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CENTRE FOR MICRO- AND NANOTECHNOLOGY

Kylmälaboratorio
Lågtemperaturlaboratoriet
Low Temperature Laboratory

Low Temperature Laboratory in Micronova

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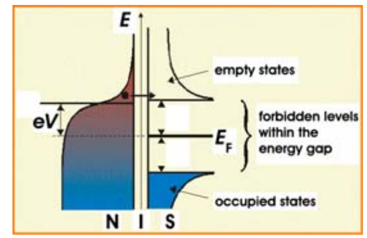
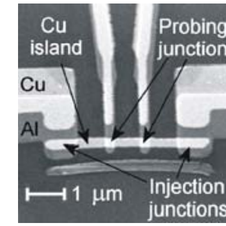
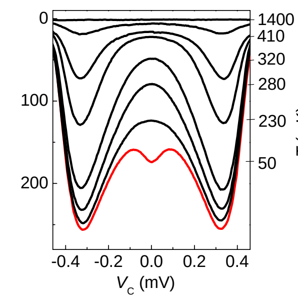
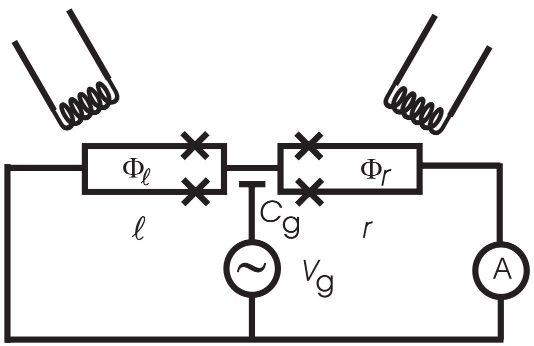
1. Electronic micro-refrigeration and cold electron Josephson transistor

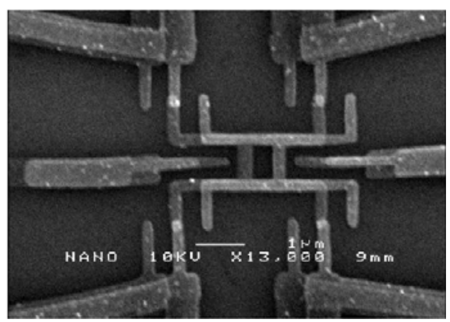


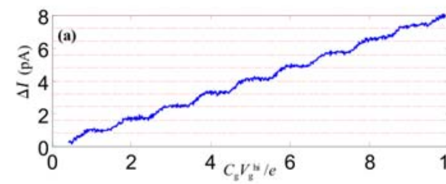


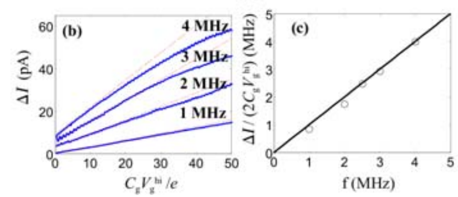


2. Single Cooper pair pumping

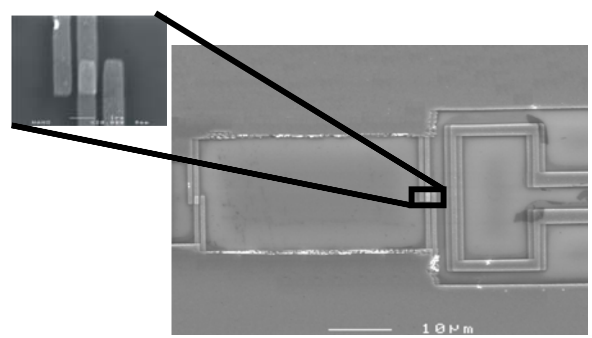








3. Hysteretic DC-SQUIDs with low critical current as read-out devices in quantum circuits



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Charge and Flux Controlled Pumping of Cooper pairs

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1. Motivation
2. Principle of the device
3. Experiments

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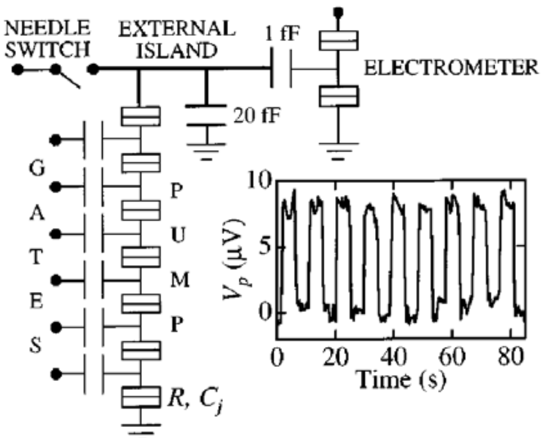
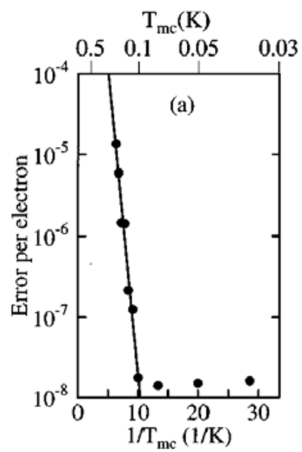
Why to pump charges?

Towards current standard



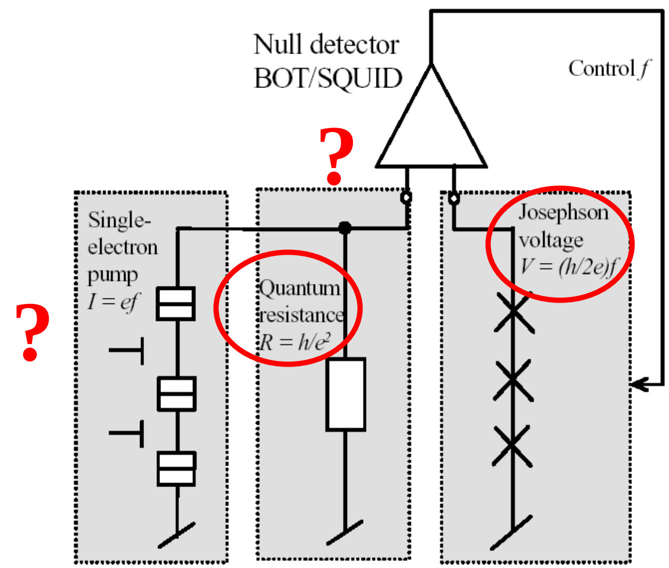


Normal single-electron pump

M. W. Keller, J. M. Martinis,N. M. Zimmerman, and A. H. Steinbach, Appl. Phys. Lett. **69**, 1804 (1996).

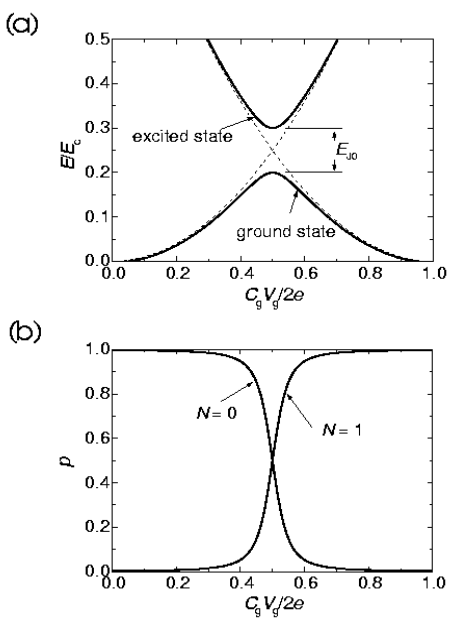
High accuracy but slow: $I < 10$ pA

”Quantum triangle”



Why to pump Cooper pairs?

