Cooper pair sluice: A flux-assisted charge pump

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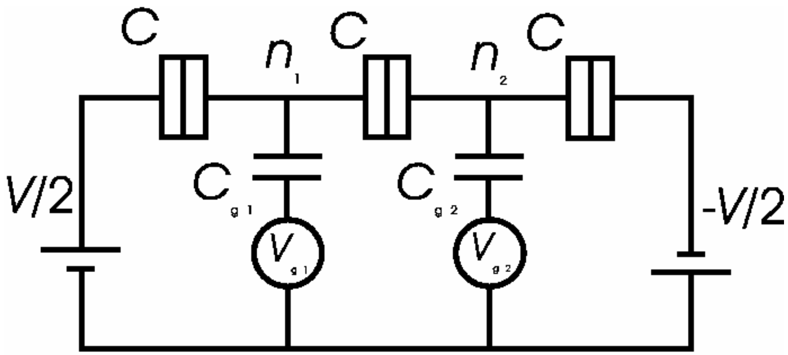
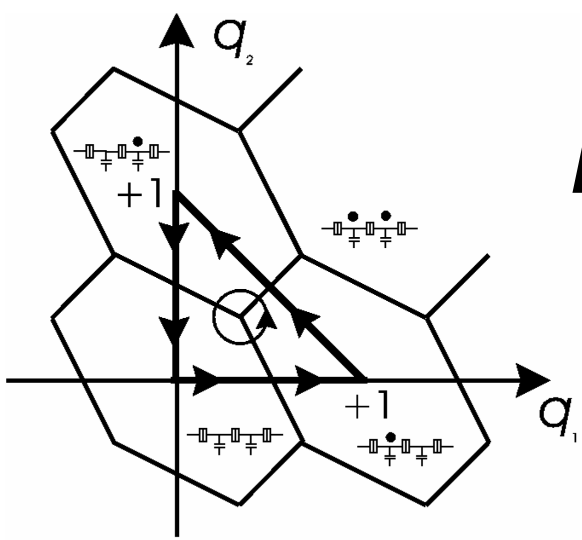
Intro/theory

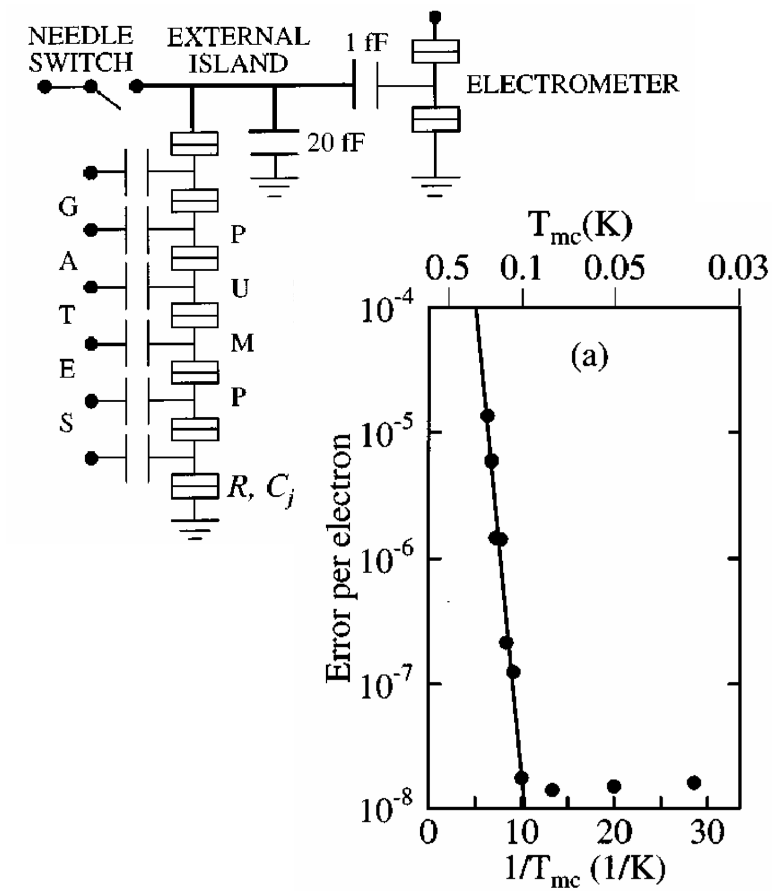
- Based on: A.O. Niskanen, J.P. Pekola, and H. Seppä, Phys. Rev. Lett. 91, 177003 (2003).
- What is a charge pump?*.*
- An adiabatic Cooper pair pump? $I=2nef$
- Charge pump outputs a DC current in response to an AC signal
- Cooper pair pumps are in principle capable of producing a higher current.
- Typically: long arrays with voltage gates or e.g. Surface Acoustic Wave pumps..
- Modulating each gate in turn leads to controlled tunneling of n (2n) charges per cycle.

Pumping of single electrons





$I = ef$



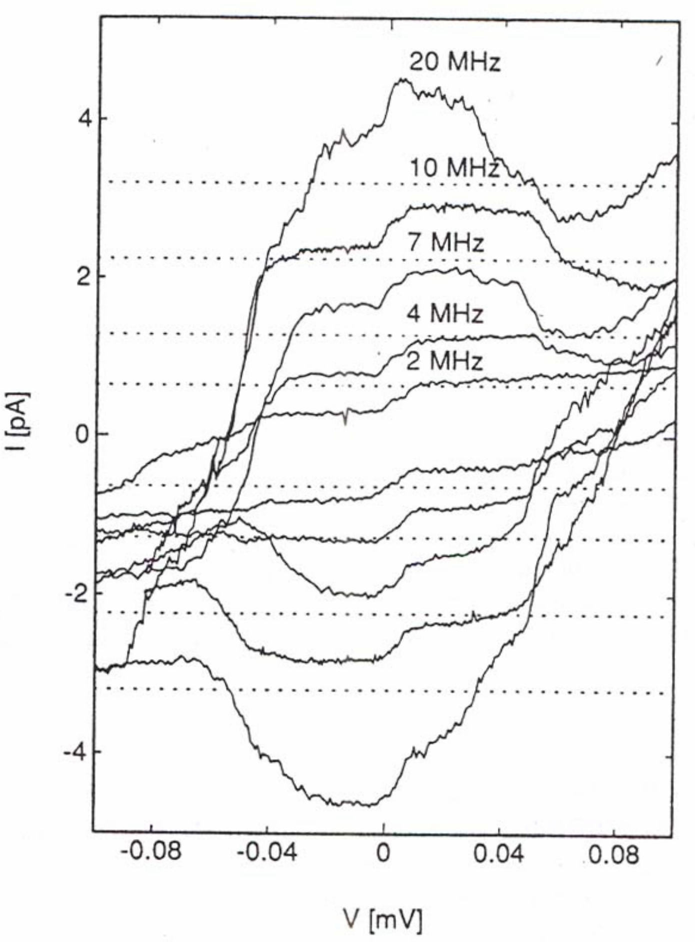
H. Pothier, P. Lafarge, C. Urbina, D. Esteve, M. Devoret, EPL 17, 249 (1992).

