Current Measurement by Real-Time Counting of Single Charges

- Introduction, single electron counting
- Results
  - Counting of single electrons
  - Crossover from electron to Cooper-pair counting
- Summary

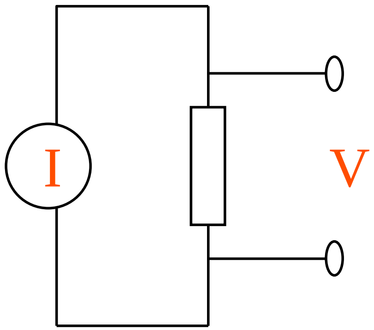
Jonas Bylander, Tim Duty and Per Delsing
Nature 434, 361 (2005)
LT 24 (2005), ISEC (2005)

Measuring current by counting single electrons

Normal current measurement

Measurement of a voltage drop across a resistor

Referenced to quantum Hall resistance and Josephson voltage



I=V/R

The COUNTer:

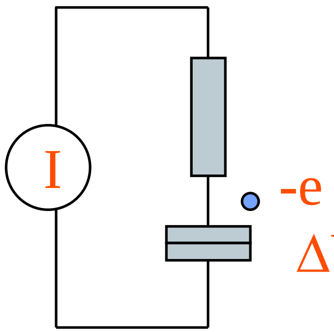
Counts the electrons one by one that are passing through a circuit

Can be coupled in parallel

$f_{SET}=I/e$

1-10Hz<f<10MHz

1aA<I<1pA

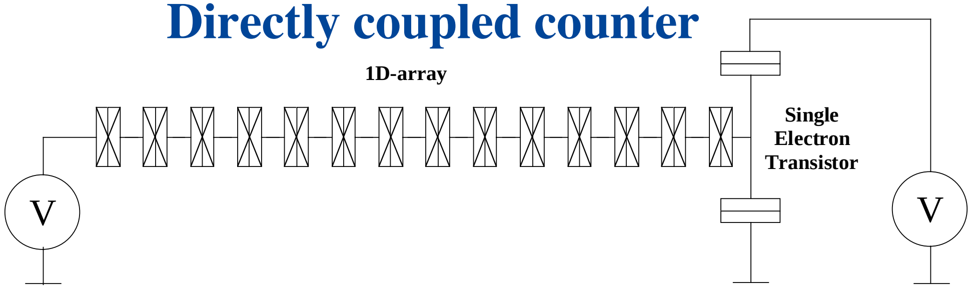


Suggestions for electron counters by Likharev, Visscher, Teunissen et al.

Coupling the array to the SET

As charge in the array approaches the SET the current in the SET is modulated.

