Development of Single Cooper Pair Box based quantum bits

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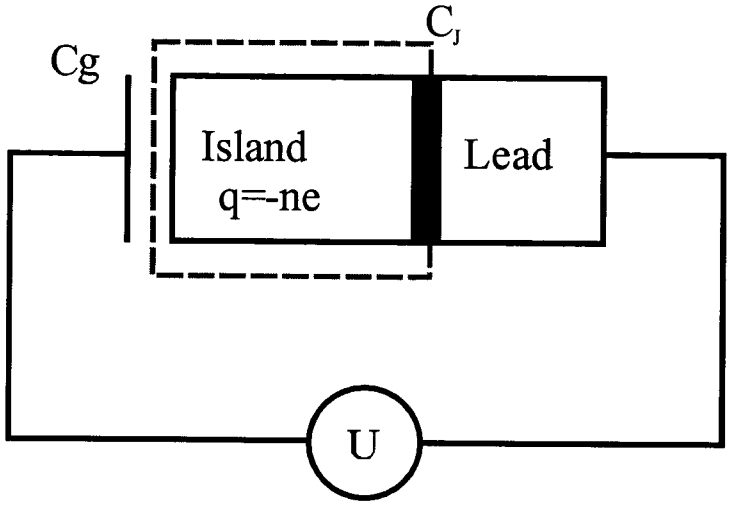
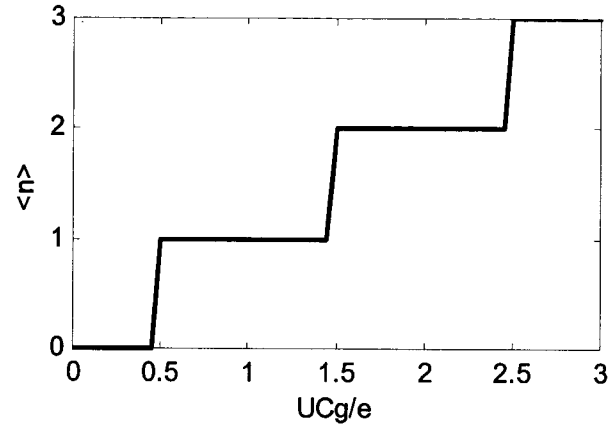
Outline

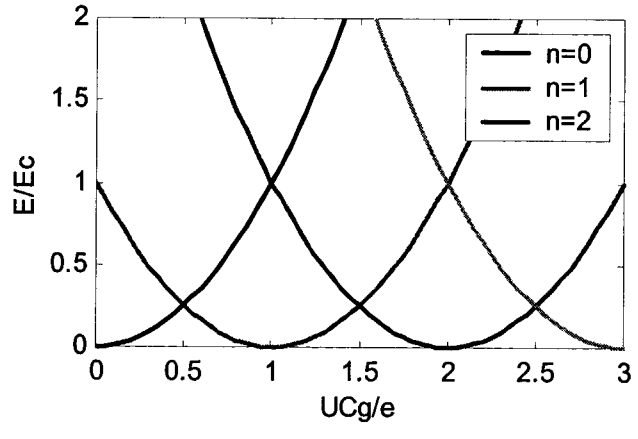
- Introduction to SCB-based qubits

- Experimental work
  - Dilution refrigerator
  - Fabrication
  - RF-SET characterization
  - SCPB staircase measurements
  - Coherent Oscillations
  - Simulation
  - New design

Single Electron Box

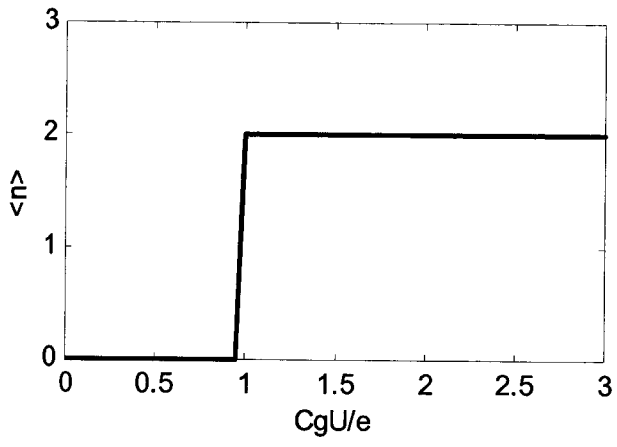


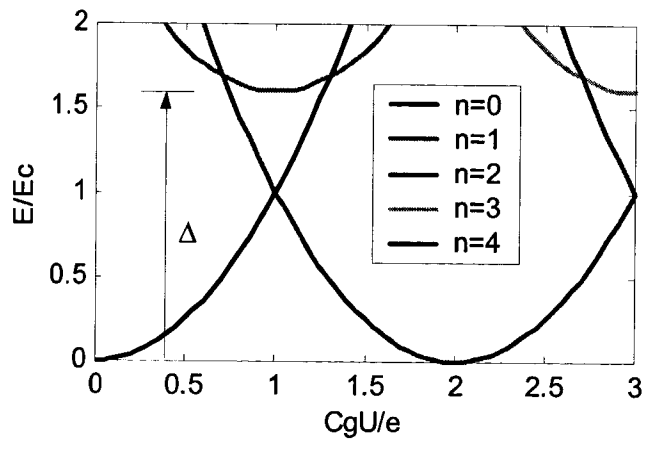




- Small tunnel junction in series with gate capacitance
- UC_g is continuous, n*e* discrete
- Energy cost of adding one electron to island is $E_c = e^2/2(C_J+C_g) >> k_B T$
- Average number of electrons in island is step like function

Single Cooper Pair Box





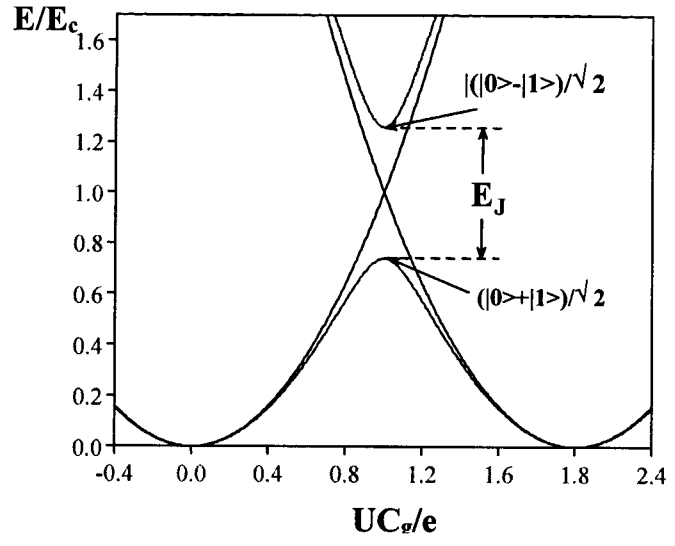
- Superconducting Single Electron Box
- Odd n costs an extra energy Δ
- Even n costs no additional energy
- Number of excess Cooper Pairs -> binary levels 0 and 1
- Coherent superposition demonstrated(Nakamura in Science April 99)

1 Qubit gate

$$H = \frac{1}{2}\begin{bmatrix} -E(U) & -E_J(\Phi_{ext}) \\ -E_J(\Phi_{ext}) & E(U) \end{bmatrix}$$

