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JOINT ICTP-INFM SCHOOL/WORKSHOP ON "ENTANGLEMENT AT THE NANOSCALE"

(28 October – 8 November 2002)

"A Josephson charge qubit using radio-frequency single-electron-transistor readout"

presented by:

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A Josephson Charge Qubit using Radio-Frequency Single-Electron-Transistor Readout

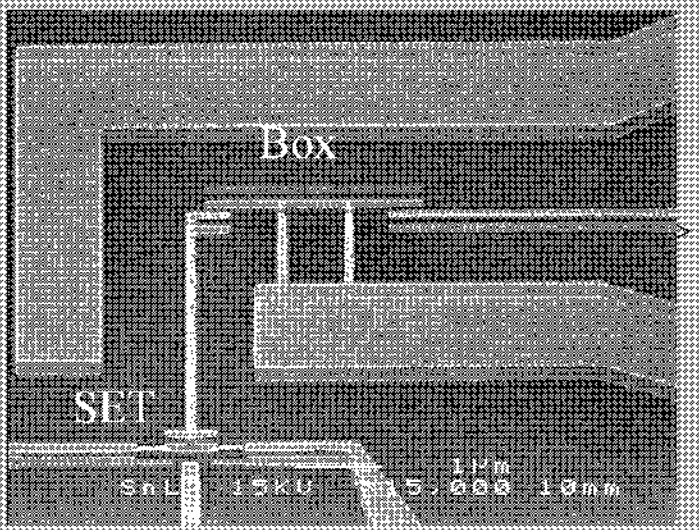
Tim Duty

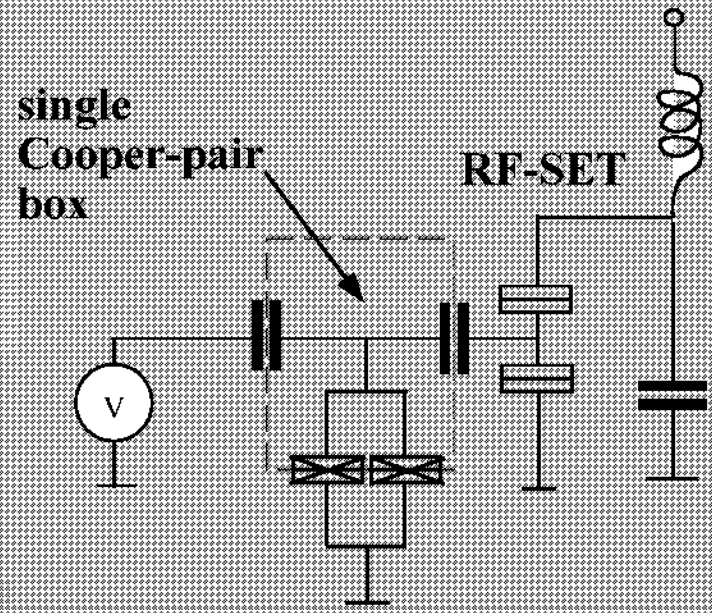
1. **The single-Cooper-pair box and the single-electron transistor**
2. **Measuring the box: quasi-particle states and back-action**
3. **Spectroscopy**
4. **Coherent charge oscillations**
5. **Measuring T_1**
6. **Pulsed Measurements**

D. Gunnarsson
K. Bladh
P. Delsing

Yale:
R. Schoelkopf
K. Lehnert

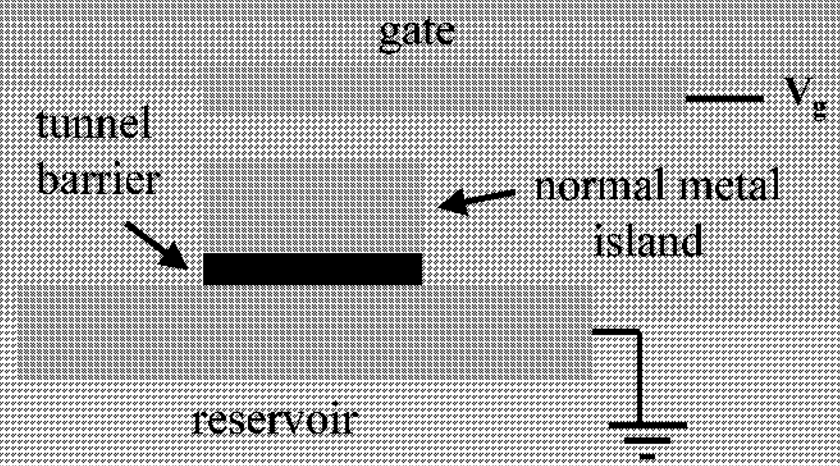
A Single Cooper-pair Box Qubit
Integrated with an RF-SET Read-out system





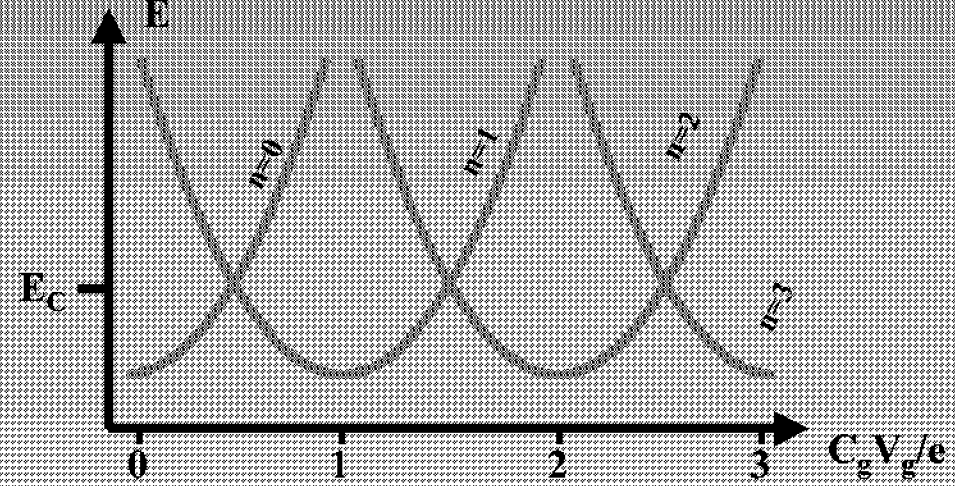
Δ	>>	E_C	>>	$E_J(B)$	>>	T
2.4K		1.7K		0.7-0.05K		20mK