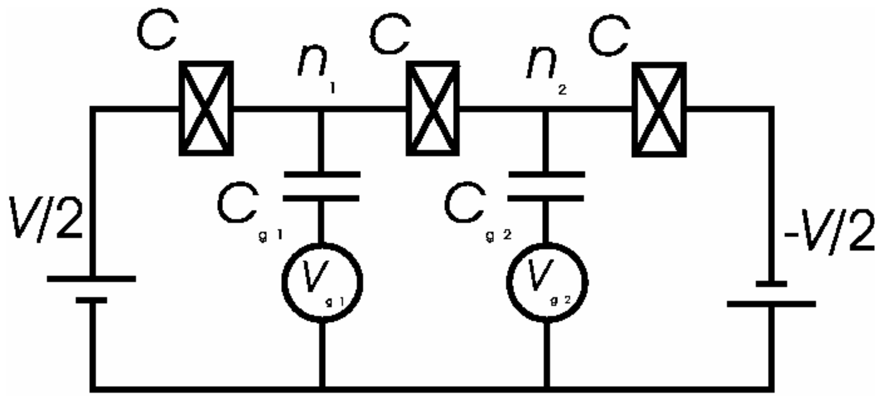
Martinis at al., Appl. Phys. Lett. 69, 1804 (1996).

Pumping of Cooper pairs

I=2ef

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





-Also "R-pump" by
Zorin, Lotkhov, Bogoslovsky, Niemeyer (2000, 2001)
and....

Turnstile behaviour of the Cooper-pair pump

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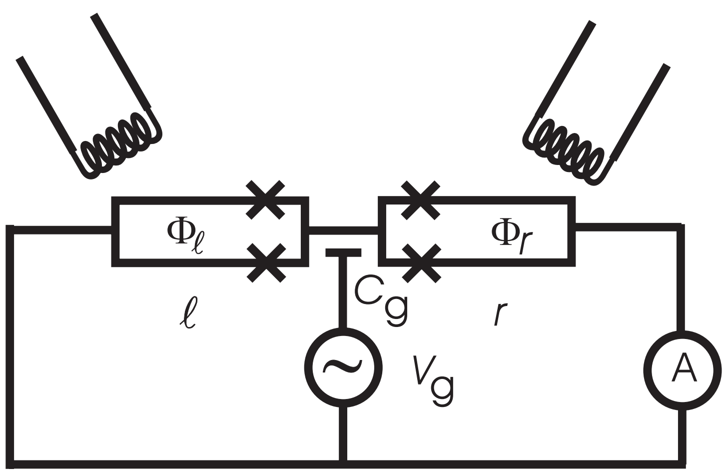
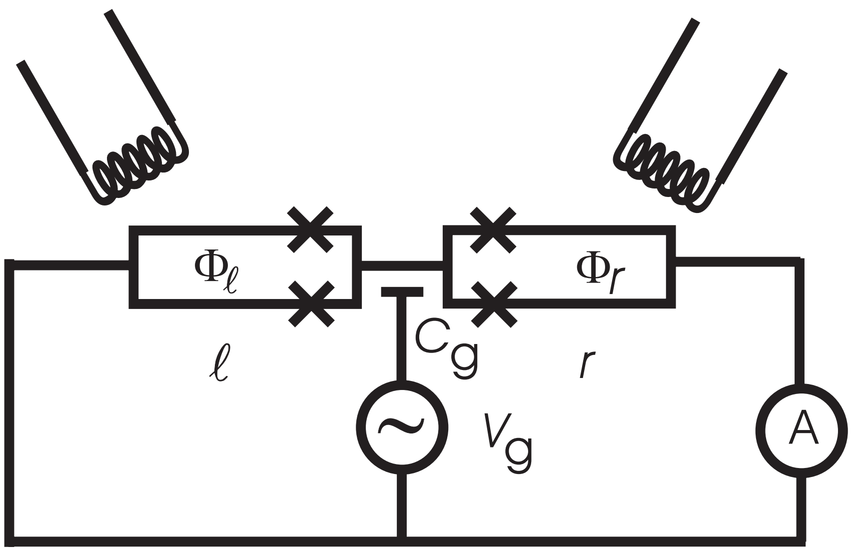
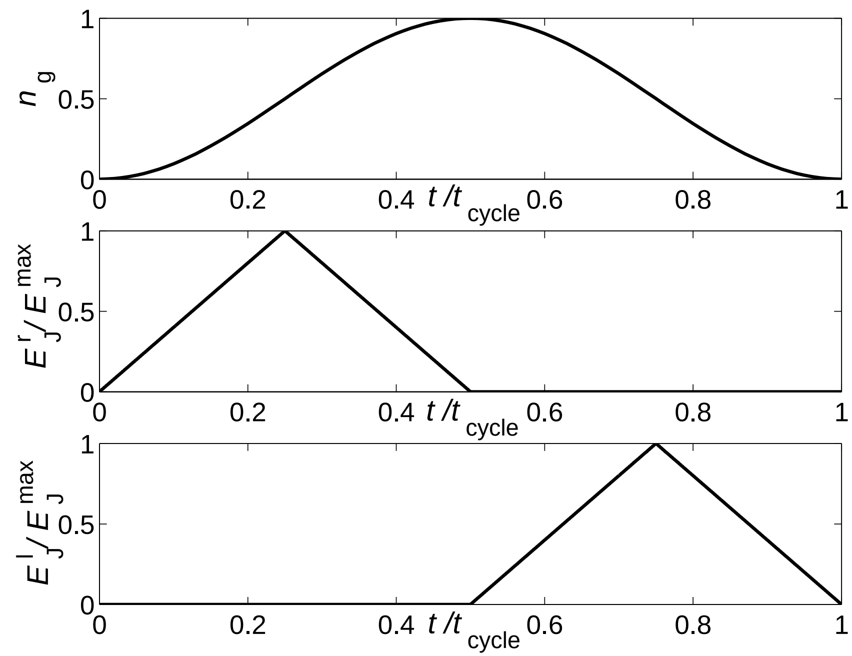
Our design: Cooper pair "sluice"

- It is an adiabatic Cooper pair pump / A two-end Cooper pair box.
- Just one mesoscopic superconducting island, two SQUIDs (tunable junctions) and a gate voltage.
- Voltage controls the gate charge.
- Flux through SQUIDs modulates the effective Josephson energy. (sluice doors)
- Only three controls. These are periodically modulated.



Model parameter sequence:

