Coherent oscillations in a Single Cooper-pair Box

1. Introduction
2. Coulomb Staircase
3. Spectroscopy
4. Coherent oscillations

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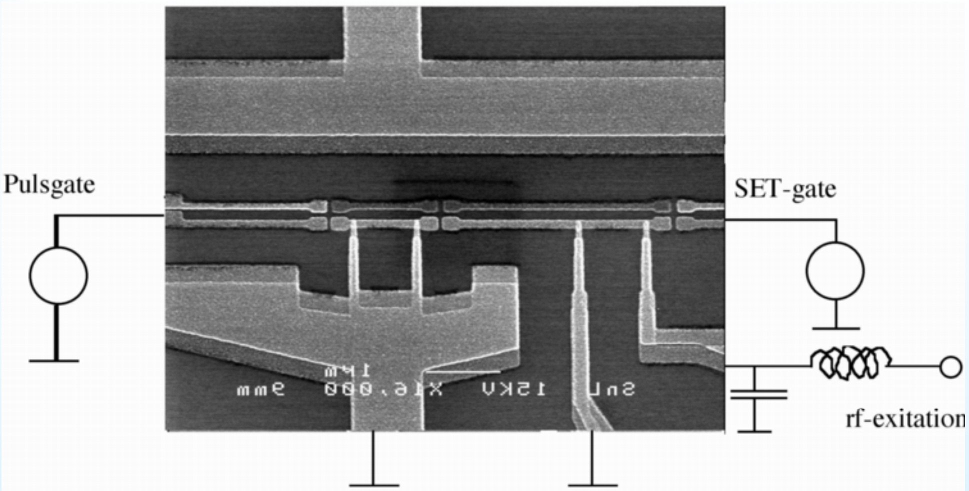
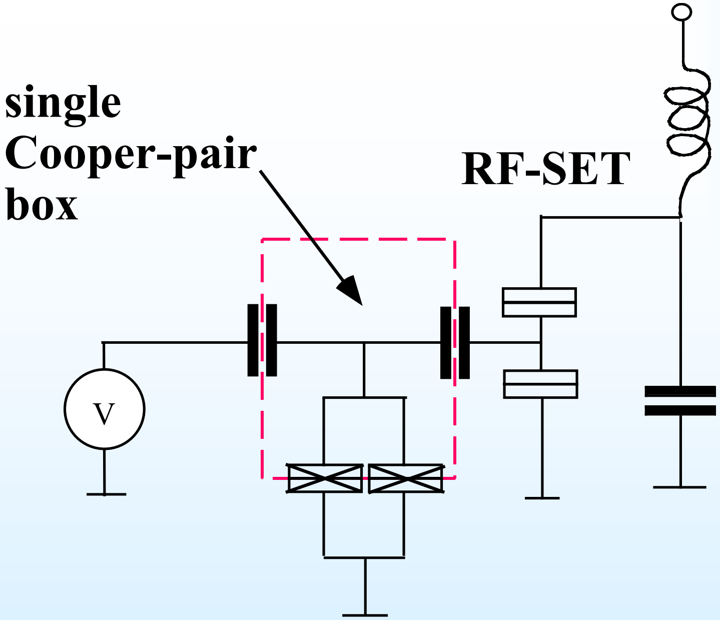
A Single Cooper-pair Box Qubit Integrated with an RF-SET Read-out system

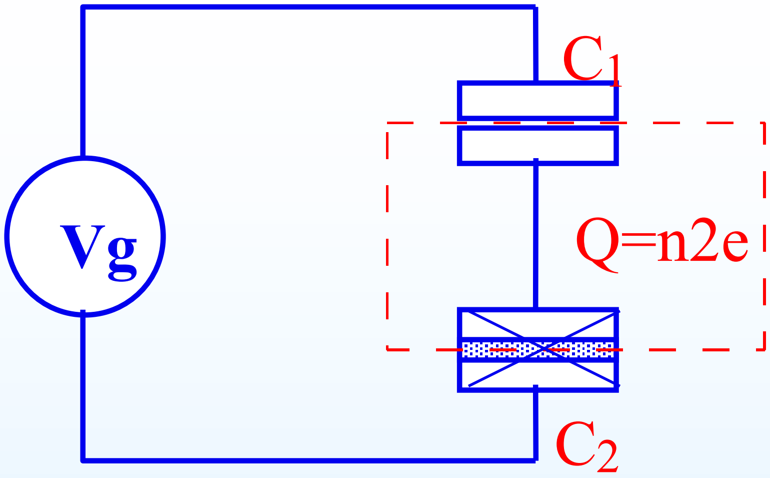




Δ	>>	E_C	>>	$E_J(B)$	>>	T
2.5K		1K		0.5-0.05K		20mK

Bouchiat et al. Physica Scripta (99)
Makhlin et al. Rev. Mod. Phys. (01)
Aassime, PD et al., PRL (01)

The Single Cooper-pair box (SCB)



$$H = \frac{Q^2}{2C_\Sigma} - E_J \cos\theta$$

c.f. Hamiltonian for Bloch electrons

$$\frac{p^2}{2m} + U(x)$$

Bouchiat et al., Physica Scripta (98)
Nakamura et al., Nature (99)
Makhlin et al., Nature (00)

