Coherent and incoherent charge pumping with Coulomb blockade devices

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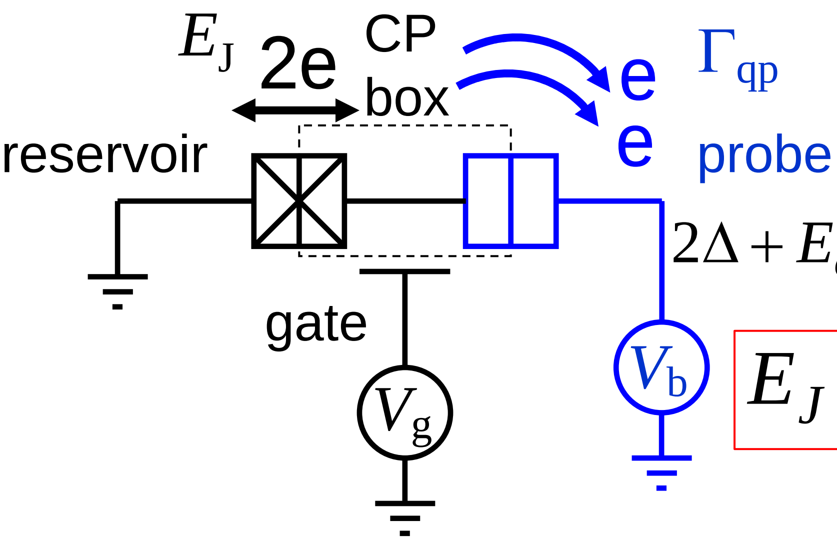
Chernogolovka - 19 June 2012

Coherent Cooper pair pumping using nonadiabatic voltage pulses

F. Hoehne et al., arXiv:1109.5543 (2011)
PRB 85, 140504(R) (2012)

Nonadiabatic qubit manipulation with probe readout

Nakamura, Pashkin, Tsai, Nature (1999)



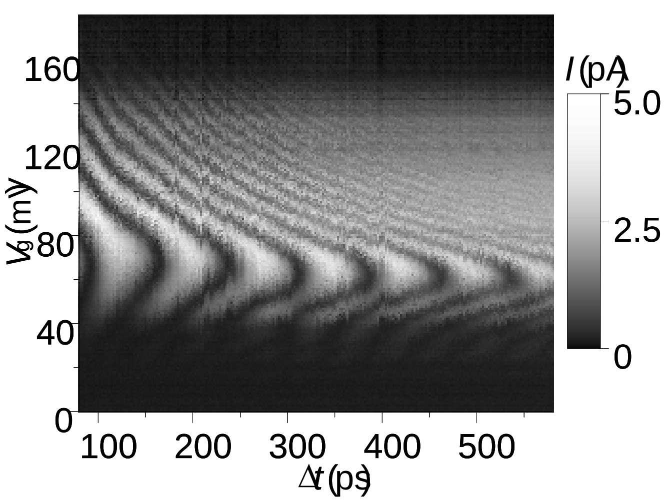
Josephson-quasiparticle (JQP) cycle

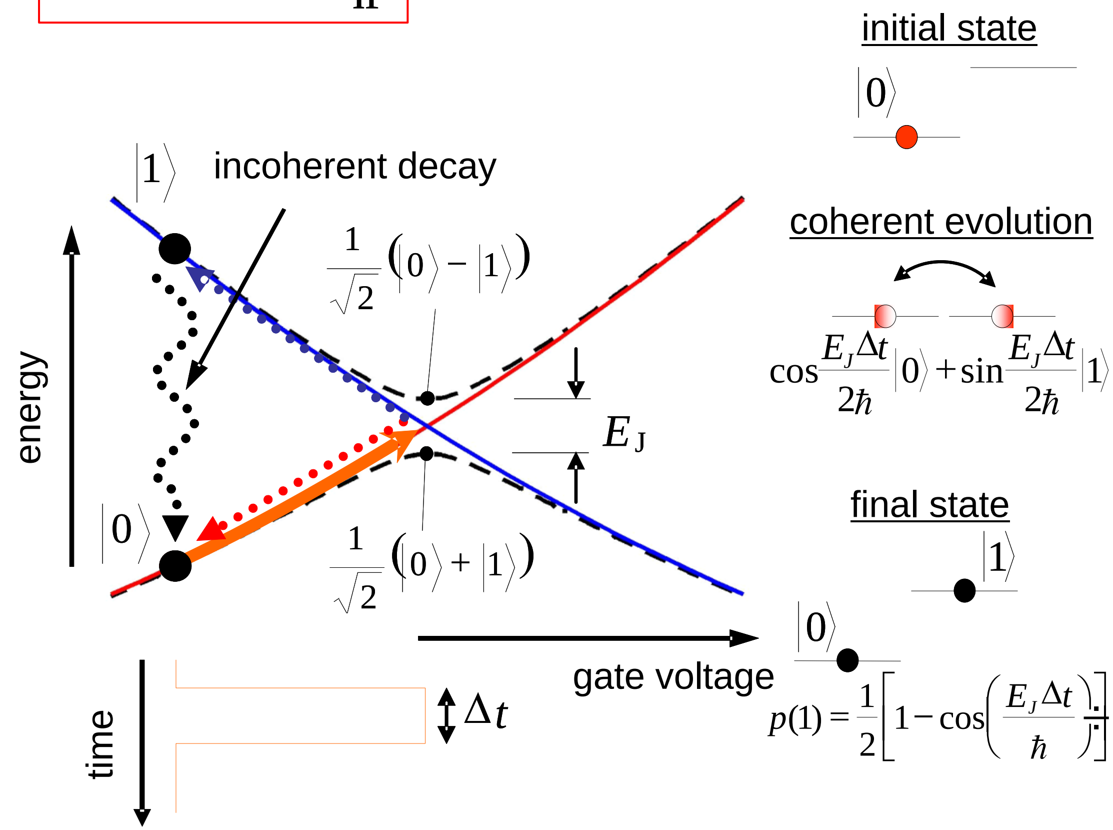
Fulton et al. (1989)

