Coherent oscillations in a charge qubit

- The qubit
- The read-out
- Characterization of the Cooper pair box
- Coherent oscillations
- Measurements of relaxation and decoherence times

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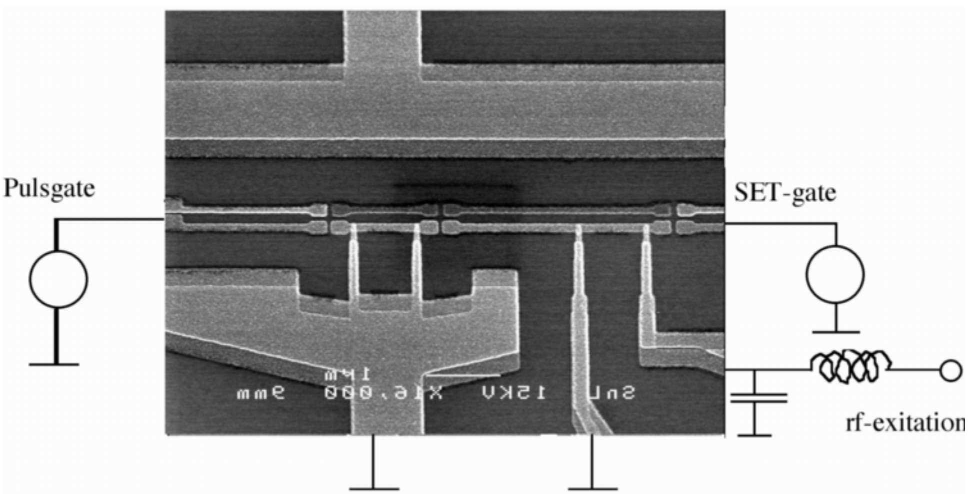
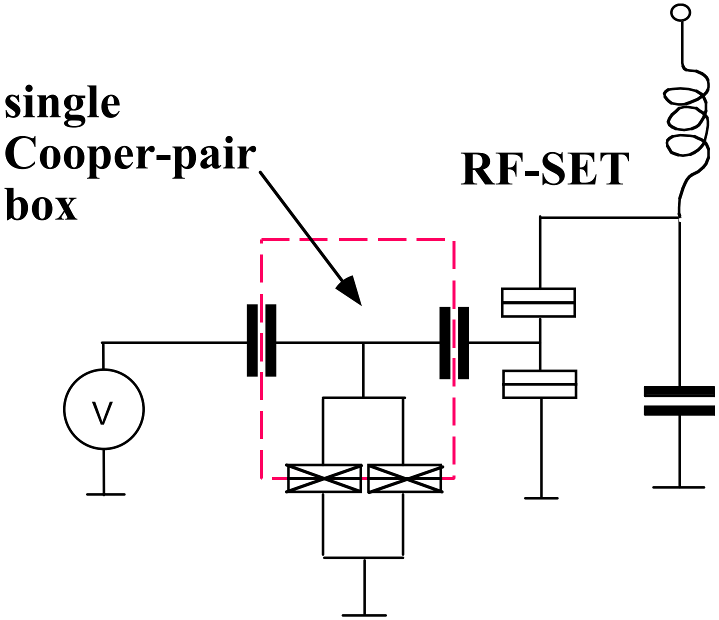
A Single Cooper-pair Box Qubit Integrated with an RF-SET Read-out system





|1> = One extra Cooper-pair in the box

|0> = No extra Cooper-pair in the box

Bouchiat et al. Physica Scripta (99)
Nakamura et al., Nature (99)
Makhlin et al. Rev. Mod. Phys. (01)
Aassime, et al., PRL (01)
Vion et al. Nature (02)

The Qubit

The Single Cooper-pair Box (SCB)

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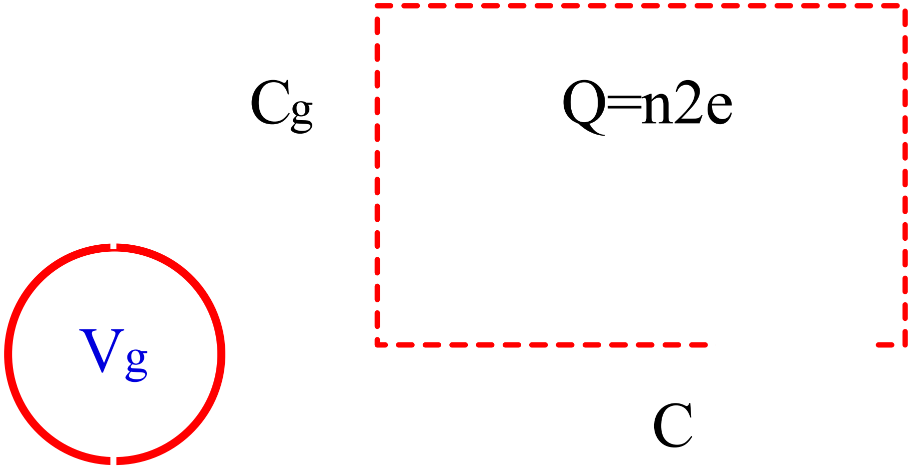
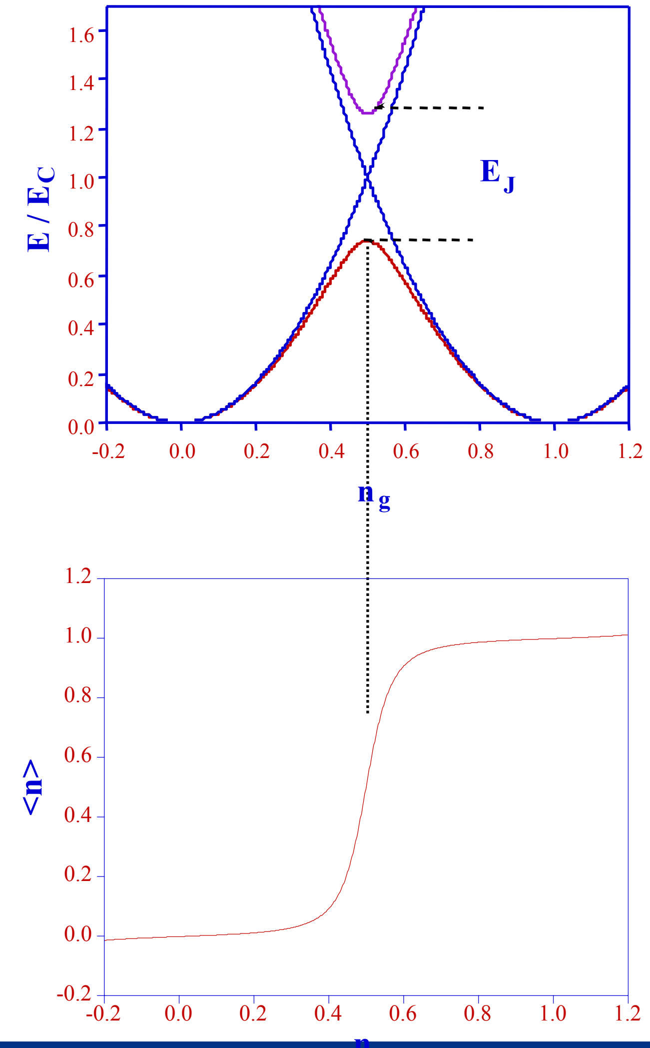




$$H = \frac{Q^2}{2C_\Sigma} - E_J \cos\theta = 4E_C (n - n_g)^2 - E_J \cos\theta$$

$$E_C = \frac{e^2}{2C}, \quad n = \frac{Q}{2e}, \quad n_g = C_1 V_g$$

Δ	>	E_C	>	E_J	>	T
2.5K		1.5K		0.5K		20mK

The SCB as a two level system and qubit

$$H = 4E_C(n-n_g)^2 - E_J\cos\theta$$

using ket representation we get

$$H = 4E_C\sum_n \left(n-n_g\right)^2 |n\rangle\langle n| - \tfrac{1}{2}E_J\sum_n \left(|n\rangle\langle n+1| + |n+1\rangle\langle n|\right)$$

If we assume that $E_J << E_C$ and we stay close to the degeneracy point, only two states, $|0\rangle$ and $|1\rangle$, matters. Thus we get :

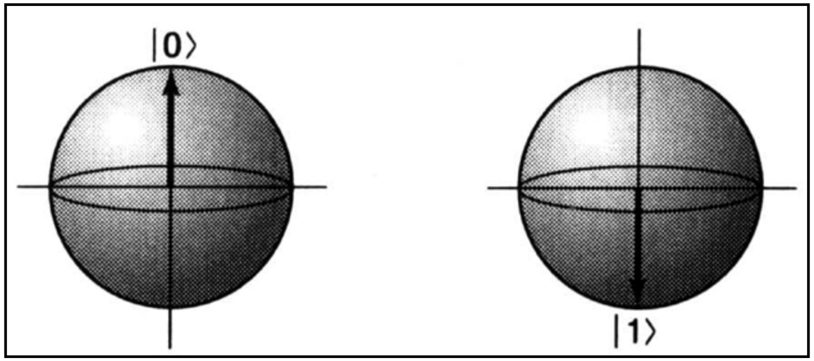
$$H = 4E_{Ch}(V_g)\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix} - \tfrac{1}{2}E_J(B)\begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix}$$

$$= 4E_{Ch}(V_g)\sigma_z - \tfrac{1}{2}E_J(B)\sigma_x$$

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle = \begin{pmatrix}\alpha\\ \beta\end{pmatrix}$$

α and β are complex numbers

$$|0\rangle = \begin{pmatrix}1\\ 0\end{pmatrix},\ |1\rangle = \begin{pmatrix}0\\ 1\end{pmatrix}$$



The read-out

The Radio-Frequency Single-Electron-Transistor (RF-SET)

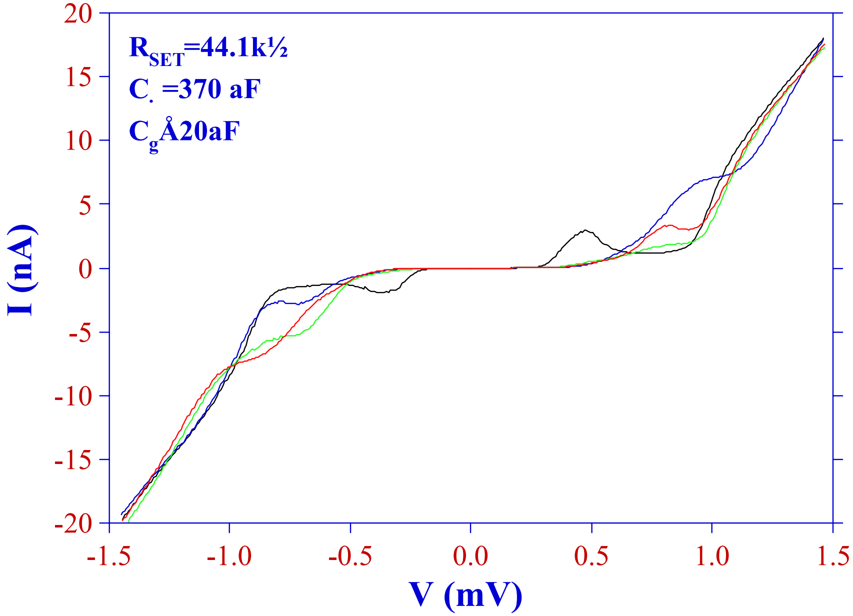
The Radio-Frequency Single Electron Transistor

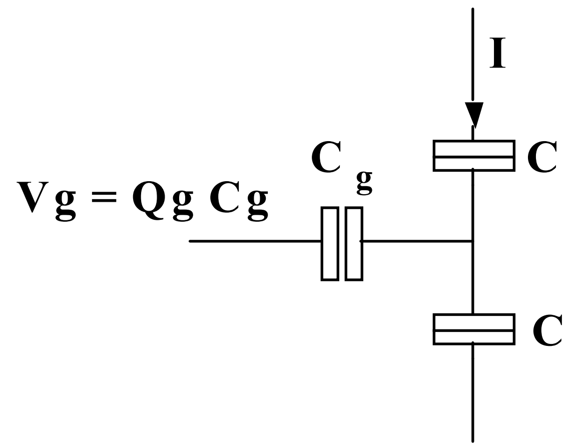
Very high speed: **137 MHz**
R. Schoelkopf, et al. Science (98)

