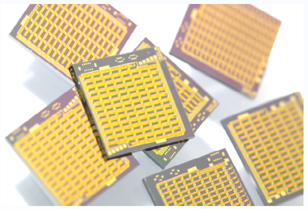
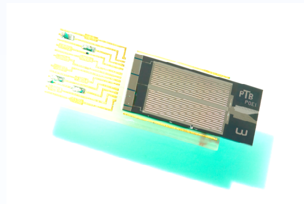
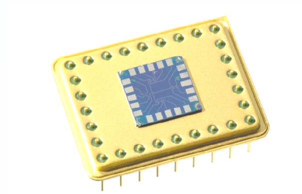
Study of single electron tunneling devices for electrical metrology: a contribution to the metrological triangle experiment



Barthélémy Steck





28/11/2007

Metrology = science of measurement

$$q = \{q\}\,[q]$$

$\{\}$ numerical value

$[\,]$ unit

Towards a coherent system of units

•1789

Cahiers de doléances (Of grievances) :

« Ils demandent que les seigneurs à qui est dû des rentes en grains soient obligés de tenir au lieu principal du fief des mesures marquées et jaugées à l'ancienne et petite ou grande mesure, suivant que l'exigent les redevances. » (Cdd. Pas-de-Calais (Selles), II, P. 436)

« Qu'ils paient désormais leurs rentes à une seule et unique mesure royale » (Cdd. Quimber (Beuzac-Cap-Caval))

« Qu'il n'y eût plus qu'une mesure pour tout le Royaume, et que les grains de différentes espèces se mesurassent dans une même mesure.» (Cdd. Troyes (Chapvalonn), I, pp. 542/543)

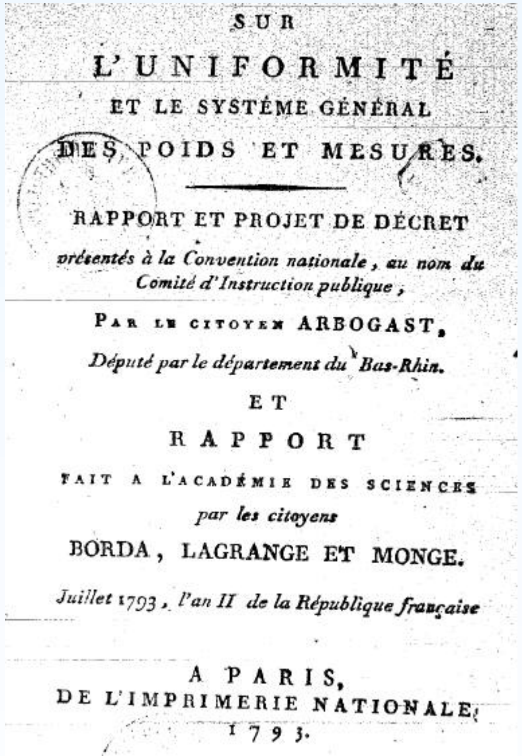
•18 germinal an III (April 7, 1795)

Décret relatif aux poids et aux mesures

The Convention decreed that the new "Republican Measures" were to be henceforth legal measures in France.

The metric (and decimal) system was adopted:

- the metre was defined as the length of 1/10 000 000 of the northern quadrant of the Paris meridian;
- the gram was defined as the absolute weight of a volume of pure water equal to a cube of one hundredth of a meter, and to the temperature of the melting ice.



SUR
L'UNIFORMITÉ
ET LE SYSTÊME GÉNÉRAL
DES POIDS ET MESURES.

RAPPORT ET PROJET DE DÉCRET
présentés à la Convention nationale, au nom du Comité d'Instruction publique ;

PAR LE CITOYEN ARBOGAST,
Député par le département du Bas-Rhin.

ET

RAPPORT
FAIT A L'ACADÉMIE DES SCIENCES
par les citoyens
BORDA, LAGRANGE ET MONGE.

Juillet 1793, l'an II de la République française

A PARIS,
DE L'IMPRIMERIE NATIONALE,
1793.

M. J. de Caritat, baron de Condorcet

G. Monge

Towards a coherent system of units

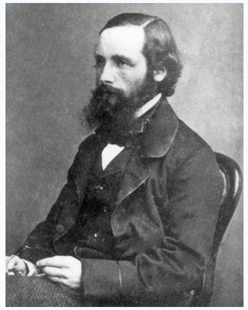
- 1832

C.F. Gauss performed measurements of Earth's magnetic field, by using a decimal system based on three quantities: length, mass and time (mm, g, s).

C.F. Gauss

- 1860/1870

J.C. Maxwell proposed a coherent system of units: CGS (centimetre, gram, second)



J.C. Maxwell

- 1875 : convention du mètre

- 1901

G. Giorgi completed the system MKS (metre, kilogram, second) by adding an electrical unit: the ampere

G. Giorgi

- 1948 -> 1960

Creation of the *Système international d'unités (SI)*

Outline

- The SI and the electrical units
- Single electron pump
- Experimental set-up
- Measurements
- The metrological triangle experiment

Outline

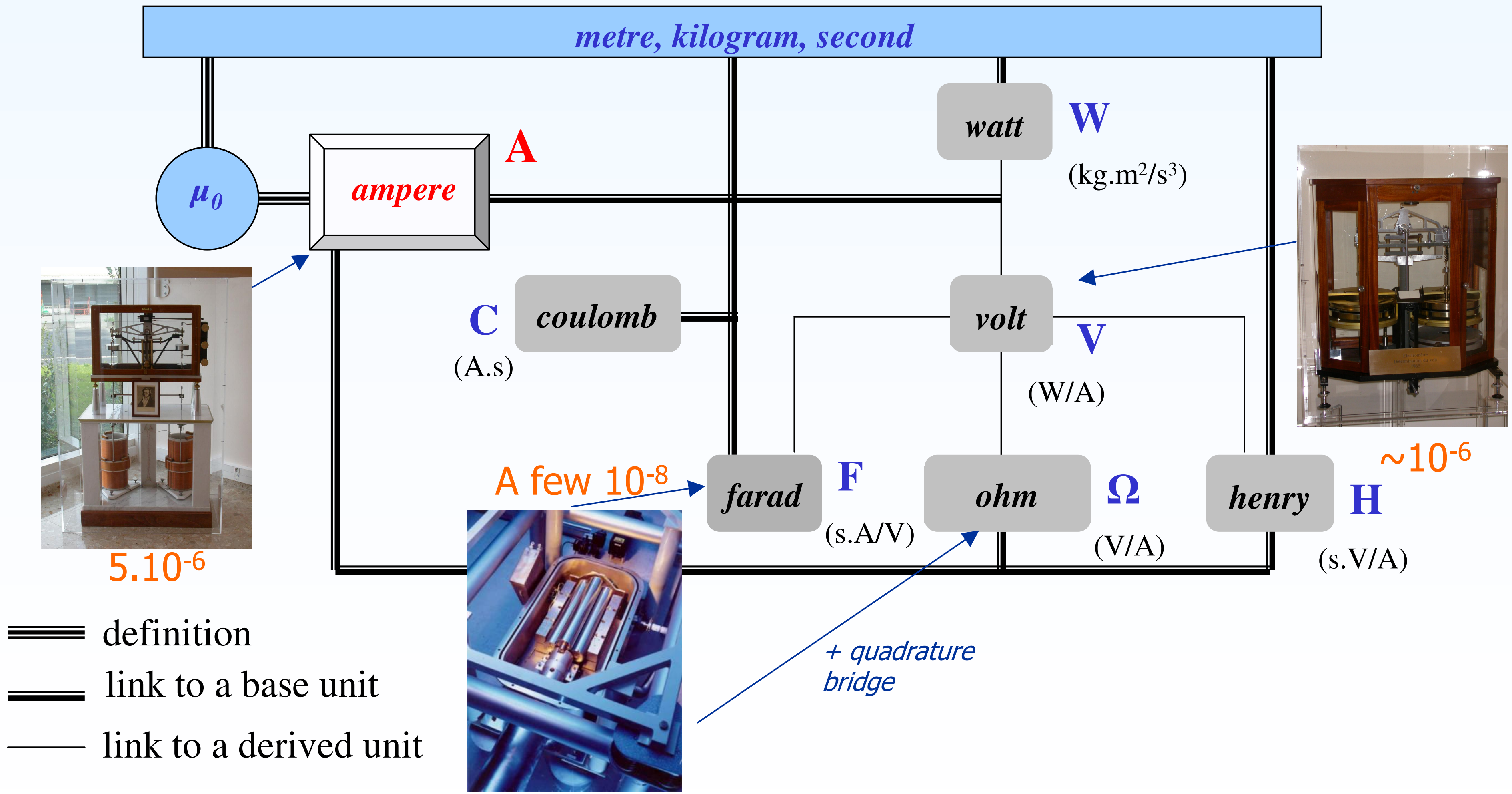
- The SI and the electrical units
- Single electron pump
- Experimental set-up
- Measurements
- The metrological triangle experiment

Système international d'unités (SI)

Base quantity	Unit	Definition
mass	*kilogram* ***(kg)***	The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram. *(3^{rd} CGPM, 1901)*
electric current	*ampere* ***(A)***	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 m apart in vacuum, would produce between these conductors a force equal to 2.10^{-7} newton per metre of length. *(9^{th}CGPM, 1948)*
thermodynamic temperature	*kelvin* ***(K)***	The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water. *(10^{th} CGPM, 1954)*
time	*second* ***(s)***	The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom. *(13^{th} CGPM, 1967/68)*
amount of substance	*mole* ***(mol)***	1.The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12. 2.When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles. *(14^{th} CGPM, 1971)*
luminous intensity	*candela* ***(cd)***	The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 1012 hertz and that has a radiant intensity in that direction of 1/683 watt per steradian. *(16^{th} CGPM, 1979)*
length	*metre* ***(m)***	The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second. *(17^{th} CGPM, 1983)*

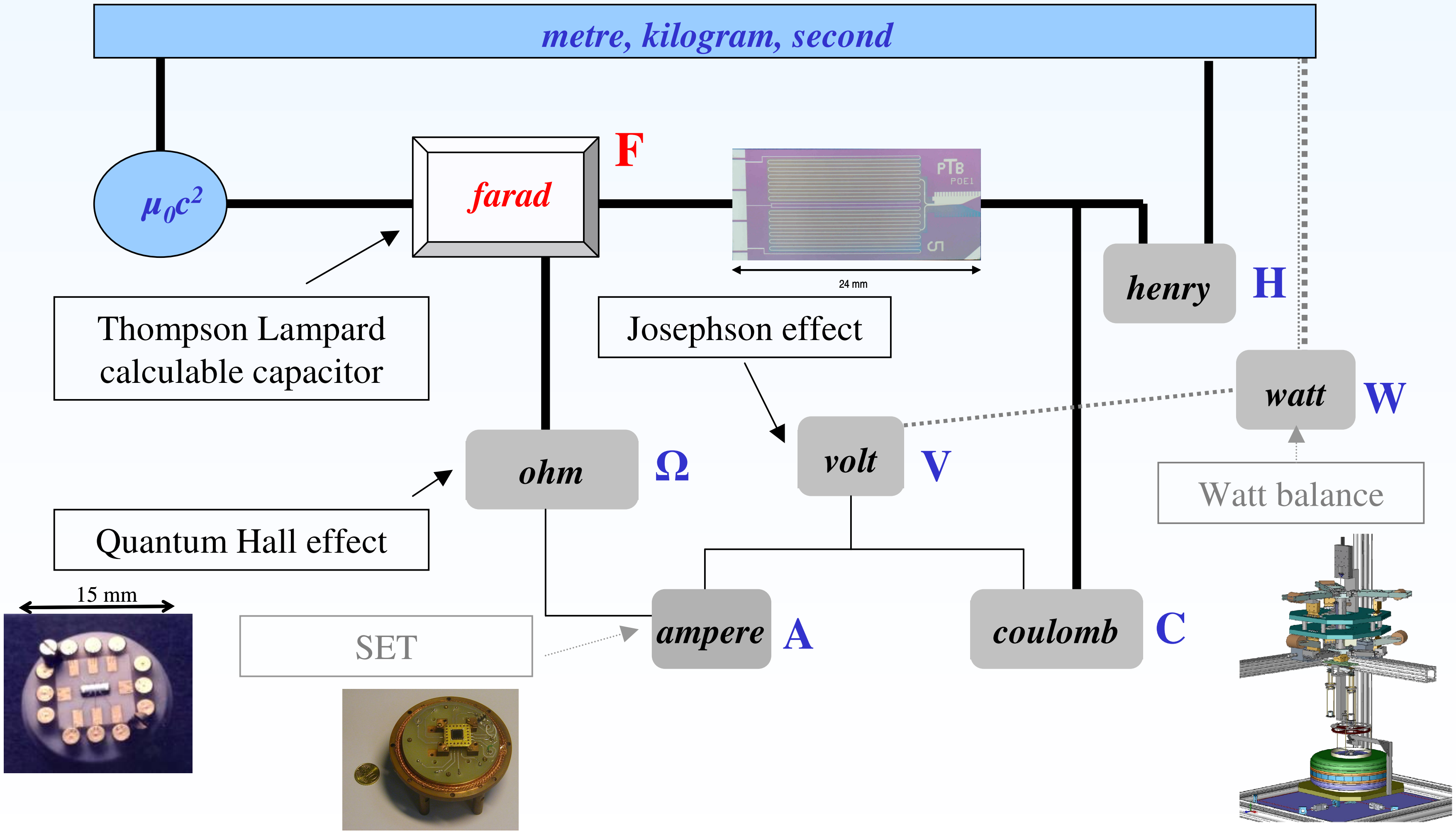
Electrical units : definition

*The **realisation** of a unit is a physical experiment or artefact, based on well-established principles, that produces the unit in terms of **the SI definition**.*



Electrical units : representation

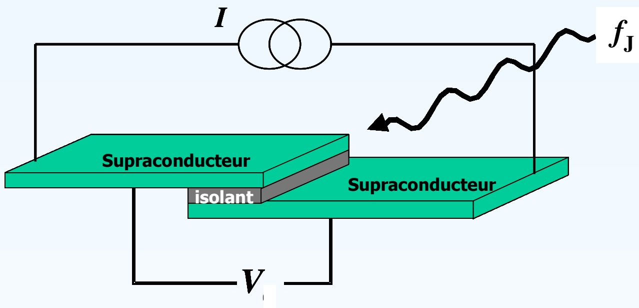
*The **representation** of a unit is an experiment or artefact which produces a quantity which can be routinely compared to other standards. The routine nature of a representation allows us to disseminate from one primary standard to a large number of secondary standards.*



Quantum electrical metrology

- Josephson effect

$$V = \frac{n_j f_j}{K_J}$$



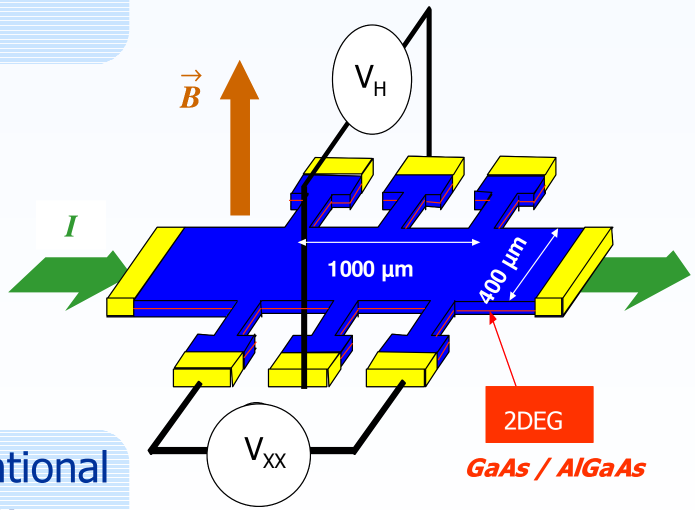
$$K_J \equiv \frac{2e}{h}$$

Volt reproducibility with a conventional value of K_J (K_{J-90}=483 597.9 GHz/V):

1 part in 10^{10}

- Quantum Hall effect

$$R_H = \frac{R_K}{i}$$



$$R_K \equiv \frac{h}{e^2}$$

Ohm reproducibility with a conventional value of R_K (R_{K-90}= 25 812.807 Ω):