$$2\Delta + E_C < eV_b < 2\Delta + 3E_C$$

$$\boxed{E_J >> \hbar\Gamma_{qp}}$$

coherent evolution through one junction, incoherent decay through the other

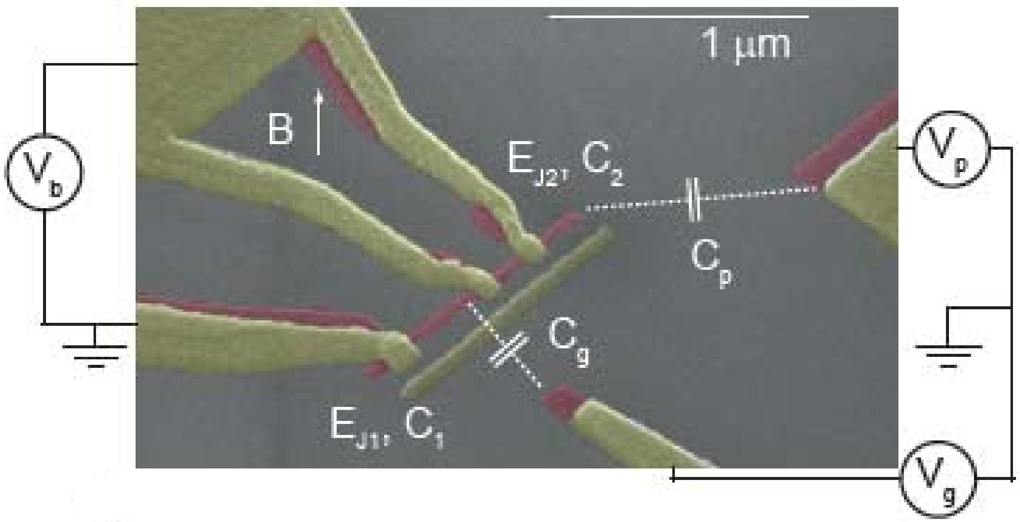




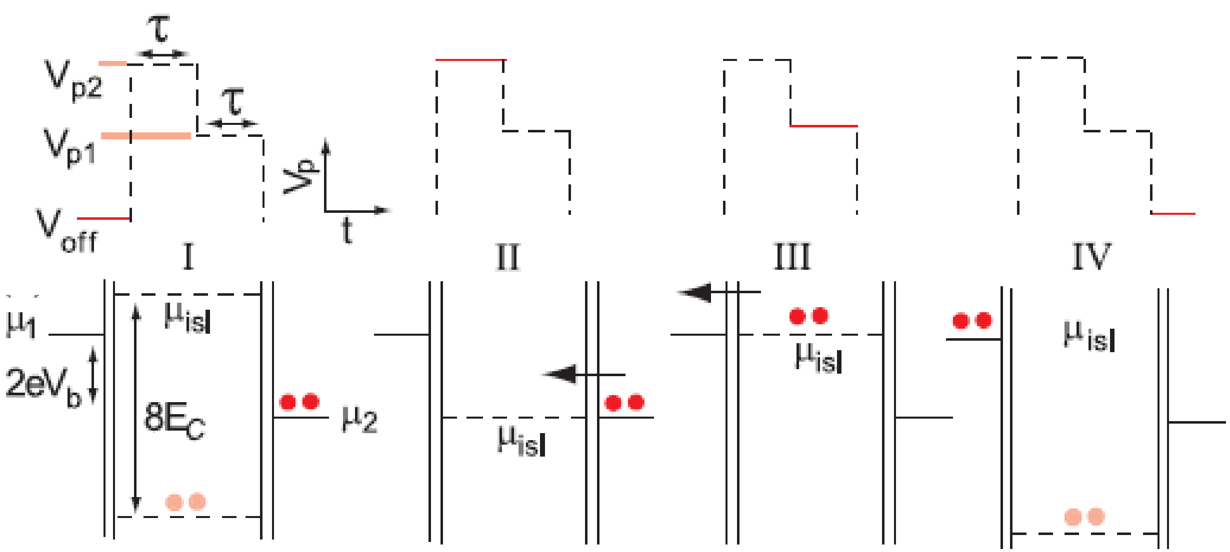
Superconducting quantum pump

Superconducting SET

F. Hoehne et al., arXiv:1109.5543 (2011)
PRB 85, 140504(R) (2012)



Resembles nonadiabatic manipulation of charge qubits, but both tunneling events are coherent



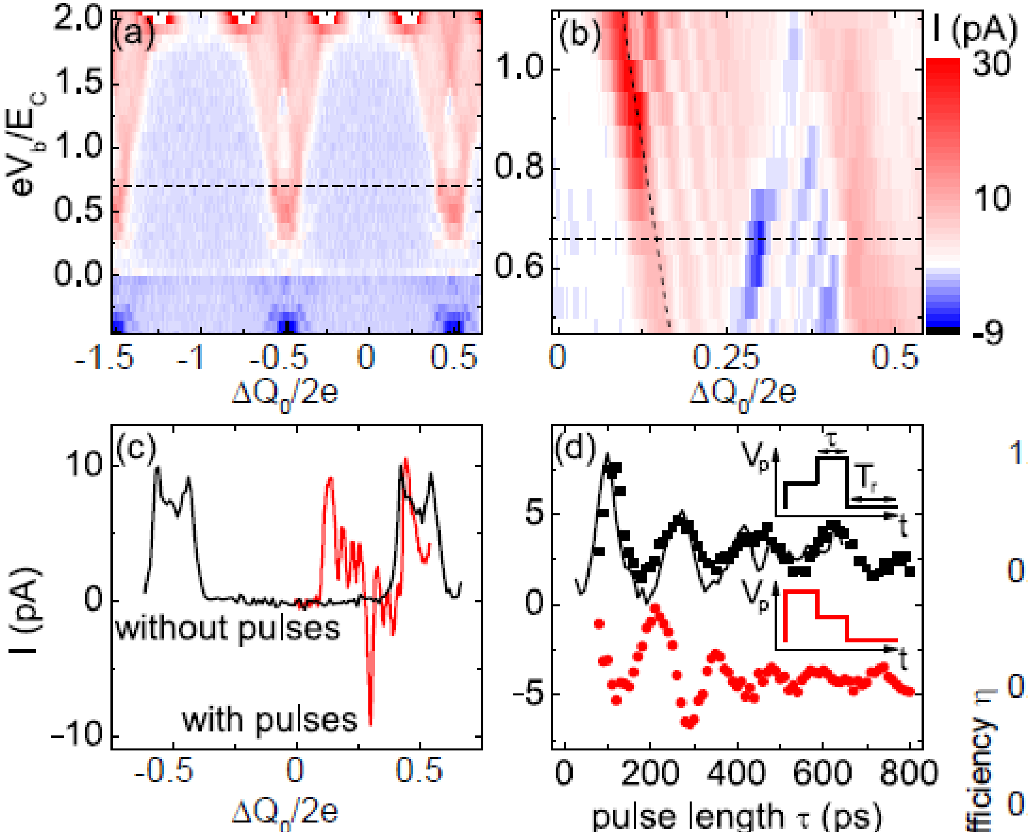
$\tau = h/2E_J$ - π-pulse

$\boxed{E_J = 10\text{ GHz} \Rightarrow I \sim 3\text{ nA}}$

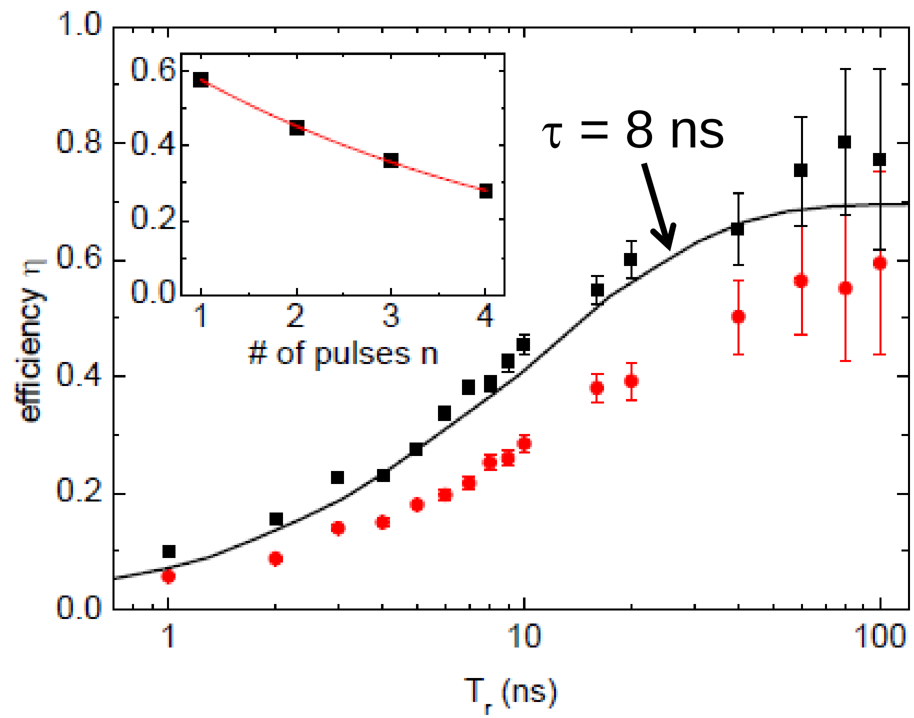
However, this does not work, needs system reset after every pulse

Superconducting quantum pump

F. Hoehne et al., arXiv:1109.5543 (2011)
PRB 85, 140504(R) (2012)



longer repetition time gives better accuracy, but lower current



efficiency $\eta = I_{max}/I$

$I_{max} = 2en/T_r$

Single-electron pumping using SINIS SETs

1. J. P. Pekola et al., Nature Phys. (2008)
2. A.Kemppinen et al., APL **94**, 172108 (2009)
3. V.F. Maisi et al., New J. Phys. **11**, 113057 (2009)
4. J.P. Pekola et al. PRL **105**, 026803 (2010)

Motivation

1. Redefinition (different implementation) of the unit of Ampere

$$\boxed{I = nef}$$

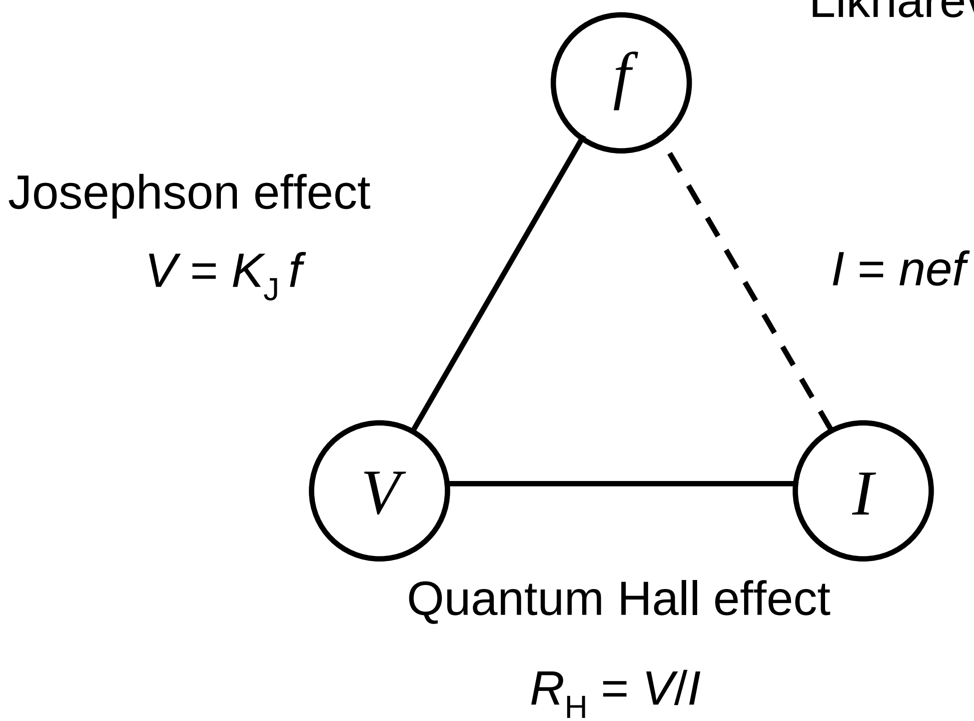
1 Coulomb = $6.24150948 \times 10^{18} e \Rightarrow 1\ \mathrm{A} = 6.24150948 \times 10^{18} e/\mathrm{s}$

