Charge pumping with Coulomb blockade devices

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Windsor Summer School – 16 August 2012

International System of Units (SI)

SI base units:

meter for length

kilogram for mass

second for time

ampere for electric current

kelvin for temperature

candela for luminous intensity

mole for the amount of substance.

<u>Pre-SI definition of A:</u> the current required to deposit 1.118 milligrams of silver per second from a solution of silver nitrate

<u>SI definition:</u> The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} N/m.“ 9th CGPM (1948)

impractical, usually realized through the Josephson and Hall effects

Motivation

Idea: to define the units in terms of fundamental constants h, e, k_B and N_A

In 2005, CIPM approved the preparation of new definitions for the kilogram, the ampere and the kelvin

1. Redefinition of the unit of ampere

<u>Proposed definition: Ampere = Coulomb/second</u>

will not depend on the definition of the meter and kilogram

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

Can we pump electrons $I = nef$?

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

- working with lower frequency
- parallelization of charge pumps
- current amplification
  (CCC: gain 10^4, accuracy 10^{-8})

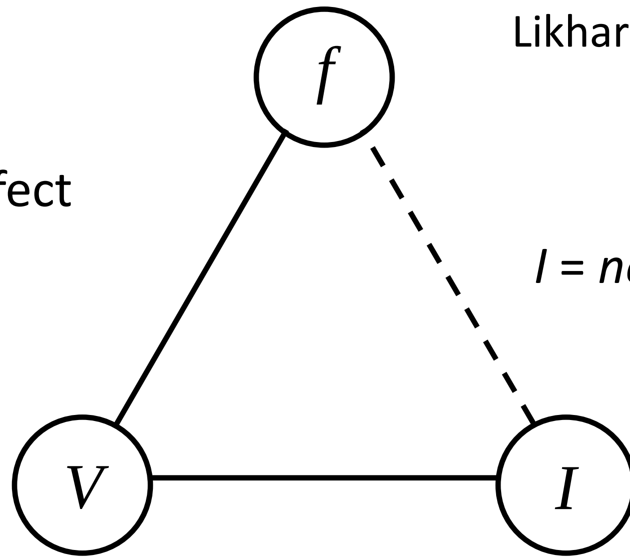
Motivation (2)

2. Quantum metrological triangle

Likharev, Zorin, JLTP **59**, 347 (1985)

Josephson effect

$V = K_J f$



$I = nef$

even currents ~ 1 nA may be useful

Quantum Hall effect

$R_H = V/I$

Reaching stable current ~ 1 nA:

- understanding error processes
- effect of the EM environment

Turnstiles in public transportation

passengers can go one by one

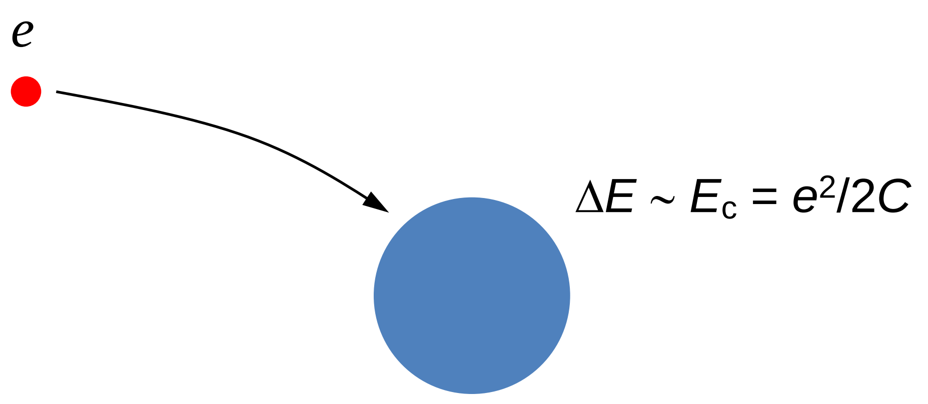
Parallel turnstiles in public transportation

Parallel operation possible, but not synchronized

Error events in public transportation

must be suppressed

Coulomb blockade

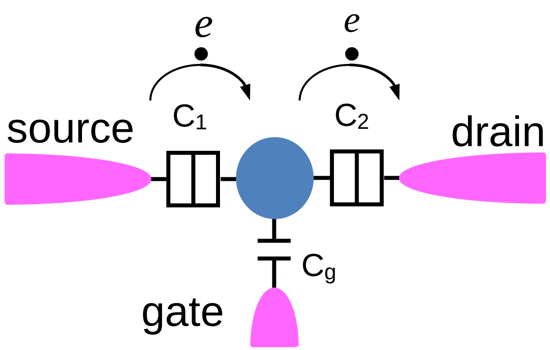


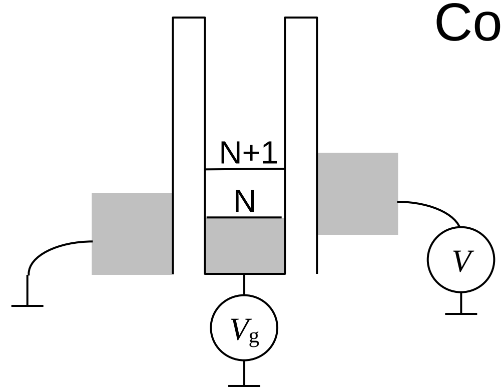
C (F)	0.8×10^{-15}	0.8×10^{-16}	0.8×10^{-17}	0.8×10^{-18}
E_c	100 μeV	1 meV	10 meV	0.1 eV
E_c/k_B (K)	1	10	100	1000

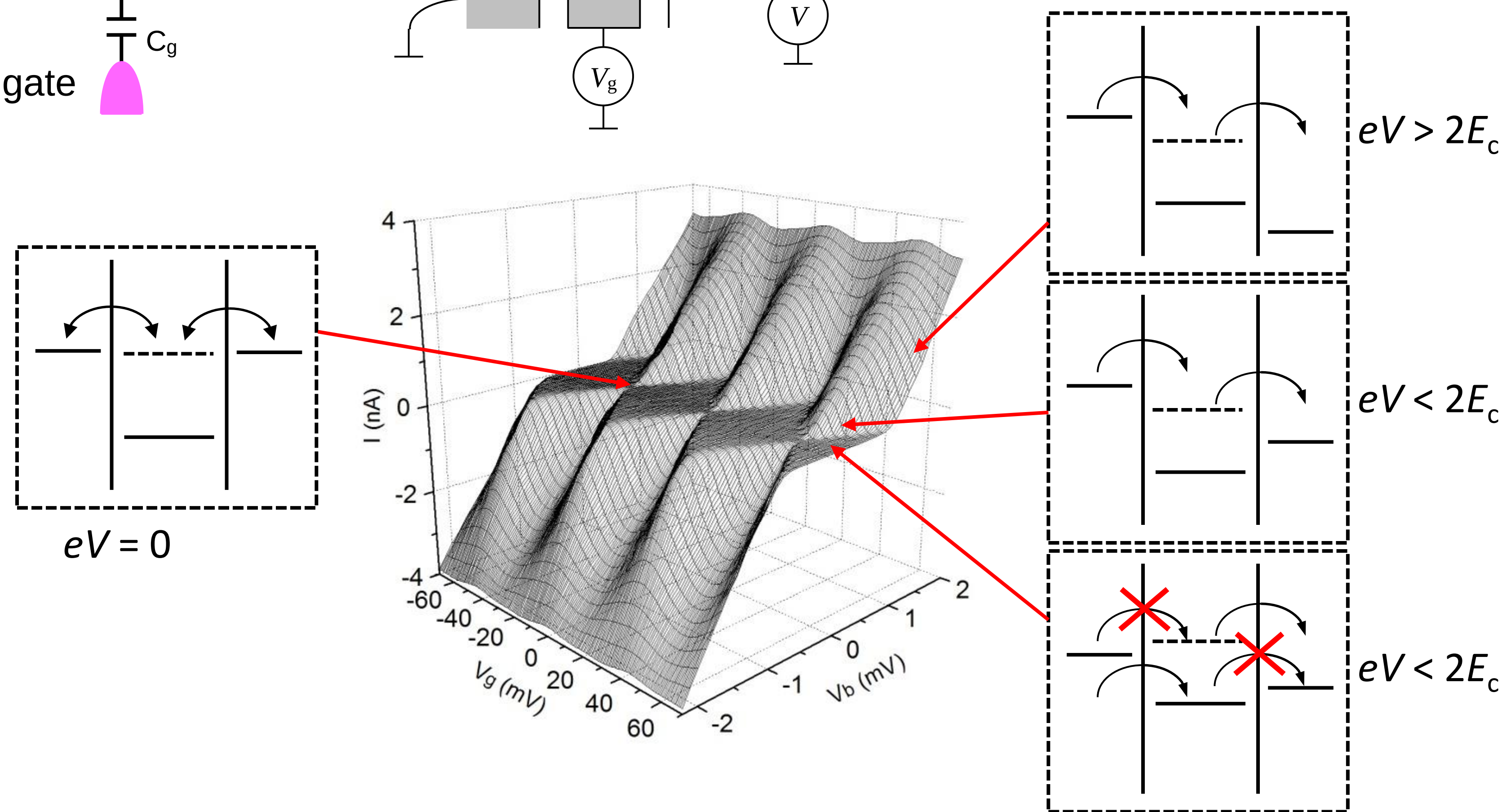
Single-electron transistor (SET)

Averin, Likharev (1986) theory
Fulton, Dolan (1987) exp.

Conditions: $k_B T << E_c \equiv e^2/2C_\Sigma$
$R >> R_Q \equiv h/4e^2 \approx 6.5\ \mathrm{k\Omega}$

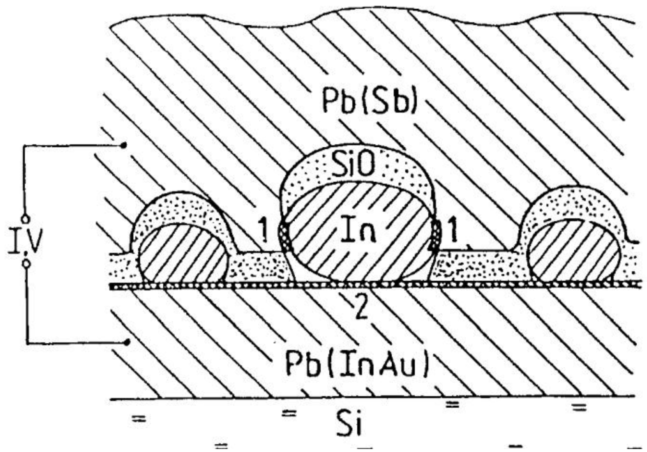






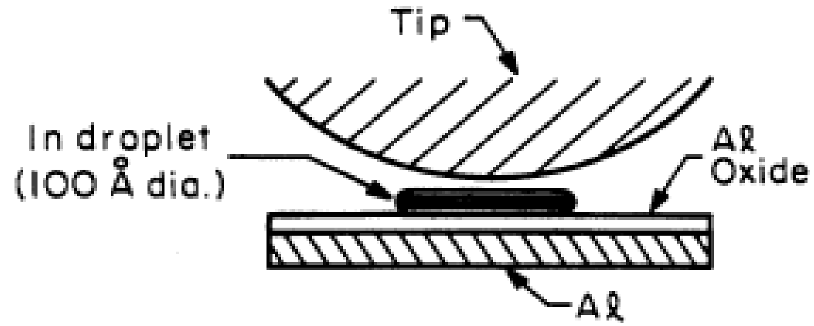
Implementations of SETs

Granular films



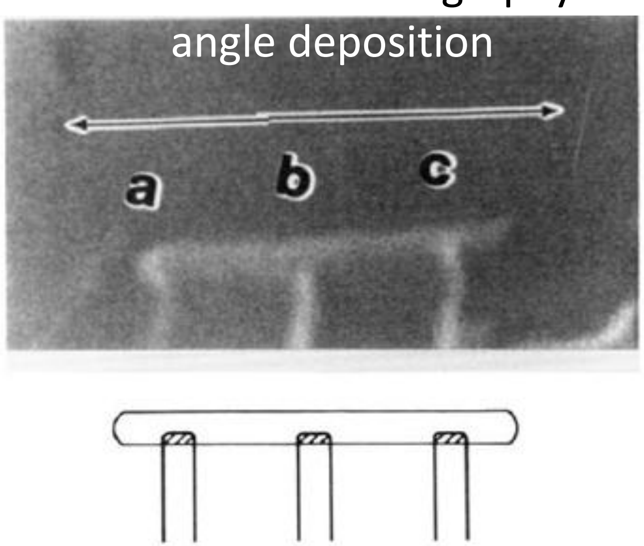
Kuzmin and Likharev *JETP Lett.* (1987)
Barner and Ruggiero *PRL* (1987)