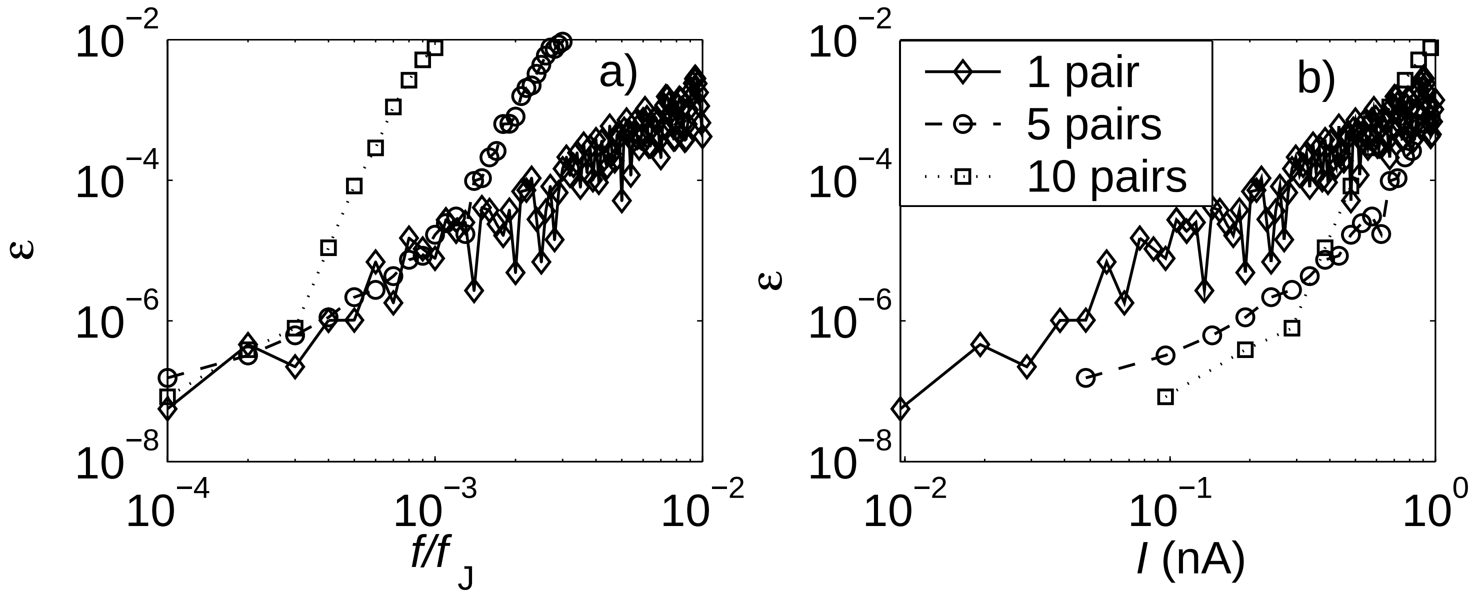




- Can be generalized to pump 2ne. (n=1,2,…?)
- Several practical issues and sources of error:
  - *Non-adiabaticity*
  - non-ideal *suppression of* E_J
  - environmental *impedance*
  - background *charge noise*
  - *Quasiparticles*

- But: tolerant against 1/*f* background charge fluctuations and insensitive towards the definite operating point. (provided $k_B T$ is small)
- Quasiparticles should not be a problem in theory.

Adiabaticity errors:



- Error in the pumped charge for ideal suppression of E_J.
- 0.1-0.2 nA at <10^{-6}.

- $f_J \equiv E_J^{max} / \hbar = e^2 / C\hbar \approx 300 \times 10^9 s^{-1}$
- $\varepsilon \equiv 1 - Q_P / 2ne \equiv \Delta I / I$

Non-ideal *suppression of* E_J

Adiabatic approximation

(J.P. Pekola, J. J. Toppari, M.T. Savolainen and D.V. Averin PRB **60**, R9931 (1999).)

$$Q_P = -2e\frac{\partial}{\partial \varphi}\left(\theta_{\text{Berry}}\right)$$

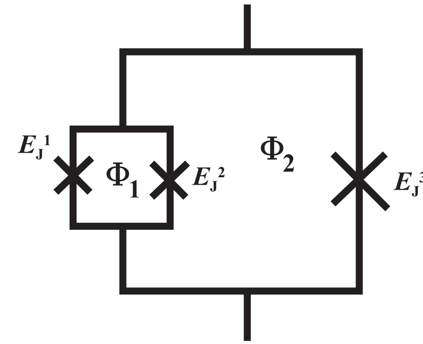
(M. Aunola and J. Toppari PRB **68**, 020502 (2003).)

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

- Cooper pair is tunneling in “wrong” direction…
- Also $\sin\varphi$ dependent superconducting leakage current…

Suppression of E_J (closing the doors)

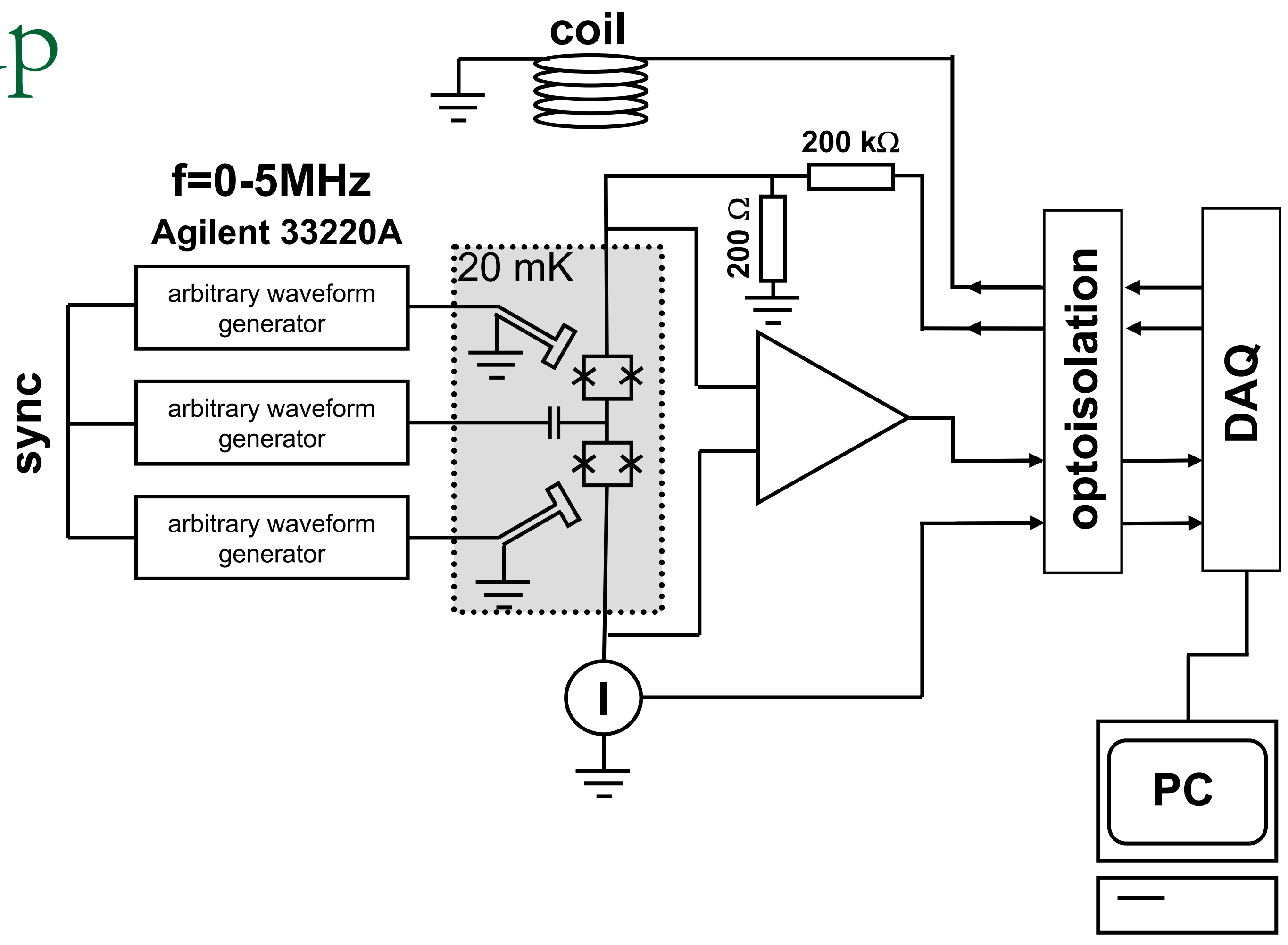
- In practice, 0.1-1% is good enough and should be possible experimentally. Limits set by:
  - Asymmetry of the junctions (3 junctions ? →)
  - Self-inductance
  - Flux noise
- Still: two error terms: ~cosφ & ~sinφ.
- Phase fluctuations (or constant voltage) can cancel these without suppressing tunneling.
- Therefore the environmental impedance is in key role…