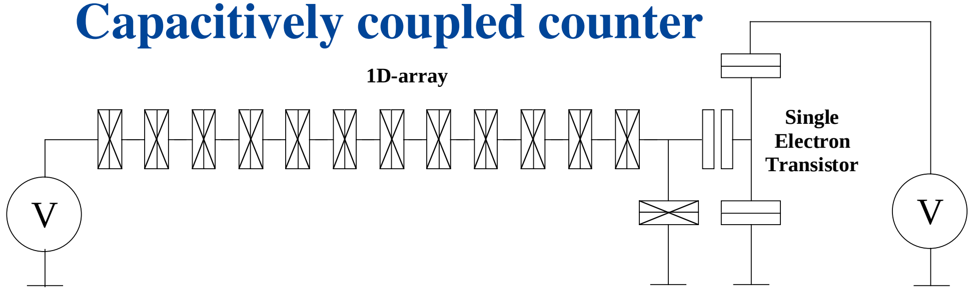
Directly coupled counter



Direct coupling gives full *e* charge

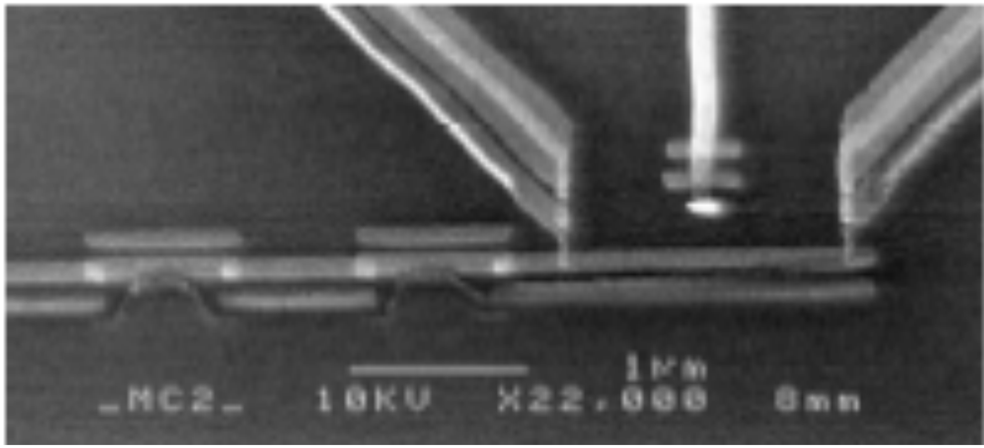
and thus better Signal to noise

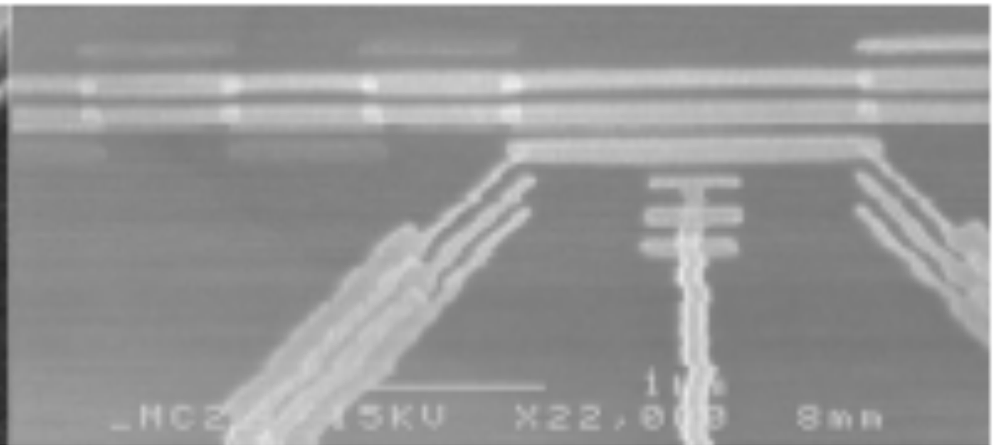
Capacitively coupled counter



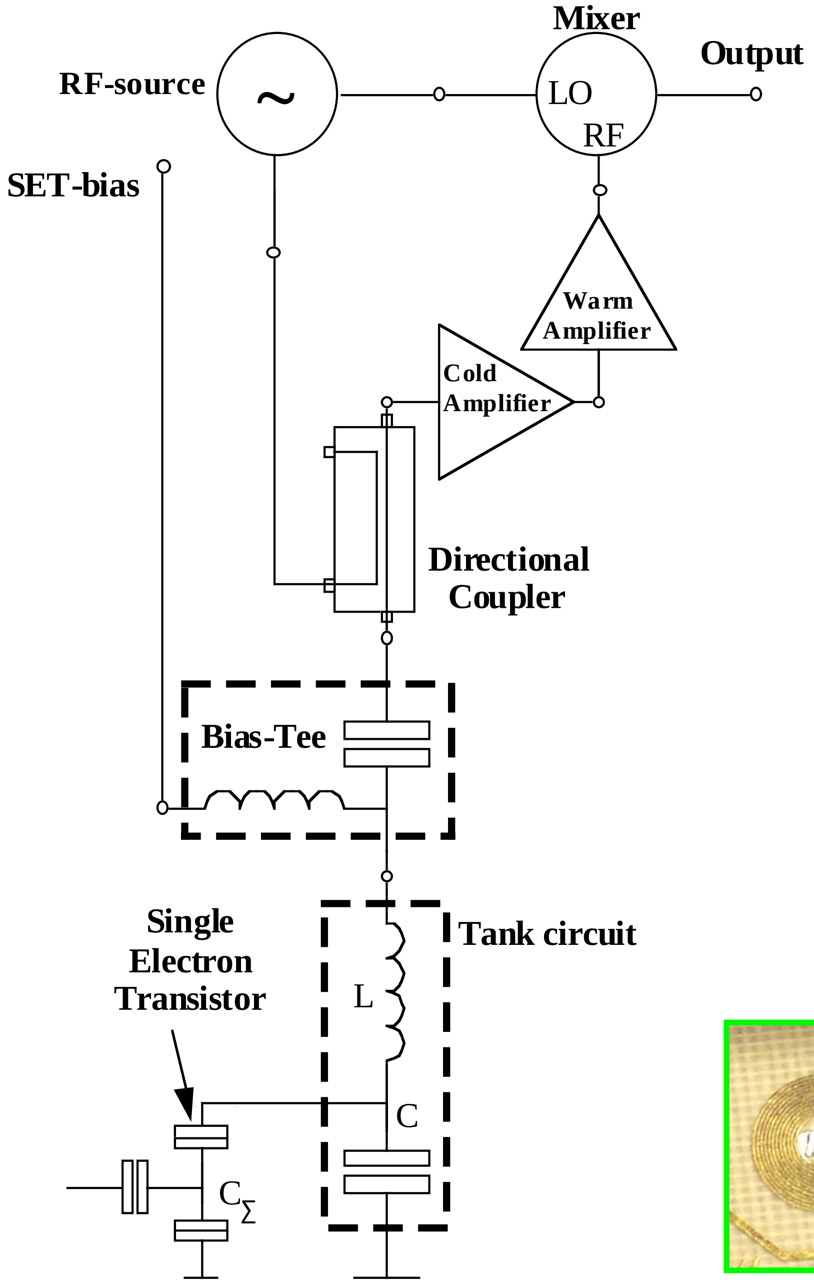
Capacitive coupling, more linear

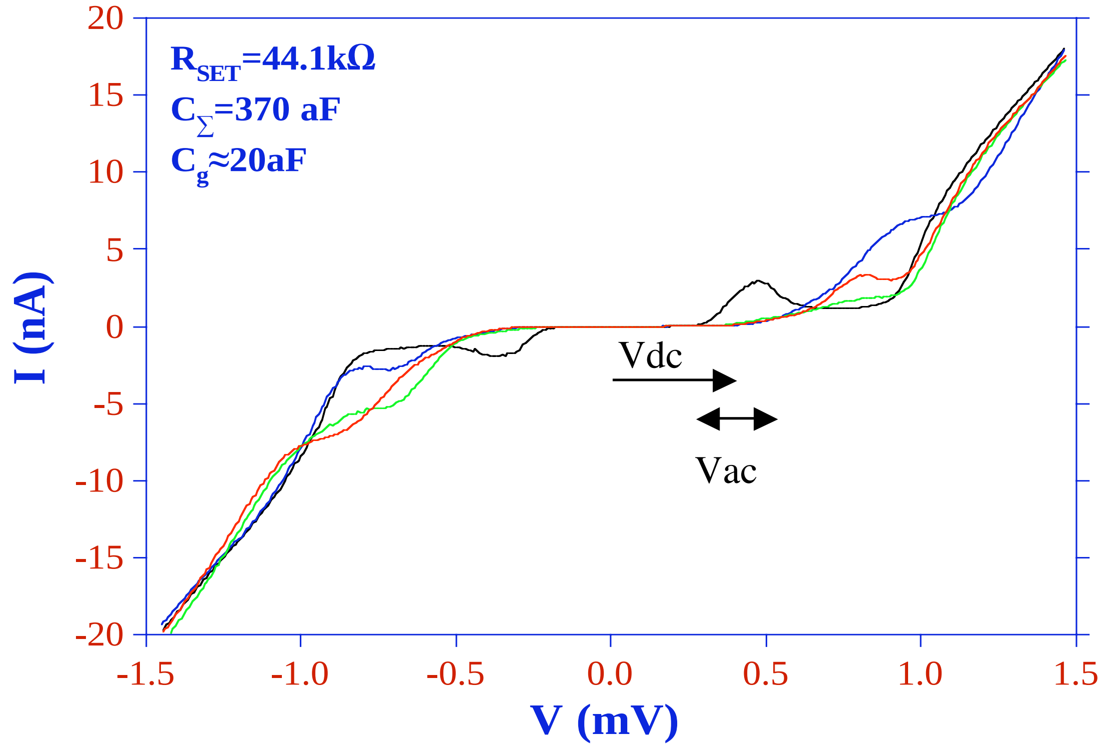
Eliminates back tunneling

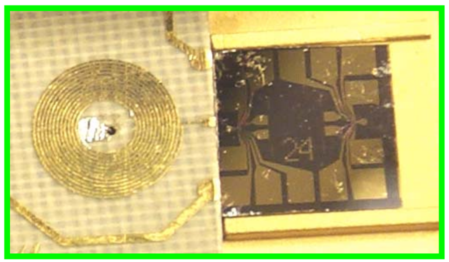




The Radio-Frequency Single Electron Transistor



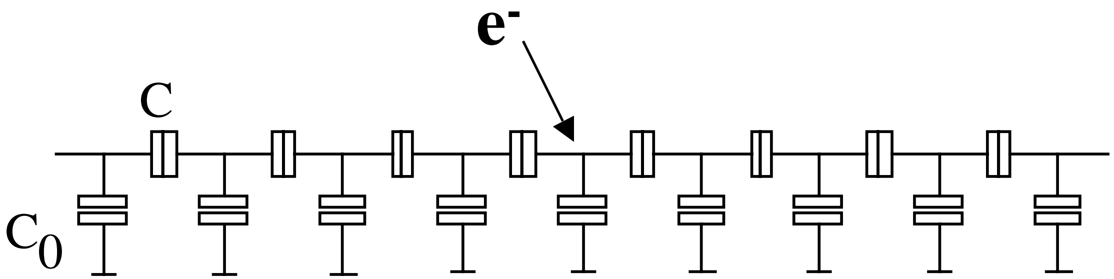


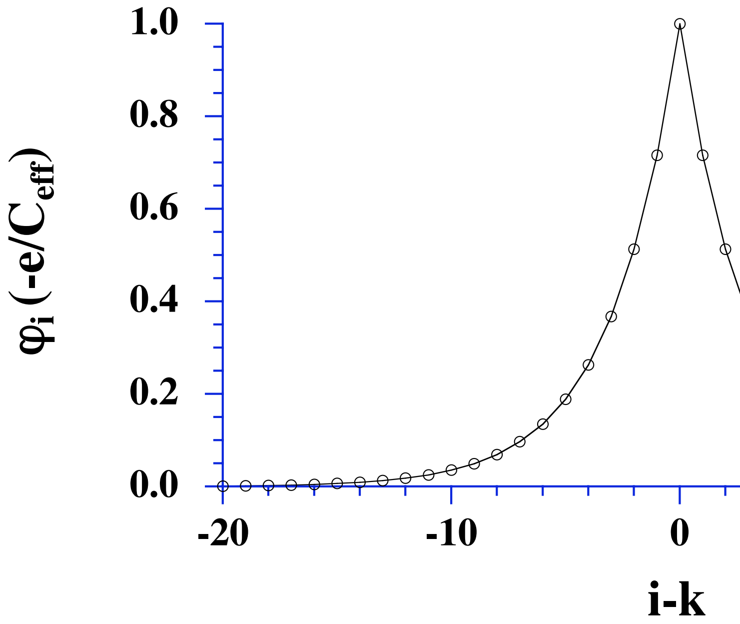


Very high speed: 137 MHz
R. Schoelkopf, et al. Science (98)