STM configuration



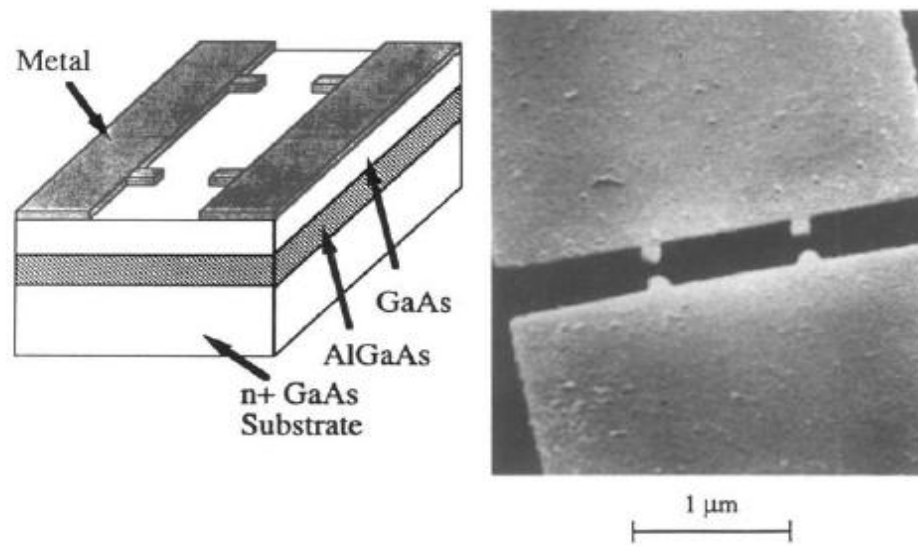
van Bentum et al., *PRL* (1987)
Wilkins et al., *PRL* (1989)

Electron-beam lithography + angle deposition



Fulton and Dolan, *PRL.* (1987)

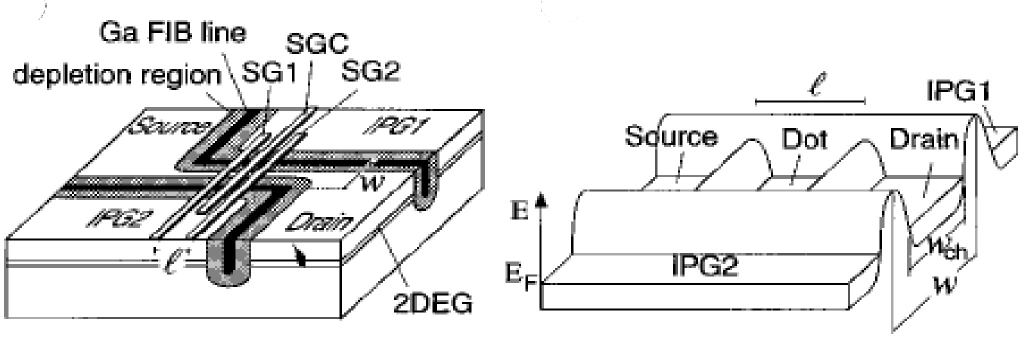
2D gas – split gates



Meirav et al. *PRL* (1990)

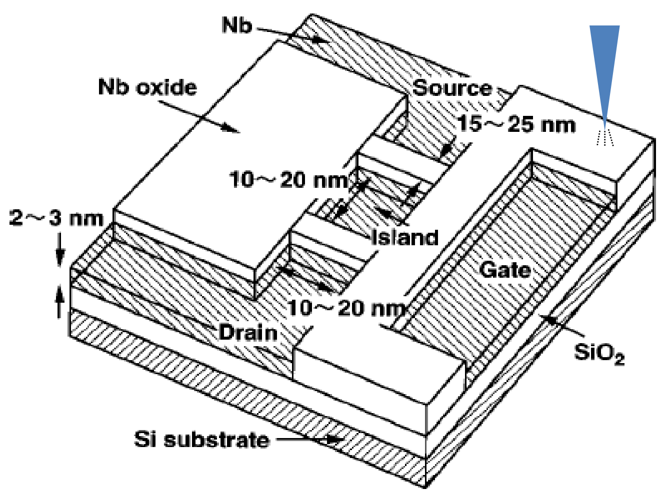
Implementations of SETs (2)

2D gas – dry etching + split gates



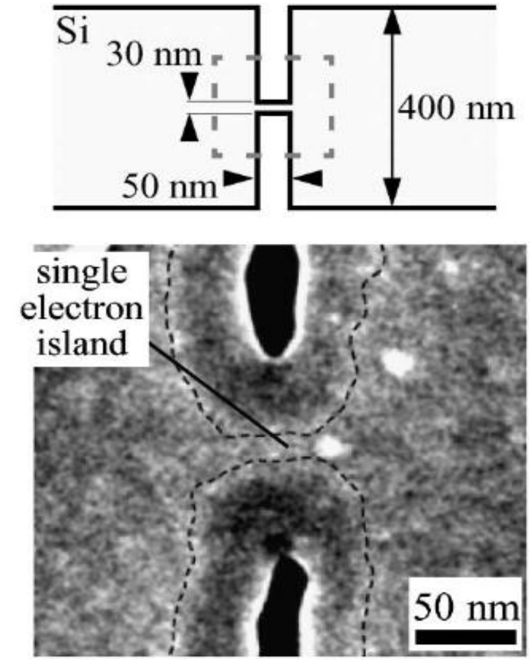
Fujisawa et al. *APL* (1996)

STM anodization of Nb



Shirakashi et al. *APL* (1998)

PAttern Dependent OXidation of Si



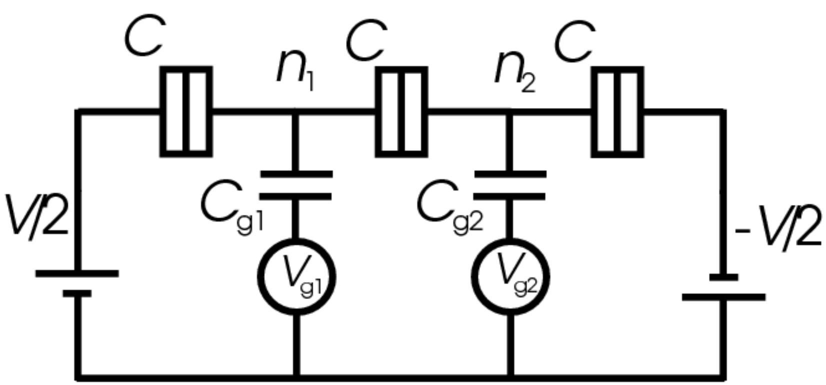
Takahashi et al. *Electron. Lett.* (1995)

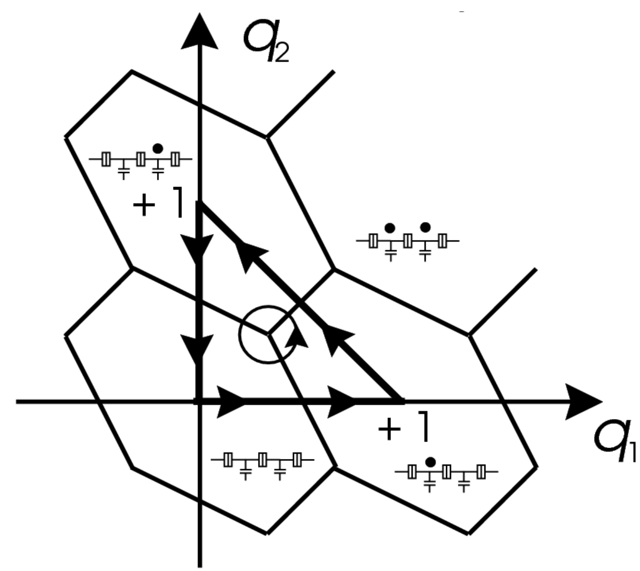
EB based technologies:

- excellent control of parameters
- precise positioning on chip

Charge pumps: operation principle

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





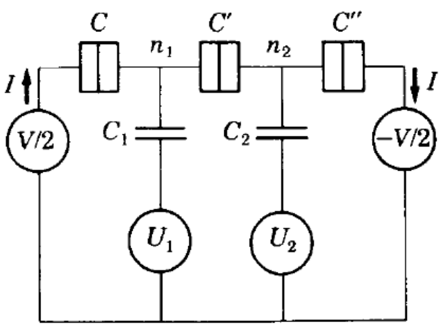
$I = ef$

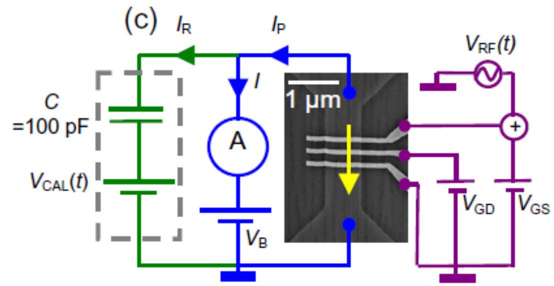
10^{-8} accuracy in f !

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

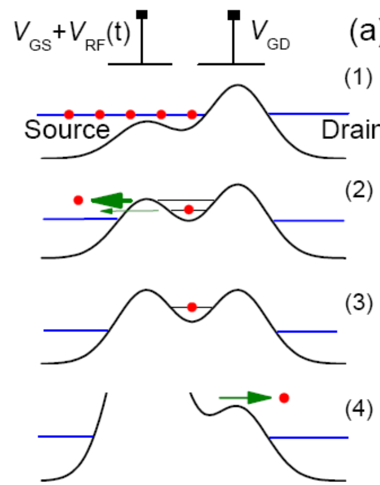
Sources of quantized current

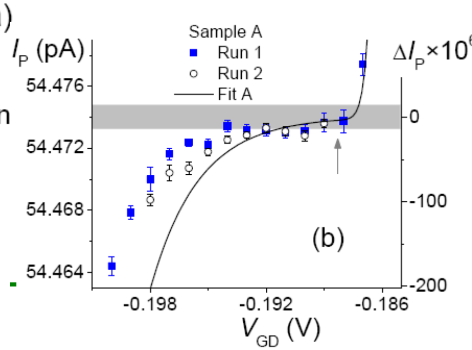
Frequency to current conversion: $I = nef$

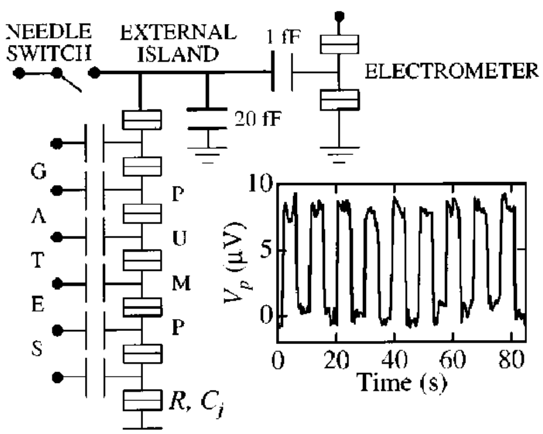


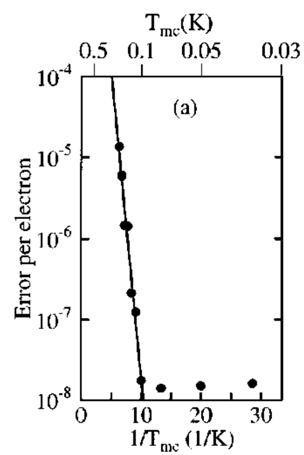


Semiconducting devices:
Kouwenhoven et al. 1991
Shilton et al. 1996
Fujiwara et al. 2004
Blumenthal et al. 2007
Kaestner et al. 2007
Giblin et al. 2010





