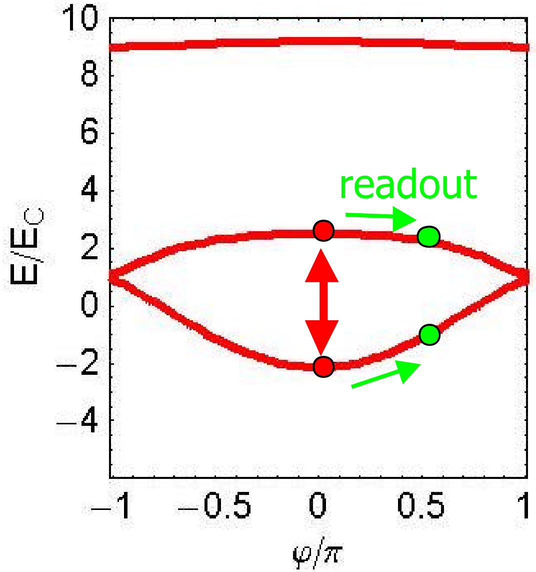
CEA Saclay

Vion et al. Science 296, 886 (2002)

Optimal operation point

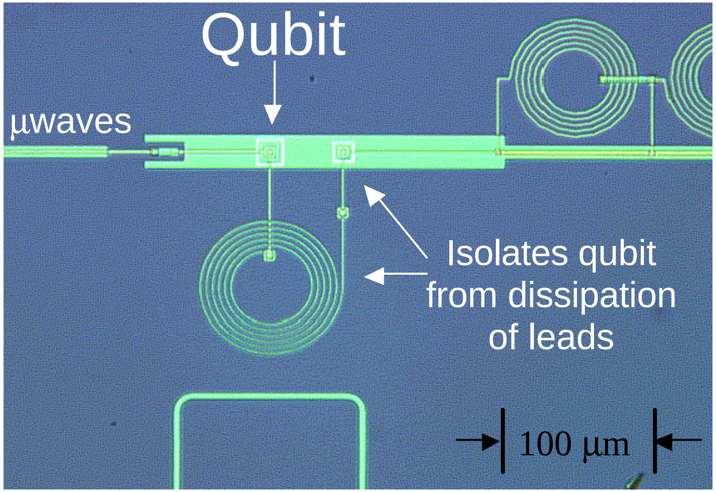


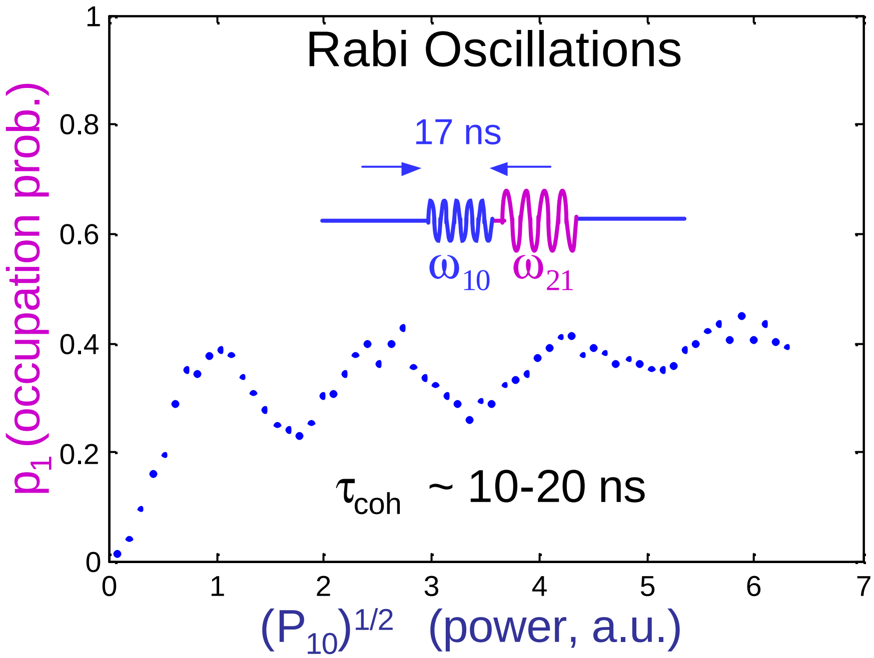


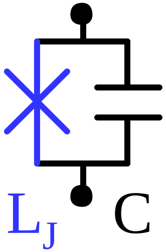


Rabi Oscillations in a Large Josephson-Junction Qubit

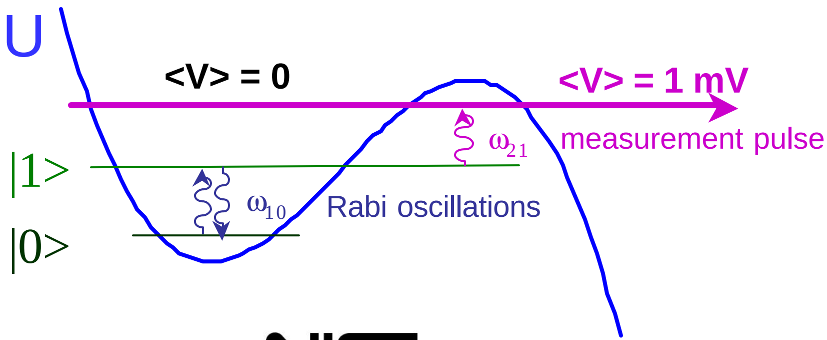
John Martinis, S. Nam, J. Aumentado (NIST Boulder) ; C. Urbina (CNRS/CEA Saclay)





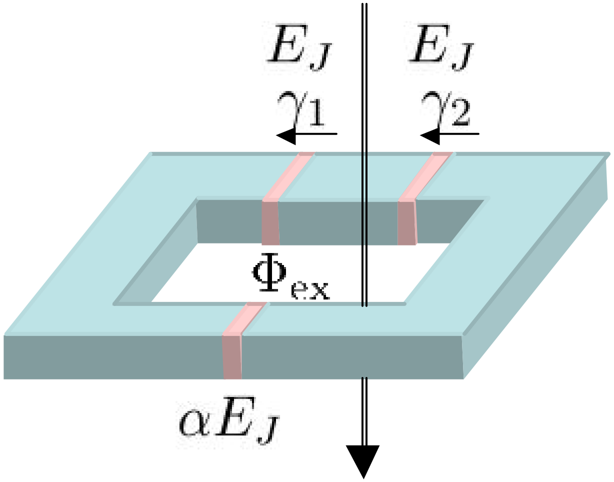


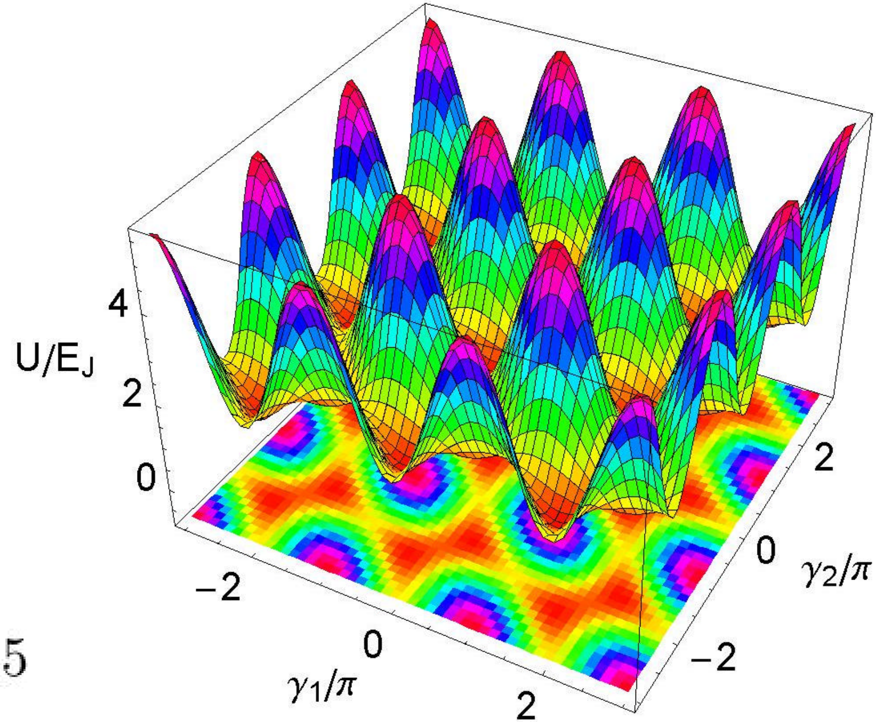
Josephson junction qubit: nonlinear LC resonator



- Demonstrated qubit operation
  - State preparation - fidelity of >99%
  - State manipulation - Rabi oscillations
  - State measurement - fidelity of 85%
- **Scalable system** - large junctions, microfab.
- ~1 μs coherence times at Saclay, U. Kansas

3-Josephson-junction loop qubit





$$E_J/E_C \gg 1,\ \alpha \sim 0.8,\ \Phi_{ex}/\Phi_0 \approx 0.5$$

$$U = -E_J\left[\cos\gamma_1 + \cos\gamma_2 + \alpha\cos\left(2\pi\frac{\Phi_{ex}}{\Phi_0} - \gamma_1 - \gamma_2\right)\right] + \text{const.}$$