Cooper pair pumps could possibly be faster than normal electron pumps



Charge transport adiabatic up to

$$f_{\mathrm{LZ}} \sim \frac{E_{\mathrm{J}}^2}{\hbar E_{\mathrm{C}}}$$

Interesting also in terms of quantum coherent effects in small Josephson junction circuits

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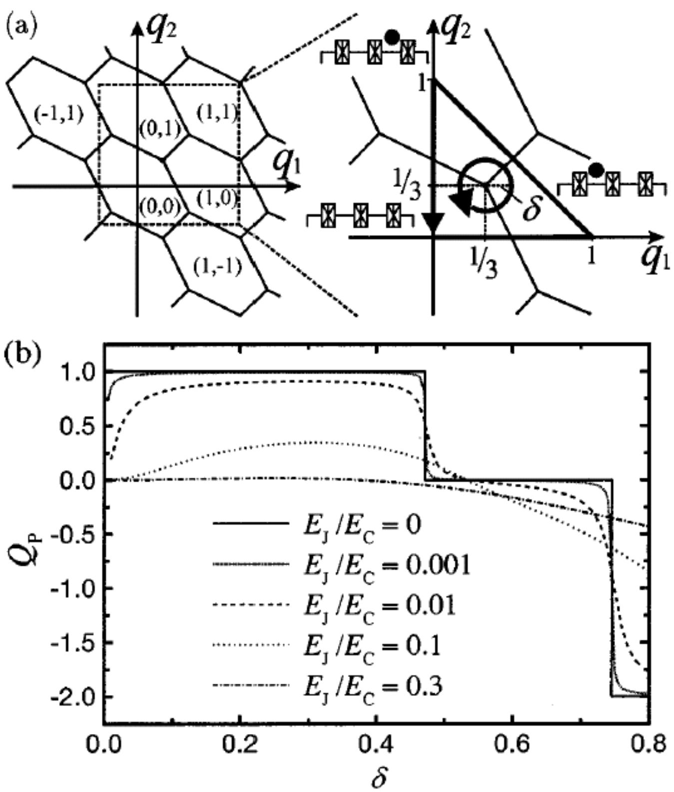
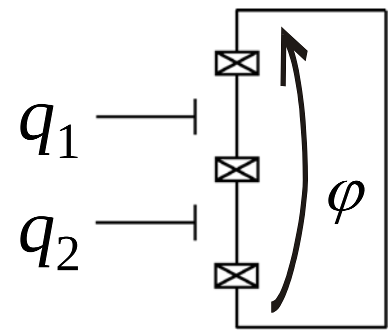
But: there are errors due to large E_J



Perfectly phase-biased adiabatic CPP



$$Q_P = 2\hbar\Im\mathrm{m}\left[\sum_{n\neq m}\oint\frac{(\hat{I}_l)_{mn}}{E_m - E_n}\langle n|\partial_{\vec{q}} m\rangle\cdot d\vec{q}\right]$$

$$Q_\mathrm{P}/(2e) \simeq 1 - 9E_\mathrm{J}/E_\mathrm{C}\cos\varphi$$

This adds to ”normal” supercurrent $I_\mathrm{S} \propto E_\mathrm{J}\sin\varphi$

J. P. et al., PRB **60**, 9931 (1999); R. Fazio et al., PRB **68**, 054510 (2003).

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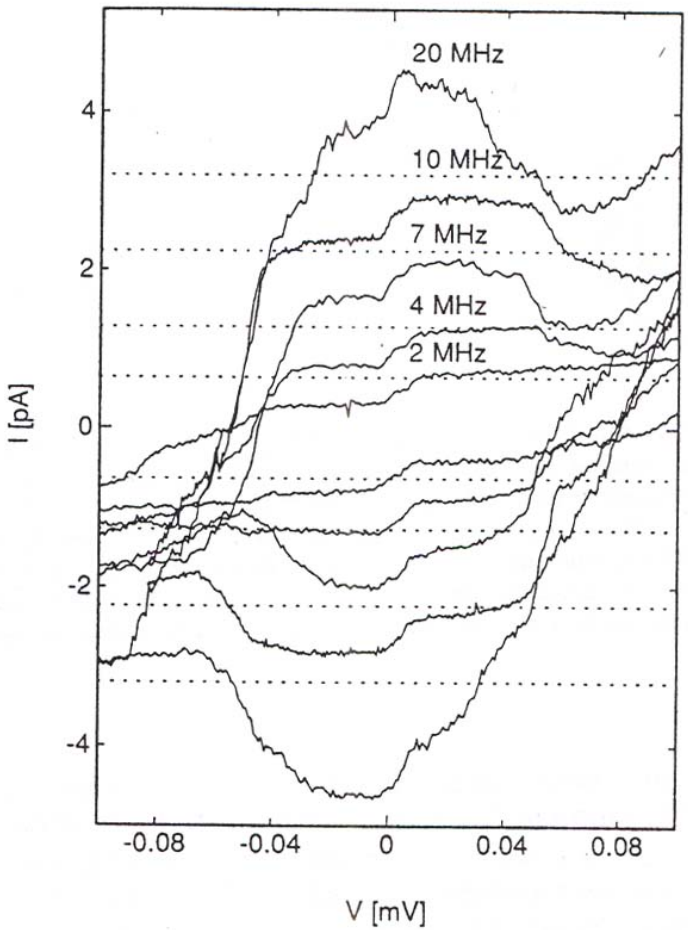
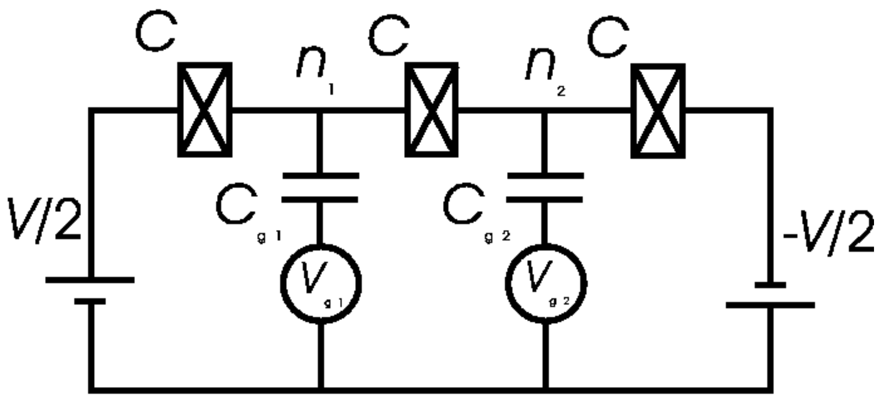
The first three-junction CPP