Frequency 6×10^{18} Hz too high for controlling solid-state devices:

- working with lower frequency
- parallelization of charge pumps
- current amplification

2. Quantum metrological triangle

Likharev, Zorin, JLTP 59, 347 (1985)



even currents ~ 1 nA may be useful

Turnstiles in metro/subway/underground

passengers can go one by one

Parallel turnstiles in metro/subway/underground

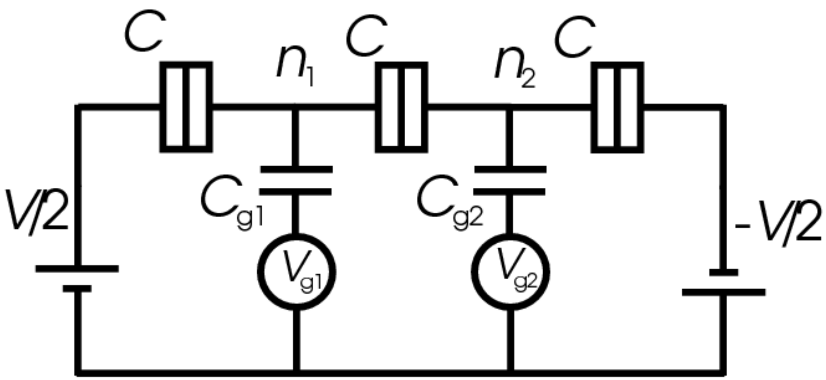
Parallel operation possible, but not synchronized

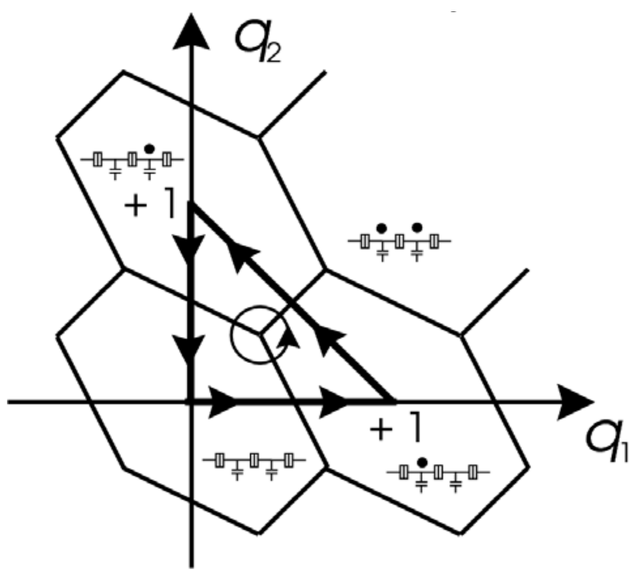
Error events in metro/subway/underground

must be suppressed

Charge pumps: operation principle

Cyclic gate operation (with frequency *f*), $q_i = C_{gi}V_{gi}/e$, charge transfer through the circuit



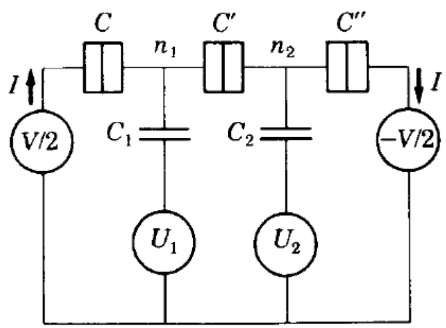


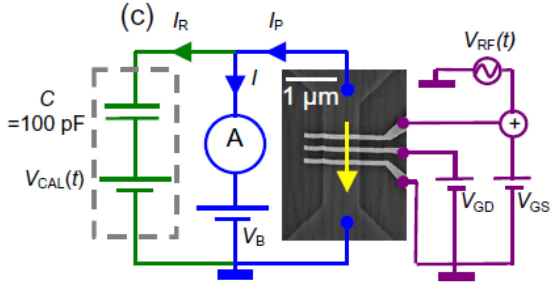
$$I = ef$$

H. Pothier et al., EPL 17, 249 (1992)

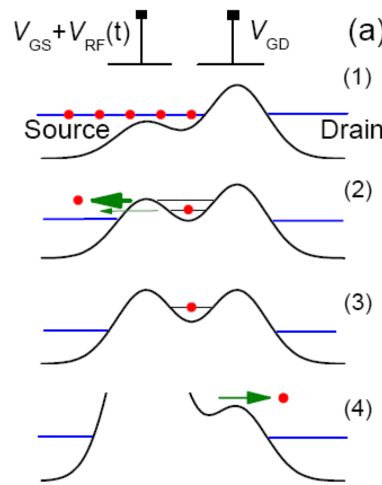
Sources of quantized current

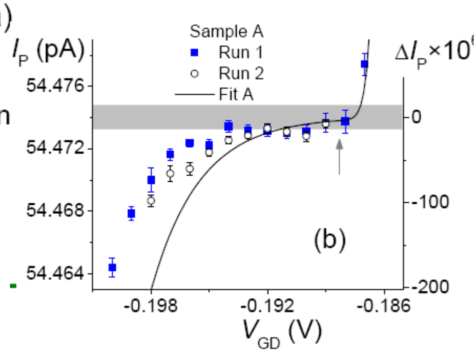
Frequency to current conversion: $I = nef$

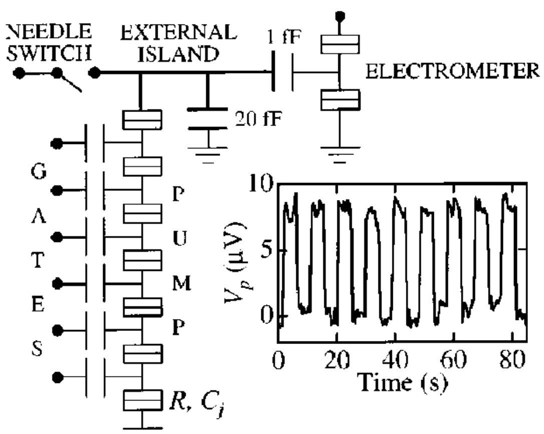


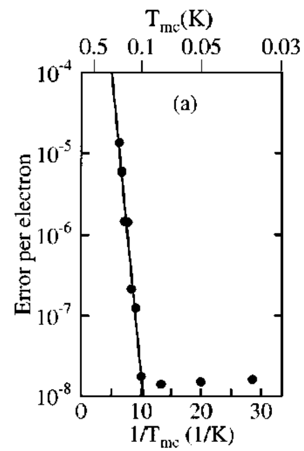


Semiconducting devices:
Kouwenhoven et al. 1991
Shilton et al. 1996
Fujiwara et al. 2004
Blumenthal et al. 2007
Kaestner et al. 2007
Giblin et al. 2010