Very high sensitivity: **3.2 $\mu e/\sqrt{Hz}$**
Limited by cold amplifiers
A. Aassime, et al., APL (01)

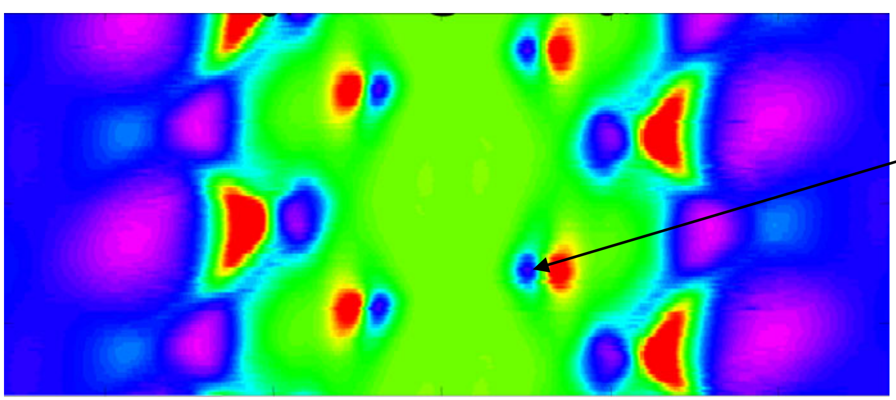
Typical values **∂Q= 30 $\mu e/\sqrt{Hz}$**
Bw= 15 MHz