Charge sensitivity: ∂Q= 3.2 μe/√ Hz
Aassime et al., APL 79, 4031 (2001)

The 1D-array





$$\varphi_i = \frac{e}{C_{eff}} e^{-|i-k|/\Lambda}$$

Placing a single electron on one of the electrodes polarizes the array and gives rise to a **"Charge soliton"**

These charge solitons repel each other and thus line up in a **1D quasi Wigner lattice**

Spatial correlation transfers to **time correlation**

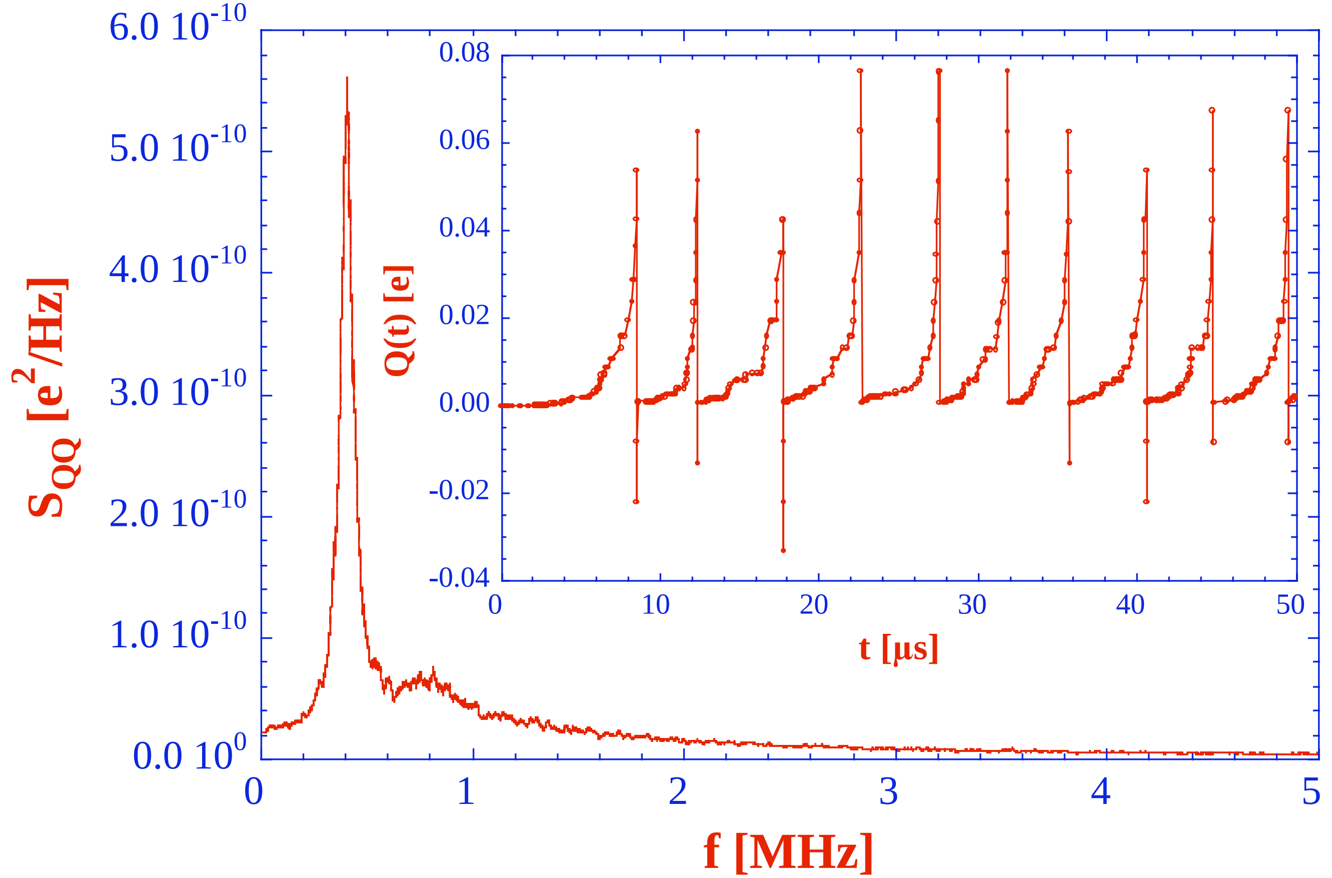
Soliton size

$$\Lambda = \sqrt{\frac{C}{C_0}}$$

Bakhvalov et al, Zh. Eksp. Teor. Fiz. (1989))

Simulations

We expect to see a time signal at the output of the SET which has a frequency $f_{SET}=I/e$, *i.e.* SET-oscillations.