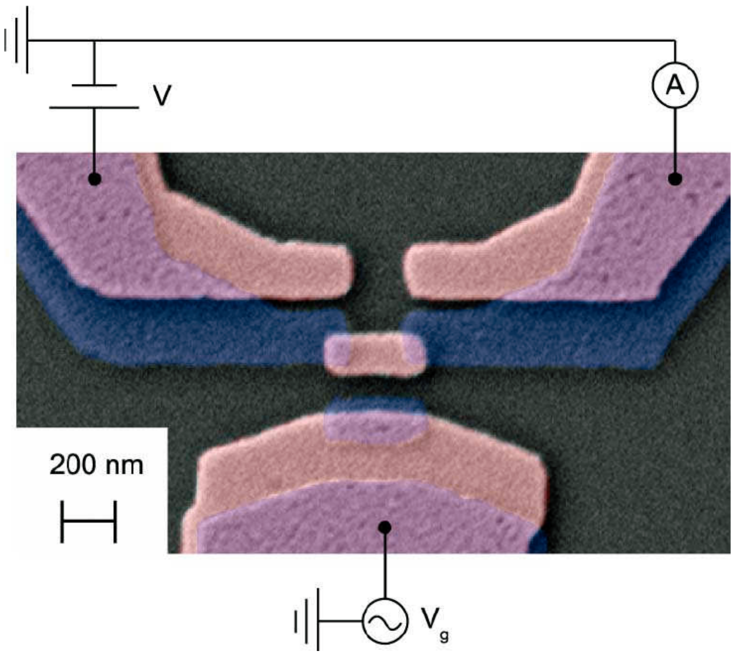


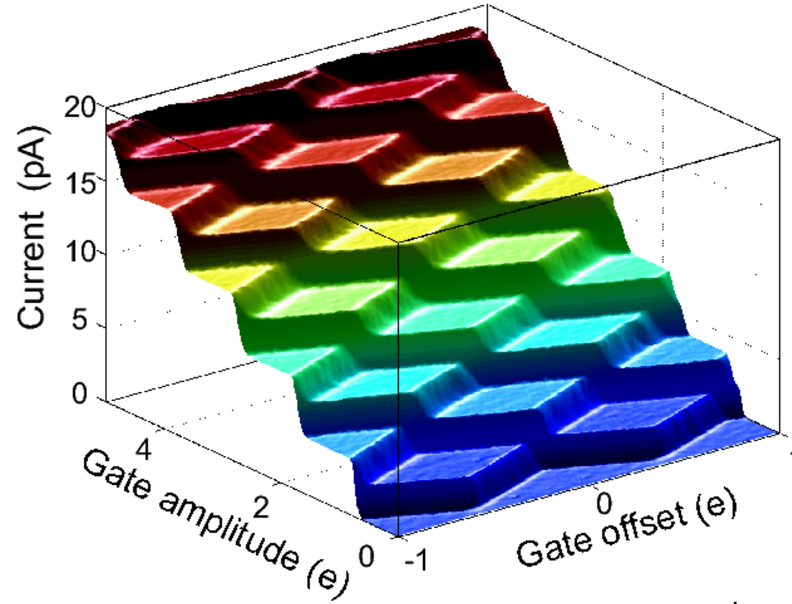
Superconducting devices:
Geerligs et al. 1991, Aumentado et al. 2003
Mechanical shuttles:
Konig et al. 2008
Graphene pumps: *inaccurate*
Low et al. 2012

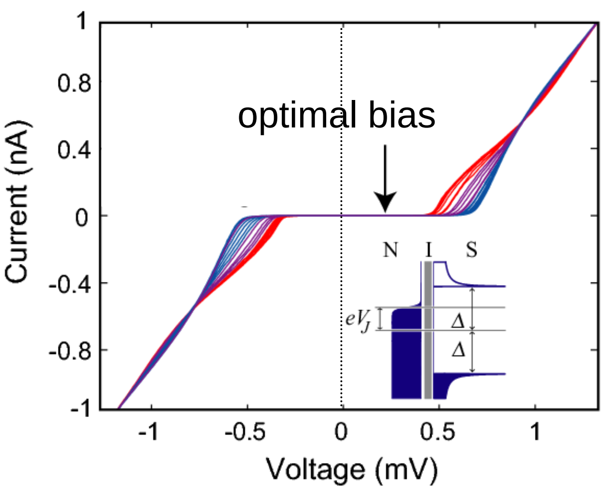
Single-electron turnstiles and pumps:
Geerligs et al. 1990, Pothier et al. 1992,
Keller et al. 1996, Lotkhov et al. 2000
High accuracy, but low current:
$I < 10$ pA

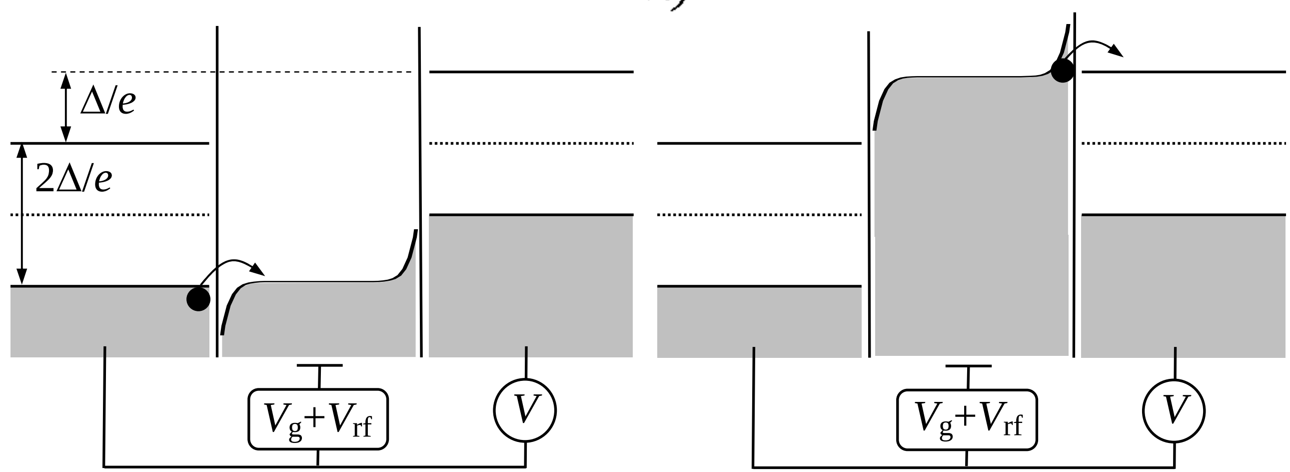
Hybrid single-electron pump (SINIS)

J.P. Pekola et al.,
Nature Physics 4, 120 (2008)





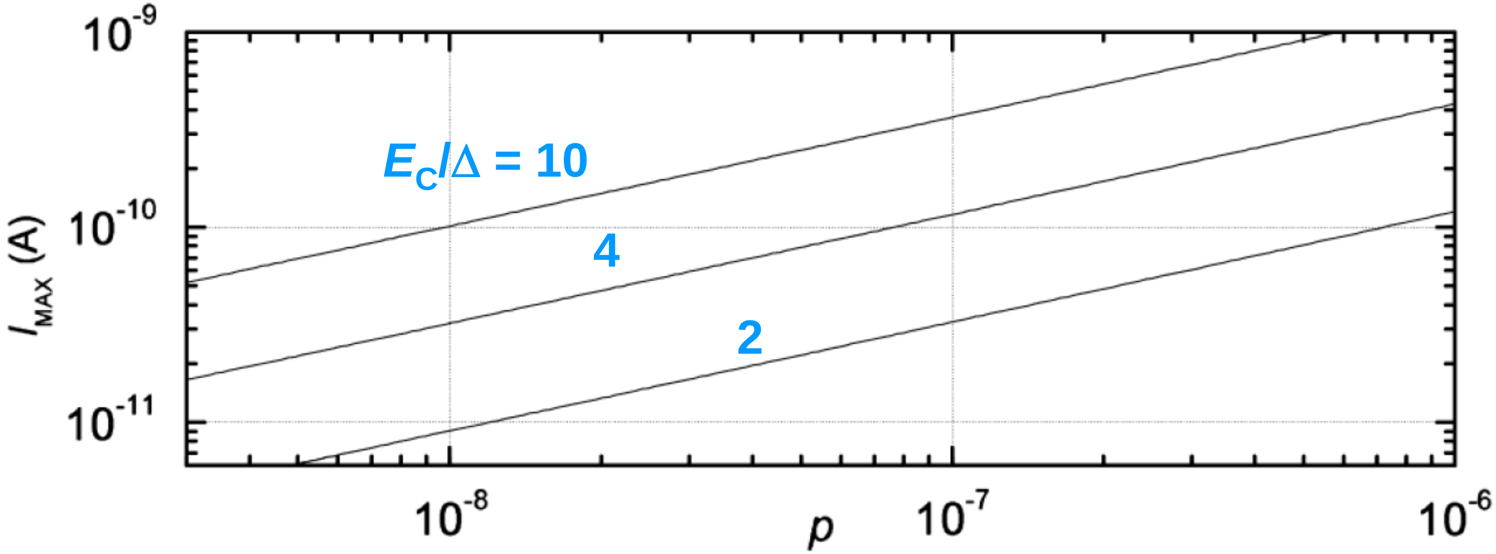




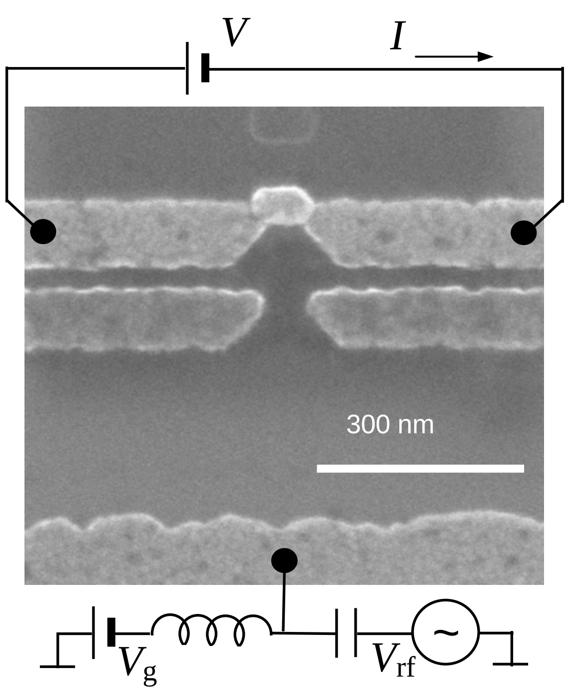
One electron is transferred during each cycle of the control frequency: *I* = *ef*.