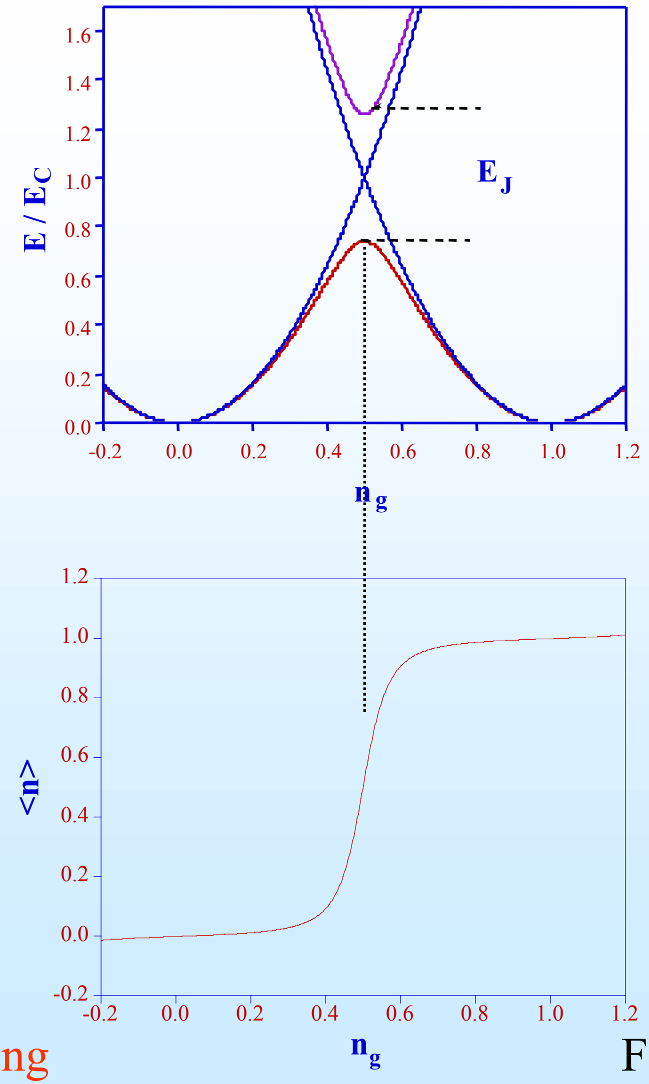


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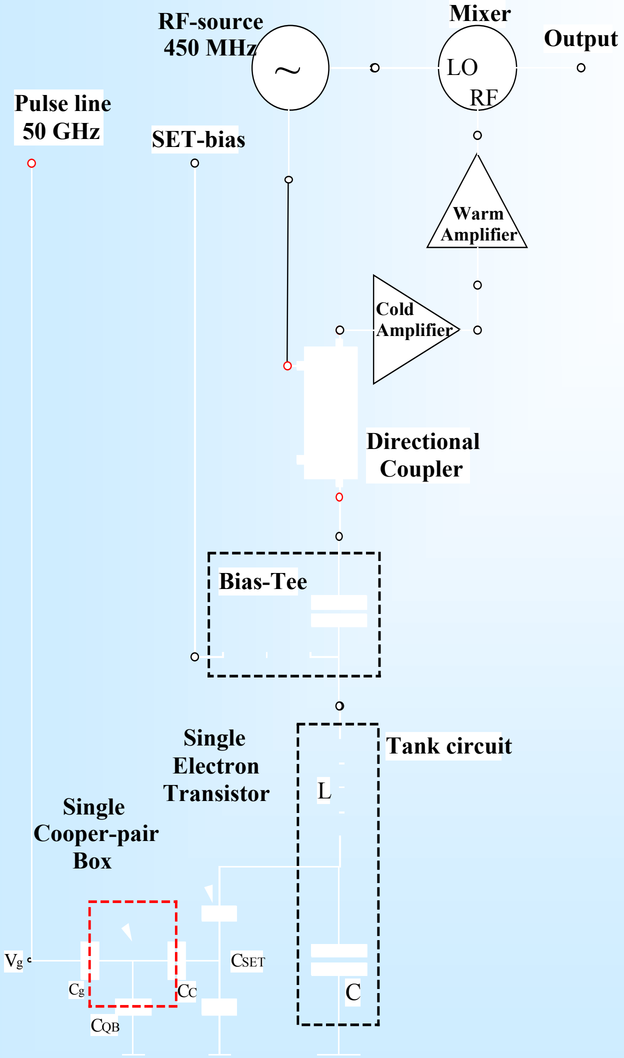
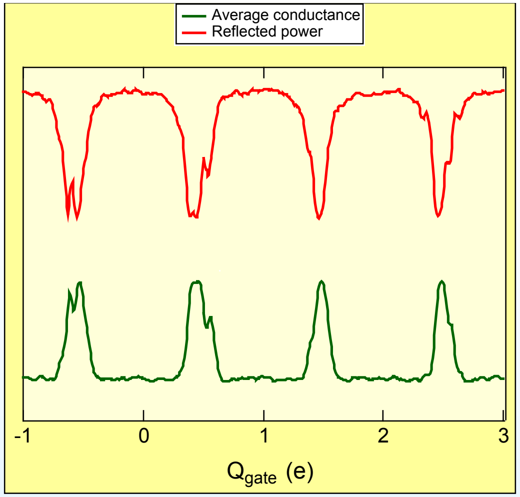
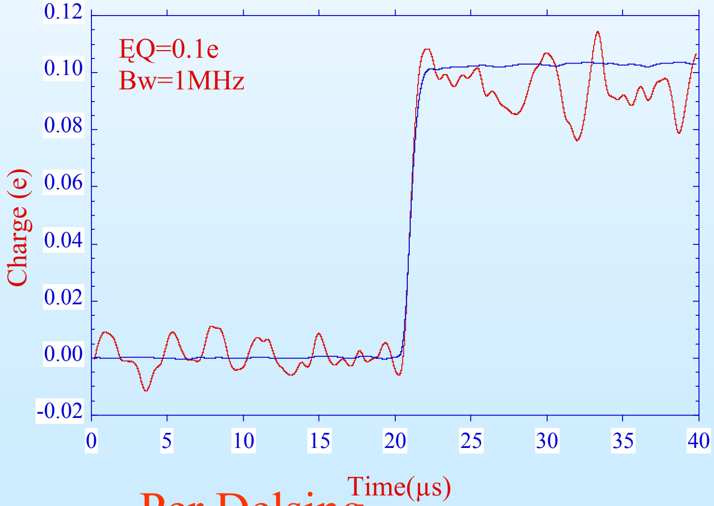
Fig. 3

The Radio-Frequency Single Electron Transistor





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



Very high sensitivity:
3.2 μe/√Hz
A.Aassime, PD et al.
APL (01)

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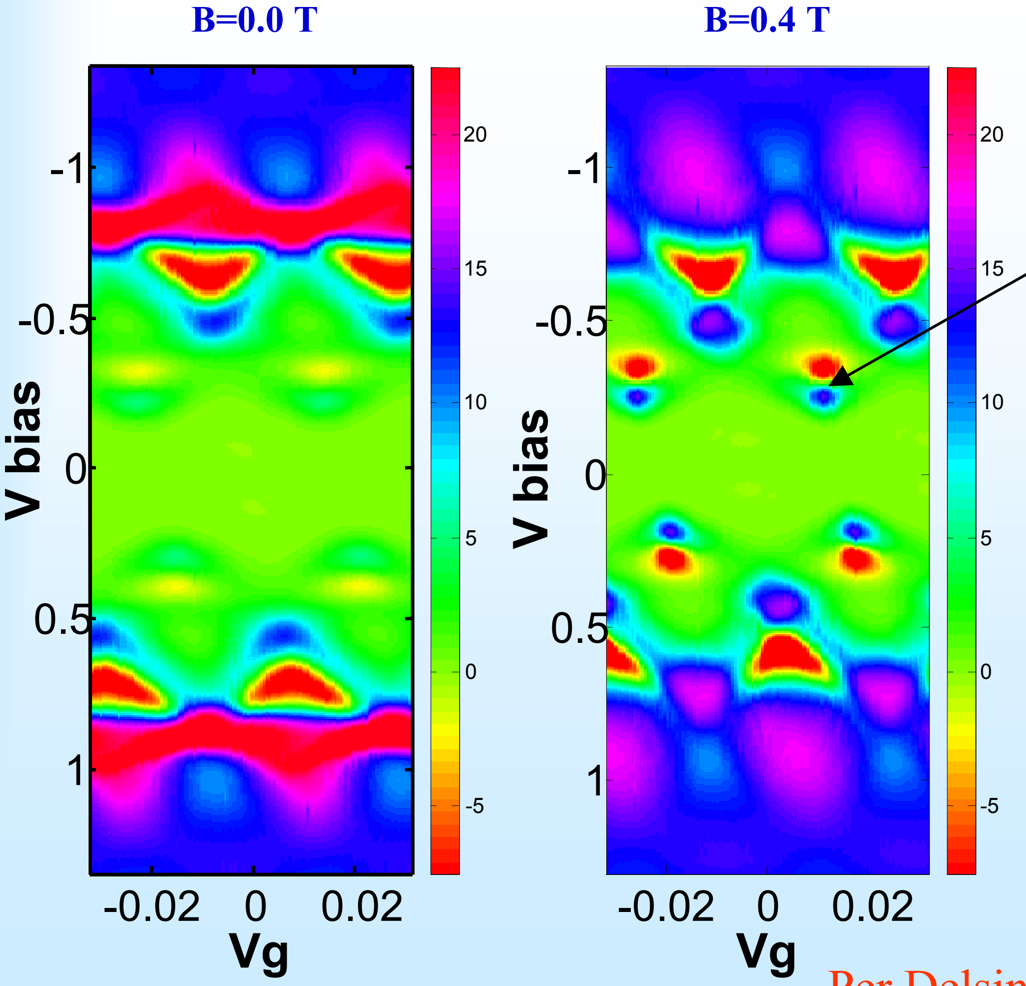
Fig. 4

SET IV-characteristics and Conductance vs. V_b and V_g



Operation point double JQP

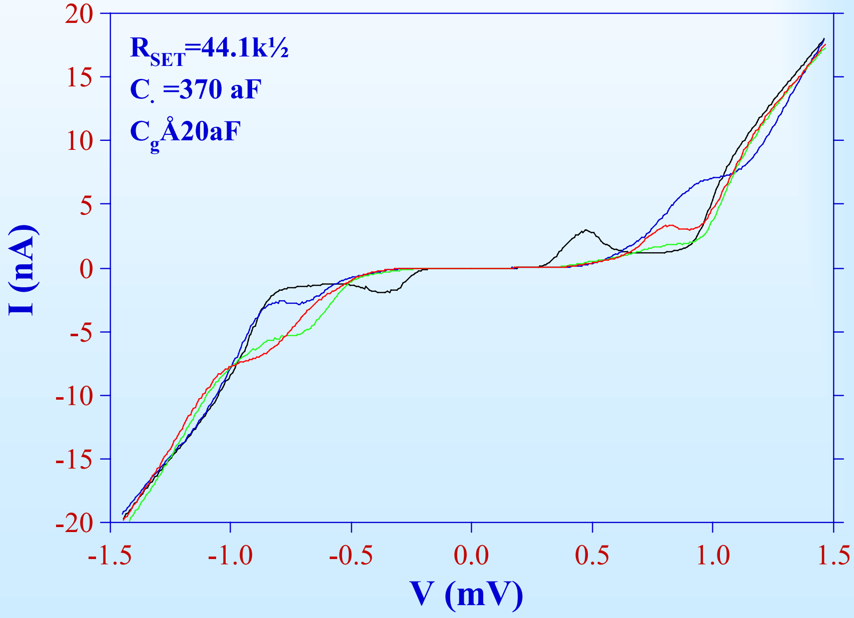


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Fig. 5

The Sample holder

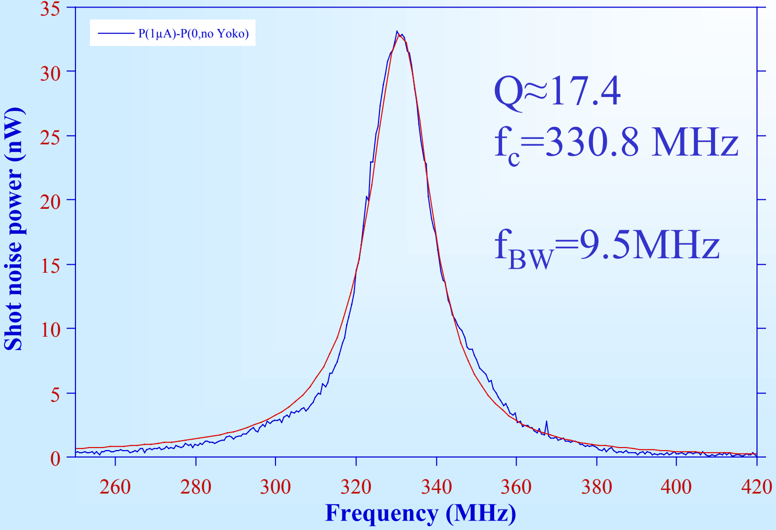
Fabricated in oxygen free high conductivity copper and gold plated