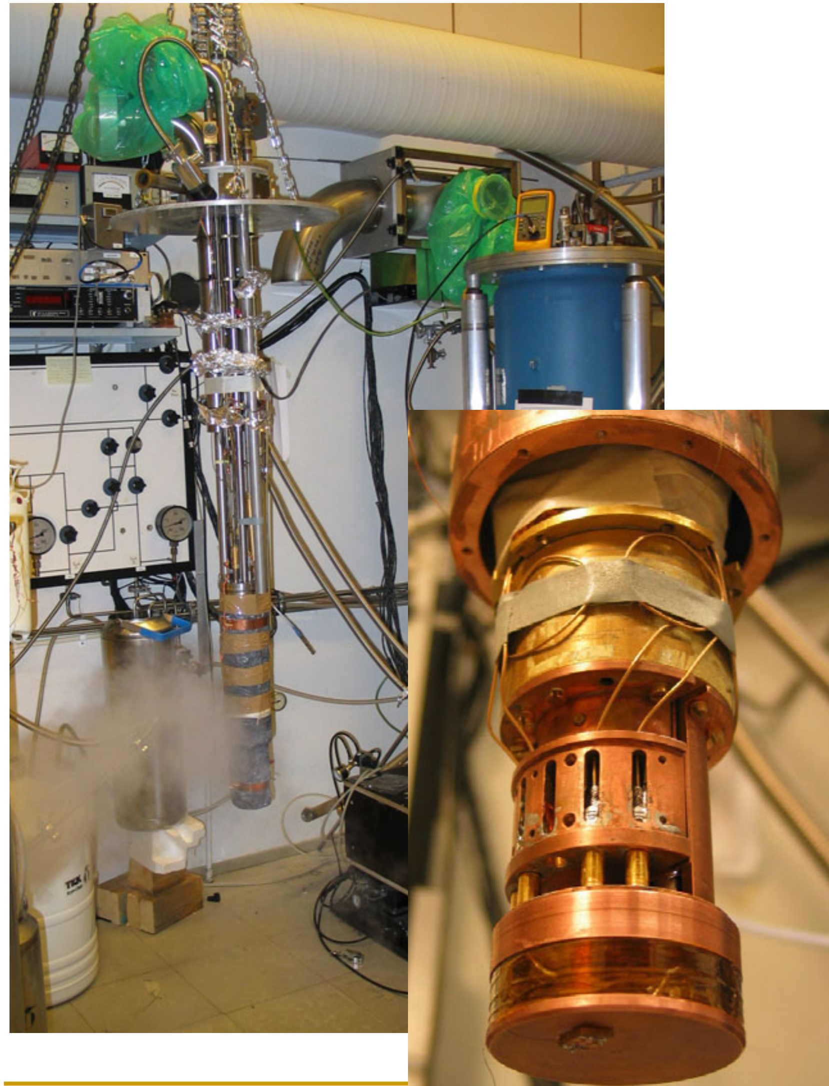
Very first measurements on the "sluice"

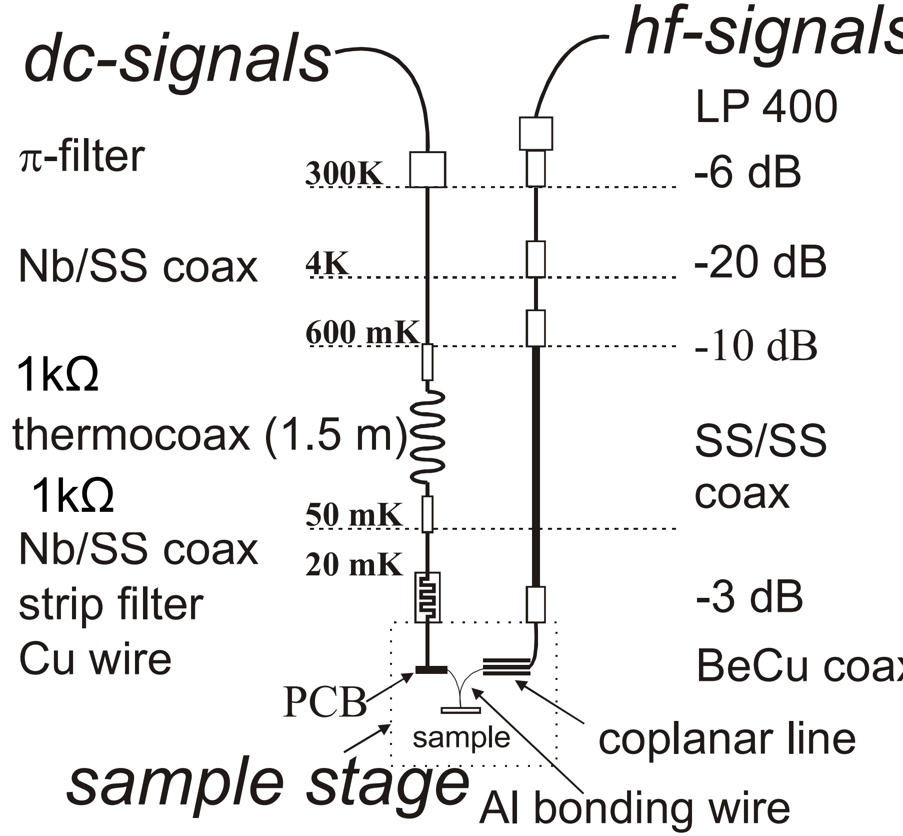
- We have measured at around 20mK in a two-probe setting:
  - 1e and 2e periodicity -> $C_g \approx 0.3fF$.
  - Flux modulation
  - Pumping
    - Heavy quasiparticle leakage underneath due to a heating input coil
    - Also supercurrent leakage
    - However, as high as 0.3 nA pumped currents
  - Future looks bright