Andreev reflection and CP-SE cotunneling

D. Averin and J.P. Pekola, PRL 101, 066801 (2008)



ERROR RATE



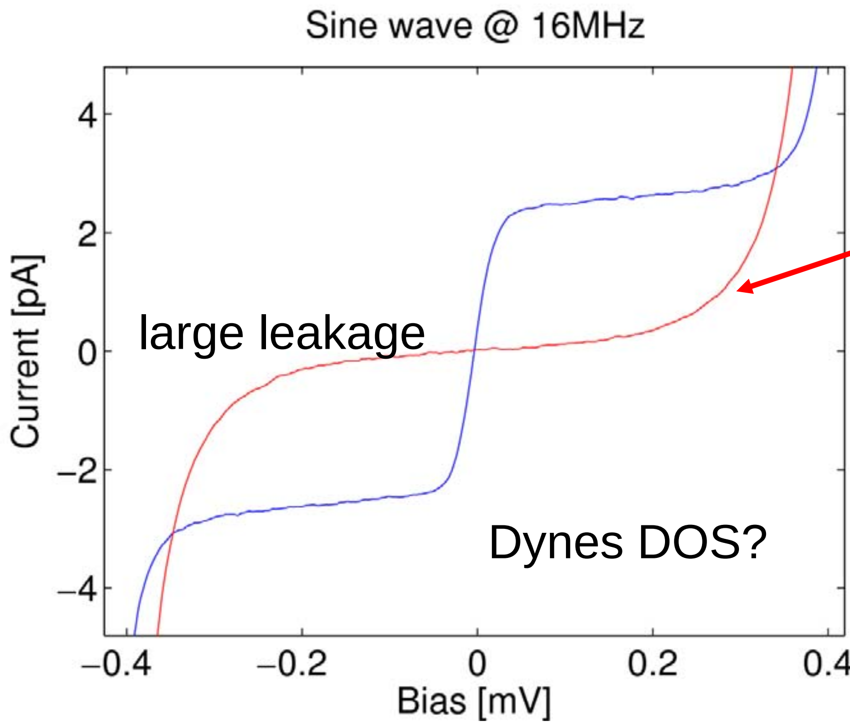
metrological accuracy can be reached (at least in theory)

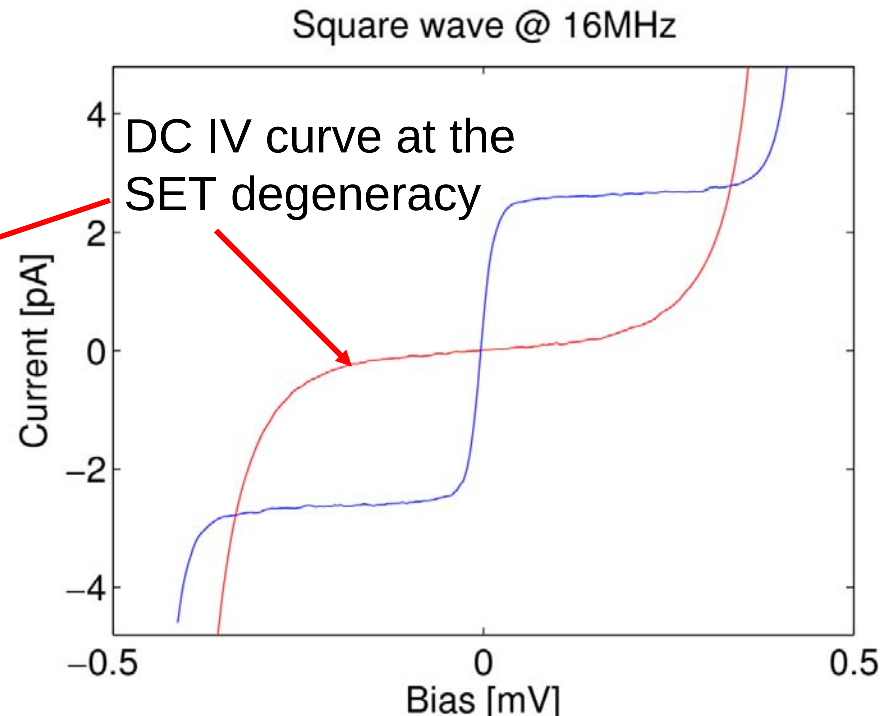
high charging energy good for reaching higher pumping accuracy

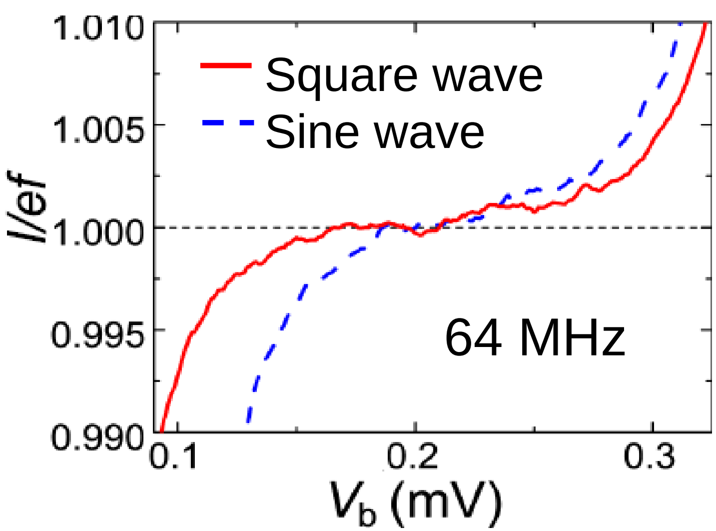
high charging energy pump measured

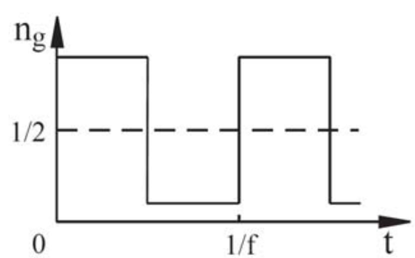
A. Kemppinen et al., APL 94, 172108 (2009)

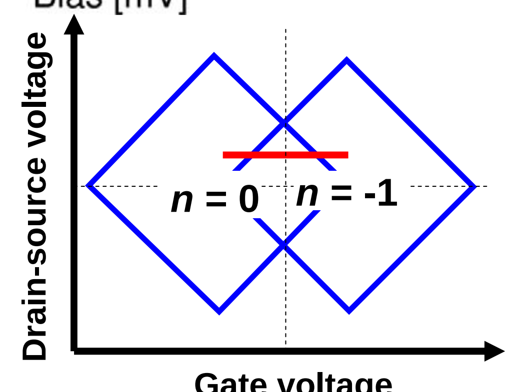
Pump with high charging energy ($E_C/\Delta \sim 10$)