Loop inductance is not necessary ⇒ small loop can be used

cf. RF-SQUID (single-junction loop) requires ~100-μm loop

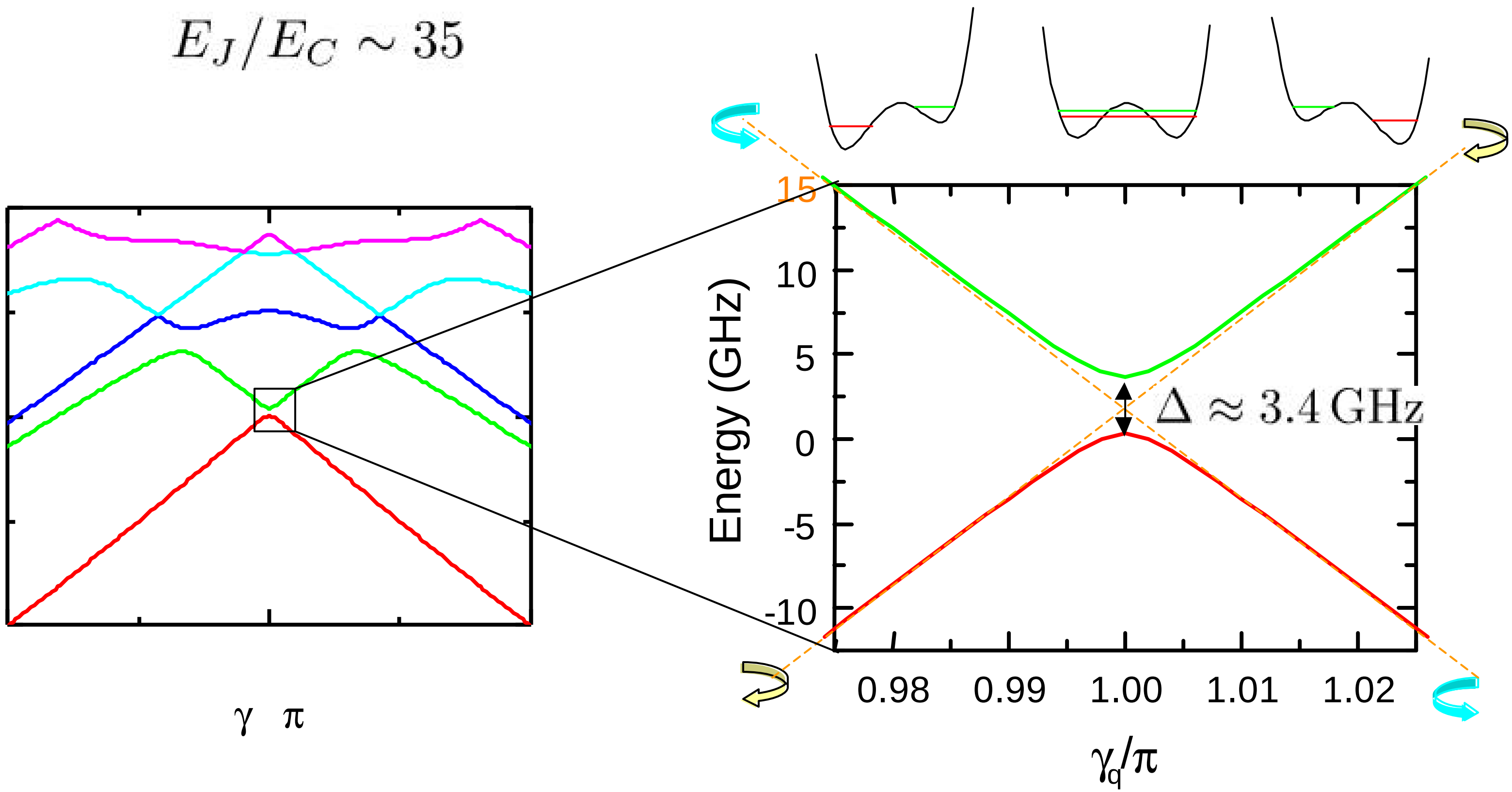
Mooij et al. Science 285, 1036 (1999)

Energy levels

- Two-level approximation holds in a narrow range of γ_q
- Relatively immune to charge fluctuations

$$\gamma_q \approx 2\pi \frac{\Phi_{\rm ex}}{\Phi_0}$$

$$E_J/E_C \sim 35$$

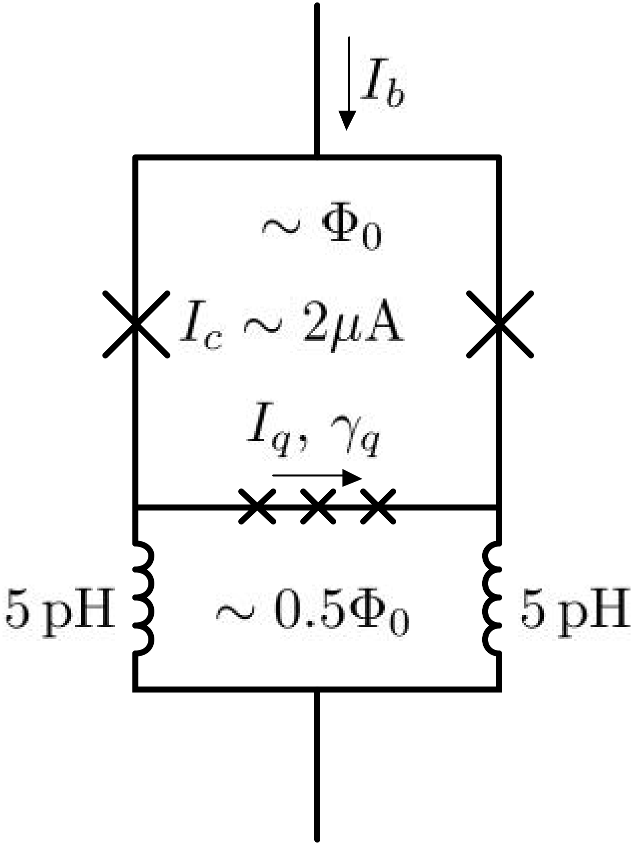


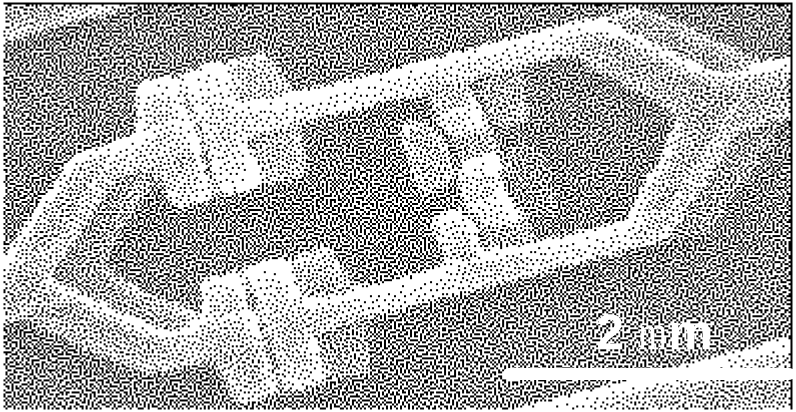
$$E_J = 1055\,\mu\mathrm{eV},\;\; E_C = 30.44\,\mu\mathrm{eV},\;\; \alpha = 0.80$$

$$E_J = 255\,\mathrm{GHz},\;\; E_C = 7.36\,\mathrm{GHz}$$

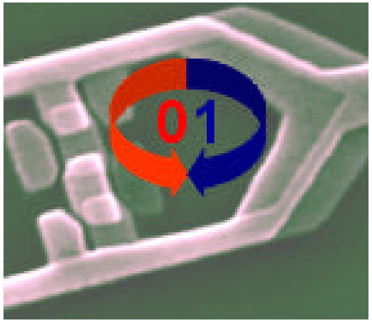
Sample

qubit + readout SQUID

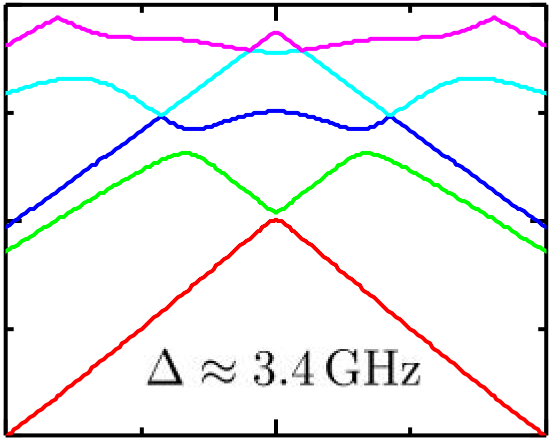




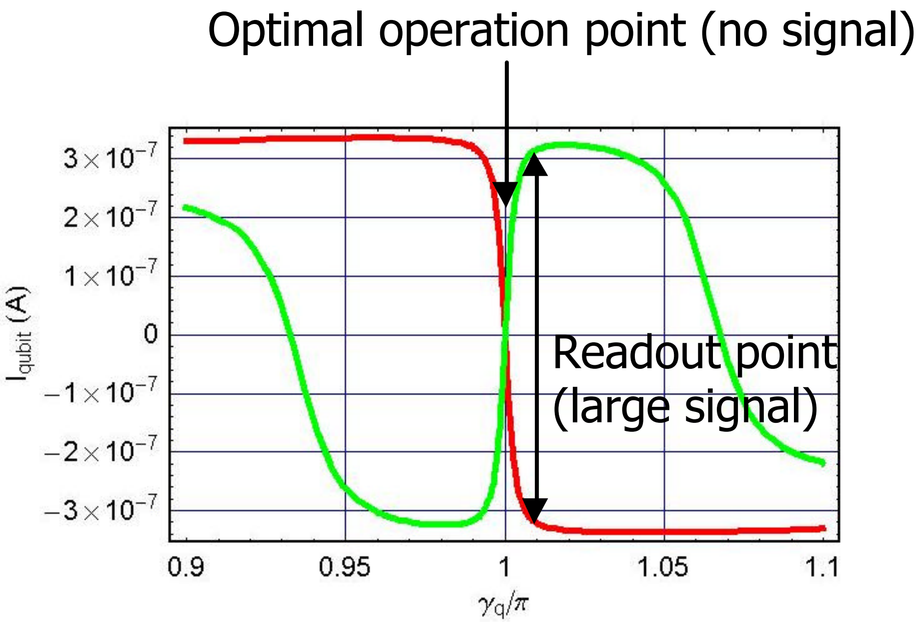
Qubit signal: Energy levels and circulating current