1 part in 10^9

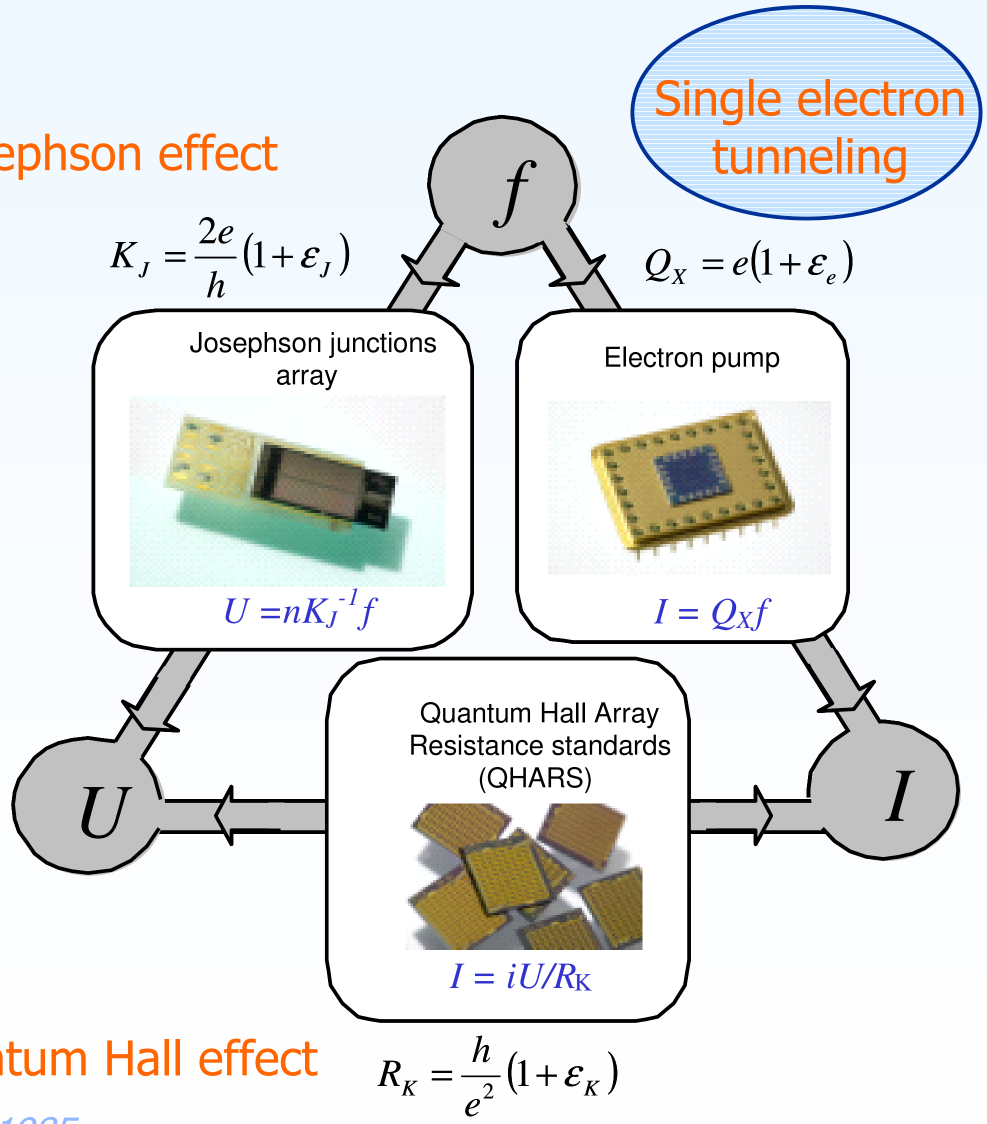
Reproducibility of the ampere in the SI: 10^{-7}

The metrological triangle experiment (MTE)

- Checking the consistency of the three constants involved in electrical quantum metrology:

R_K, K_J, Q_X

- Determination of the elementary charge Q_X involved in the pump



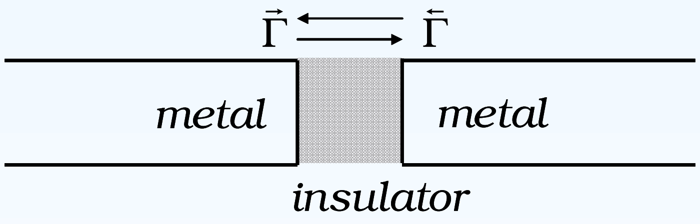
Likharev and Zorin, J. Low. Temp. Phys., 59, p. 347, 1985

Outline

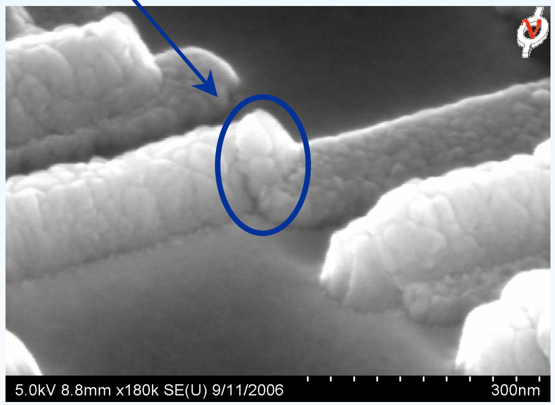
- The SI and the electrical units
- Single electron pump
- Experimental set-up
- Measurements
- The metrological triangle experiment

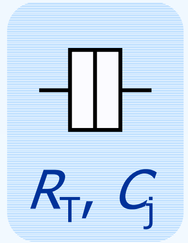
The Coulomb blockade

The tunnel junction

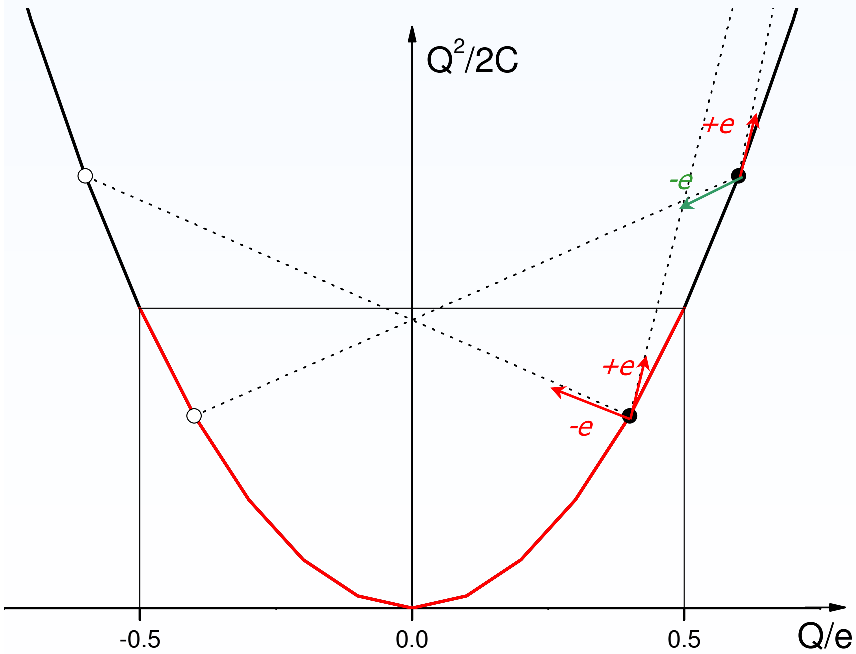


Tunnel junction





Typical values:
R_T~100 kΩ, C_j~100-200 aF
(C=100 aF ó (50 nm)^2.2 nm)



If thermal and quantum fluctuations are negligible compared to the charging energy $Q^2/2C_j$, *i.e.*:

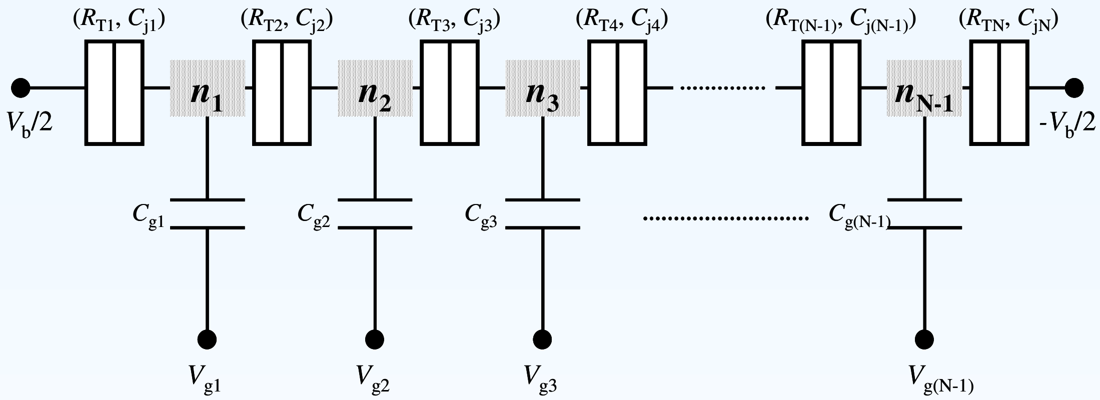
$$R_T >> R_K\ (=h/e^2) \text{ and } C_j << 2/(e^2 k_B T)$$

then SET *(single electron tunneling)* phenomena occur.

$$|Q| < \frac{e}{2}$$ -> Transfer of electron is blocked

Averin and Likharev J. Low. Temp. Phys., 62, p. 345, 1986

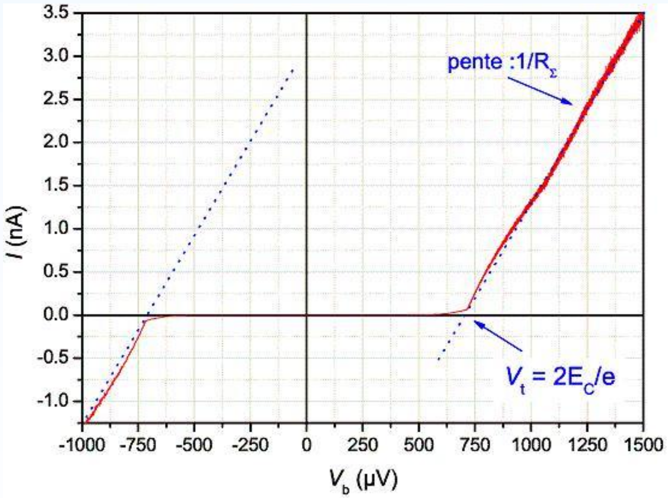
The single electron pump



N junctions (R_{Ti},C_{ji}),

N-1 islands controlled by *N-1* gates C_{gi}, V_{gi}

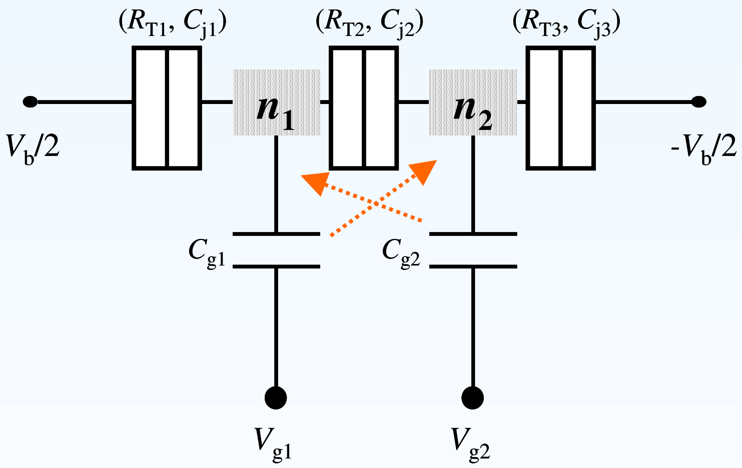
(n_1,n_2,...,n_{N-1}) are the excess electrons on each island



I-V_b curve presents a plateau for $|V_b|<V_t$ ($E_C=e^2/2C_\Sigma$) when the junctions are in the blockade state.

Charging energy $E(n_1,n_2,\ldots,n_{N-1})$ is a function of the capacitance parameters of the pump.
Each combination (n_1,n_2,...,n_{N-1}) has a stability domain in the space (V_{g1}, V_{g2},..., V_{gN-1})

The single electron pump: stability diagram for 3 junctions

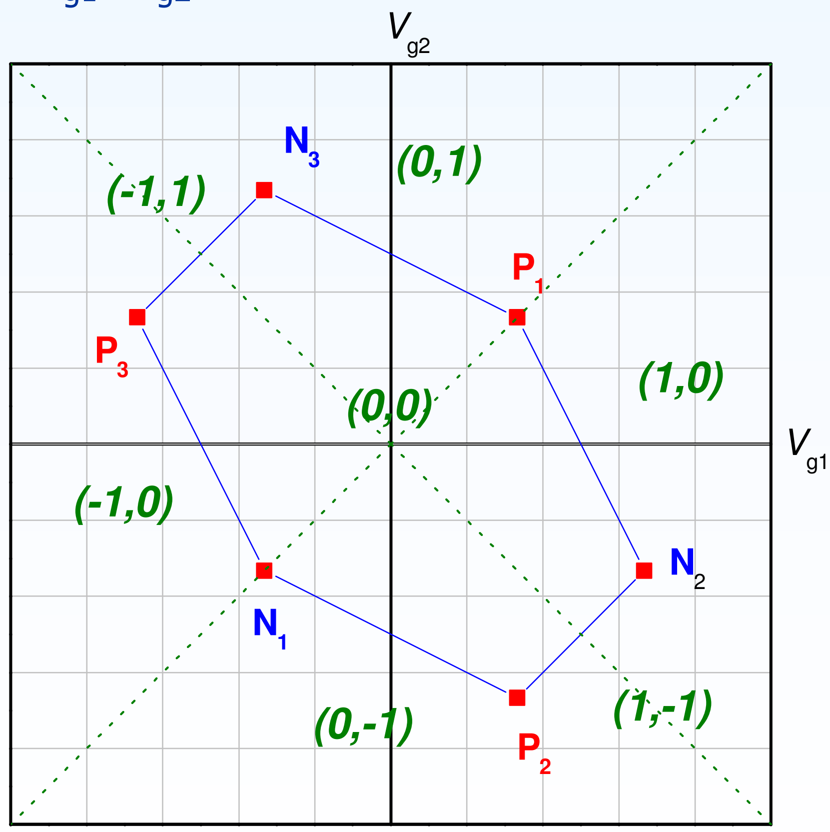


$$E(n_1,n_2)=\frac{e}{C_aC_b-C_{j2}^2}\left[\frac{e}{2}\left(C_bn_1^2+C_an_2^2\right)+eC_{j2}n_1n_2 -V_{g1}C_{g1}\left(C_bn_1+C_{j2}n_2\right)-V_{g2}C_{g2}\left(C_{j2}n_1+C_an_2\right)\right] + \text{termes indépendants de } (n_1,n_2)$$

$$\begin{cases} C_a = C_{j1} + C_{j2} + C_{g1} \\ C_b = C_{j3} + C_{j2} + C_{g2} \end{cases}$$

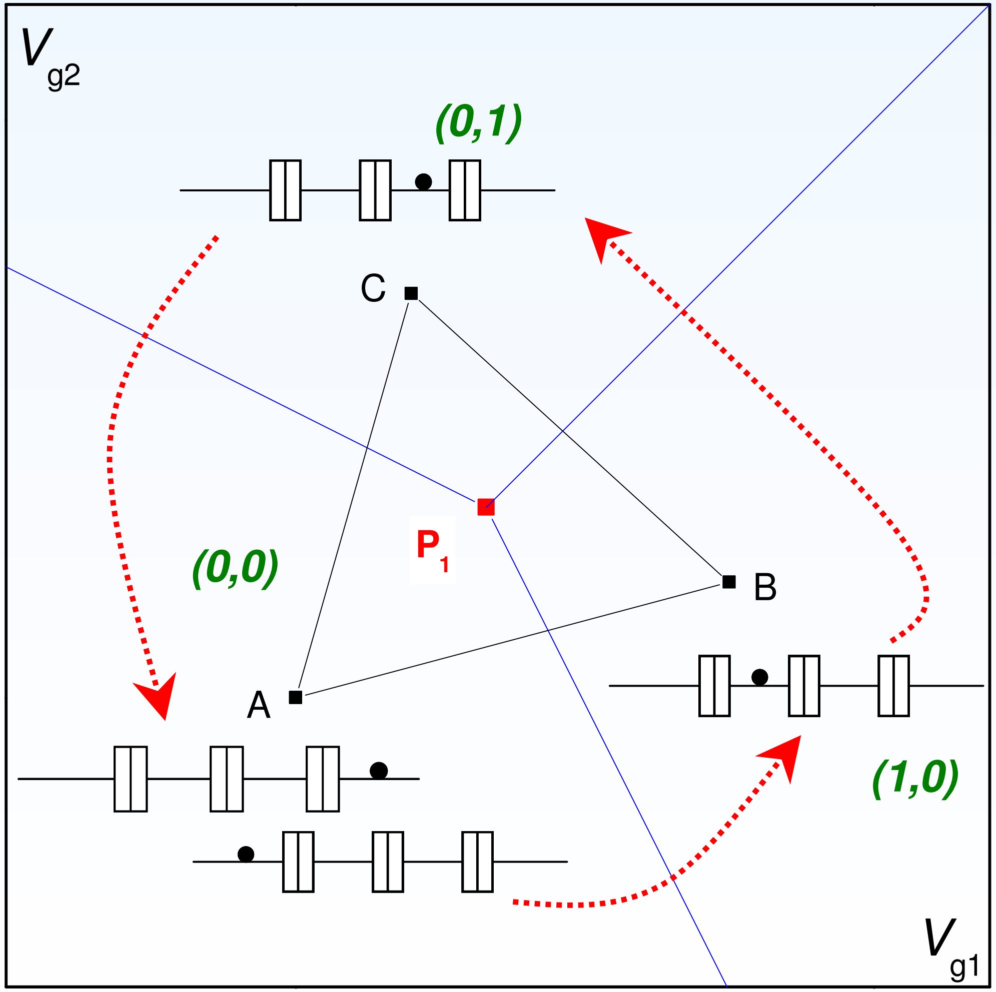
In experiments, the honeycomb lattice is put out of shape by the dissymmetry of the junctions and by the cross talking terms.