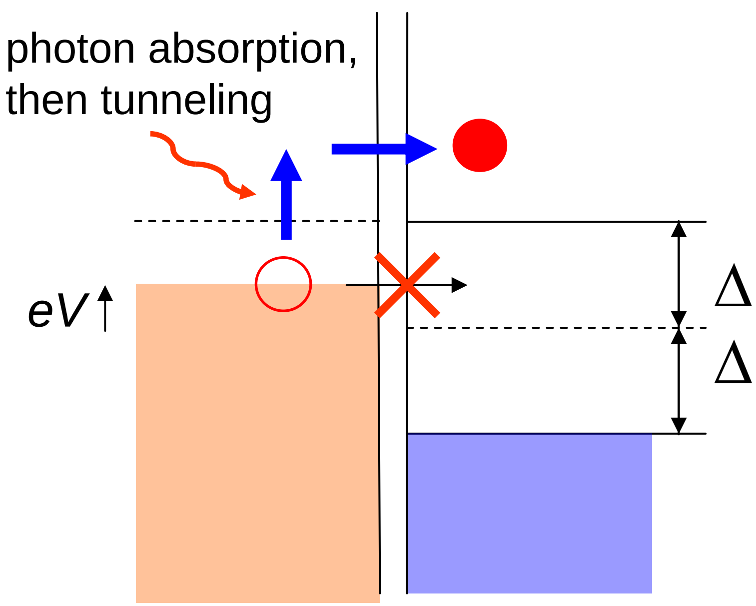


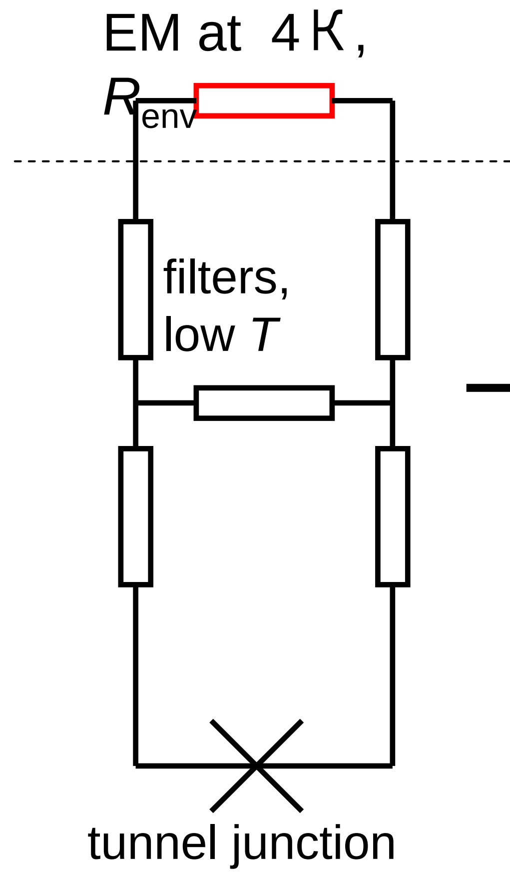


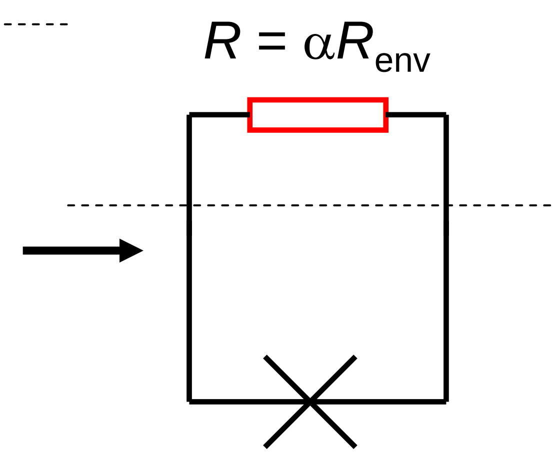
Square-wave signal improves plateau flatness: degeneracy point is passed faster

Environment-assisted tunneling (EAT)

Tunneling rate depends not only on the junction parameters, but also on the EM environment.
P(E)-theory: tunneling rate through the junction taking into account energy exchange between electrons and EM environment.

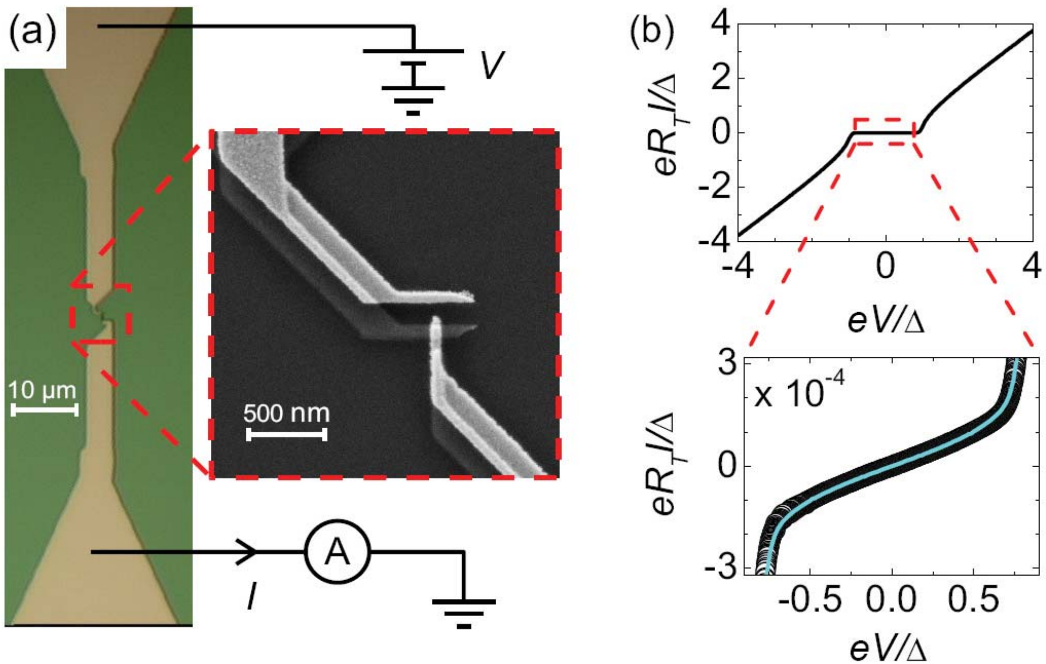






Typical parameters:
$R_{env} = 100\ \Omega$,
$R < 1\ \Omega$

Effect of EM environment is the same as the effect of the Dynes density of states



J.P. Pekola et al., arXiv1001:3853
PRL **105**, 026803 (2010)

Excellent agreement of exp. data with the model taking into account EM environment with weak dissipation and finite temperature

$$I(V) = \frac{1}{eR_T}\int_{-\infty}^{\infty} dE\, n_S^\gamma(E)\,[f_N(E-eV) - f_S(E)]$$

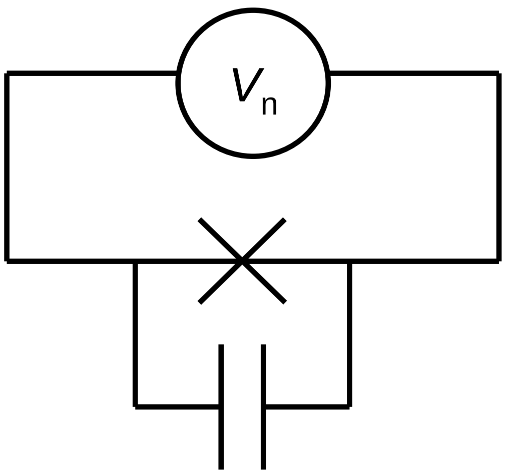
with

$$n_S^\gamma(E) = \left|\mathrm{Re}\frac{E/\Delta + i\gamma}{\sqrt{(E/\Delta+i\gamma)^2-1}}\right|$$

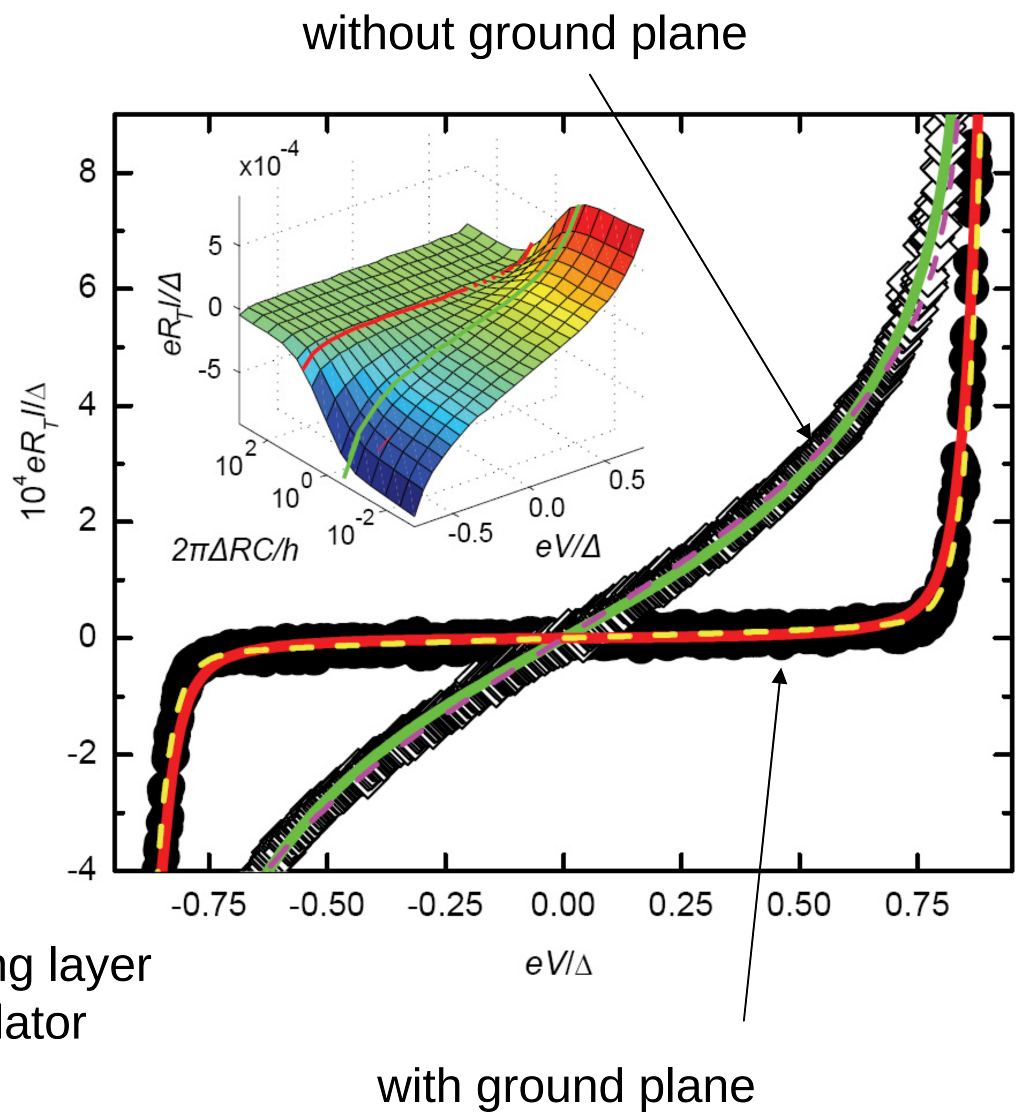
$$\gamma = 2\pi\frac{R}{R_K}\frac{k_B T}{\Delta}$$