Measurement setup



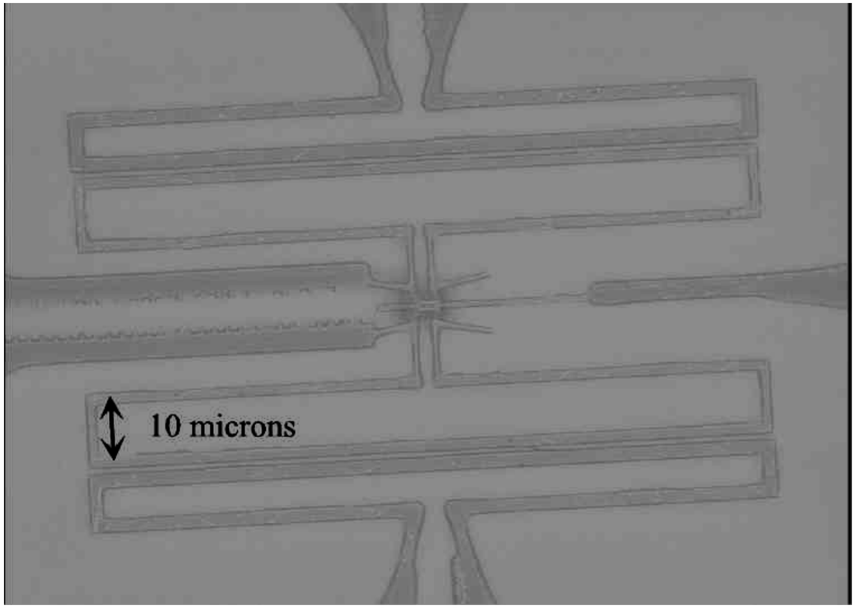
Fridge

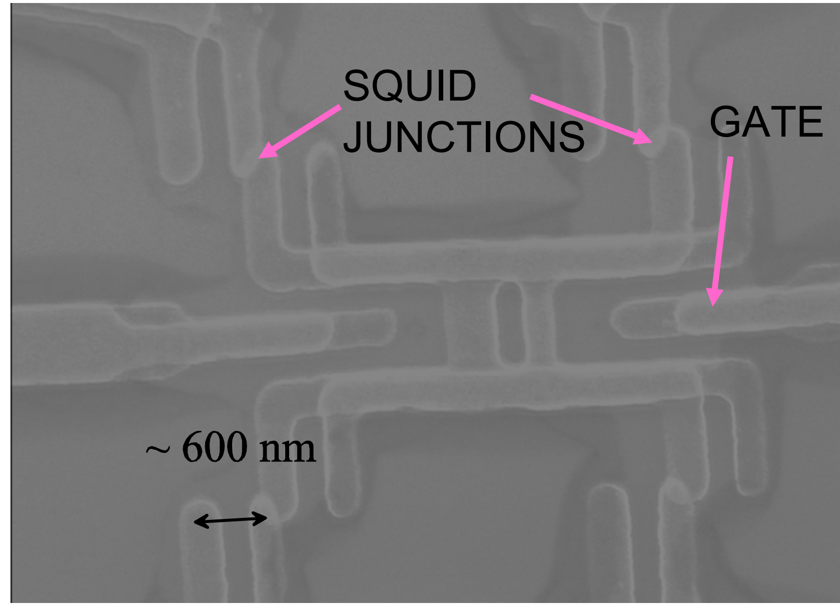


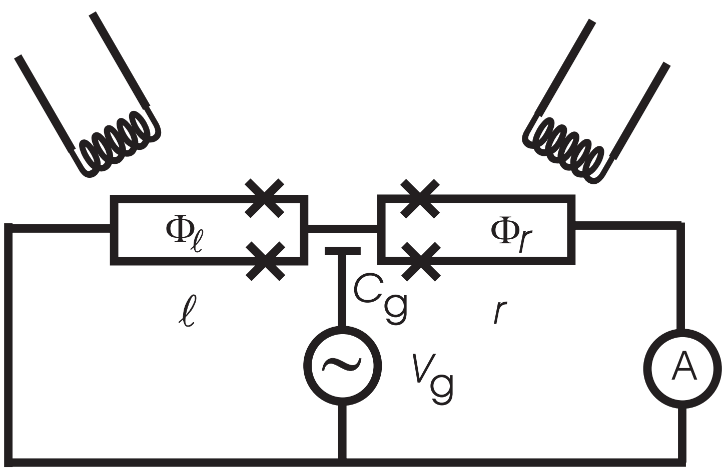


- Minimum temp. around 20 mK
- High filtering needed for cooling electron gas also!
- High frequency lines have BW up to 12 GHz

Sample:

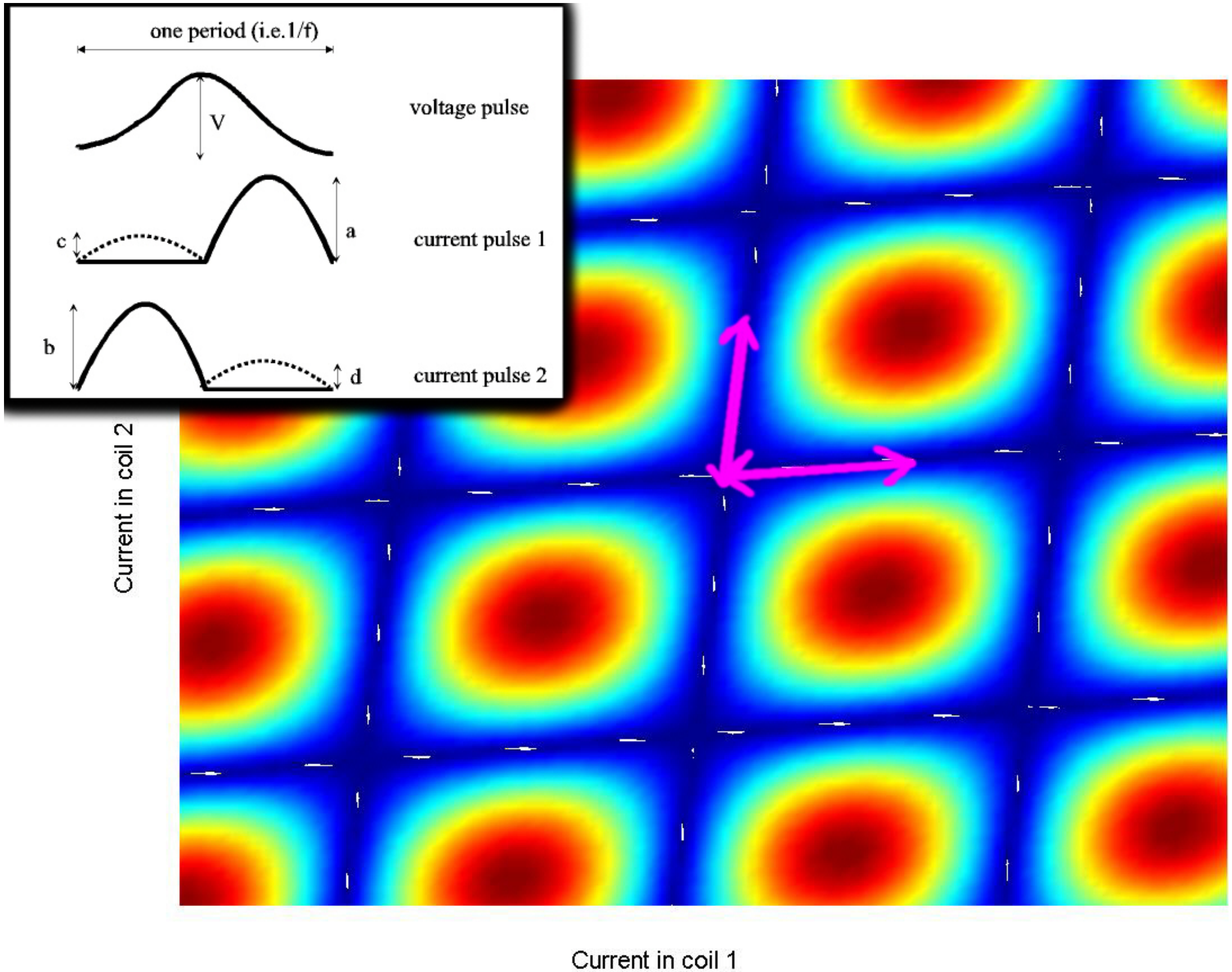


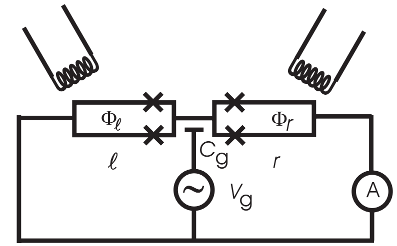




$E_c \approx 1.2K$ and $E_J \approx 2.2K$

Flux modulation of current and pulsing



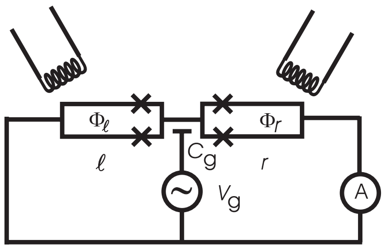


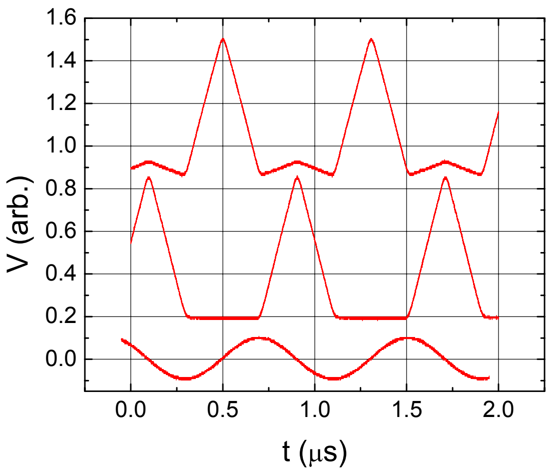
Theoretical prediction for effective I_c with 10% cross coupling