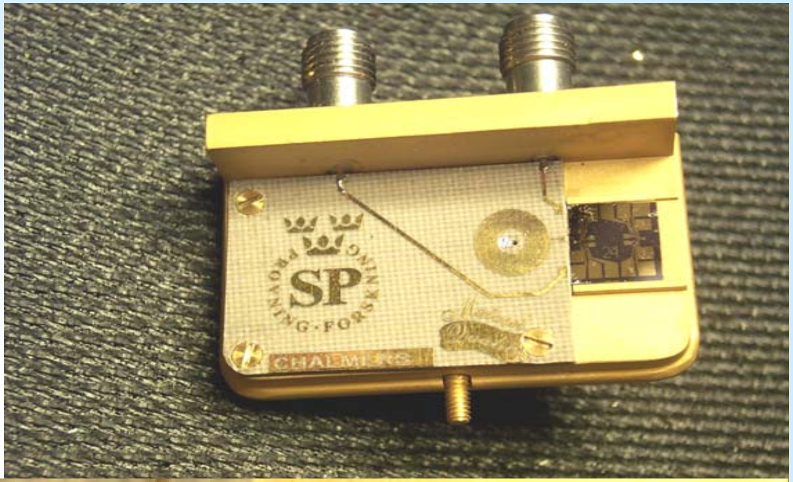
Inductance can be changed by changing the distance to the ground plane with a tuning screw

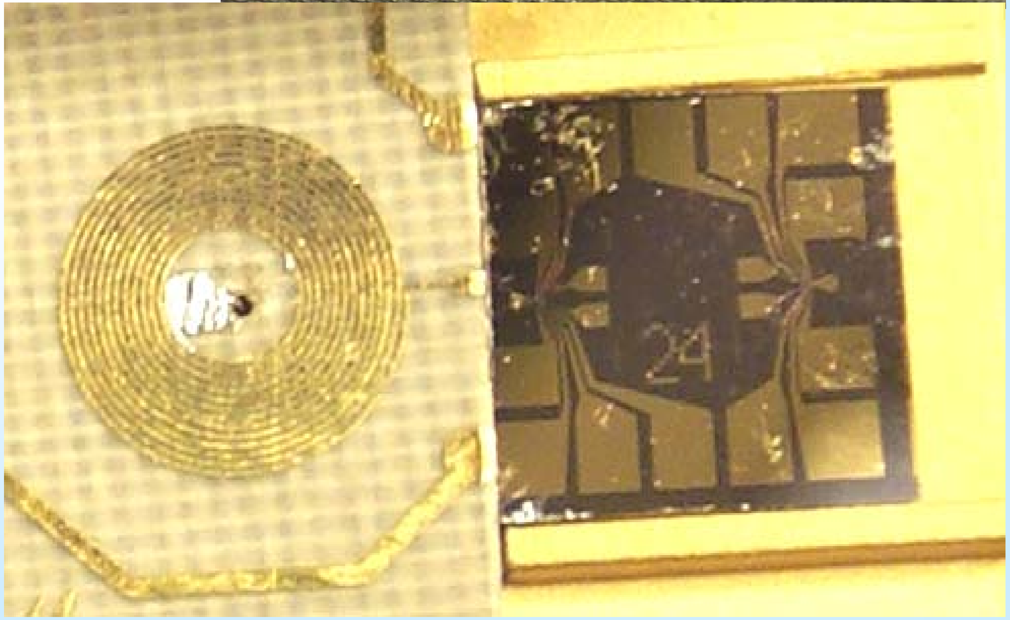
Inductor can be made Superconducting to minimize losses

Tank circuit : L≈400nH, C_{pad}≈300fF

Shot noise from the SET, I=1µA







Improving sensitivity by adding a SQUID amplifier

Cold HEMT amplifiers has $T_N \approx 2.5$ K

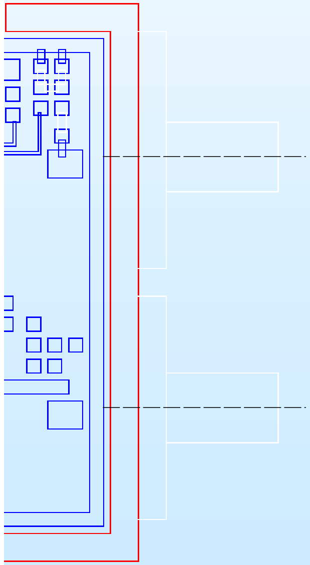
SQUID amplifier has $T_N \approx 50$ mK

Collaboration with Berkeley

M. Mück, J.B. Kycia, and J. Clarke
Appl. Phys. Lett., 78, 967 (2001)

A transmission RF-SET would then be better

T. Fujisawa and Y. Hirayama
Appl. Phys. Lett., 77, 543 (2000)



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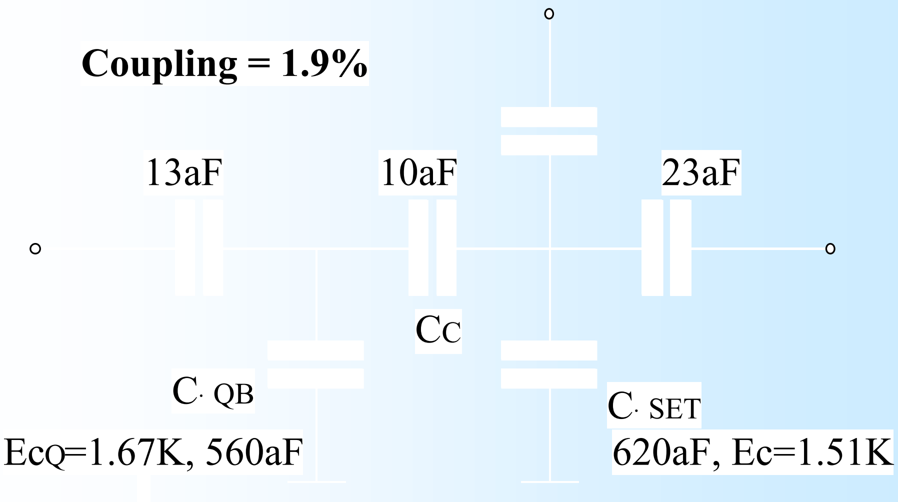
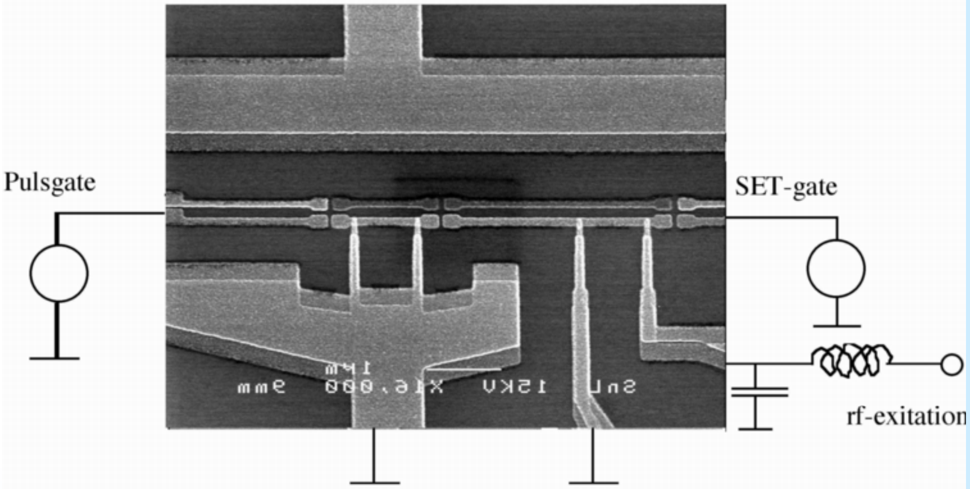
Qubit measurements

Circuit parameters

$R_{SET} \approx 45 k\Omega$
$E_{CSET} \approx 1.51K$
$E_{CBOX} \approx 1.65K$
$E_J \approx 0.6K$
Box to SET coupling=1.9%
B-field parallel to substrate
$f_{carrier} = 450$ MHz
RF-amplitude≈-100dBm
Staircase sweep frequency =141Hz