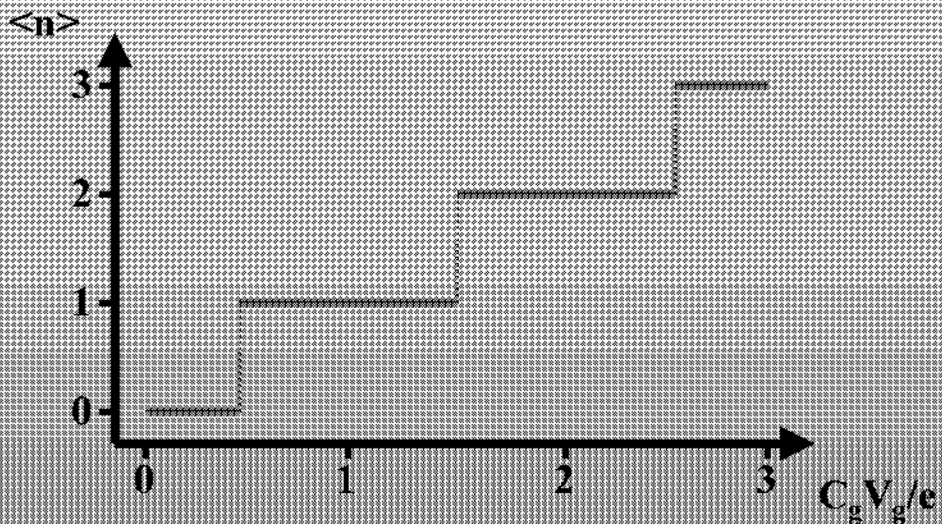
The Single-Electron Box



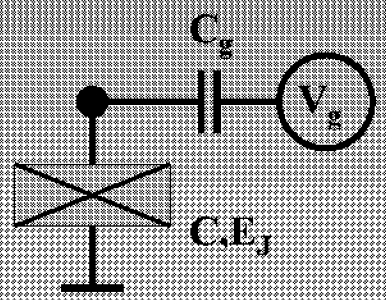
$$E_C = \frac{e^2}{2C_\Sigma}$$

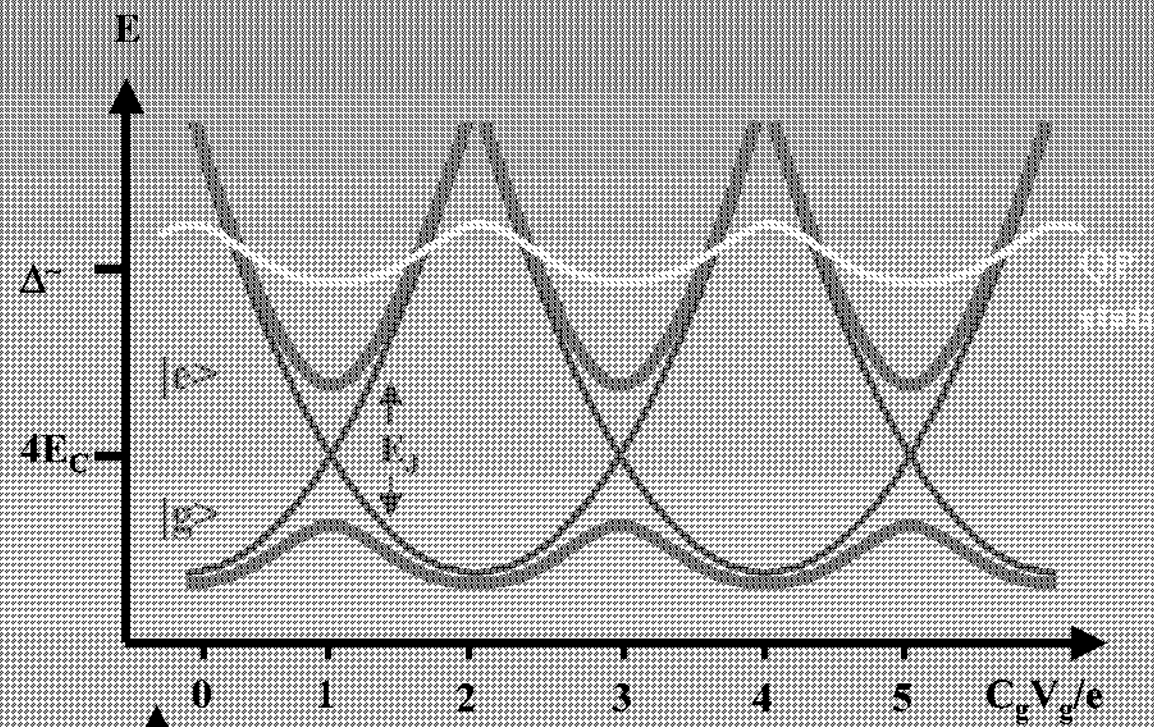
$$k_B T < E_C$$



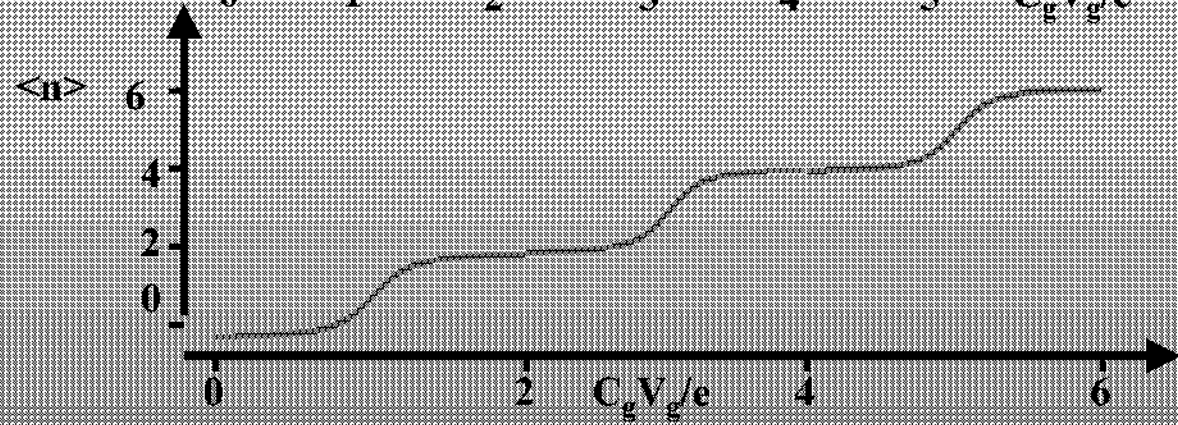


The Single-Cooper-Pair Box

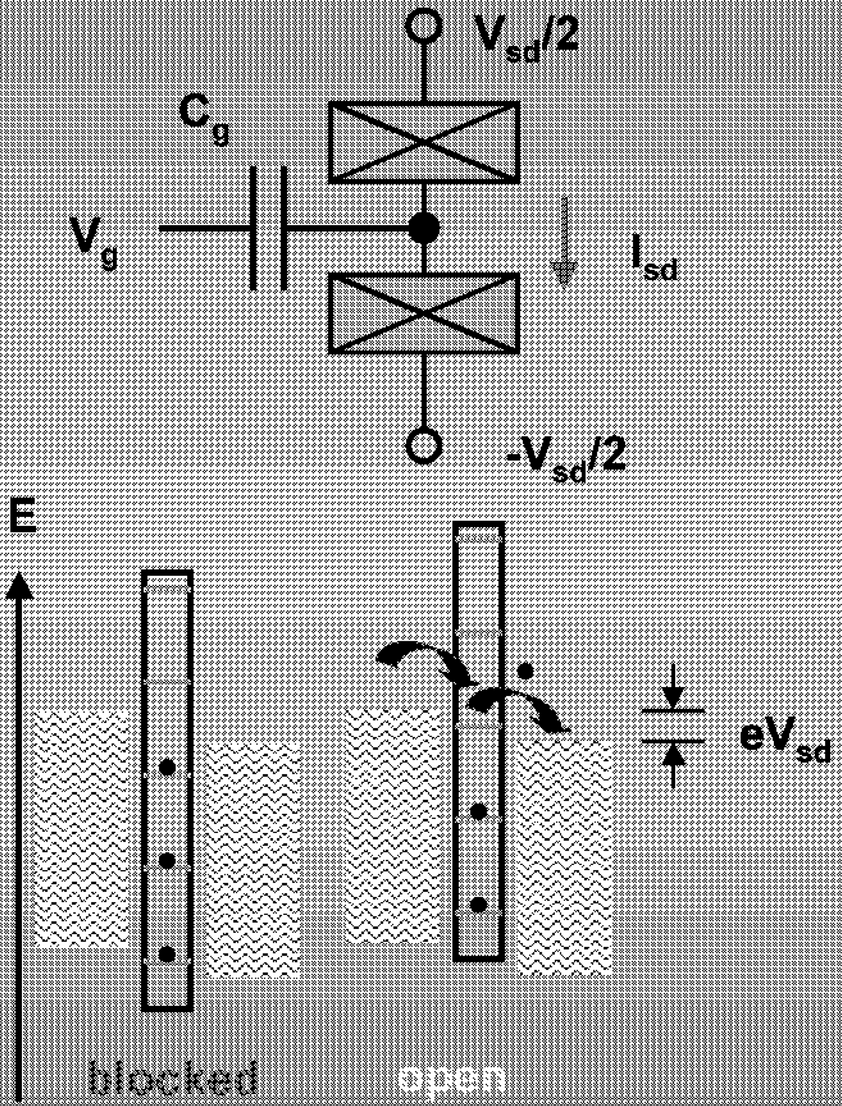


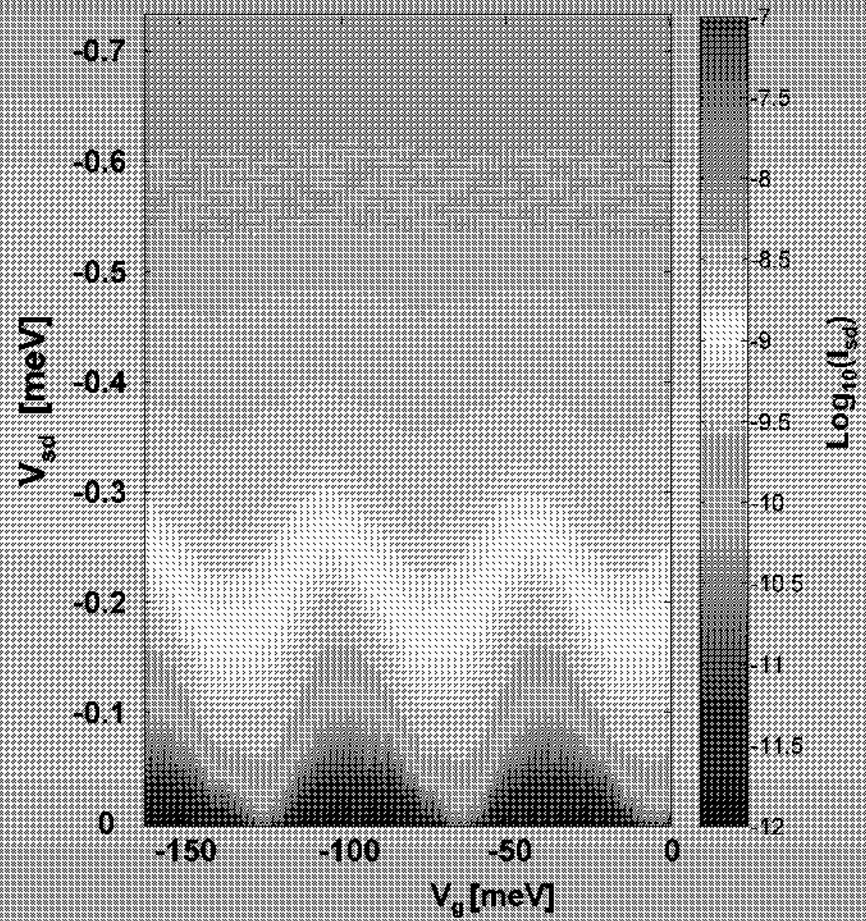


$$k_B T < E_J < E_C < \tilde{\Delta}$$



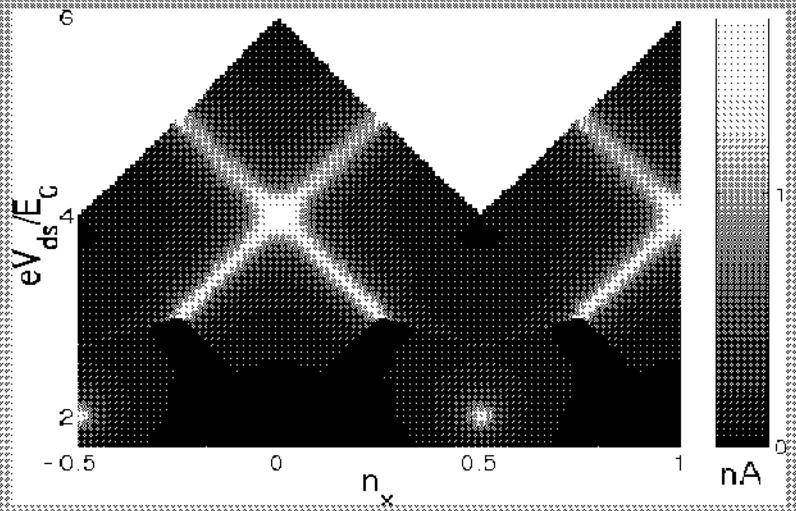
The Single Electron Transistor



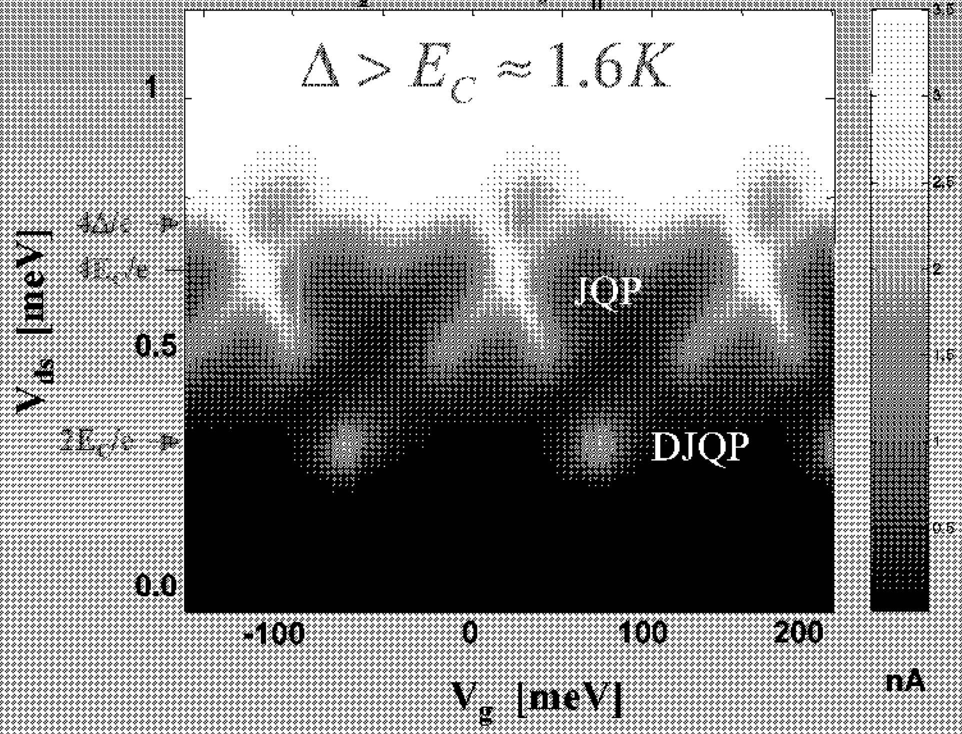


Cooper-Pair-Transistor DC Current

Theory



Experiment, $B_{||}$=0.4T

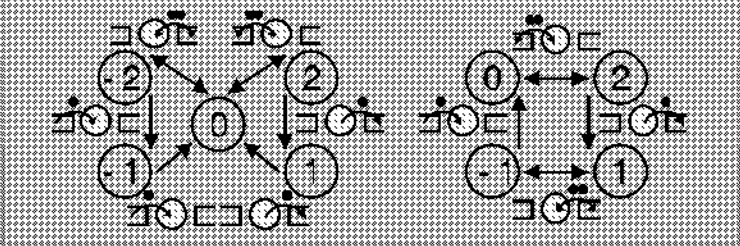


from: Johansson, cond-mat/0210539

Fulton & Dolan (1987)

van den Brink *et. al.* (1991)

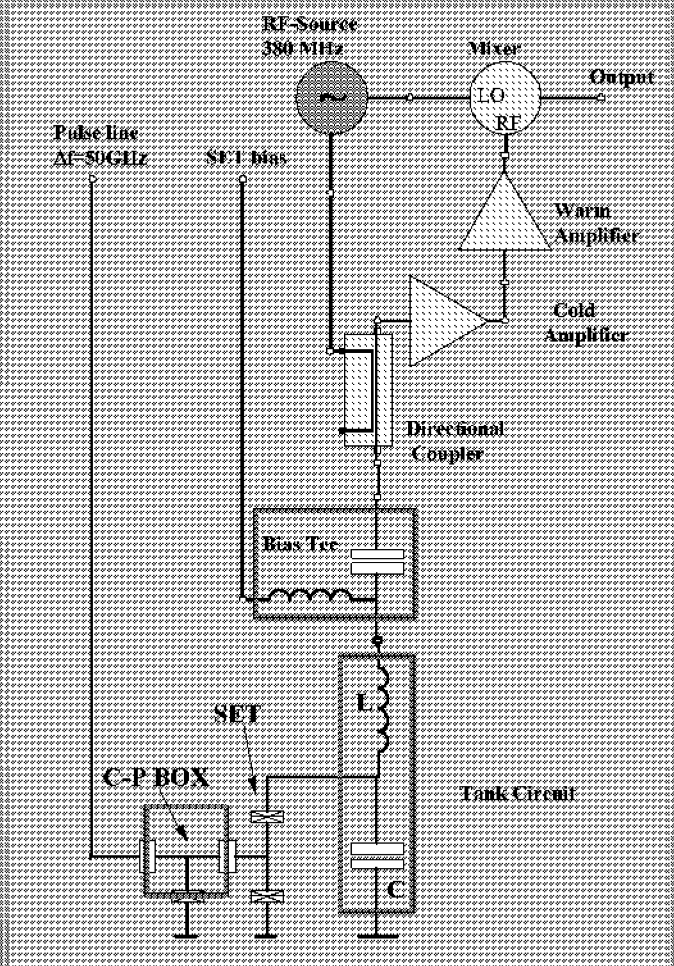
Hadley *et. al.* (1998)



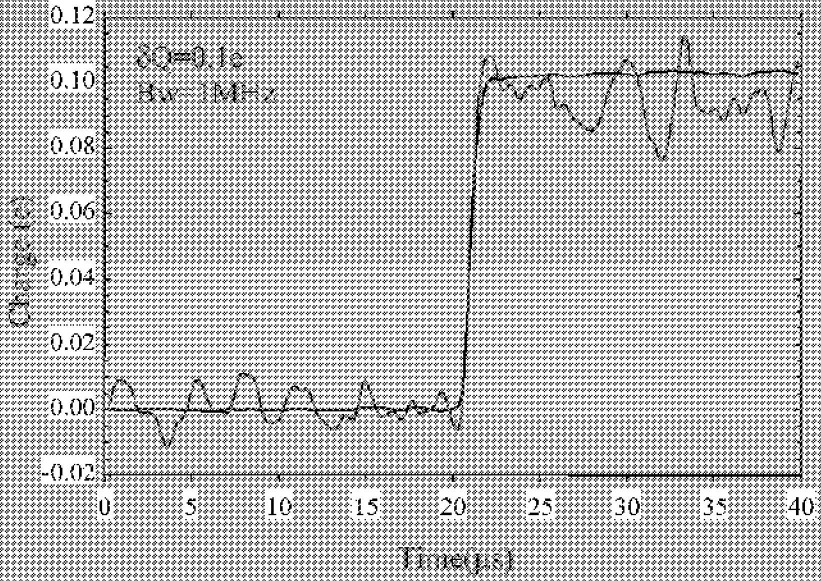
JQP DJQP

The SET as an Electrometer

- Very Sensitive: can detect fractions of an electron charge.
- But it is slow: each junction must be of order of R_Q, leading to a $R_T \sim 100k\Omega$. For typical lead capacitance, 0.1-1nF, this gives a bandwidth of a few kHz---unacceptable for solid-state QC.
- How can one take advantage of the intrinsic bandwidth, due to capacitance of junctions, which can be as high as 10GHz?
- The 'best' solution is to incorporate the SET into a tank circuit and measure damping.