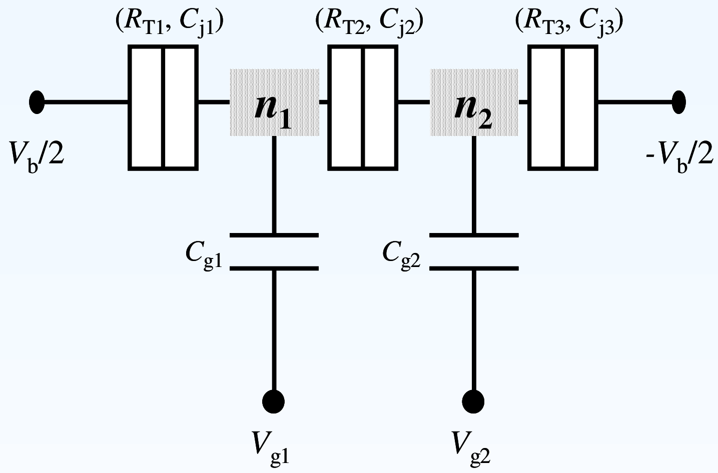
The stability domain of a couple (n_1,n_2) in the space (V_{g1}, V_{g2}) is an honeycomb lattice.



Stability diagram for a 3 junctions pump with $R_{T1}=R_{T2}=R_{T3}$, $C_{j1}=C_{j2}=C_{j3}$ and C_{g1},C_{g2}<<C_j

Pumping operation





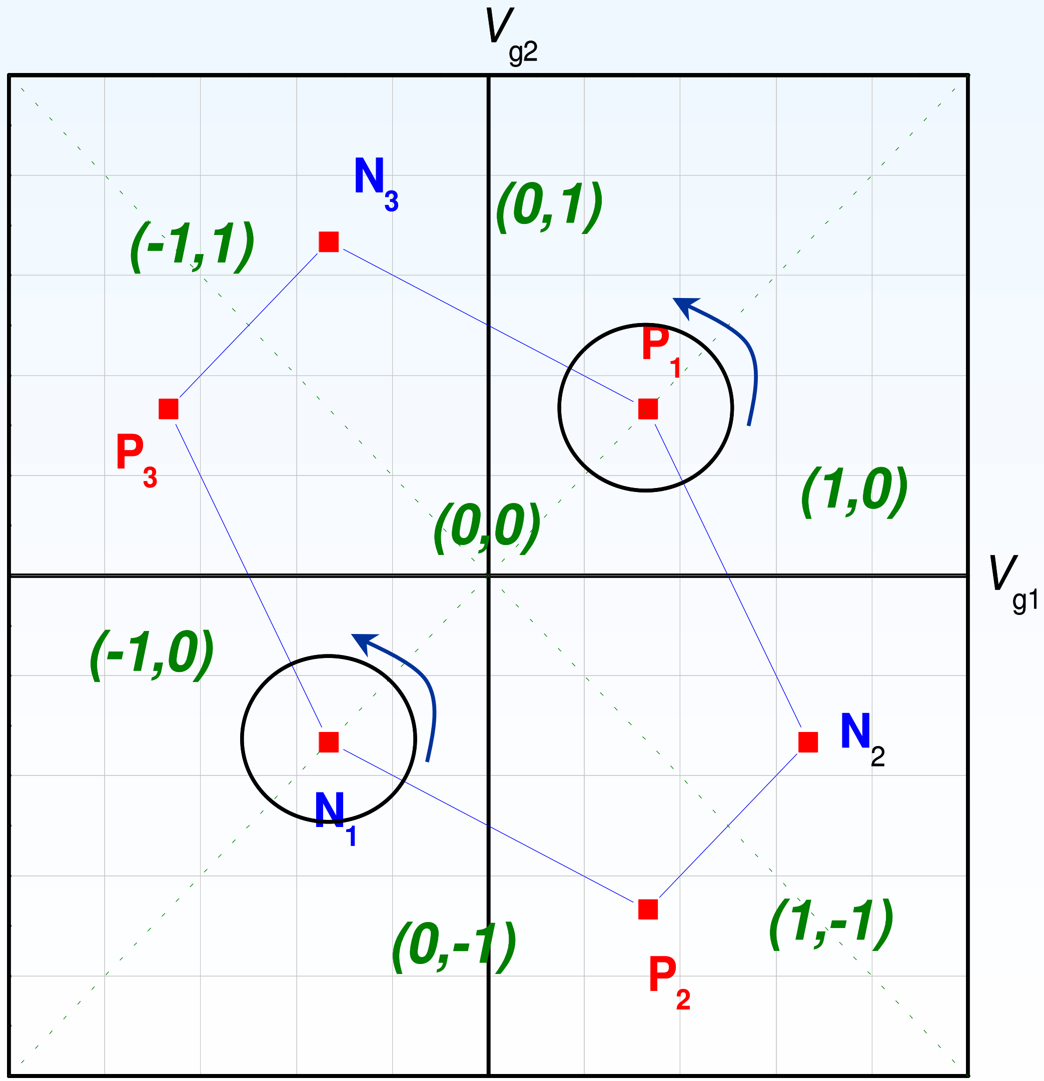
$$\begin{cases} V_{g1} = V_{g1DC} + A\cos(2\pi f t) \\ V_{g2} = V_{g2DC} + A\cos(2\pi f t + \varphi) \end{cases}$$

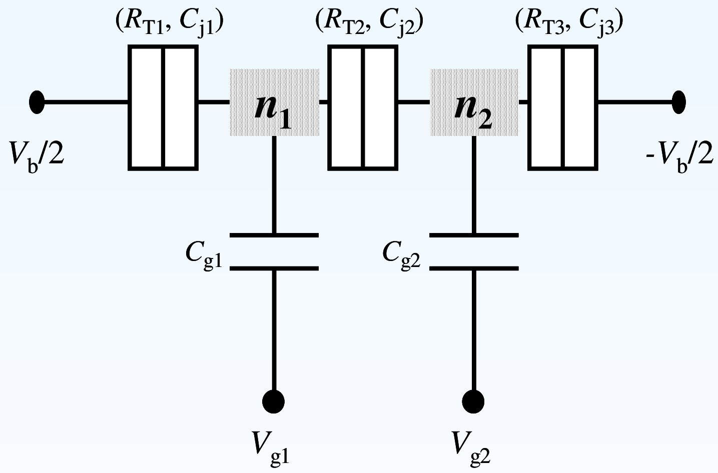
$$I = Q_X f$$

$$(Q_X \equiv e)$$

(*i.e.* I~ 0.16 pA/MHz or f = 10 MHz implies I~ 1.6 pA and f = 60 MHz, I~ 10 pA)

Pumping operation





$$\begin{cases} V_{g1} = V_{g1DC} + A\cos(2\pi f t) \\ V_{g2} = V_{g2DC} + A\cos(2\pi f t + \varphi) \end{cases}$$

$$I = Q_X f$$

$$(Q_X \equiv e)$$

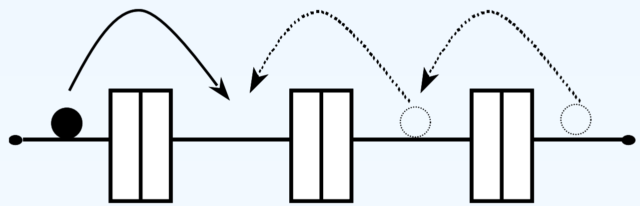
(*i.e.* $I \sim$ 0.16 pA/MHz or f = 10 MHz implies $I \sim$ 1.6 pA and f = 60 MHz, $I \sim$ 10 pA)

Error processes

- Cotunneling

Coherent transfer of *n* electrons through *n* junctions

$$q_0 = \sqrt{(\pi/2)(N-1)R_T C f} \qquad \varepsilon_{ct} = b\left(\frac{R_K}{R_T}\right)^{N-2} \left|u - q_0\right|^{2N-2}$$



- Frequency effects

The larger the pumping frequency is, the greater the probability to miss an electron is. The intrinsic limit of the device is $R_T C$ (~10 GHz)

$$\varepsilon_f = \exp\left(-\frac{a}{R_T C f}\right)$$

- Thermal errors

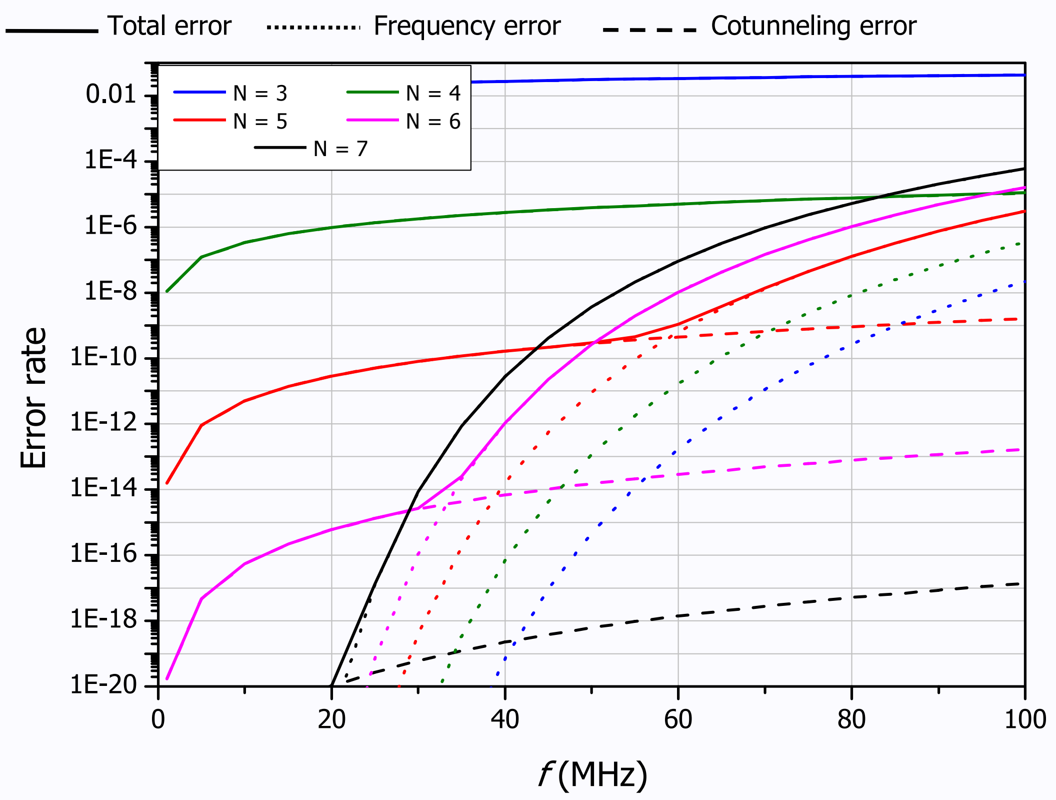
The electron temperature is not null in our measurement. This temperature is responsible for a modification of the rate transfer of the sequential transfer.

$$\varepsilon_{th} = c\exp\left(-d\,\frac{E_C}{k_B T}\right)$$

- Electromagnetic perturbations

Jensen and Martinis, Phys.Rev. B, 46, p. 13407, 1992

Metrological behaviour of a pump

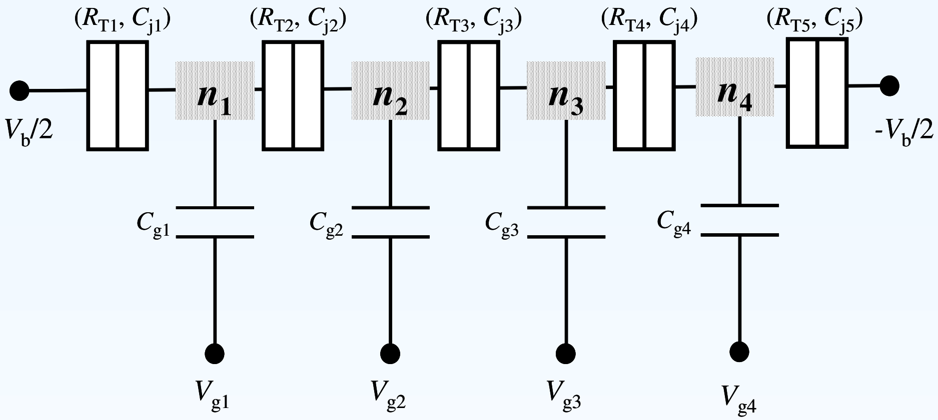


Total error for a *N* junctions electron pump with no bias voltage at 100 mK

N	$\varepsilon_{ct}/\varepsilon_f \sim 1$	Error~10^{-6}	Error~10^{-8}
3	*>>100 MHz*	*Never*	*Never*
4	*>100 MHz*	*~25 MHz*	*<5 MHz*
5	*~60 MHz*	*~95 MHz*	*~70 MHz*
6	*~35 MHz*	*~80 MHz*	*~ 60 MHz*
7	*~20 MHz*	*~75 MHz*	*~ 55 MHz*

Experimental difficulty

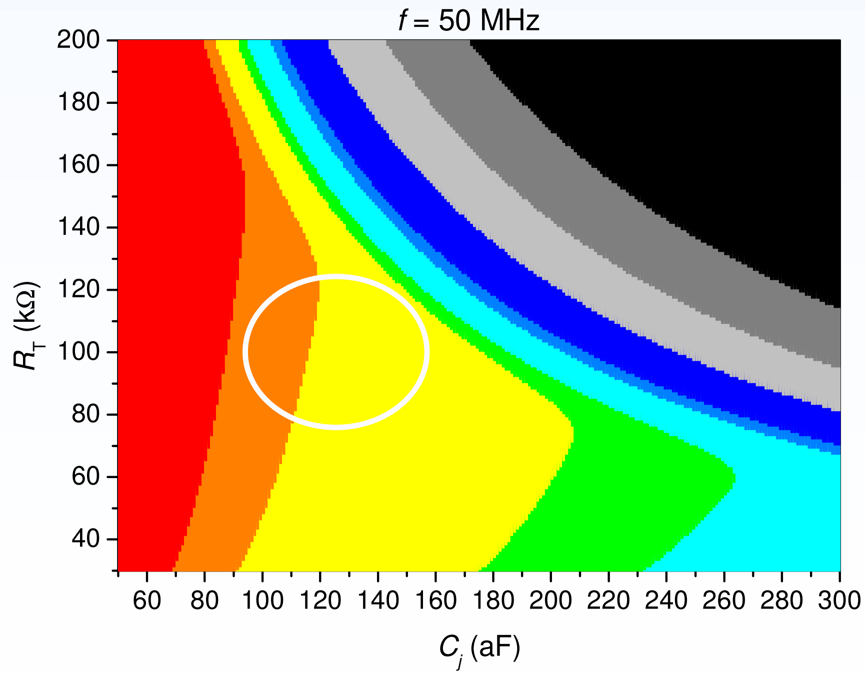
Metrological behaviour of a pump

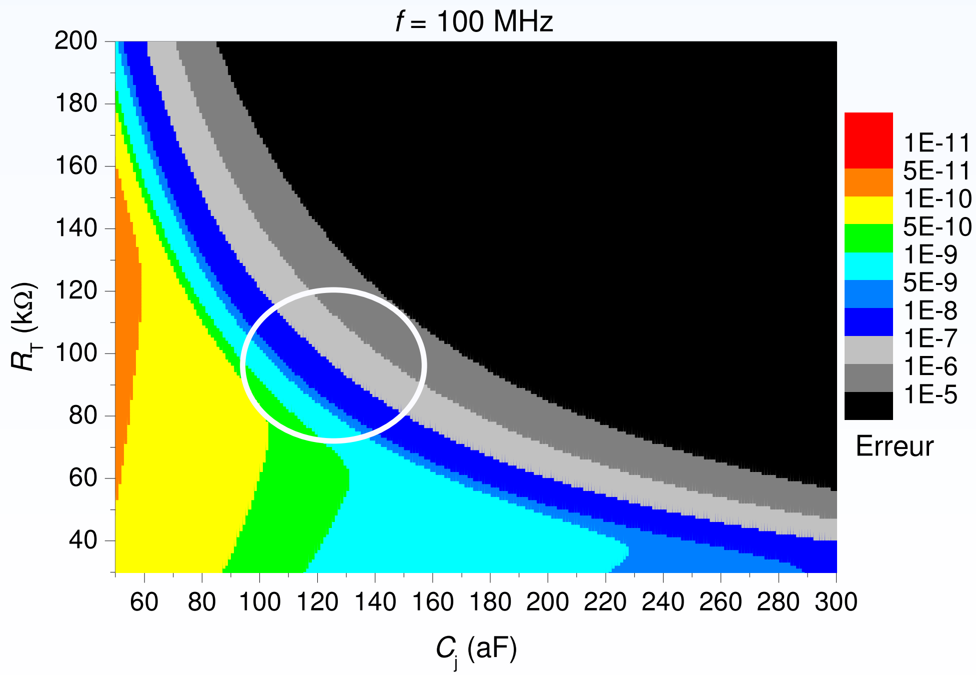


Dependence on the parameters of the pump for a 5 junctions pump.