SET IV-characteristics





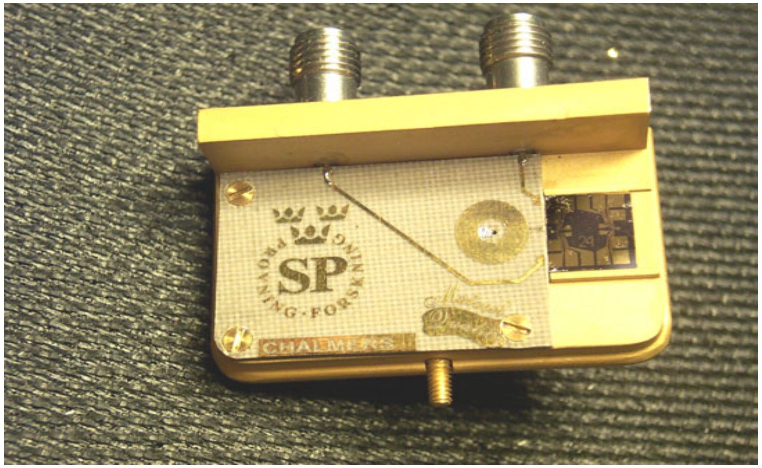
Vg



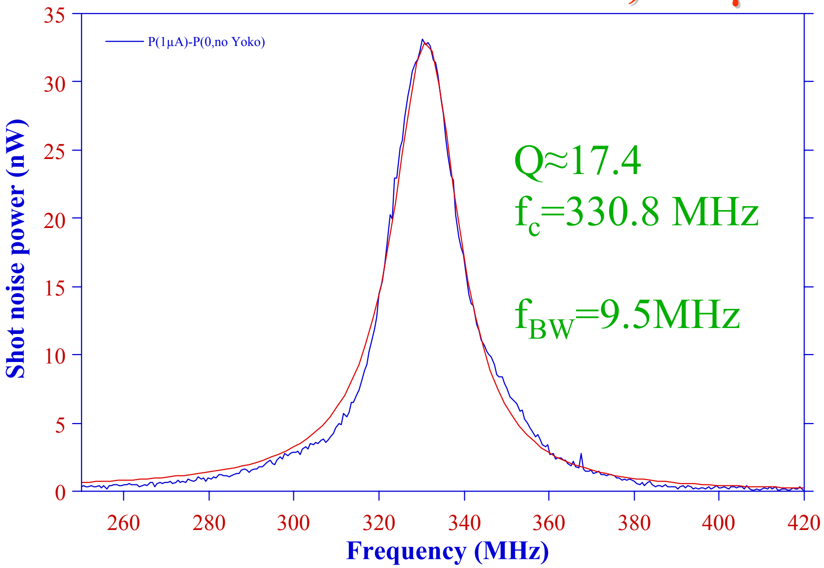
V_{bias}

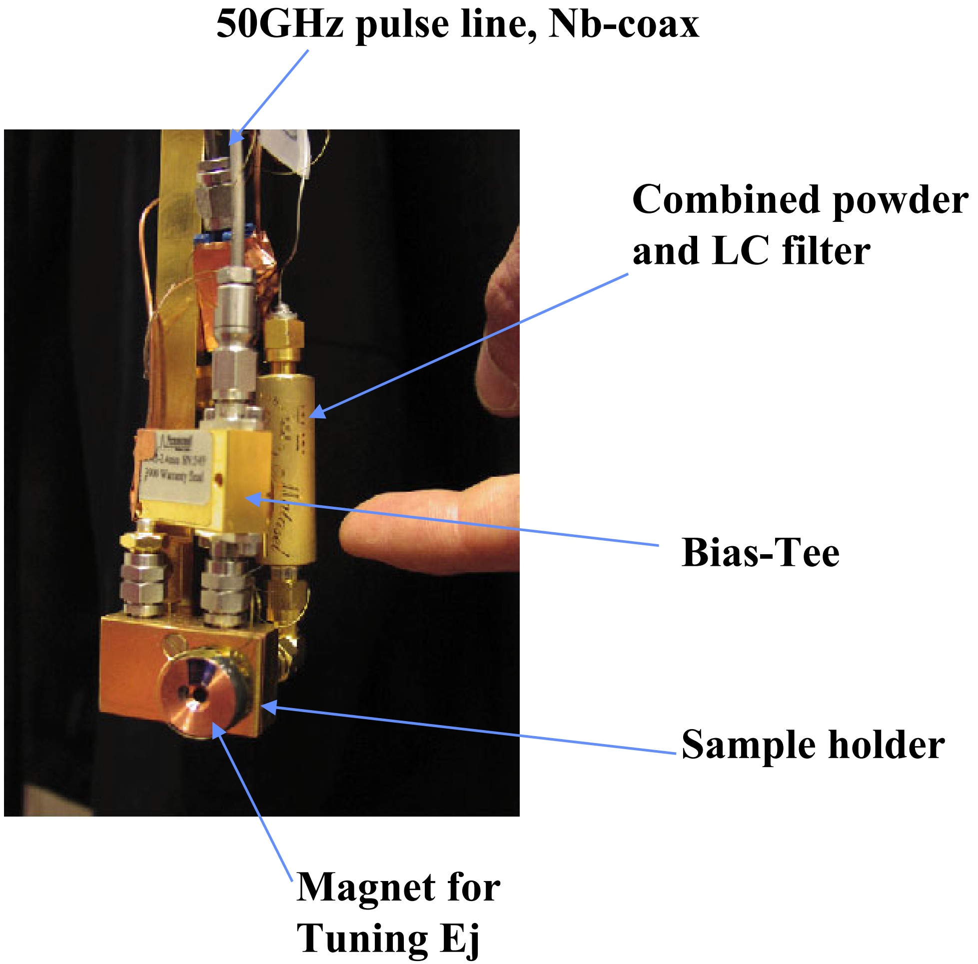
Operation point
double JQP

The sample holder



Shot noise from the SET, I=1μA

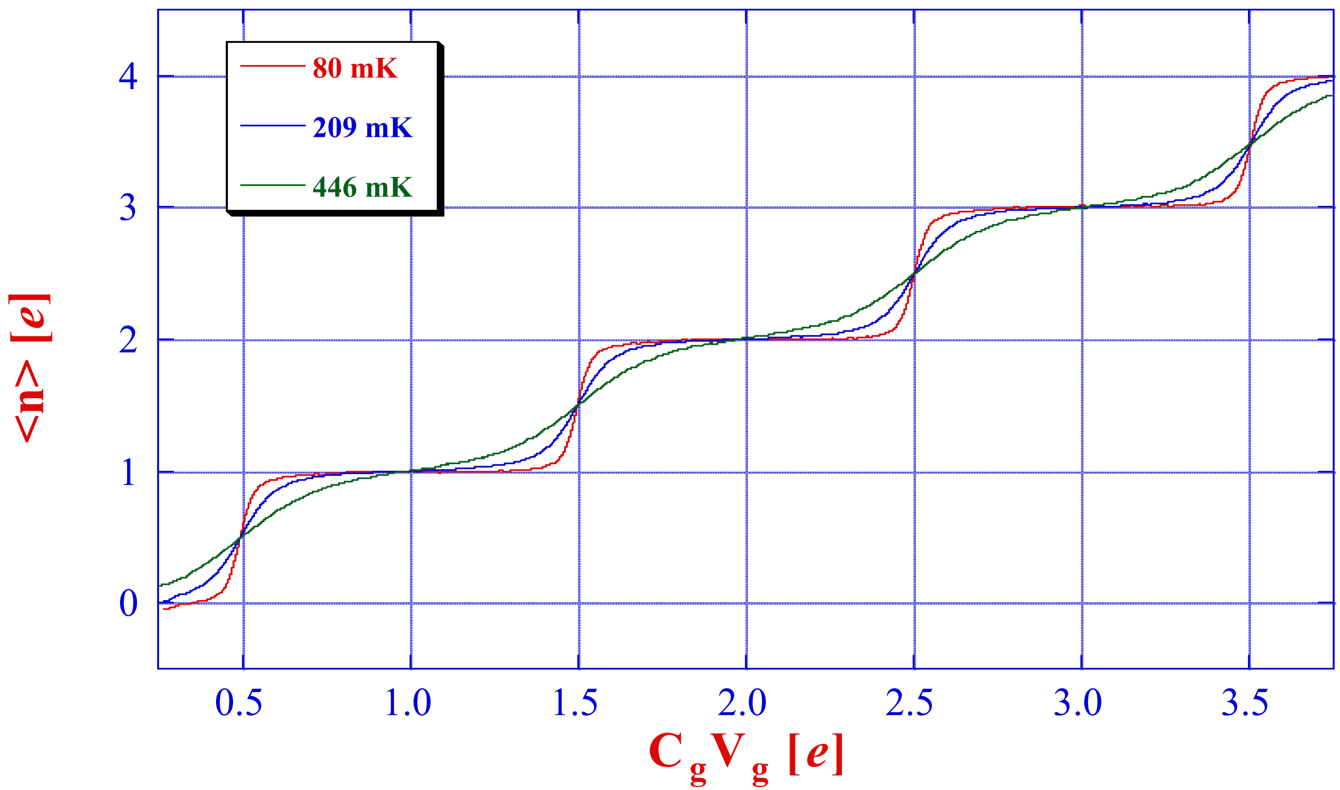




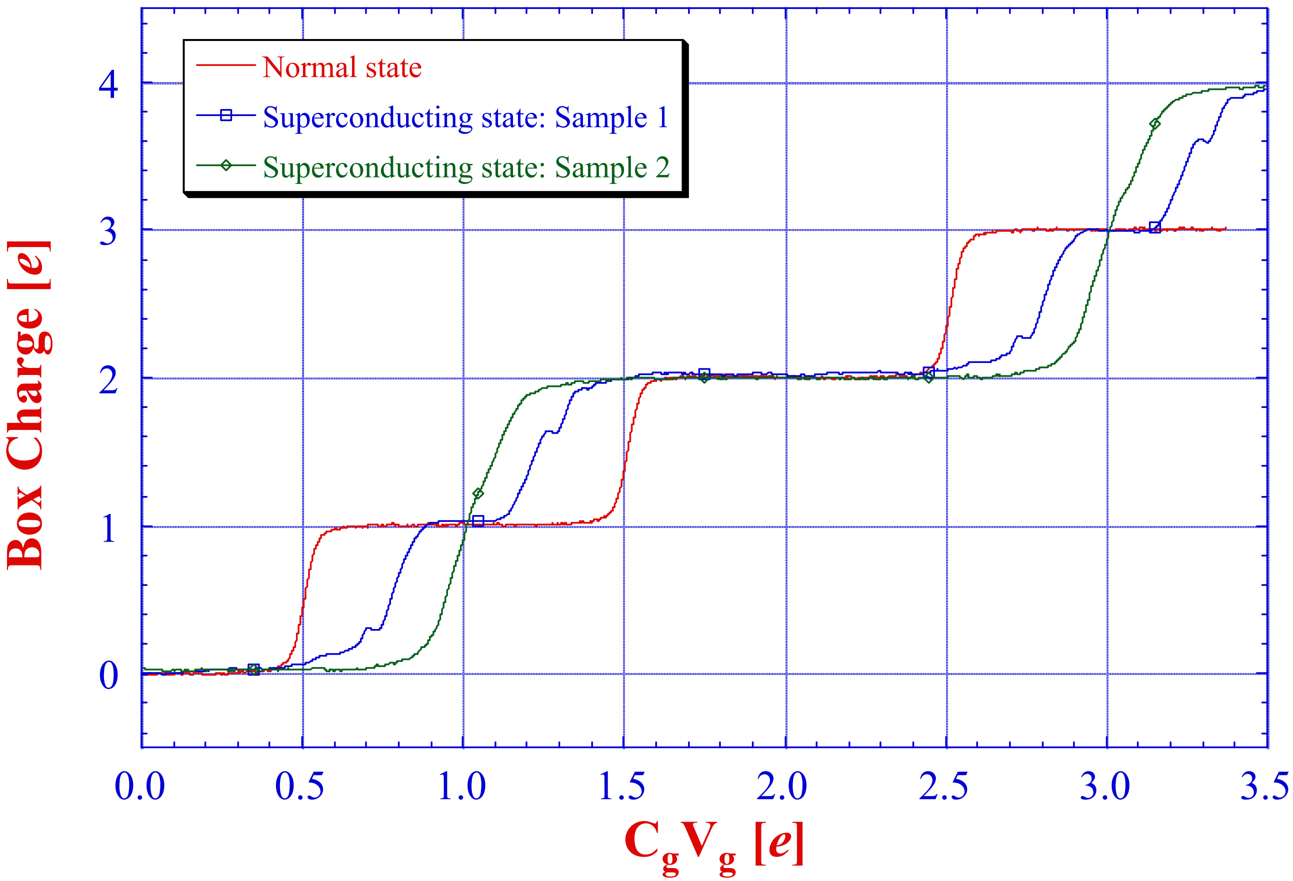
Controlling the charge on the box

The Coulomb Staircase

Temperature dependence of the staircase in the normal state



The Coulomb staircase comparing the normal and the superconducting state

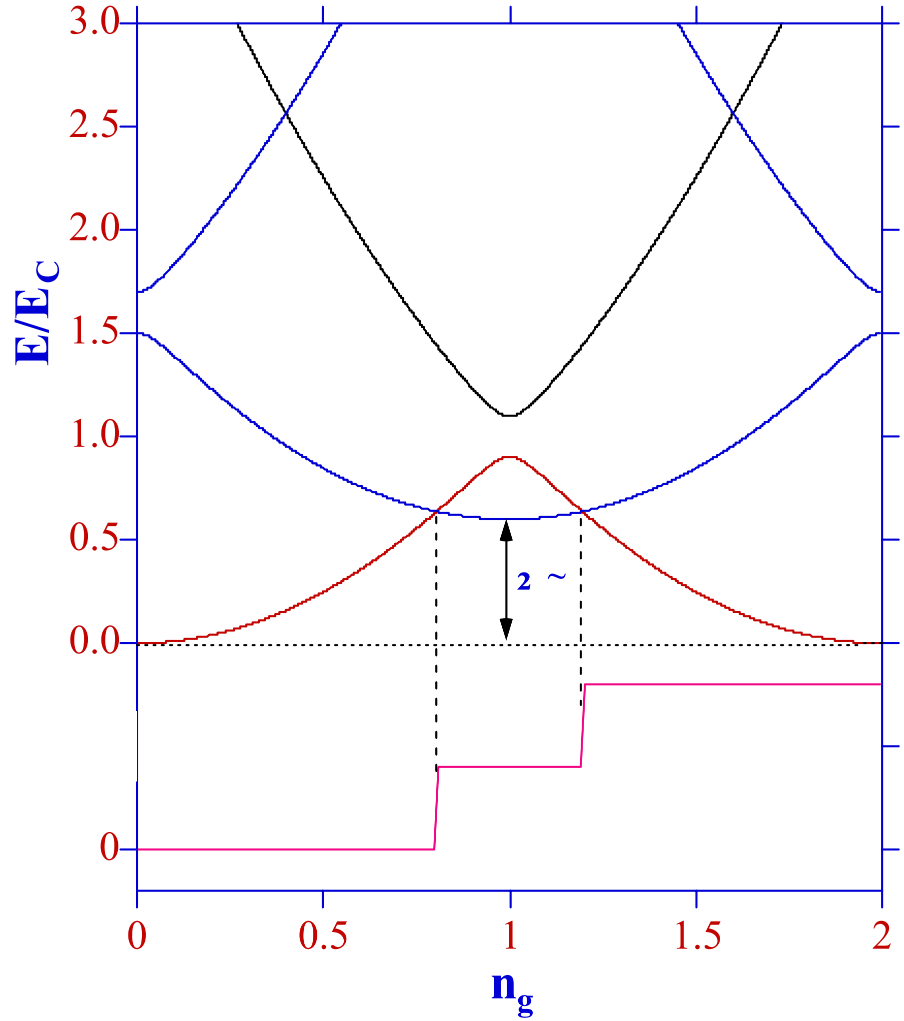


Artificial two level system

Very good control

Very sensitive read-out

What would you expect in the superconducting state



$$\tilde{\Delta} \approx \Delta_0 - k_B T \ln(N)$$

$$\Delta_0 \approx 2.4 \text{ K for Al}$$

$$\tilde{\Delta} \approx \frac{L - S}{L + S},$$

L = size of long step

S = size of short step

Using E_C<1.2K pure 2e periodicity is obtained

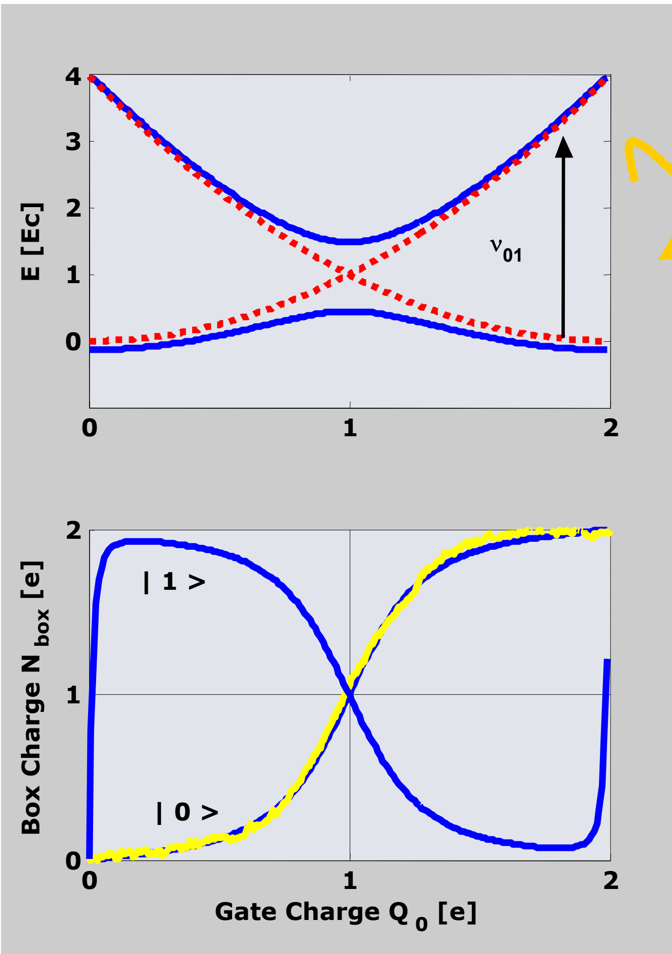
Tuominen et al. PRL (93)
Lafarge et al. Nature (93)