$$E(U) = 4E_C(1 - \frac{C_g U}{e})^2$$

$$E_J(\Phi_{ext}) = E_J\left|\cos(\frac{\pi\Phi_{ext}}{\Phi_o})\right|$$



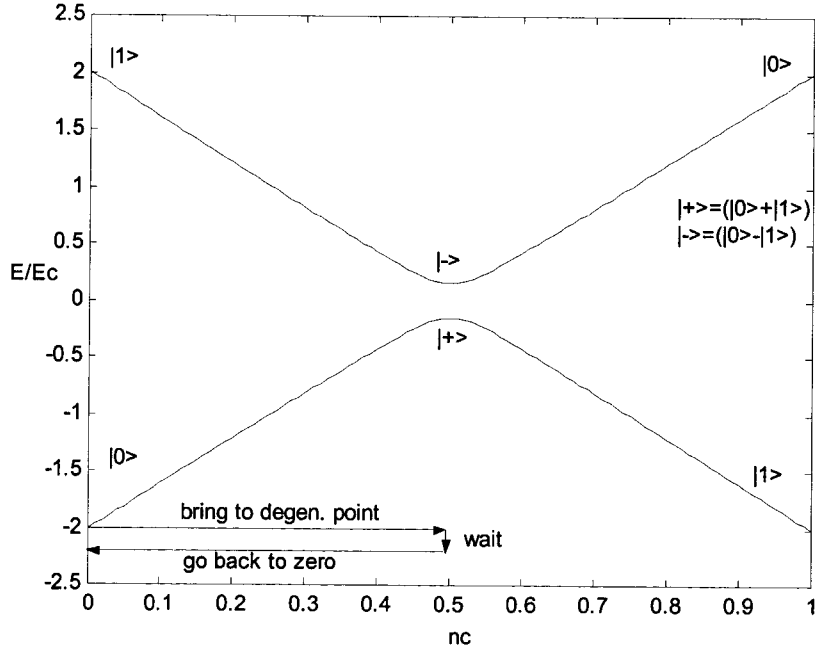
Time evolution

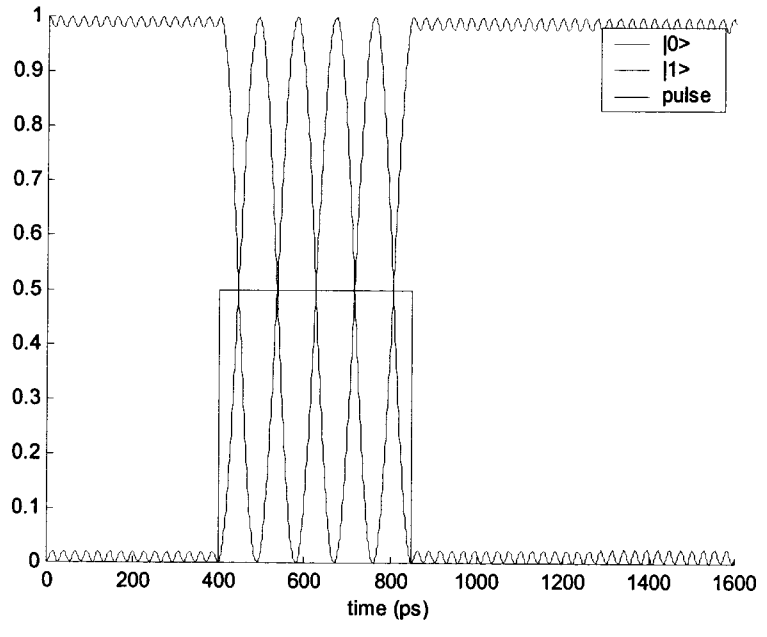
$$|\psi\rangle_t = e^{-i\frac{H}{\hbar}t}|\psi\rangle_o$$

Defines a gate

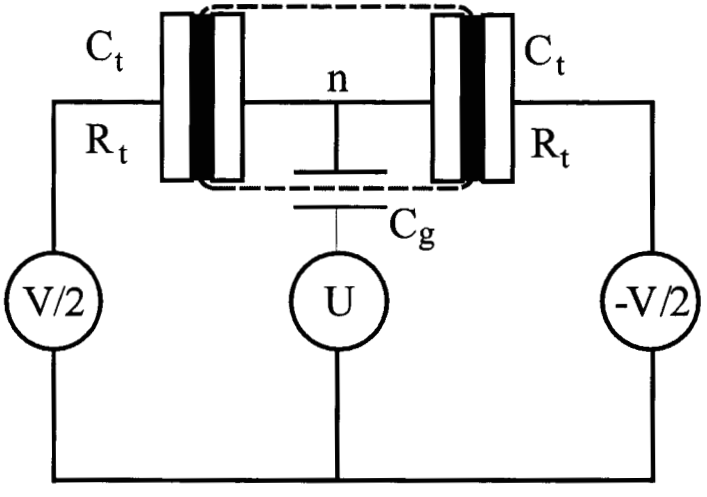
$$e^{-i\frac{H}{\hbar}t} = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$$

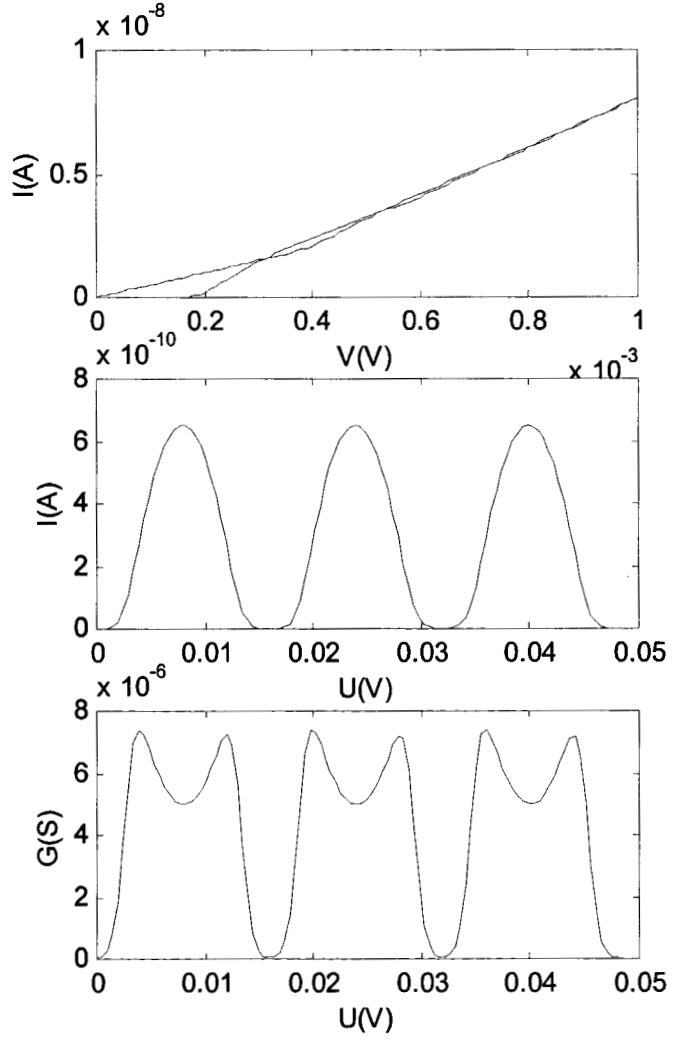
Qubit manipulation





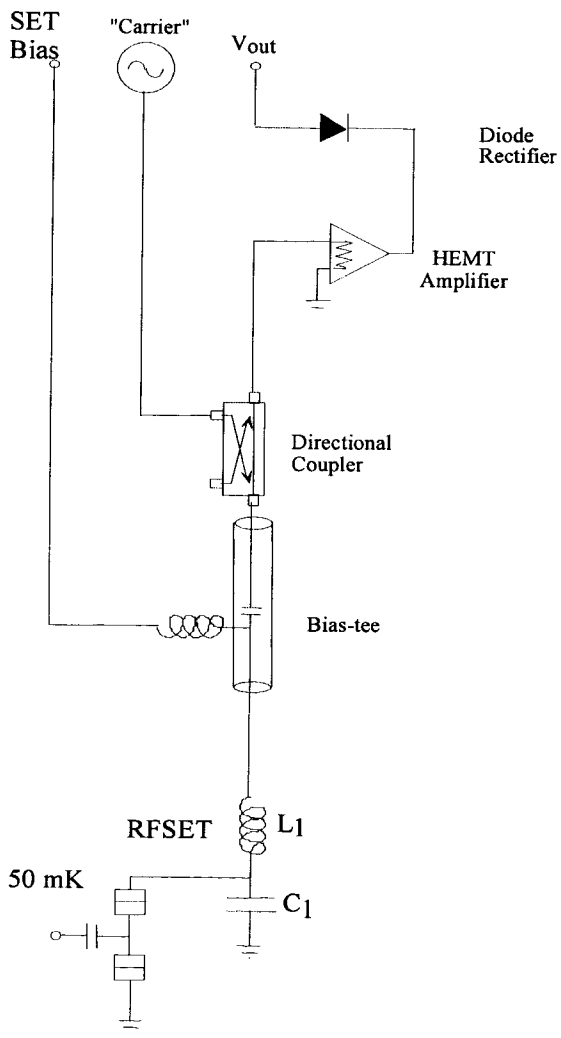
Single Electron Transistor





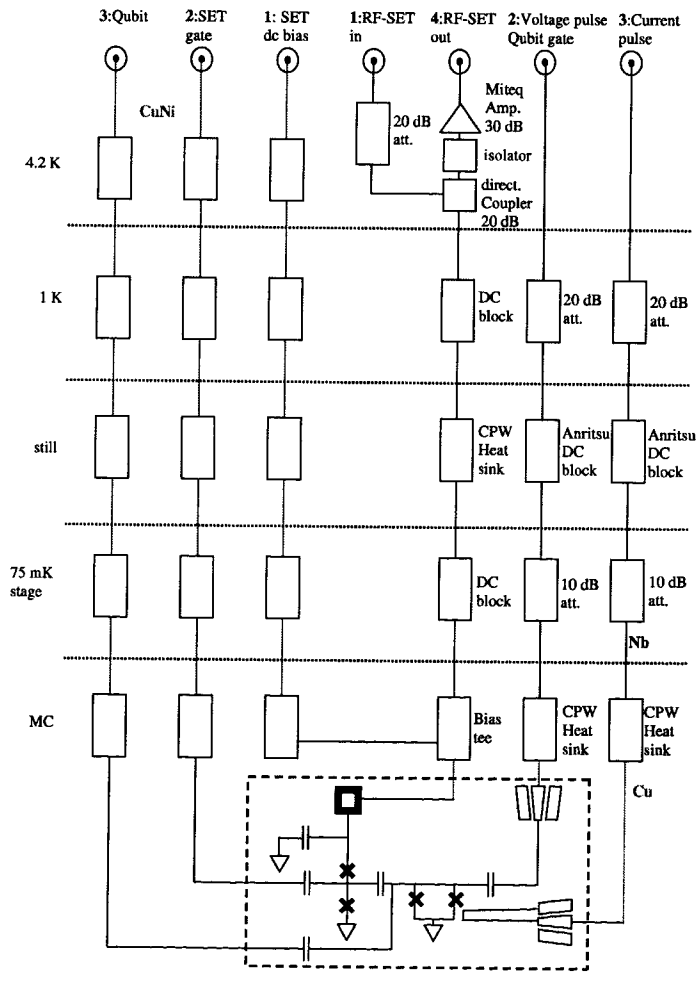
- SET to measure <n>
- Current modulated by charge
- Sensitivities of 10^{-5} e/Hz$^{1/2}$