The Radio-Frequency Single Electron Transistor



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

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

Measuring the box

Circuit parameters

$R_{SET} \approx 47k\Omega$

$E_{CSET} \approx 1.51K$

$E_{CBOX} \approx 1.67K$

$E_J \approx 0.7K$

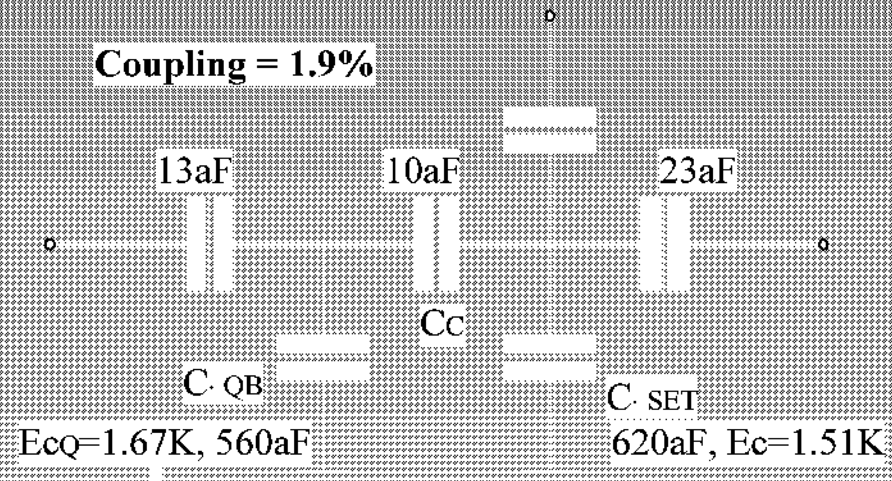
Box to SET coupling = 1.9%

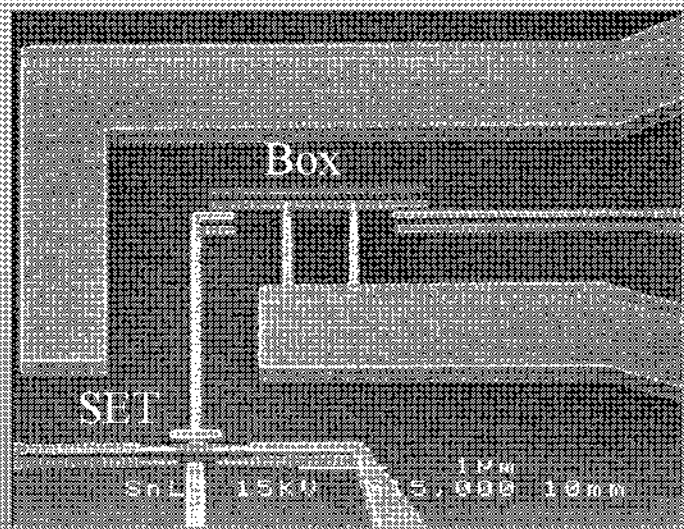
B-field parallel to substrate

$f_{carrier}$ = 380 MHz

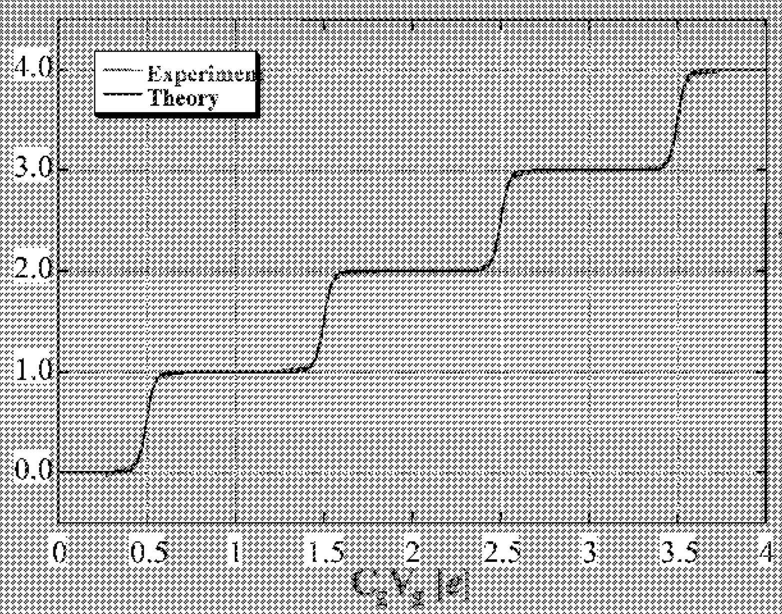
RF-amplitude ≈ -100dBm

Staircase sweep frequency typically 100-300Hz

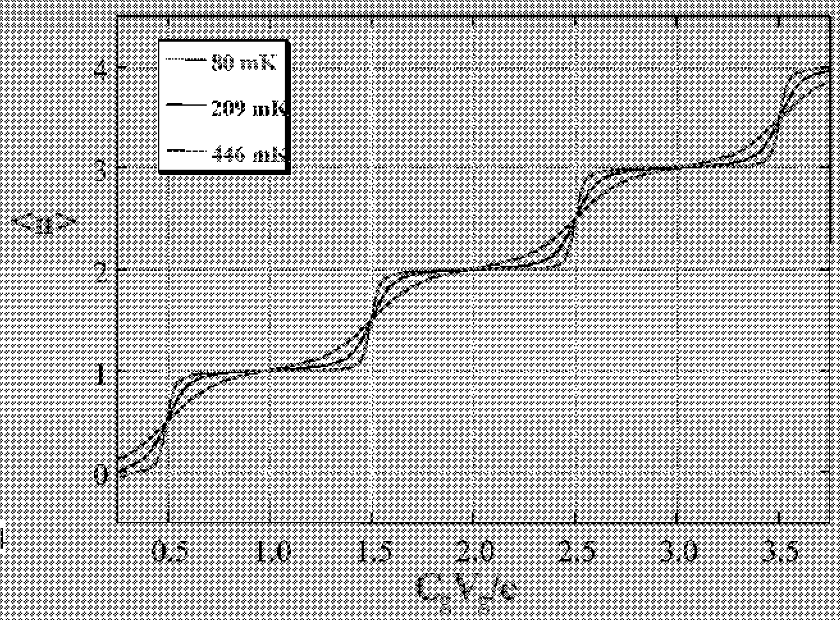




The Coulomb blockade staircase measured in the normal state, $B_{||}$=1.25T

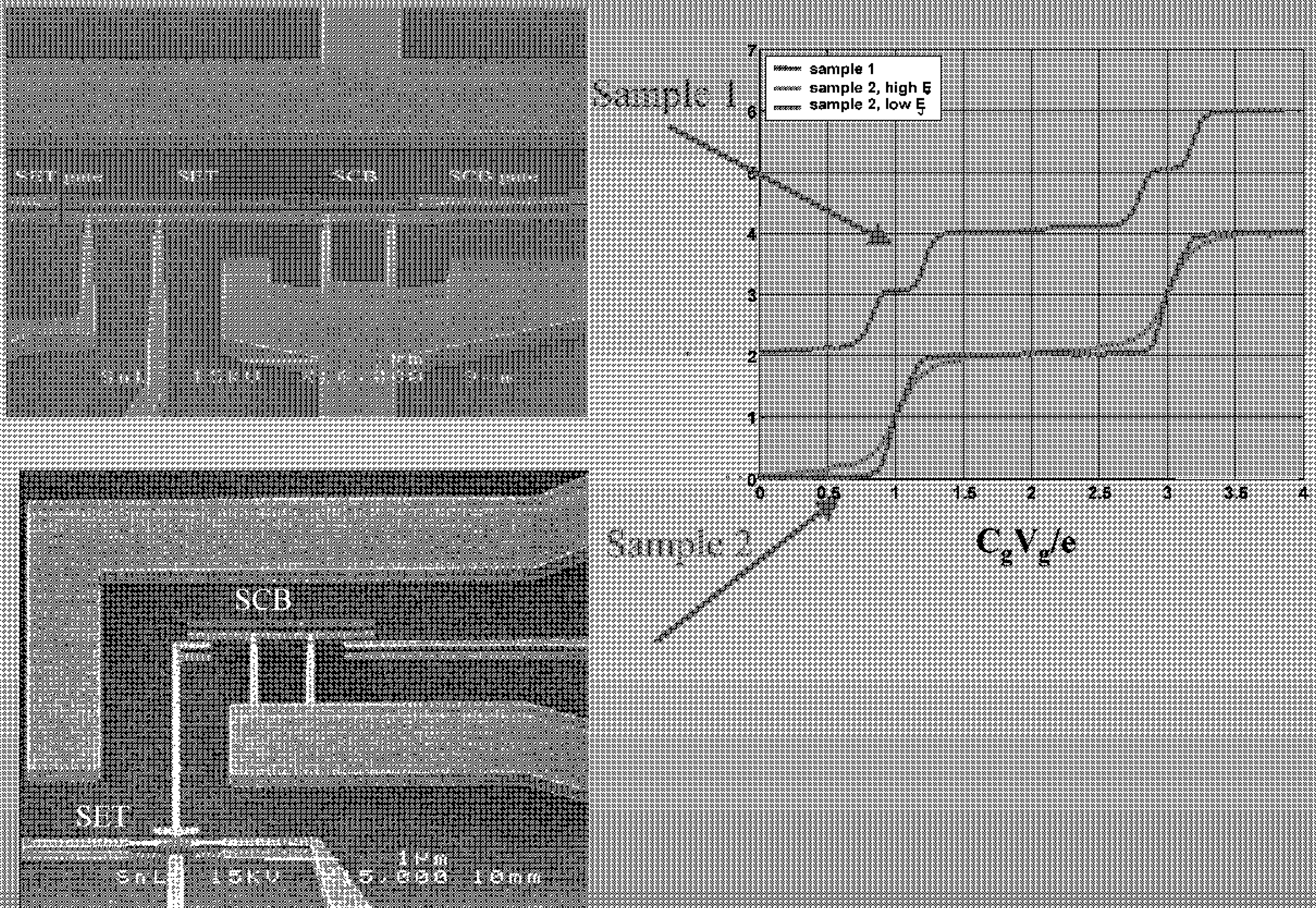


Temperature dependence of the staircase

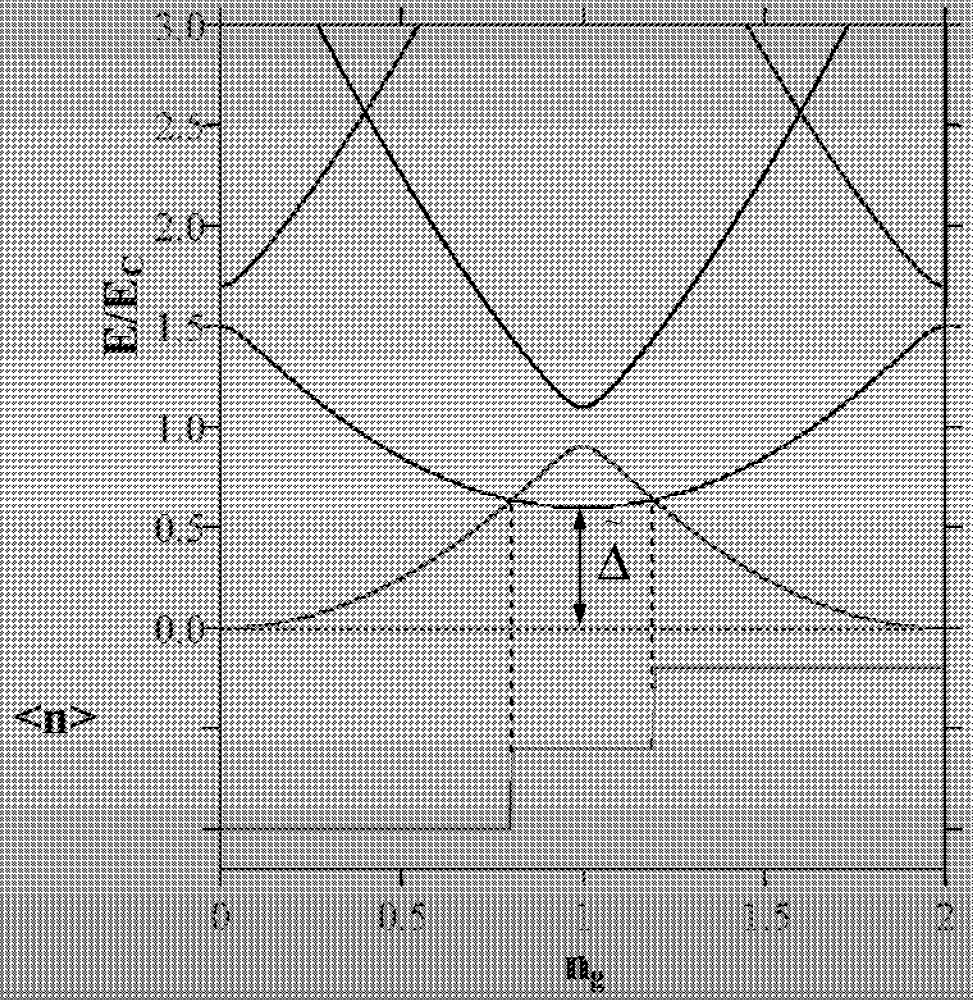


Electron temperature can be estimated from the rounding and slope of the staircase.

Single-Cooper Pair Boxes



What would you expect in the superconducting state with Δ not so large?



$\Delta = \Delta_0 - k_B T \, ln(N)$

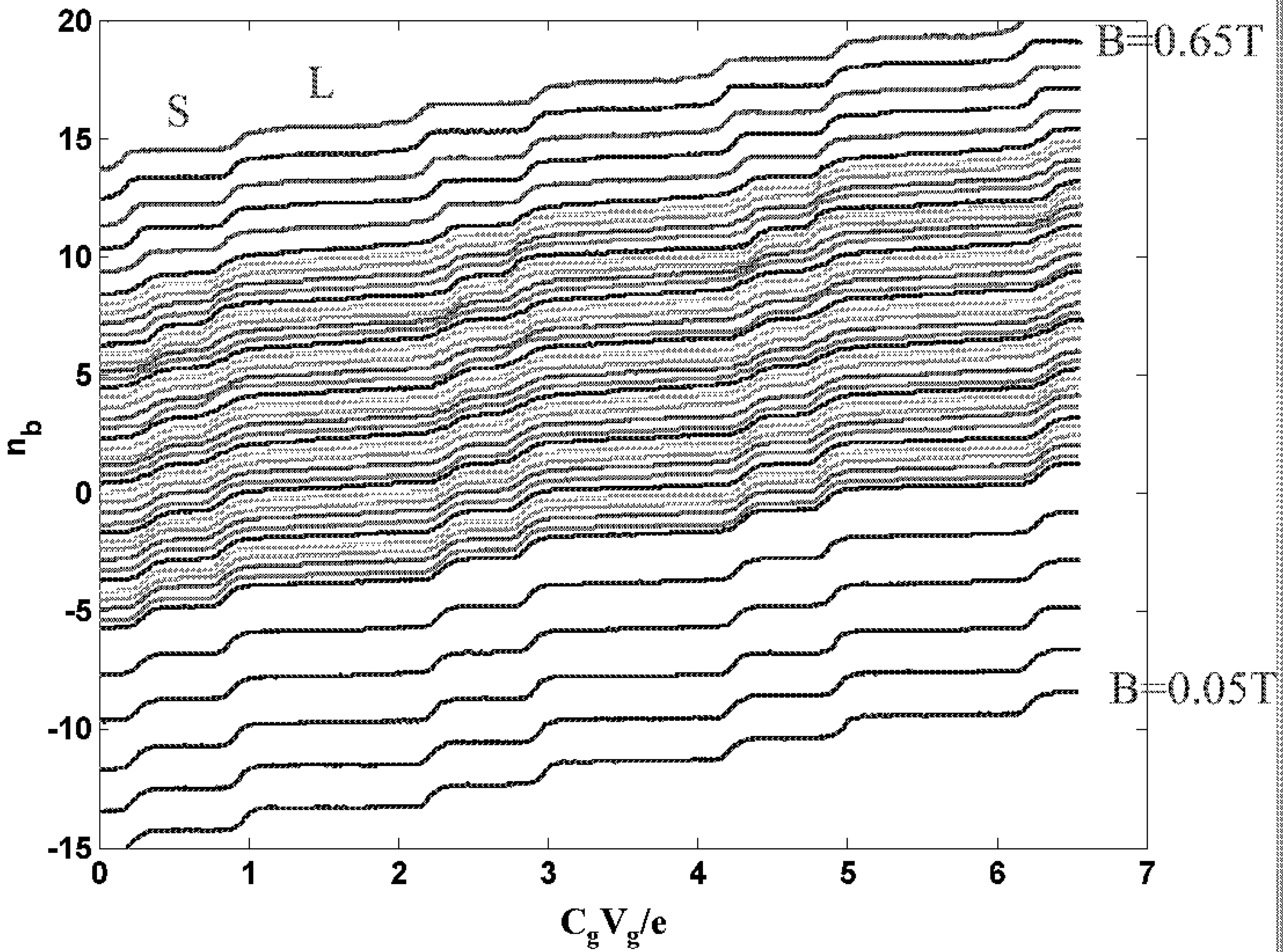
$\Delta_0 = 2.4K$ for Al

$\Delta = (L-S)/(L+S)$

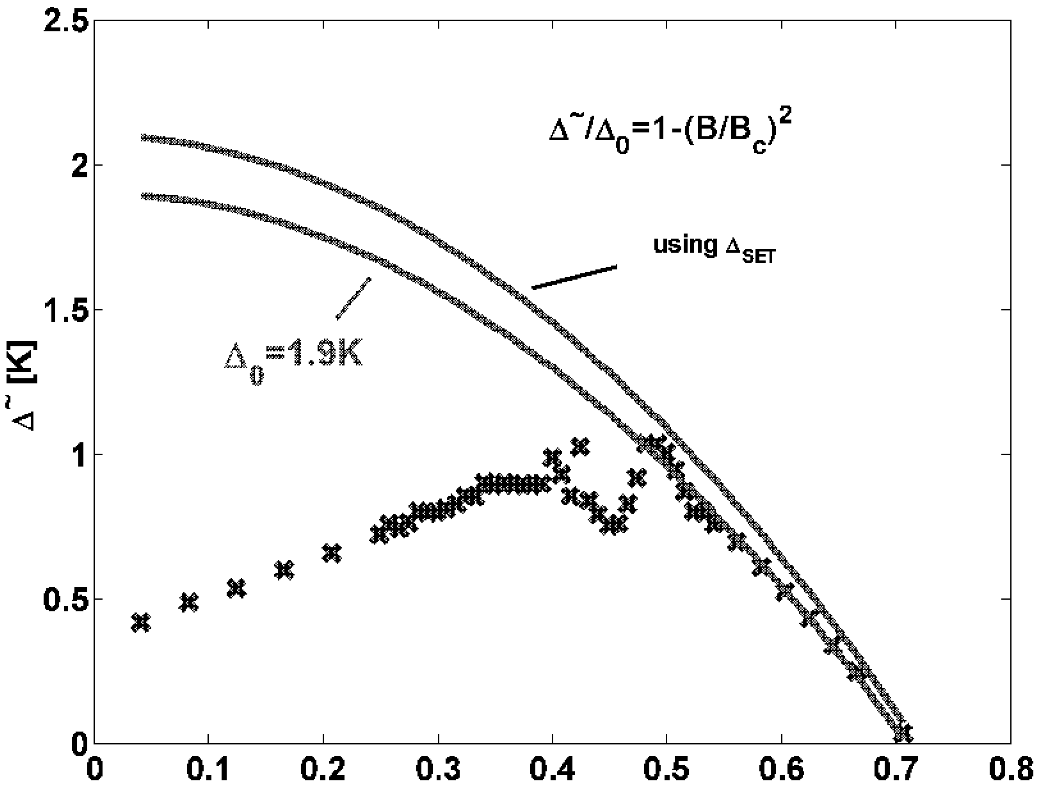
Lafarge et al. Nature (93)

Long Step versus Short Step

Magnetic field dependence of the short step



Extracting $\Delta^{\sim}(B)$



$\Delta^{\sim}=E_c(L-S)/(L+S)$

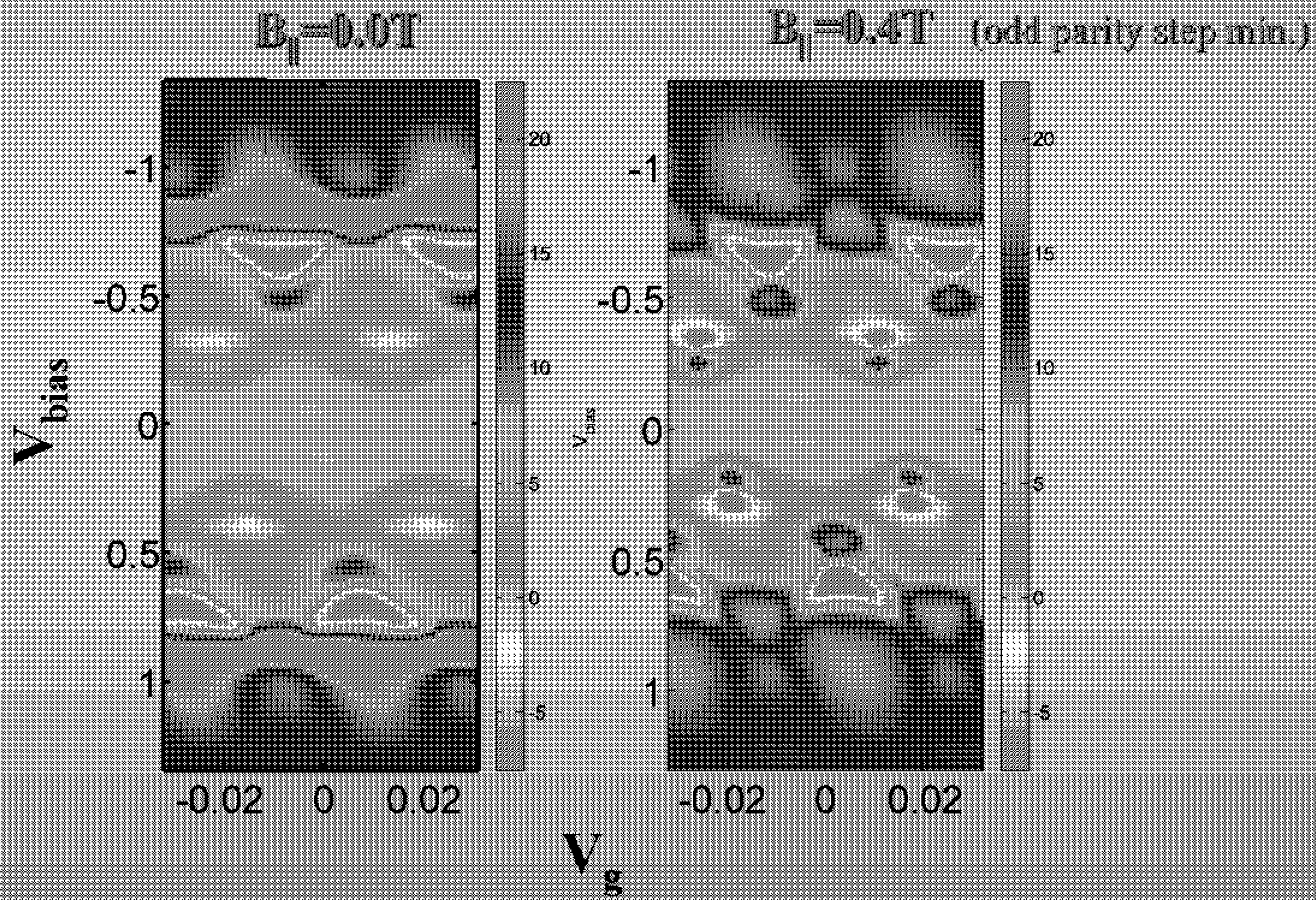
But what is going on for $B_{||}<0.4T$?