SIN junctions with different EM environment

Simple idea:
ground plane provides a large capacitance shunting noise from EM environment



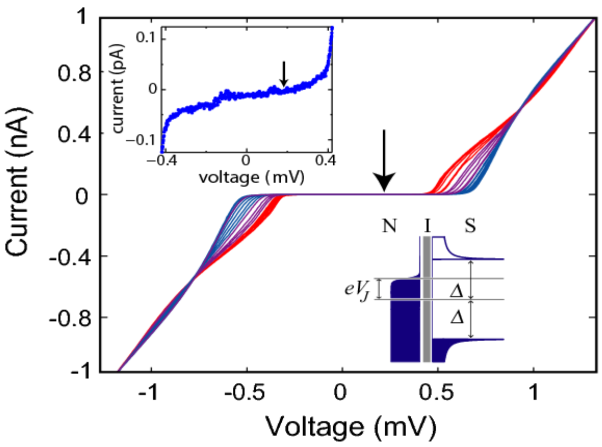
Ground plane = (super)conducting layer covered with a100-nm-thick insulator

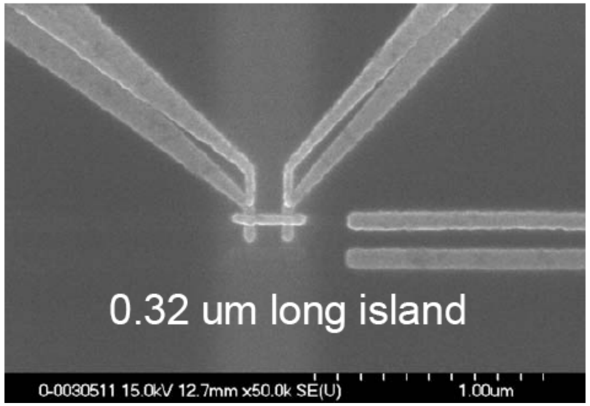


Subgap leakage in NIS junctions and SINIS pumps

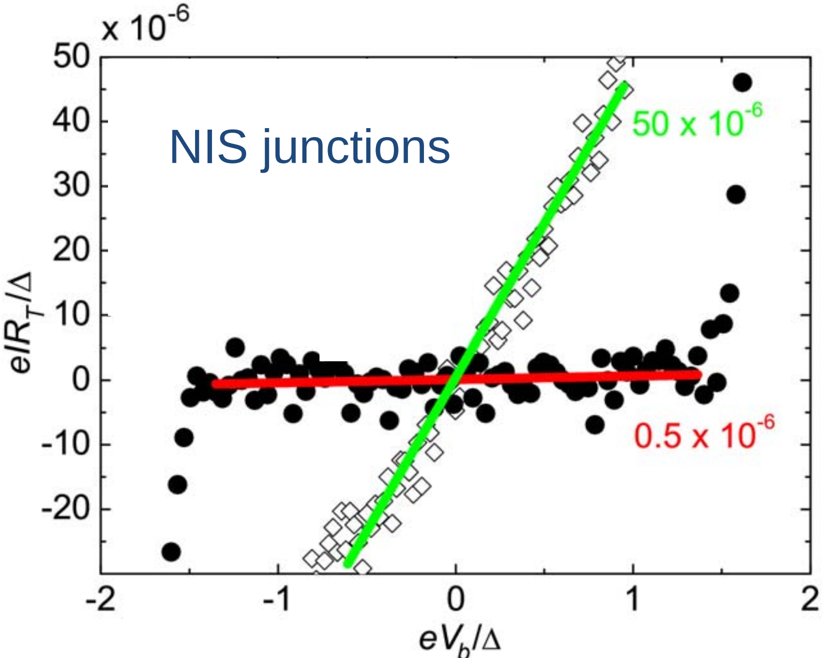
first experiments

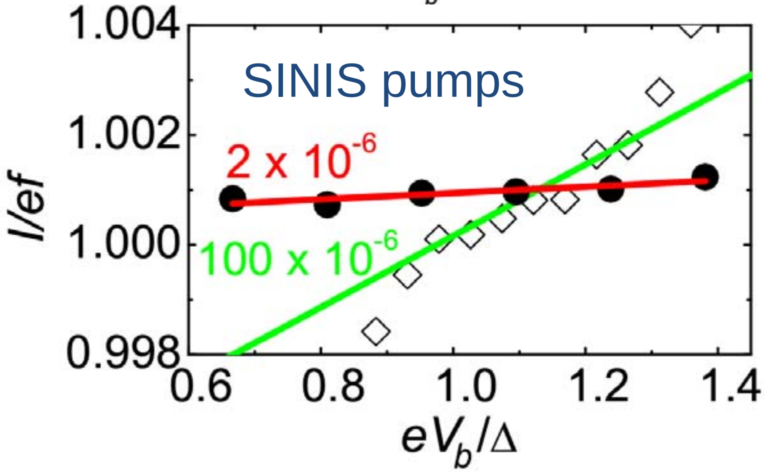
$\gamma = R_n/R_{sg} > 10^{-4}$





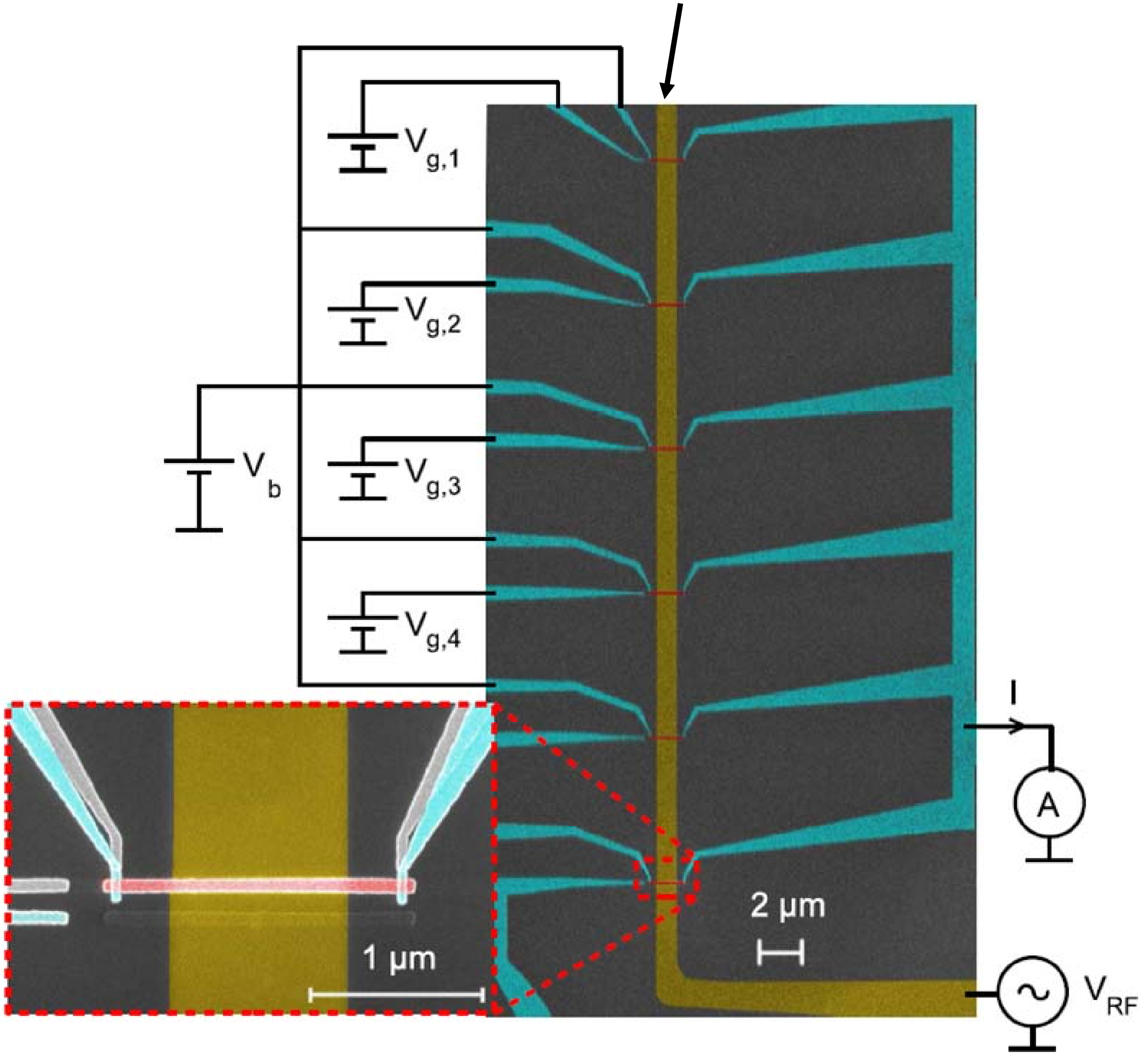
now $\gamma < 10^{-6}$



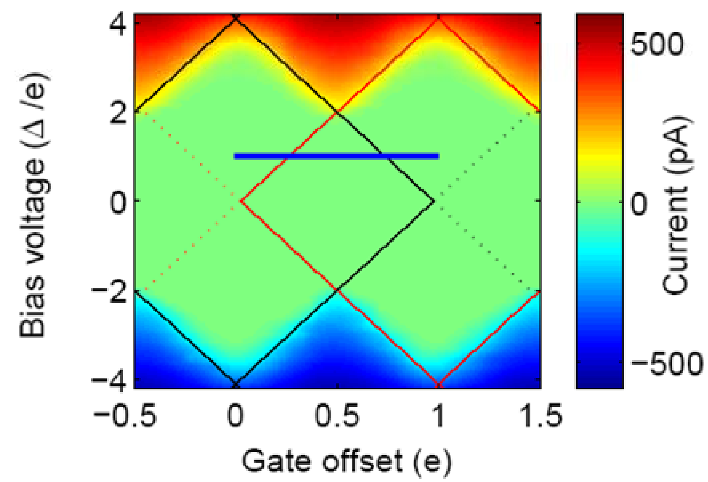


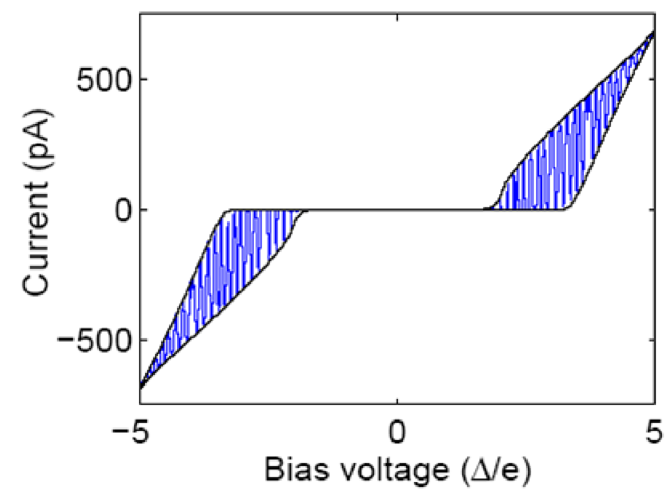
Scheme for parallel pumping of electrons

Common rf control gate for all pump