The RF-SET - a very fast SET



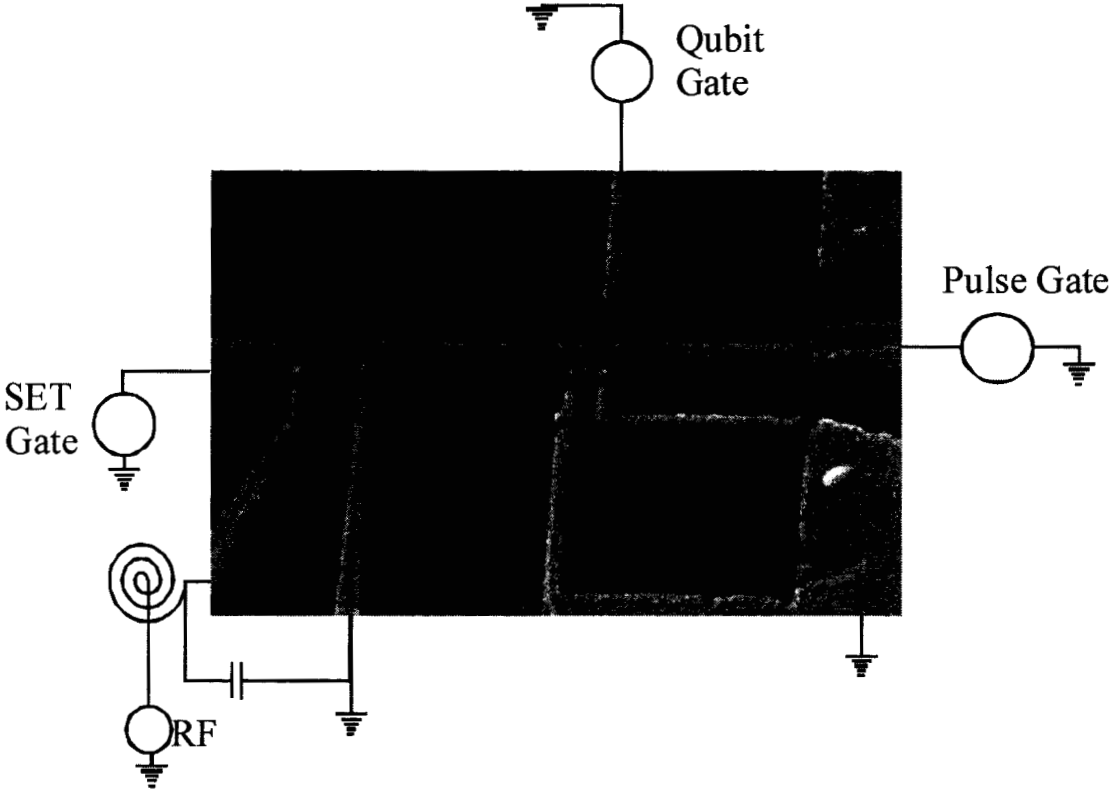
- DC SET too slow
- RF-SET -> use SET as dissipative element of a resonant circuit
- Monitor microwave power reflected from resonant circuit
- Reflected Power is a function of the dynamic resistance which in turn depends on the charge coupled to the gate
- Bandwidth of 3MHz with resolution of $7 \times 10^{-7} e/Hz^{1/2}$ demonstrated (Chalmers group)

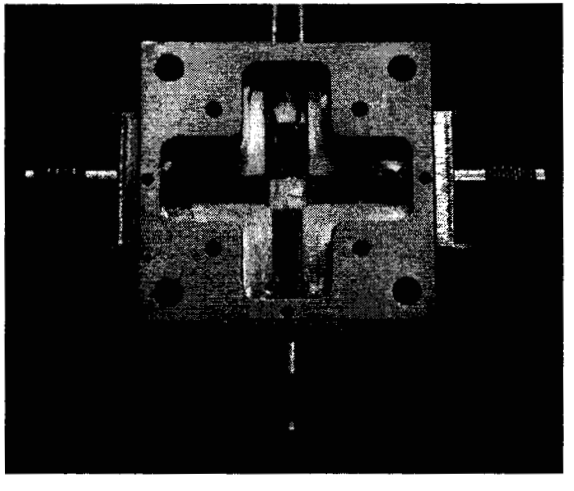
Experimental layout



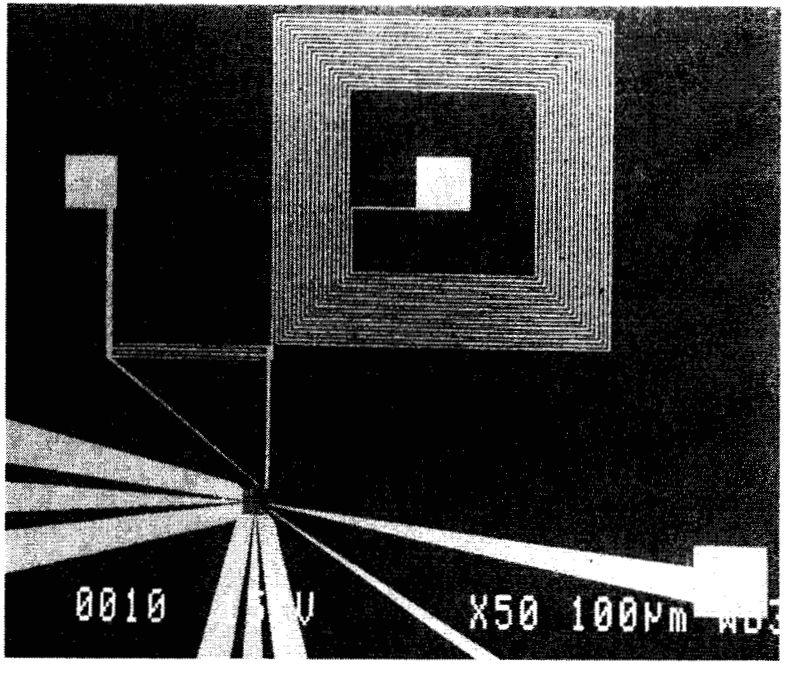
- New dilution refrigerator built
- Wiring completed
- Great care was taken heat sinking coaxial lines
  - DC blocks and attenuators
  - CPW structures on sapphire to heat sink RF coaxes
  - Lossy Cu-Ni coaxes for DC lines
  - Nb coaxes for RF lines below still
- Refrigerator reached 12 mK