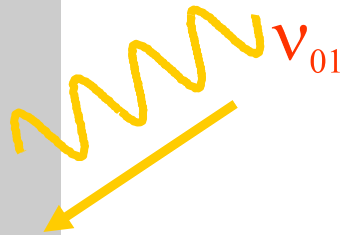
Spectroscopy

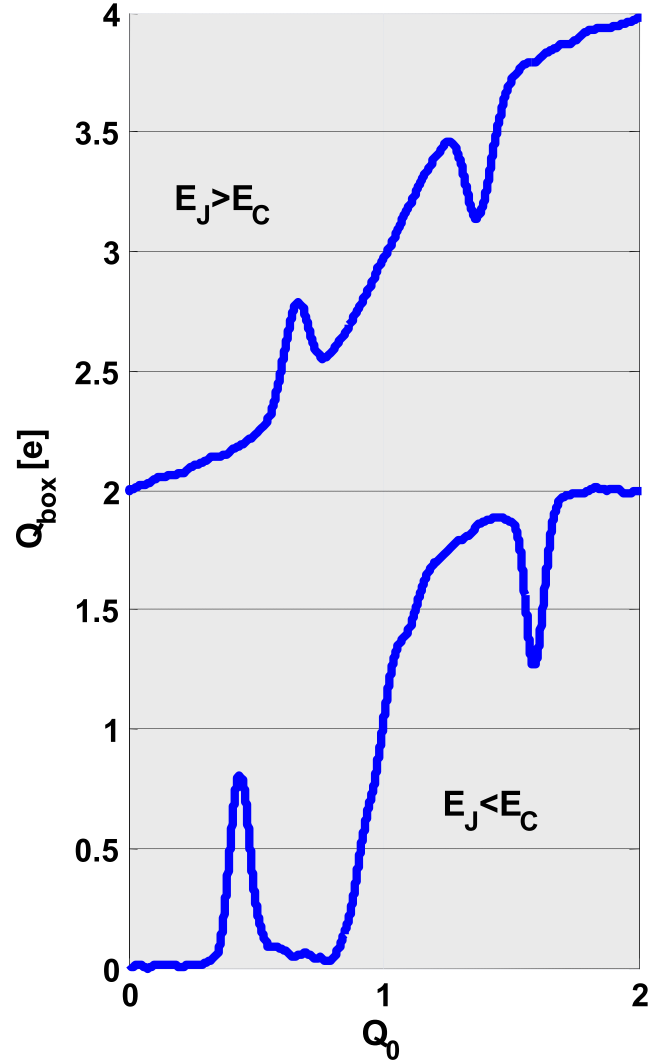
Determining E_C and E_J

Energy Levels of the Cooper-Pair Box

$$H = 2E_C\sigma_z(1-Q_0) - E_J\sigma_x/2$$

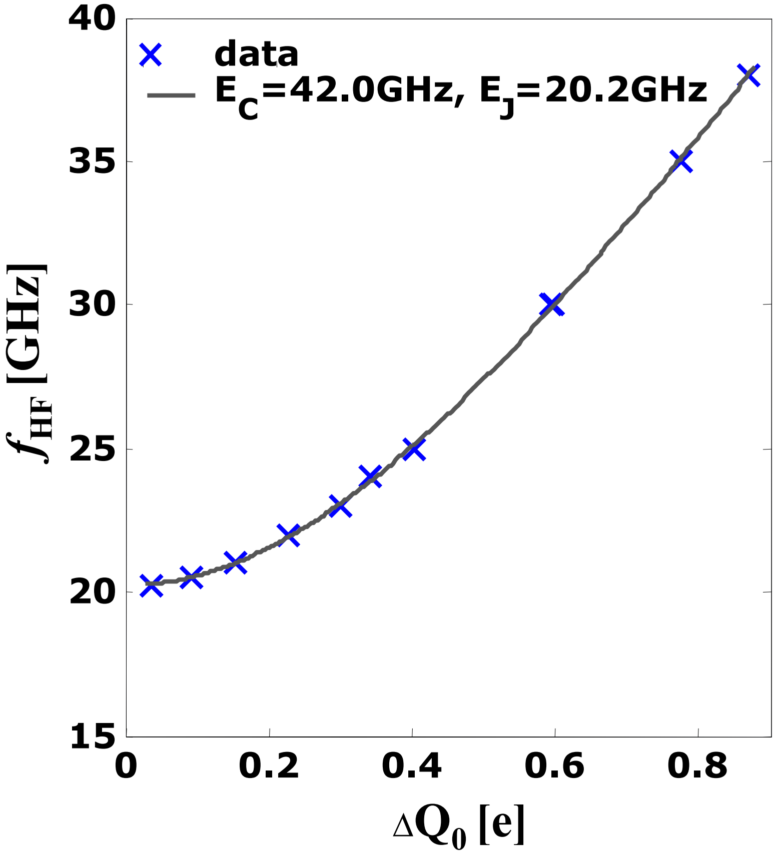




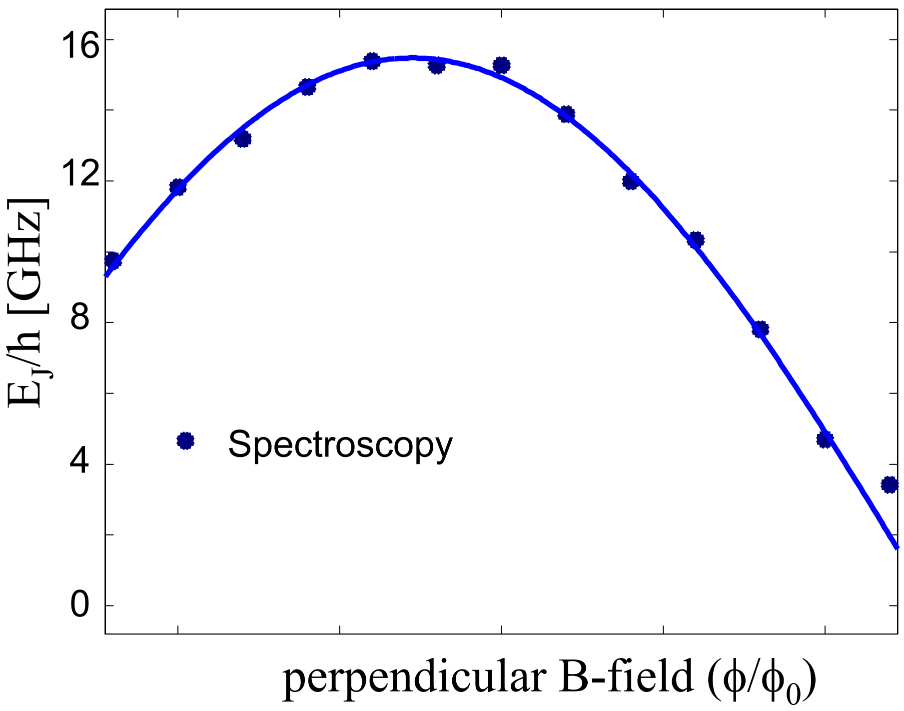


Characterization of the Cooper-pair box: Determining E_J and E_C

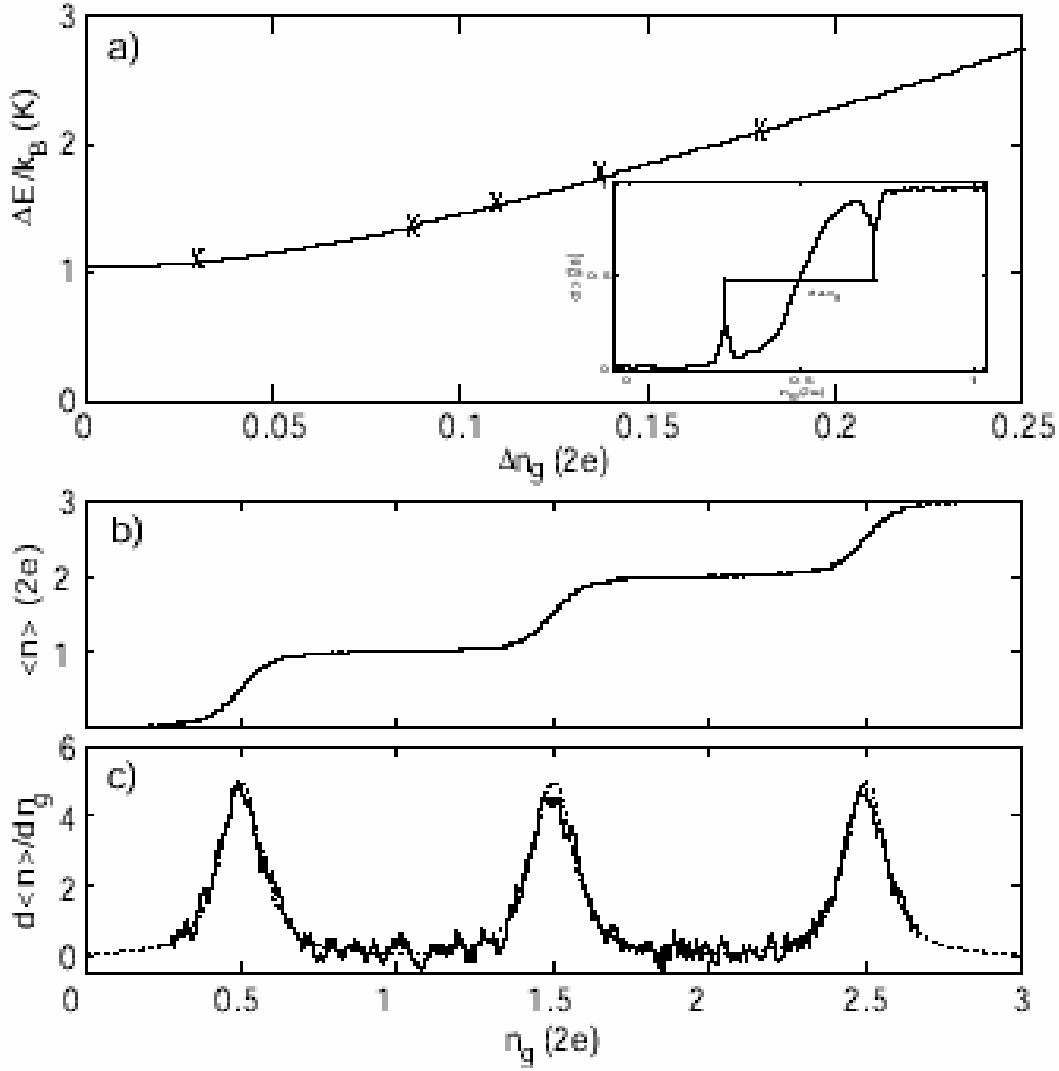
Spectroscopy



Modulation of E_J with perpendicular B-field



2e-periodic staircase: Experiment vs. theory

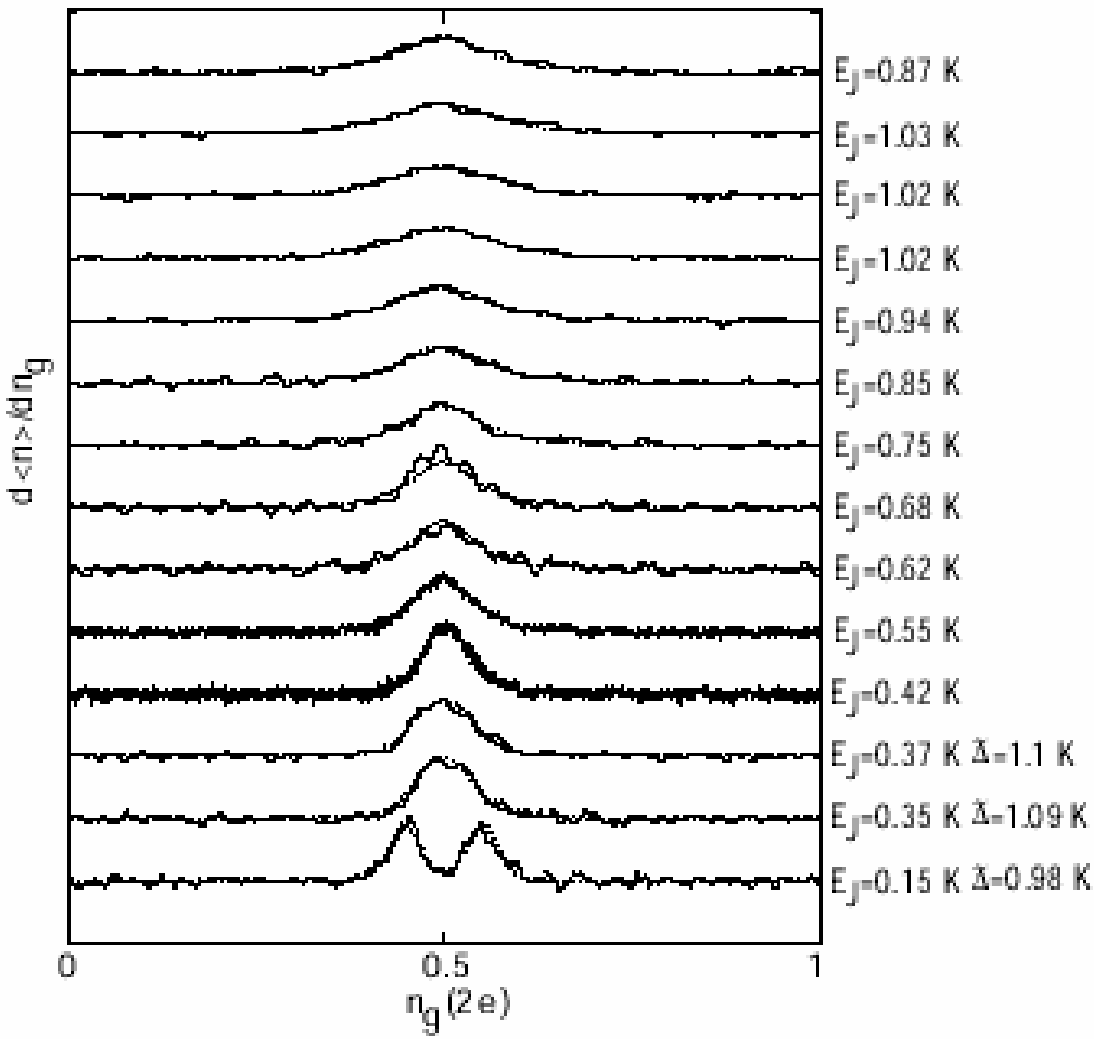


E_C and E_J extracted from spectroscopy

Stair case fit with no free parameters

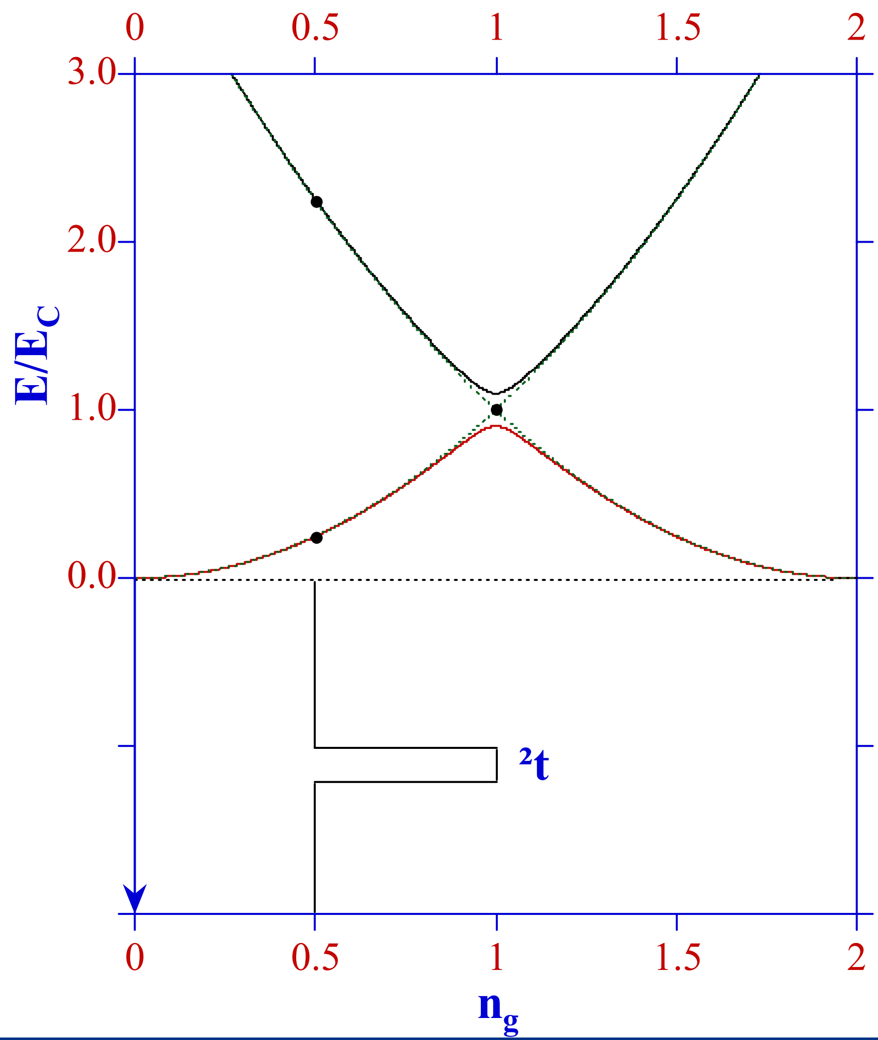
Derivative of the staircase

Staircase with Tunable E_J



Coherent oscillations

Manipulation with dc-pulses