$R_{Ti} = R_T$ and $C_{ji} = C_j$ for i=1..5

V_b=0 and T= 100 mK

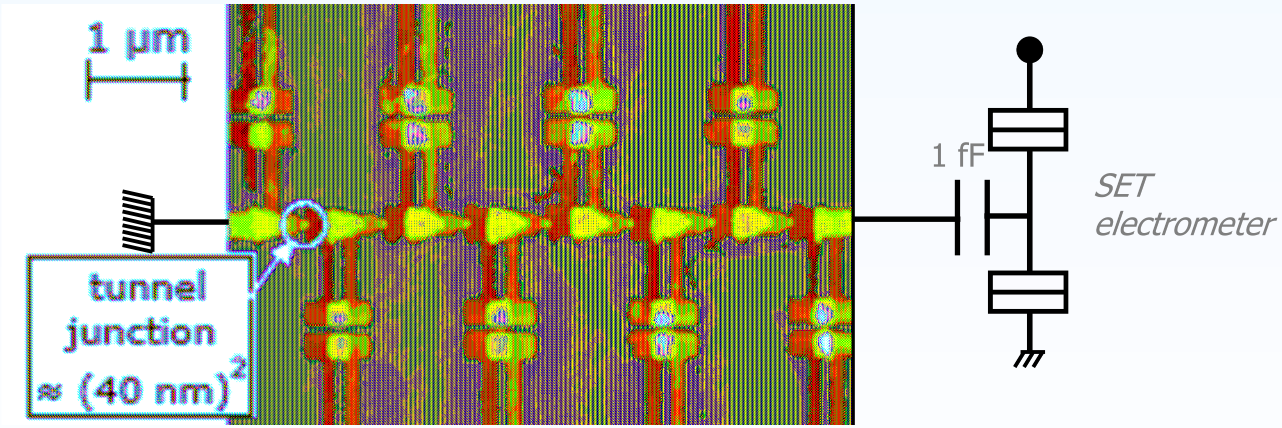




Devices expected to be metrological

Cotunneling is the main limitation for a metrological use of an electron pump

- 7 junctions electron pump
  NIST, Keller et al., Appl. Phys. Lett., 69, p. 1804, 1996

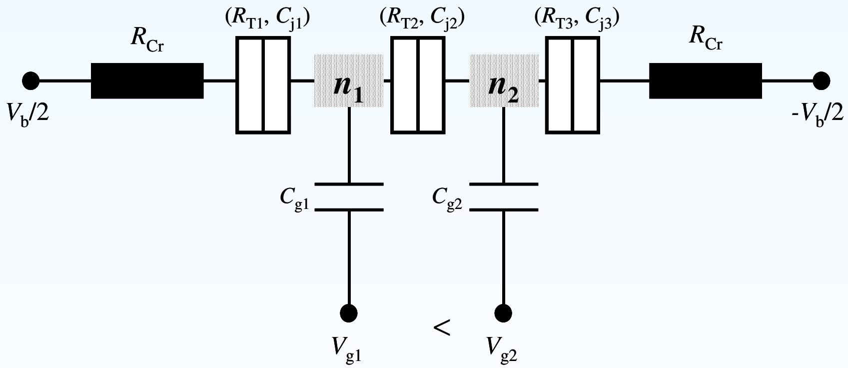


Transfer of electrons at 5 MHz,
error rate: 1.5 part in 10^8

- The R-pump
  Zorin et al., J. App. Phys., 88, p. 2665, 2000

The R-pump

Increasing the local impedance can reduce the cotunneling with preserving the transfer rate.



Typical values:

R_{Cr}~30-50 kΩ

- Conditions on R_{Cr}: $$R_K < 2R_{Cr} \lesssim R_T$$

Environment with large dissipation can absorb a part of the electron energy.

The charge equilibrium is established, then the pump behaves similarly to the case without resistor.

- The cotunneling current is roughly: $$I_{ct} \propto V_b^{\eta} \qquad \eta = 2\left(N + \frac{2R_{Cr}}{R_K}\right) - 1$$

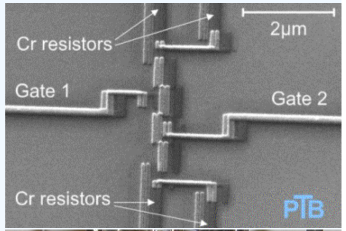
(i.e. that, in term of cotunneling, the N junctions pump is roughly equivalent to a $N+2R_{Cr}/R_K$ junctions pump)

⇒ There is no complete theory of the error processes in a R-pump

Outline

- The SI and the electrical units
- Single electron pump
- Experimental set-up
- Measurements
- The metrological triangle experiment

Observational conditions



- $E_C = e^2/2C >> k_B T$

if C = 100 aF (dimensions of the junction: (50 nm)^2.2 nm), then T << 6.5 K.

-> Fabrication of the samples by nano lithography to minimize the values of *C* (shadow evaporation technique)

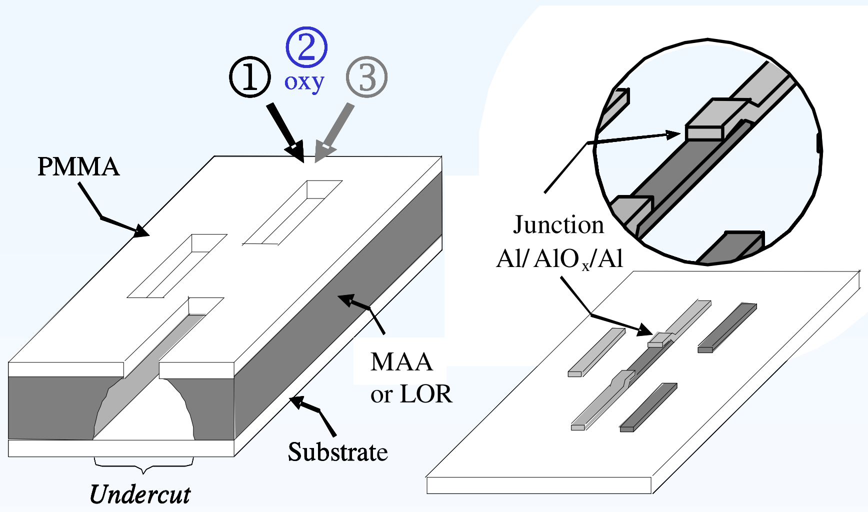
-> Dilution unit to reach the temperature where the Coulomb blockade appears

- I ~ 1 – 10 pA

a relative uncertainty of 1 part in 10^8 for a current of 10 pA (i.e. 0.1 aA)
=> we can miss 0.6 electron per second.

-> Measurement of the intensity current by using a metrological current comparator

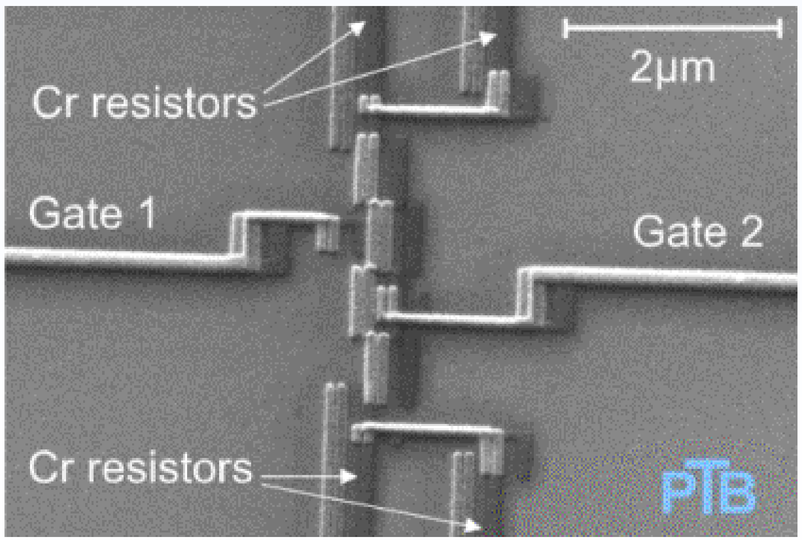
Samples

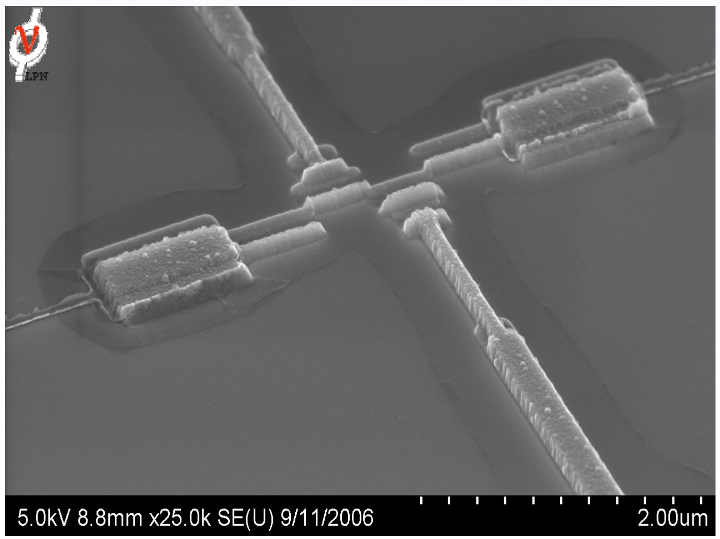


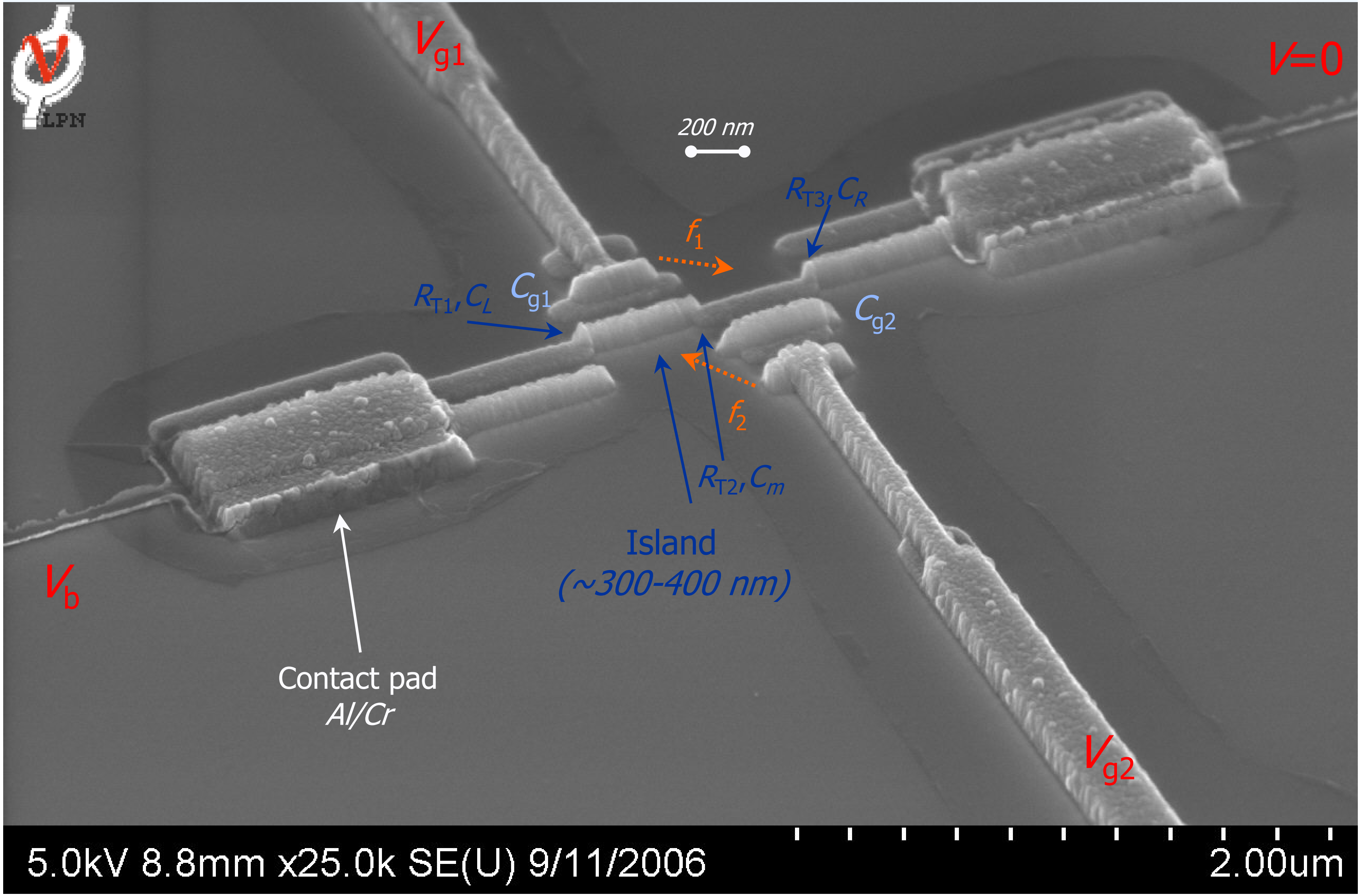
shadow evaporation technique

Cr deposition, 7 nm, angle null
(20 nm*70 µm)

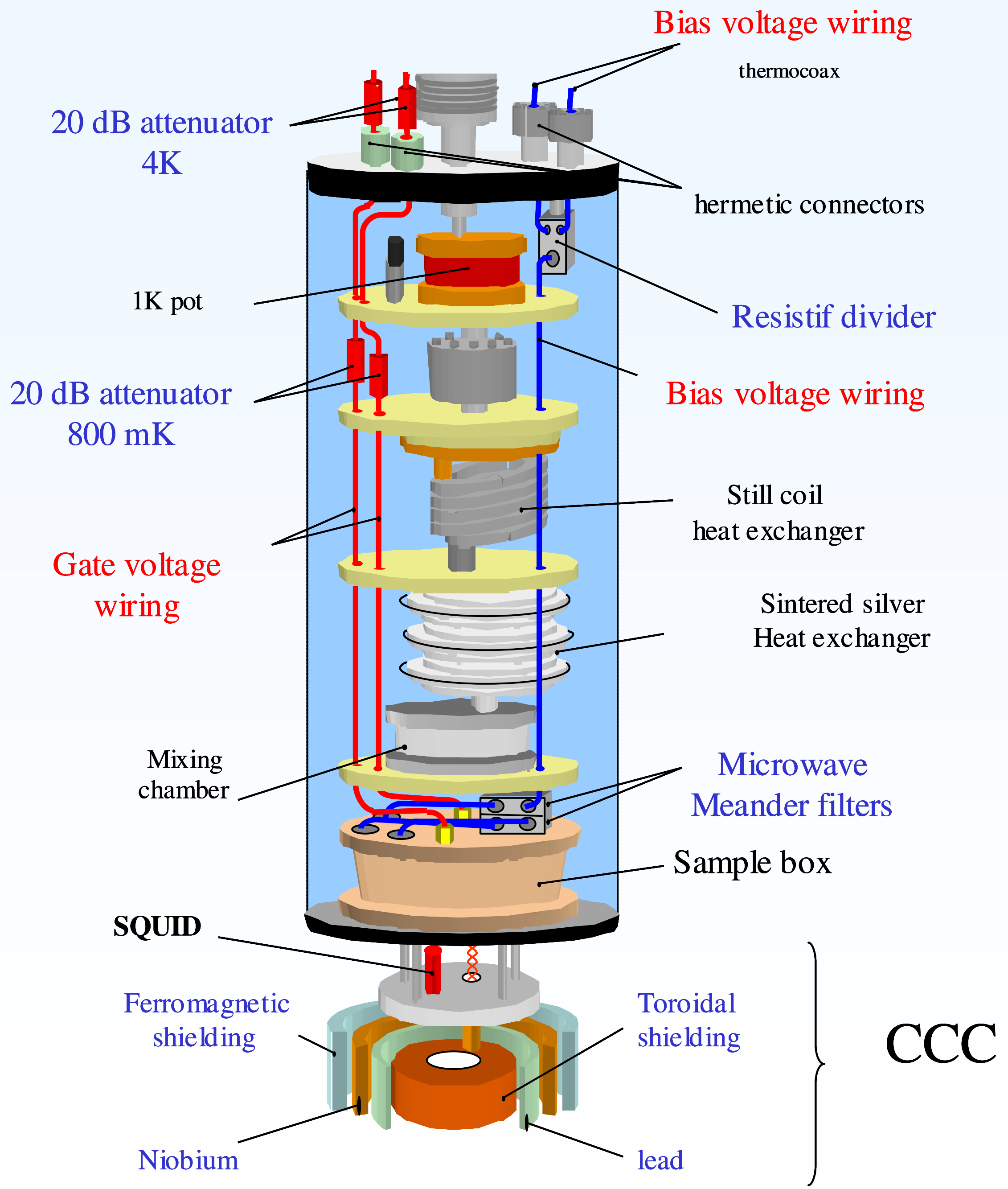
- *Al* deposition: 25 nm, angle 10°
- *Al* Oxidation: a few nm (2-3)
- *Al* deposition: 60 nm, angle –10°