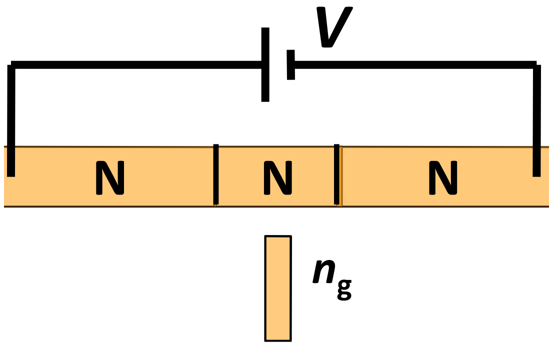




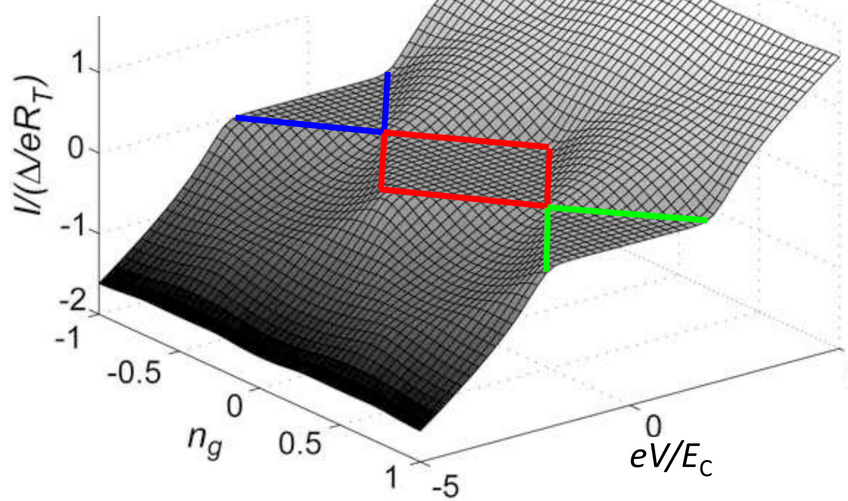
Single-electron turnstiles and pumps:
Geerligs et al. 1990, Pothier et al. 1992,
Keller et al. 1996, Lotkhov et al. 2000
High accuracy, but low current:
$I < 10$ pA

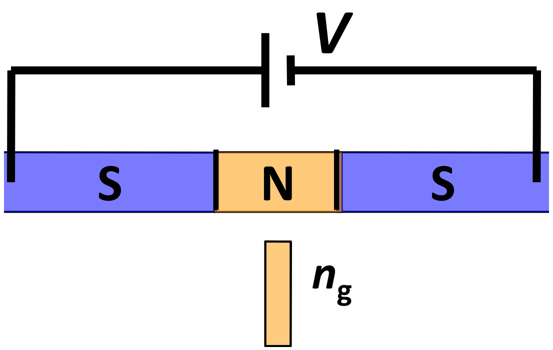
Superconducting devices:
Geerligs et al. 1991, Aumentado et al. 2003
Mechanical shuttles:
Konig et al. 2008
Graphene pumps: *inaccurate*
Low et al. 2012

Yet again a single-electron transistor

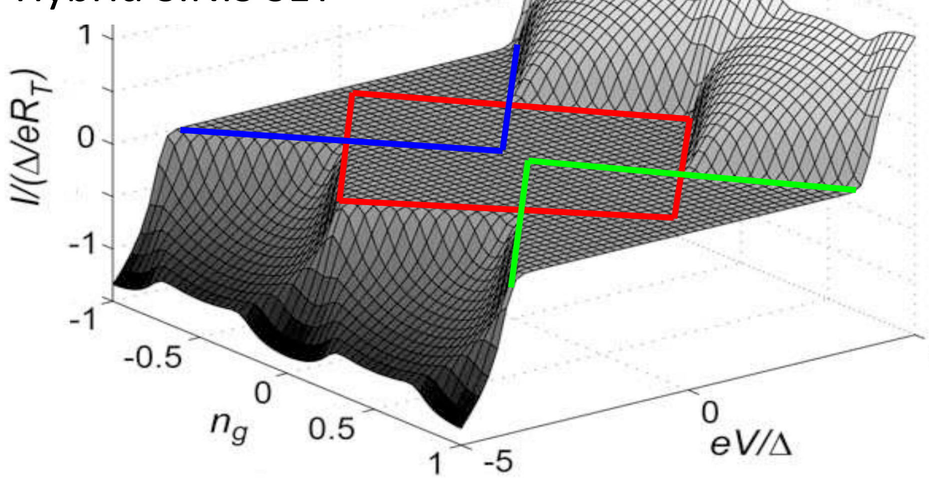


Normal-metal SET



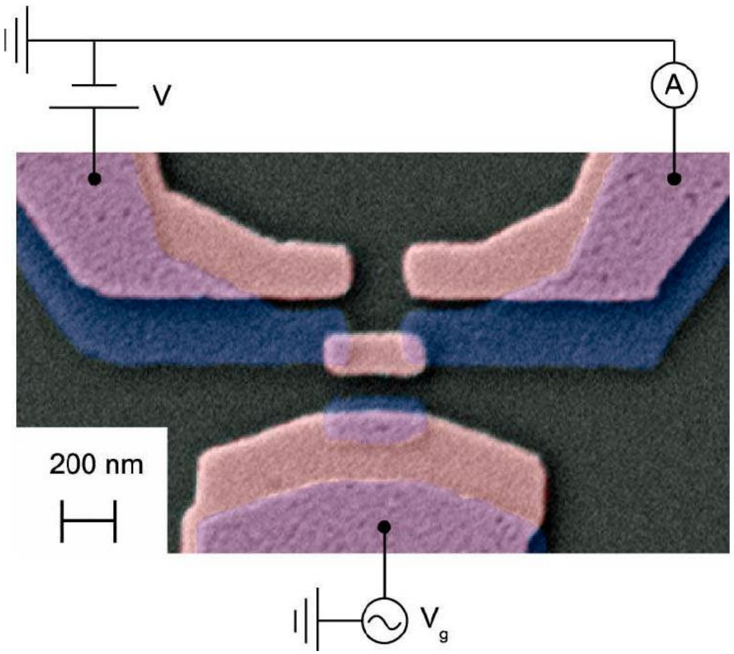


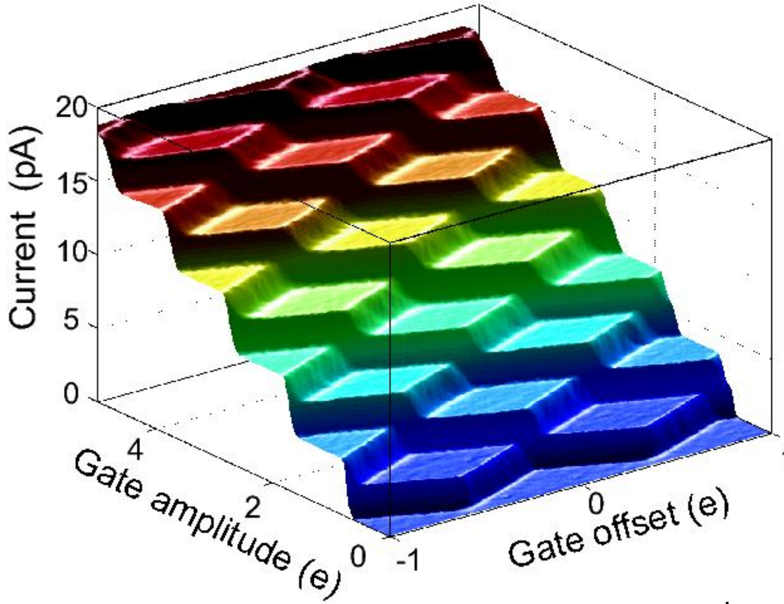
Hybrid SINIS SET

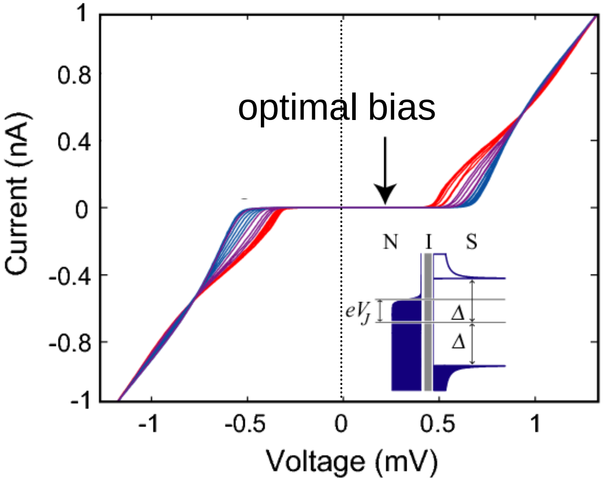


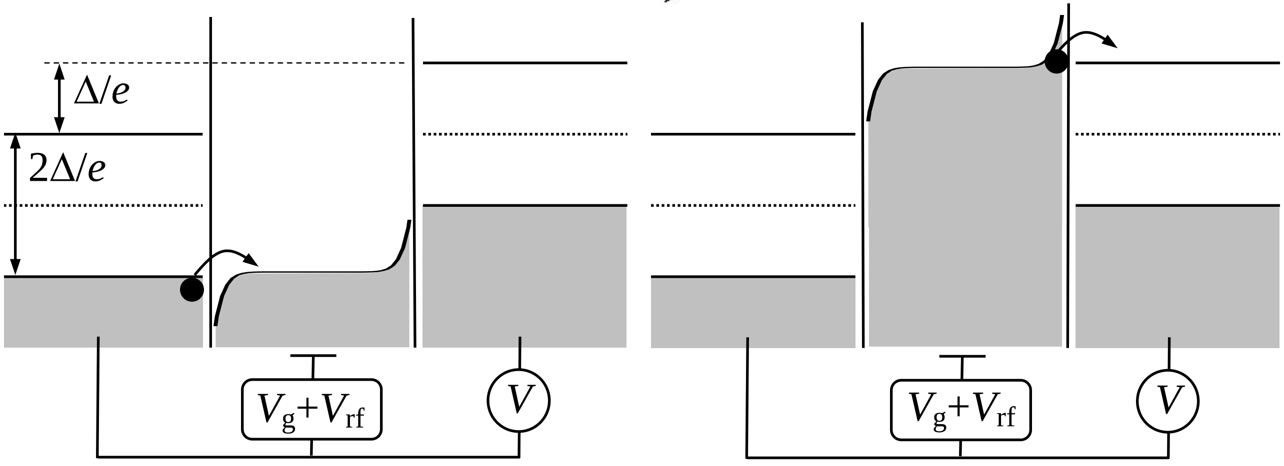
Hybrid single-electron pump (SINIS)

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





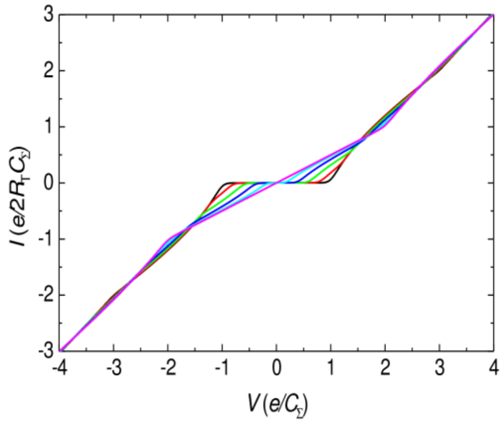




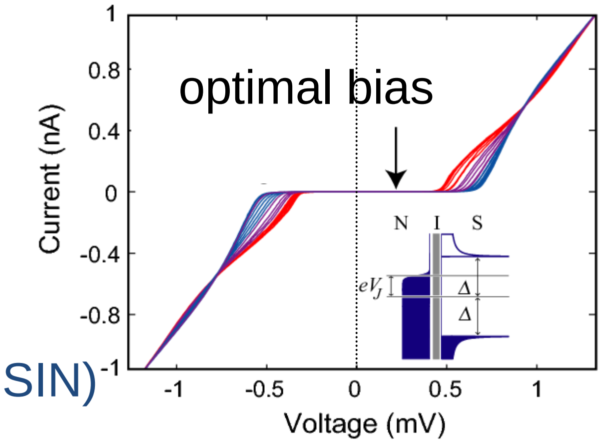
One electron is transferred during each cycle of the control frequency: $I = ef$