$$I_{q0,1} = \frac{2e}{\hbar}\frac{\partial E_{0,1}}{\partial \gamma_q}$$

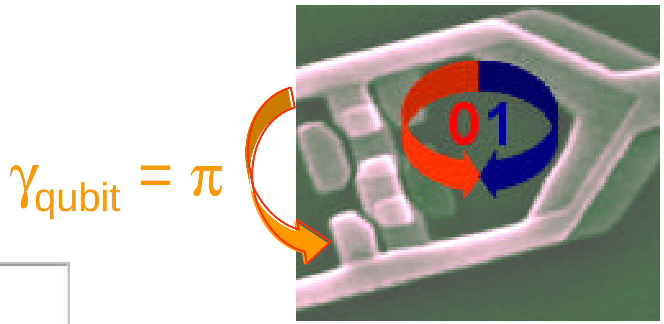


γ π

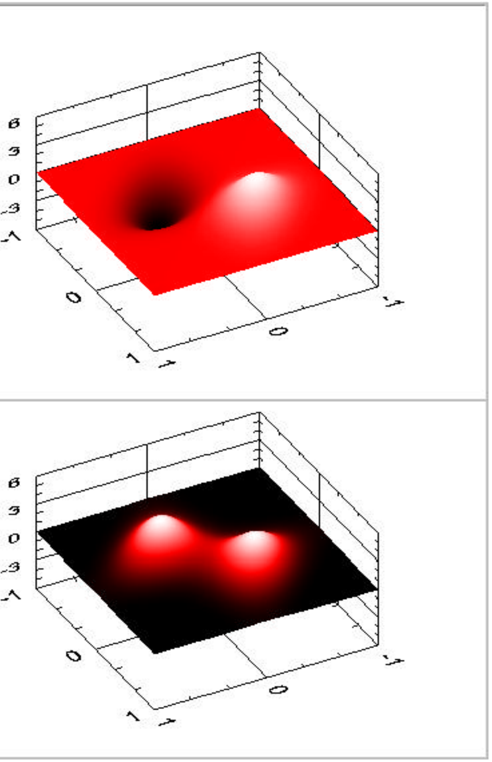


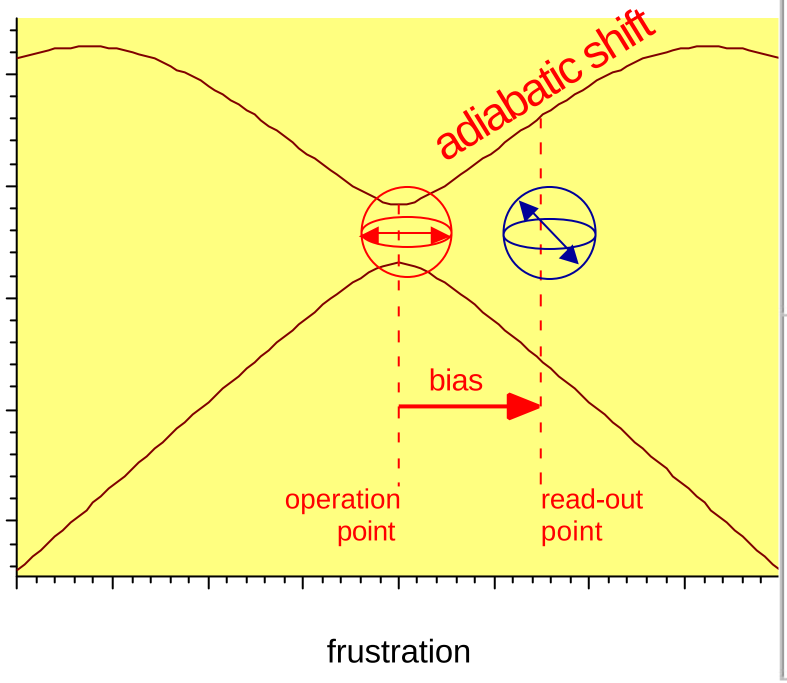
Qubit operation at optimal point

and readout after adiabatic bias phase shift

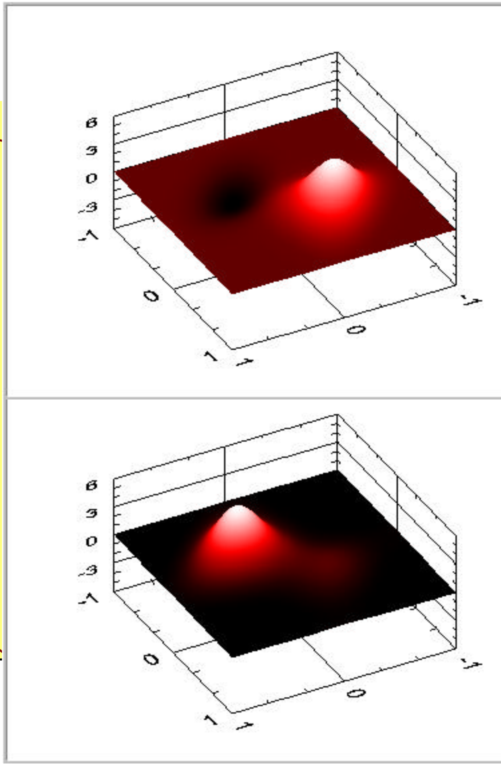


at operation point



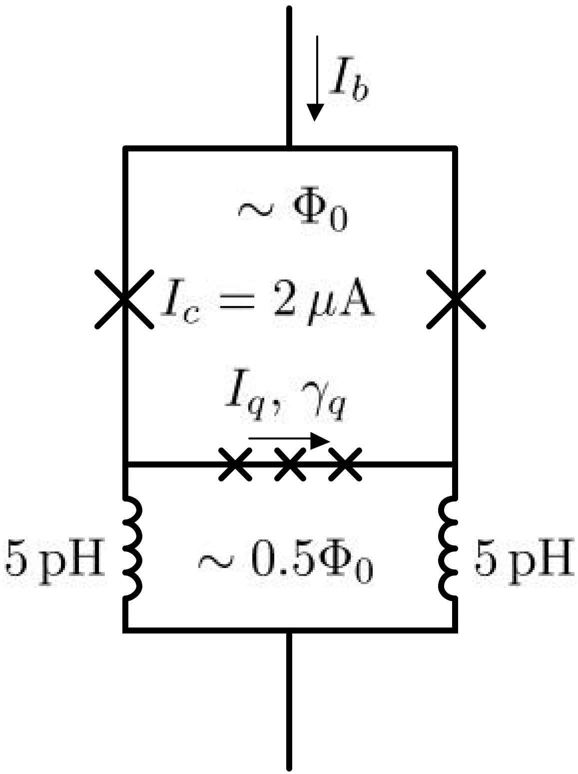


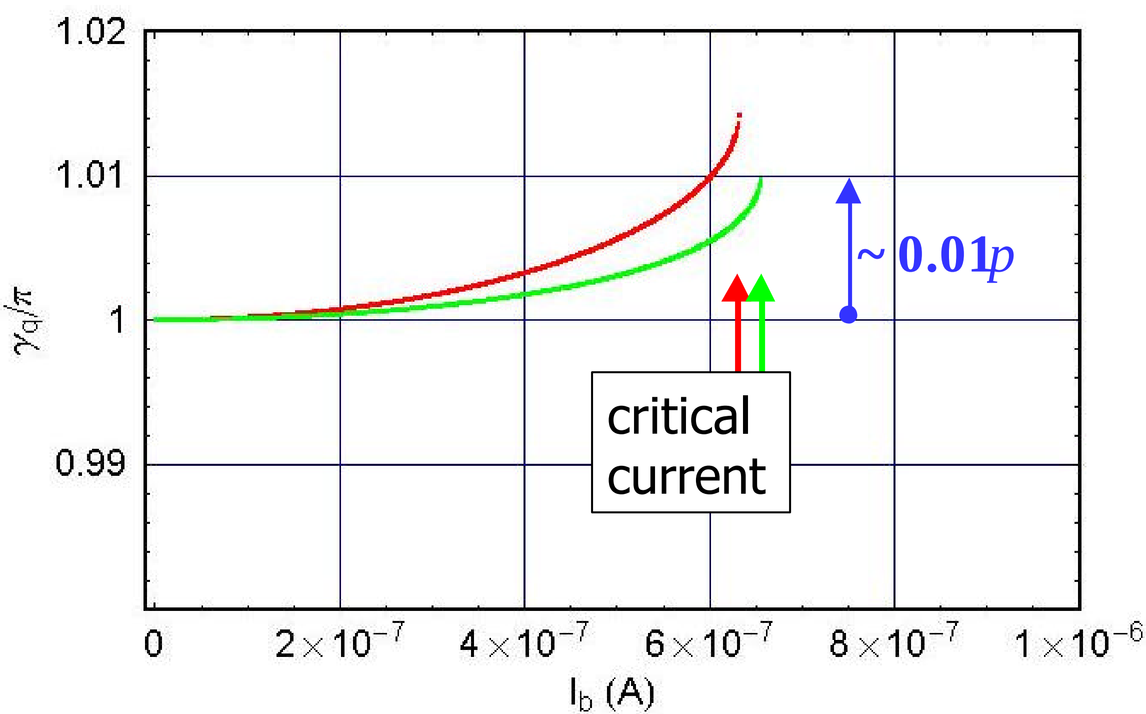
at readout point



Bias phase shift

Automatic phase shift is induced by SQUID bias current increase

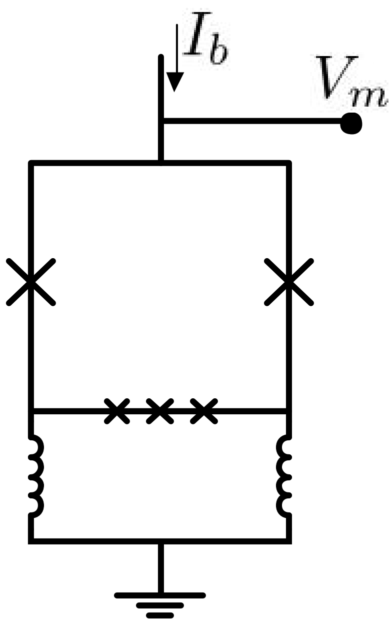




$$E_J = 1000\,\mu\mathrm{eV},\ \ E_C = 40\,\mu\mathrm{eV},\ \ \alpha = 0.75$$

$$\Delta \approx 10\,\mathrm{GHz} \qquad \Rightarrow\ \ \Delta I_{\mathrm{sw}}/I_{\mathrm{sw}} \sim 4.5\%$$

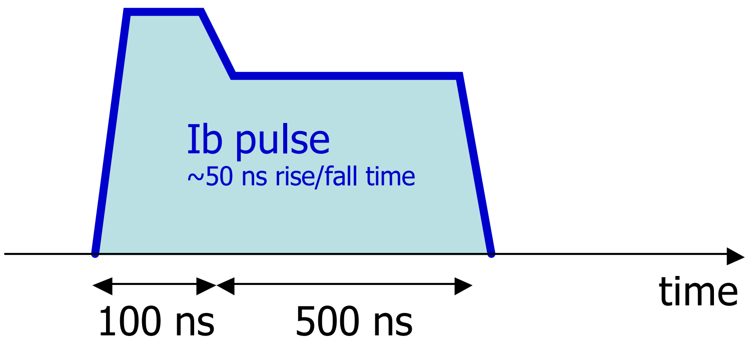
Qubit readout: switching current measurement