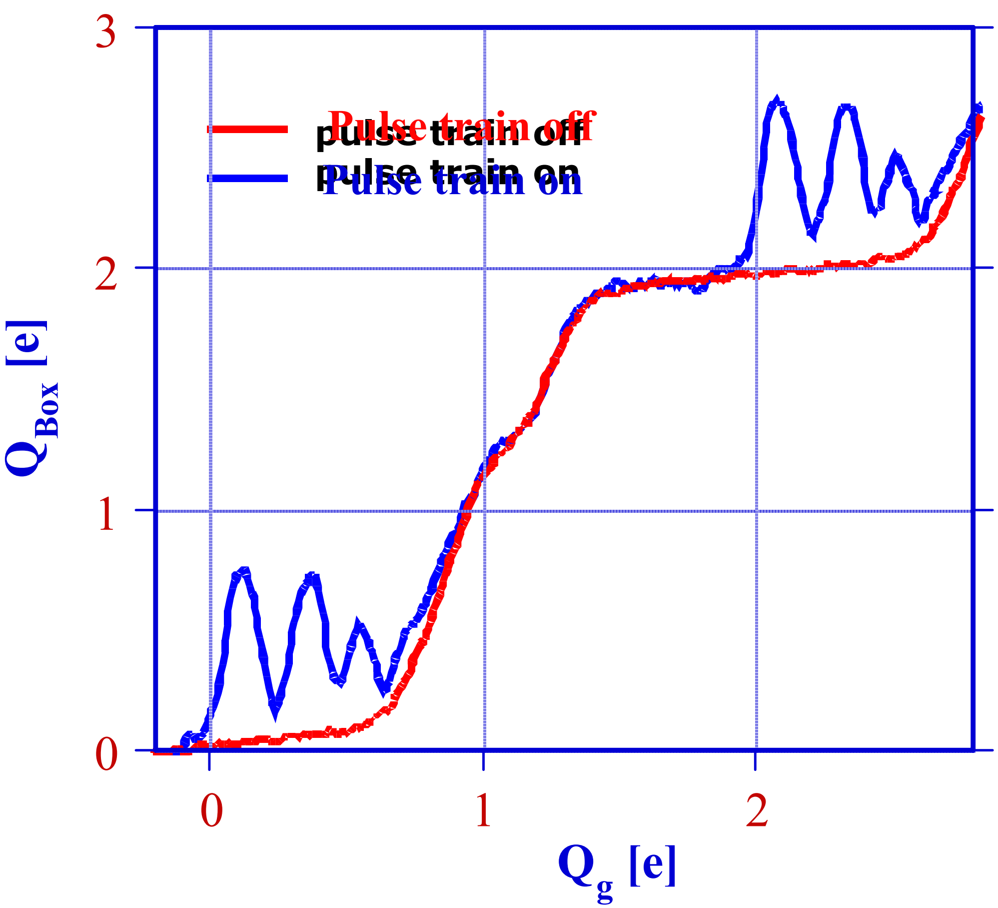


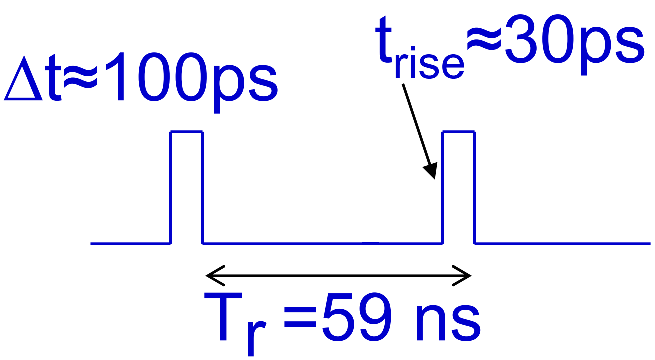
t<0	Starting at n_{g0}
t=0	Go to $n_{g0}+\Delta n_g$
t=Δt	Go back to n_{g0}

The probability to find the qubit in the exited state oscillates as a function of Δt.

After Δt the charge is measured by the RF-SET

Continuous measurement with dc-pulses T_r=59ns, amplitude 1e pulse train

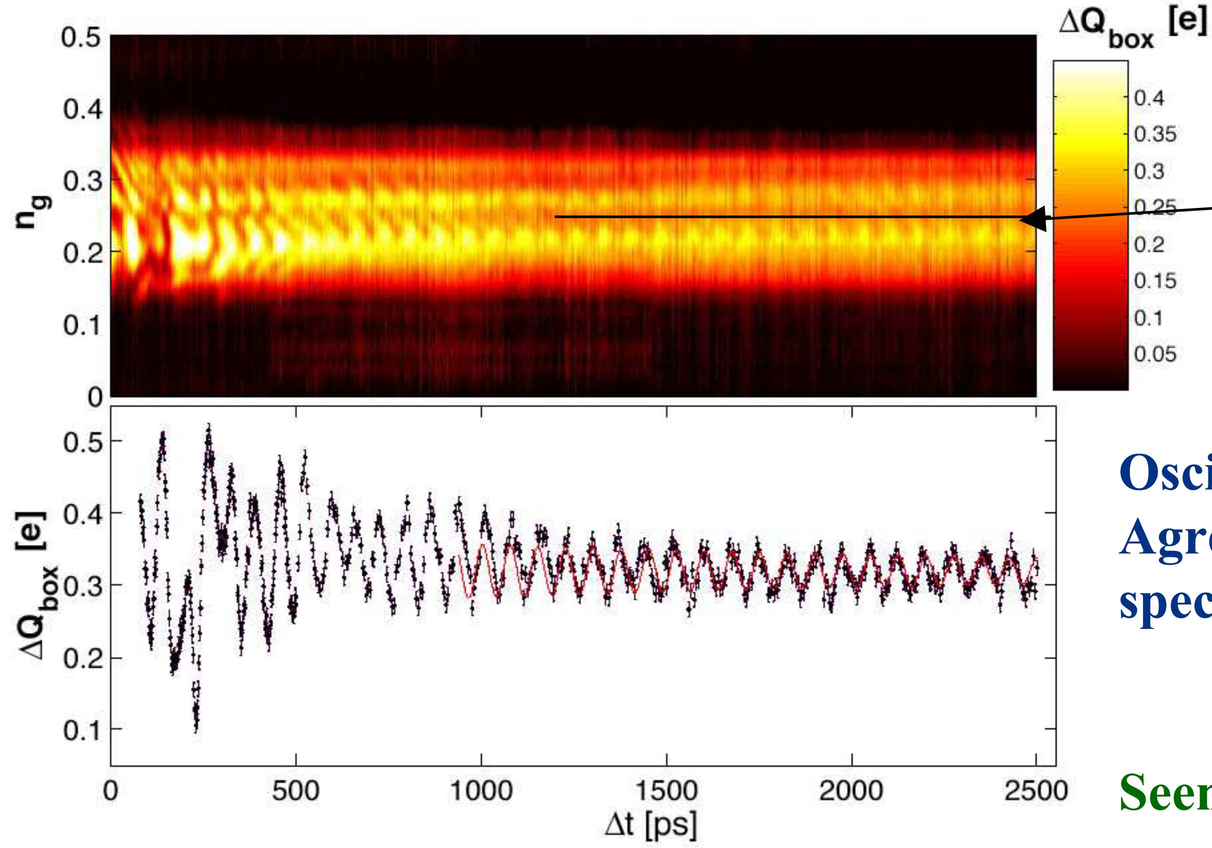




Amplitude up to 70%,
Difference from 100% can be explained by finite rise time of the pulses (30 ps)

Difference between these two curves = excess charge ΔQ_{box}

Coherent oscillations excess charge ΔQbox vs. n_g and Δt

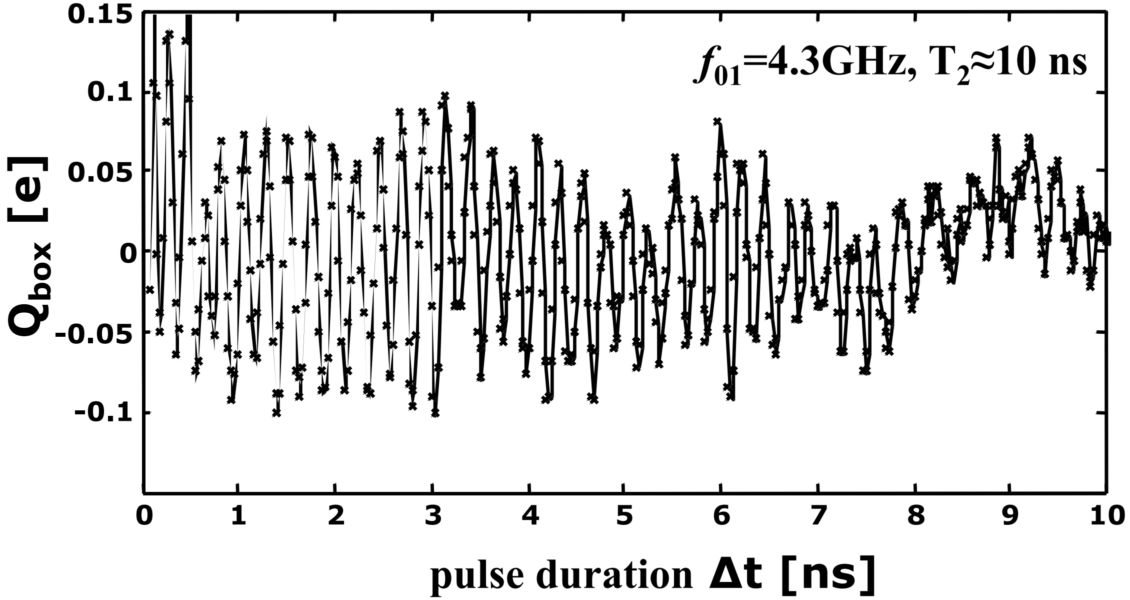


Note dead zones

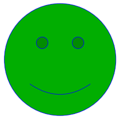
Oscillation frequency = E_J/h
Agrees well with E_J from spectroscopy