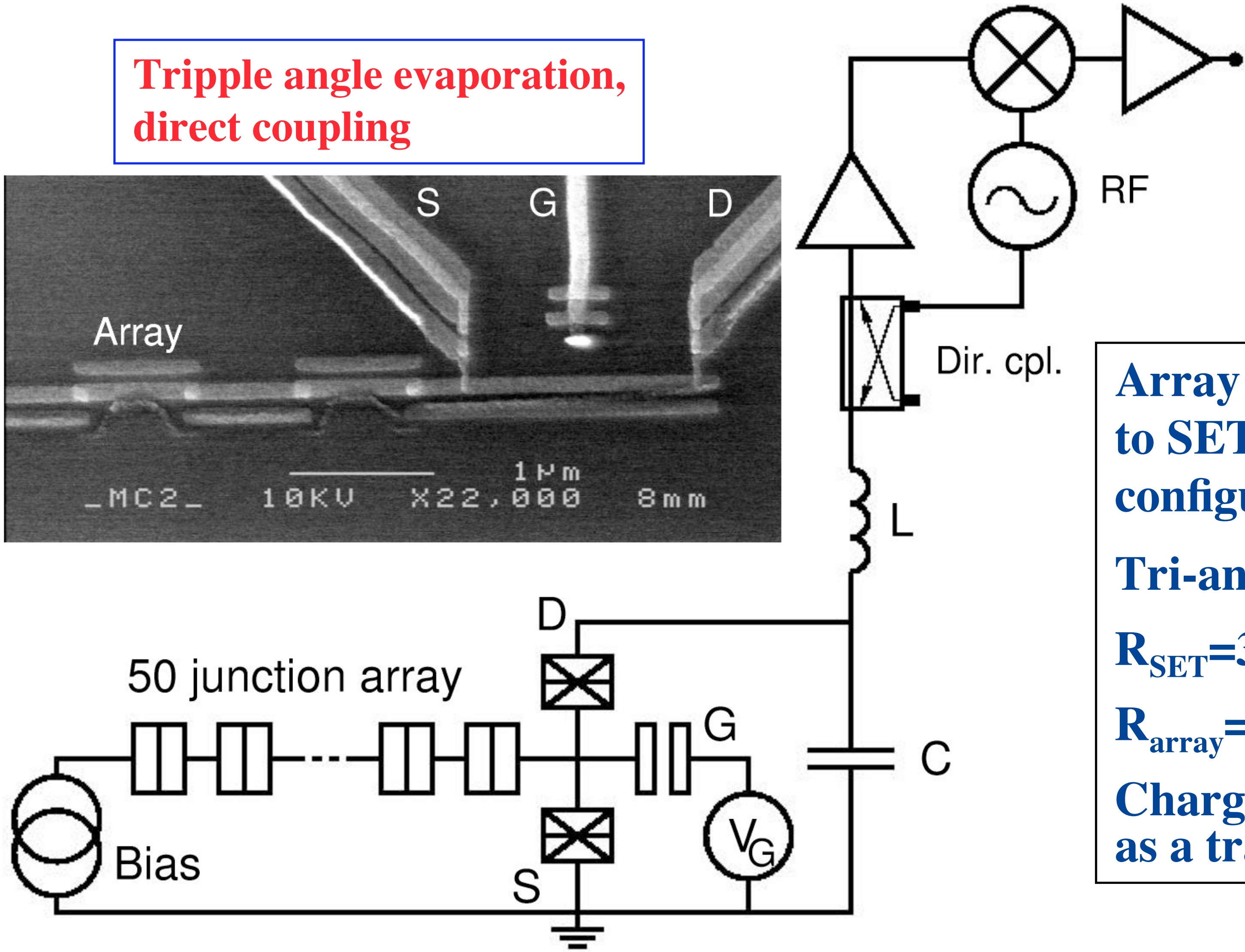


50 junctions
I= 250 fA
T=0

Capacitive coupling

The Single Electron Counter

Tripple angle evaporation, direct coupling



Array coupled directly to SET, *i.e.* R-SET configuration

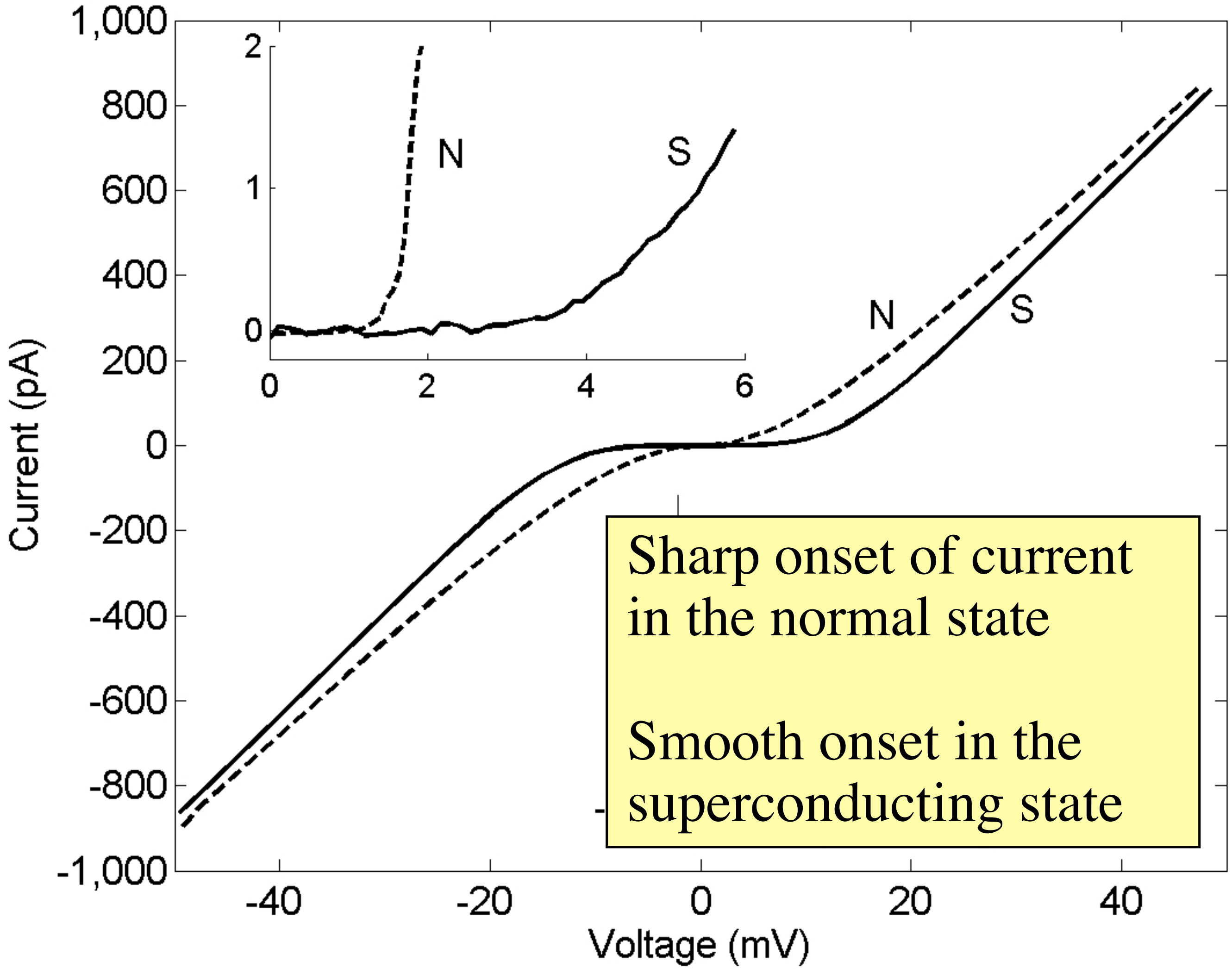
Tri-angle evaporation

R_{SET}=30kΩ

R_{array}=940kΩ/jcn

Charge solitons line up as a train in the array

Current-Voltage Characteristics of the Array



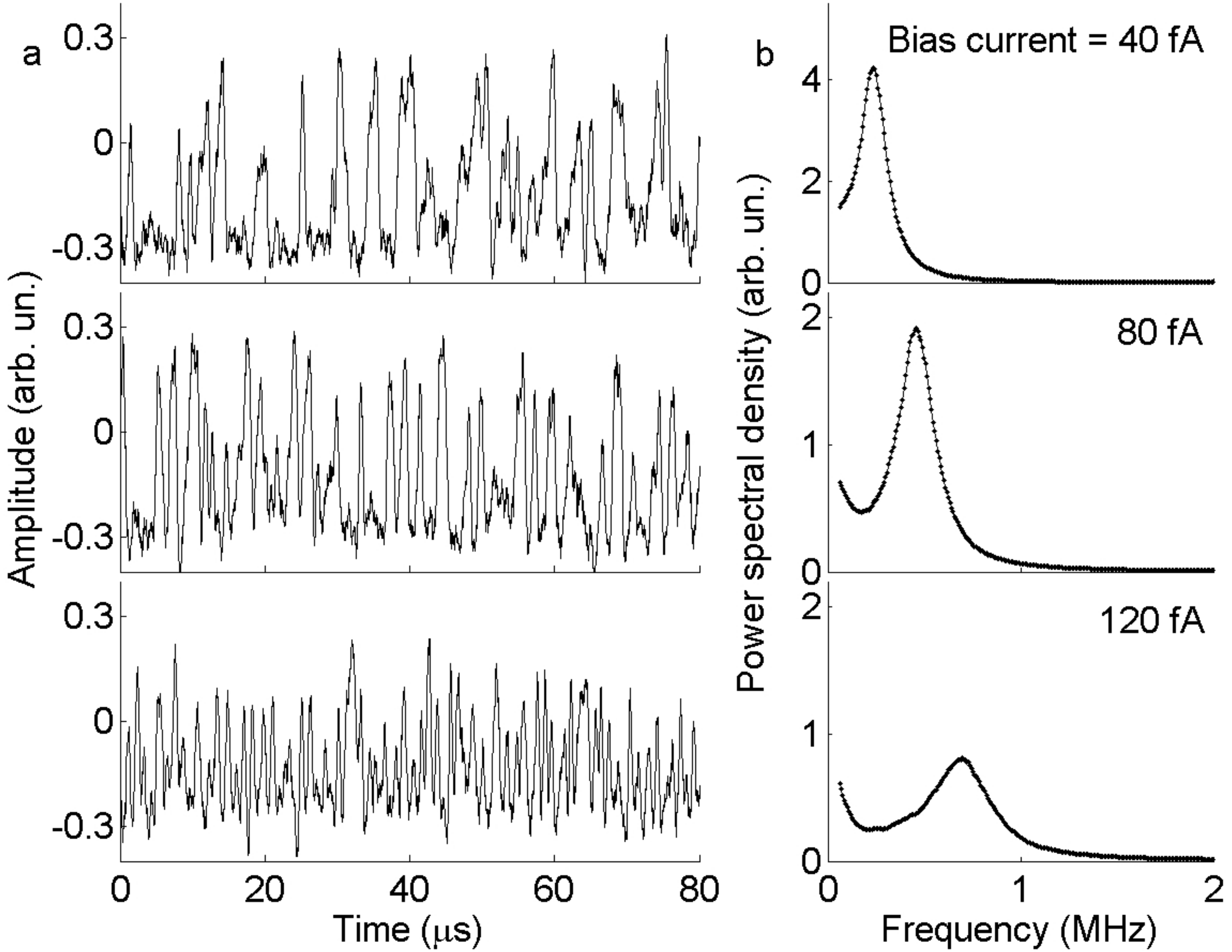
Sharp onset of current in the normal state