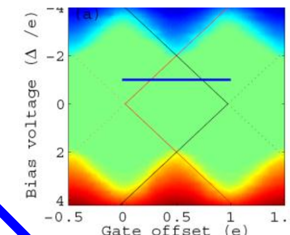
Stability diagrams

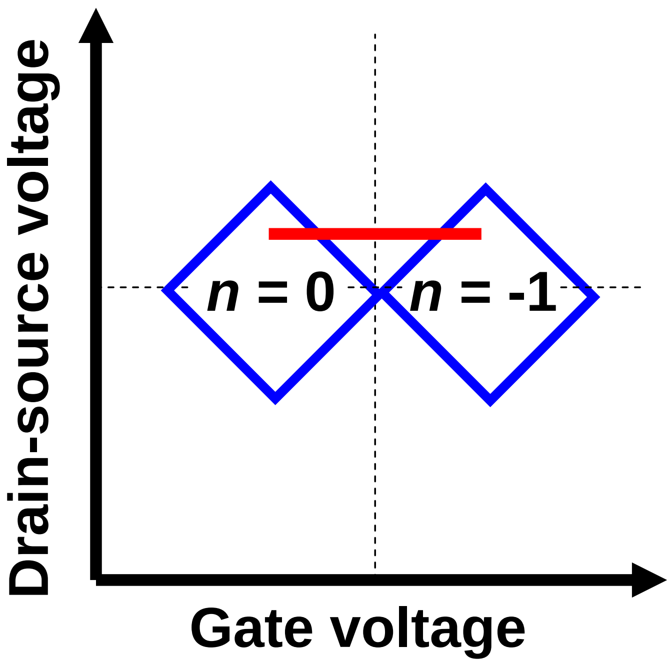
Normal-metal SET

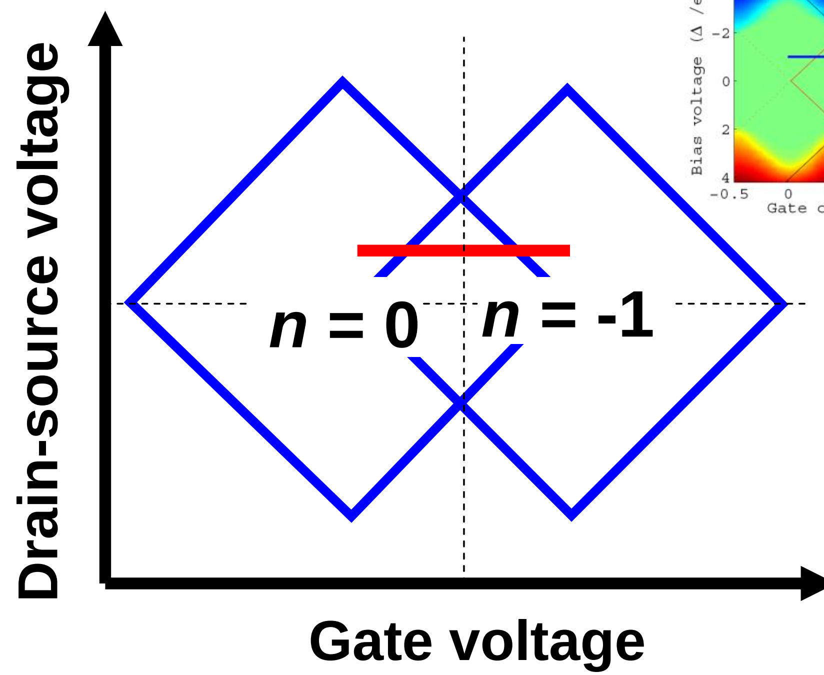


Hybrid SET
(SINIS or NISIN)









Qualitative difference: stability diagrams overlap in the hybrid SET, but not in the normal-metal SET

Thermal error rates

Probability (per cycle) of tunnelling in wrong direction is approximately

$$\exp(-\frac{eV}{k_B T_N})$$

Probability (per cycle) of tunnelling an extra electron in forward direction is approximately

$$\exp(-\frac{2\Delta - eV}{k_B T_N})$$

Optimum operation point is therefore at $eV = \Delta$, where the error rate is

$$\sim \exp(-\frac{\Delta}{k_B T_N})$$

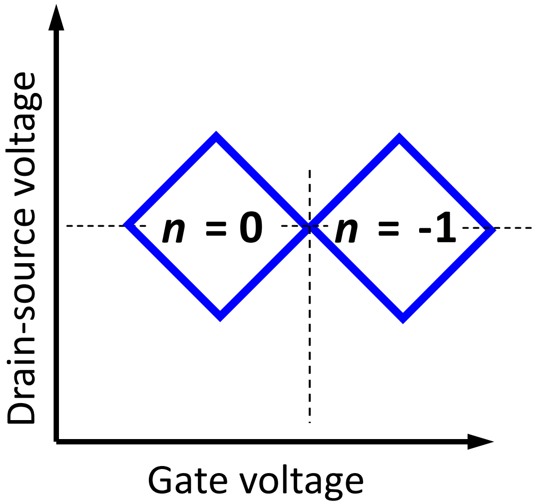
At 100 mK for aluminium as the superconductor ($k_B T_N / \Delta = 0.04$), this error is << 10^{-8}

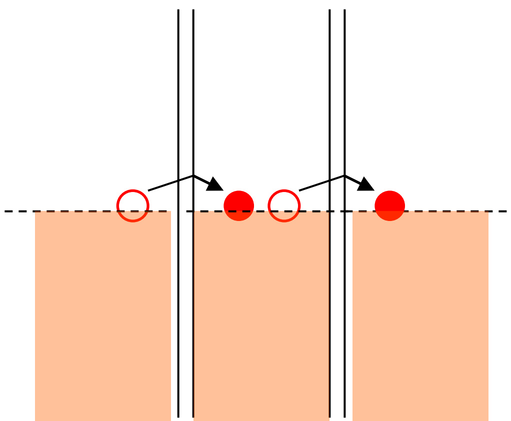
(Possibility of self-cooling, see S. Kafanov et al. PRL (2009))

Higher order processes

Electron cotunneling in SINIS structures is strongly suppressed

"regular" NININ transistor

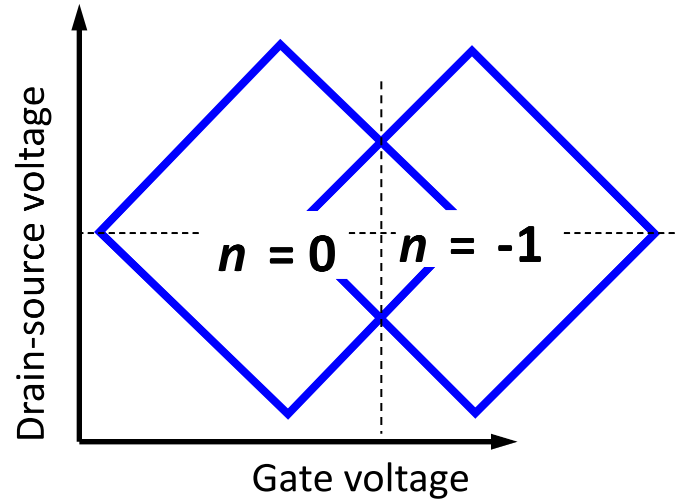


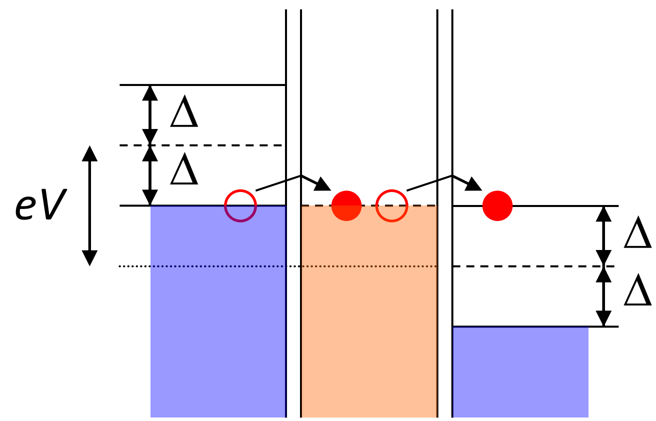


Threshold: $eV = 0$

Does not work in principle!