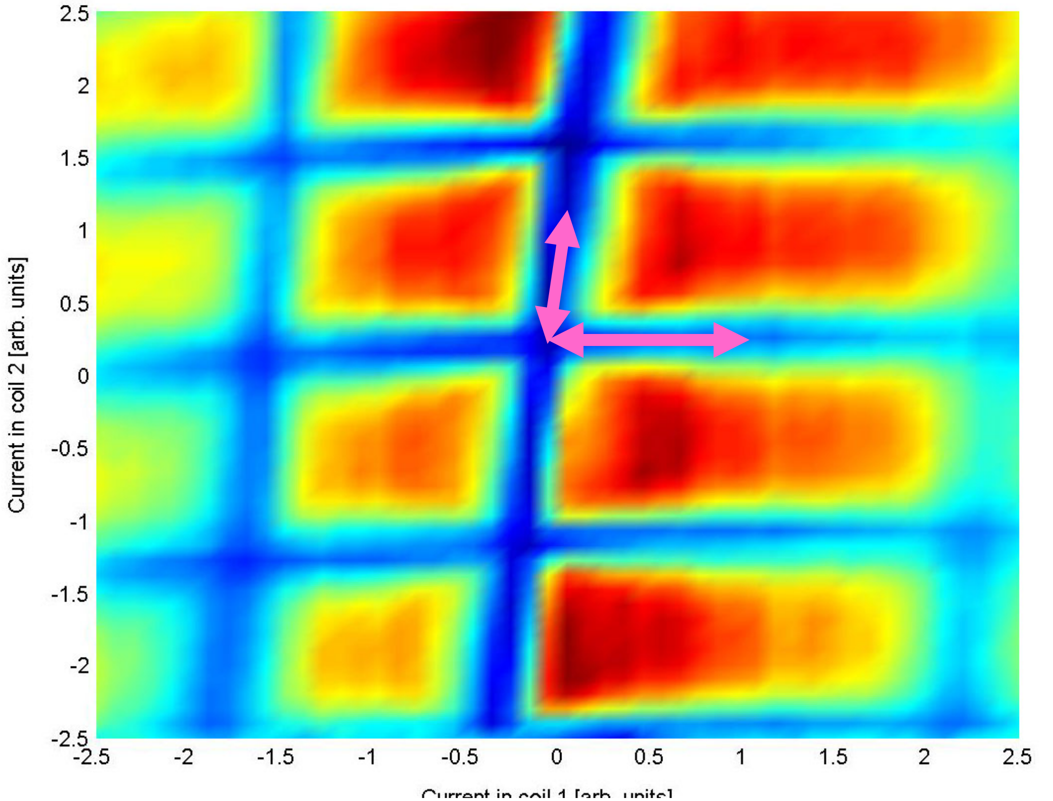
red = large current
blue=small current

$$I_c \sim |\cos(L_{11}I_1 + L_{12}I_2)\cos(L_{22}I_2 + L_{21}I_1)|$$

Experimental flux modulation and pulsing

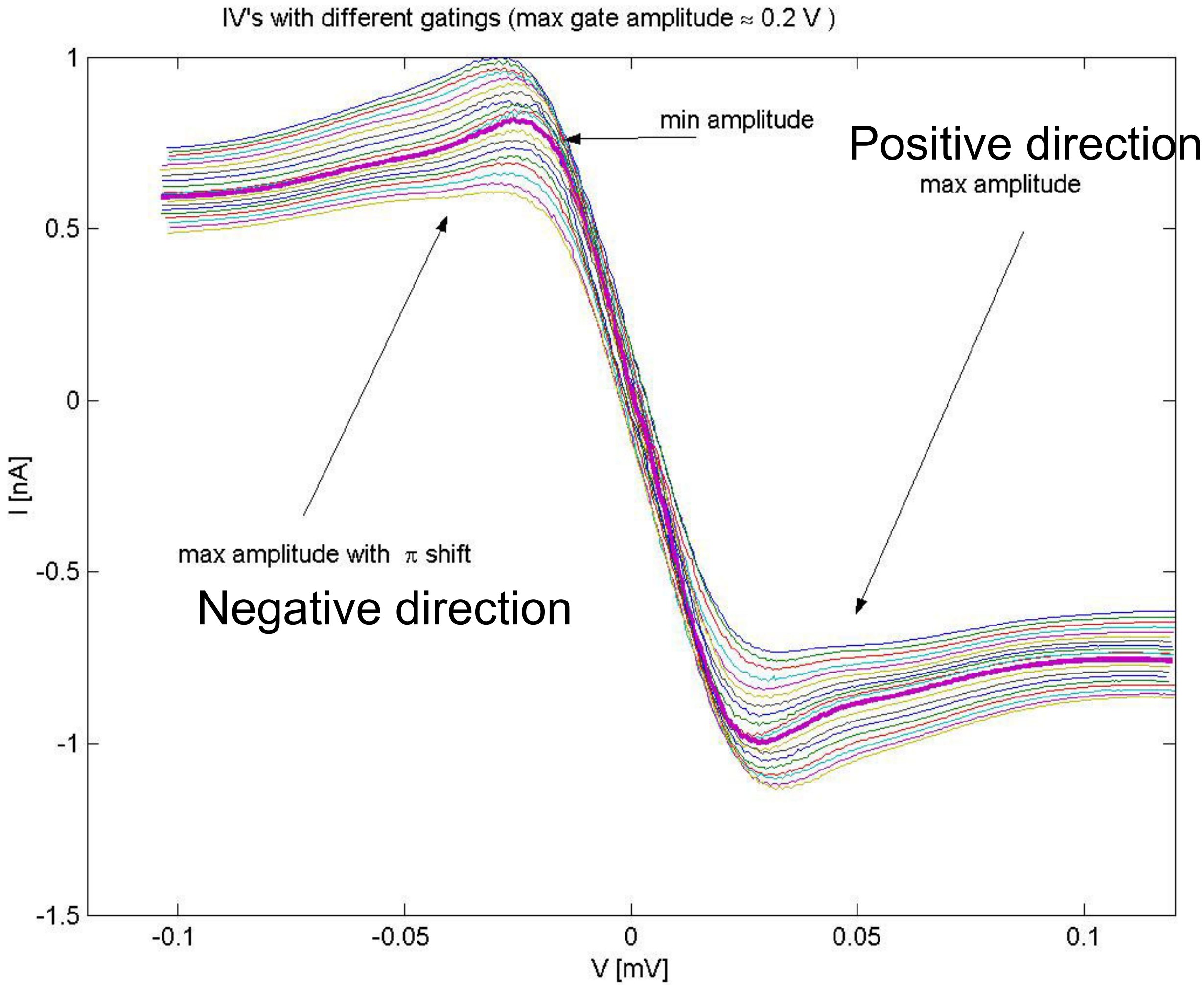






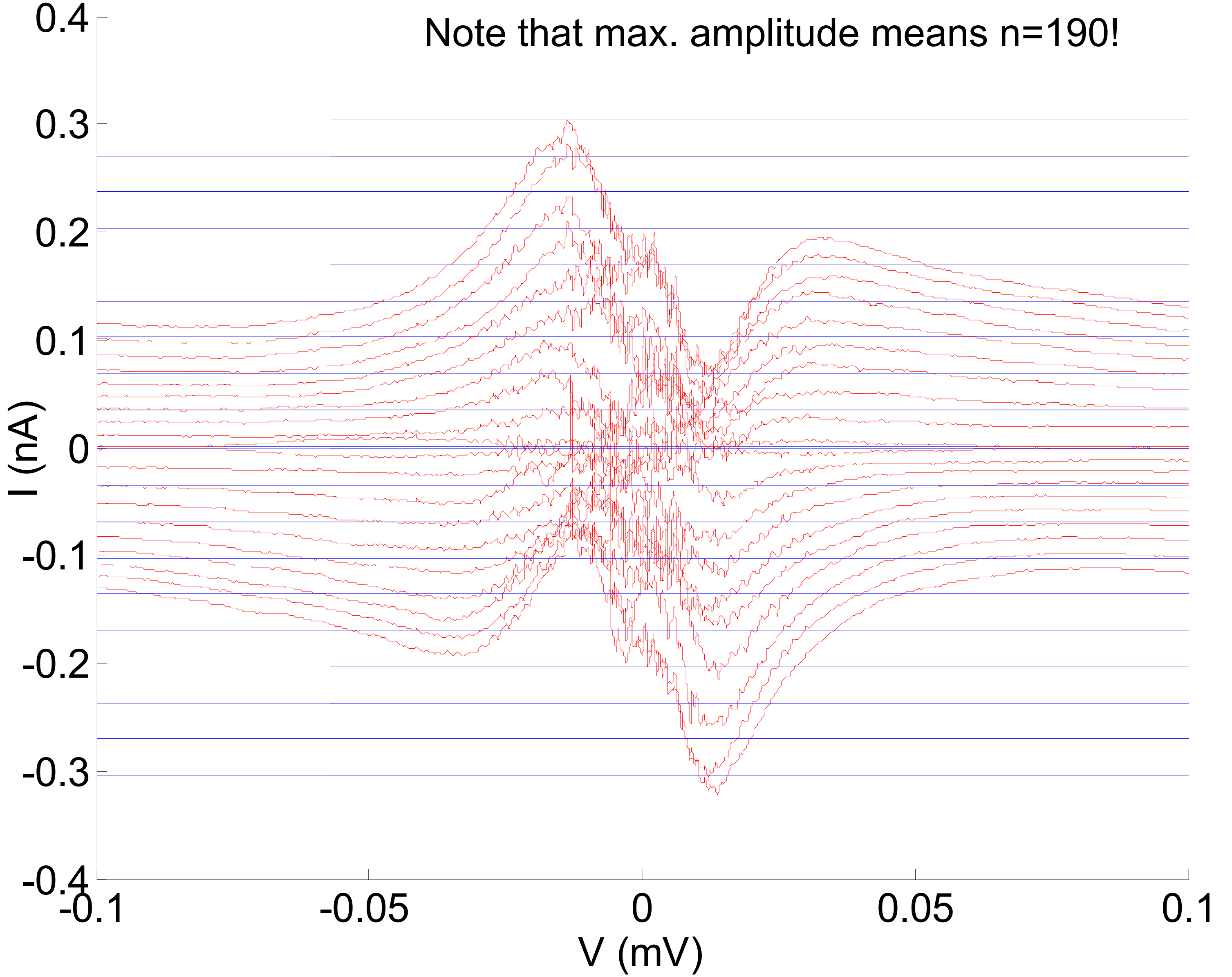