Smooth onset in the superconducting state

R_{jcn}=940kΩ
E_C≈2.2K
E_J≈6mK

Counting in the SC-state gives a more stable current.
B=475mT
Bc=650mT

Counting in Time and Frequency Domain



Direct observation of the SET-oscillations

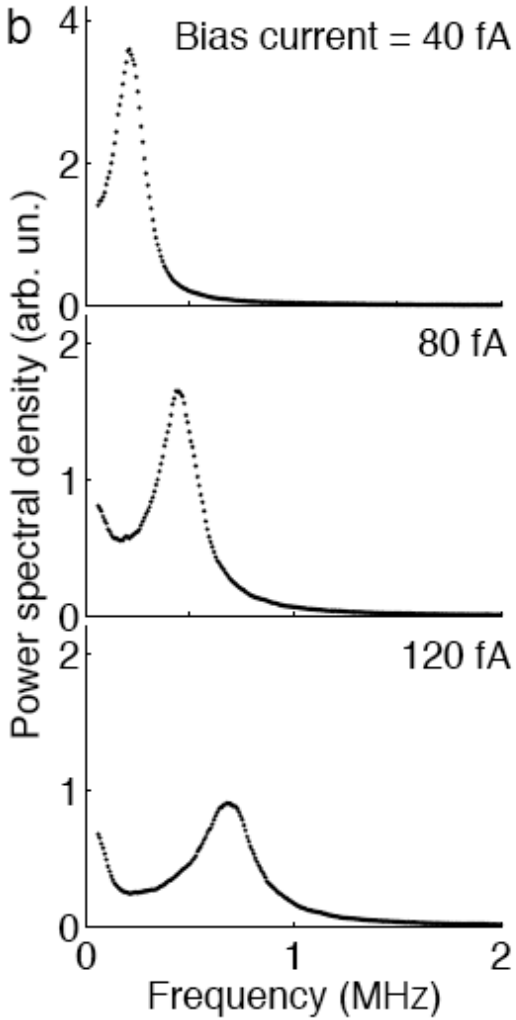
$f_{SET} = I/e$

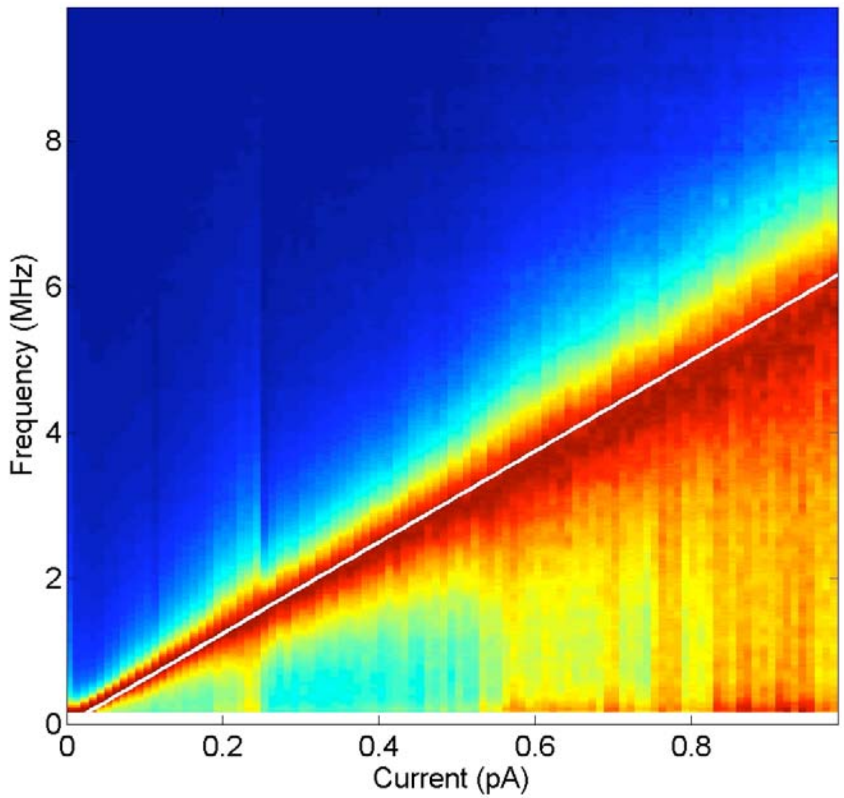
Time resolved counting of single electrons

Ben-Jacob, Gefen Phys. Lett. (1985)
Averin, Likharev JLTP (1986)

Bylander, Duty, Delsing Nature 434, 361 (2005)