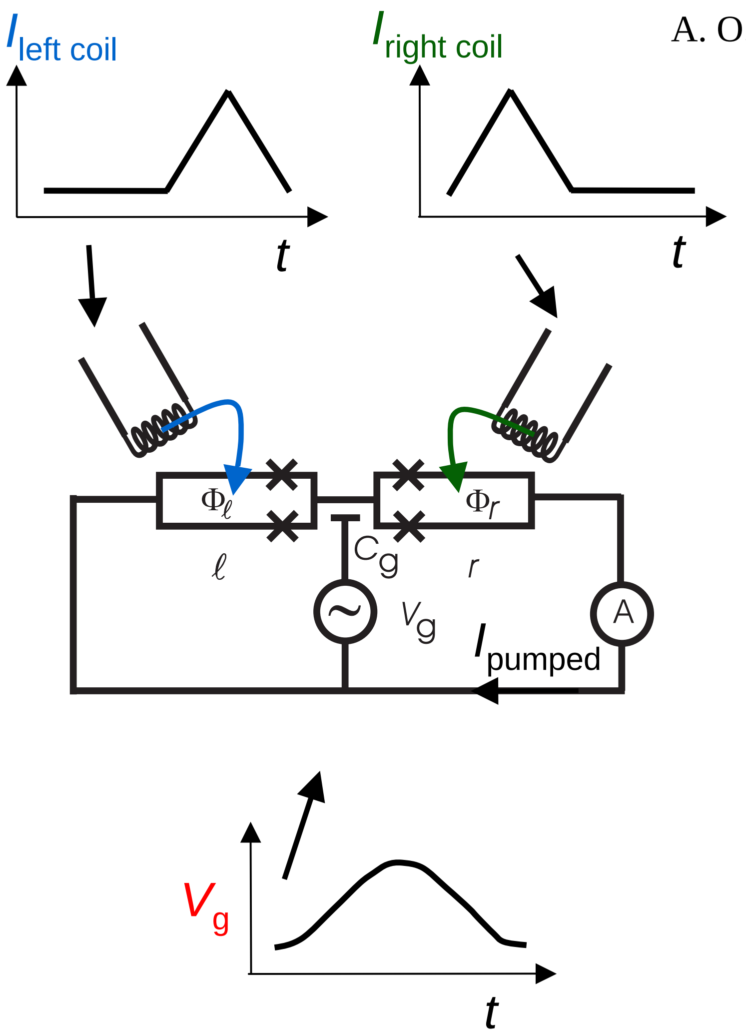


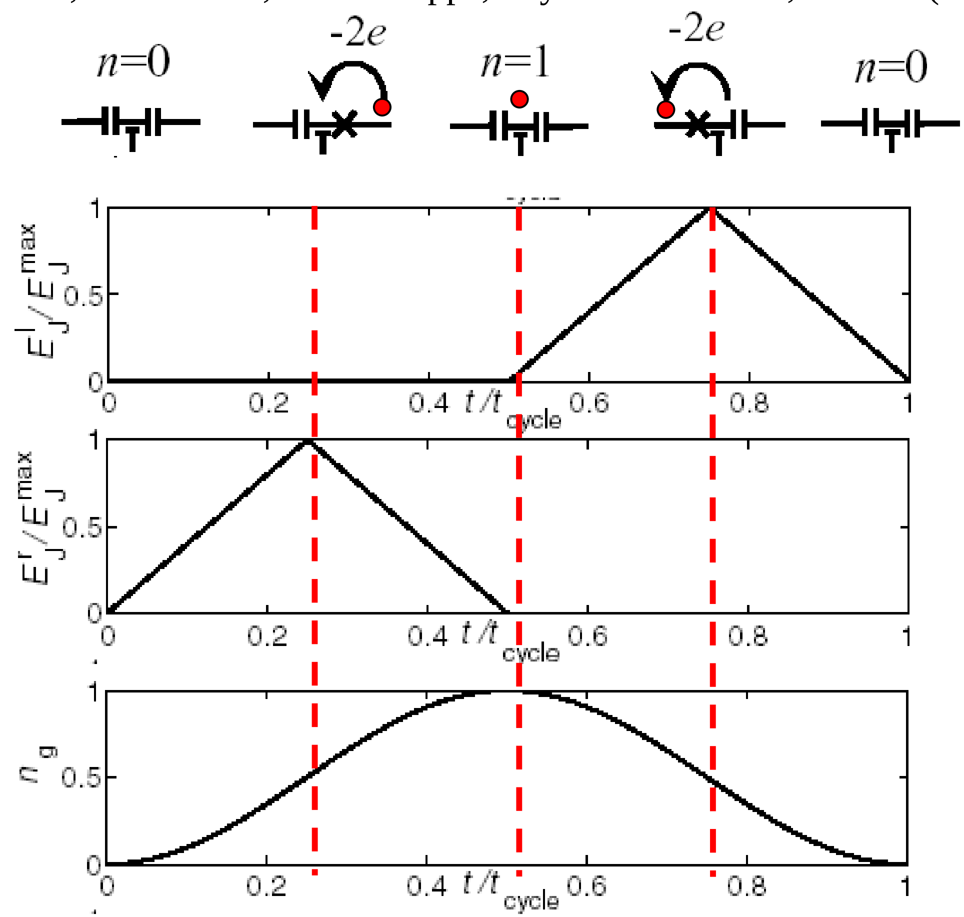


L. Geerligs et al., Z. Phys. B: Condensed Matter 85, 349 (1991).

Flux assisted pump (sluice), principle:

A. O. Niskanen, J. P. Pekola, and H. Seppä, Phys. Rev. Lett. **91**, 177003 (2003).





Can be generalized to pump $2Ne$ per cycle. ($N = 1,2,\ldots?$)

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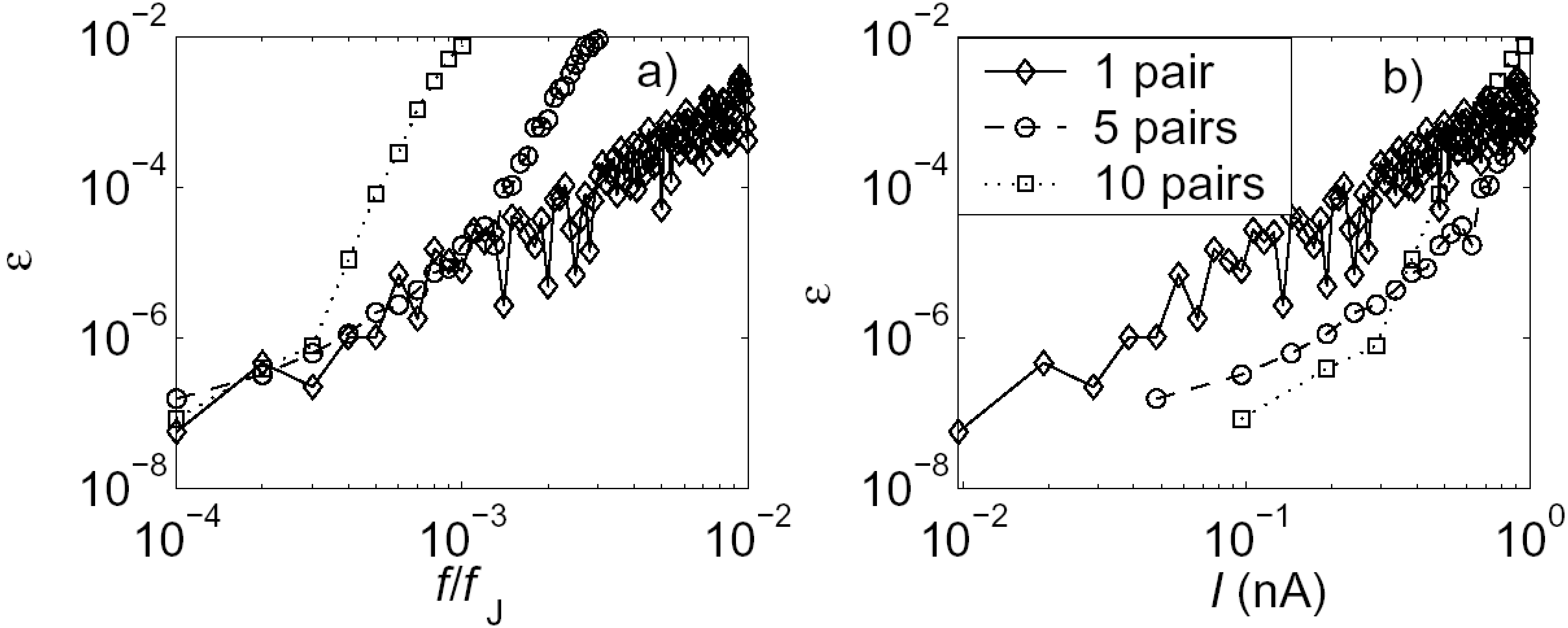
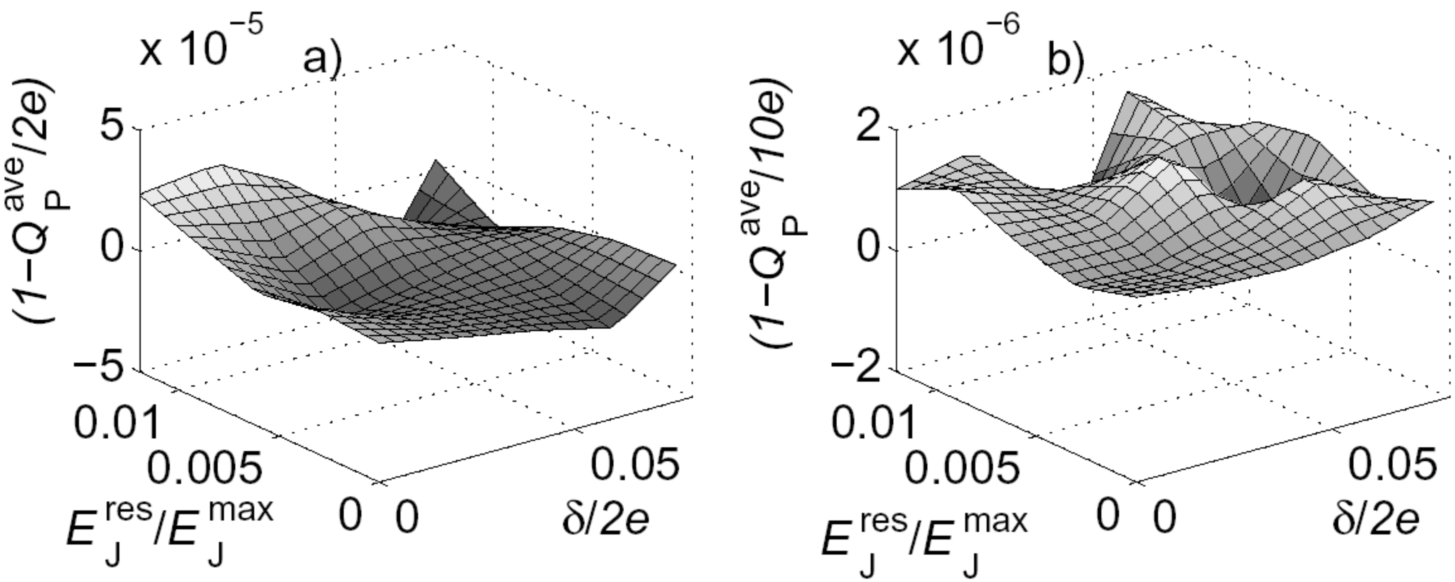
Predicted accuracy of the (ideal) device