The Coulomb blockade staircase, normal state

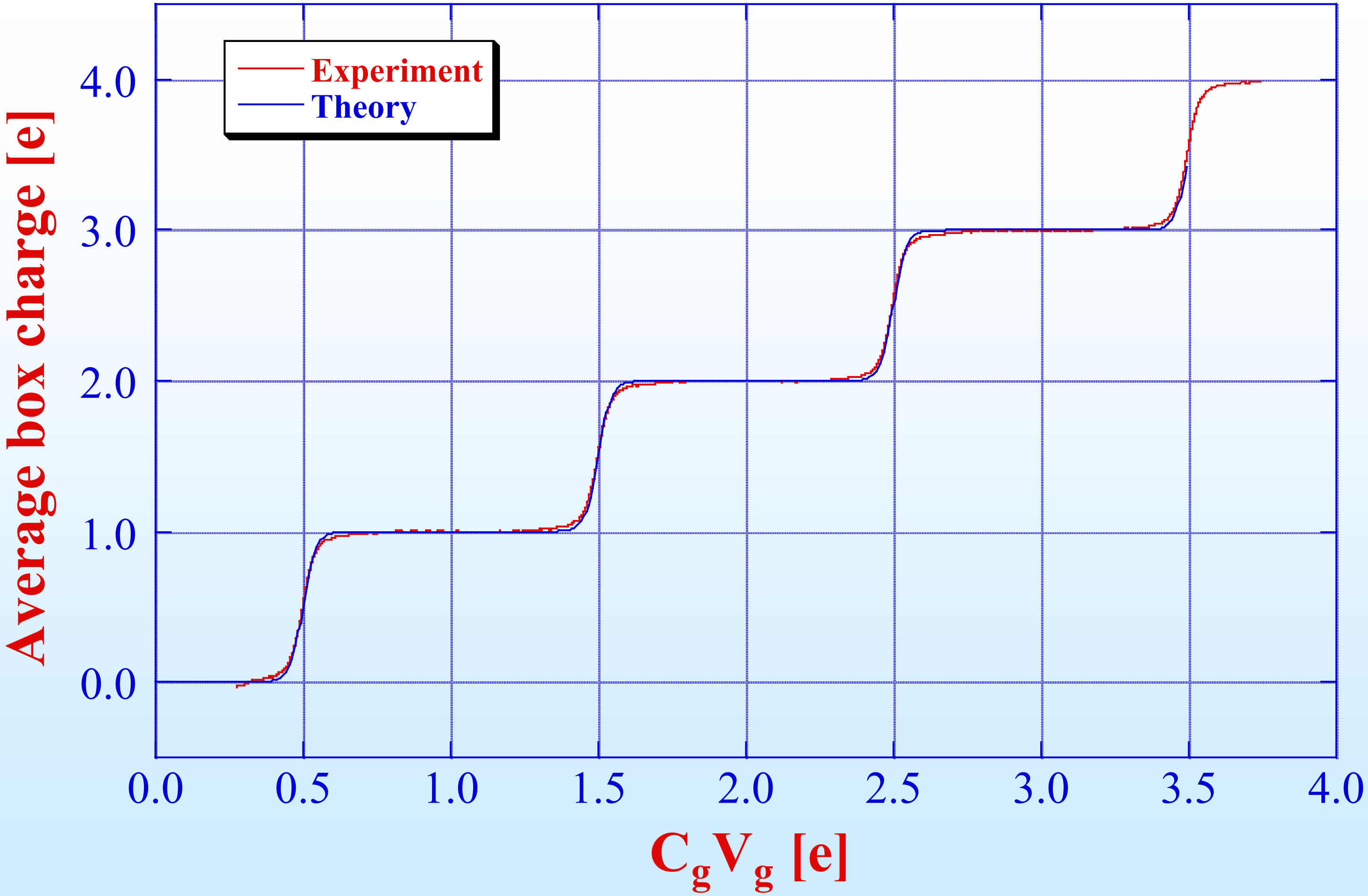


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Fig. 10

The Coulomb blockade staircase, comparing the normal and the superconducting state

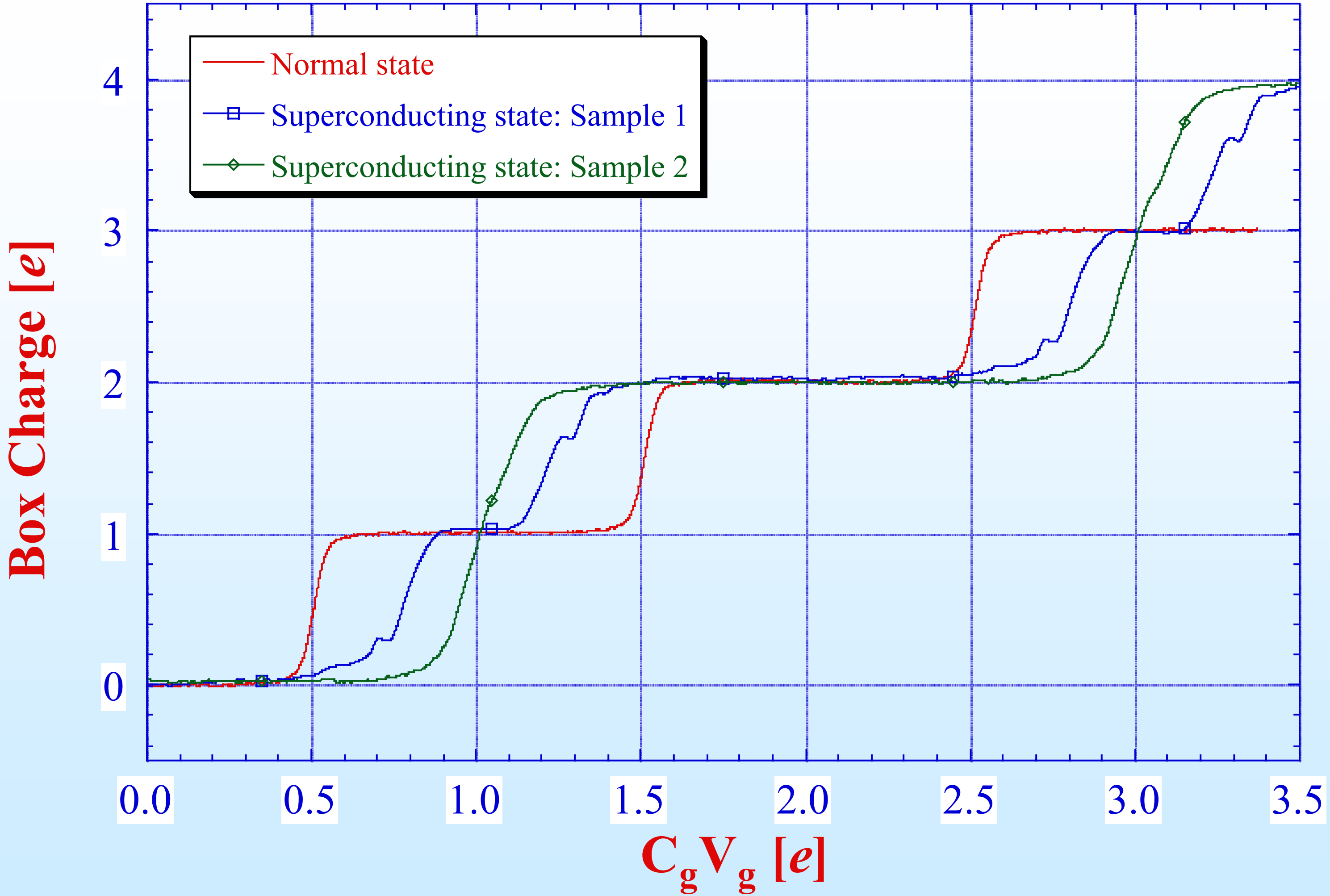

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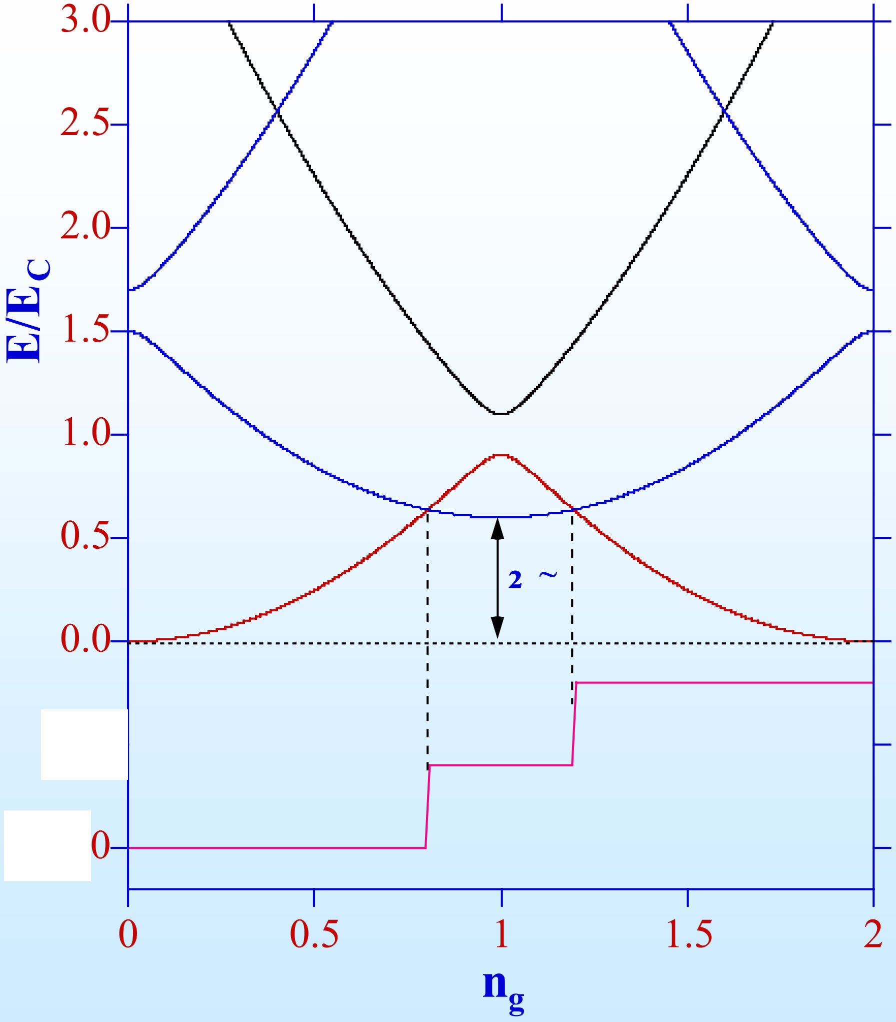
Fig. 11