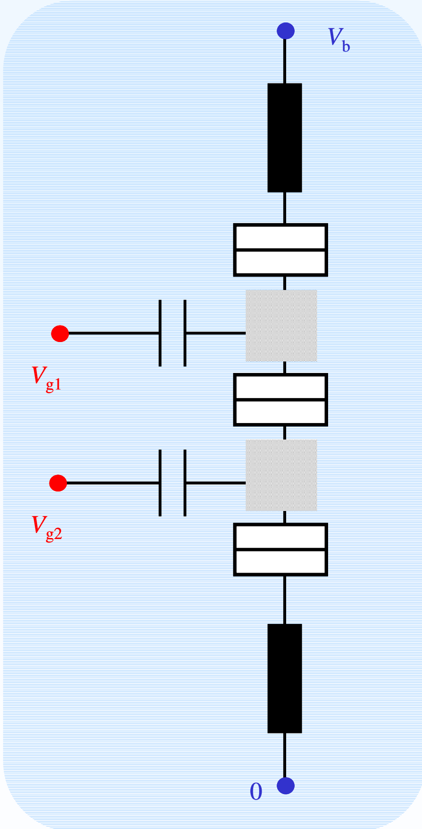






LPN
V_{g1}
V=0
200 nm
R_{T3}, C_R
f_1
R_{T1}, C_L
C_{g1}
C_{g2}
f_2
R_{T2}, C_m
Island
(~300-400 nm)
V_b
Contact pad
Al/Cr
V_{g2}
5.0kV 8.8mm x25.0k SE(U) 9/11/2006
2.00um


Bias voltage wiring
thermocoax
20 dB attenuator
4K
hermetic connectors
1K pot
Resistif divider
20 dB attenuator
800 mK
Bias voltage wiring
Still coil
heat exchanger
Gate voltage
wiring
Sintered silver
Heat exchanger
Mixing
chamber
Microwave
Meander filters
Sample box
SQUID
Ferromagnetic
shielding
Toroidal
shielding
CCC
Niobium
lead

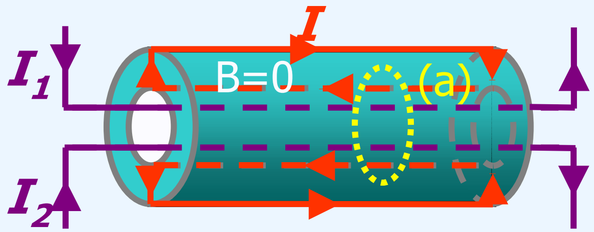

V_b
V_{g1}
V_{g2}
0

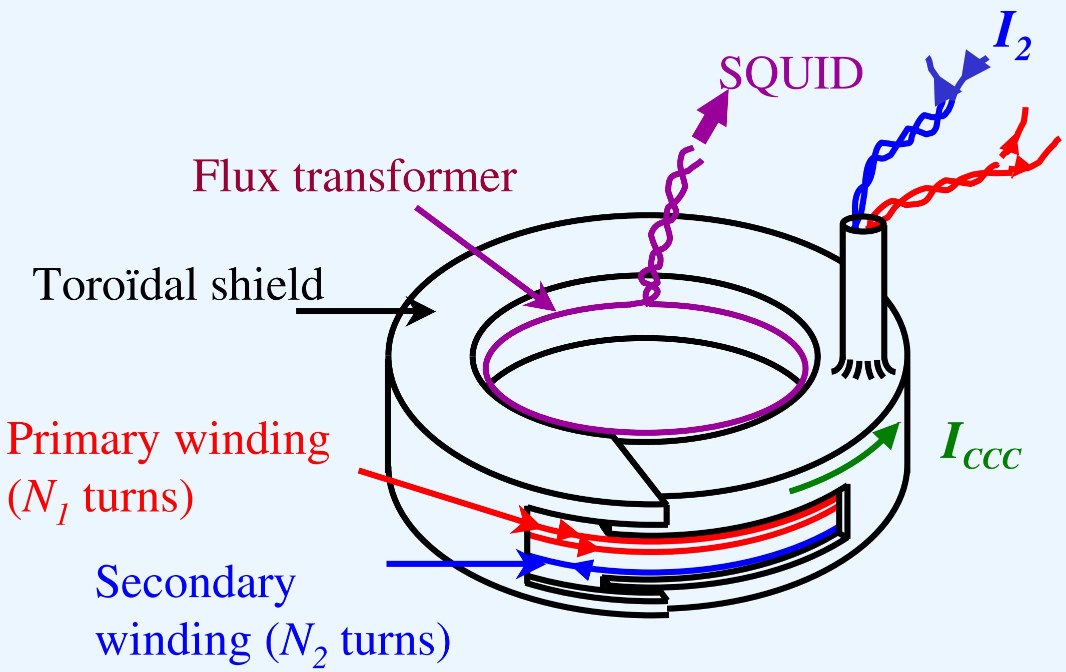
Cryogenic Current Comparator (CCC)

Theoretical principles :

Ampere's law : $\oint_{(a)} B.dl = \mu_0.(I_1 + I_2 - I)$

Meissner effect : $\oint_{(a)} B.dl = 0$





$$I_{CCC} = N_1 I_1 - N_2 I_2$$

I_2 is adjusted in order to have $I_{CCC} = 0$,

then: $N_1 I_1 = N_2 I_2$

$$I_2 = \frac{N_1}{N_2} I_1$$

Cryogenic Current Comparator (CCC)

•Current resolution δI (=the measurable minimum current circulating in the toroïdal shield)

– 3 components :

Johnson noise of the input resistance + SQUID resolution + external magnetic flux noise

Typical value: for a perfect coupling between the DC SQUID and the toroïdal shield, and N_1*=20000 turns,* $\delta I \sim 0.7\ fA/Hz^{1/2}$

•Exactness of the CCC current ratio

– Winding ratio *(a leakage flux is generated by the currents at the end of the shield)*

->The toroïdal shield has to overlap itself over a sufficient length. In practice with 2 overlaps, the uncertainty on N_1/N_2 is below 1 part in 10^{10}

– Frequency effect *(resonance at* f_R *and capacitive leakage due to parasitic capacitances)*

-> f_R decreases when N_1 increases (=2 kHz for N_1= 20 000). The current ratio error is proportional to $(f/f_R)^2$

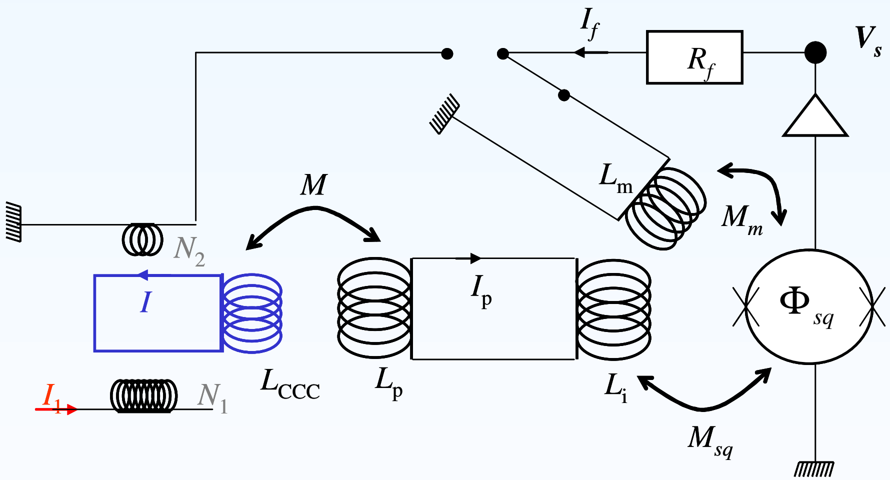
– Finite open loop feedback gain

-> An adjustment of the feedback current at 10^{-4} is necessary to have a current ratio error below 1 part in 10^9

=> With optimized parameters and shielding of the CCC and a pre-adjusting feedback current source uncertainty on the amplification of the current is below one part in 10^8

Operating modes of the CCC

Internal feedback mode



$$G_{IFB} = \frac{V_S}{I_1} = \frac{M_{sq}}{M_m} \frac{k}{2} \sqrt{\frac{L_{CCC}}{L_i}} N_1 R_f$$

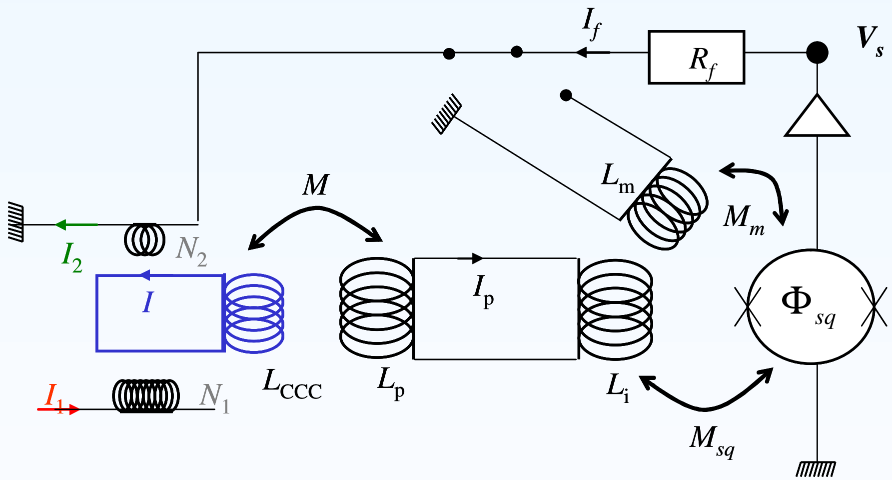
Typical values:

N_1 = 20 000 (N_2 = 1)

M_{sq}=10nH, M_m=1nH, L_i=1.8µH, L_{CCC}=15nH and k =0.8

-> $G_{IFB}/R_f \sim 7.10^3$

External feedback mode



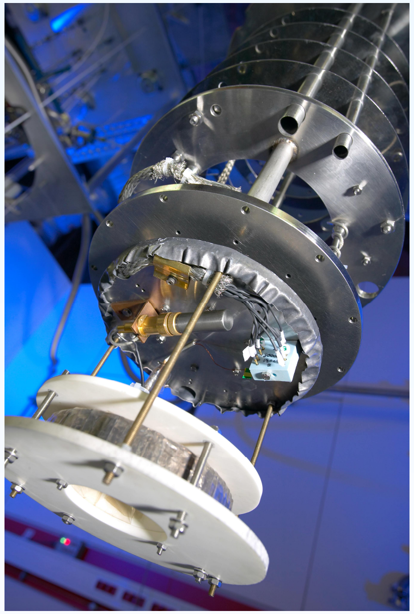
$$G_{EFB} = \frac{V_S}{I_1} = \frac{N_1}{N_2} R_f$$

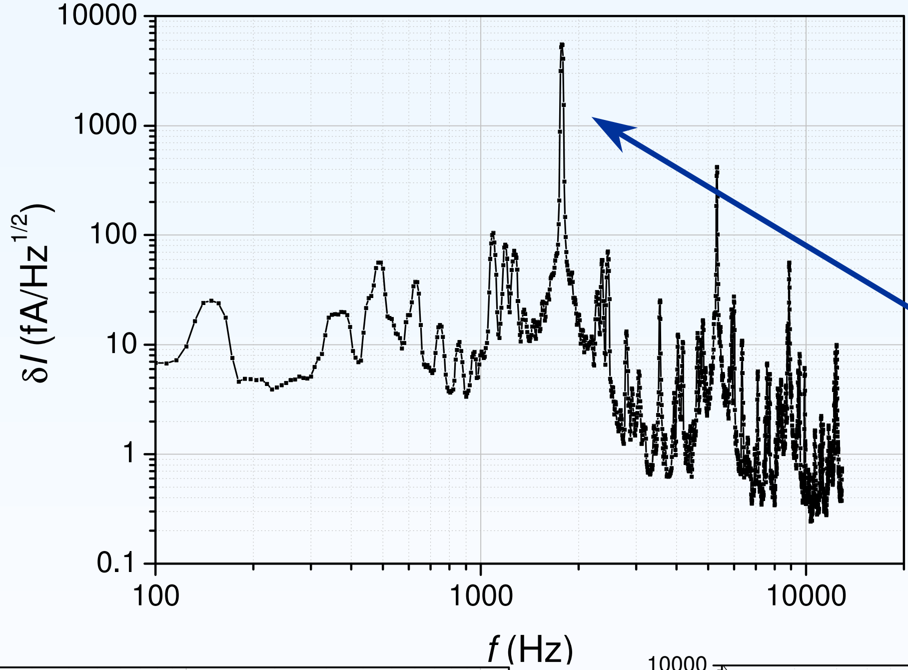
Typical values:

N_1 = 20 000, N_2 = 1

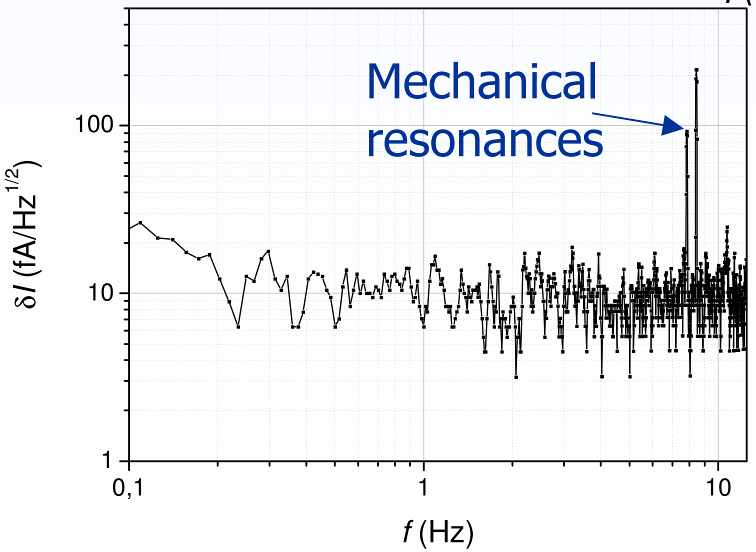
-> $G_{EFB}/R_f = 2.10^4$

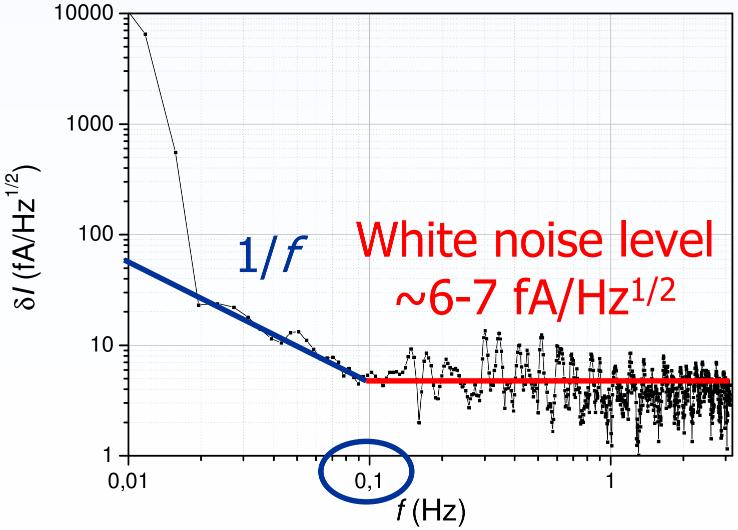
Experimental characterization of the set-up