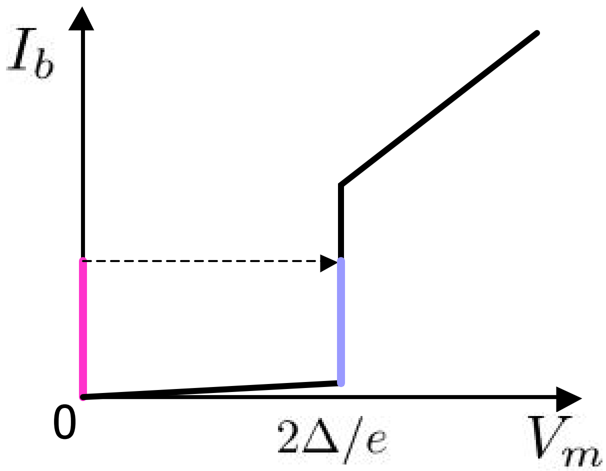


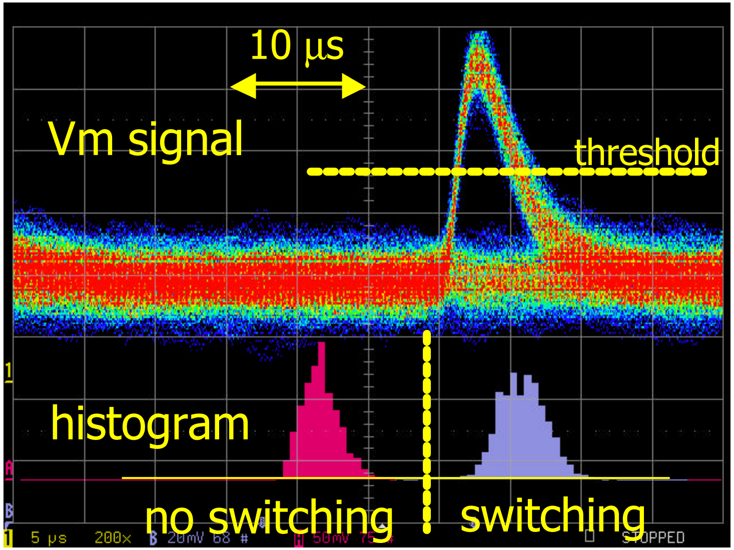
Ideally

$\alpha|0\rangle + \beta|1\rangle \Rightarrow$ Switching with probability $|\alpha|^2$

$\Rightarrow$ No switching with probability $|\beta|^2$



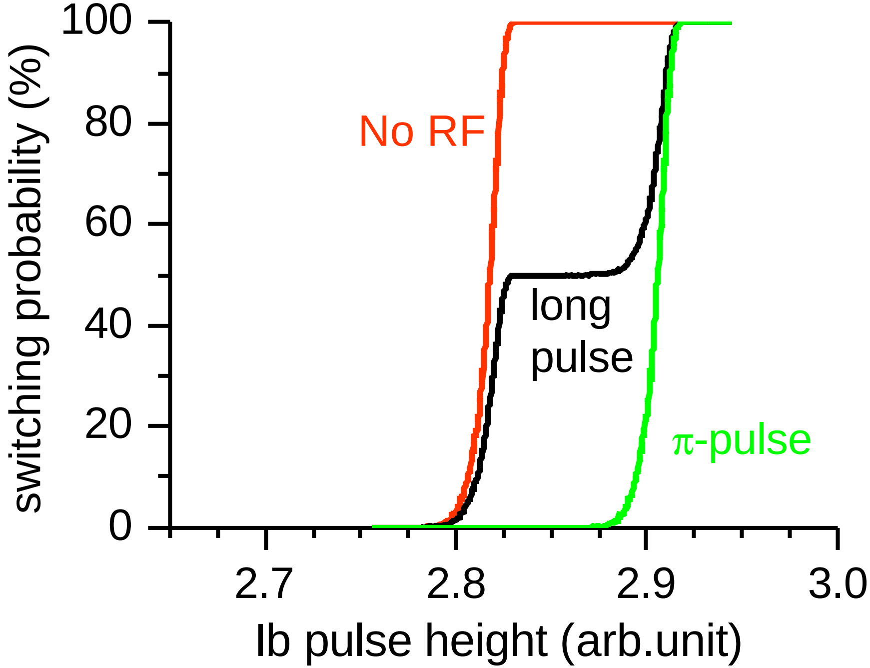




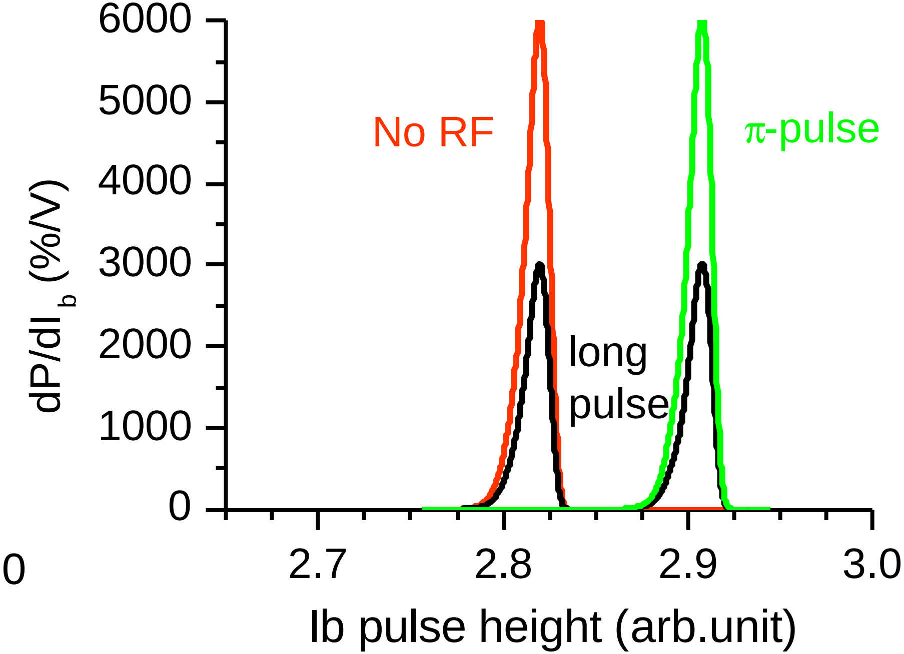
Switching probability curves: ideal case

- nominal ground state
- under saturation
- nominal excited state

switching probability P vs. I_b



derivative



Switching probability curves

- nominal ground state
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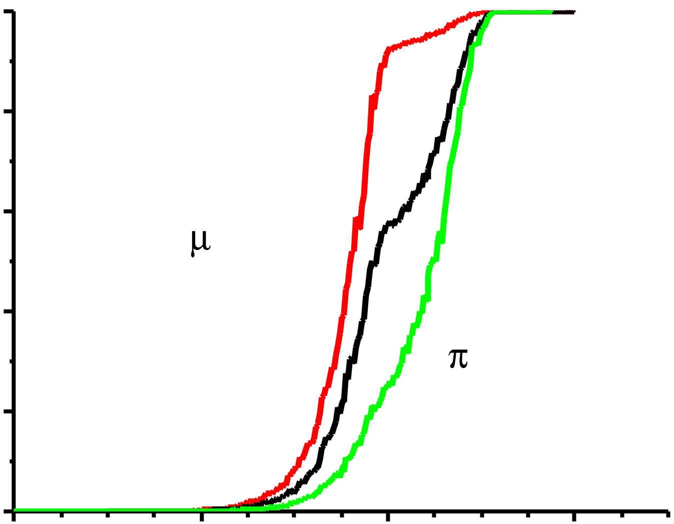
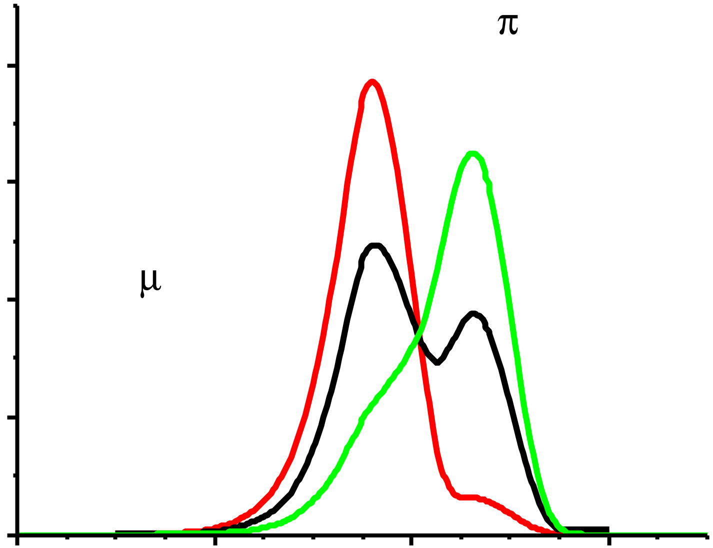


Ib pulse height (arb.unit)