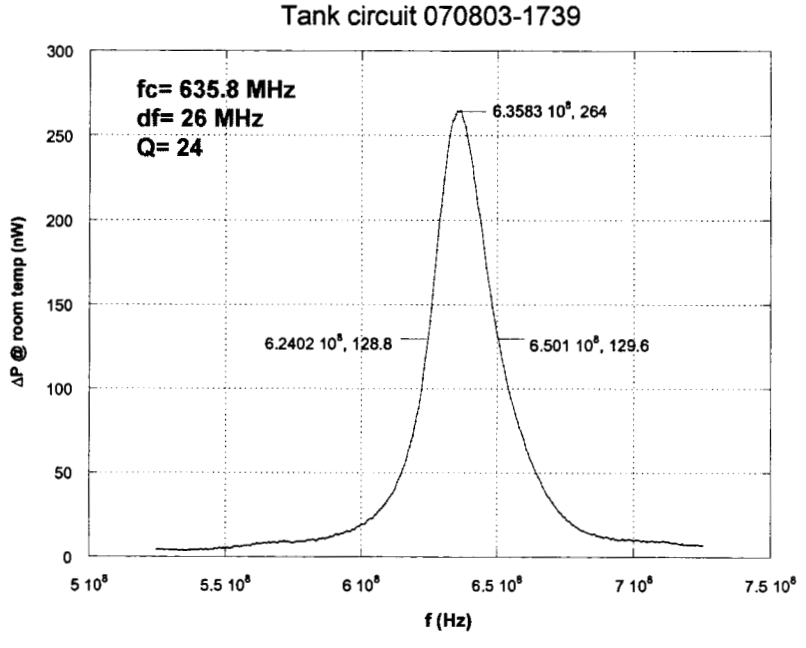
Qubit and SET readout





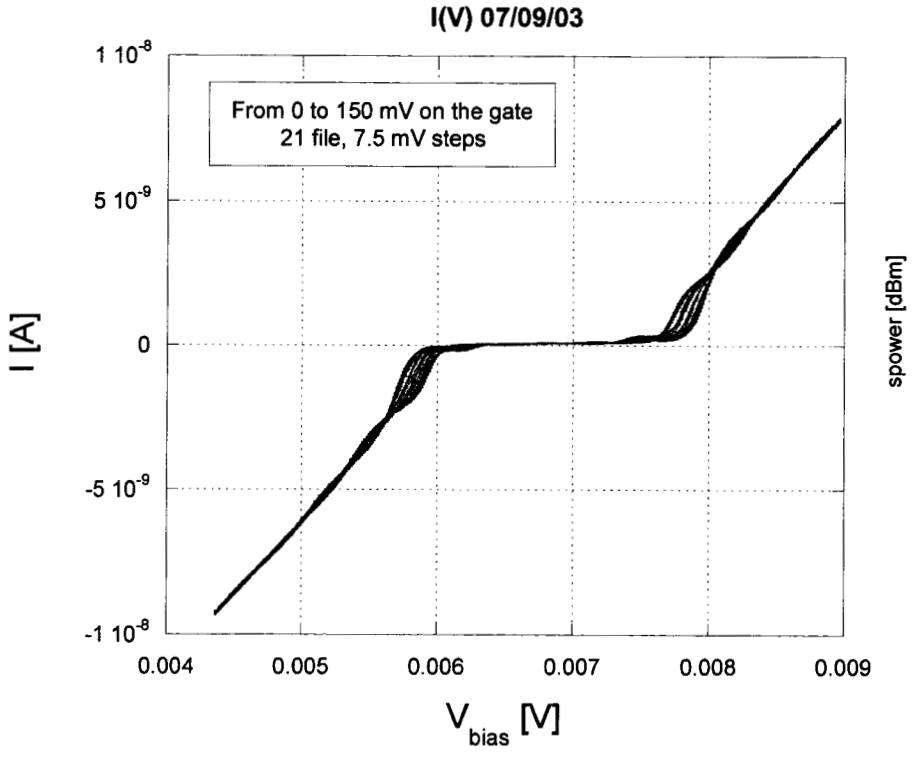
Tank circuit and waveguides



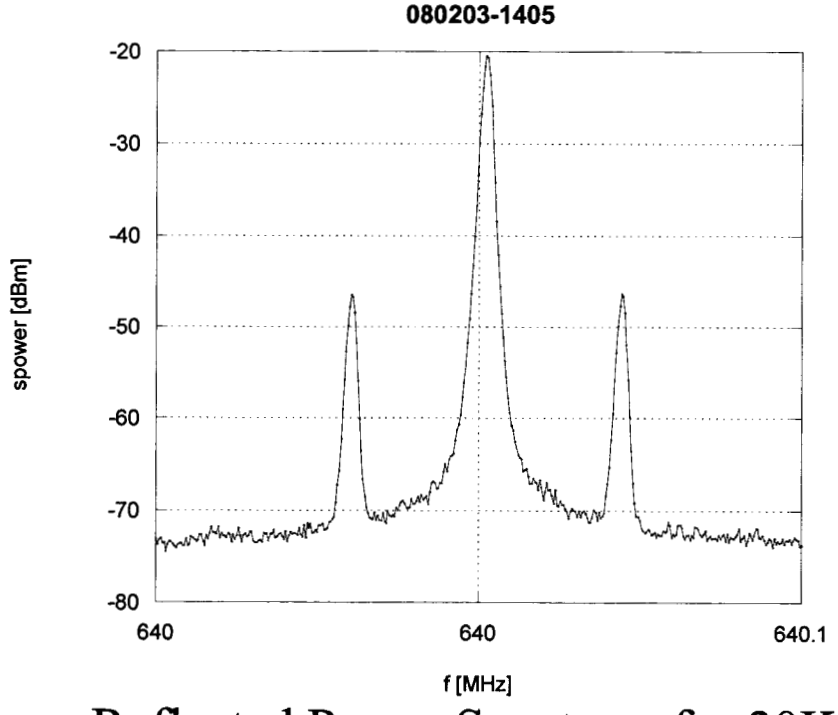


- ***RF-SET Tank circuit and waveguides fabricated with Al/Ti/Au Structures with Tc~ 530 mK***
- ***Quartz substrate***

SET characteristics



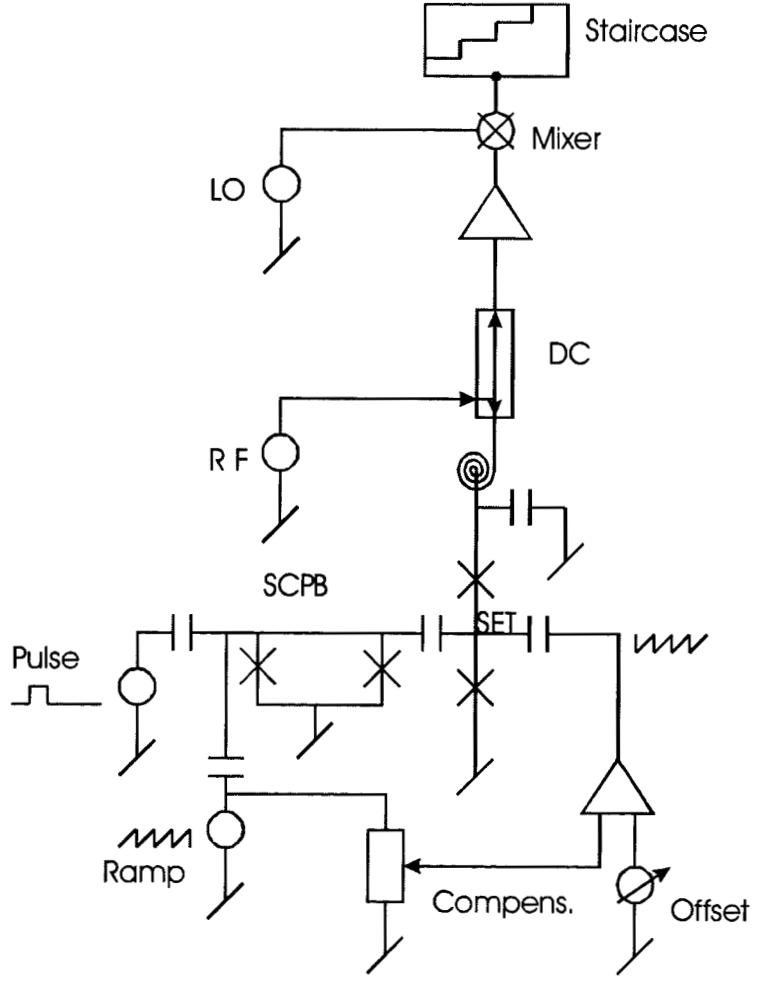
DC IV characteristics



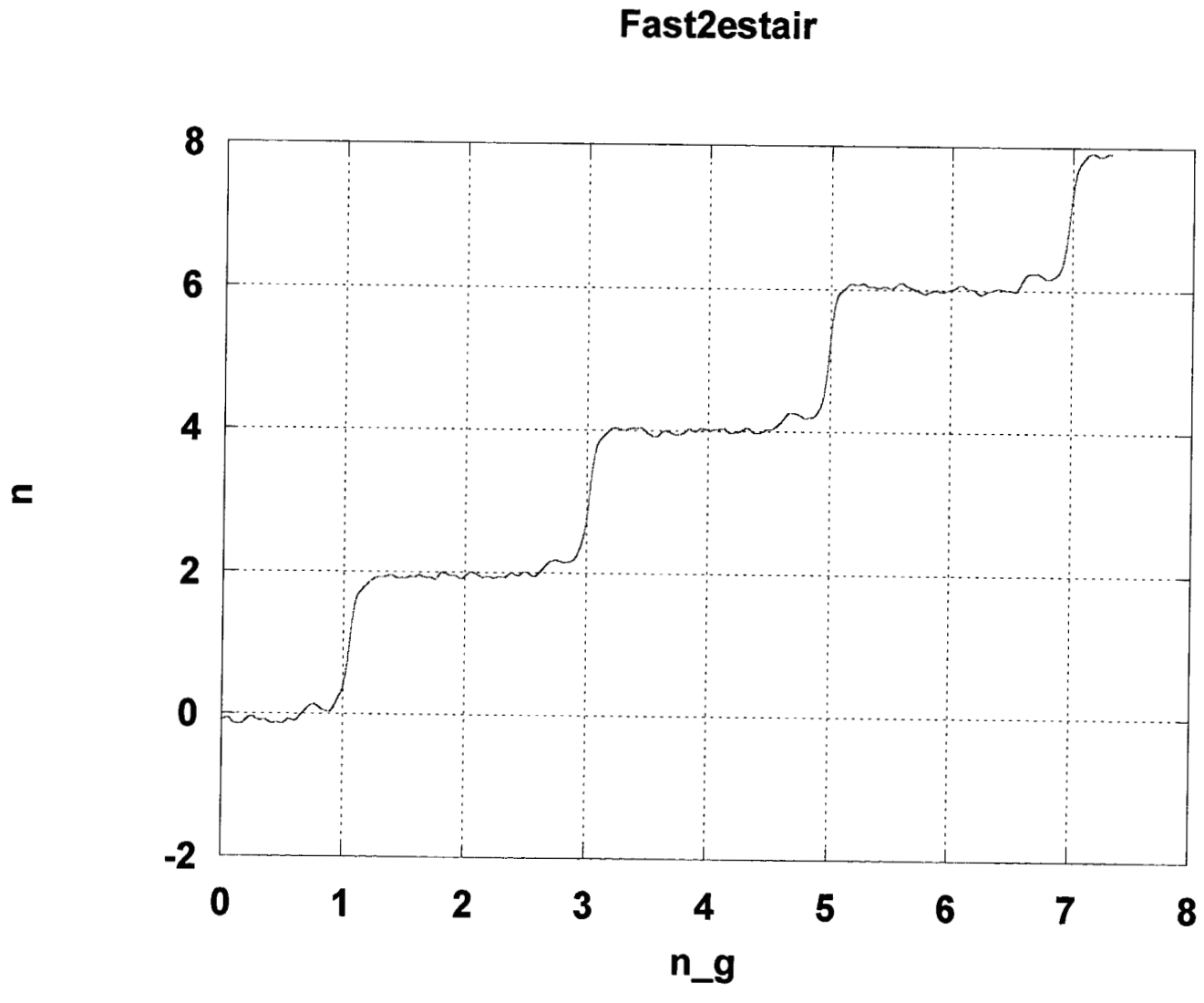
Reflected Power Spectrum for 20KHz gate modulation