SINIS transistor

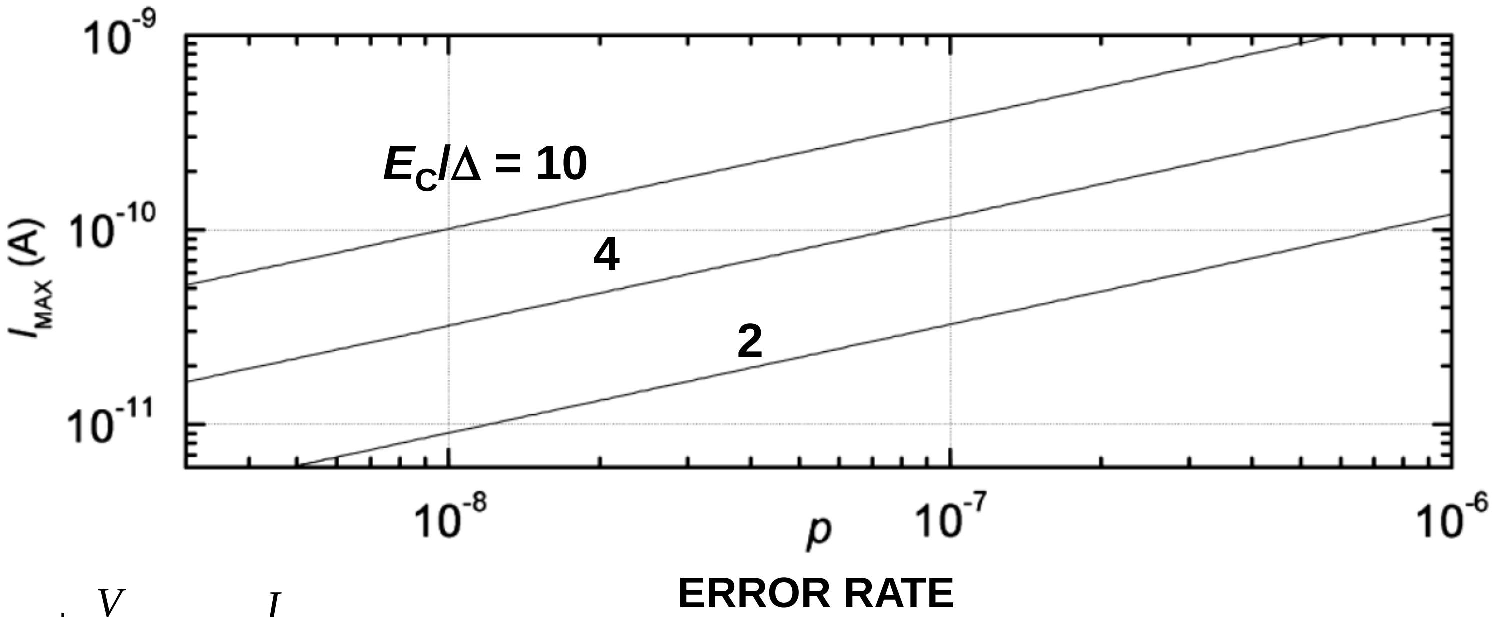


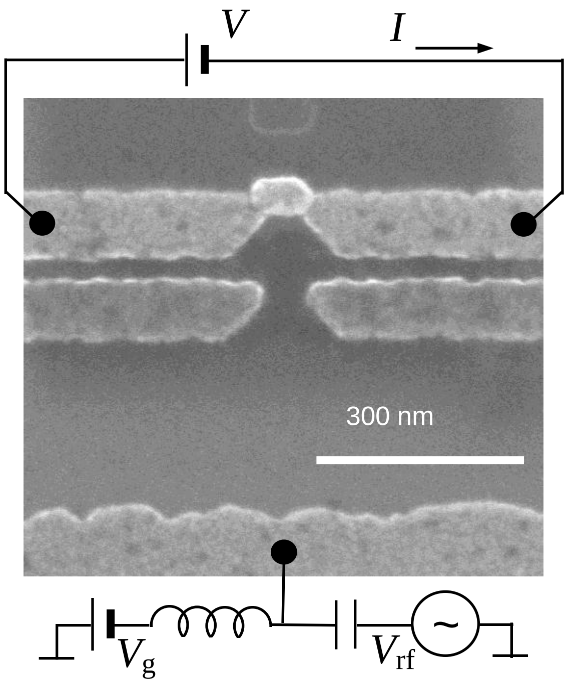


Threshold : $eV = 2\Delta$

Andreev reflection and CP-SE cotunneling

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





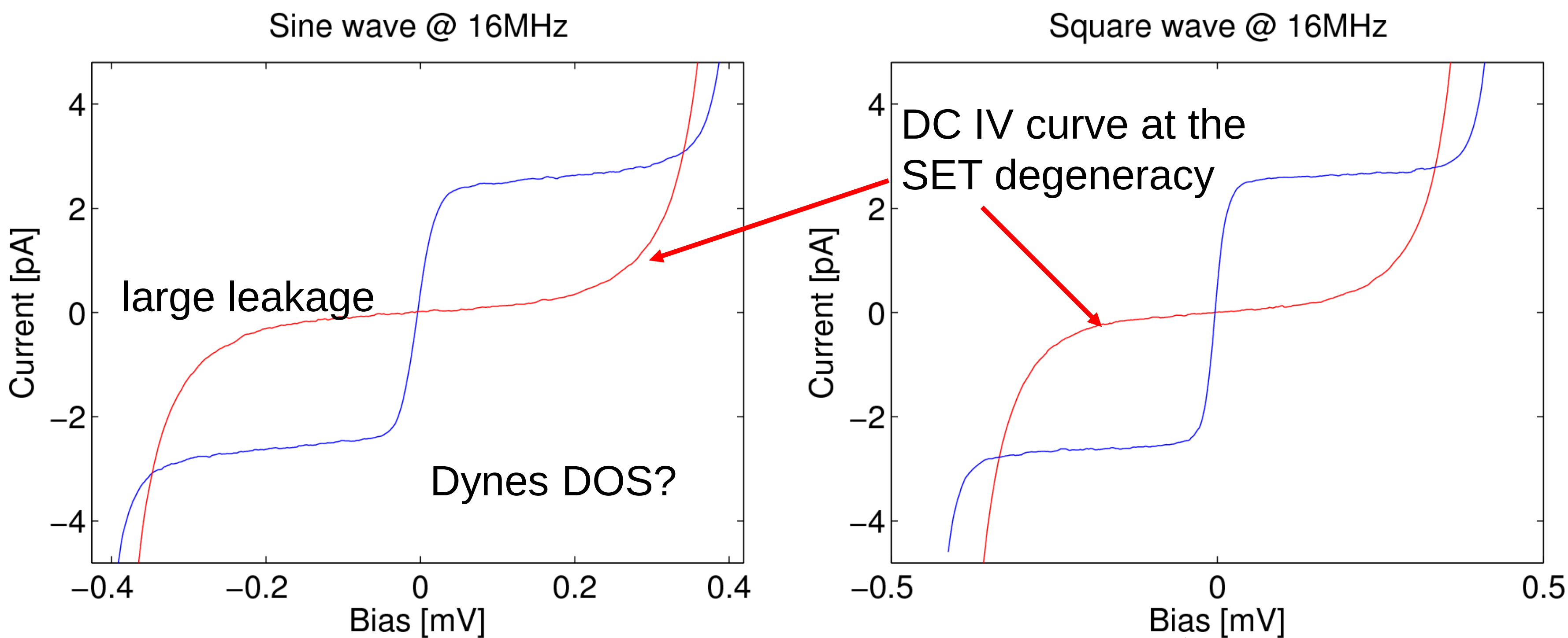
metrological accuracy can be reached (at least in theory)

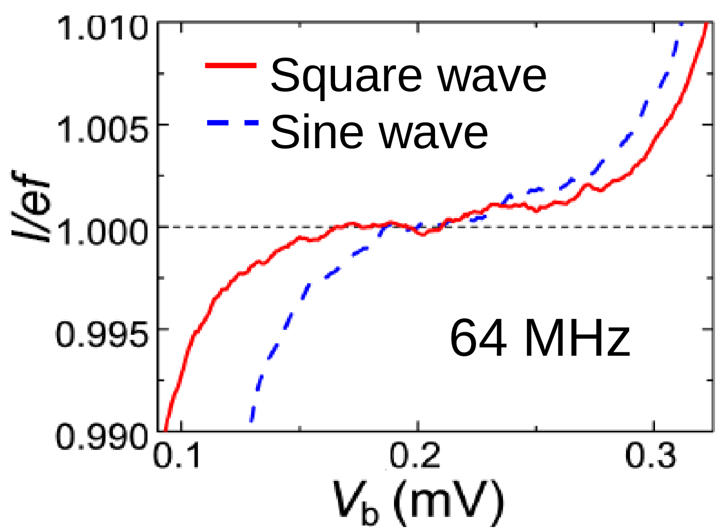
high charging energy good for reaching higher pumping accuracy

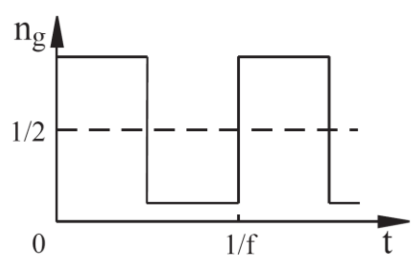
high charging energy pump measured ($E_C/\Delta \sim 10$)

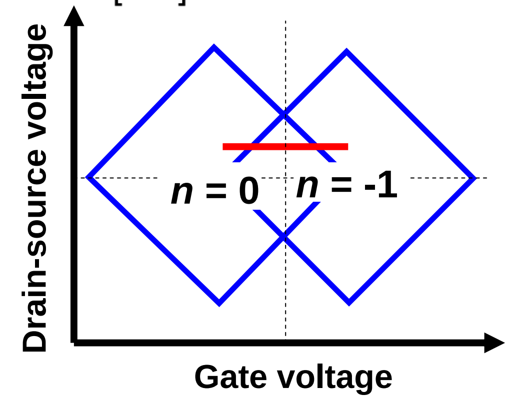
A. Kemppinen et al., APL 94, 172108 (2009)

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





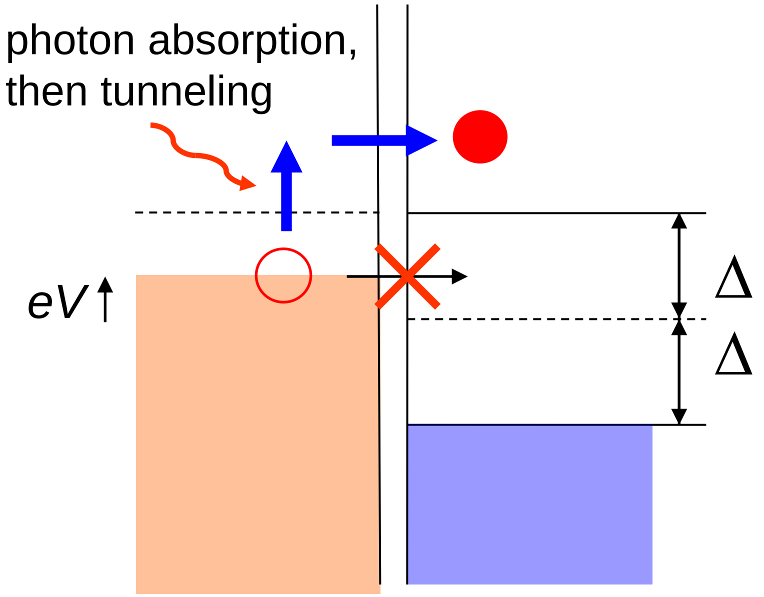


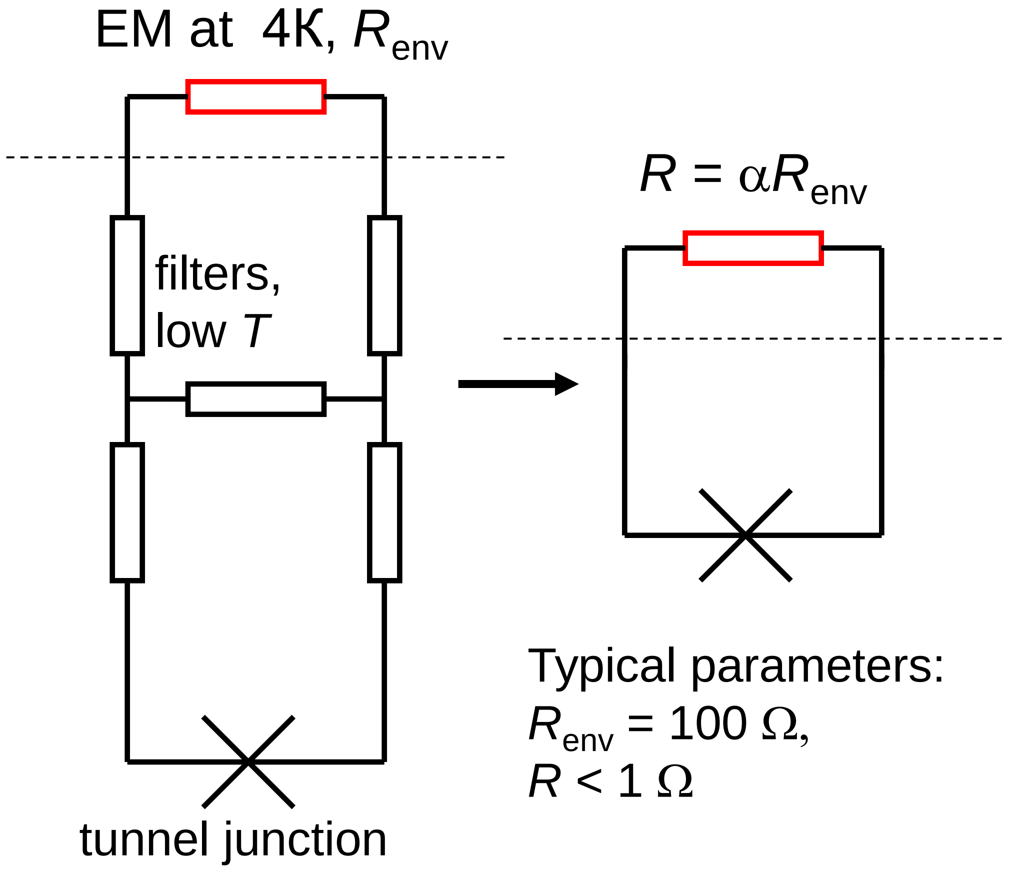


Square-wave signal improves plateau flatness: degeneracy point is passed faster

Environment-assisted tunneling (EAT)

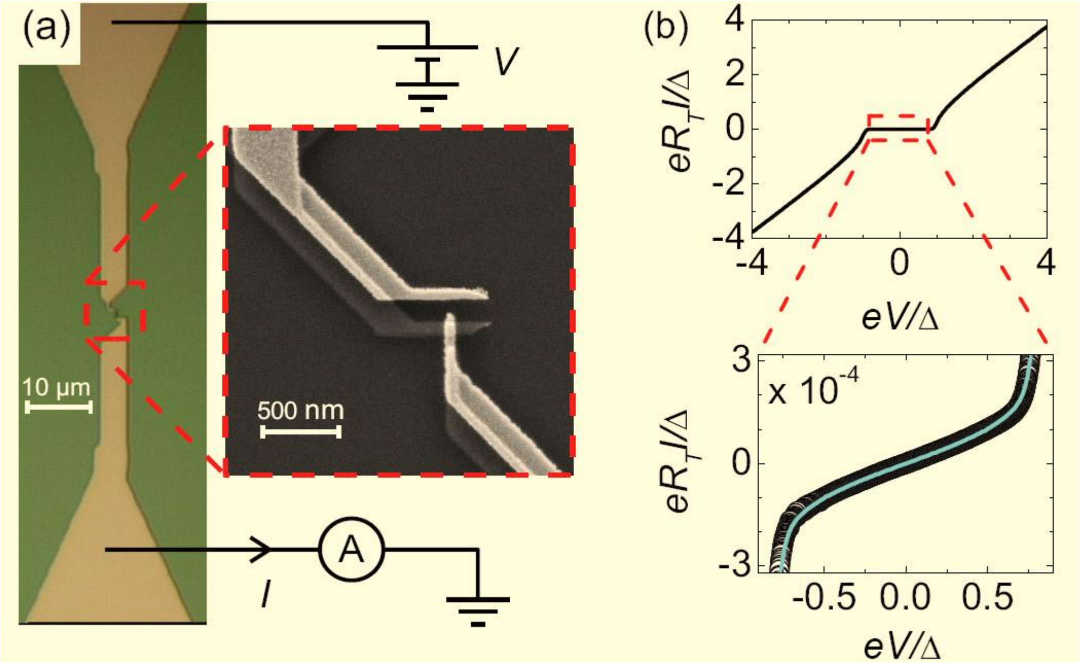
Tunneling rate depends not only on the junction parameters, but also on the EM environment.
P(E)-theory: tunneling rate through the junction taking into account energy exchange between electrons and EM environment.