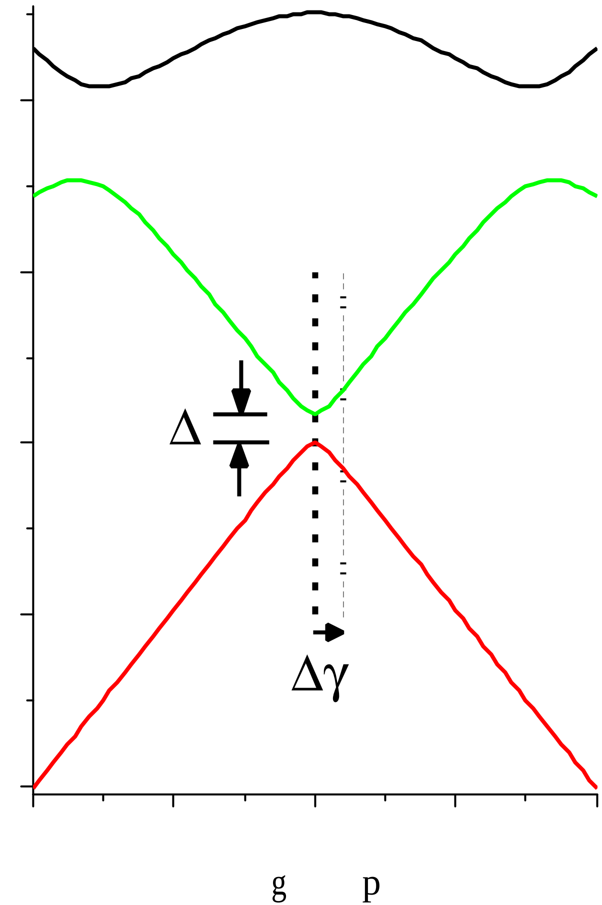
derivative



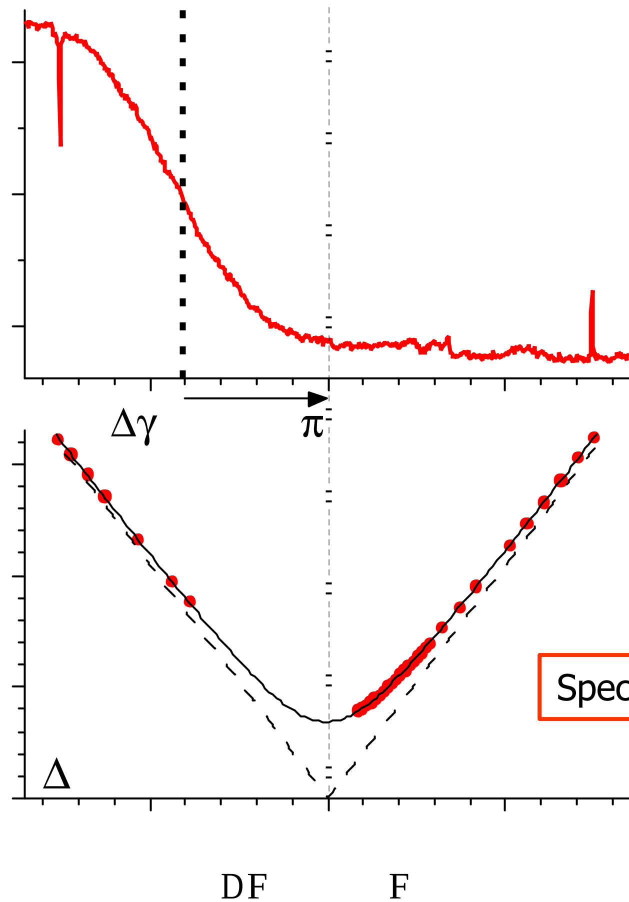
Ib pulse height (arb.unit)