To study also the non-adiabaticity errors, we obtained these results by solving Schrödinger eq. and integrating in time, not by adiabatic approximation.

Influence of residual Josephson coupling and offset charge

$$Q_{\mathrm{P}}/(2e) \simeq 1 - \frac{2\sqrt{(E_{\mathrm{J}}^{\max})^2 + E_{\mathrm{C}}^2}}{E_{\mathrm{J}}^{\max} E_{\mathrm{C}}} E_{\mathrm{J}}^{\mathrm{res}} \cos\varphi$$

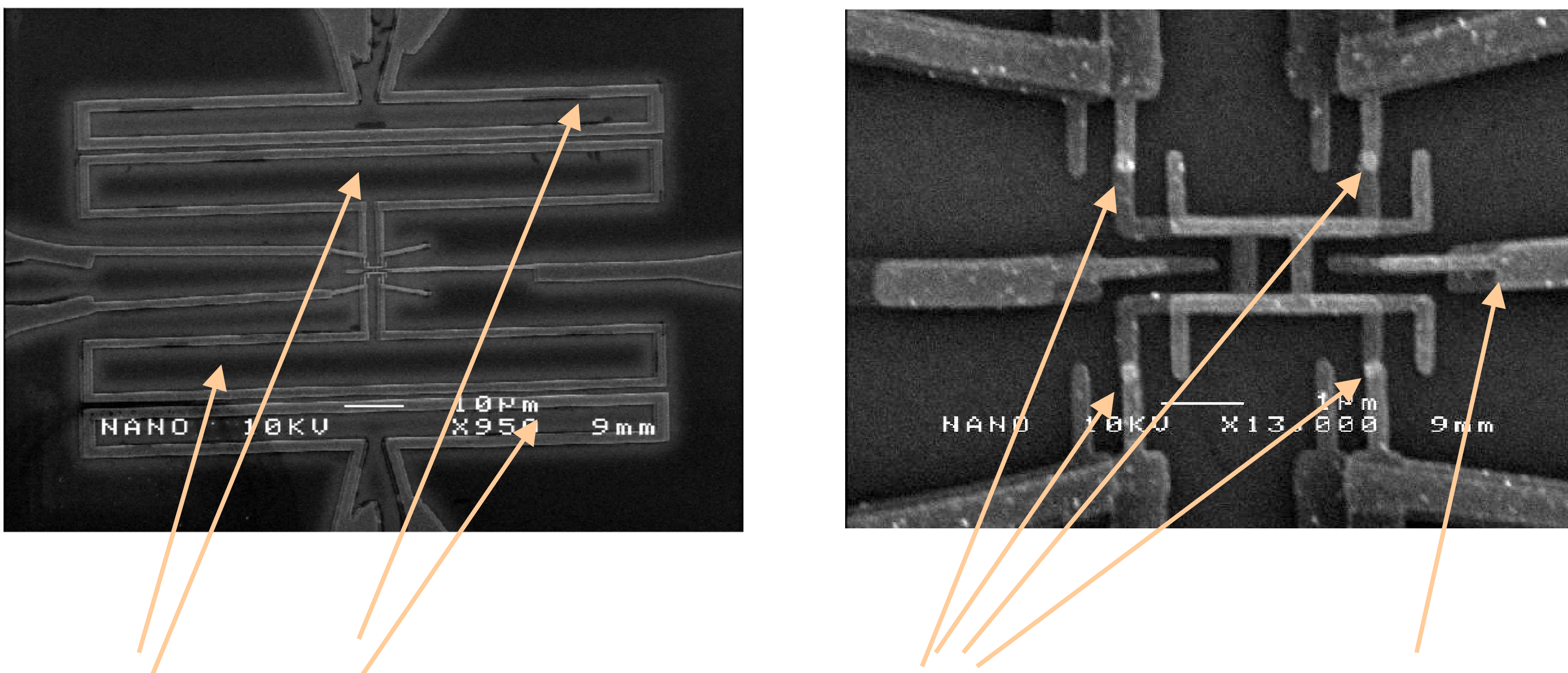


Phase noise may average part of the $E_{\mathrm{J}}^{\mathrm{res}}$ -error out.

Potential sources of error

1. non-adiabaticity
2. non-ideal suppression of E_J
3. environmental impedance
4. background charge noise
5. quasiparticles