What would you expect in the superconducting state



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

$\Delta_0 \approx 2.4$K for Al

$\tilde{\Delta} = (L-S)/(L+S)$

Lafarge et al. Nature (93)

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Fig. 12

Long Step versus Short Step

Magnetic field dependence of the short step

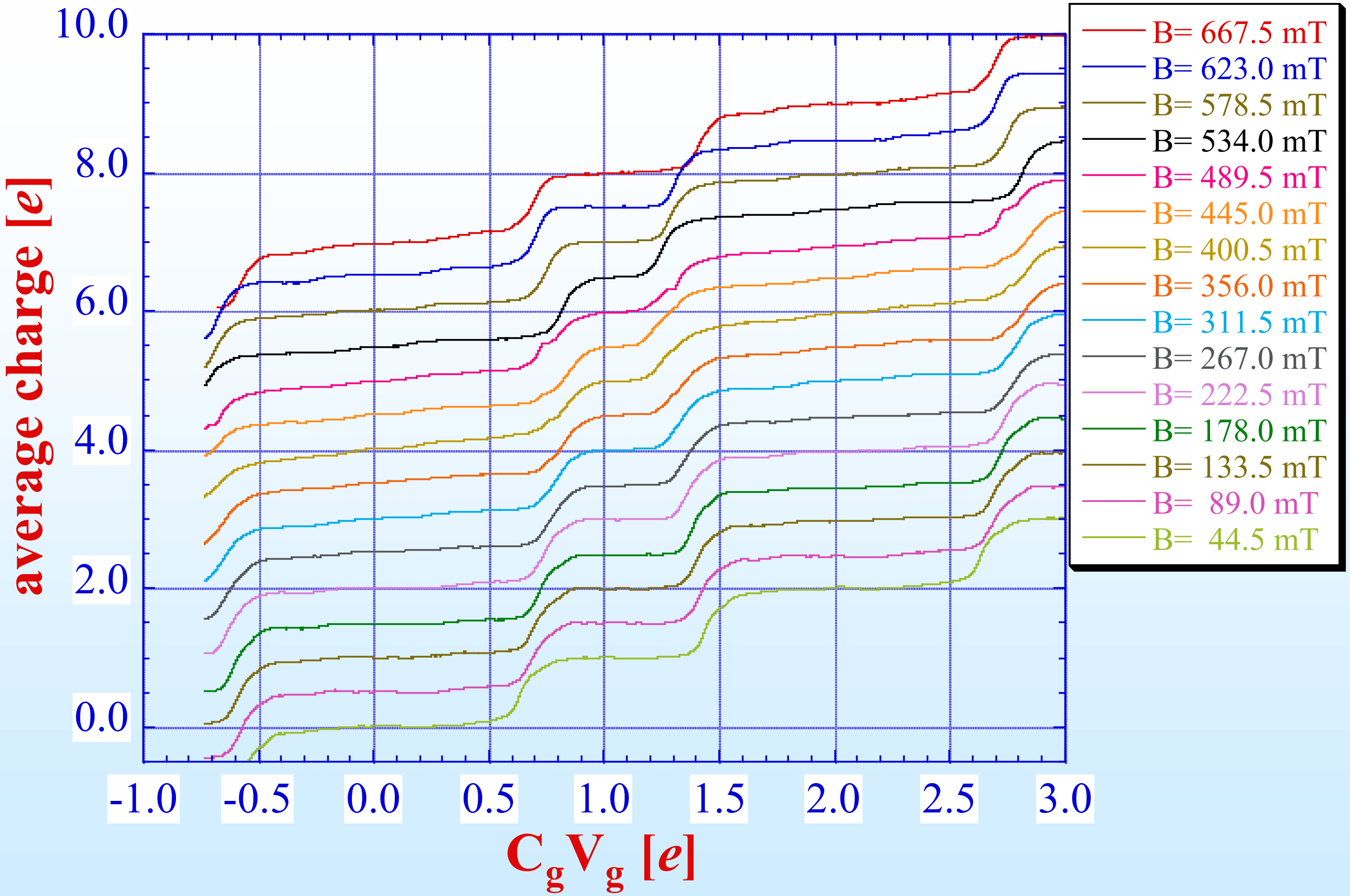

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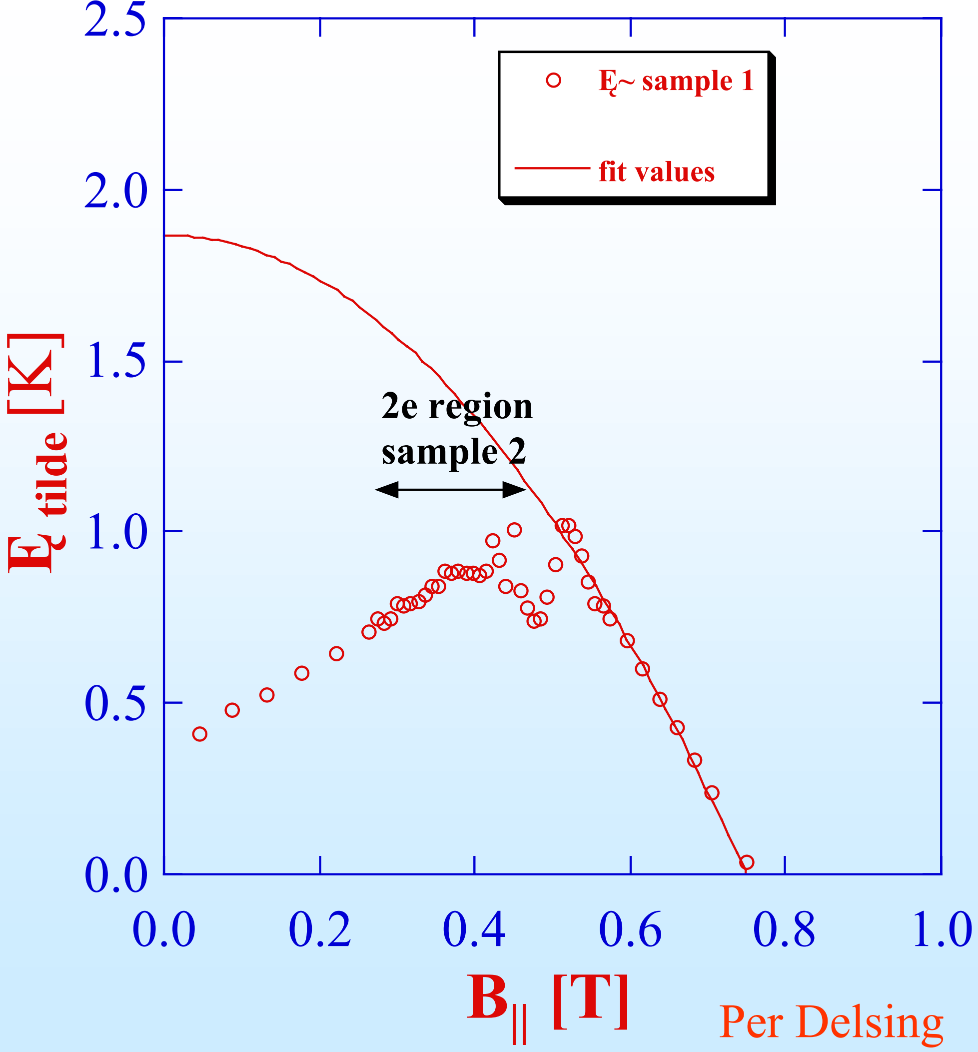
Fig. 14

Extracting $\tilde{\Delta}(B)$:

The odd even energy difference



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

$\Delta_0 \approx 2.4$K for Al

$\tilde{\Delta} = (L-S)/(L+S)$

Lafarge et al. Nature (93)