Spectroscopy and the bias phase shift

Calculated energy levels

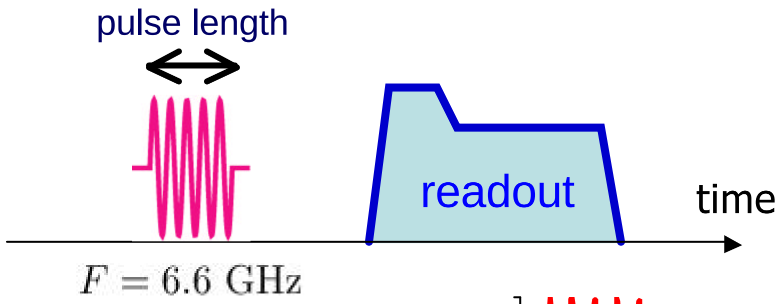


Isw: Ib pulse height which gives 50% switching

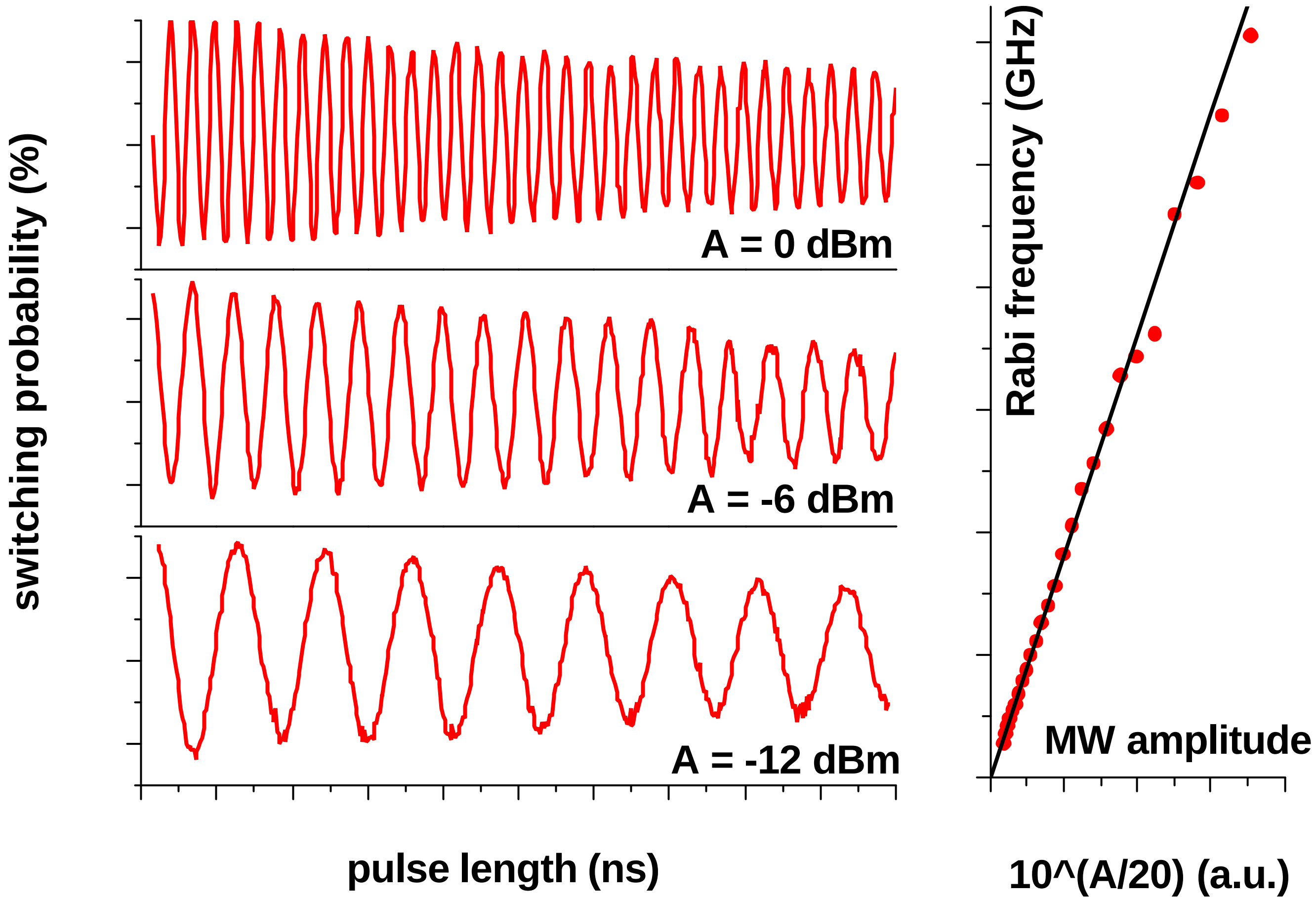


Spectroscopy

Rabi oscillations: power dependence

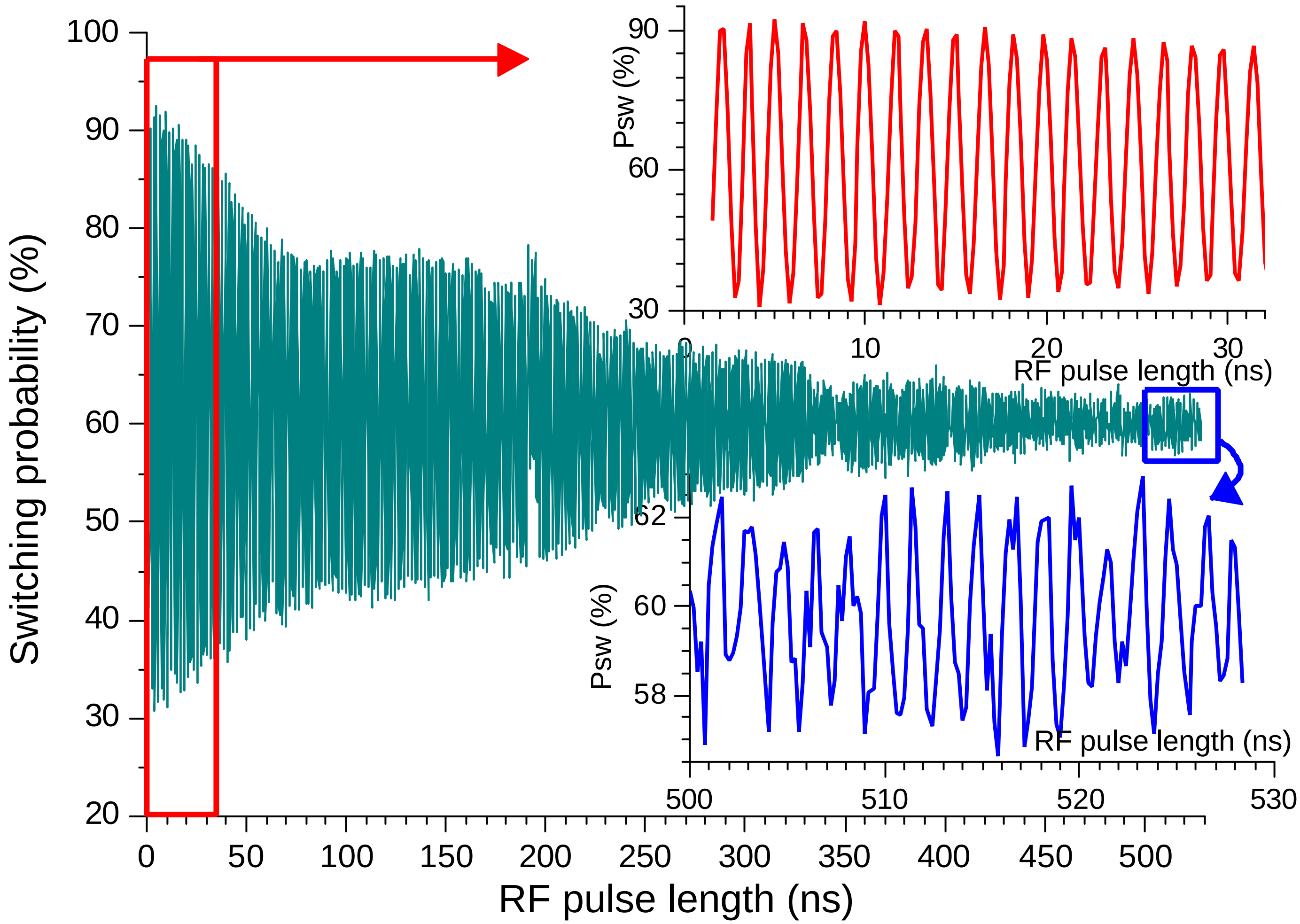


Decay time ≈ 150 ns

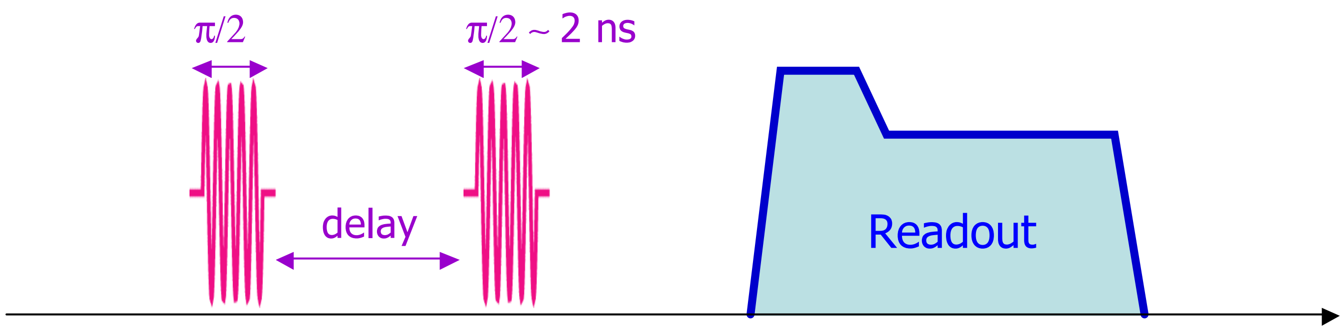


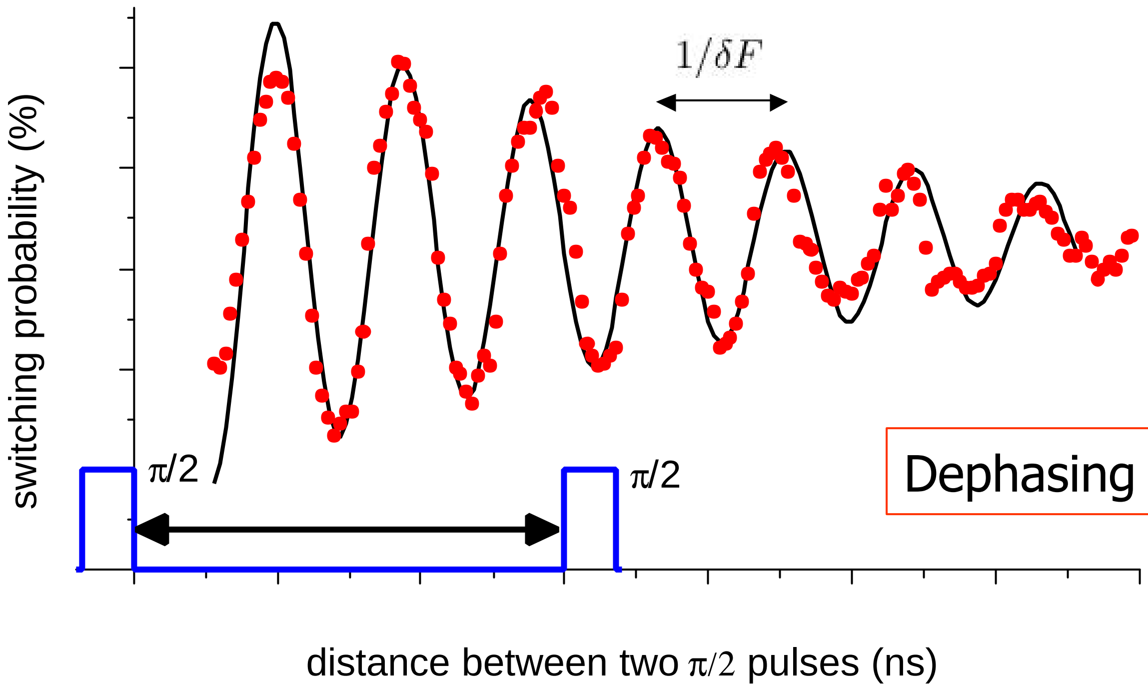
Rabi oscillations

Readout efficiency > Maximum amplitude ~ 60%



Ramsey interference (or Free-induction decay)