The measured device



SQUID loops

Input coils

Junctions

Gate line

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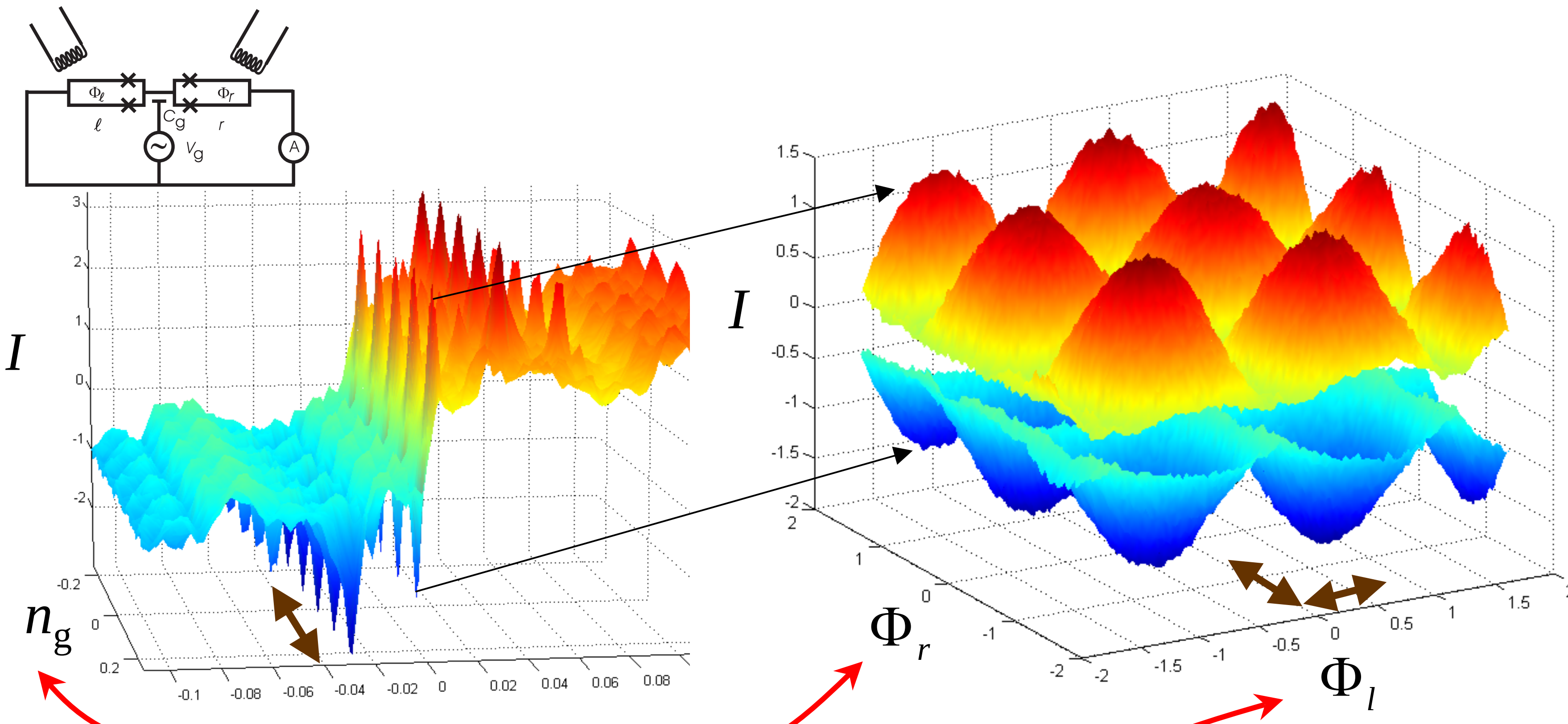
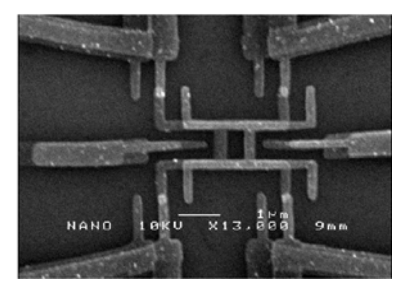
Experimental gate and flux modulation



$$\hat{H} = \frac{2e^2}{2C_J + C_g}(\hat{n} - n_g)^2 - E_J^r\left(\pi\frac{\Phi_r}{\Phi_0}\right)\cos(\phi + \varphi/2) - E_J^l\left(\pi\frac{\Phi_l}{\Phi_0}\right)\cos(\varphi/2 - \phi). \qquad (1)$$



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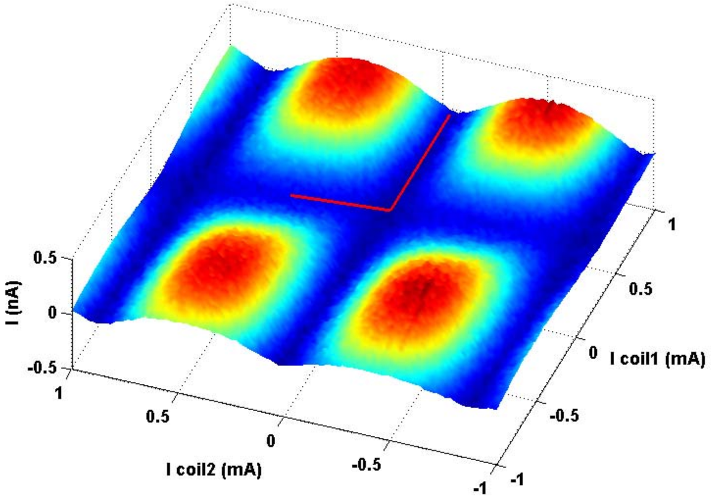
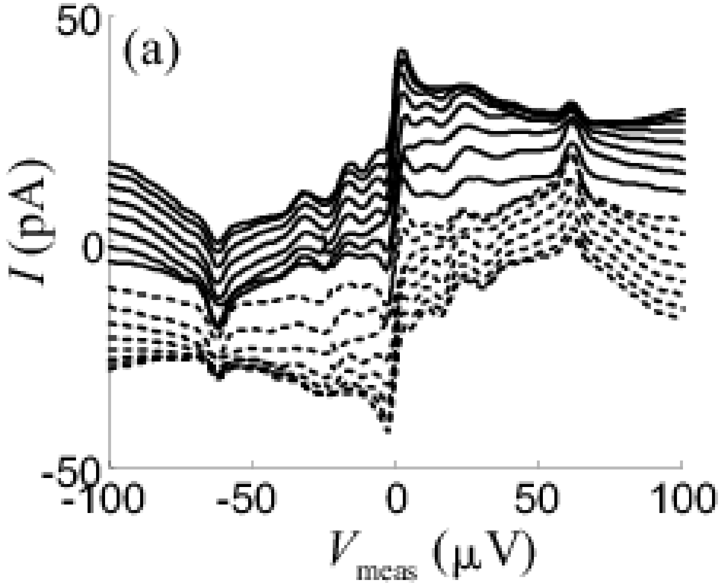
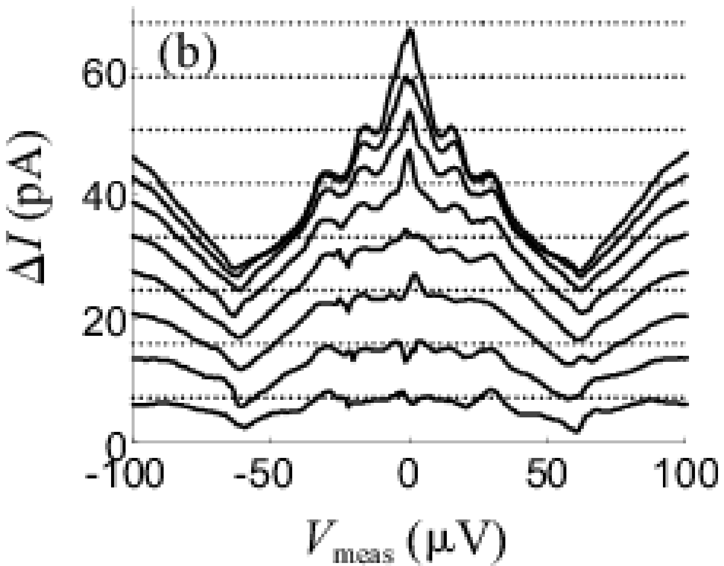
General *IV* curves, pumping