Comparing Current with Frequency





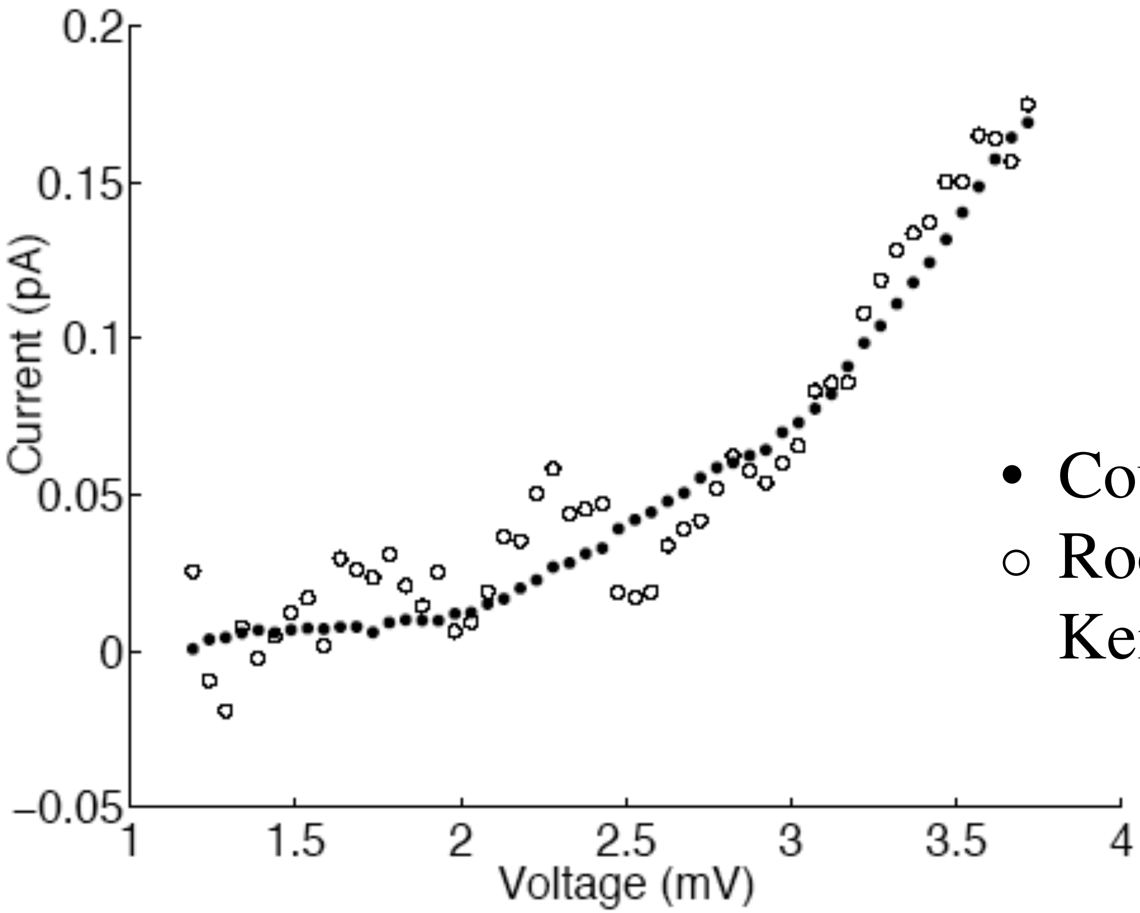
The red ridge corresponds to the peak in the frequency spectra

Peak heights have been normalized

White line is $f_{SET}=I/e$

5fA to 1pA

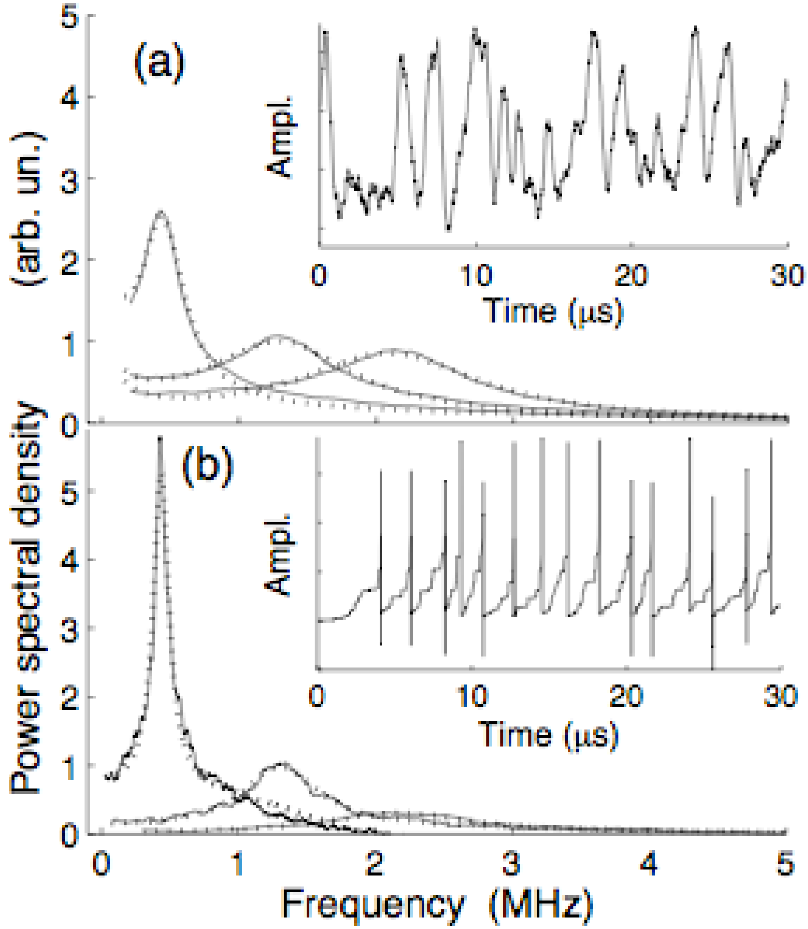
Comparing Room Temperature measurement with counter