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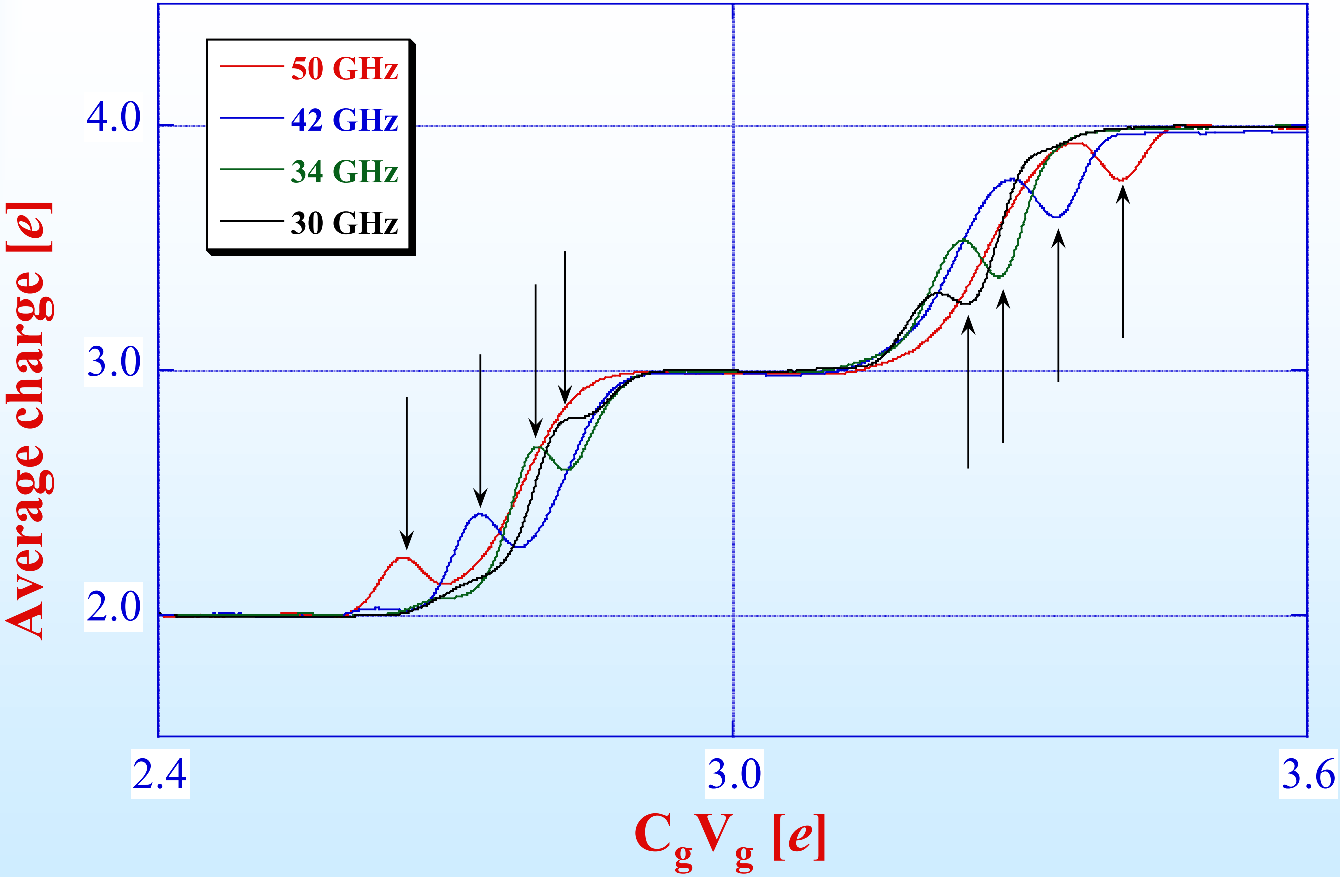
Spectroscopy

Microwave irradiation of the Cooper-pair box Frequency dependence



Limited frequency range

25-50 GHz

Two photon peaks

=> > 50 GHz

(Averaging causes broad peaks)

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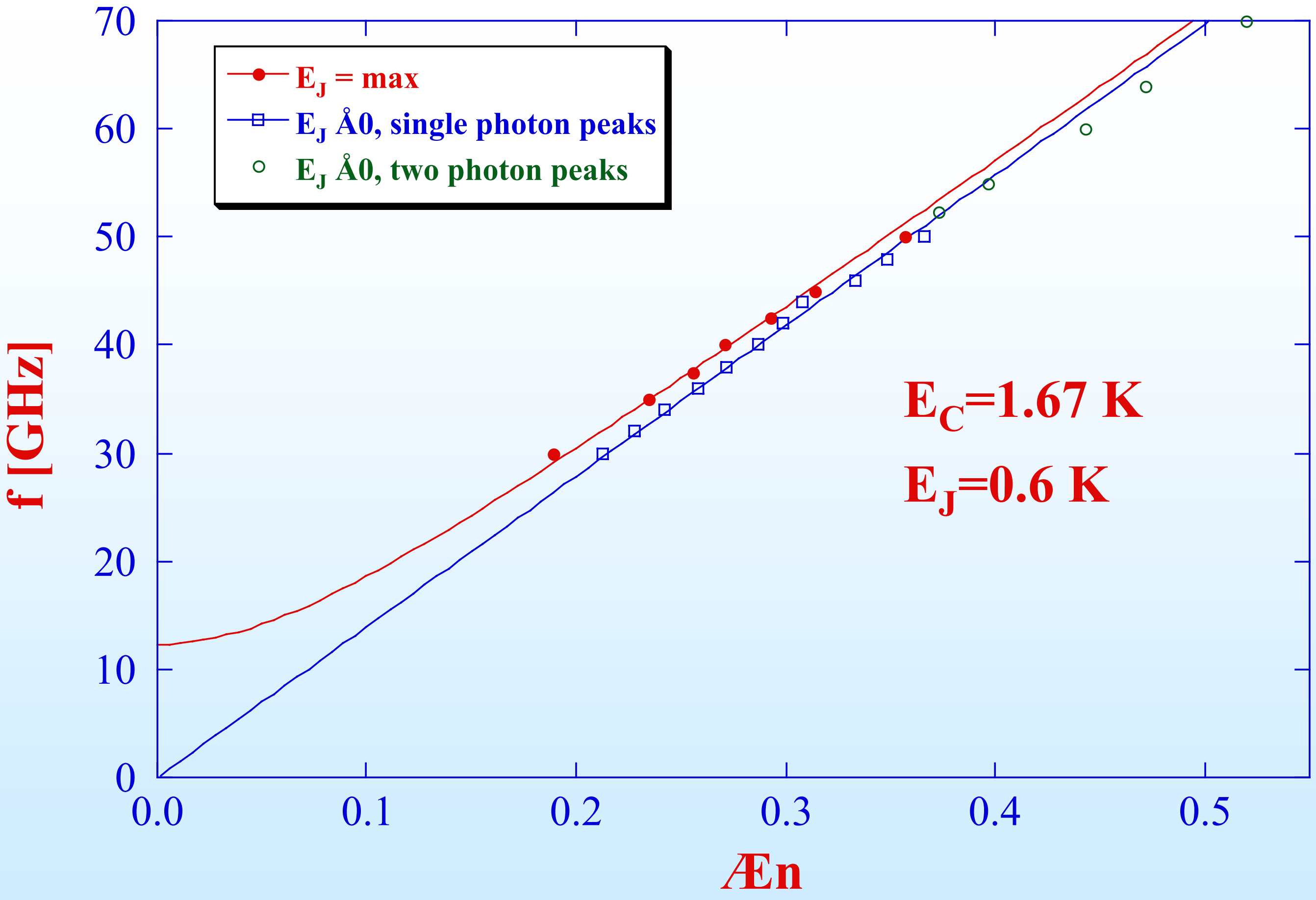
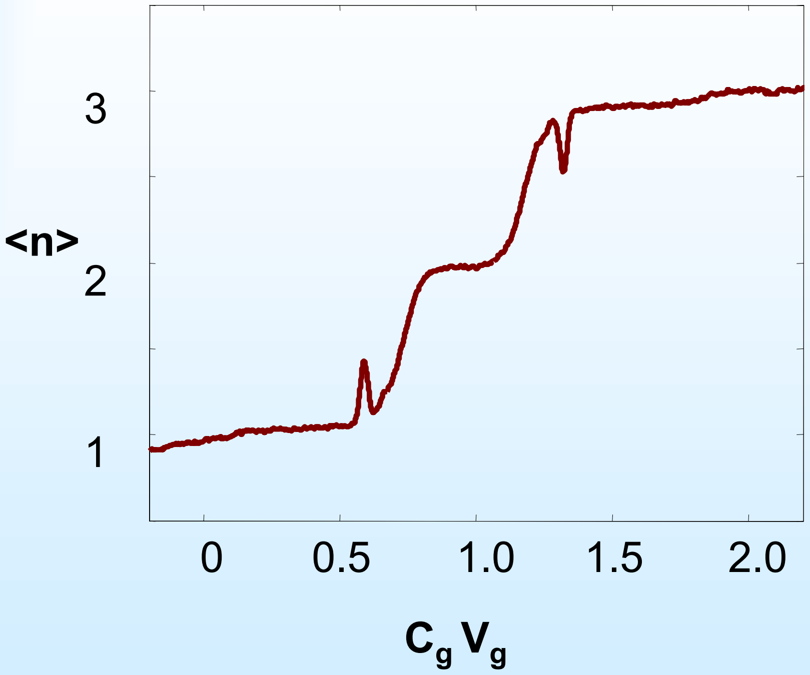
Energy levels extracted from spectroscopy