'Field-induced gap engineering' creates QP traps in the leads.

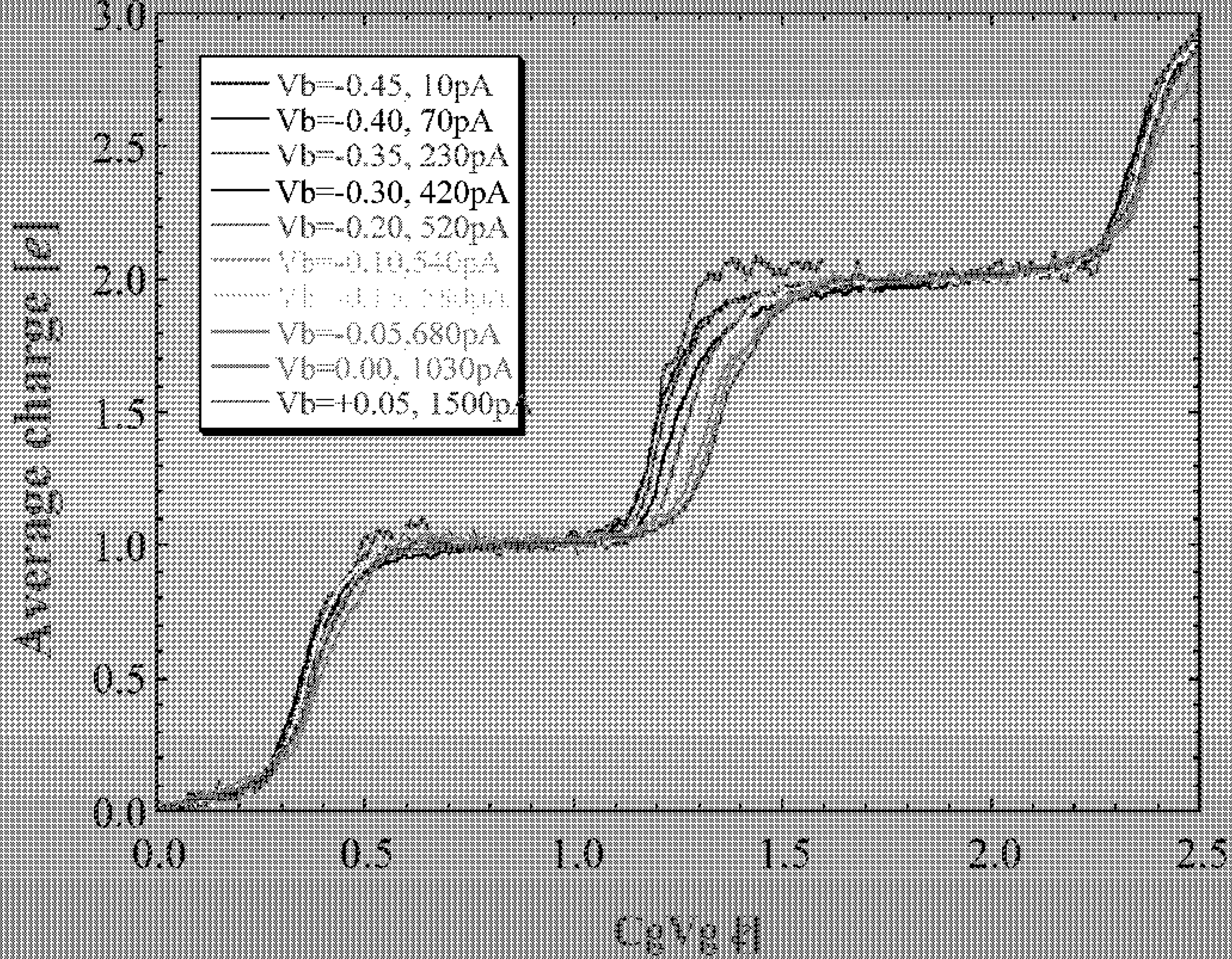
What about BACK ACTION?

How does the SET affect the staircases?

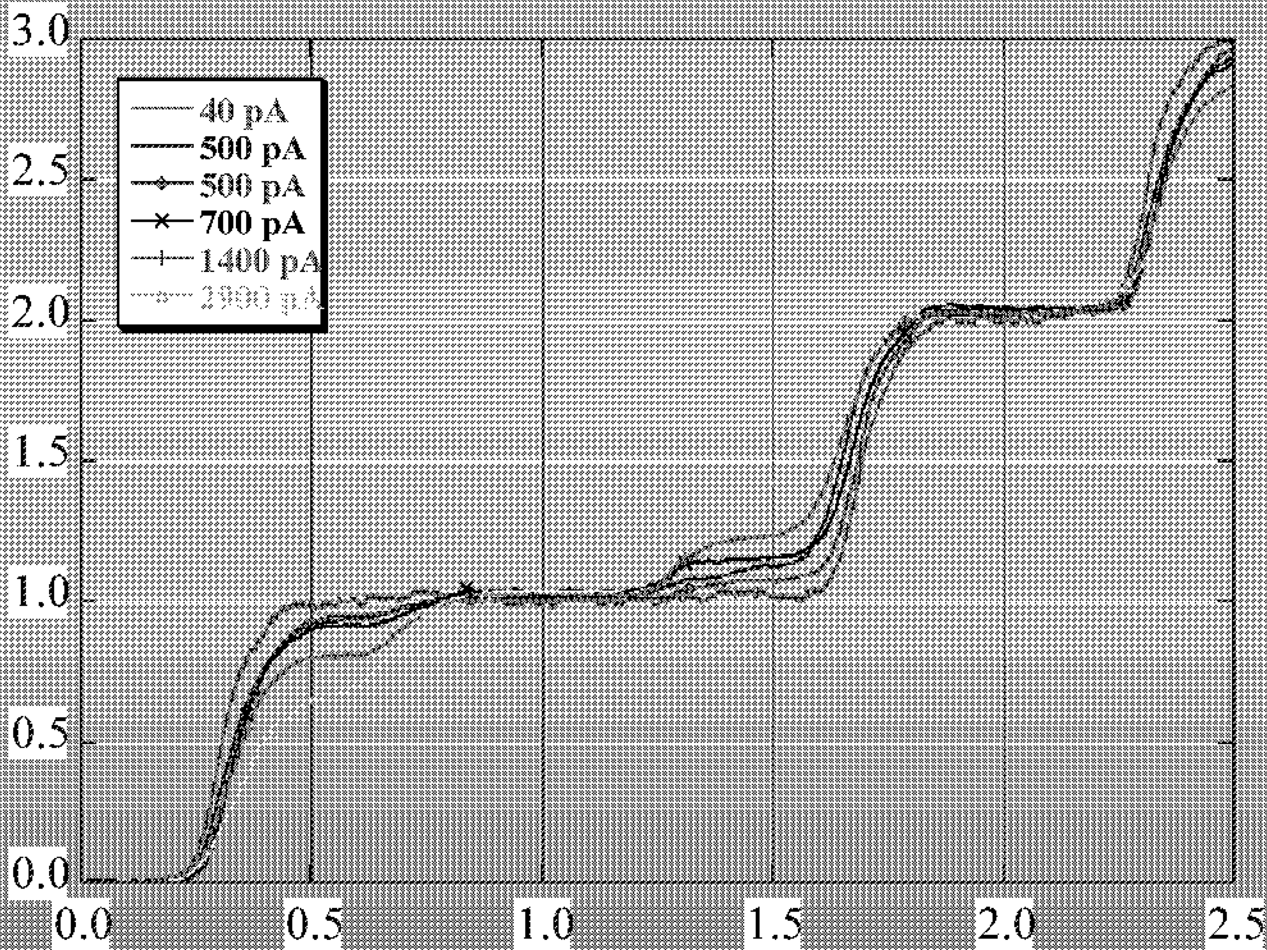
Conductance of SET vs. V_b and V_g



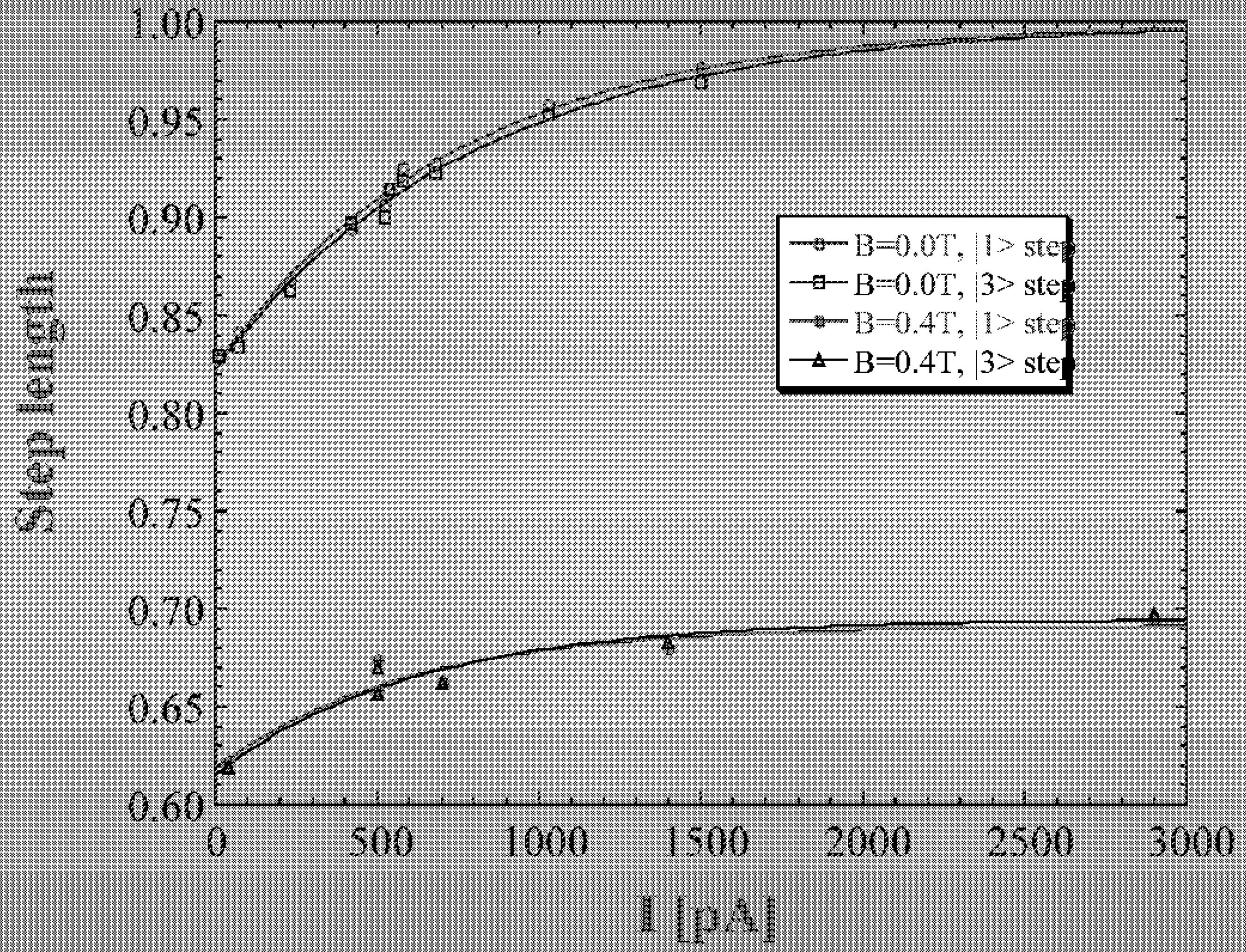
Effect of SET current at zero magnetic field



Effect of SET current at B=0.20T

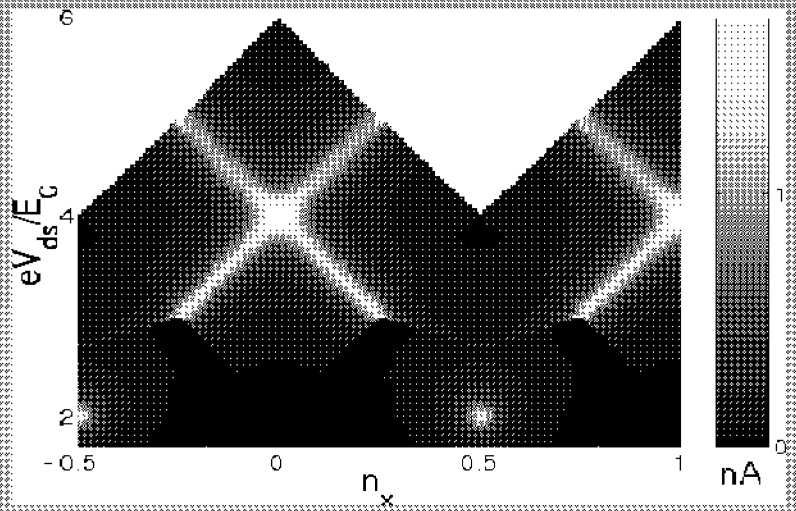


Step width vs. current



Cooper-Pair-Transistor DC Current

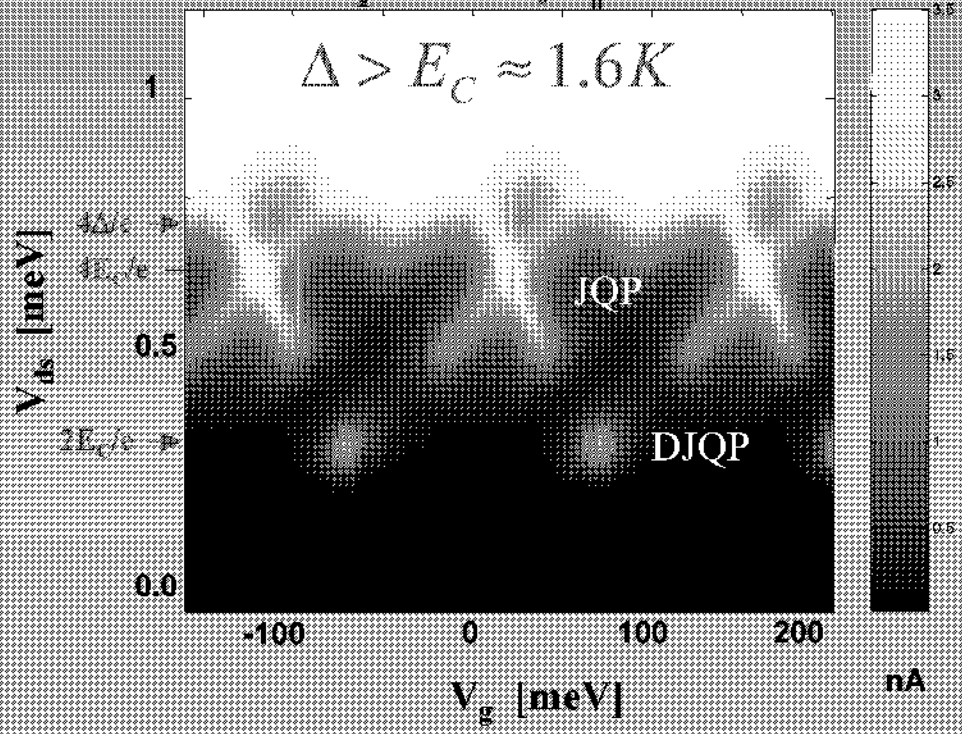
Theory

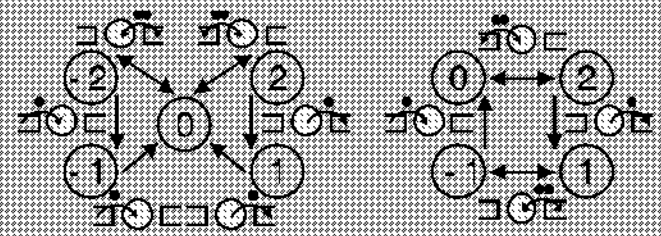


from: Johansson, cond-mat/0210539

Fulton & Dolan (1987)
van den Brink *et. al.* (1991)
Hadley *et. al.* (1998)