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

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

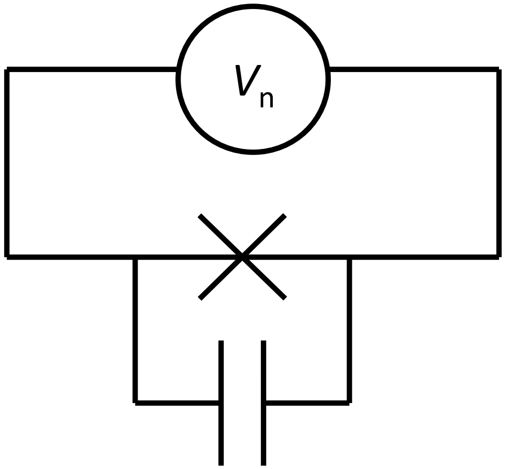
with

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

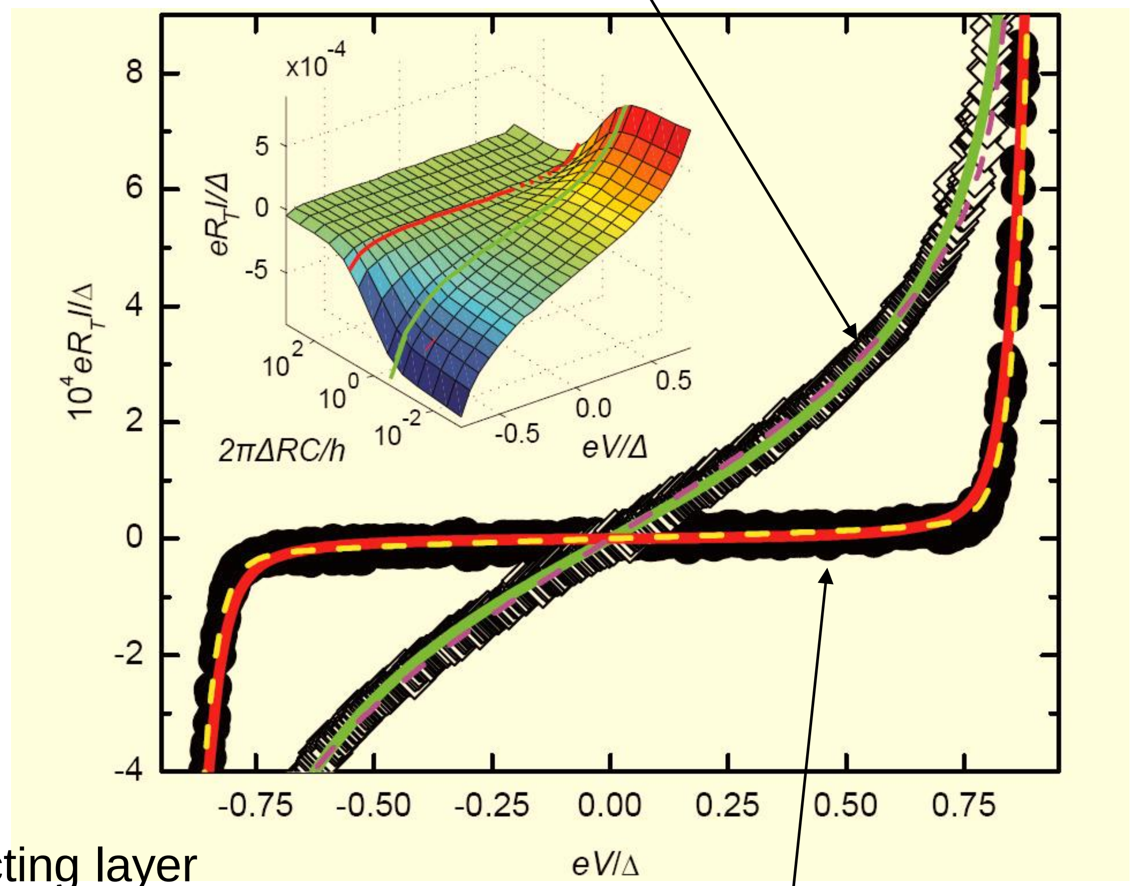
$$\gamma = 2\pi\frac{R}{R_K}\frac{k_B T}{\Delta}$$

SIN junctions with different EM environment

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



without ground plane



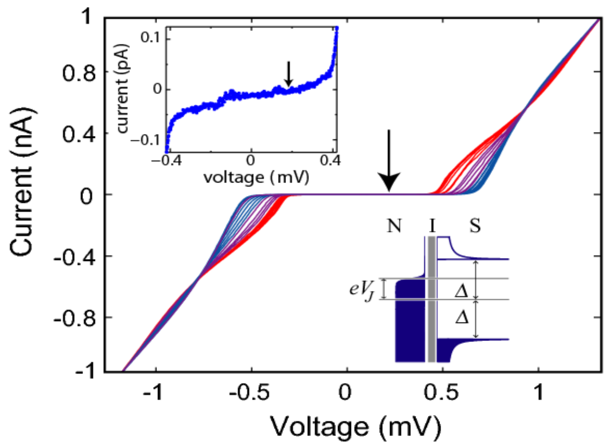
with ground plane

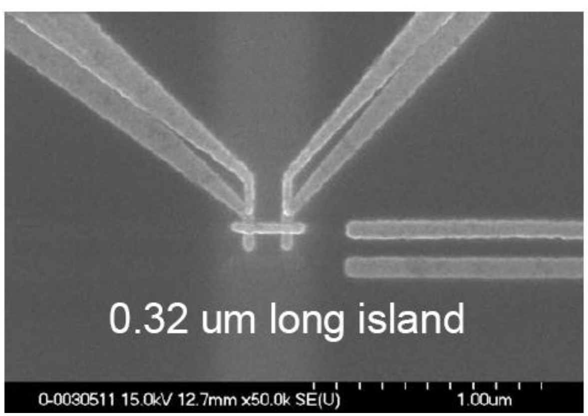
Ground plane = (super)conducting layer covered with a100-nm-thick insulator