3 MHz, 4...34 pairs / cycle pumped





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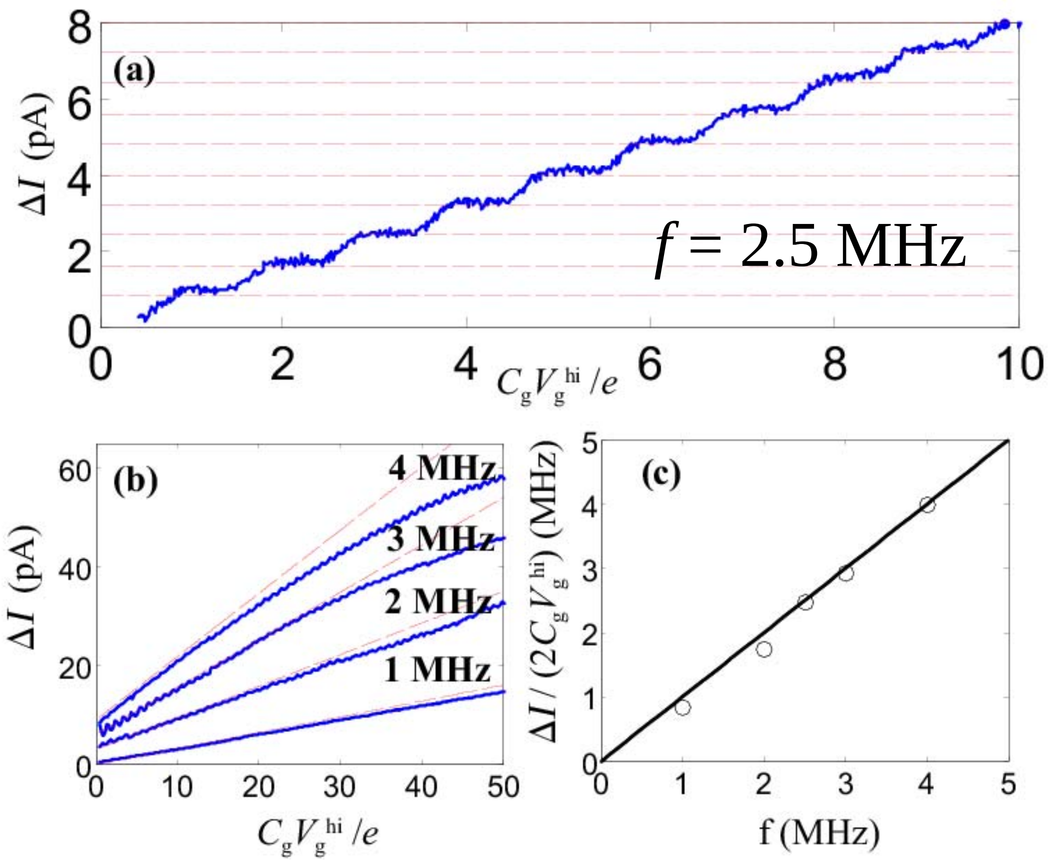
Quantitative comparison to $I = N2ef$



30 pairs per cycle at 4 MHz with accuracy of 1 % achieved

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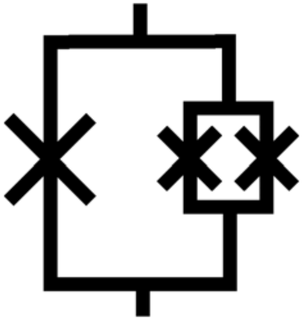
Improvements in the future



1. Better temporal suppression of E_J by three-junction SQUID or SQUID array
2. Better designed environment to suppress supercurrent leakage (fixed voltage bias)
3. Get rid of quasiparticles (by gap engineering?)
4. Higher speed by

(a) increasing E_J (by lowering junction resistance or ultimately by using Nb junctions)

(b) pulse optimisation to avoid non-adiabaticity

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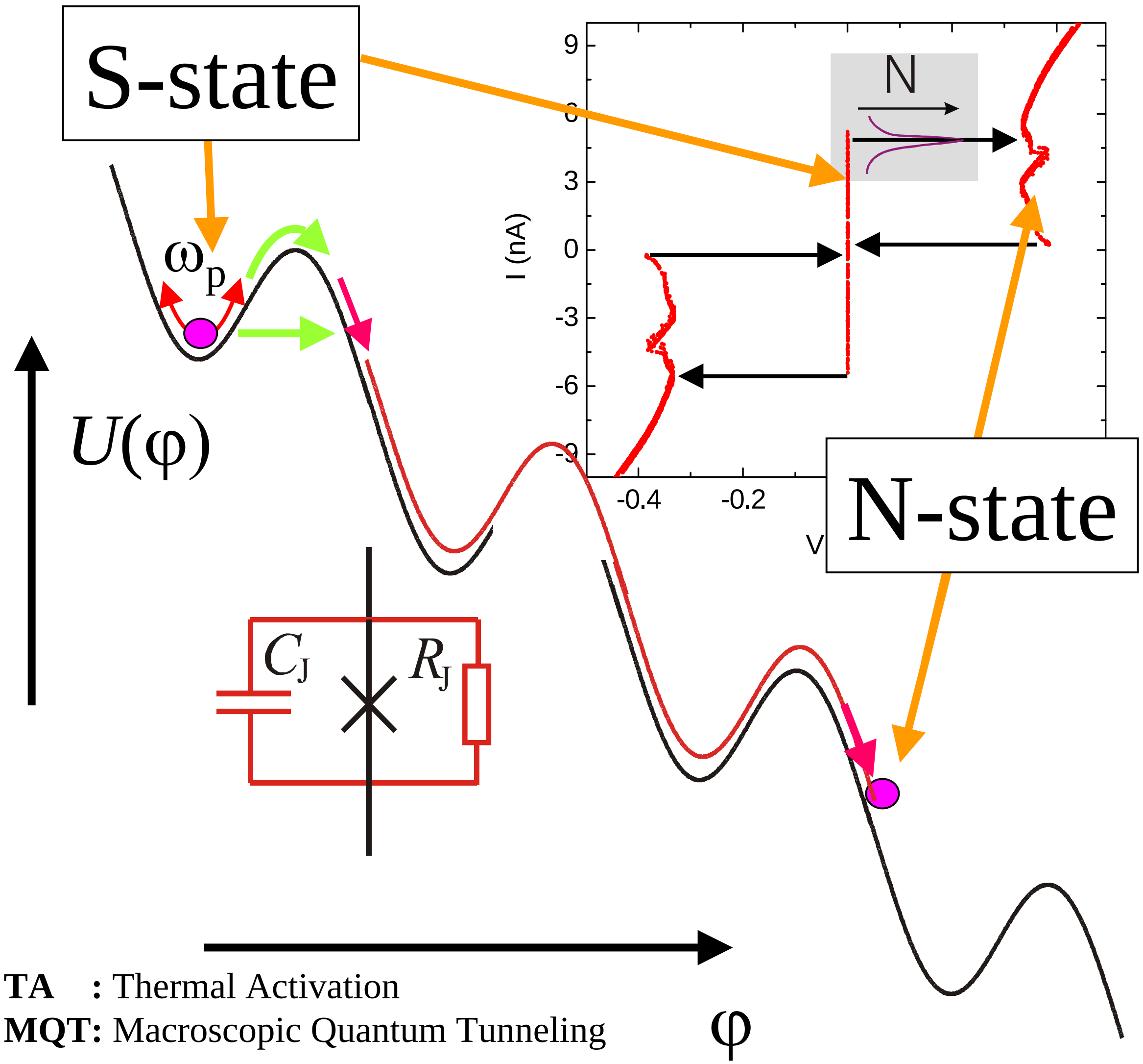
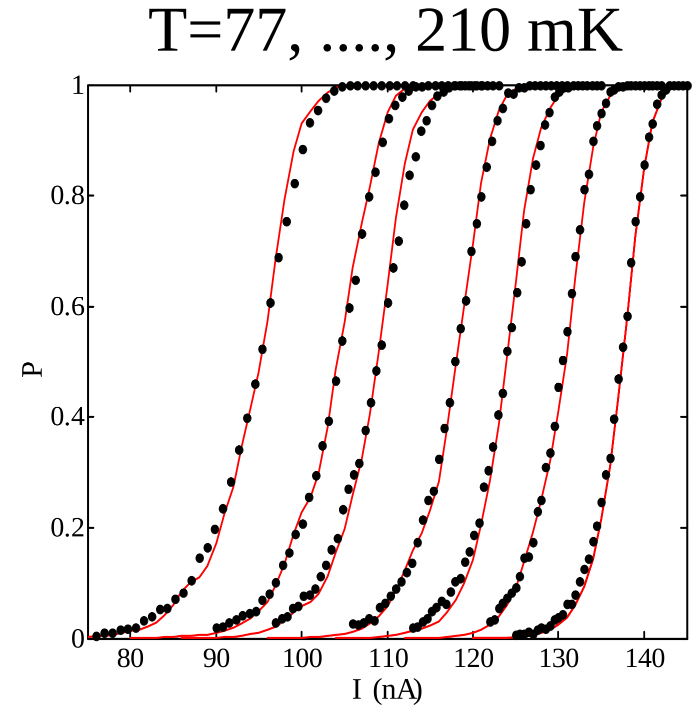
Hysteretic DC-SQUIDs with low critical current as read-out devices in quantum circuits