Experiment, $B_{||}$=0.4T

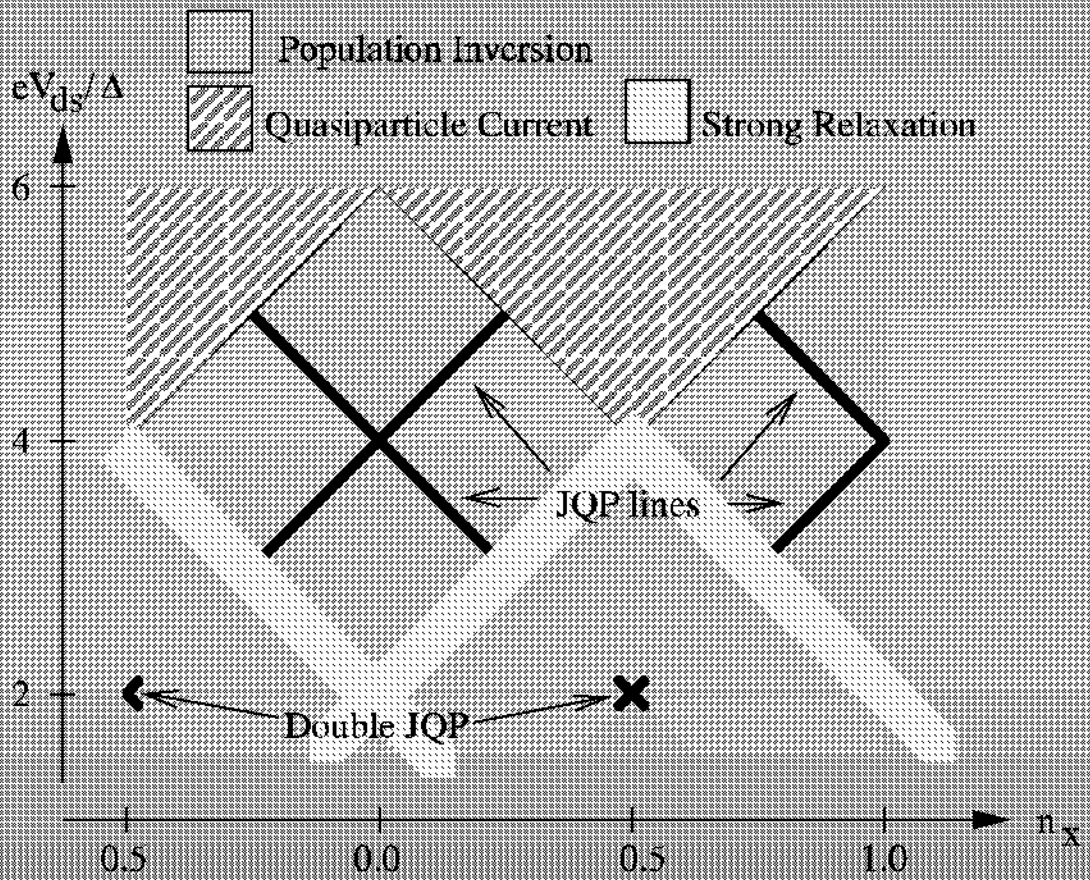




JQP DJQP

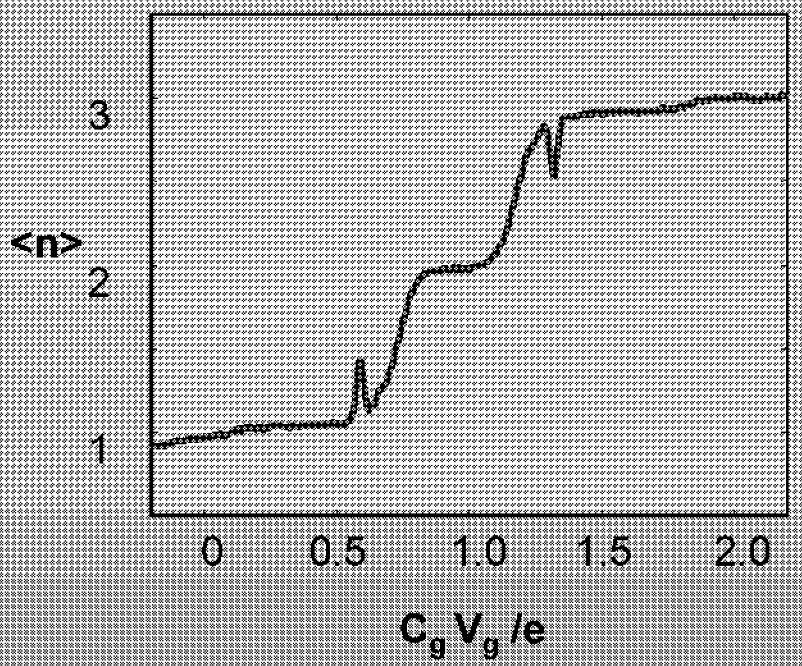
Back-action from the SET:
Population Inversion and Relaxation

Johansson, cond-mat/0210539
Clerk *et. al.* PRL (2002)
Choi *et. al.* (2001)

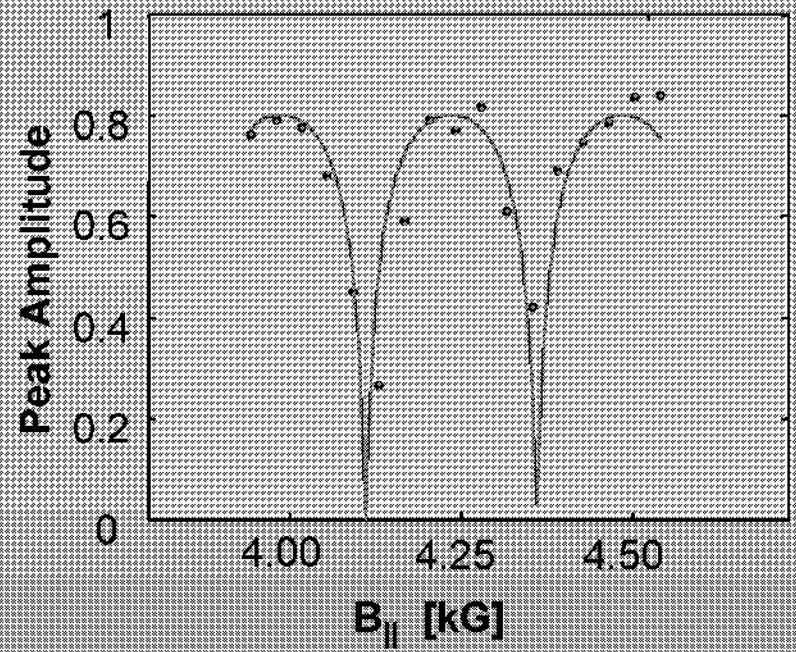


Spectroscopy

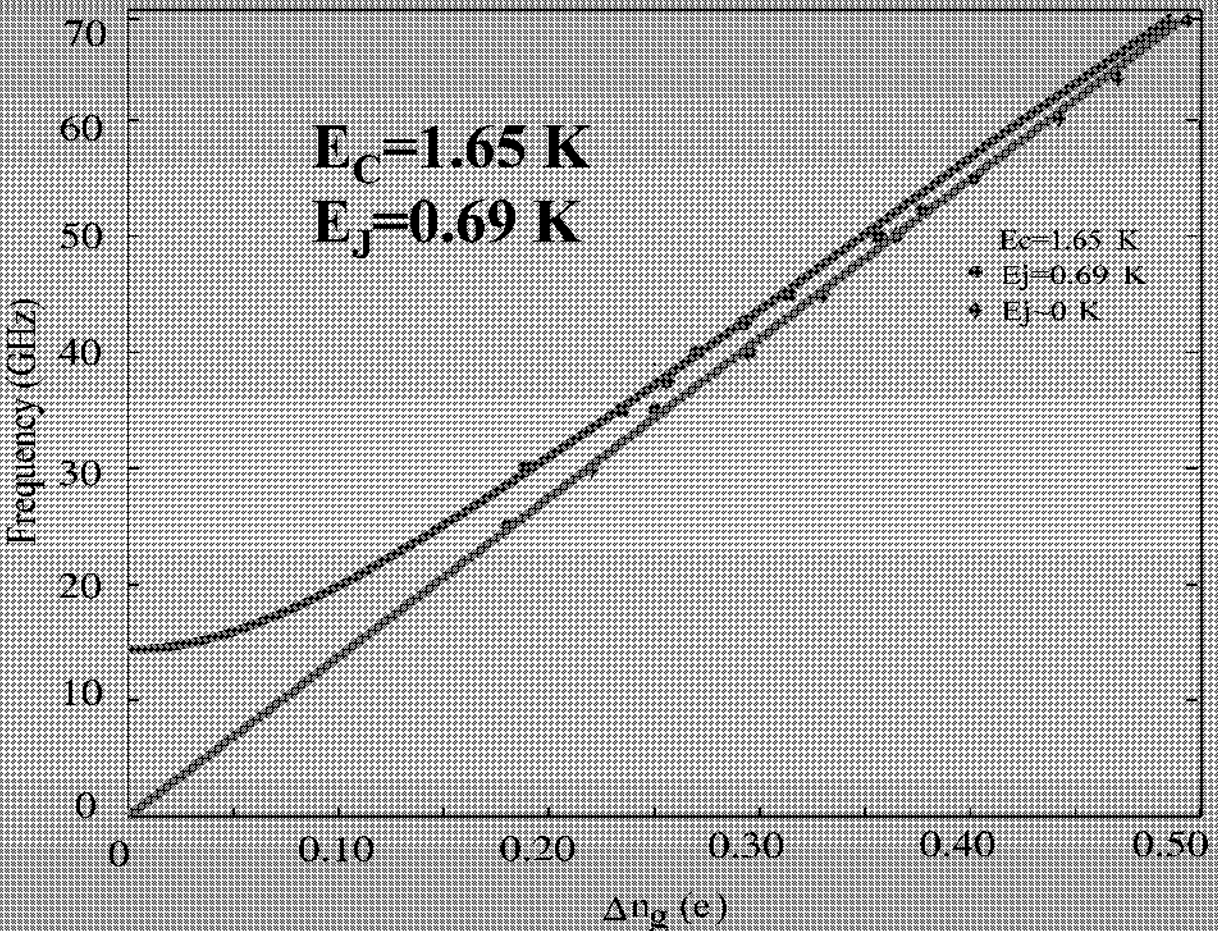
50 GHz peaks



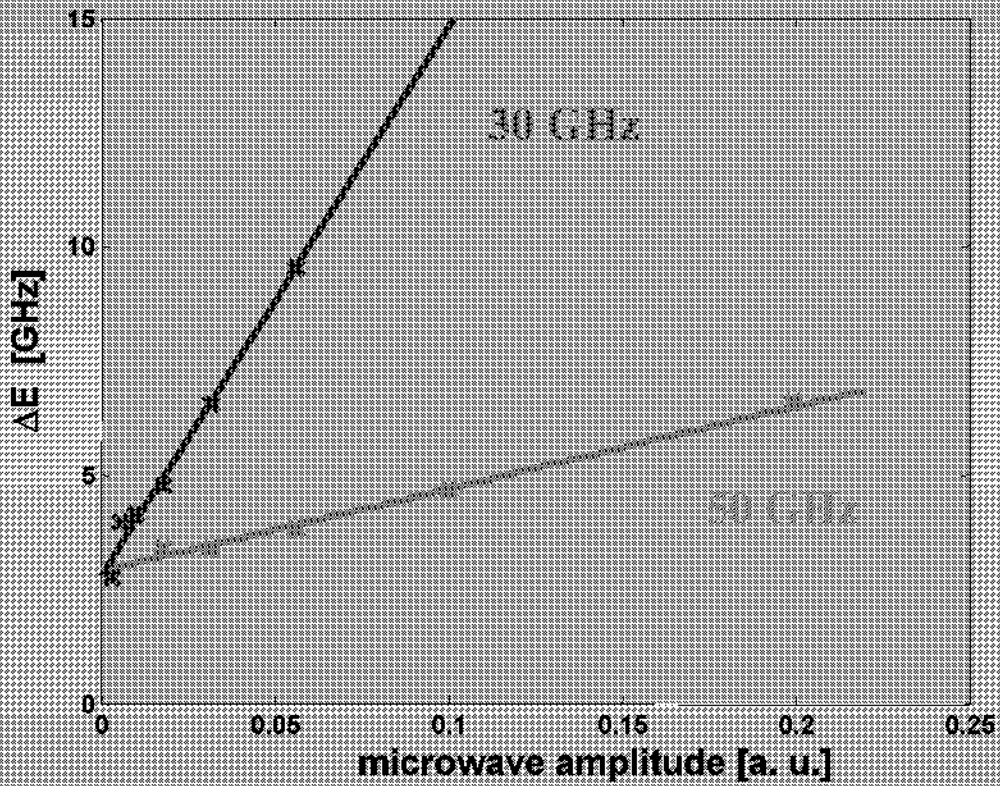
Modulation of E_J with $B_{||}$



Spectroscopic determination of E_J and E_C



Extracting T_2^* from peak width

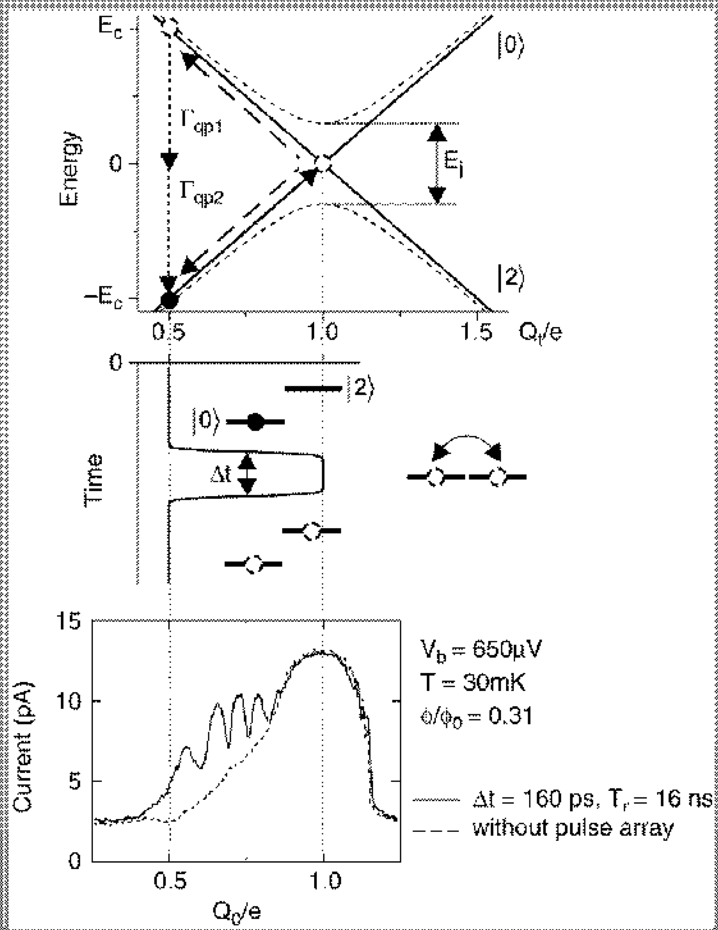


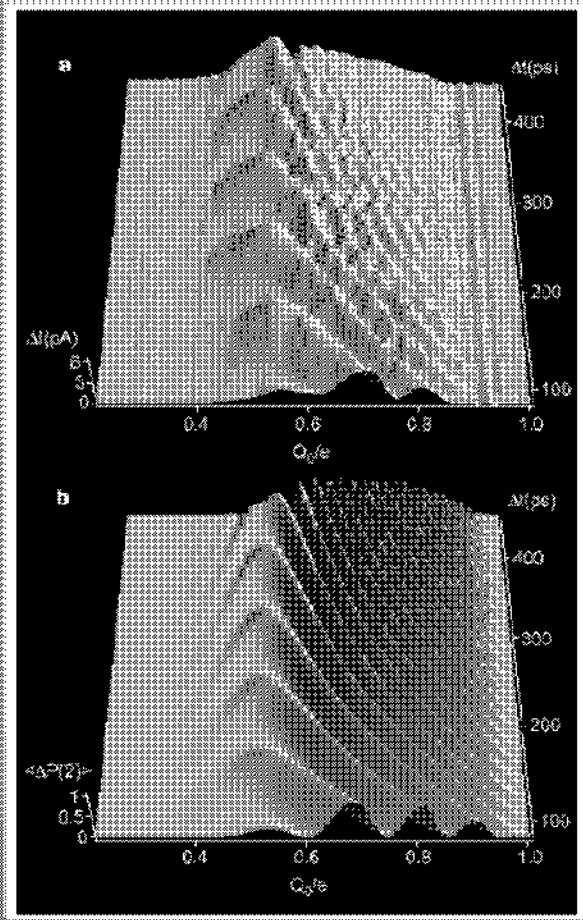
T_2^* =110ps, during continuous measurement.