Measuring the Box

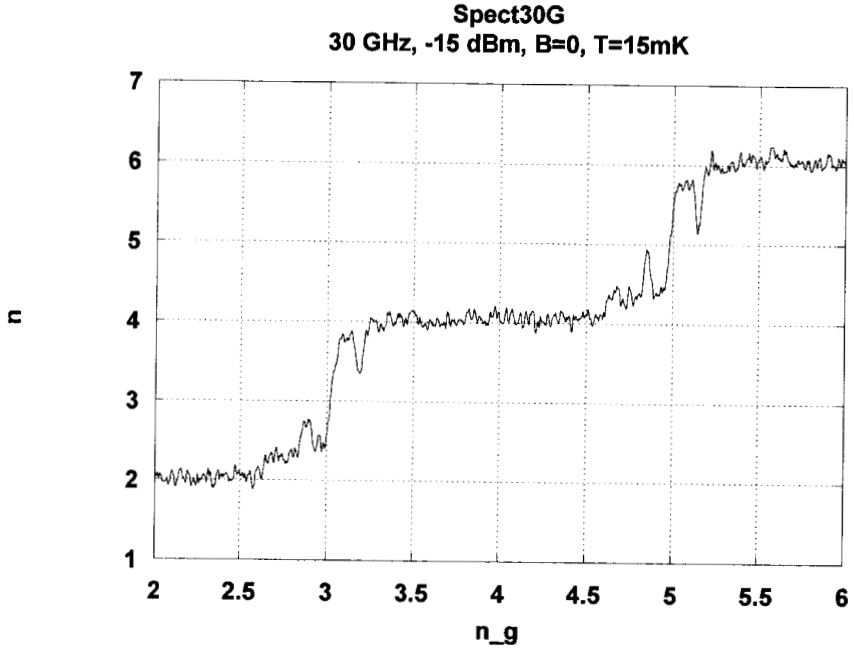
- Ramp the box gate (1200Hz)
- Compensate for cross-capacitance
- "uncompensated" signal due to electron jumps into the box
- Pulse when "operating the box"