Seen in 5 different samples

Oscillations at the charge degeneracy



Bad news:
$T_2 \sim 10$ ns



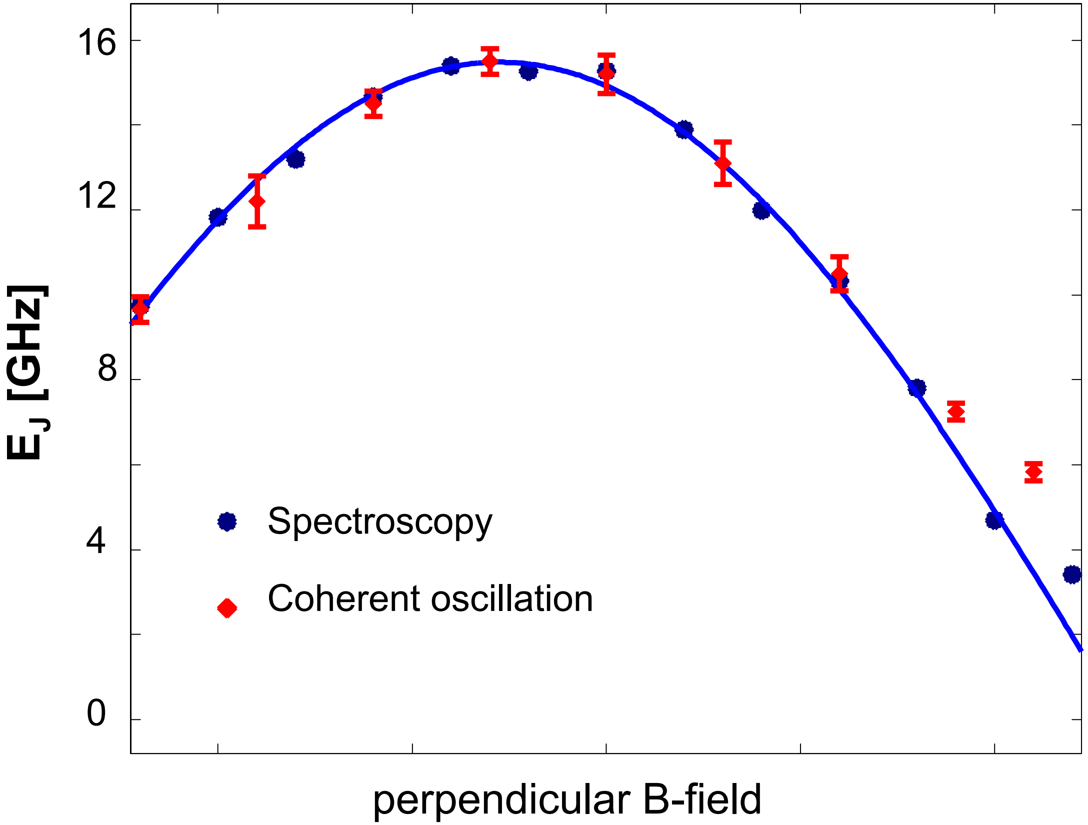
Good news:

- We observe **oscillations**
- A very **high fidelity! >70%**

Deviation from 1.0 e due to finite risetime (~30ps) of pulses, i.e. no missing amplitude

Comparison: E_J from Spectroscopy and from coherent oscillations

E_J is modulated with perpendicular B-field



Possible sources of decoherence

- **The SET: The continuous measurement** can of course decohere the system, pulsed measurements should improve the situation.
- **Non-equilibrium quasi particles** may be present in the system. Transition between exited state and qp state (Zorin, cond-mat/0312225)
- **Back ground charges** are known as an important source of decoherence. At the degeneracy point, that decoherence should be drastically reduced. However, if the dc-pulse is not perfectly square, the system is not exactly at the degeneracy point during the evolution. Then background charge noise couples stronger to the system.
- **DC-pulses** may shake up background charges or other resonant modes (environment, cavity etc.)
- **Flux-noise:** Less likely, we will test a box without squid-loop

Measurements of T_1 and T_2

Decoherence and mixing

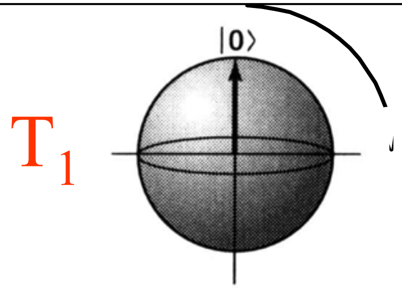
The qubit can be disturbed in two different ways.

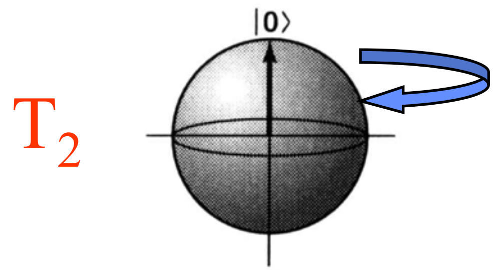
Relaxation or mixing

- The environment can exchange energy with the qubit, mixing the two states by stimulated emission or absorption. This has the characteristic time T_1
- Describes the diagonal elements in the density matrix
- Fluctuations at resonance, $S(\omega_{01})$

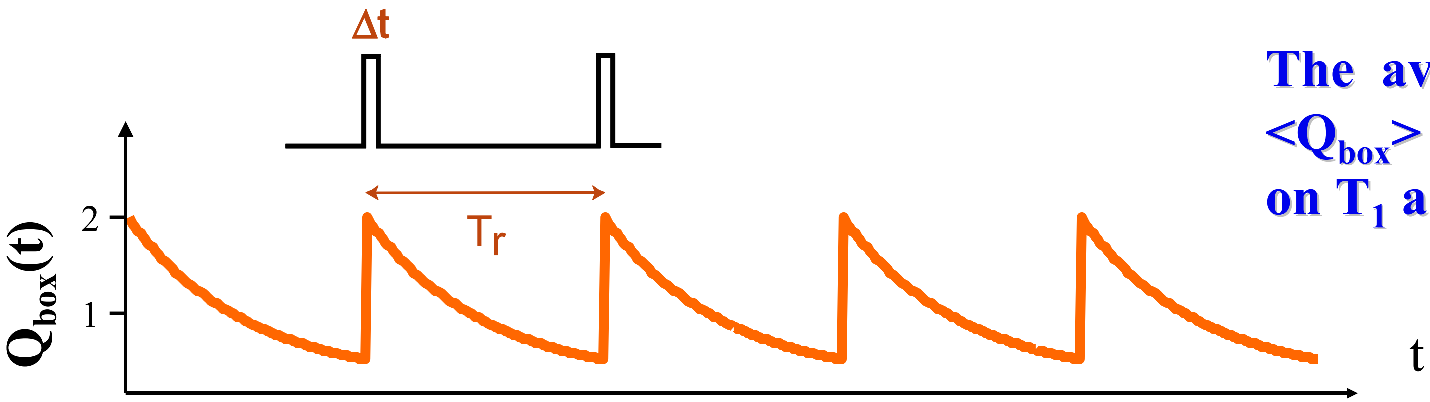
Decoherence

- The environment can create loss of phase memory by smearing the energy levels, thus changing the phase velocity. This process requires no energy exchange, and it has the characteristic time T_2
- Describes the decay of the off-diagonal elements in the density matrix
- Fluctuations at low frequencies, $S(0)$