-Measured sample cross-coupling is about 10 % and can be effectively compensated

Pumping at 5MHz



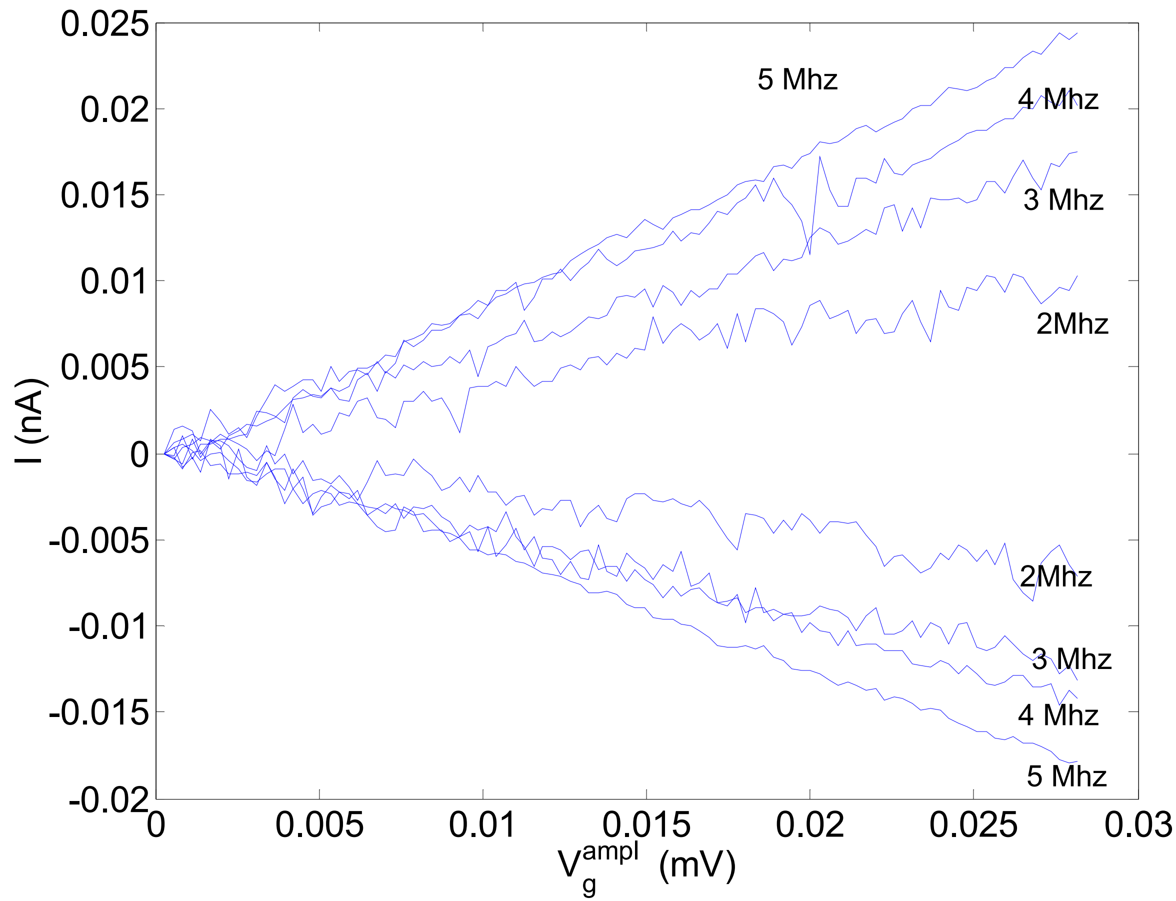
Different IV-curves are obtained with different gate amplitudes. Heavy quasiparticle contribution but *difference* obeys I≈2enf.