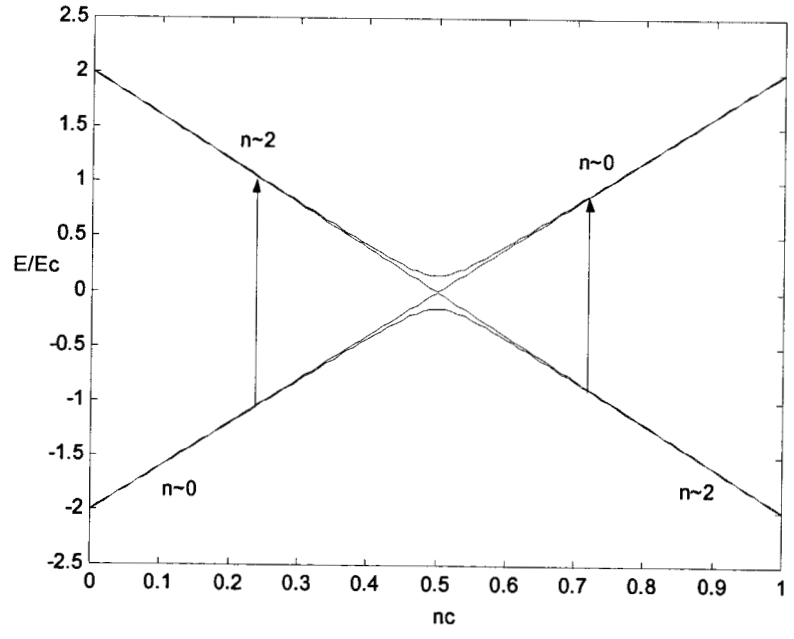


Measured Staircase



Spectroscopy





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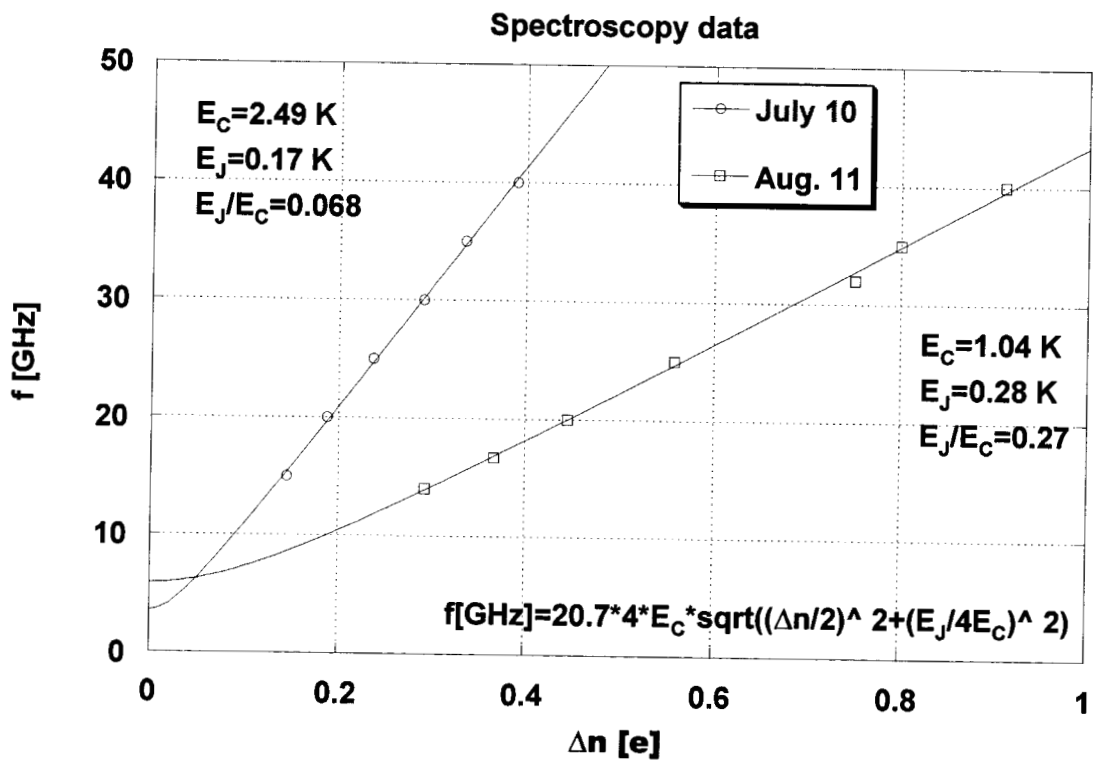
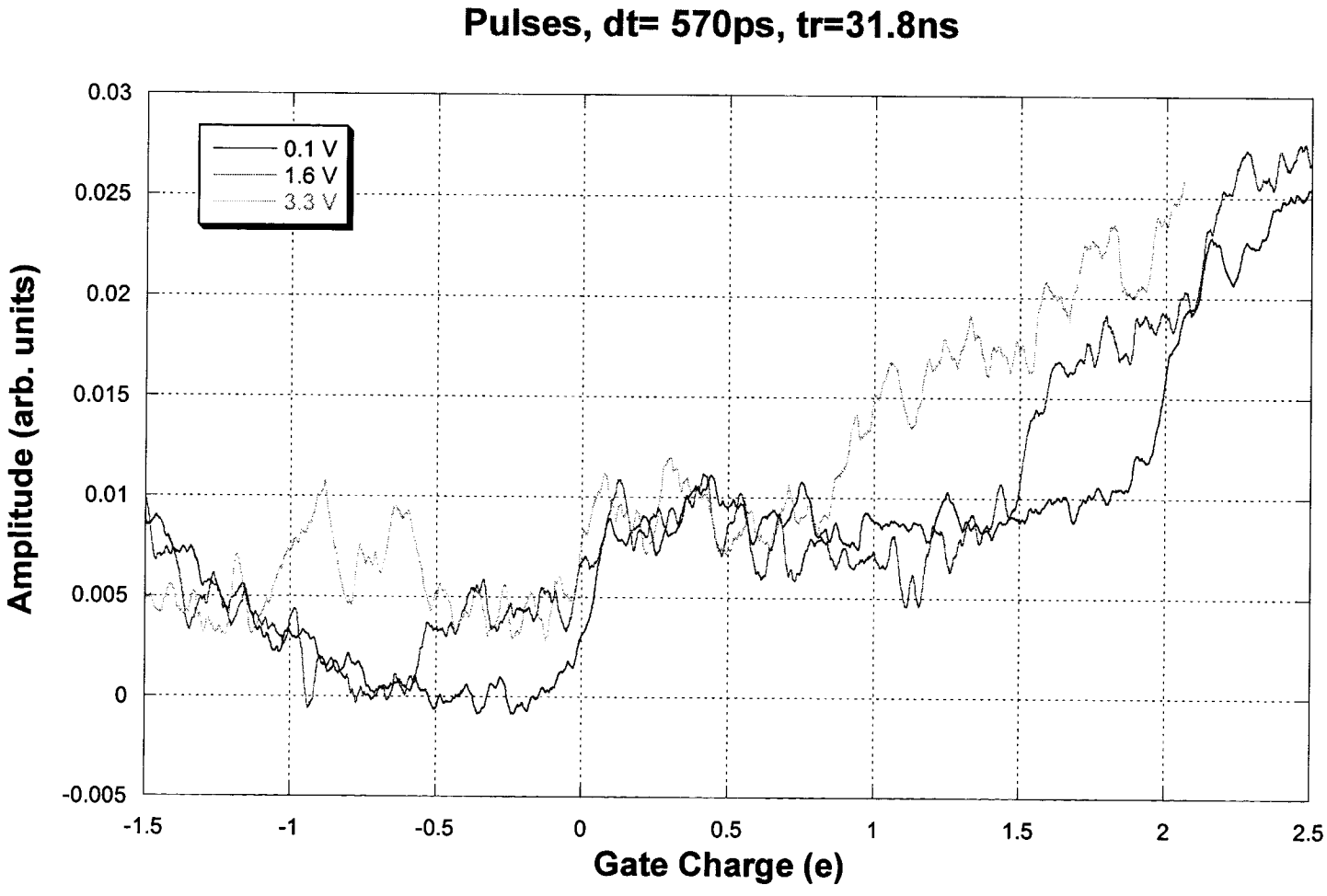
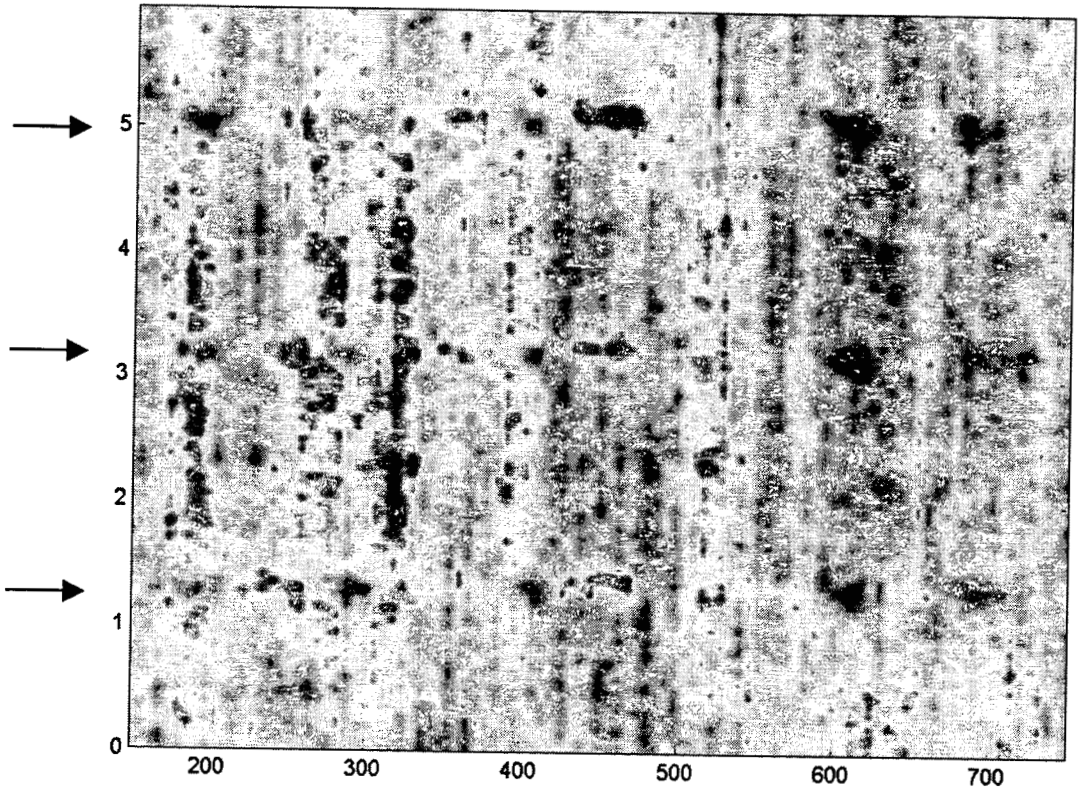