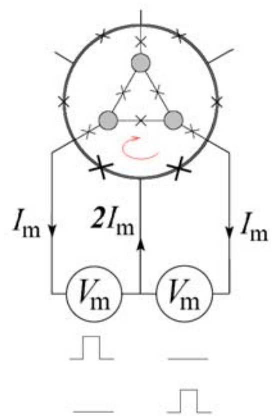
TA : Thermal Activation
MQT: Macroscopic Quantum Tunneling

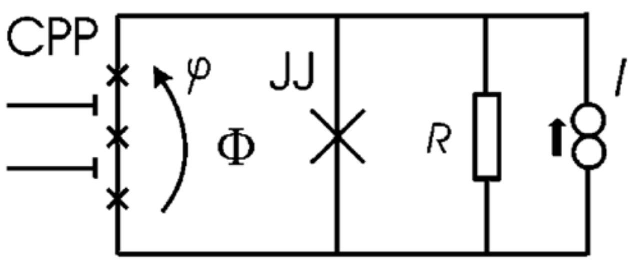
Small hysteretic Josephson junctions and SQUIDs – switching dynamics



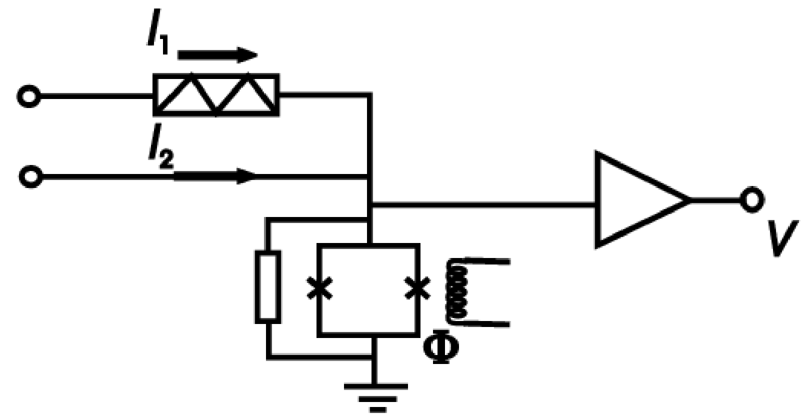
DC SQUID or Josephson junction as an ammeter: applications

Qubits and coherent Cooper pair pumps – **avoid dissipation**





”Classical” measurements (e.g. noise and FCS) can tolerate some dissipation

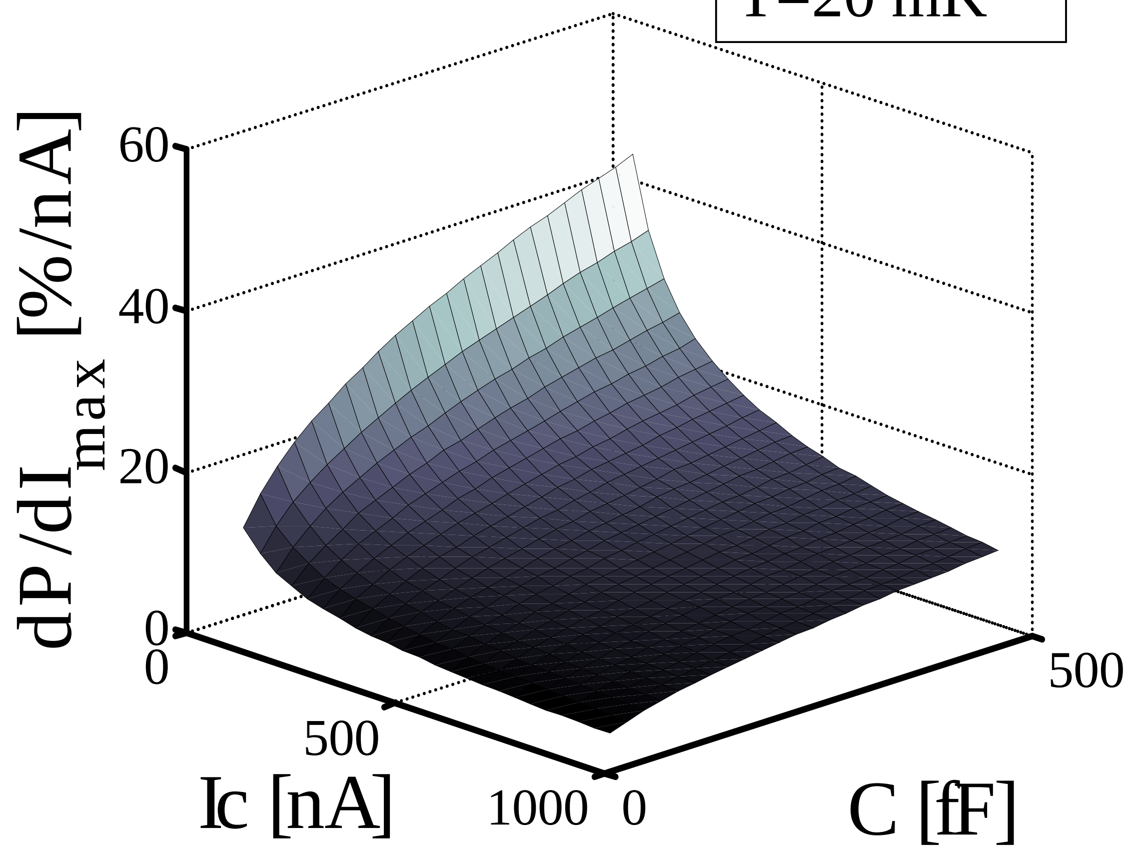


Increasing sensitivity of Josephson junction ammeters/threshold detectors

MQT & TA
T=20 mK

$$\Delta I \propto I_{\mathrm{C}}^{3/5}/C^{2/5}$$

Best resolution when both E_J (I_C) and E_C ($1/C$) are small.
But how far can we go?