N_1	20 000
N_2	1
L (H)	8
f_R (kHz)	1.8
C (nF)	1

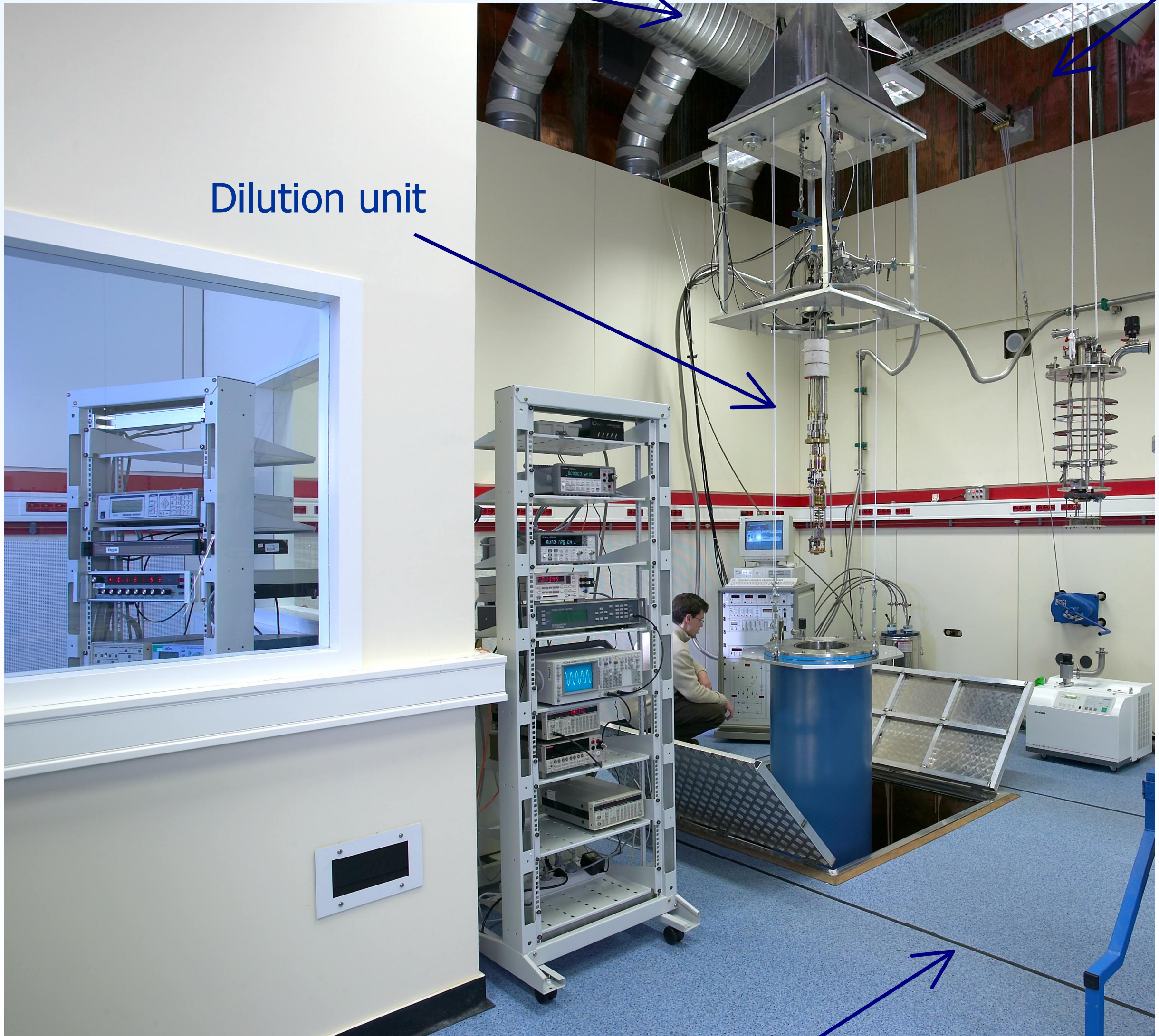


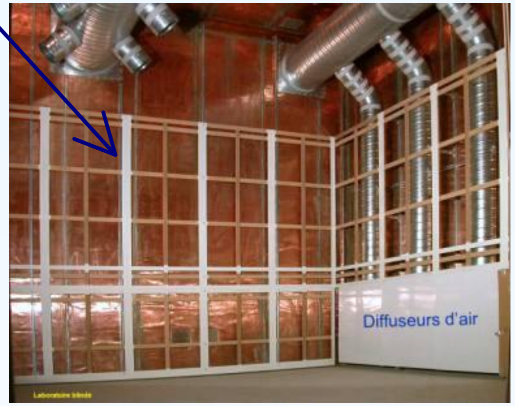


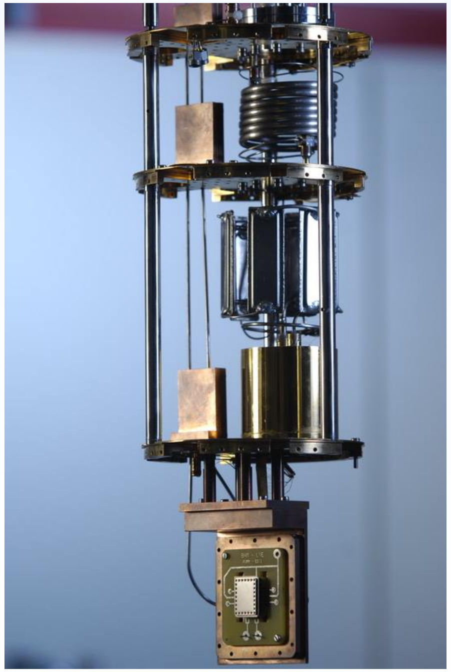
Thermal regulation

Copper shielding

Dilution unit







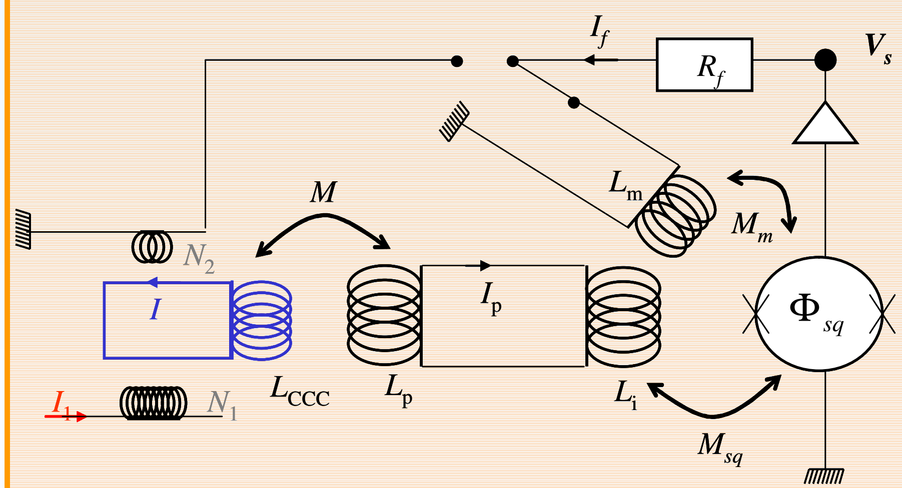
Mechanical insulation

Outline

- The SI and the electrical units
- Single electron pump
- Experimental set-up
- **Measurements**
- The metrological triangle experiment

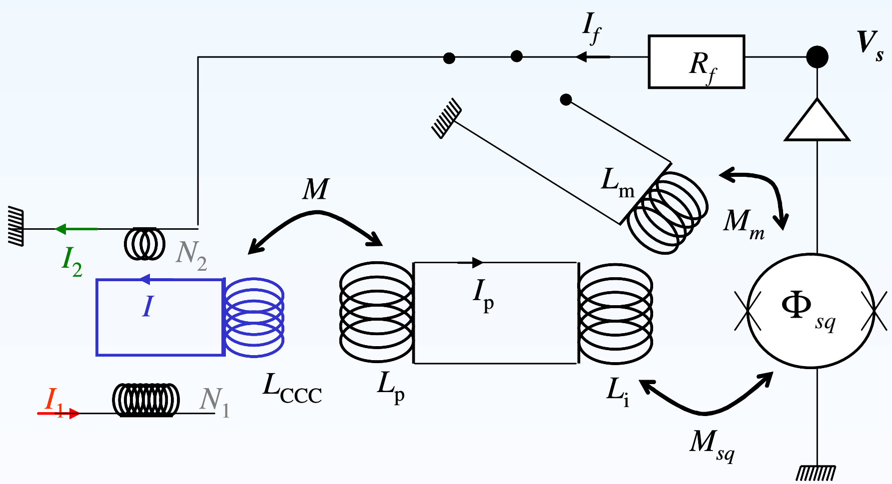
Operating modes of the CCC

Internal feedback mode



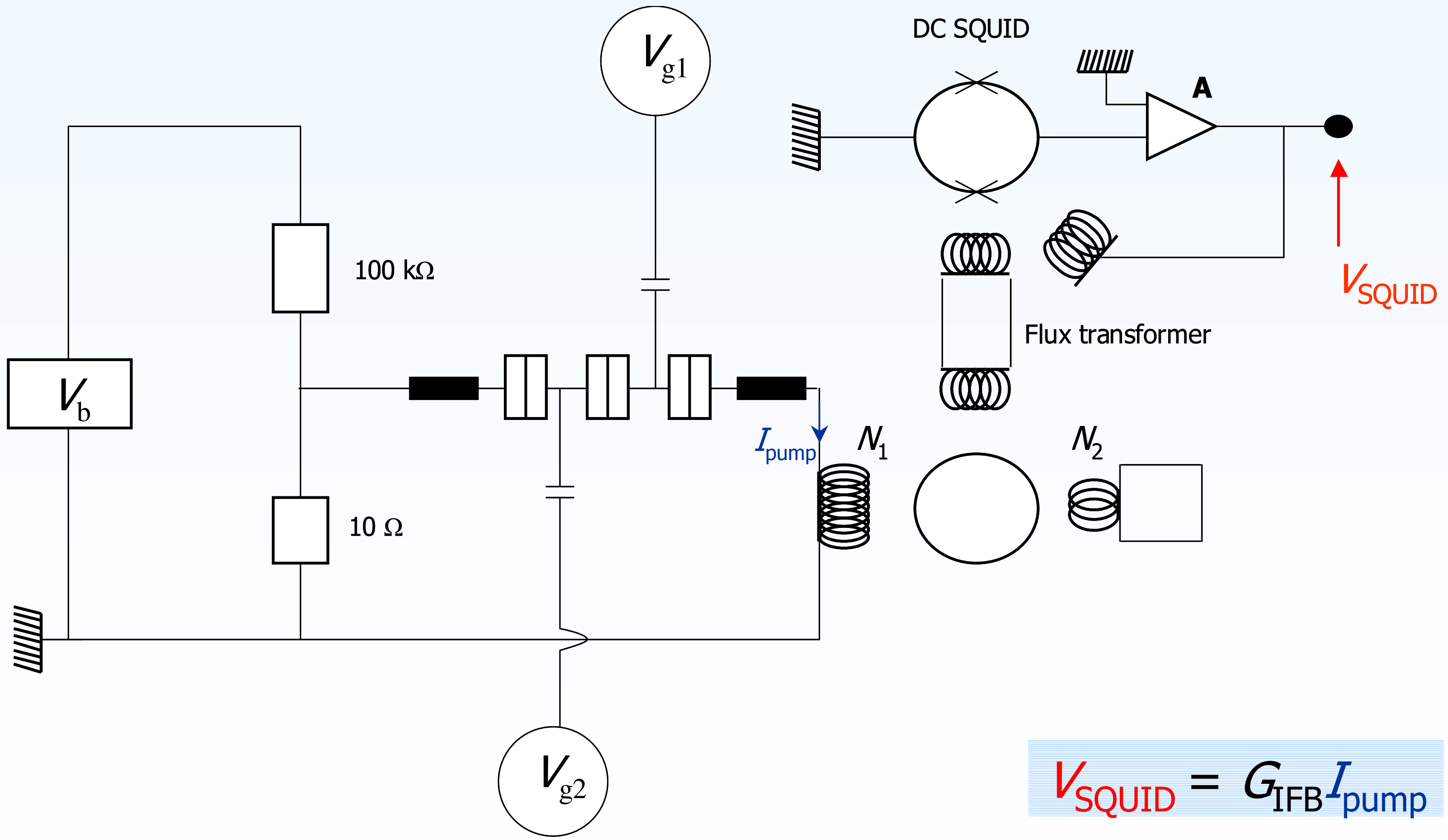
$$G_{IFB} = \frac{V_S}{I_1} = \frac{M_{sq}}{M_m}\frac{k}{2}\sqrt{\frac{L_{CCC}}{L_i}}N_1 R_f$$

External feedback mode



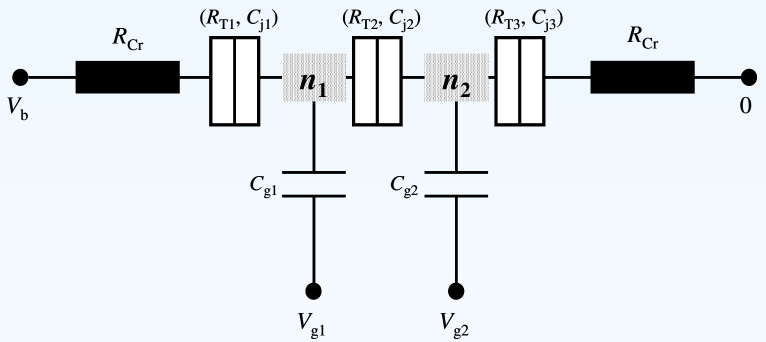
$$G_{EFB} = \frac{V_S}{I_1} = \frac{N_1}{N_2}R_f$$

The internal feedback mode



$$V_{SQUID} = G_{IFB} I_{pump}$$

Characterization of a pump: static measurements



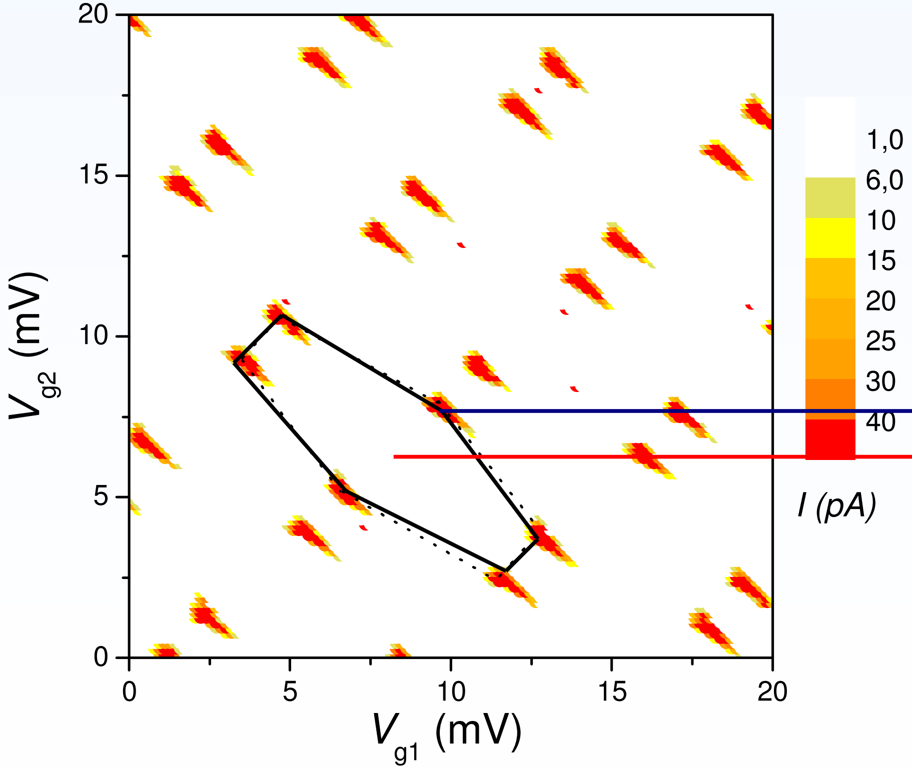
V_{g1} and V_{g2} are biased with DC voltages