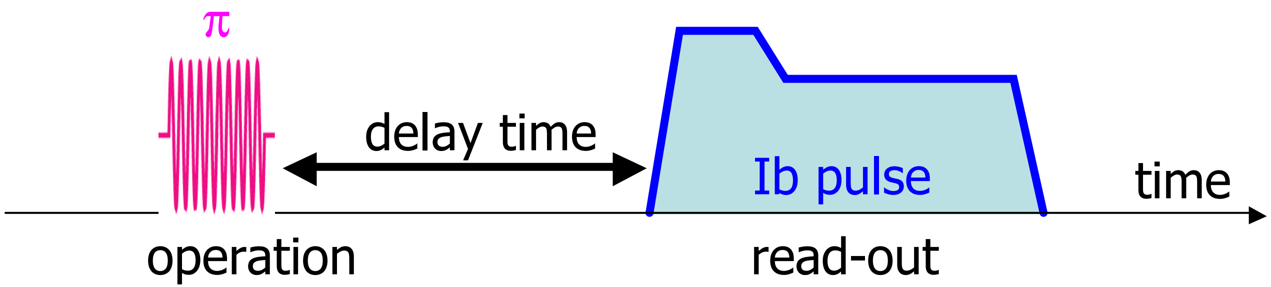


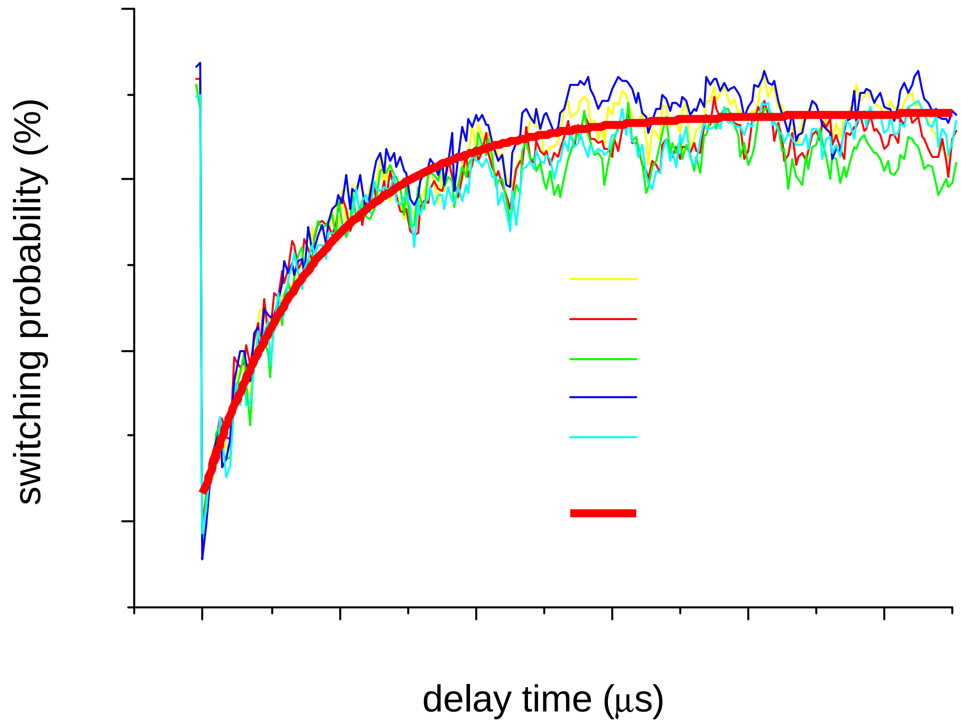
$E_{01} = 5.71$ GHz

$\delta F = 0.22$ GHz

Dephasing time $T_2^* \approx 20$ ns

Relaxation time

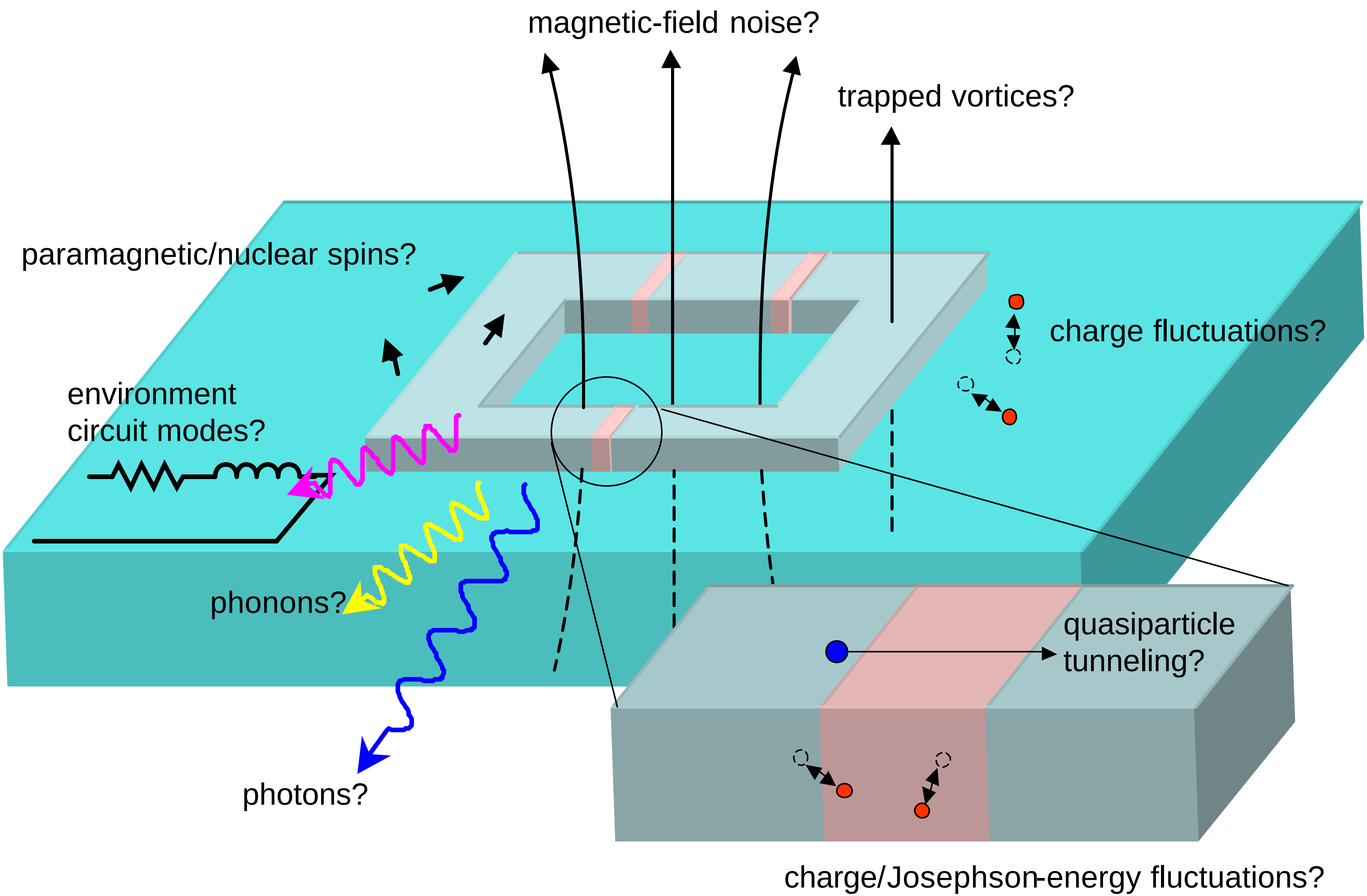




$F = 5.71$ GHz

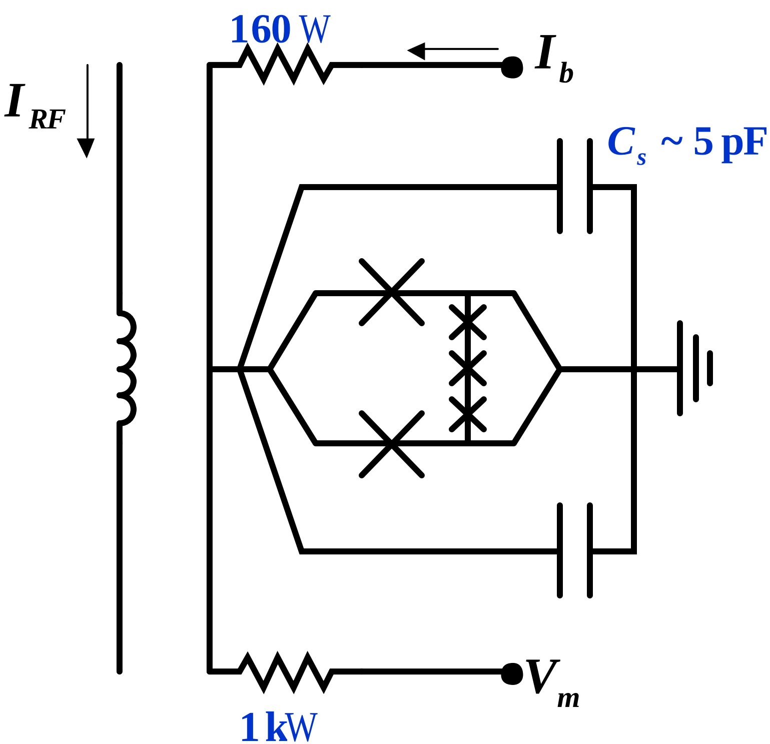
$T_1 \sim 900$ ns

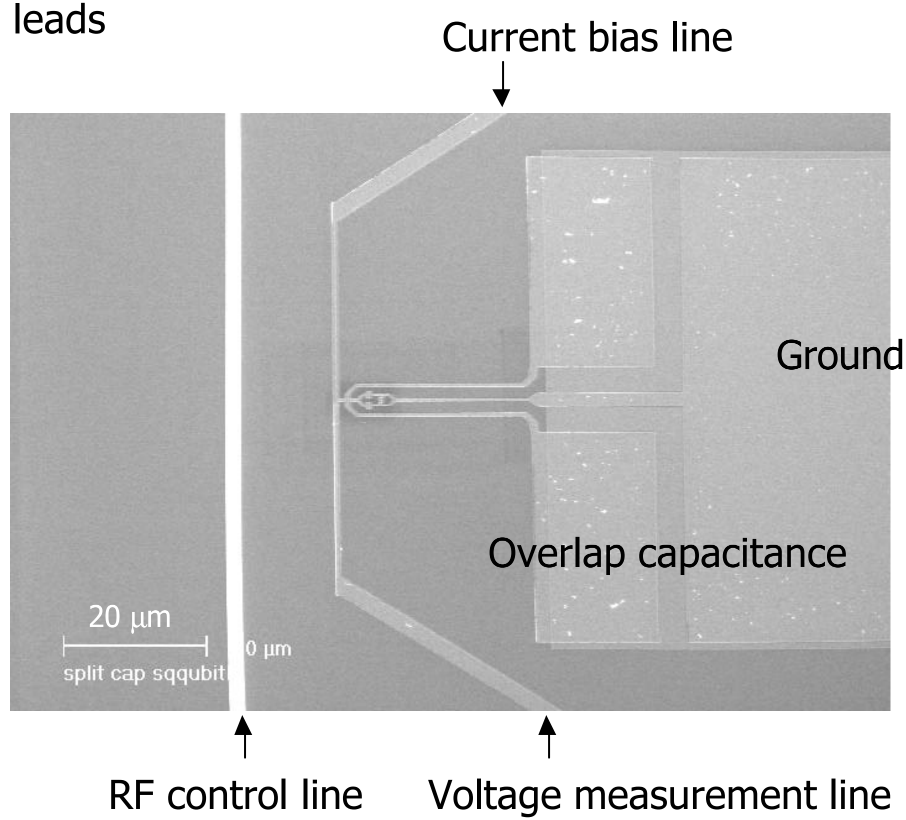
Possible decoherence sources



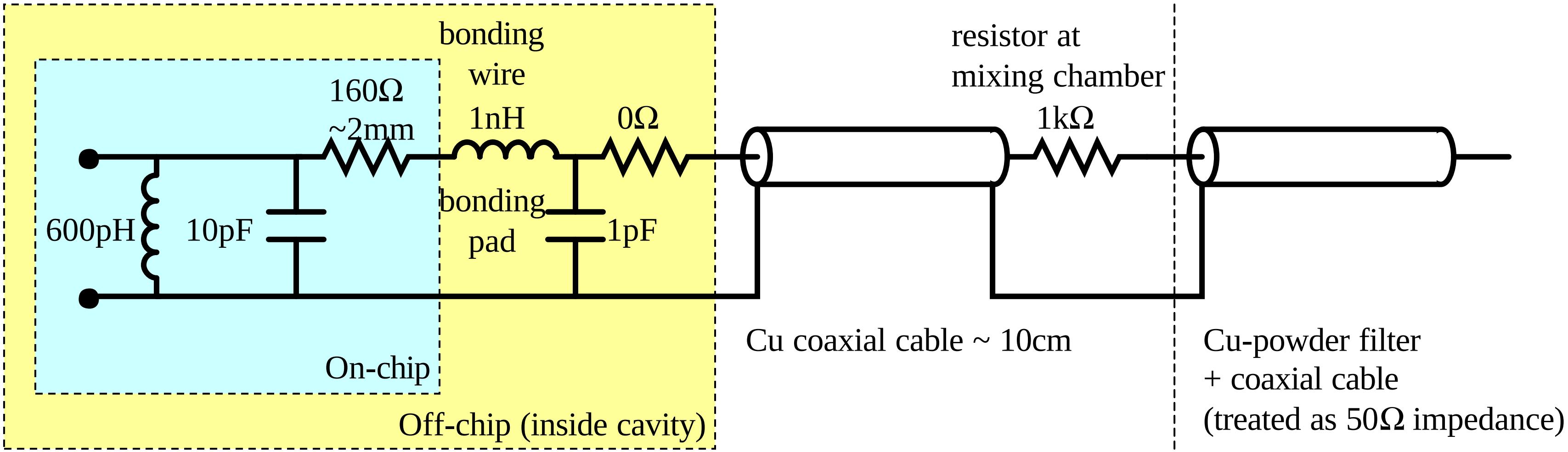
Design of electromagnetic environment

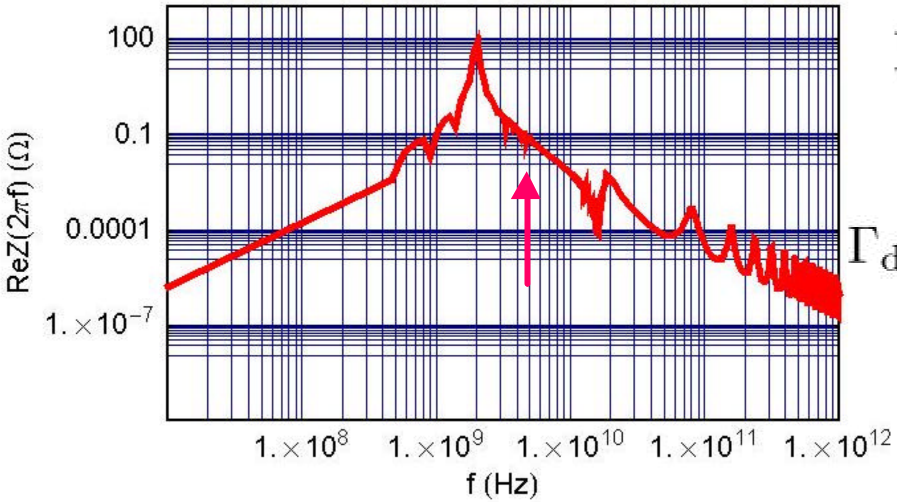
- Large shunt capacitor
  - Filter noise
- Symmetric plasma mode
  - Avoid coupling between control pulse and SQUID plasma excitation
- On-chip resistor
  - Suppress parasitic resonance in the leads