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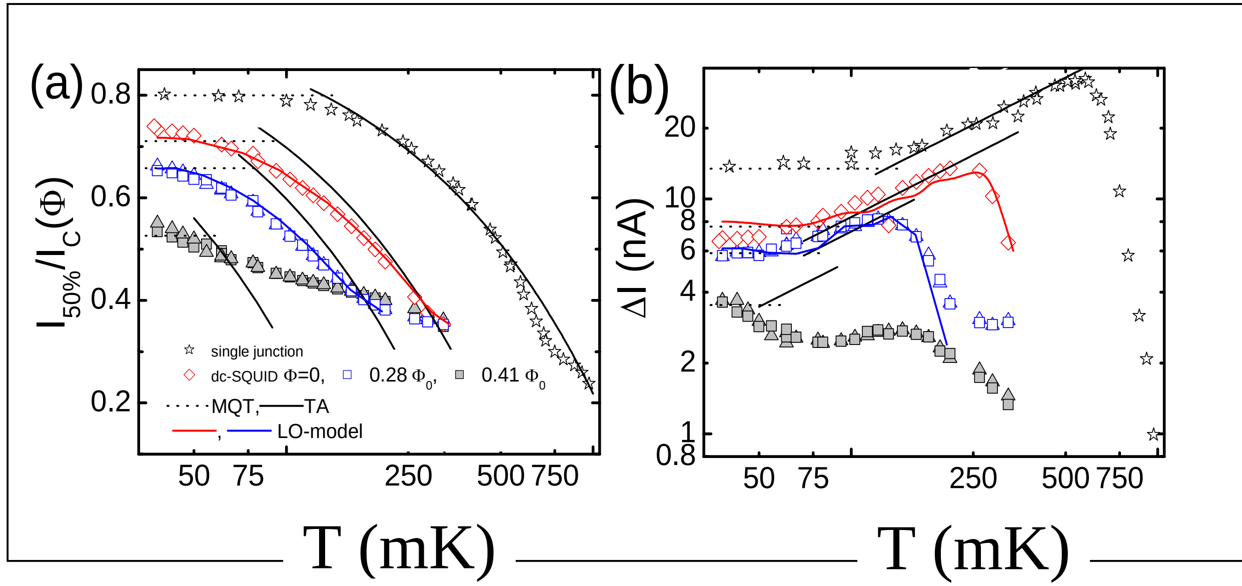
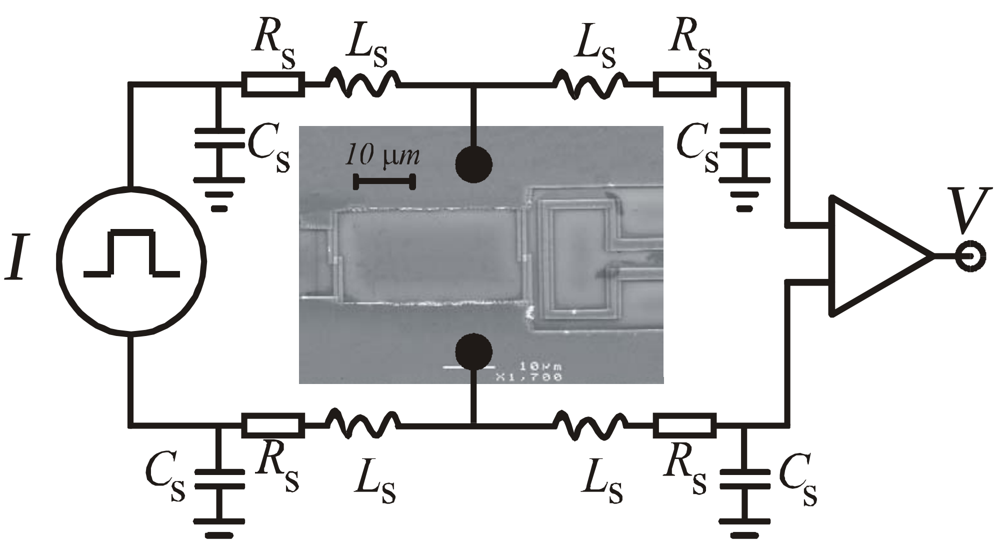
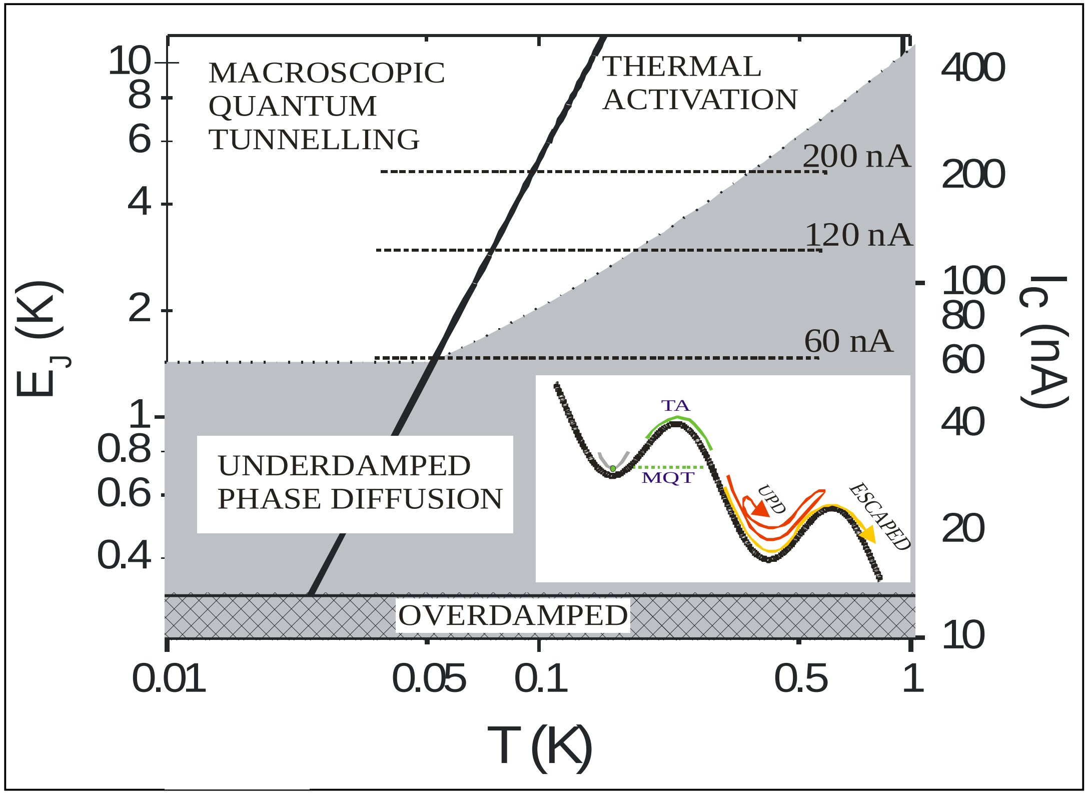
RESULTS

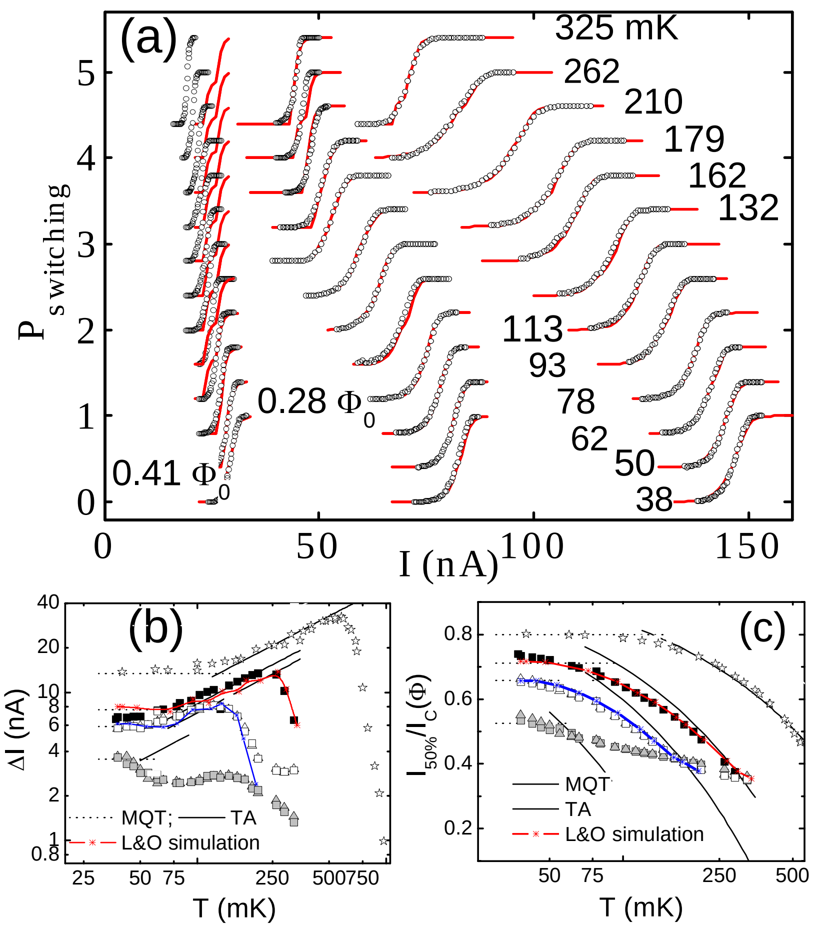




Phase diagram of small Josephson junctions and SQUIDs



THE END


(a)
325 mK
262
210
179
162
132
113
93
78
62
50
38
0.28 Φ0
0.41 Φ0
P switching
I (nA)
(b)
ΔI (nA)
MQT; —— TA
L&O simulation
T (mK)
(c)
I50%/IC(Φ)
MQT
TA
L&O simulation
T (mK)

ENERGY LEVEL MODEL and DISSIPATION