Coherent Charge Oscillations

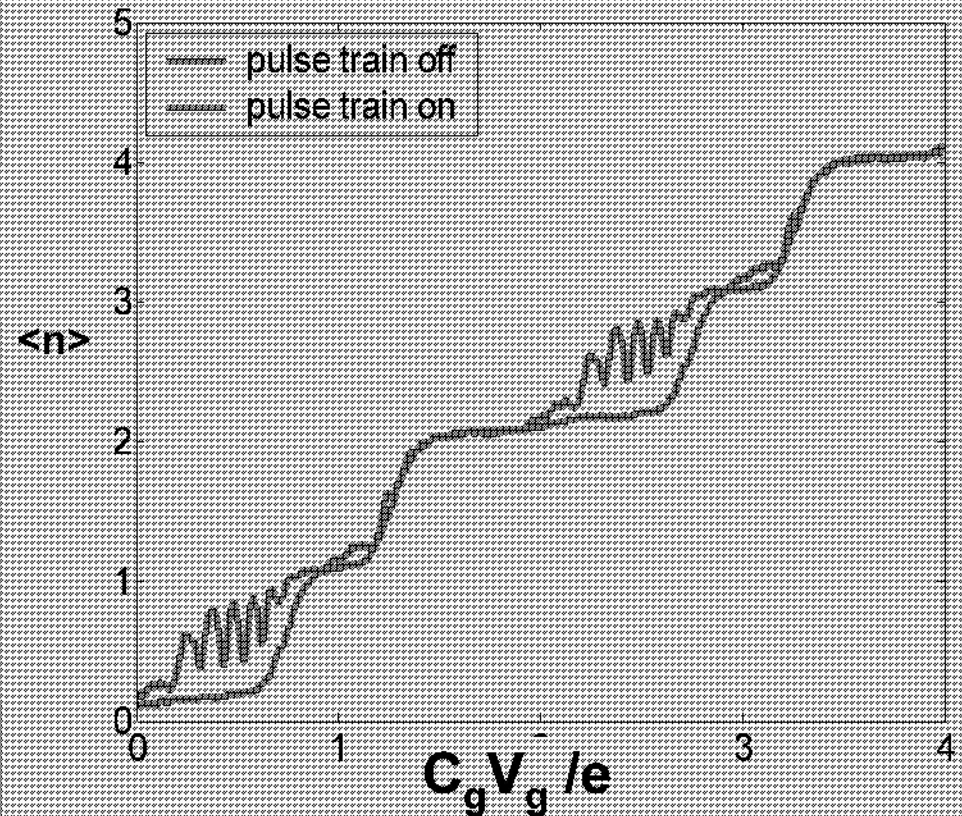
Observed by continuous measurement with the RF-SET,
while applying fast pulses to the box gate.

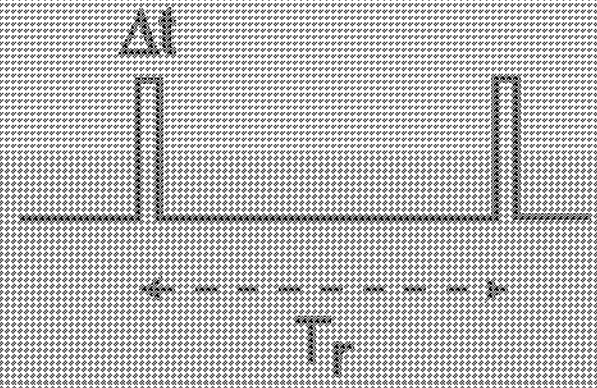
Nakamura, Pashkin and Tsai (1999)



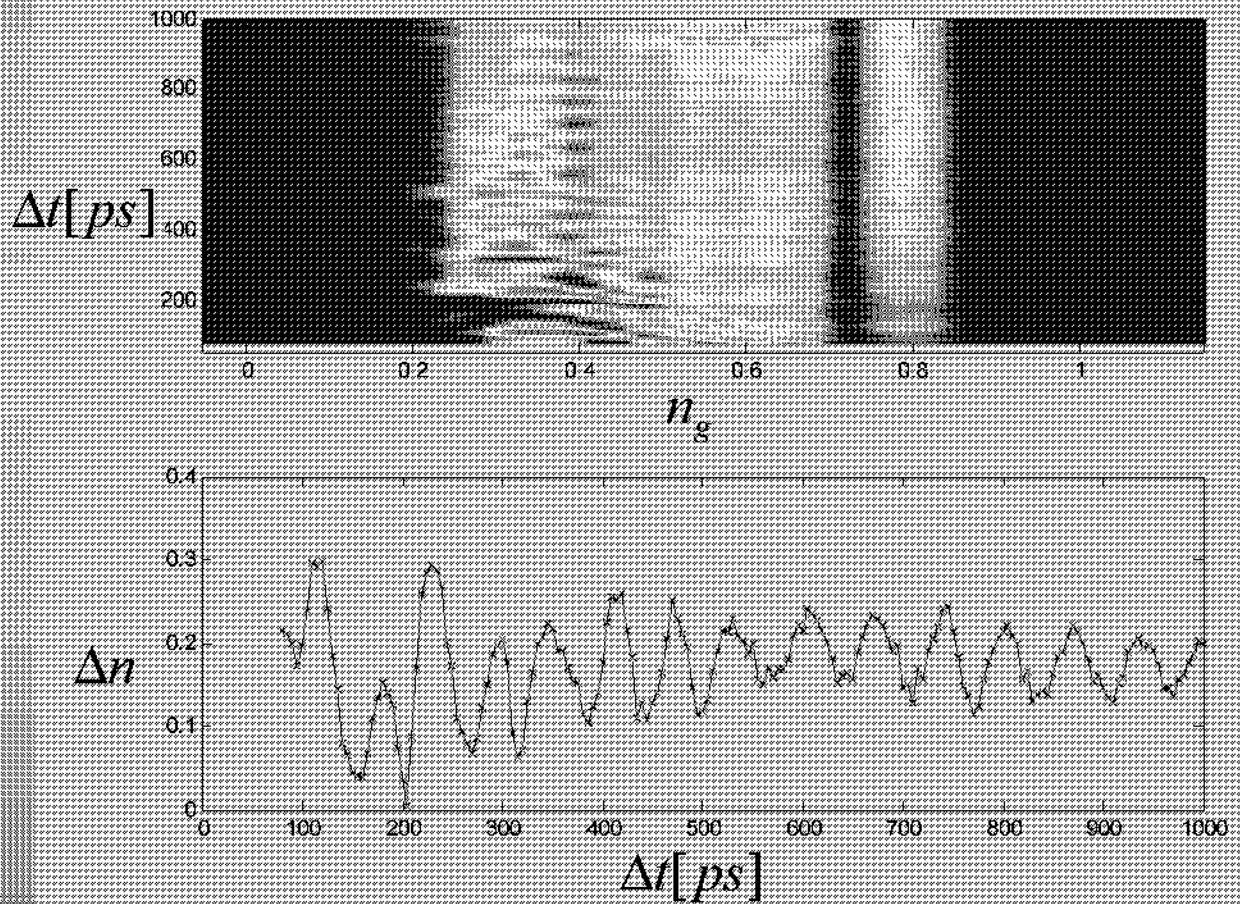


Continuous measurement with T_r=59ns, amplitude 1e pulse train

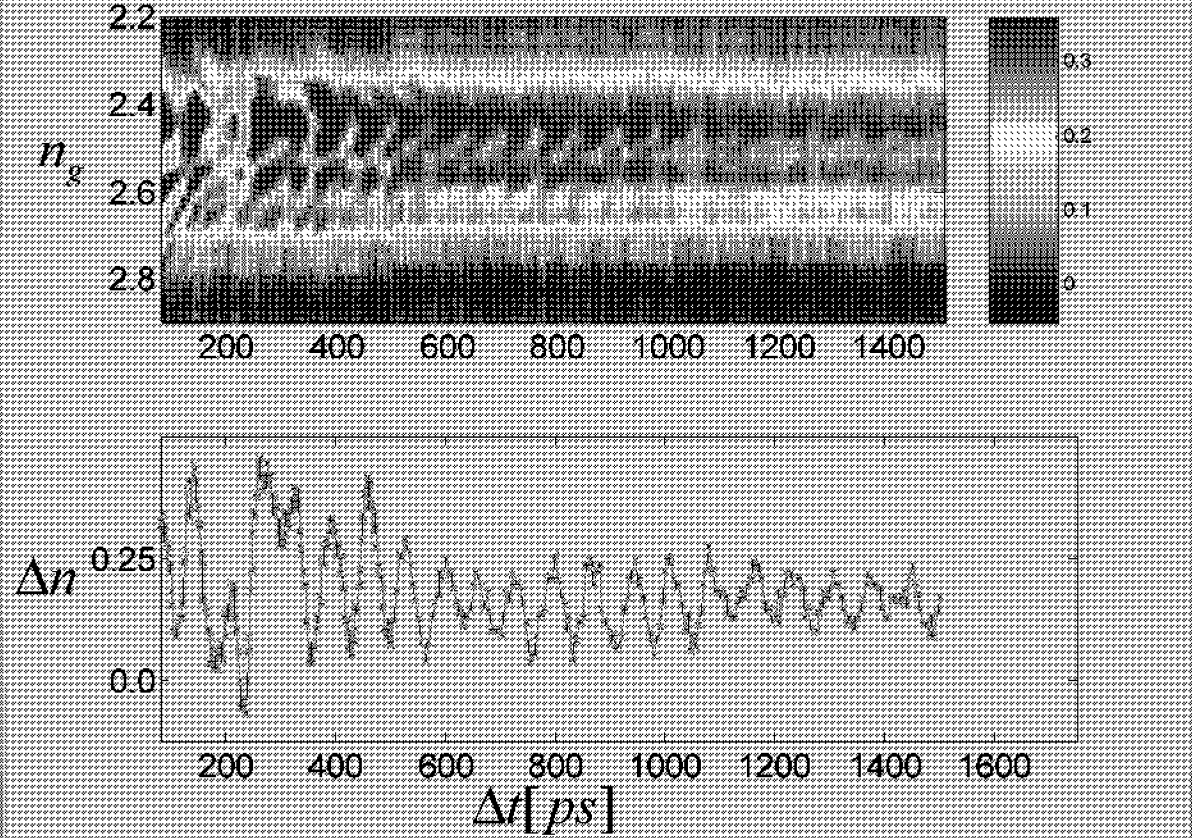




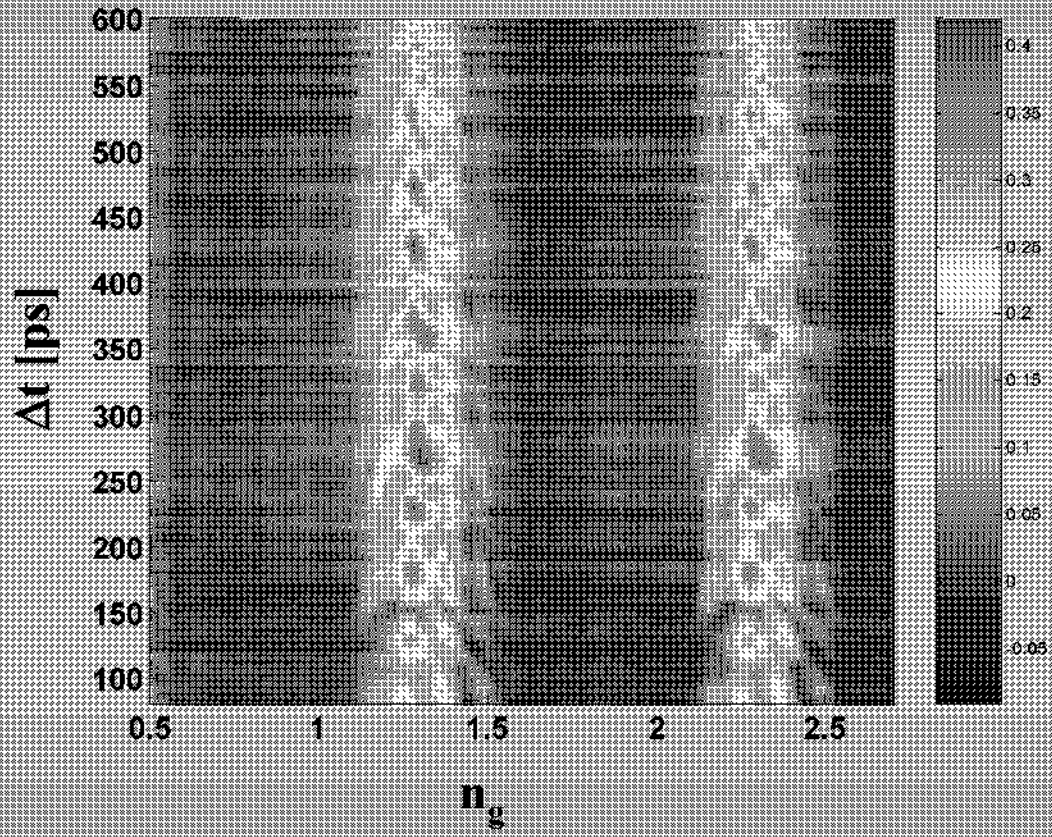
Coherent Oscillations



$B_{\|}$=0.30 T, E_J=0.67 K



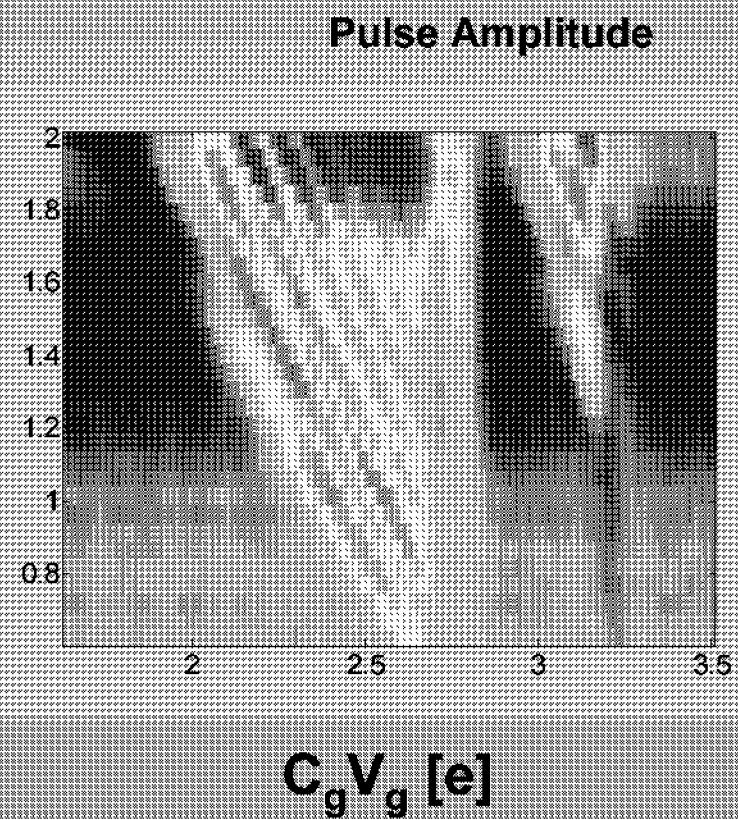
Oscillations of even AND odd parity states!