Subgap leakage in NIS junctions and SINIS pumps

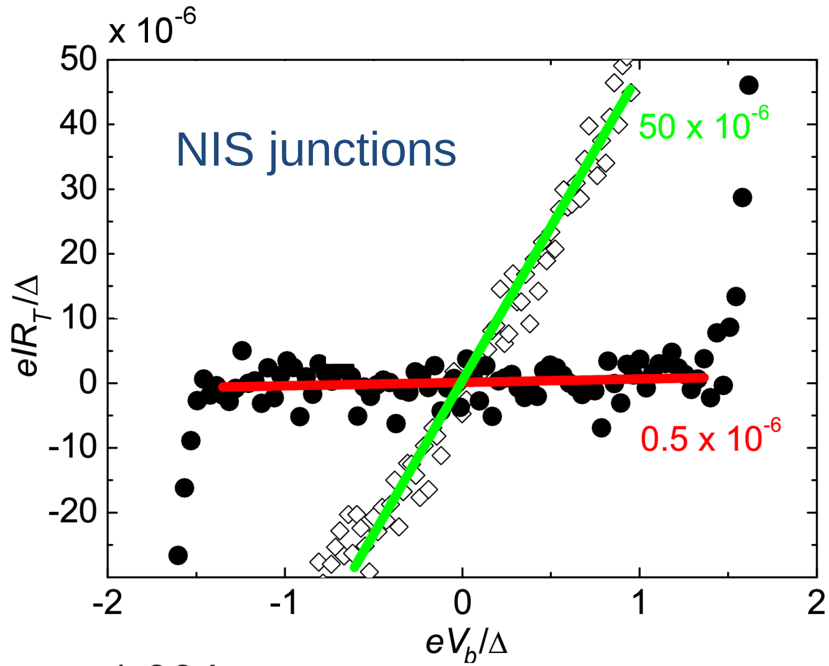
first experiments

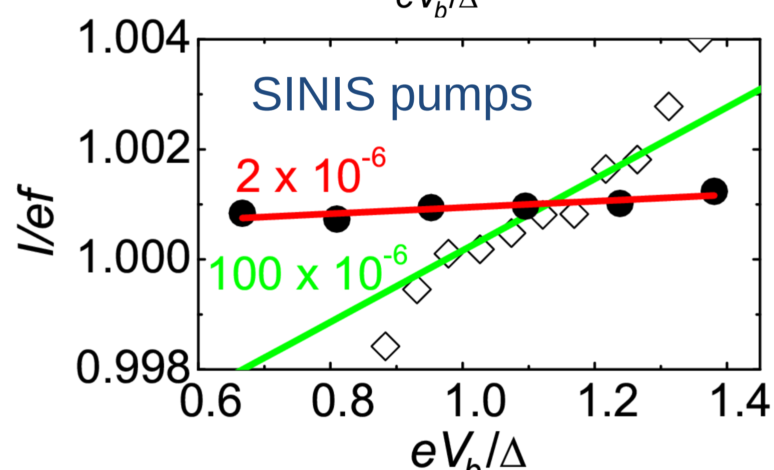
$\gamma = R_n/R_{sg} > 10^{-4}$





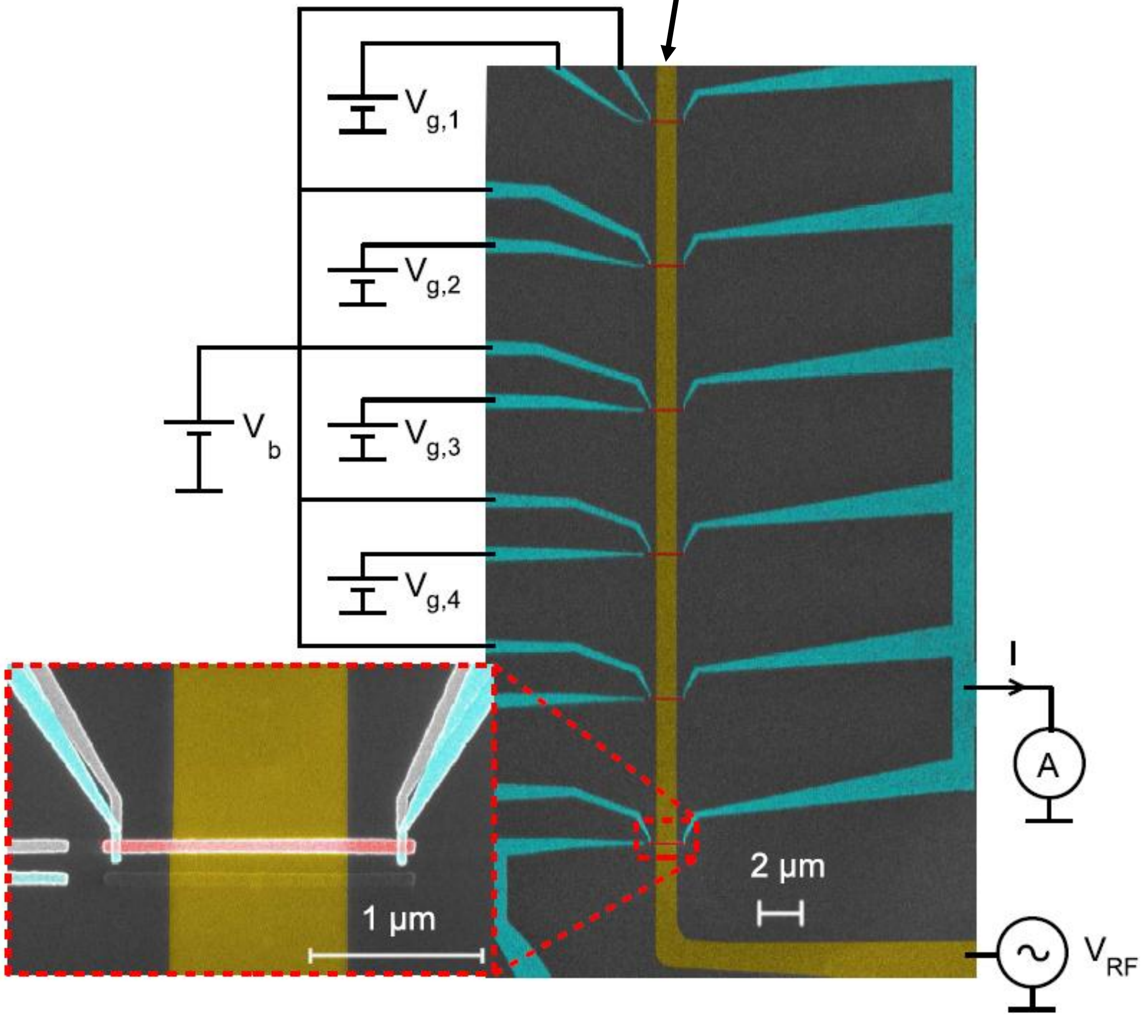
now $\gamma < 10^{-6}$





Scheme for parallel pumping of electrons

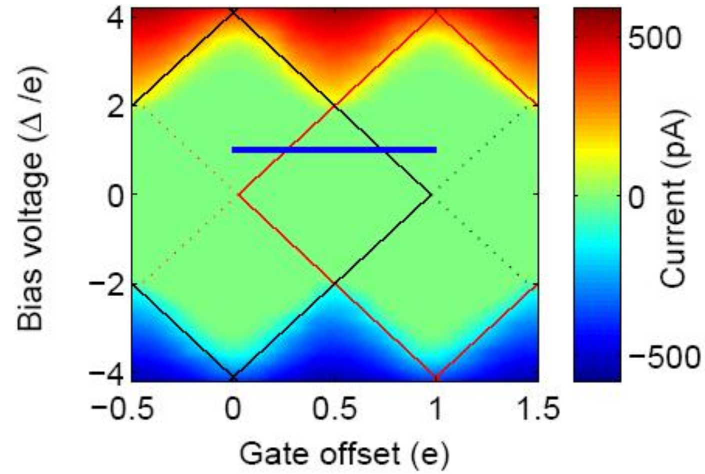
Common rf control gate for all pump

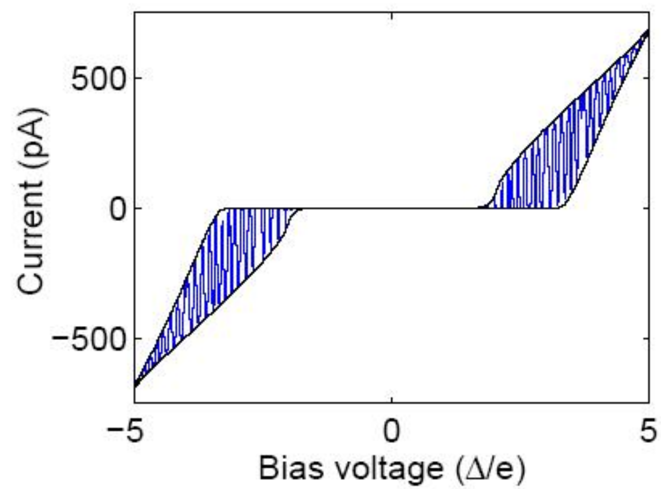


only N + 2 dc leads needed

N – number of pumps

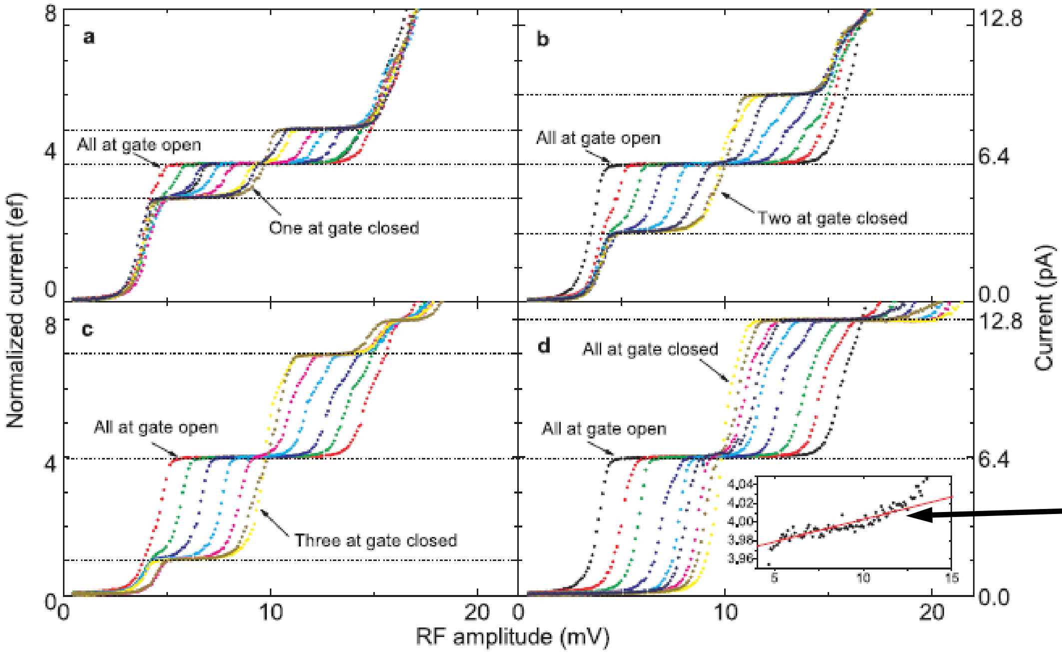
Each pump measured in dc regime





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

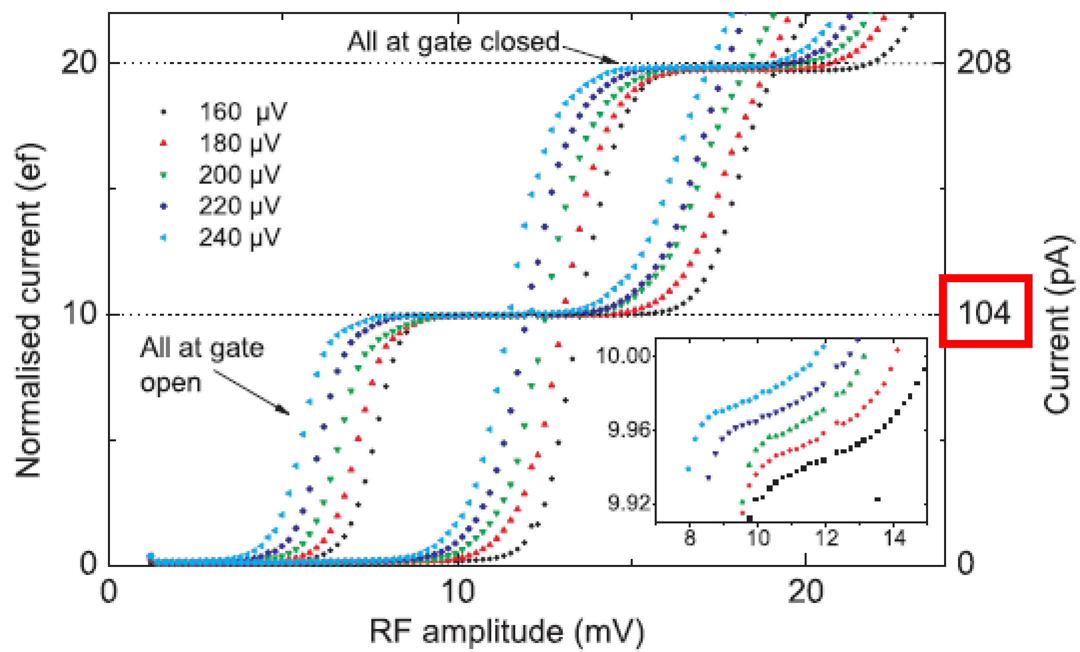
Parallel electron pumping



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}

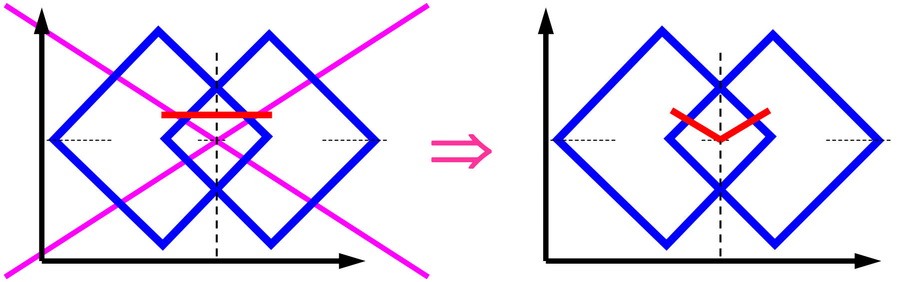
  - $E_c/\Delta \approx 2 - 4$

  - shunting devices with large capacitance

  - square-wave control signal

  - thermalization of quasiparticles

  - optimization of the control signal



  - well-calibrated, stable instruments needed

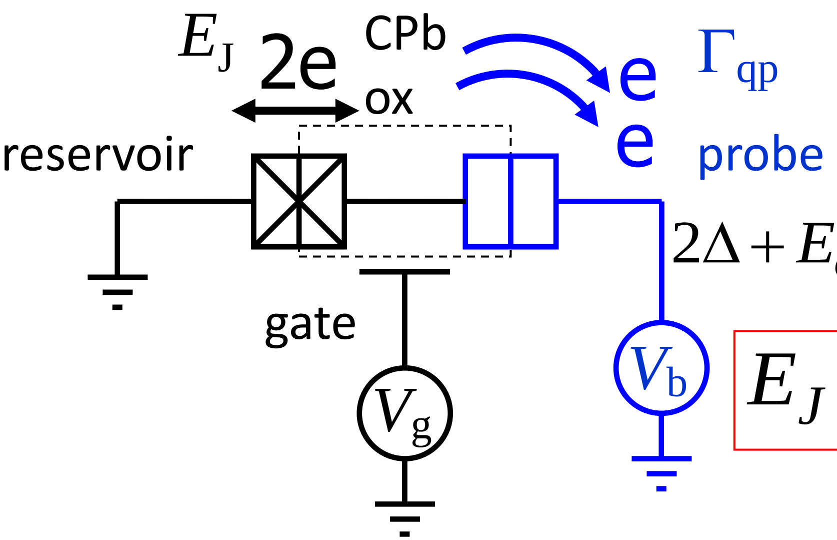
  - temperature control

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)