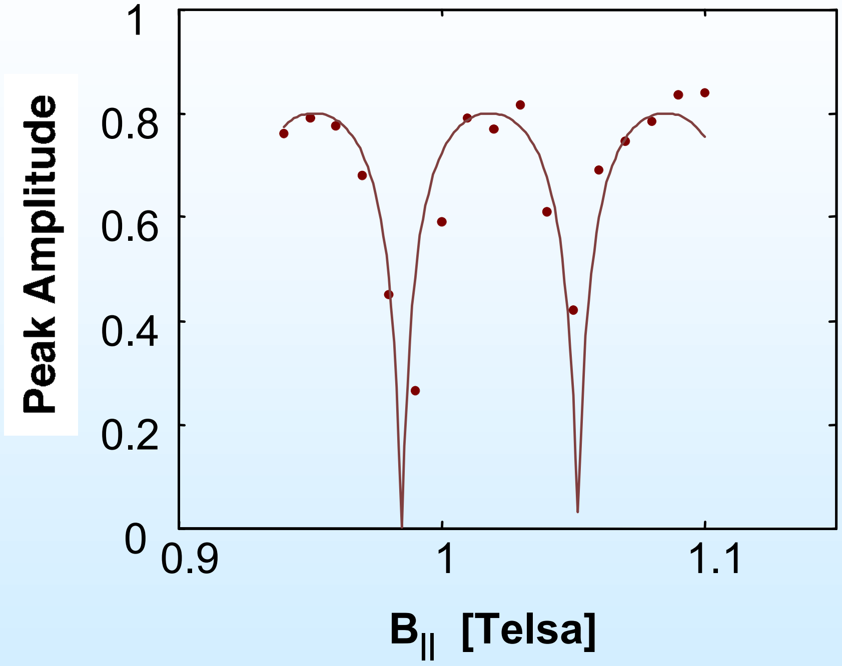


Spectroscopy
B-field dependence

Irradiation by 50 GHz μ-waves

Modulation of E_j with $B_{||}$





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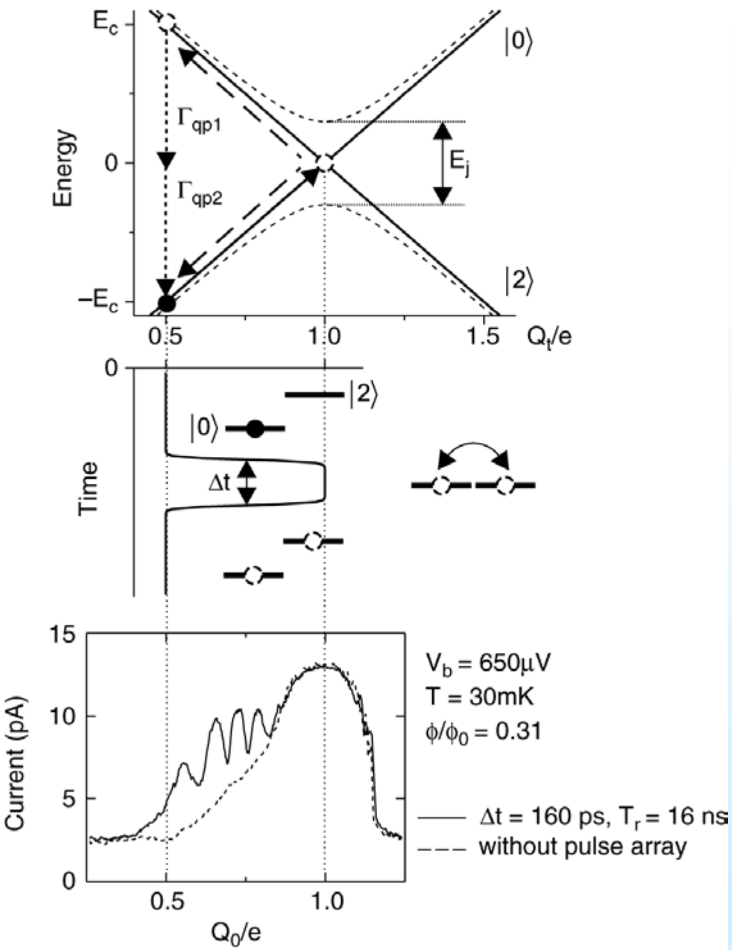
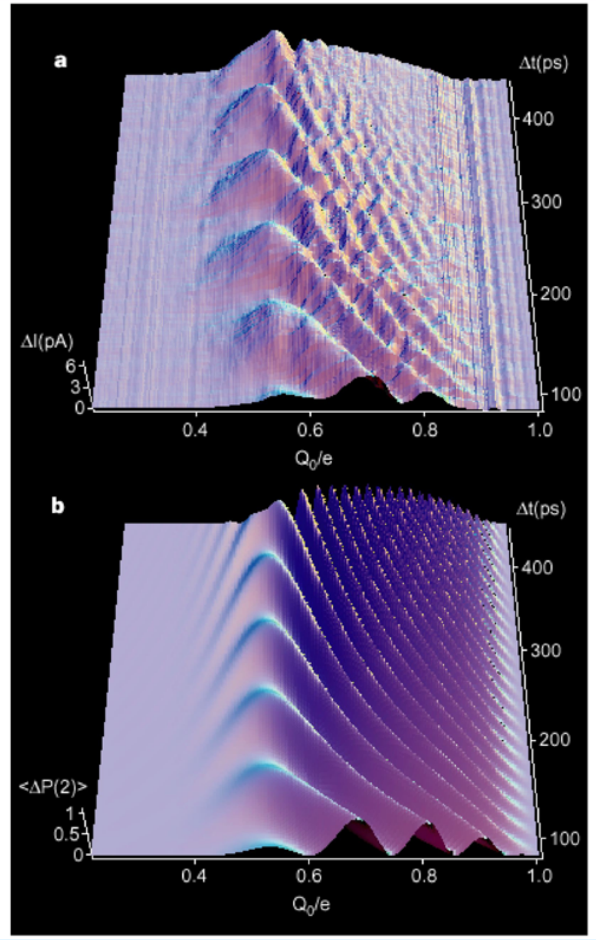
Coherent oscillations

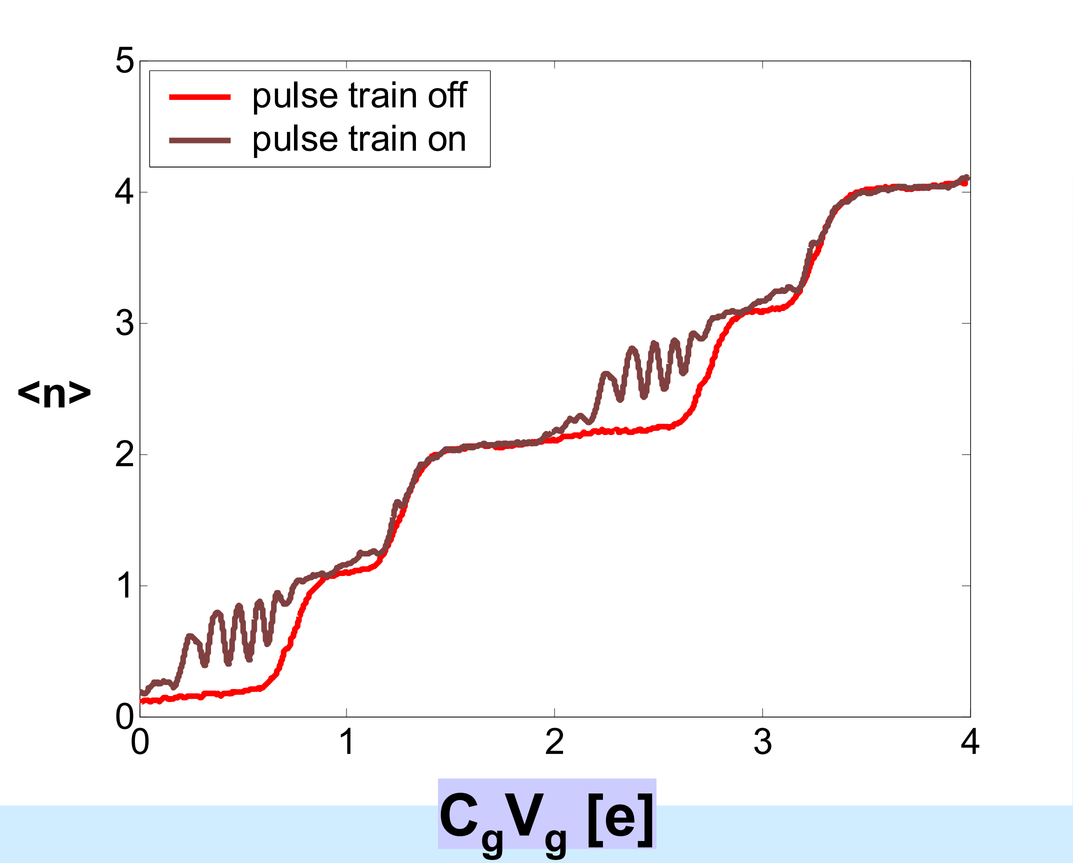
Nakamura, Pashkin and Tsai (1999)