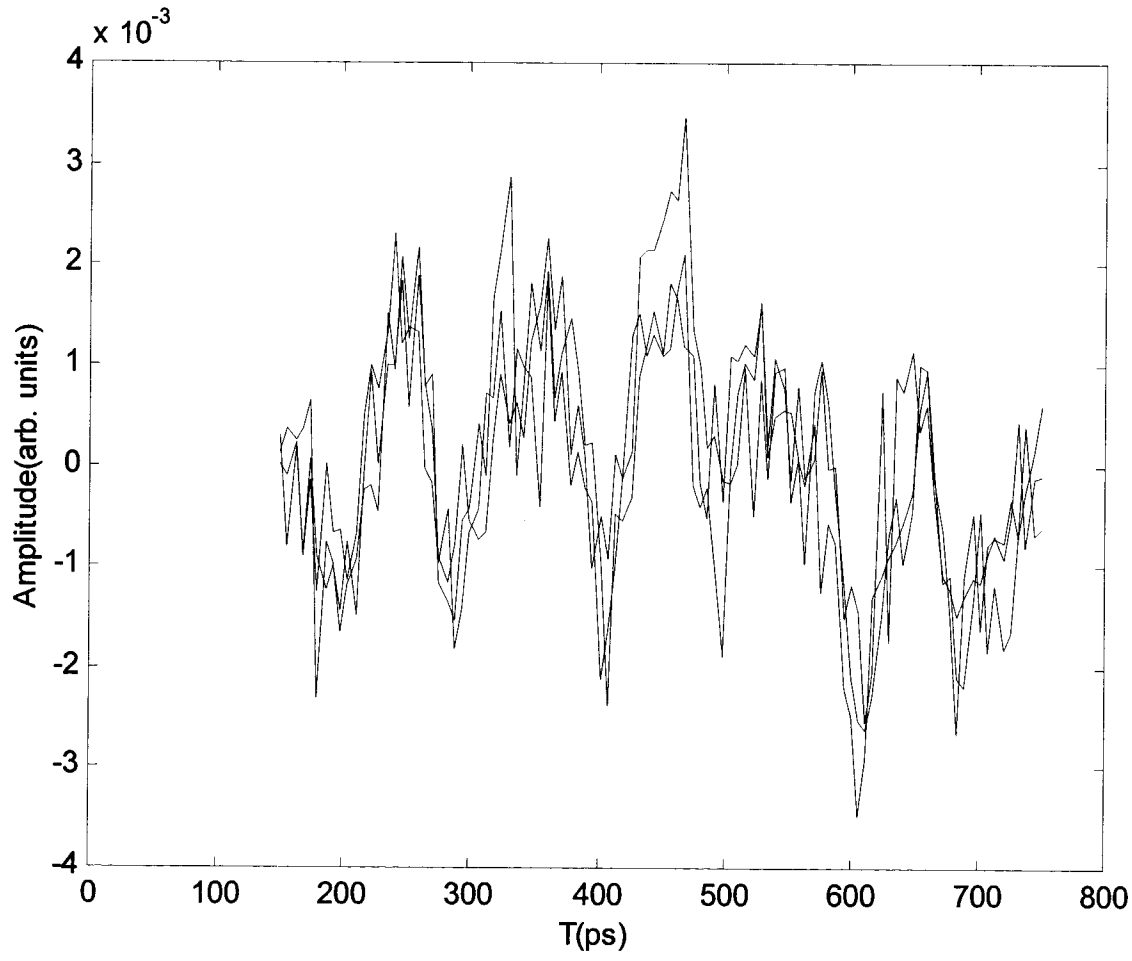
Staircase with pulses



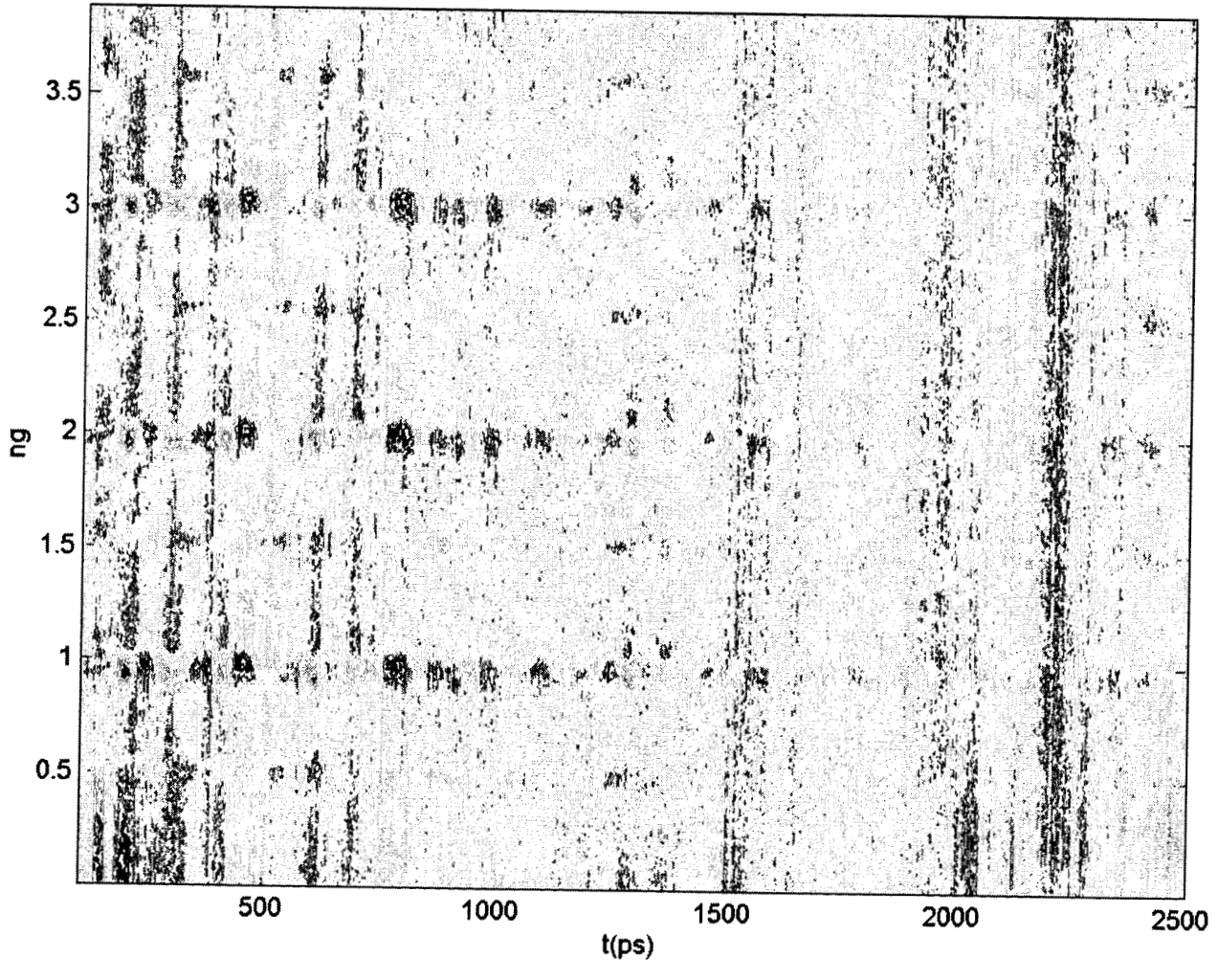
Contour plot of coherent oscillations



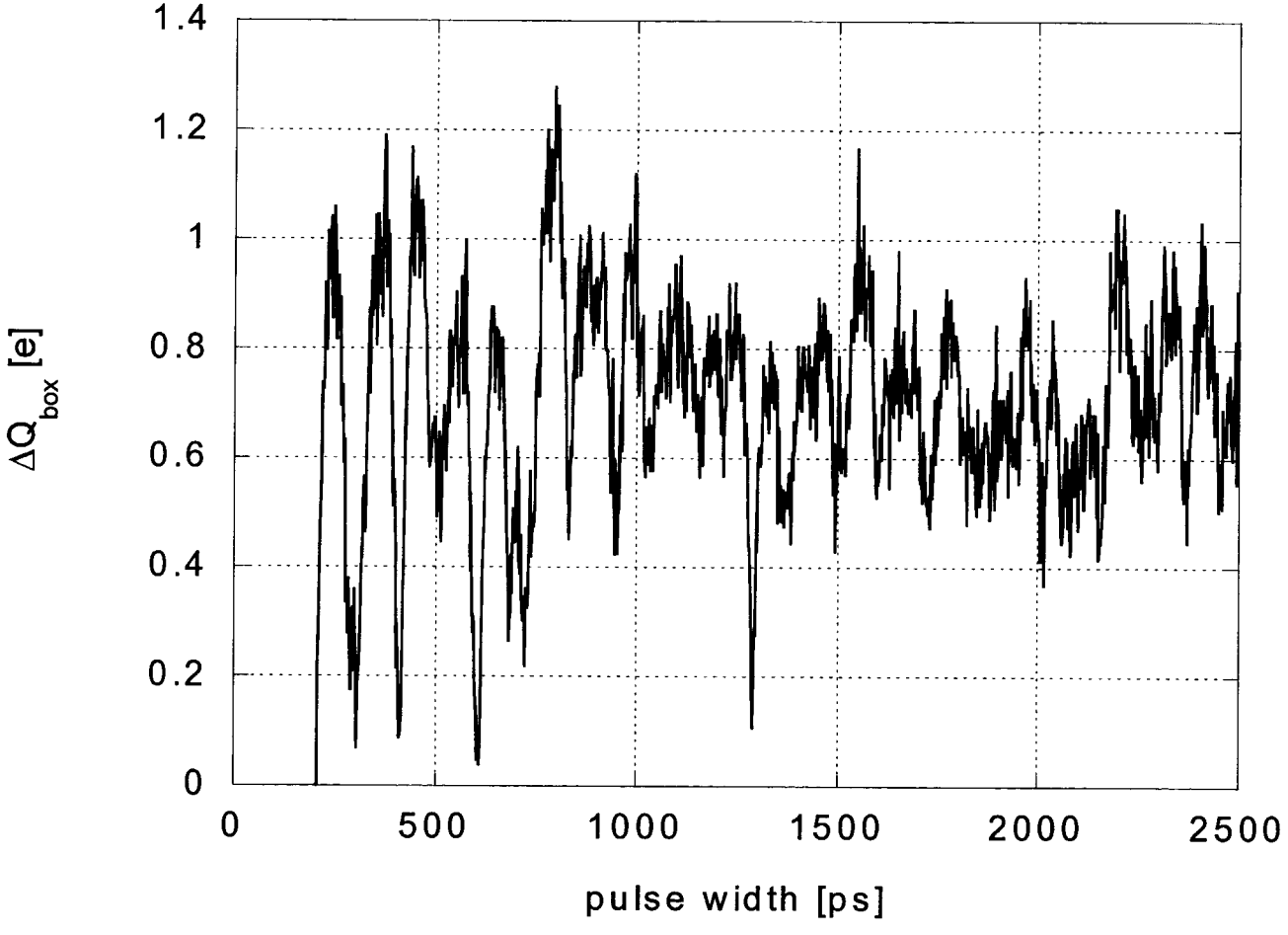
First oscillations



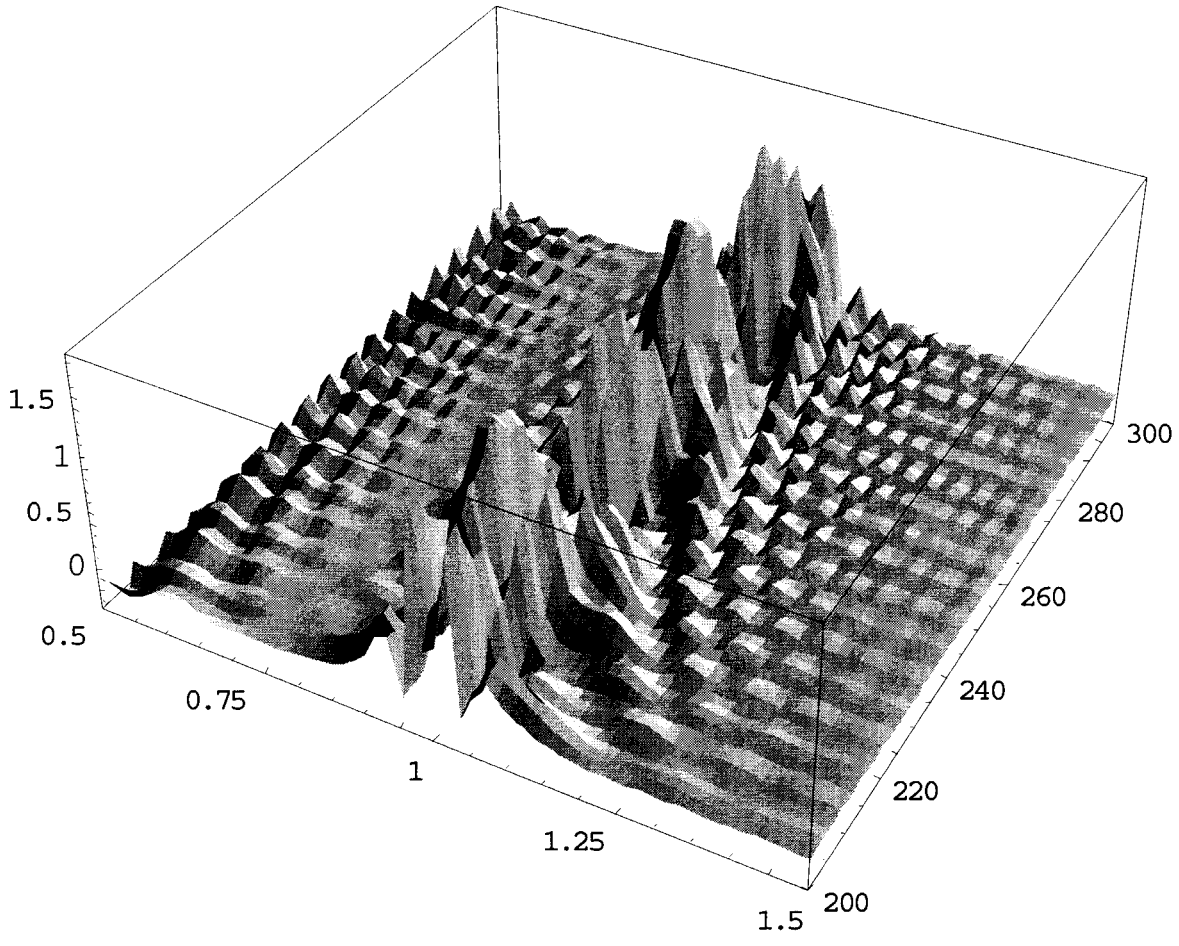
More oscillations



More oscillations



Simple Simulation