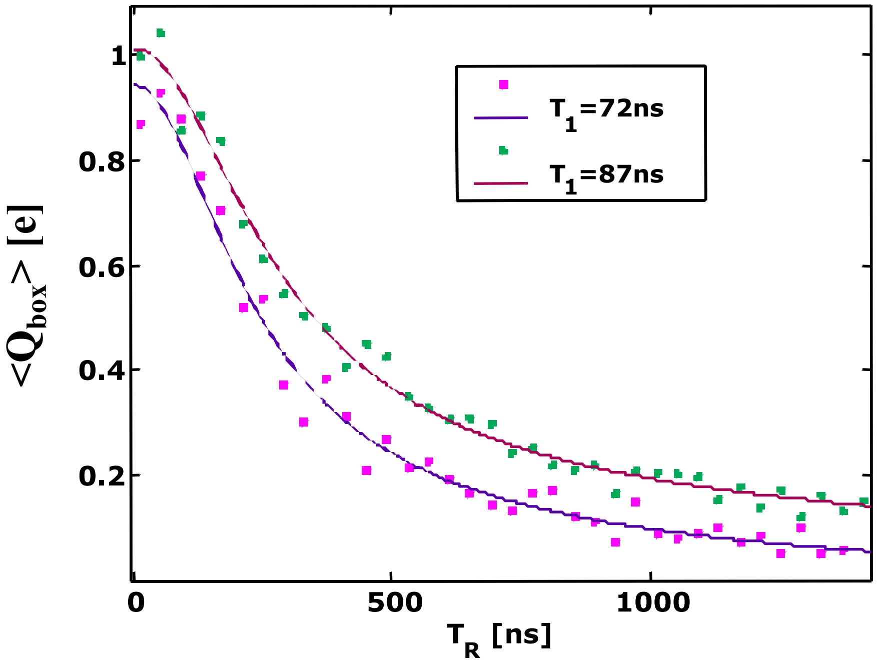




Determining a T_1 that is smaller than T_{meas}



The average charge $<Q_{box}>$ depends both on T_1 and T_R

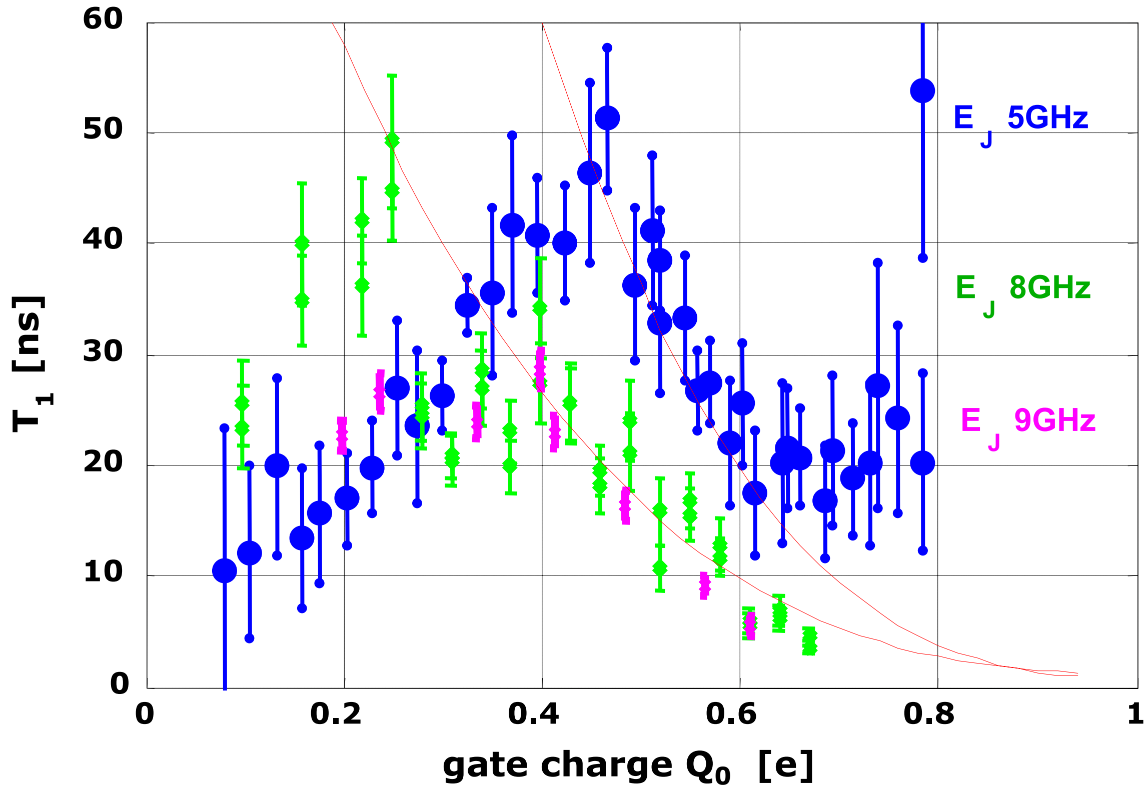


n_0 depends on the pulse rise time

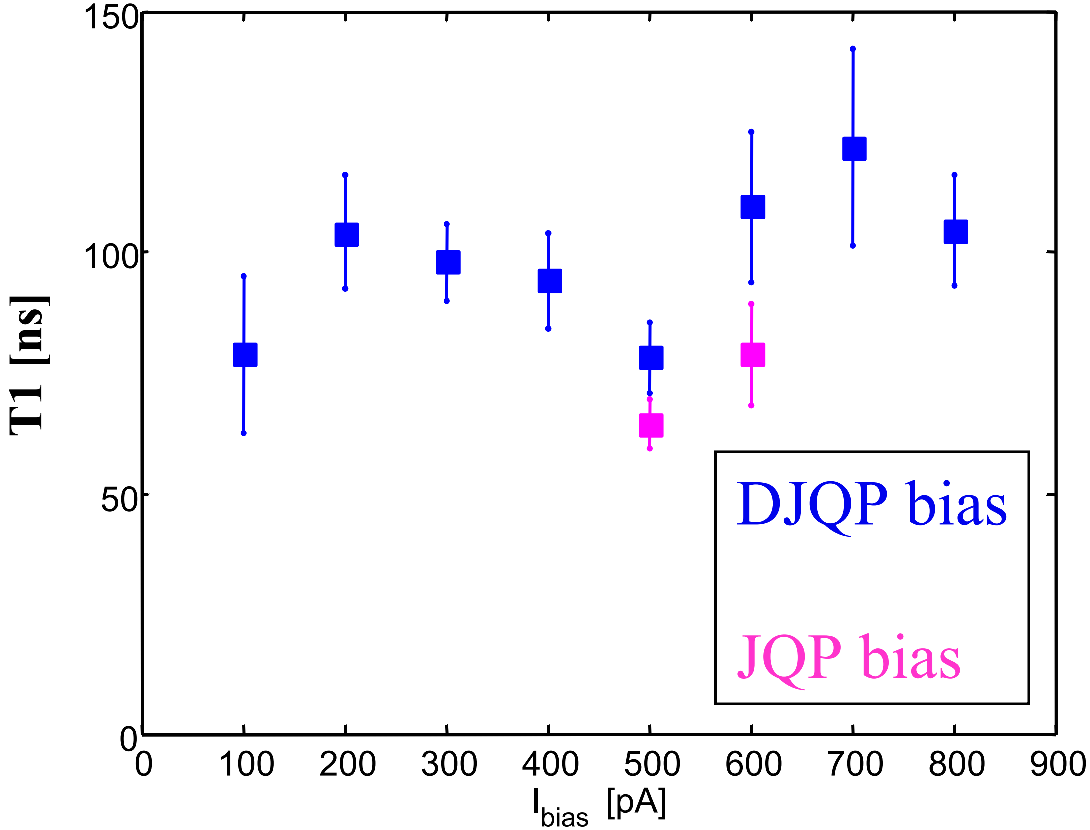
$$< n > (t_R) = 2n_0 \frac{t_1}{t_R} \frac{1 - e^{-t_R/t_1}}{1 + e^{-t_R/t_1}}$$

T_1 Measurements vs Q_0 and E_J provide info on $S(\omega)$ and form of coupling

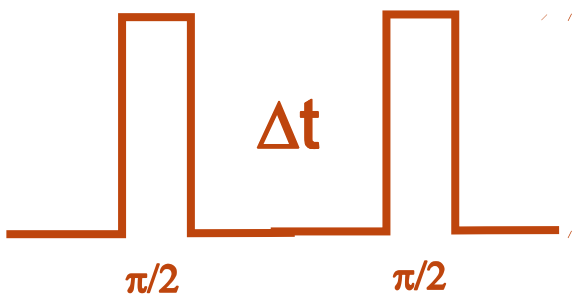
$$\Gamma_{relax} \equiv T_1^{-1} = \kappa \sin^2 \eta \, S(\omega = \Delta E)$$



We find T_1 short and independent of SET bias in 6 different samples.



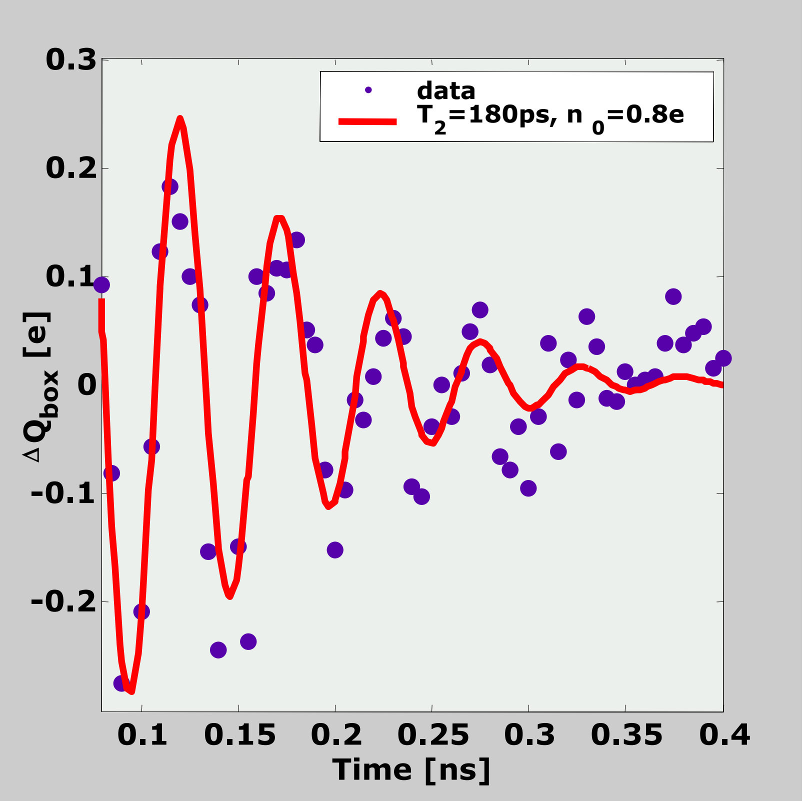
Dephasing far away from charge degeneracy



twin pulse:
Δt=0ps to10ns

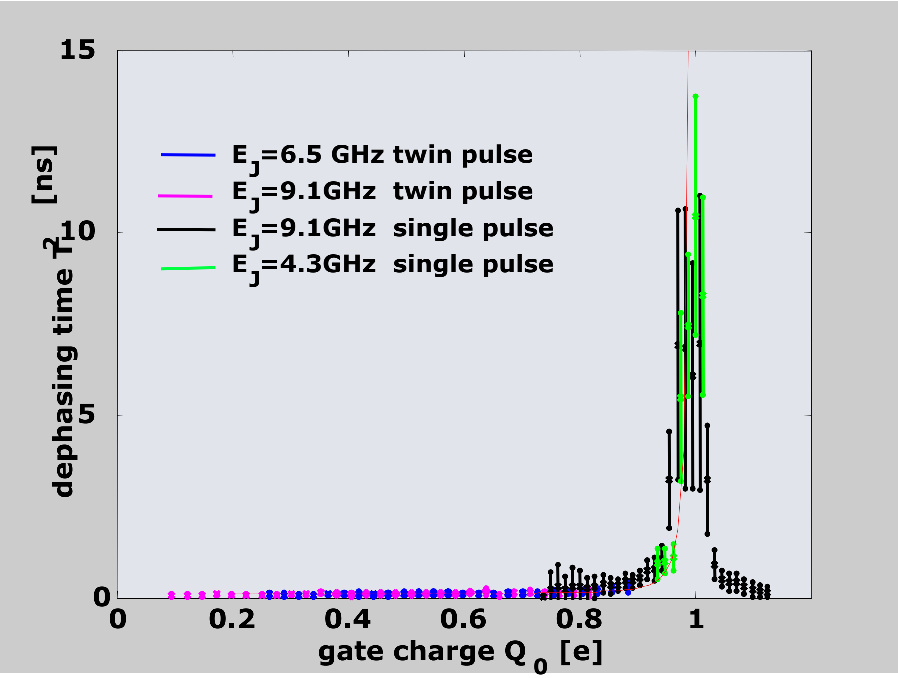
Rotation in x-y plane

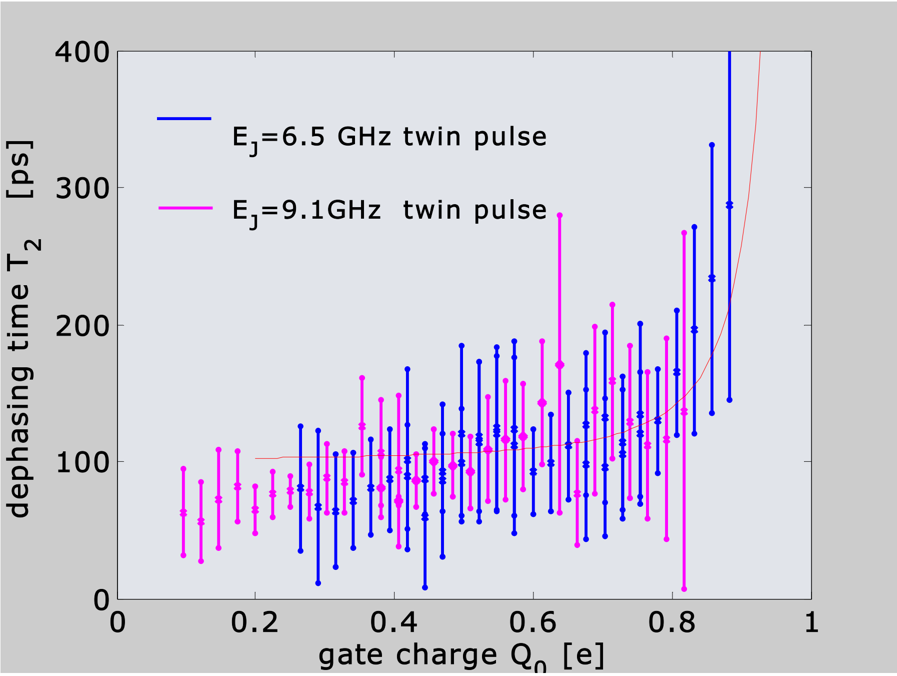
•(Nakamura *et al.* 2002)