- Counter
- ○ Room temp am-meter Keithley Calibrator/source

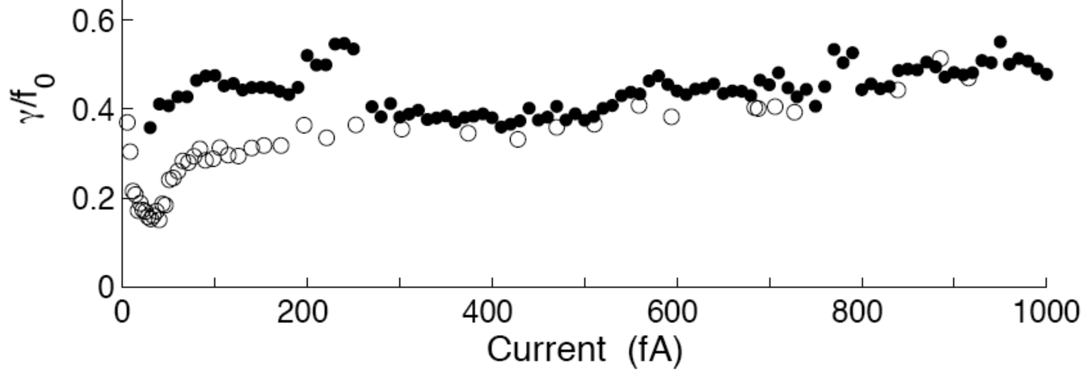
Line width of the oscillations

Measurement



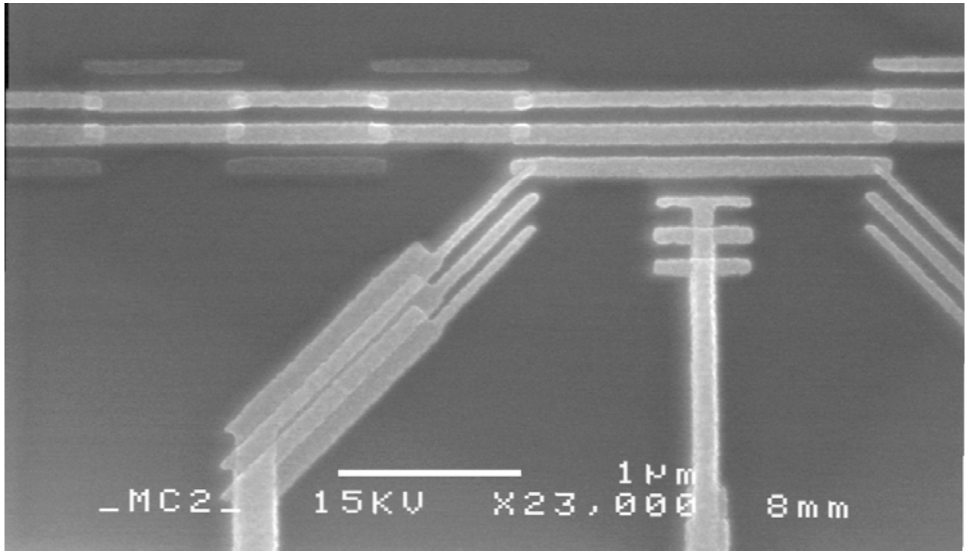
Simulation

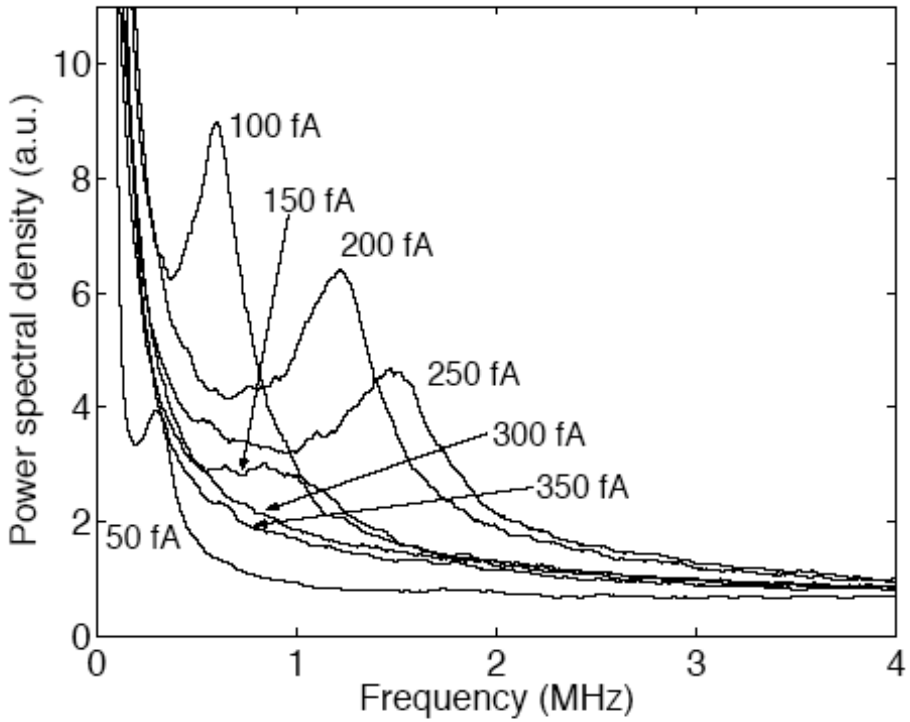
Normalized line width

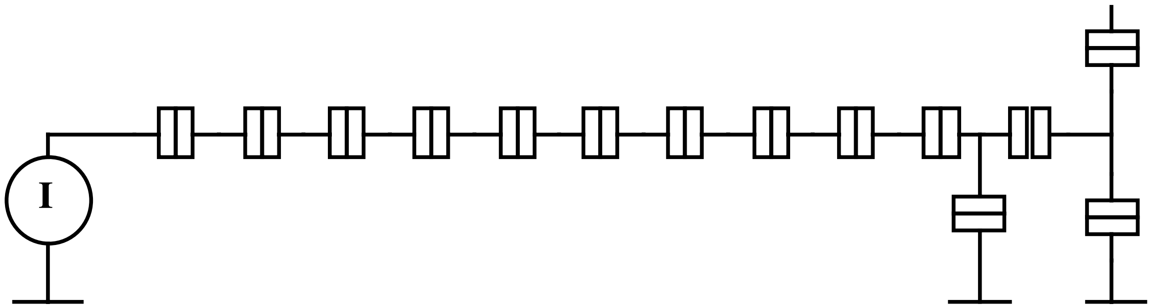


The line width is can be well fitted to a Lorentzian shape.
The measured line width agrees very well with the simulated line width.
At low current there is an additional broadening, probably due to uncertainty in the bias.

The capacitively coupled counter



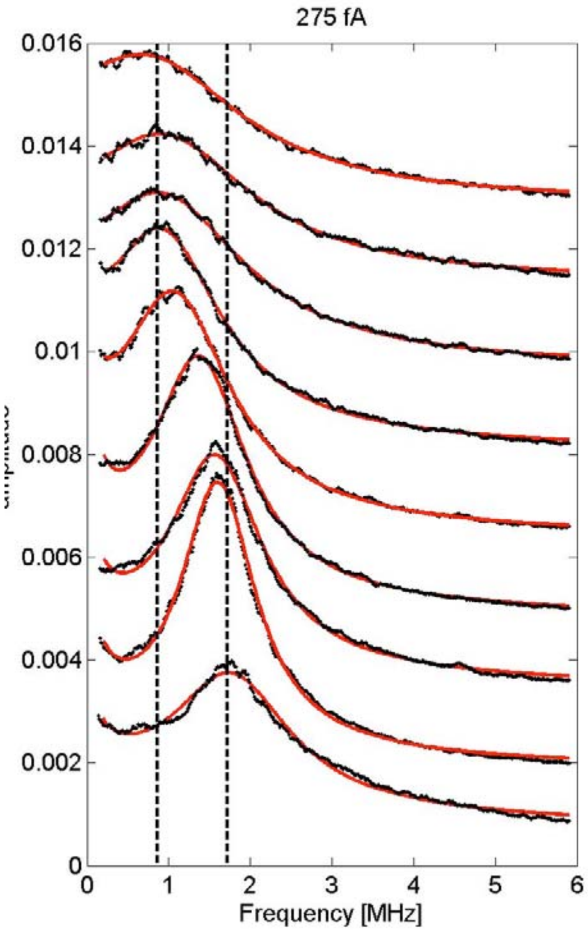




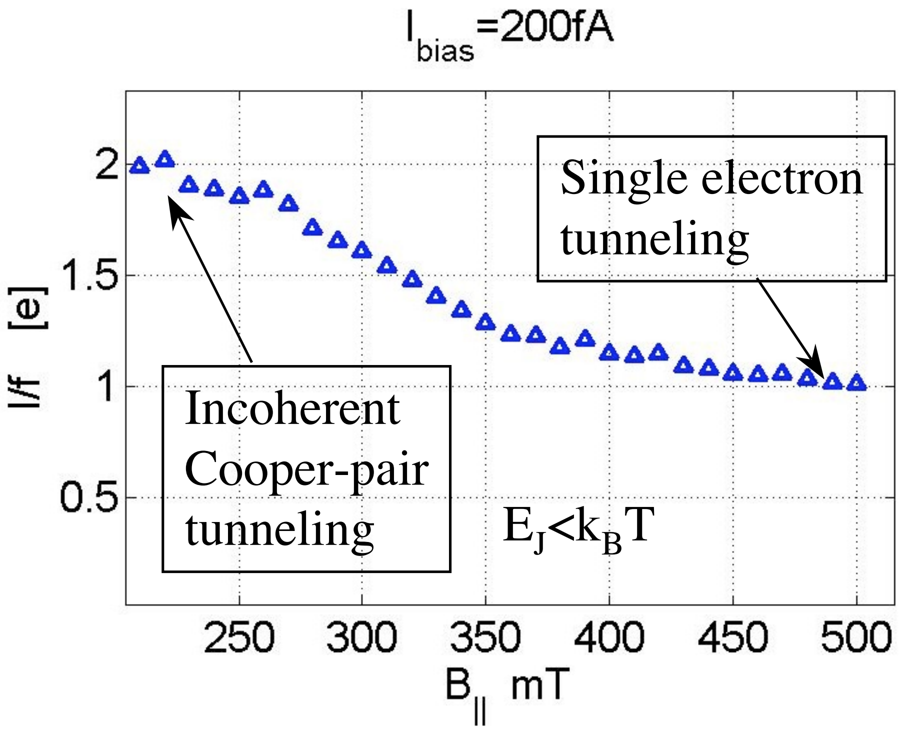
Response is more linear,
Signal to noise is not so good.