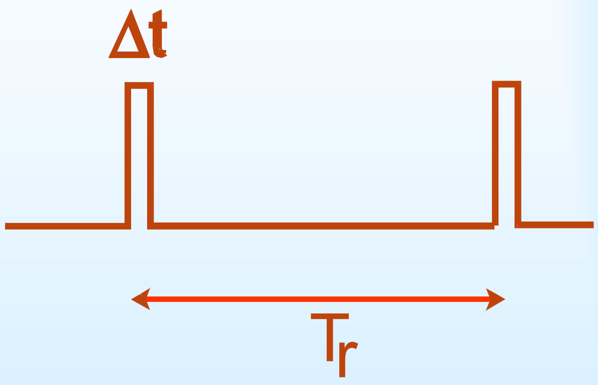




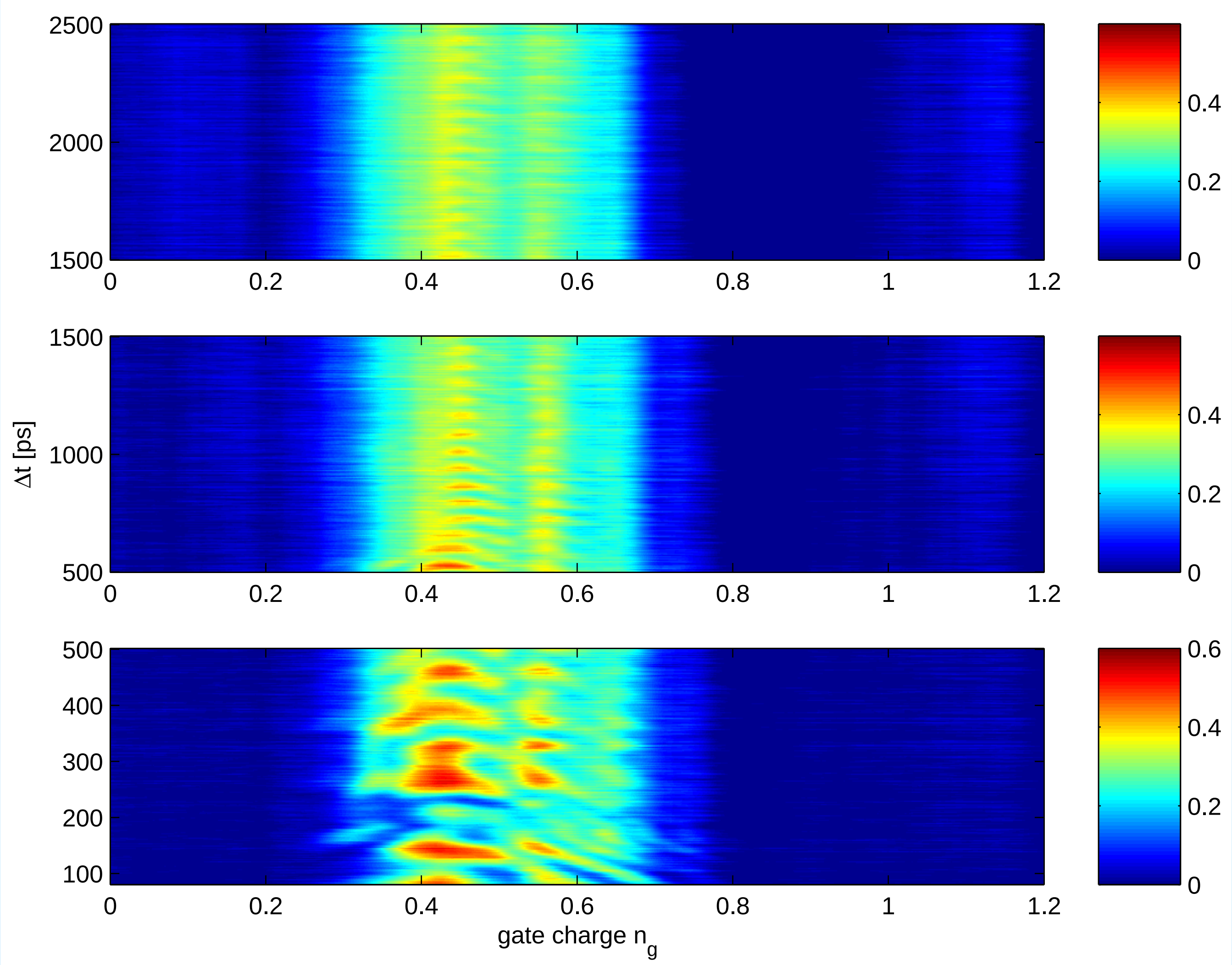
Nakamura et al., Nature (99)

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





Coherent Oscillations

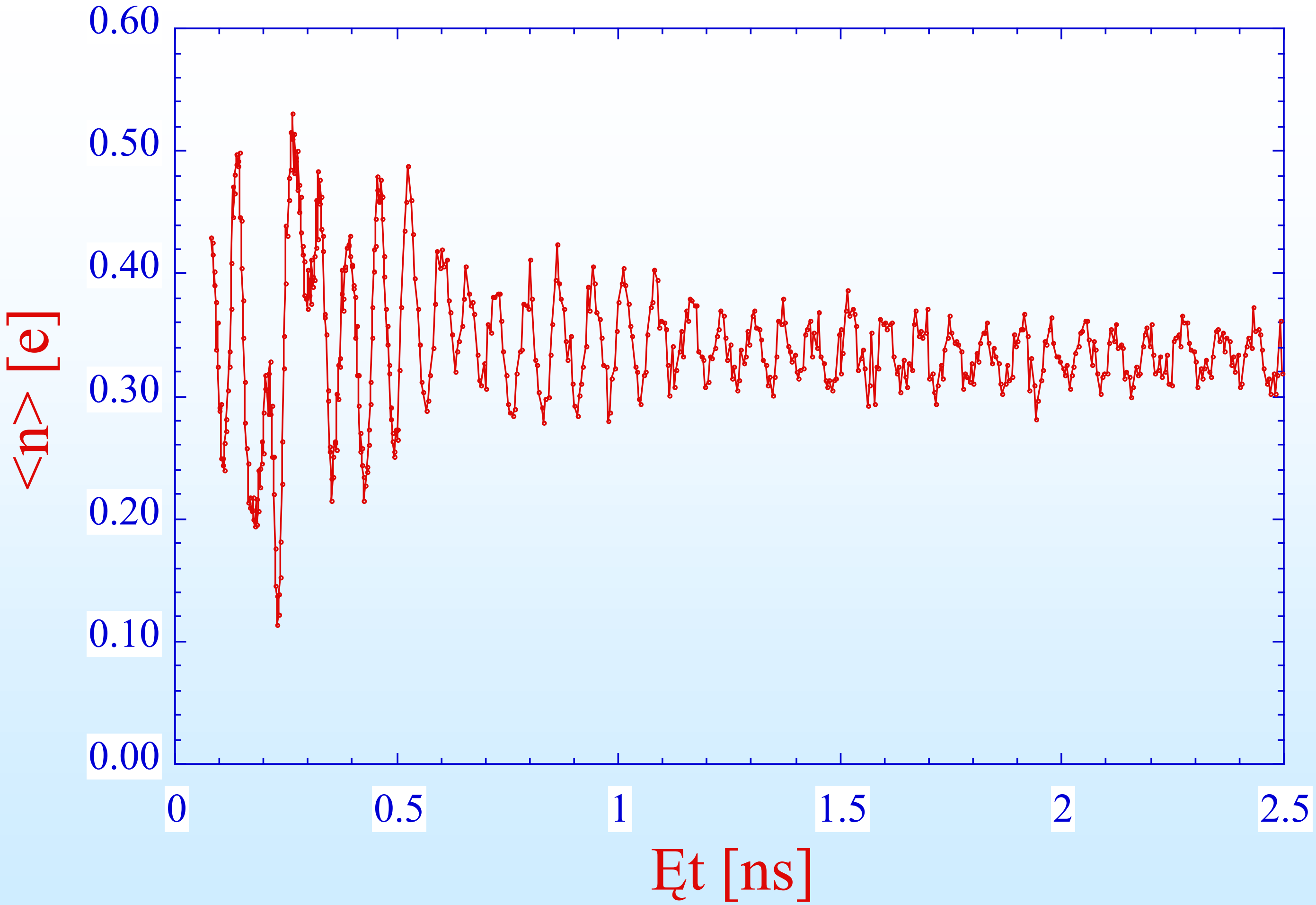


Period=70 ps agrees well with Ej

Color represents difference between pulsed staircase and ”unpulsed” staircase

Fig. 23

Signal versus pulse duration



Possible sources of decoherence

- Continuous measurement of course decoheres the system, pulsed measurements should improve the situation.
- Non-equilibrium quasi particles are obviously present in the system.
- Non-perfect dc pulses: the pulse is not perfectly square and thus the system is not exactly at the degeneracy point during the evolution. Therefore background charge noise couples stronger to the system

Summary

- **RF-SET optimized, ∂Q=3.2 μe/√Hz achieved**
- **Fabrication of integrated Qubit and RF-SET**
- **Characterization of Cooper-pair box**
  - Demonstrated continuous (and pulsed) read-out of box charge.
  - Observation of microwave induced transitions between |0> and |2>
  - Determination of E_C and E_J from spectroscopy.
  - Coherent Oscillations observed (reproduced Nakamura's results with RF-SET read-out).