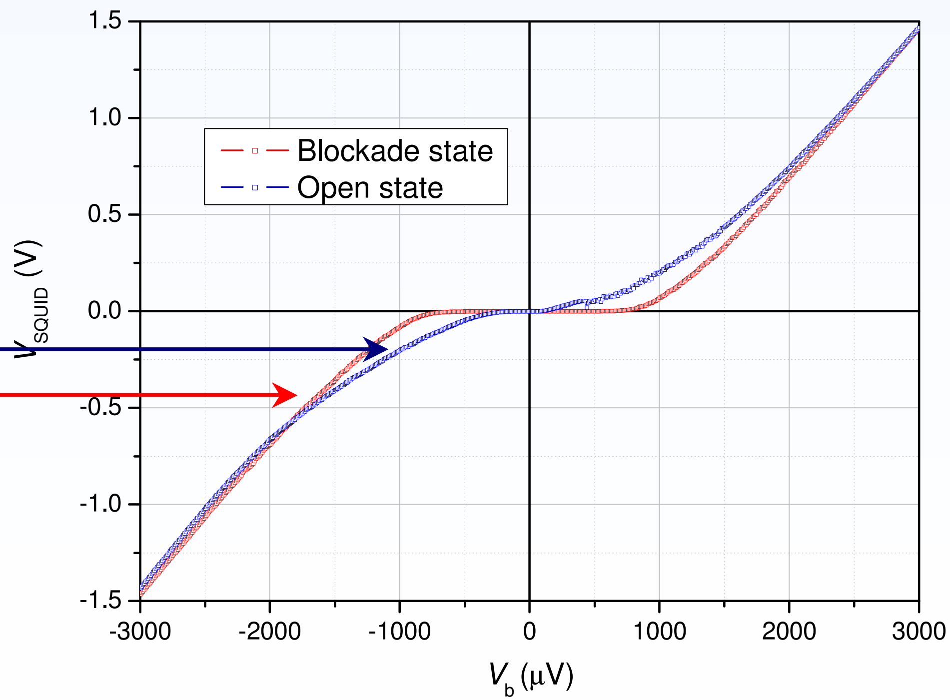
-> Stability diagram :

V_b is fixed and V_{g1} and V_{g2} change

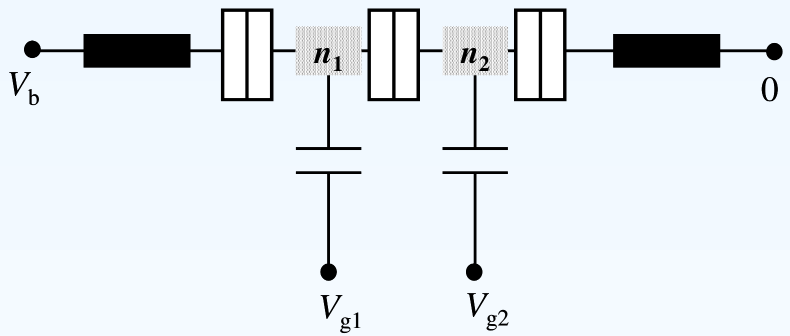
-> I-V_b curve :

A couple (V_{g1}, V_{g2}) is fixed and V_b varies





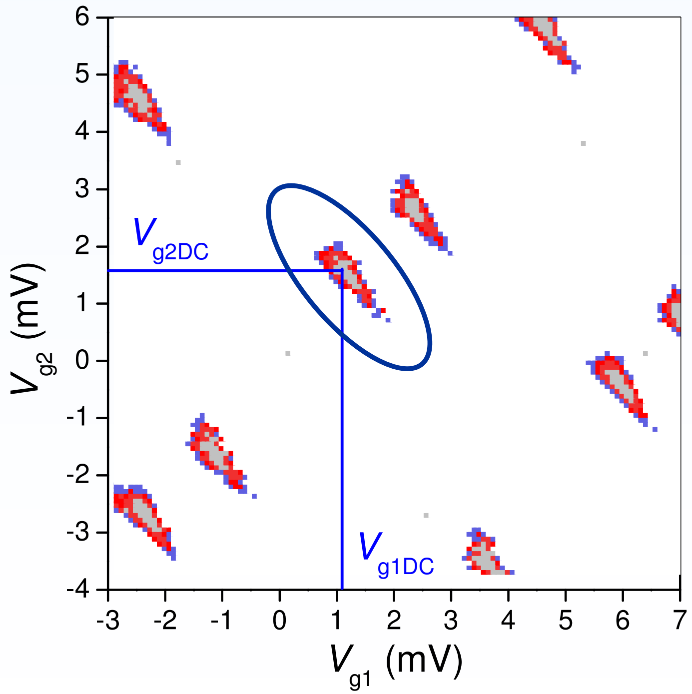
Characterization of a pump: pumping parameters

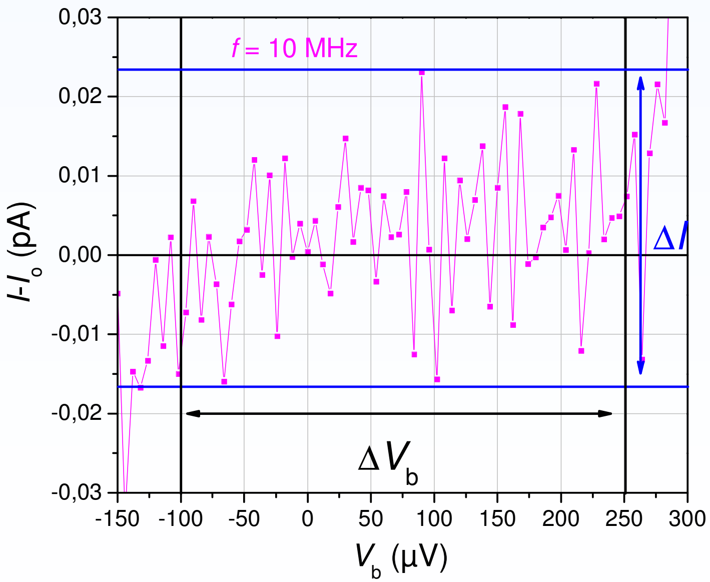


$$\begin{cases} V_{g1} = V_{g1DC} + A\cos(2\pi ft) \\ V_{g2} = V_{g2DC} + A\cos(2\pi ft + \varphi) \end{cases}$$

- V_{g1DC} and V_{g2DC} are coordinates of a triple point
- Adjusting parameters: A and φ

In dynamic mode I-V_b curve presents a current step at I=ef.





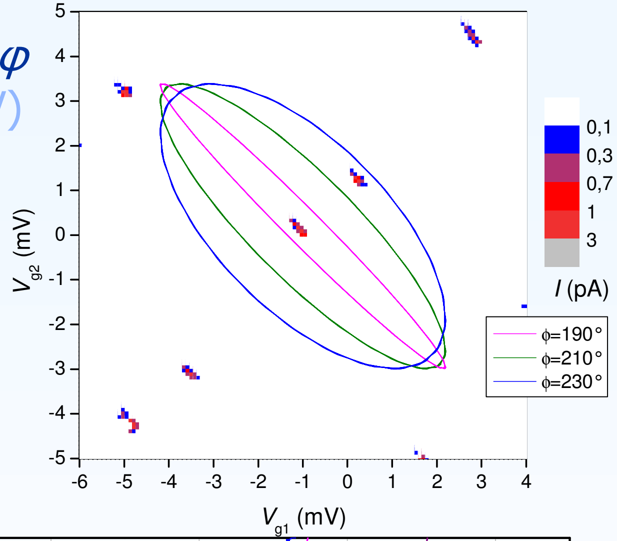
Current step measured at 10 MHz

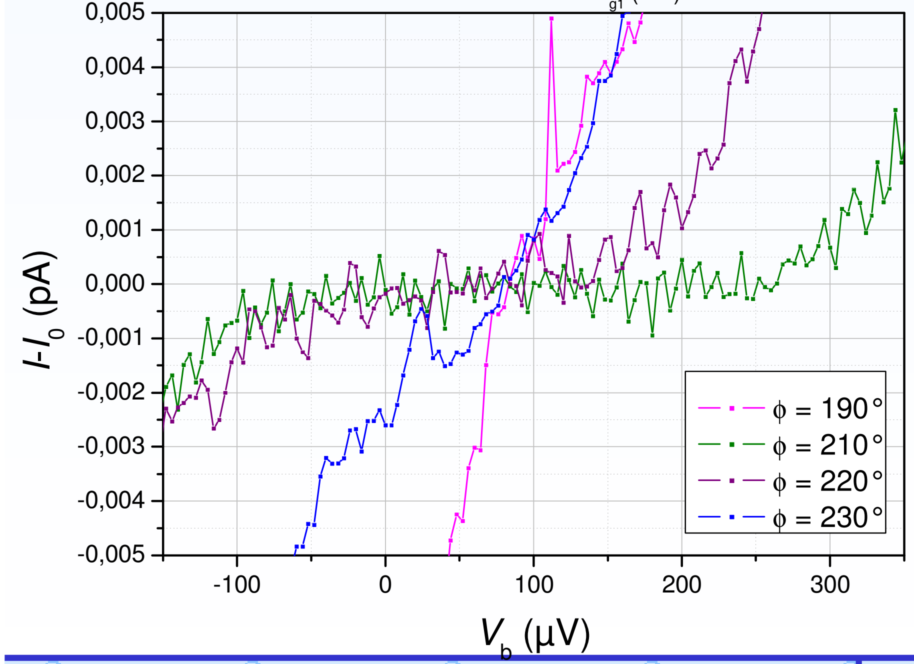
Criterion:

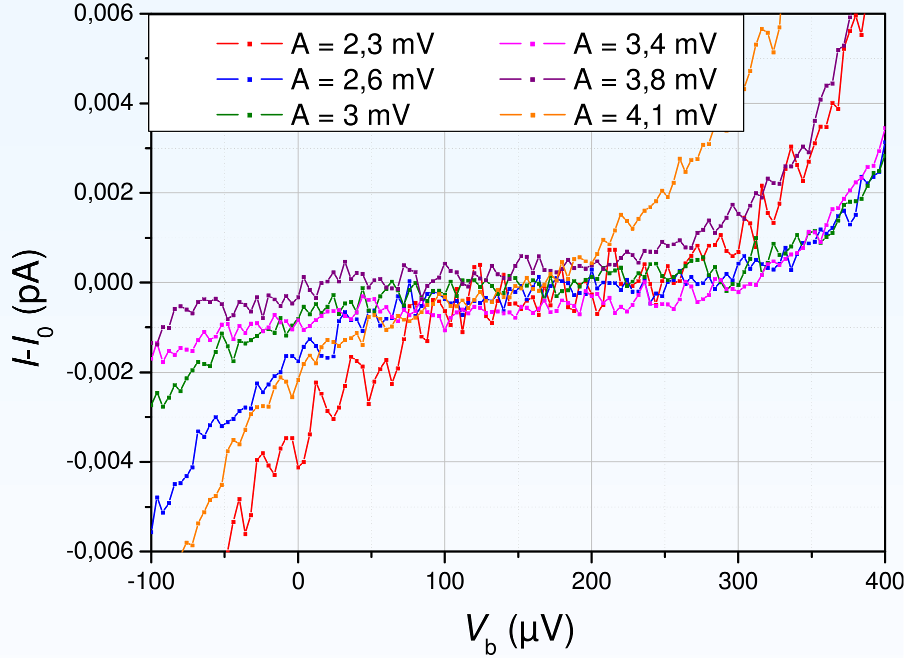
for ΔI corresponding to observable fluctuations, A and φ maximize ΔV_b

Characterization of a pump: pumping parameters

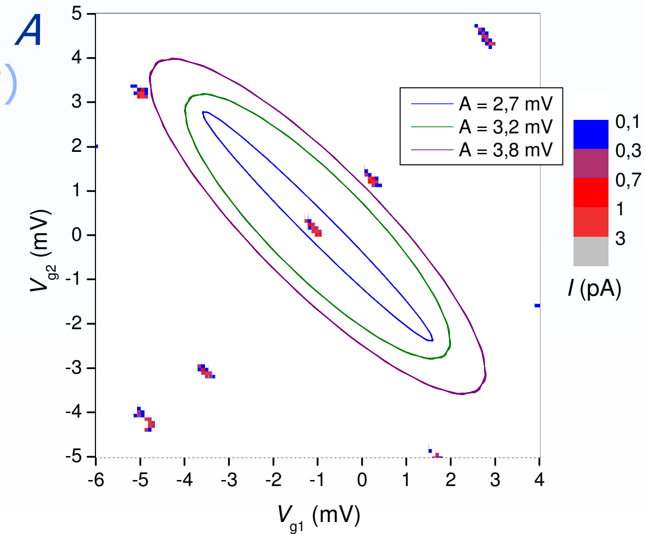
Dependence on φ
(with A=3.2 mV)



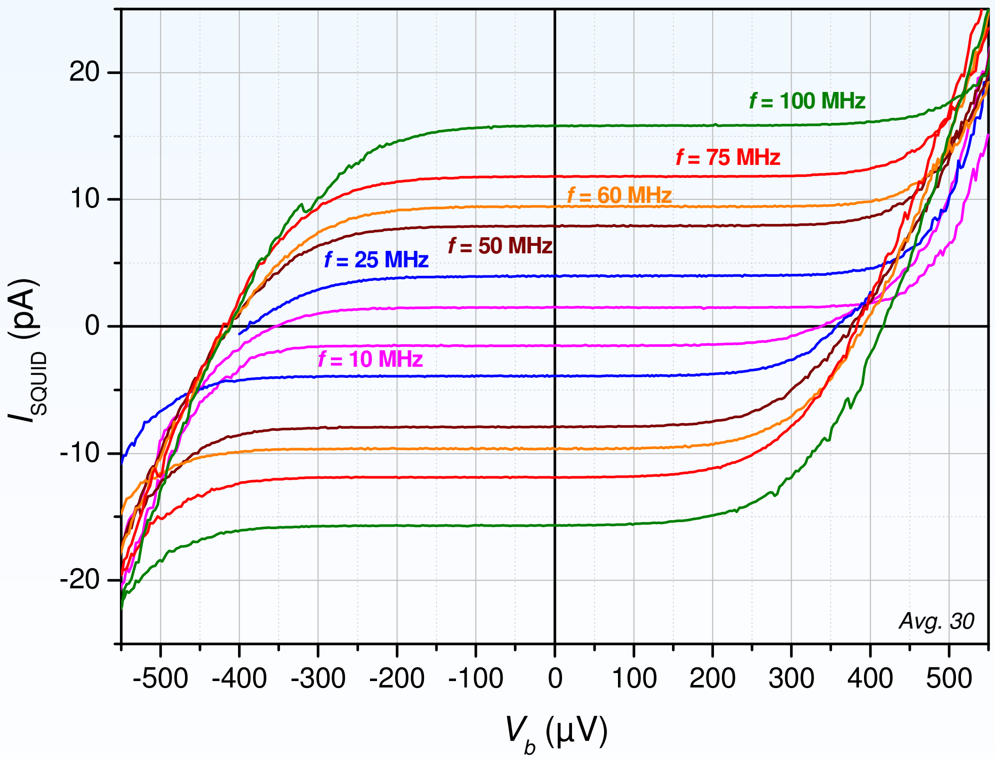


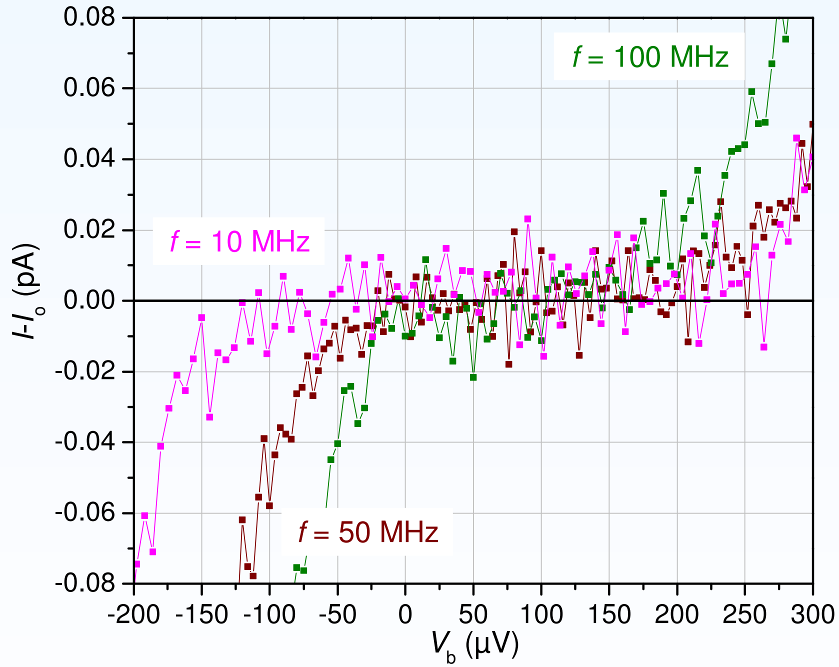


Dependence on A
(with φ=210°)



Characterization of a pump: current steps





Current steps obtained with a 3 junctions R-pump in the internal feedback mode.
The current was reversed by modifying φ.

f (MHz)	10	50	100
ΔV_b (µV)	350	300	150

(ΔI = 40 fA)

Type A uncertainty

GUM gives some rules to express the result of a measurement.