Each pump measured in dc regime



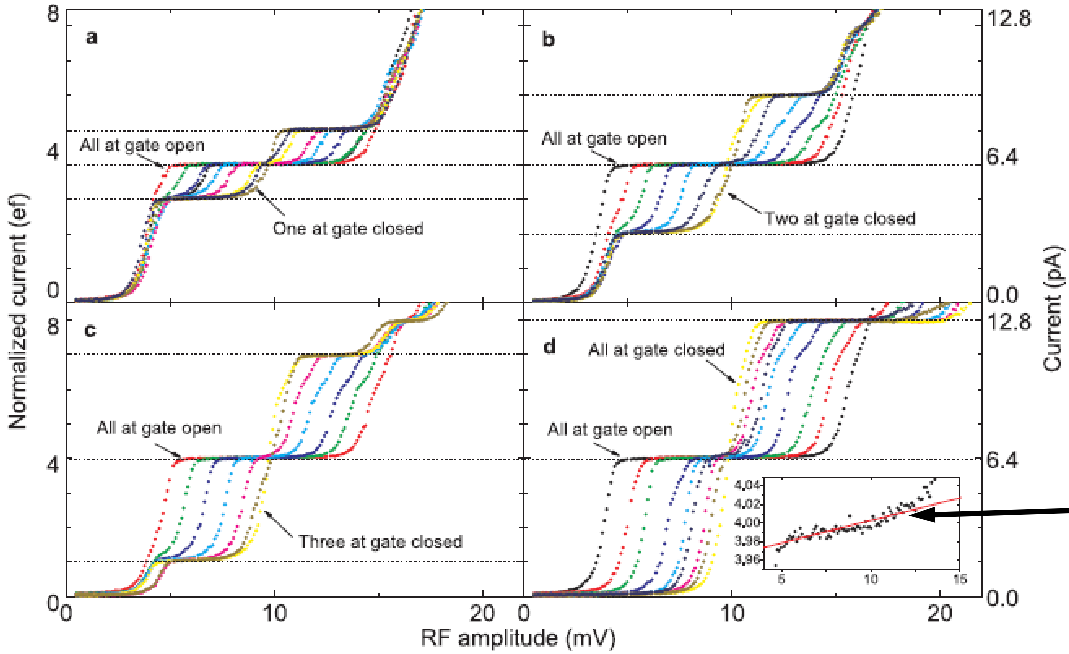


only N + 2 dc leads needed

N – number of pumps

V.F. Maisi et al., NJP 11,113057 (2009)

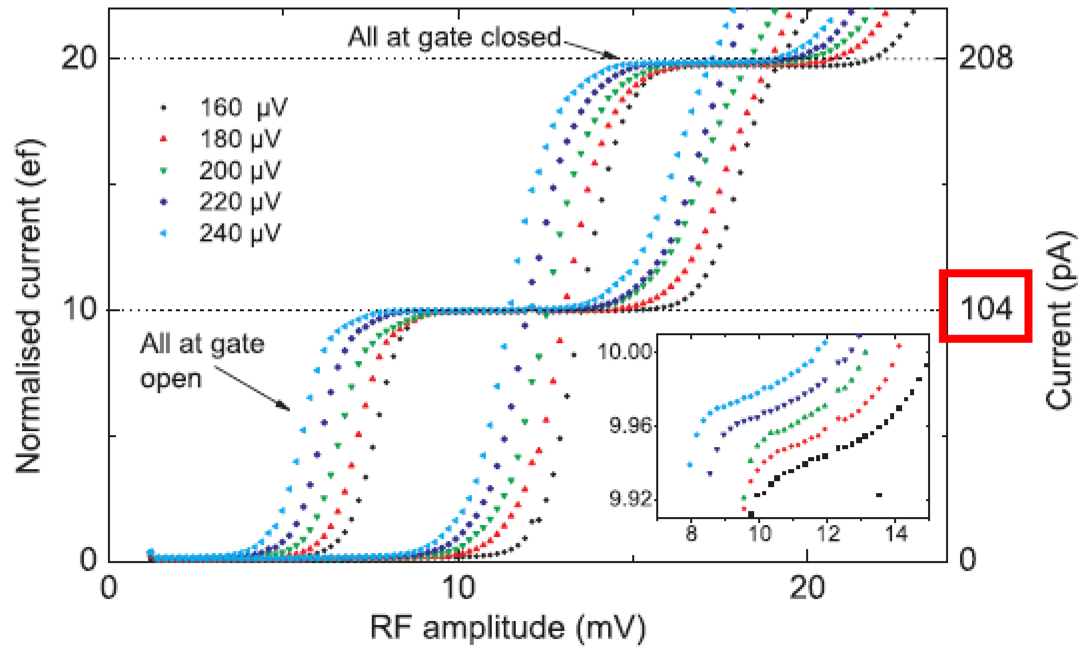
Parallel electron pumping



4 parallel pumps
f = 10 MHz

plateau slope 200 GOhm

10 parallel pumps
f = 65 MHz



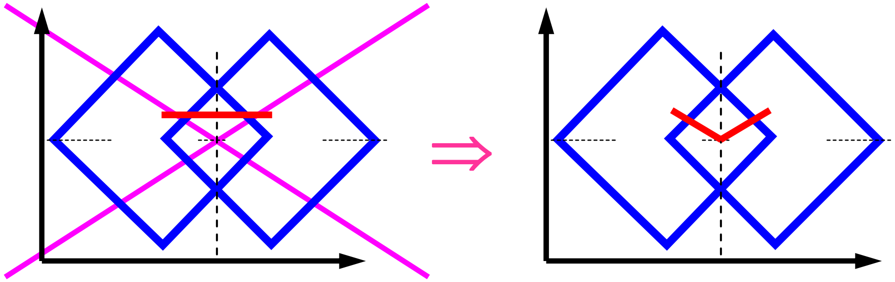
Summary

• current level ~ 1 nA seems feasible

- parallel operation of 10 - 20 electron pumps

• reaching accuracy of 10^{-6}

- $E_c/\Delta \approx 2 - 4$
- shunting devices with large capacitance
- square-wave control signal
- thermalization of quasiparticles
- optimization of the control signal



- well-calibrated, stable instruments needed
- temperature control