Impedance of surrounding circuit

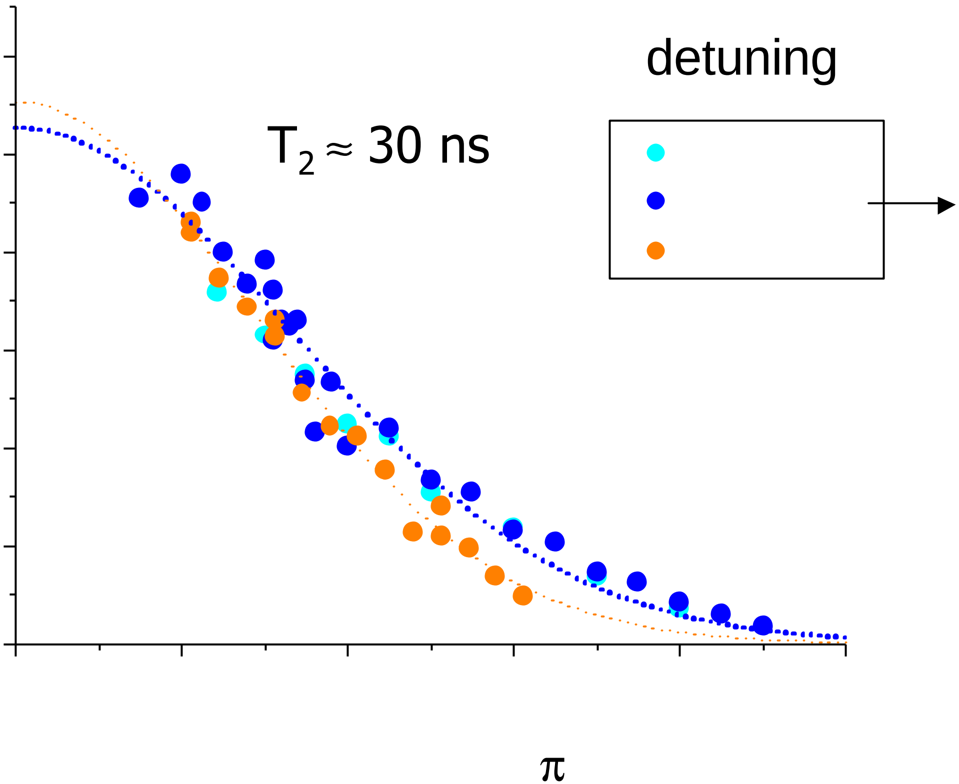




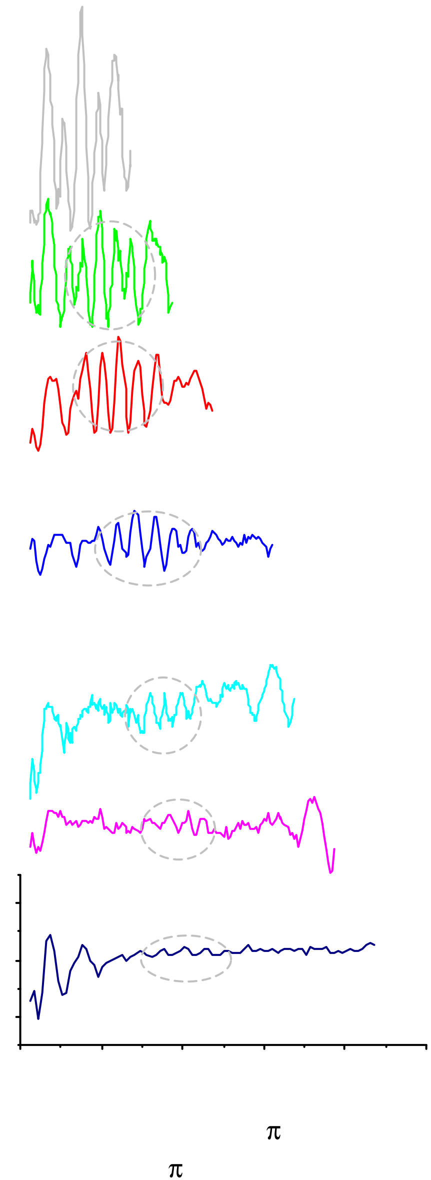
$$\Gamma_{\text{relax}} \propto \mathrm{Re}Y(\omega_{01}) \sim \frac{\mathrm{Re}Z_{SQ}(\omega_{01})}{\omega_{01}^2}$$

$$\Gamma_{\text{dephase}} \propto \lim_{\omega\to 0} \mathrm{Re}Y(\omega) \sim \lim_{\omega\to 0} \frac{\mathrm{Re}Z_{SQ}(\omega)}{\omega^2}$$

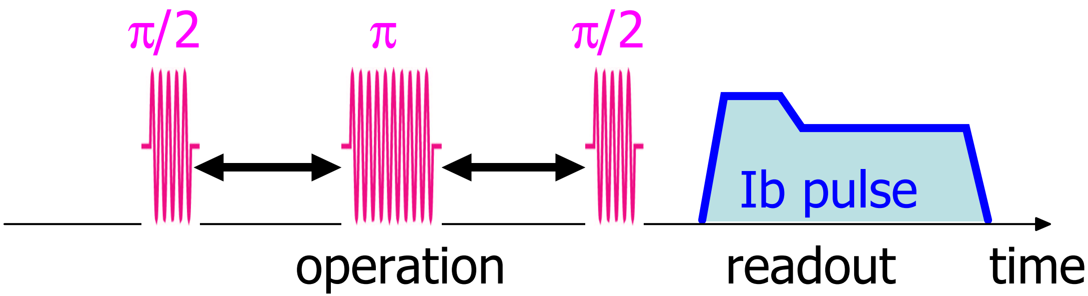
Spin echo



detuning
$T_2 \approx 30$ ns
π



π
π

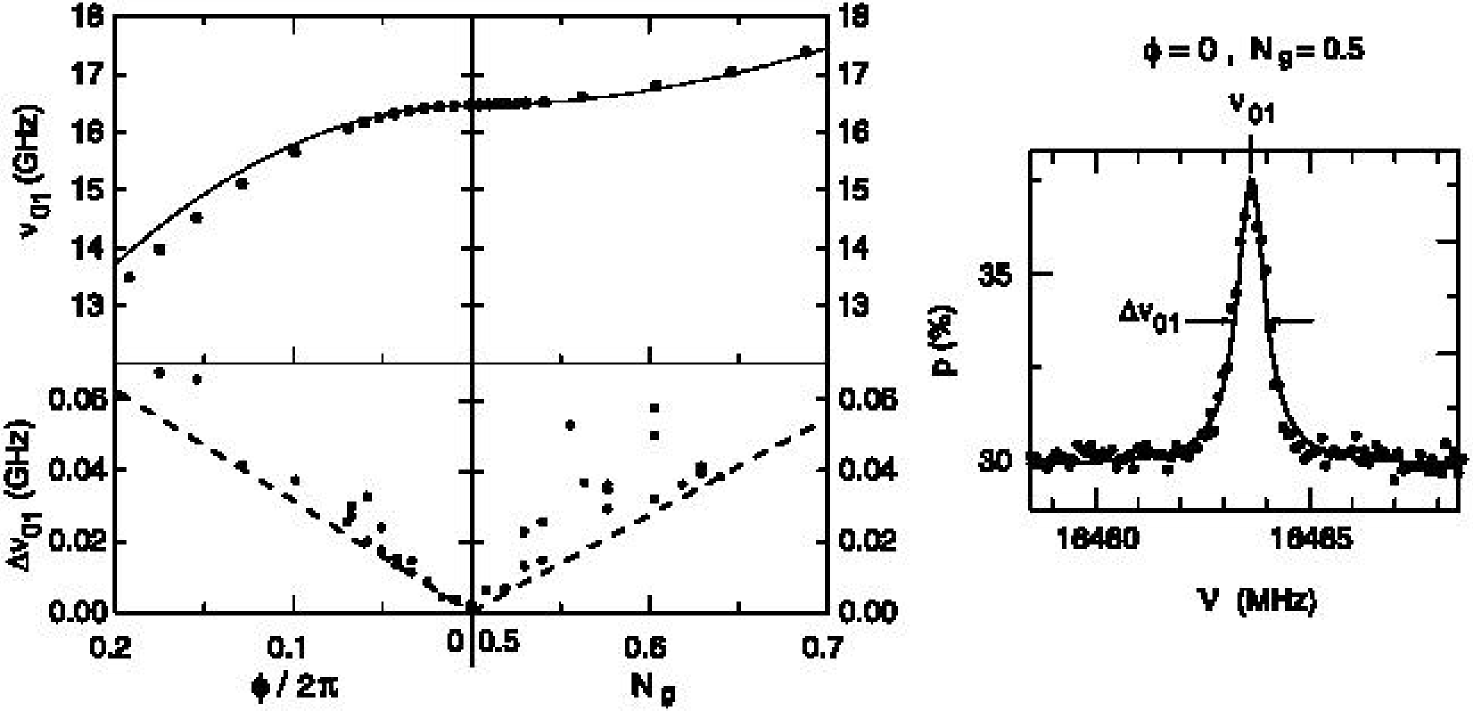


π/2
π
π/2
Ib pulse
operation
readout
time

Charge noise and phase noise

resonant frequency

resonant peak width



phase bias charge bias

CEA Saclay

D. Vion et al. Fortschritte der Physik, **51**, 462 (2003).

Summary

coherent control of 3-junction-loop flux qubit

- Rabi-oscillation period >~1.5 ns
- High readout efficiency ~60%
- Relaxation time T_1~0.9 μs
- Dephasing time T_2^*~20 ns

Future works

- Identification of the decoherence sources
- Operation at the optimal point
- Understanding switching dynamics in the readout
- Optimization of the parameters

Chiorescu, Nakamura, Harmans, Mooij, Science 299, 1869 (2003).