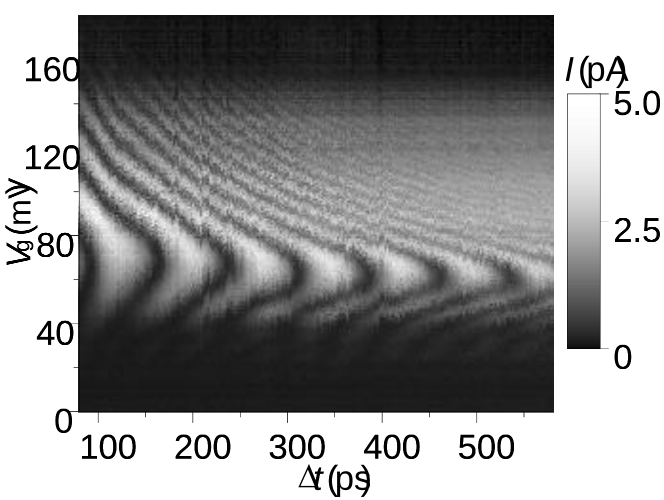
Josephson-quasiparticle (JQP) cycle

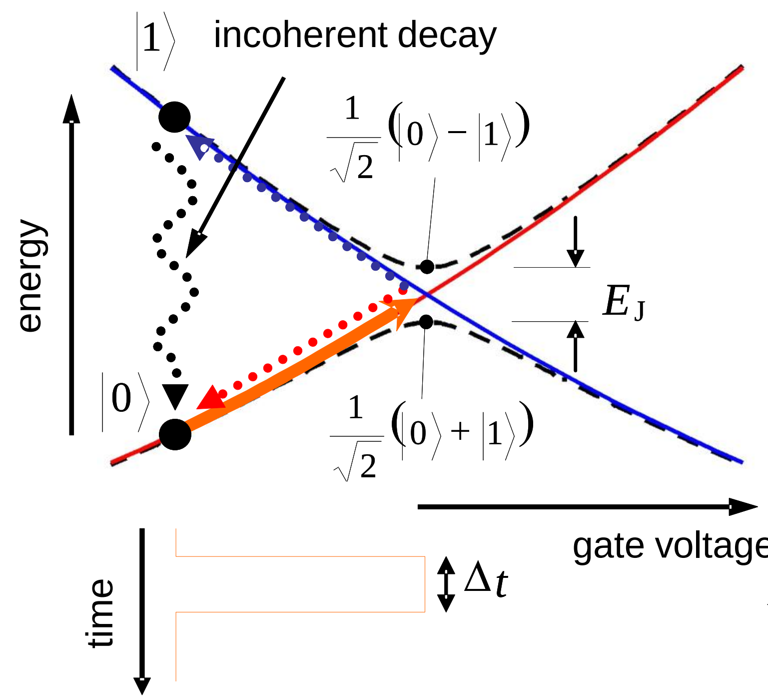
Fulton et al. (1989)

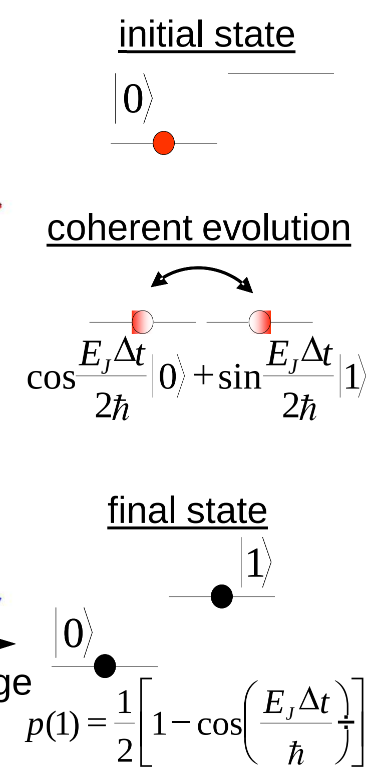
$$2\Delta + E_C < eV_b < 2\Delta + 3E_C$$

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

coherent evolution through one junction, incoherent decay through the other



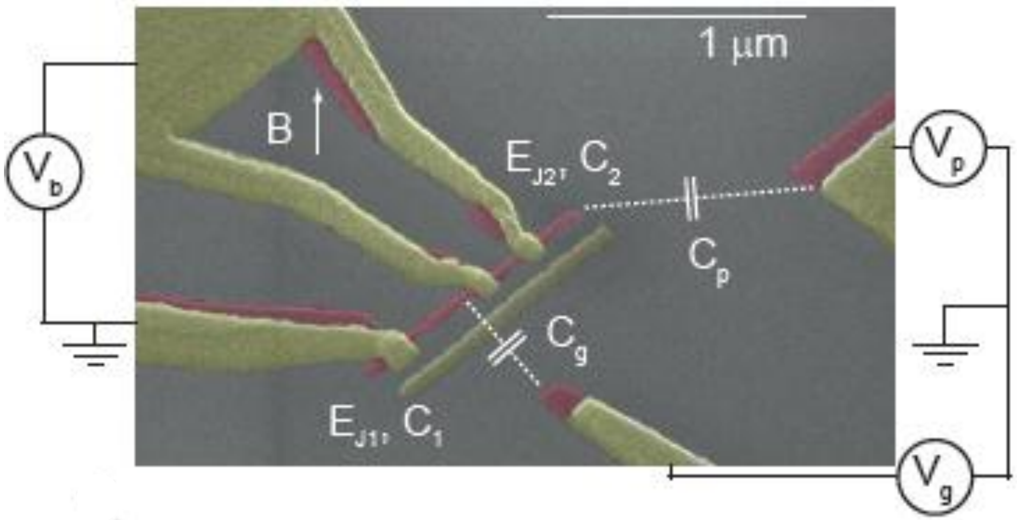




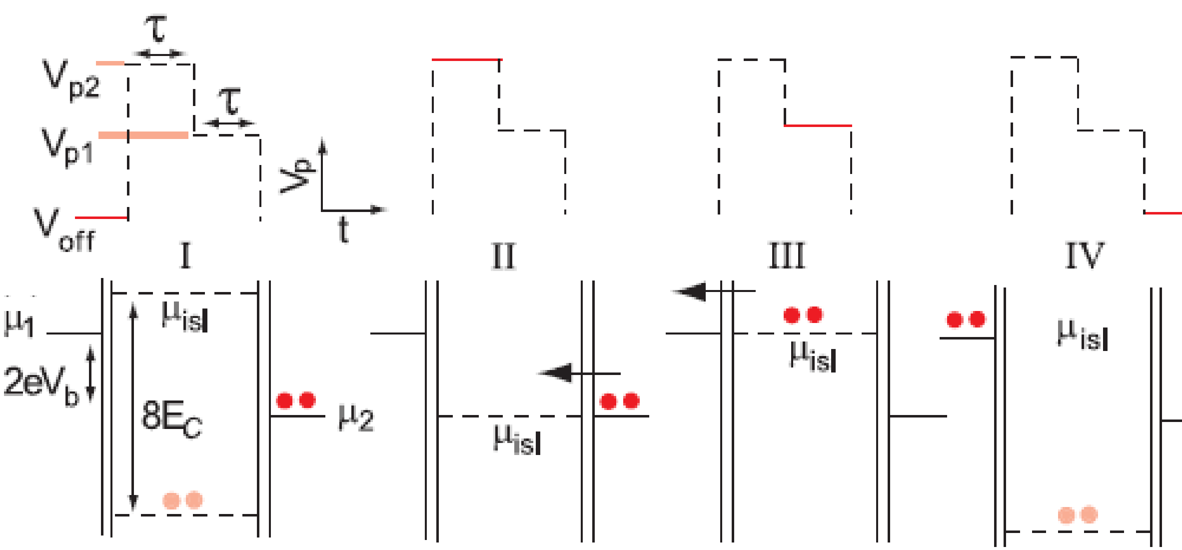
Superconducting quantum pump

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



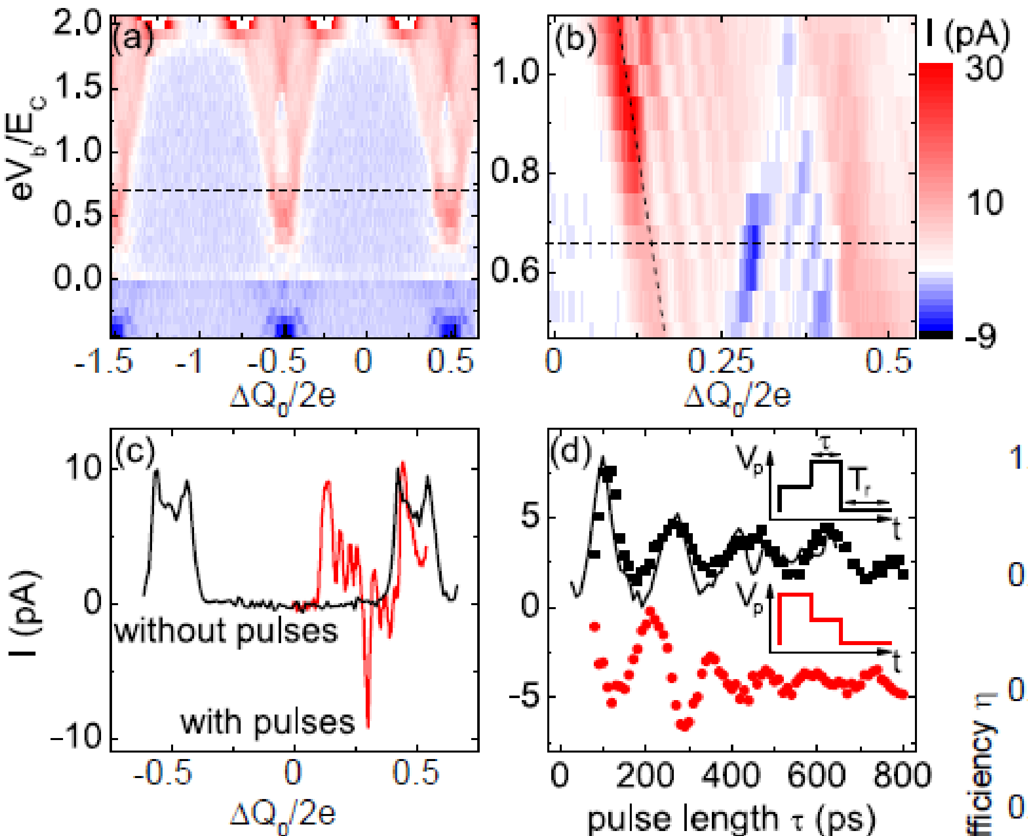
$\tau = h/2E_J$ - π-pulse

E_J = 10 GHz $\Rightarrow$ I ~ 3 nA

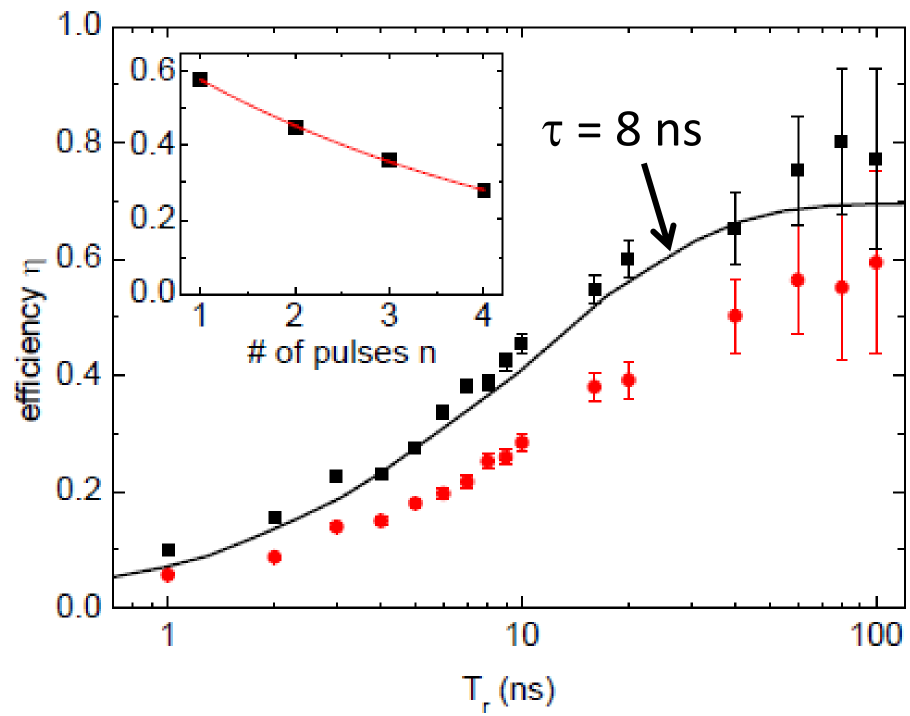
However, this does not work, needs system reset after every pulse

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 $\eta = I_{max}/I$

$I_{max} = 2en/T_r$