Crossover from electron to Cooper-pair counting

Power spectra for several different magnetic fields 200-500 mT



Q_{count} = Current divided by f_{peak}



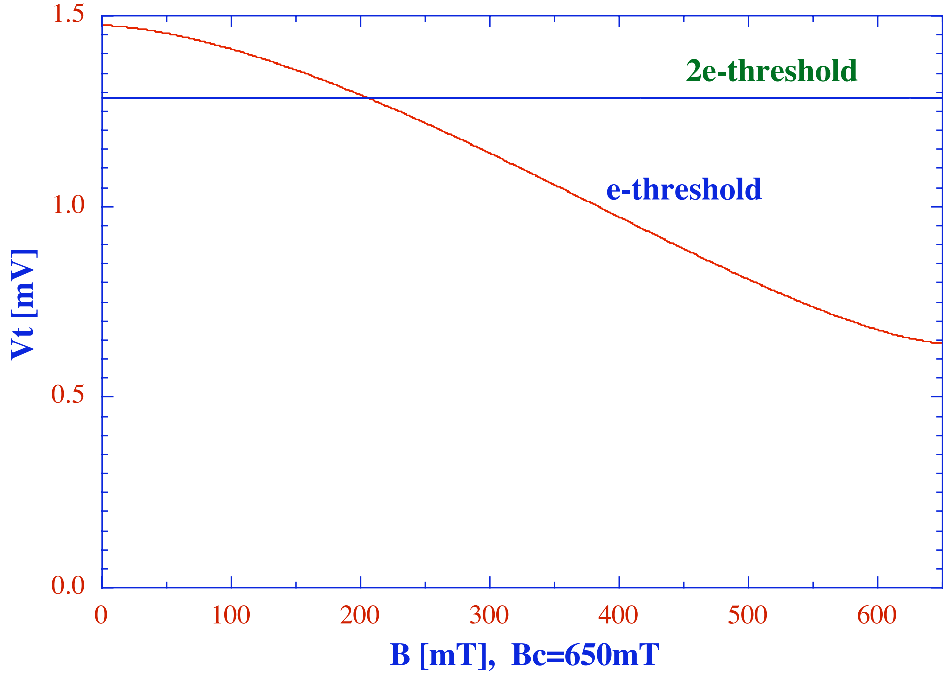
$E_J/k_B \approx 5$ mK
$T \approx 150$ mK

Duty, Bylander, Delsing in preparation

Crossover from electron to Cooper-pair counting

Whether electrons or Cooper-pairs tunnel in the array depends on the threshold voltage. When the voltage is higher than both thresholds, the rates become important.

The threshold voltages depend on magnetic field (and background charge)



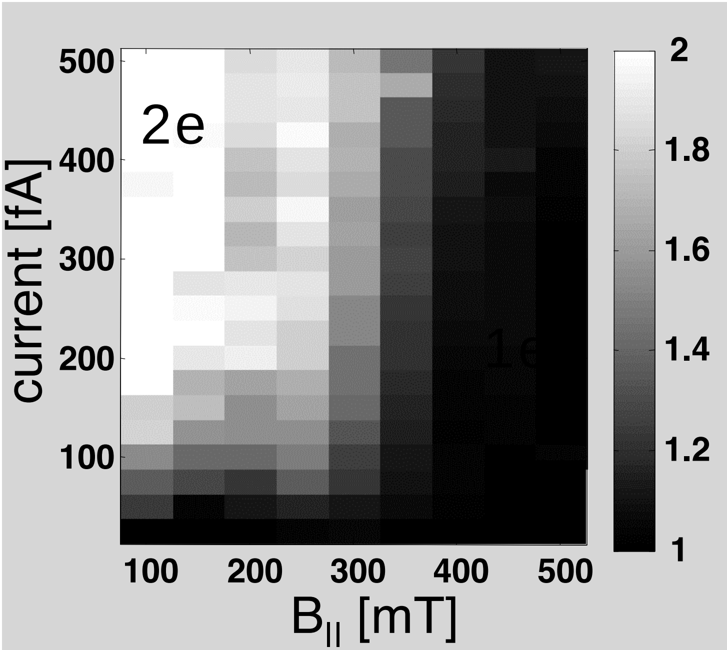
When the voltage exceeds both injection thresholds, the tunneling probablities will start to be important.

$$\frac{\Gamma_e}{\Gamma_{2e}} = ?$$

The Tunnel probabilities depend on energy gap and (subgap-) resistance, and on back ground charges ….

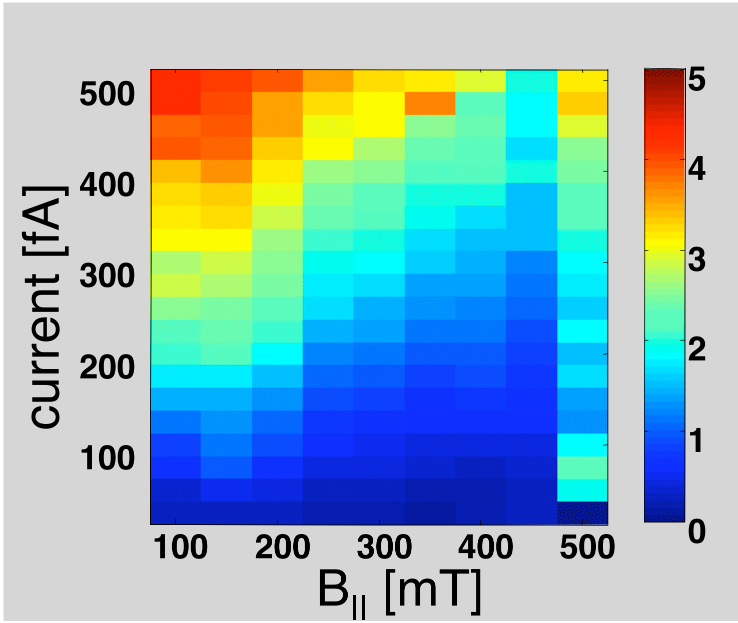
Crossover from electron to Cooper-pair counting

$<n> = I/ef$



1e both at low voltage and high field

Peak width γ/f_{peak}



1e peaks are more narrow

Upper and lower current limits

Minimum counting rate

At low currents only one electron is present in the array, spatial and thus temporal correlation is lost

Current stability will smear the peak in the frequency domain.

Maximum counting rate

To maintain time correlation the current needs to be low, typically $I < 0.03\ e/RC$

Speed of the RF-SET, in our case ~10MHz.

Future directions

- Improving signal to noise, Squid amplifier
- Coherent versus incoherent 2e, Bloch oscillations
- Accuracy, how small currents can we measure
- Larger currents, parallel counters
- Looking at other systems, nanotubes, nanowires ….
- Counting statistics, (linear detectors)…