T_2 =180ps and large initial amplitude

Measurements of T_2 vs. gate charge Q_0





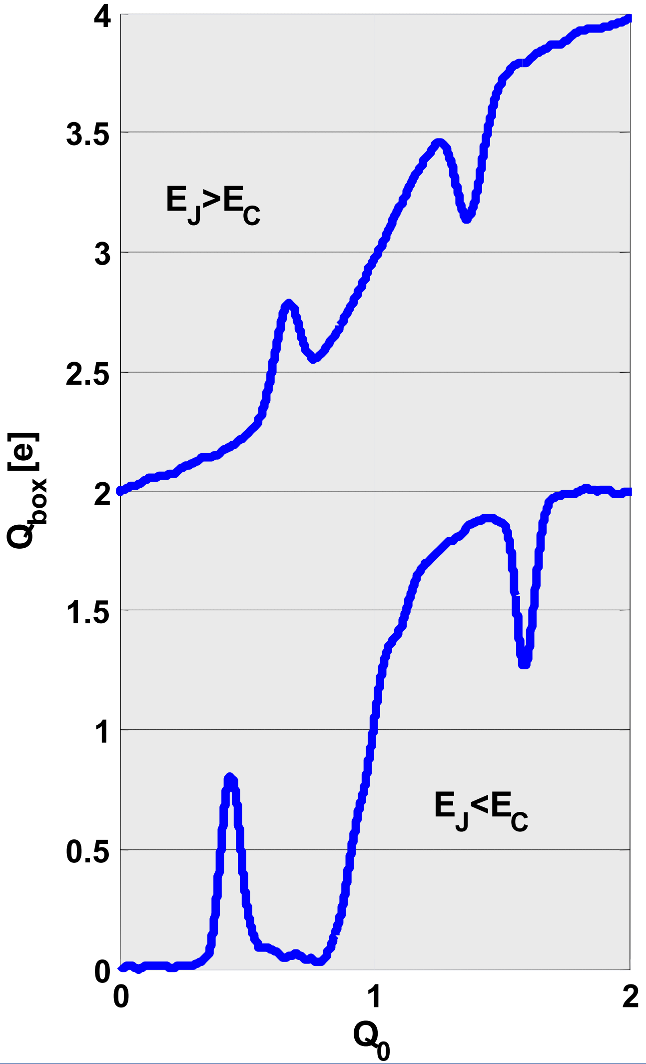
Q_0 dependence → coupling to charge

Very similar to data from NEC

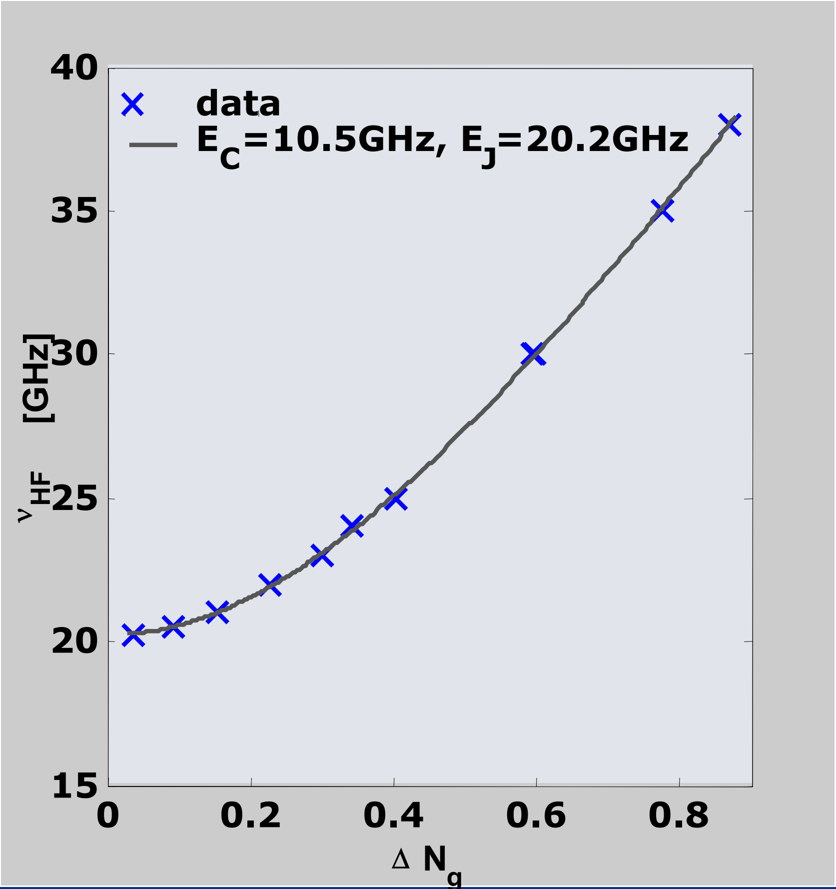
Summary

- 2e periodic staircase for E_C<1.2 K
- Characterized Cooper-pair box, E_C and E_J determined with good accuracy
- Observed coherent oscillations in 5 samples, oscillation period agrees well with E_J
- $T_1 \leq 100$ns, scales with $\sin^2\eta$ intermediate gate charge
- $T_2 \leq 10$ns, due to charge noise
- $T_2 \approx T_1$ at the degeneracy point

Microwave irradiation of the Cooper-pair box



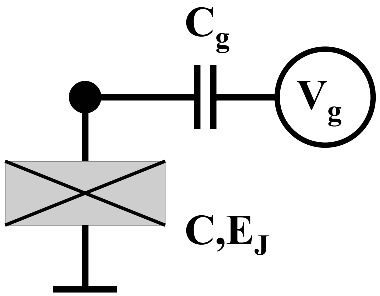
By irradiating the "atom" with microwaves, we can change the population of the levels. This also allows us to determine the parameters of the artificial atom: E_C and E_j.

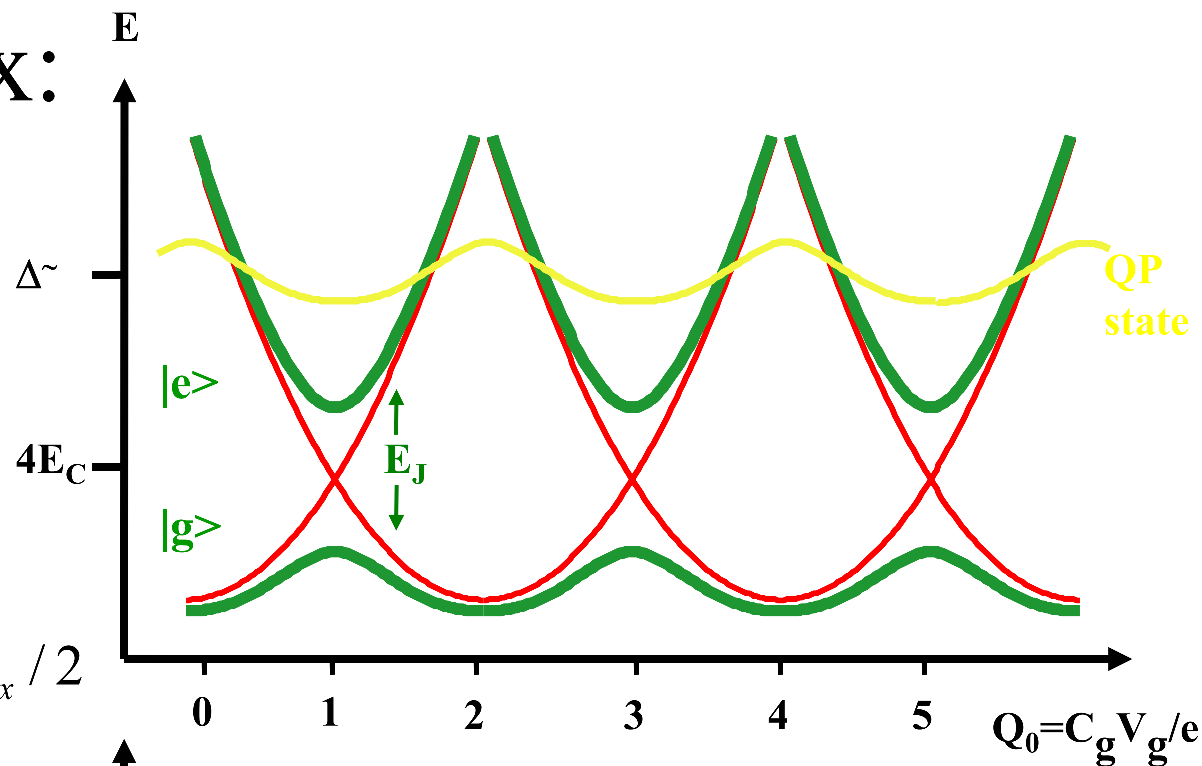


The Single-Cooper-Pair Box:

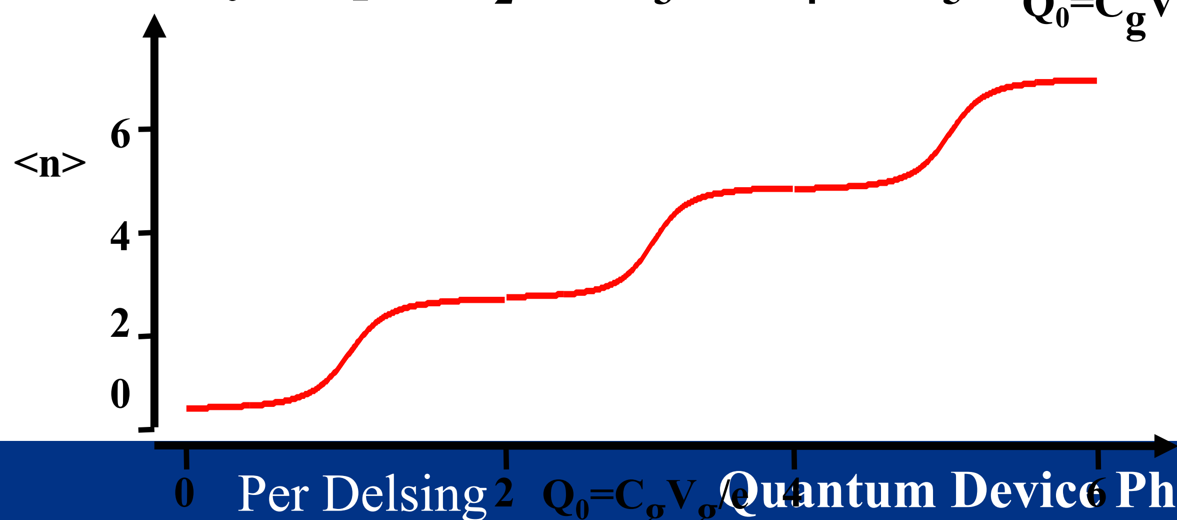
$\Delta \gg E_C \gg E_J(B) \gg T$

2.4K 0.9-1.7K 1.0-0.05K 20mK

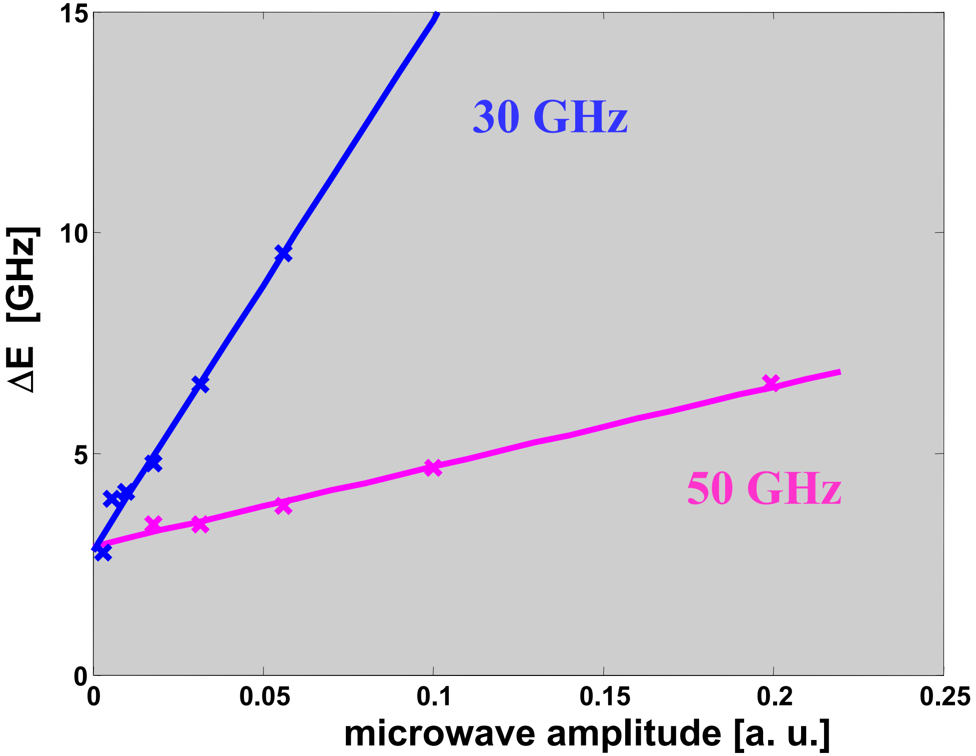




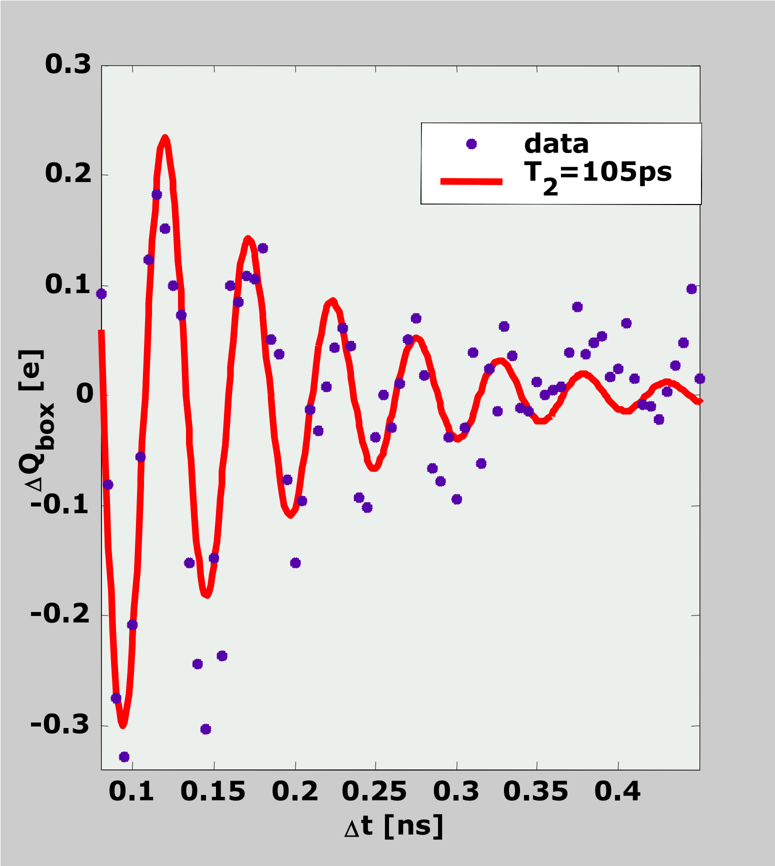
$$H = 2E_C\sigma_z(1-Q_0) - E_J\sigma_x / 2$$



Determining T_2



T_2 =110ps, from spectroscopic peak width



T_2 =105ps, from twin $\pi/2$ pulses