Difference (blue: I=2enf and red experimental):

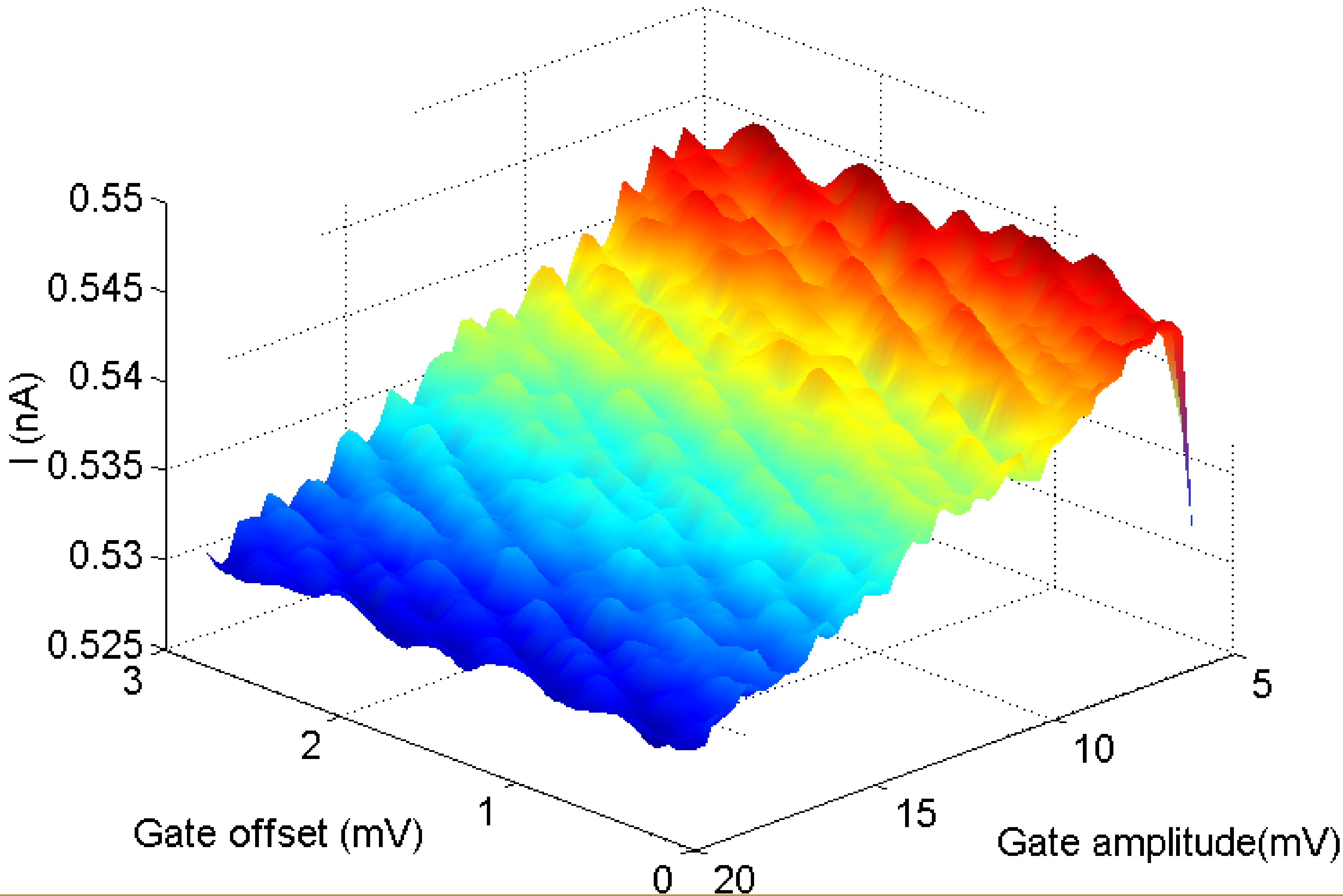


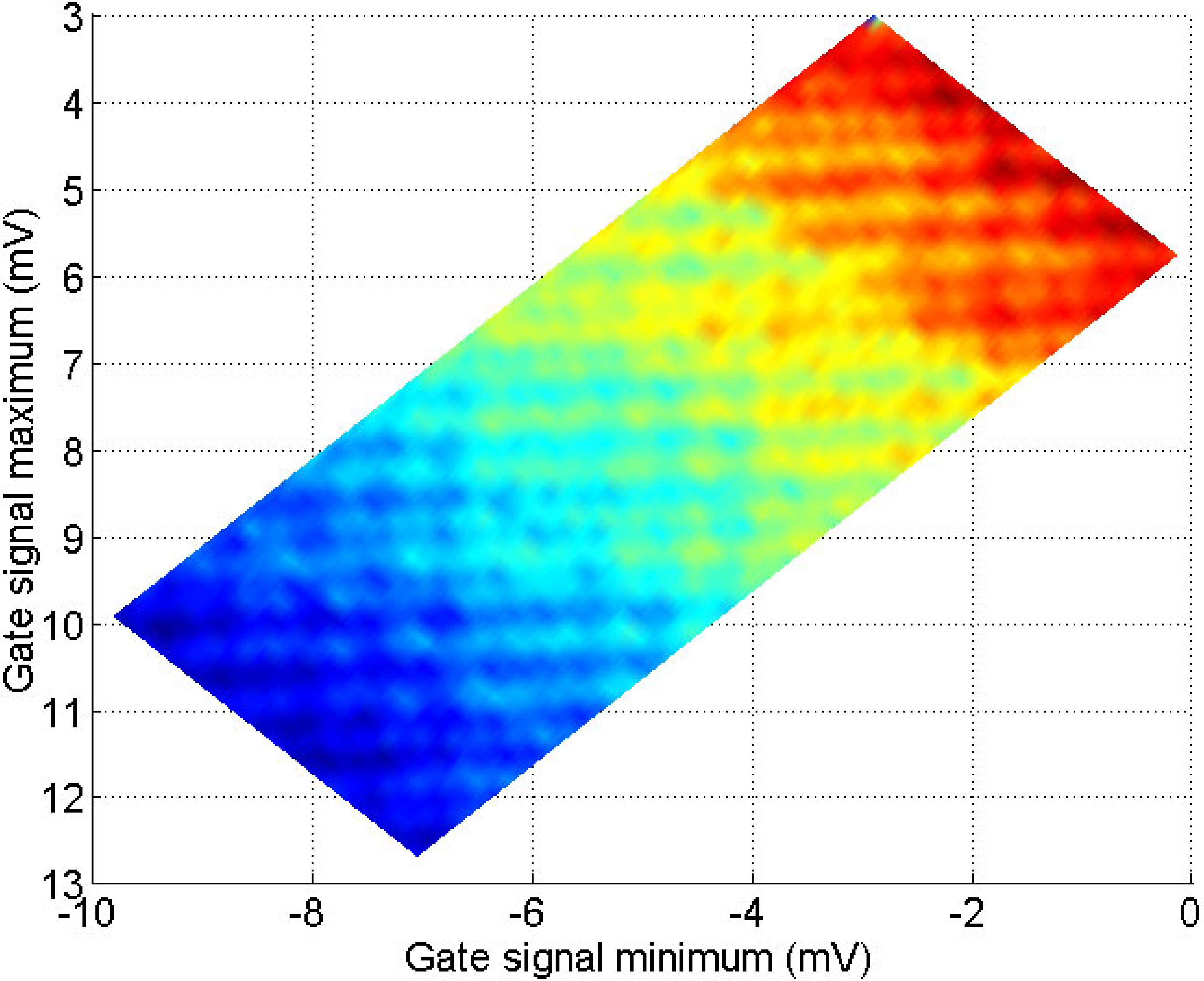
Pumping vs. frequency (non-ideal V_{bias})

About half
is missing at this
bias
point (due to bad
bias) but frequency
response is roughly
linear.



Fine structure in pumping





Gate signal maximum (mV)
Gate signal minimum (mV)
3
4
5
6
7
8
9
10
11
12
13
-10
-8
-6
-4
-2
0

Conclusions

- The Cooper pair sluice is a novel single-island tunable Cooper pair box that acts as an accurate and high-yield flux and voltage driven adiabatic charge pump.
- May be useful in metrology (triangle), in QC and other fields (?).
- Strengths: We expect to get more current ~0.1 nA at sub ppm error with less controls
- First measurements have been carried out and results are very promising:
  - Frequency and amplitude response is linear and current changes direction under π-phase shift.
  - Max. current is very high: 0.3 nA with 5 MHz.
- Things to improve: Environment, V-bias electronics, and quasiparticles (i.e. working coil).
- We expect to get rid of (most of) pumping errors with these improvements.
- See: [1] A.O. Niskanen, J.P. Pekola, and H. Seppä, PRL 91, 177003 (2003).