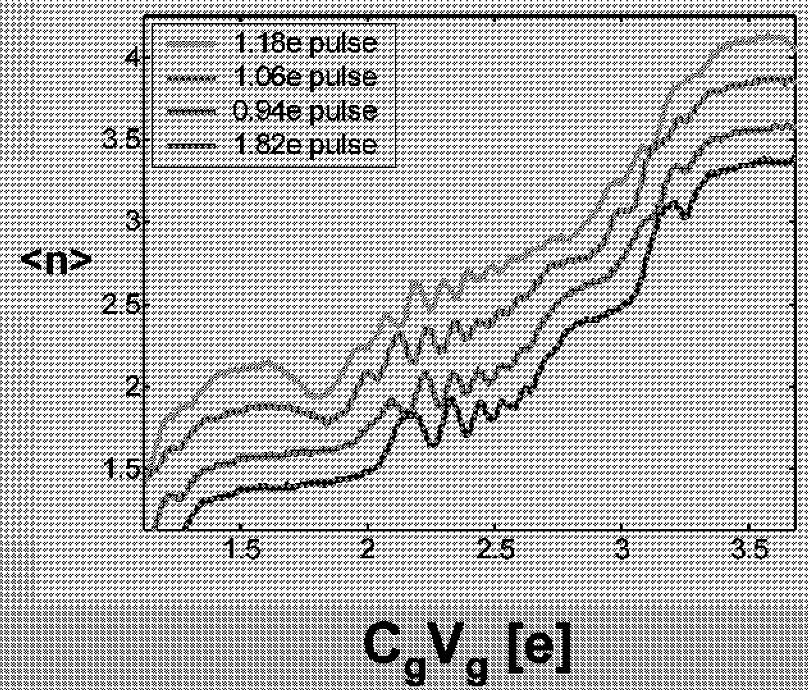


$B_{||}$=0T, bias at JQP where staircases are e-periodic.

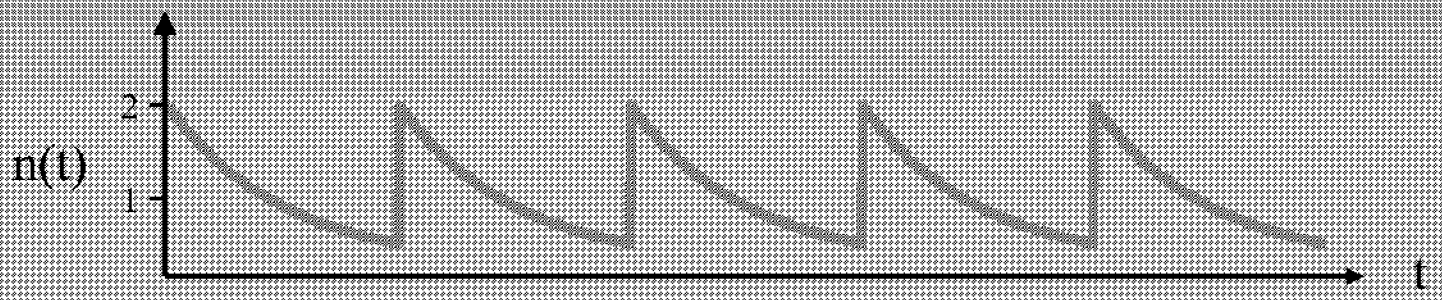
Quasi-particles not always 'bad'?

Pulse Amplitude Dependence



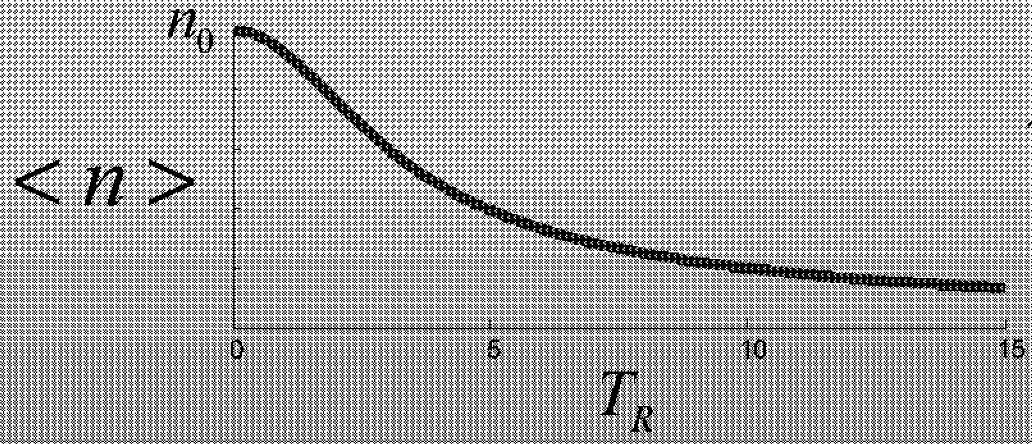


Dependence of Amplitude on T_1 and T_R

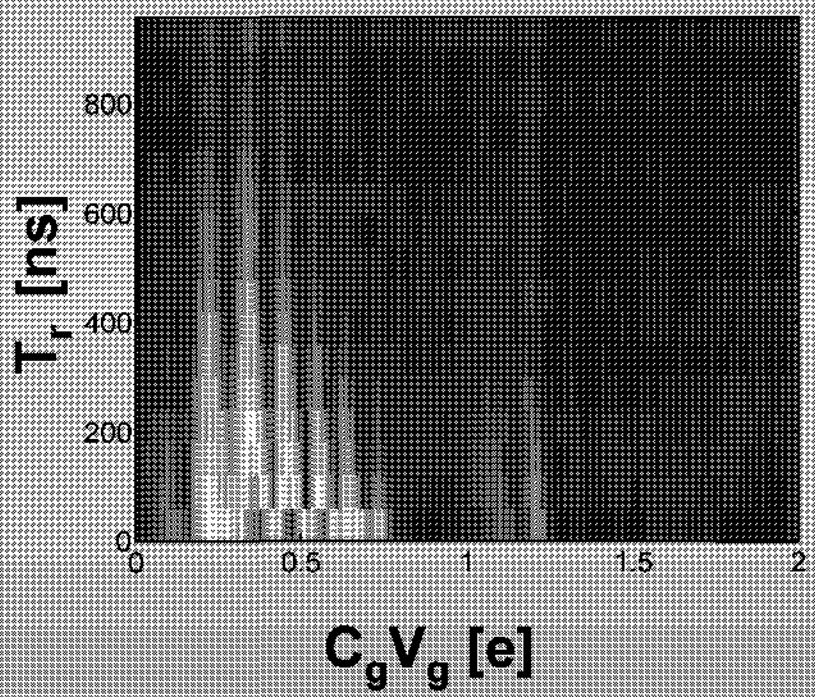


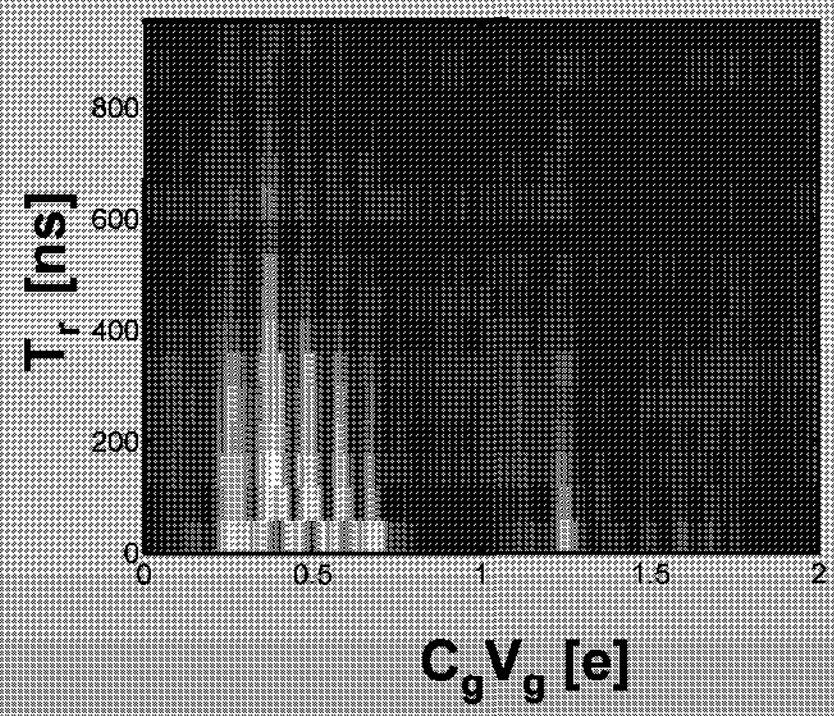
$$<n>(T_R) = 2n_0 \frac{T_1}{T_R} \frac{1-e^{-T_R/T_1}}{1+e^{-T_R/T_1}}$$

$$\sim 2n_0 \frac{T_1}{T_R}$$

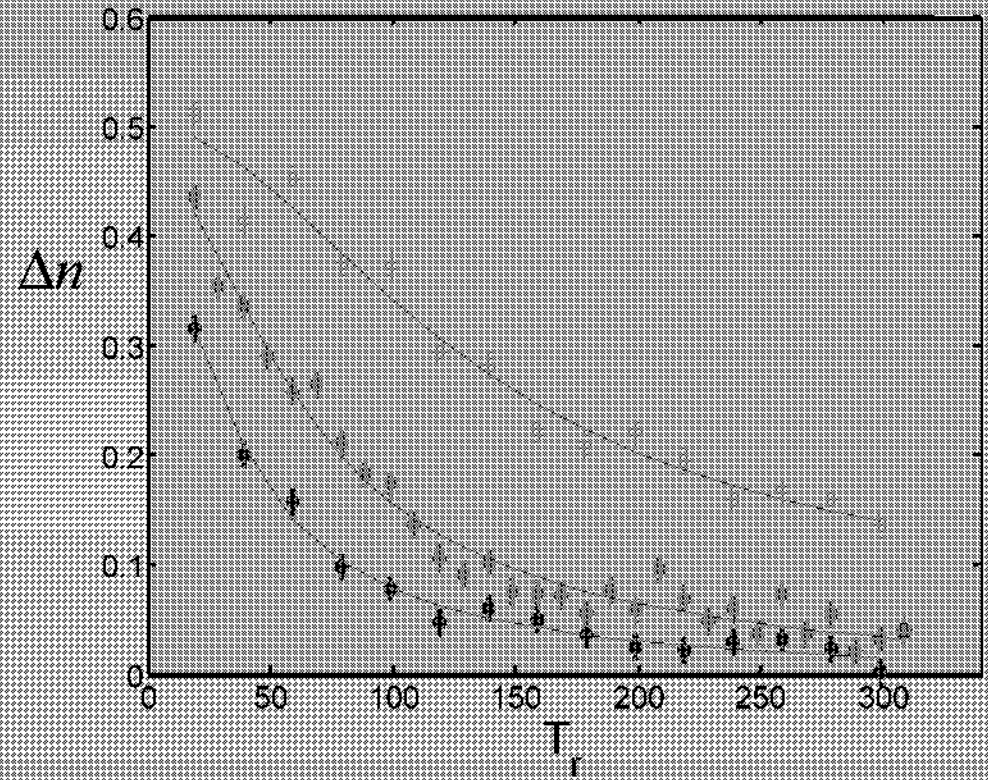


T_1 Measurements at $B_{\|}$=0.30T





T_1 measurements at $B_\parallel$=0.0T



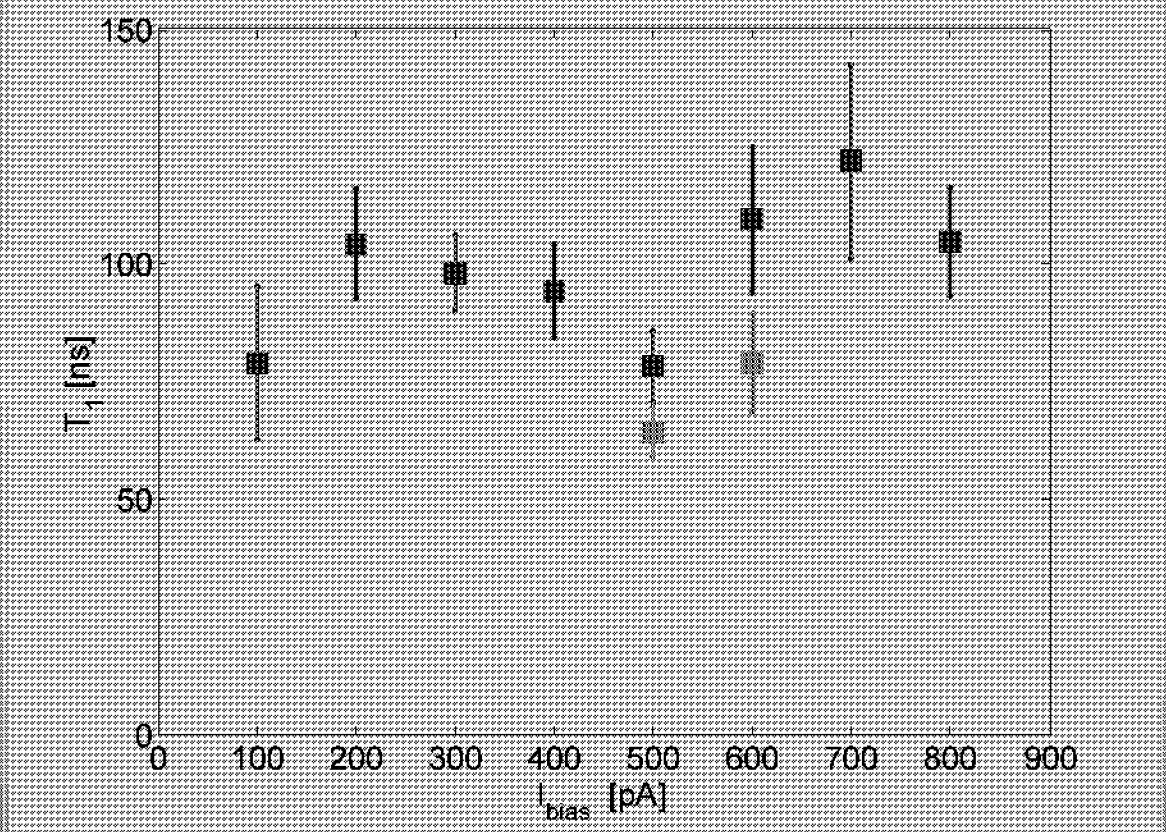
DJQP: I_b= 300pA, T_1=40ns

JQP: I_b=1300pA, T_1=19ns

JQP: I_b=2300pA, T_1=12ns

Note that measurement fidelity is > 50%.