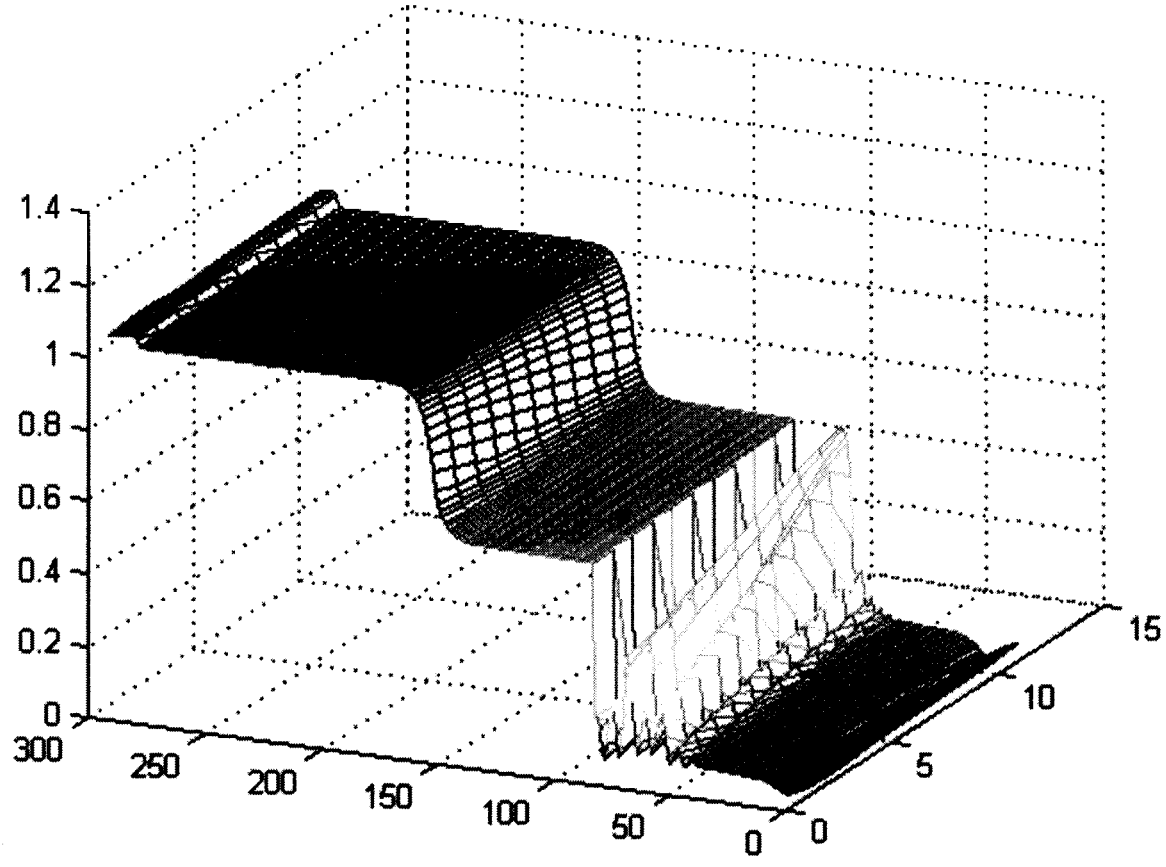
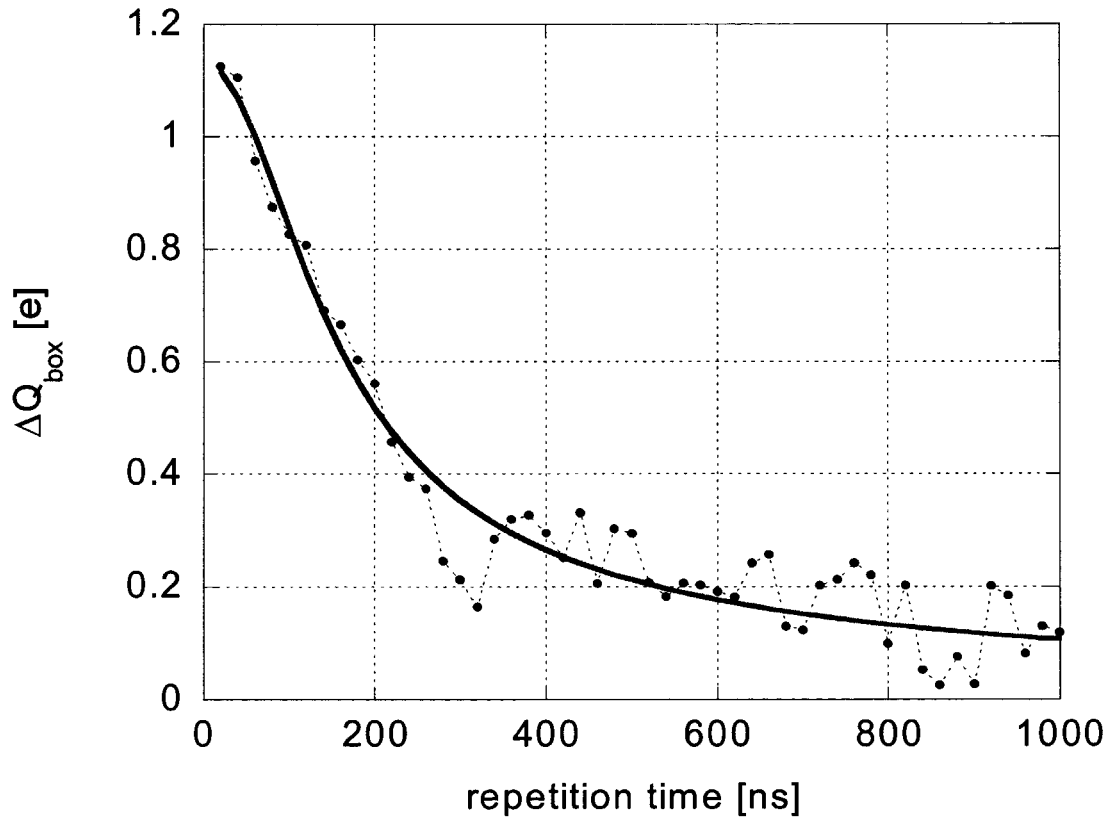
More sophisticated Simulation

Simulation by Korotkov an Hristov.

Period of oscillations much longer

"Half step"

Again frequency of oscillations increases when going away form degeneracy point



Relaxation Time