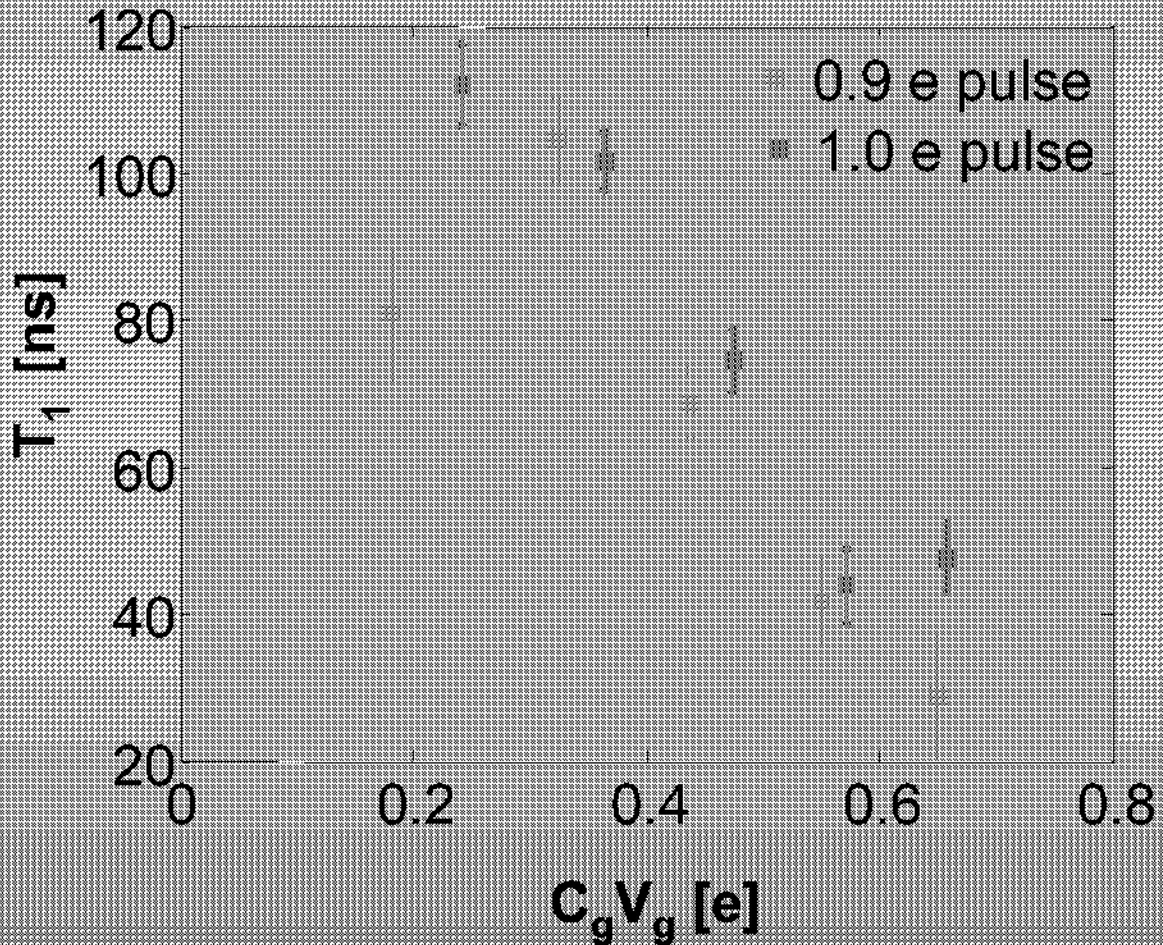
T_1 measurements at $B_{\parallel}$=0.30T



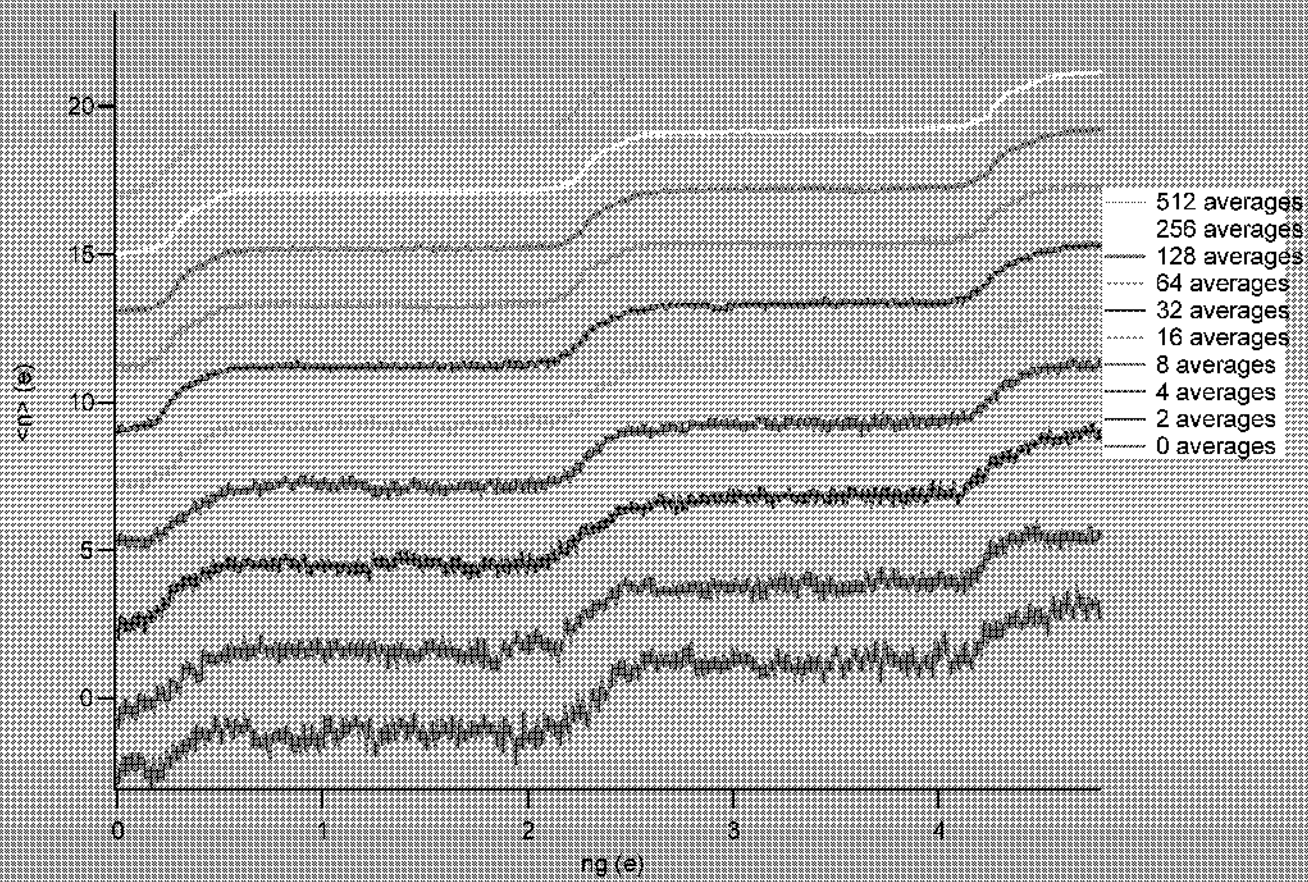
DJQP bias

JQP bias

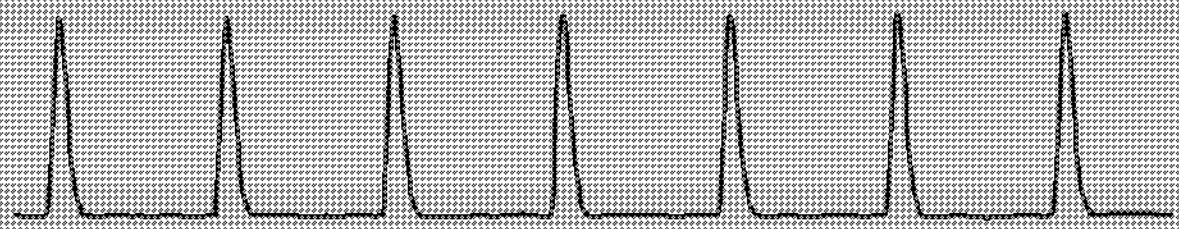
Dependence of T_1 on ΔE at $B_\parallel$=0.30T



Approaching Single-Shot Sensitivity



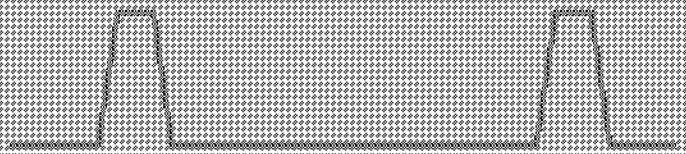
Pulsed Mode Measurements



Pulsed RF Read-out

width: 0.3-2.0 μs

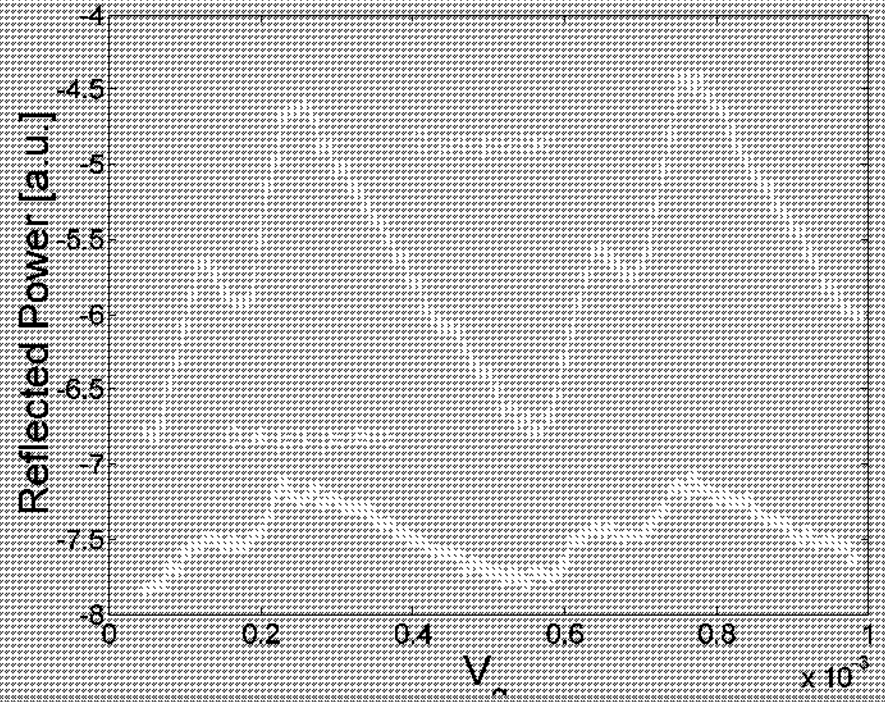
T_r: 10 μs



Low RF power, 3e DC bias

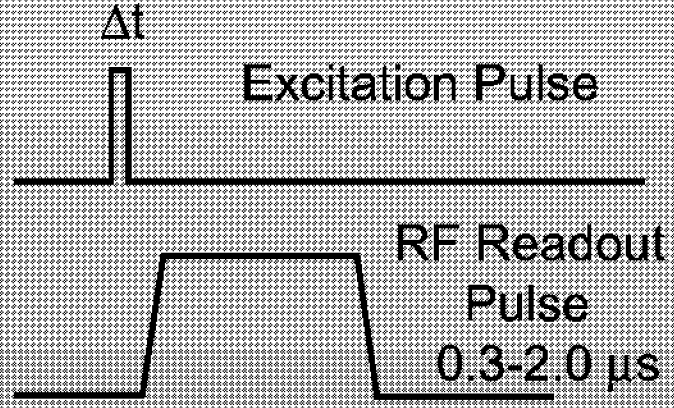
and

High power, mid-gap DC bias

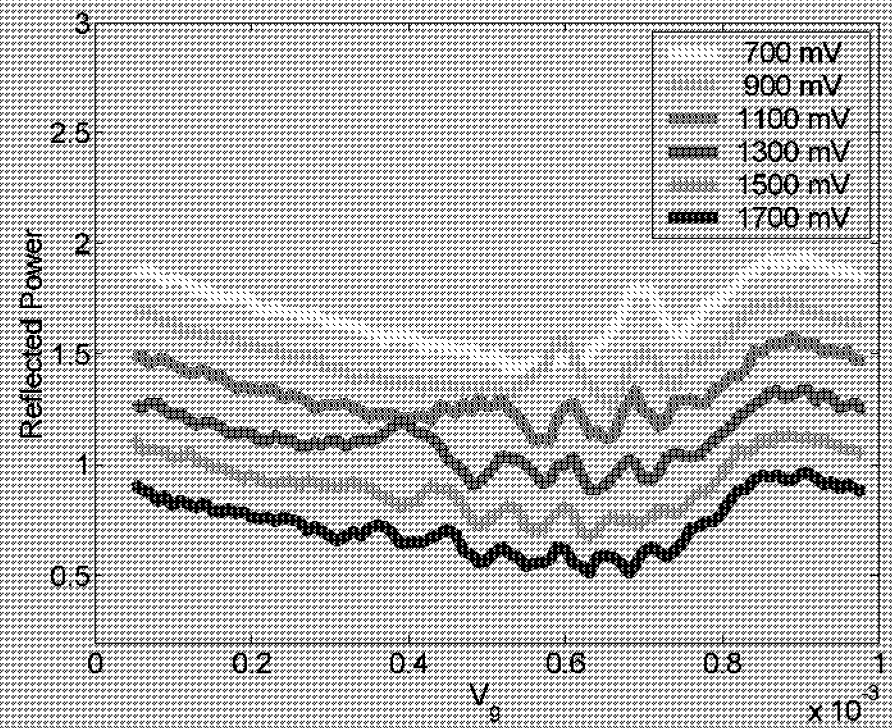


512 repetitions / pt.

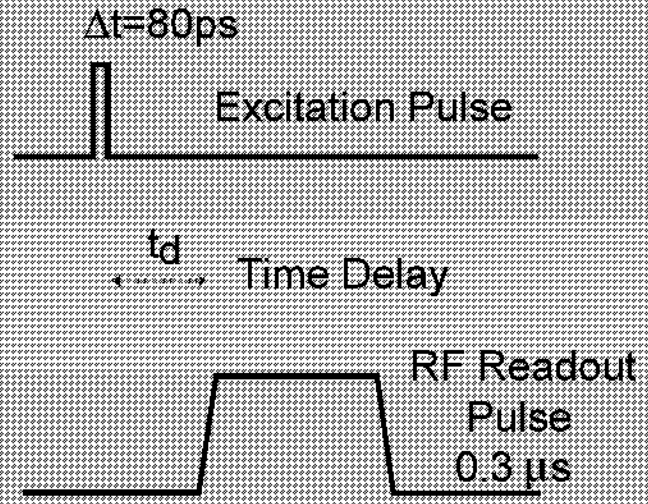
Pulsed Read-out of Excited State

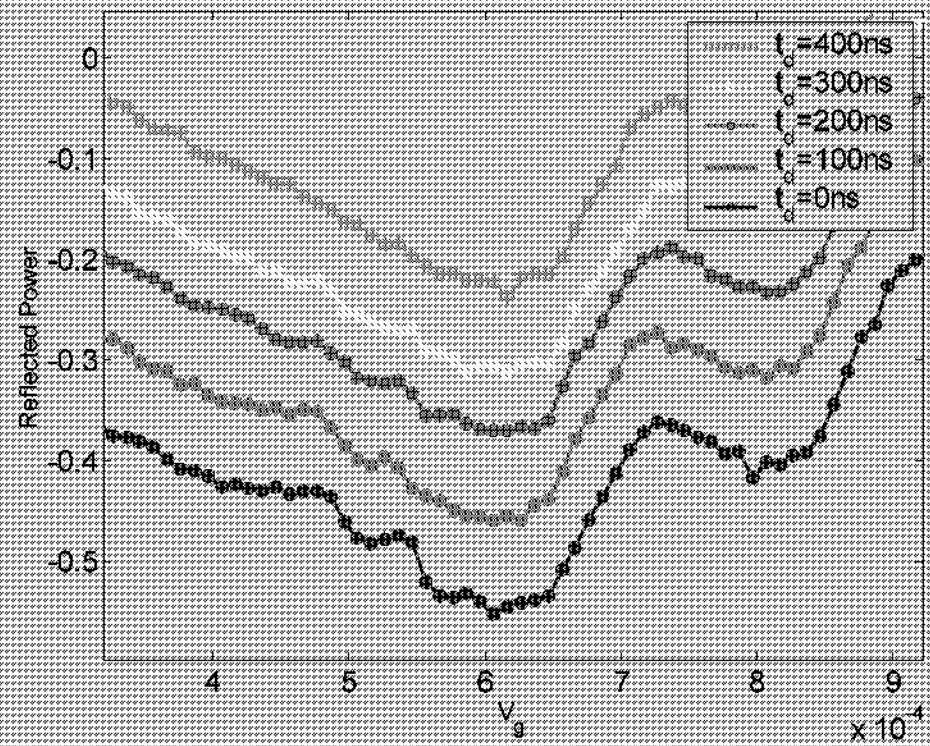


0.3 µs read-out pulse, B=0.72T



Probing T_1 with Pulsed Measurement





Conclusions

- Demonstrated continuous and pulsed read-out of box charge.
- Observed coherent free-precession of charge (reproduced Nakamura's results using fast pulses and RF-SET read-out).
- RF-SET coupled to a single-Cooper-pair box is a very unique system: a ~~macroscopic~~, er, mesoscopic quantum device measuring mesoscopic quantum coherence.
- T_1 measurements show effects of 'back-action', although T_1 saturates at ~100ns, even with pulsed measurement.
- Improvements needed and planned:
  - Quasi-particle traps, lower E_C, better microwave engineering.
  - SQUID amplifier
  - Coplanar waveguides
  - Better control of E_J
  - Capability of fast pulsing on SET gate and bias.