Uncertainty is divided in two parts:

-type A: uncertainty linked to statistical processes

-type B: uncertainty linked to other processes

- Objective: to reduce the type A uncertainty

(*by accumulating data*)

- If measurement are performed in white noise regime, then the type A uncertainty is the *experimental standard deviation of the mean*:

$$s^2(\bar{I}) = \frac{1}{n(n-1)} \sum_{k=1}^{n} \left(I_k - \frac{1}{n} \sum_{i=1}^{n} I_i \right)^2$$

(*n*: number of measurements of the current intensity *I*)

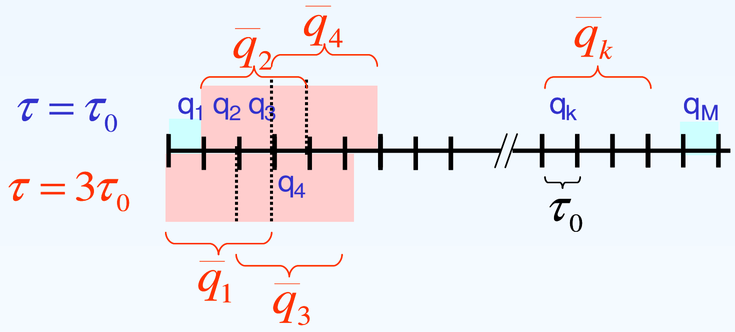
Hypothesis of white noise must be validate

Allan variance

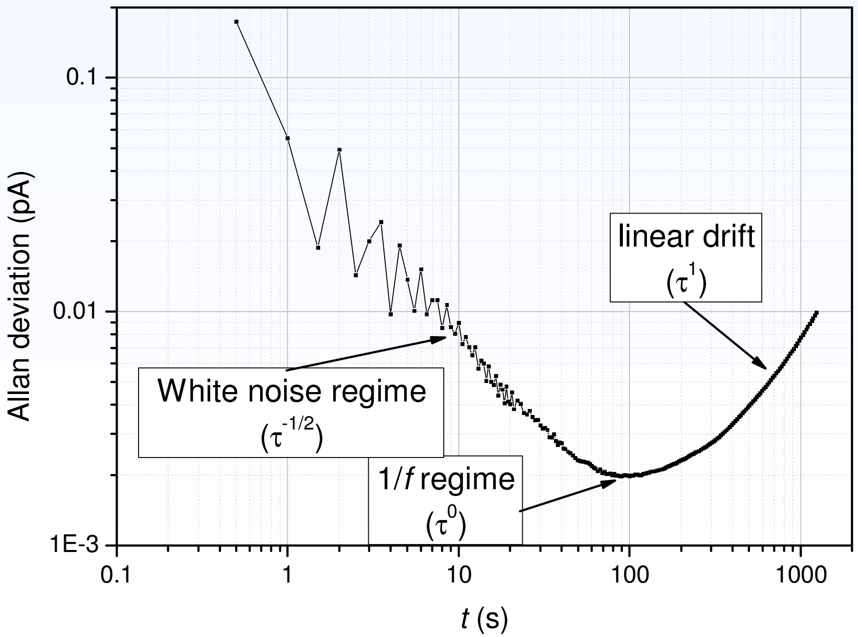
Hypothesis to use the Allan variance:

- Normal distribution
- PSD has a power law dependence on frequency
- Observations are equally spaced in time

<u>The overlapping Allan variance:</u>



$$\sigma_q^2(m\tau_0) = \frac{1}{2m^2(M-2m+1)} \sum_{j=1}^{M-2m+1} \left(\sum_{i=1}^{j+m-1} [q_{i+m} - q_i] \right)^2$$



Allan deviation calculus made on an accumulation of data of a R-pump (with f= 10 MHz)

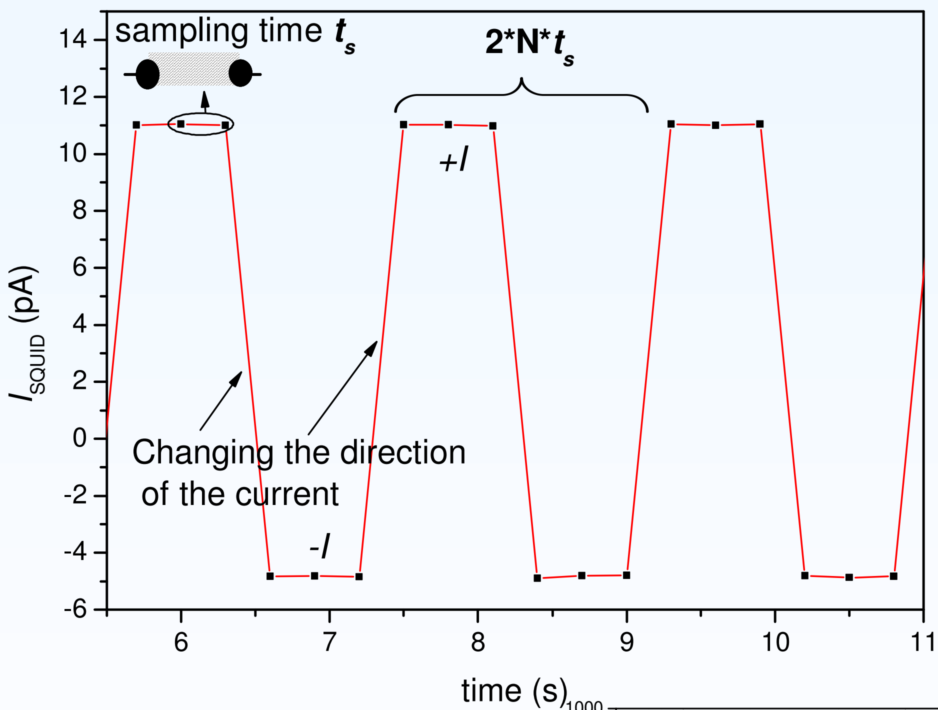
In case of white noise regime, Allan variance is an unbiased estimator of the true variance

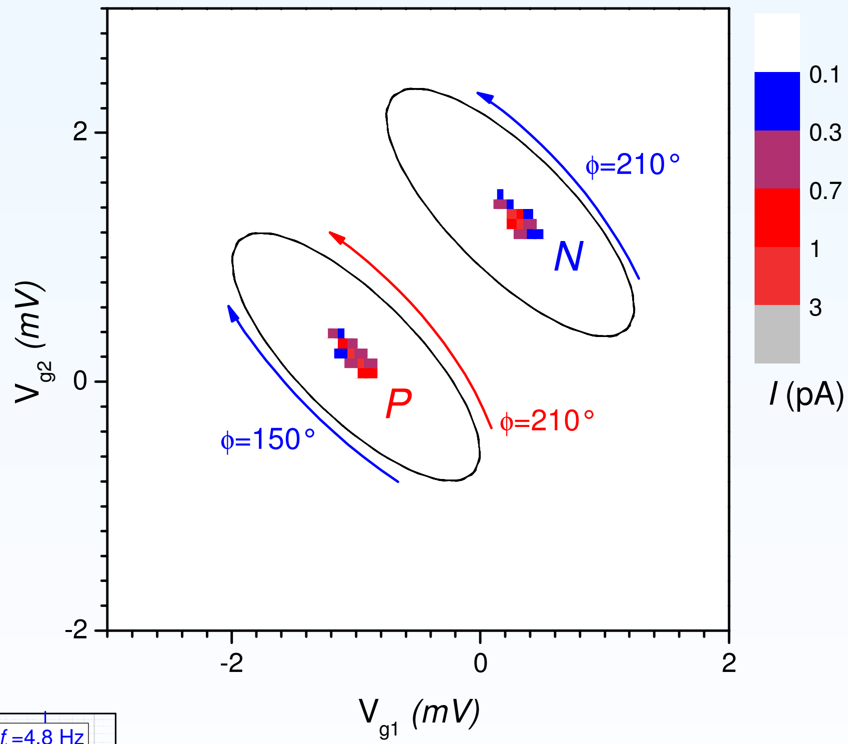
$$\sigma_q(m\tau_0) = \sqrt{\frac{h_0}{2m\tau_0}}$$

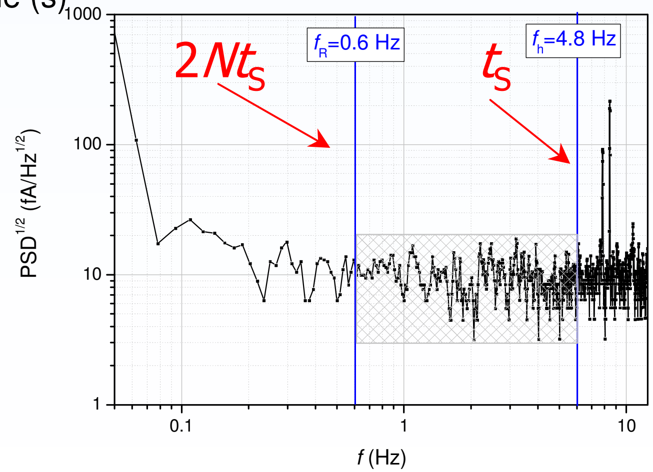
$h_0^{1/2}$ is the white noise level (in A/Hz$^{1/2}$)

Allan, IEEE Trans. Instrum. Meas., 36, p. 646, 1987 ; Witt, IEEE Trans. Instrum. Meas., 50, p. 445, 2001

Long term measurements: principle







Determination of ***N*** and ***t_S***:

-> Measurement of the PSD

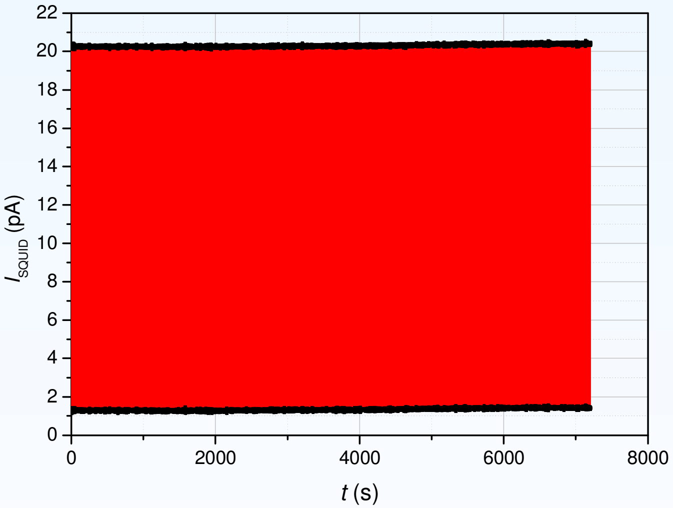
-> Determination of an interval $[f_R, f_h]$ where the noise is white.

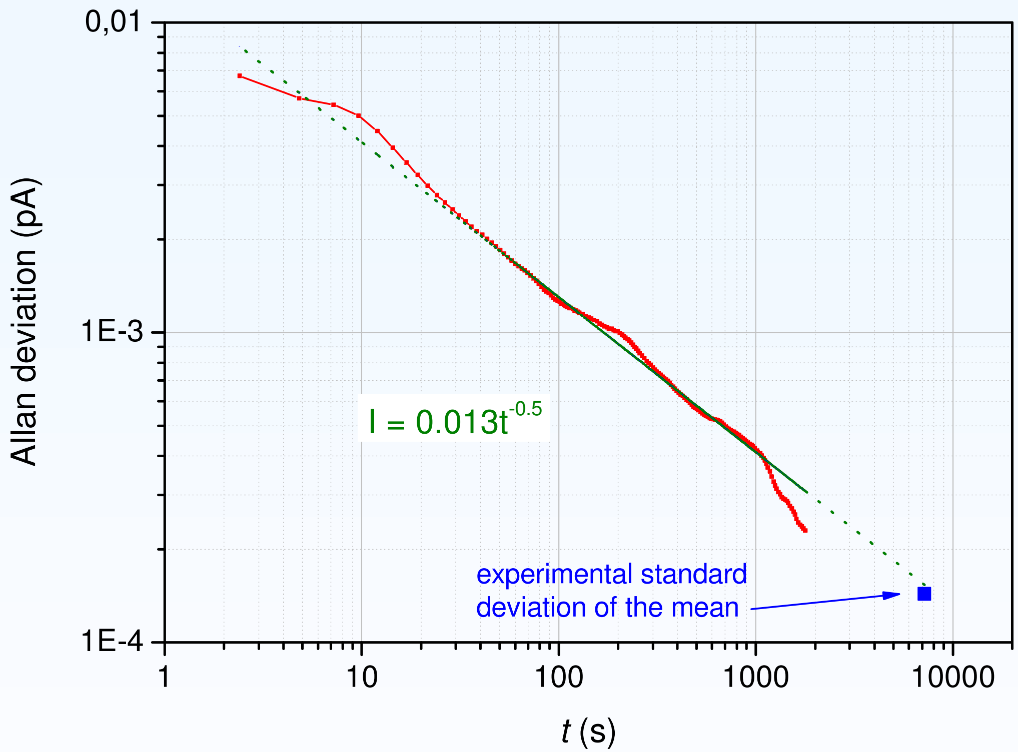
Changing the direction of the current:

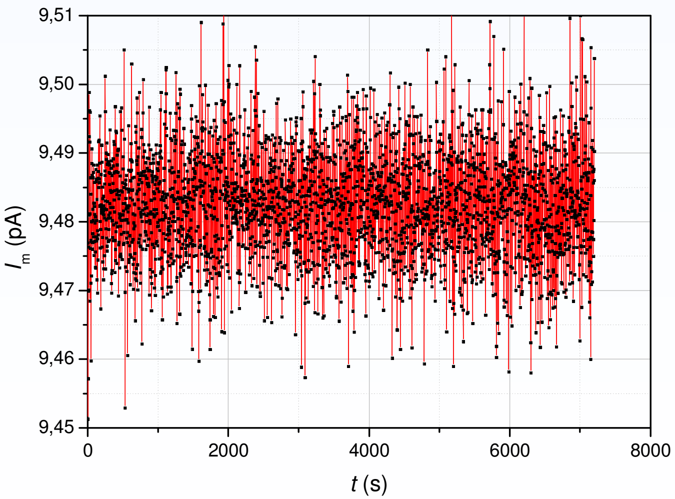
-> Around a triple point: modification of the phase

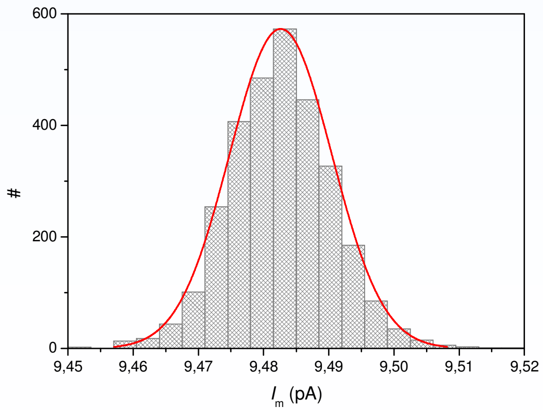
-> With a given phase: modification of the triple point

A long term measurement at f = 60 MHz









Results

Measuring time

2 h

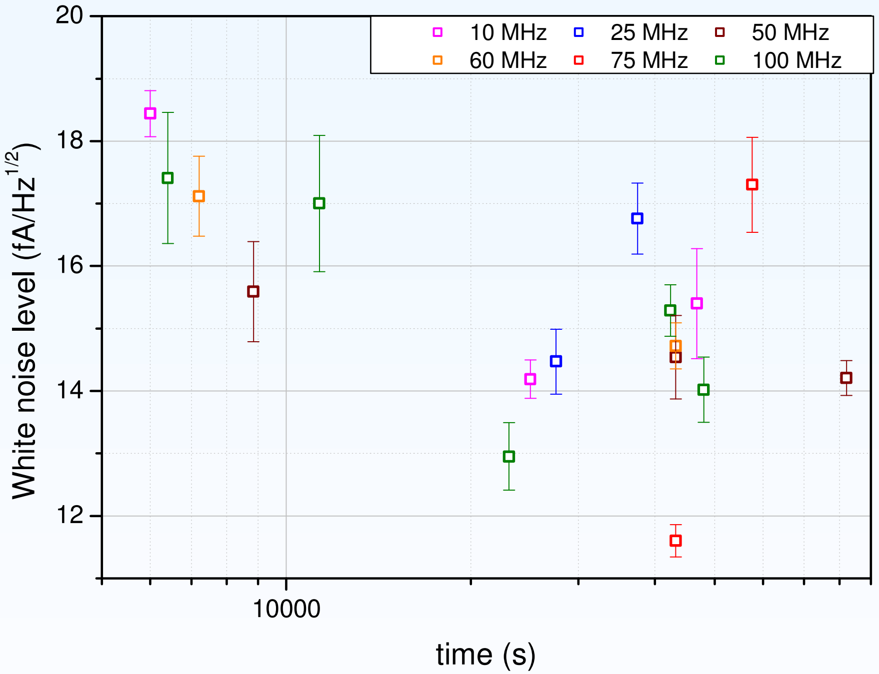
White noise level:

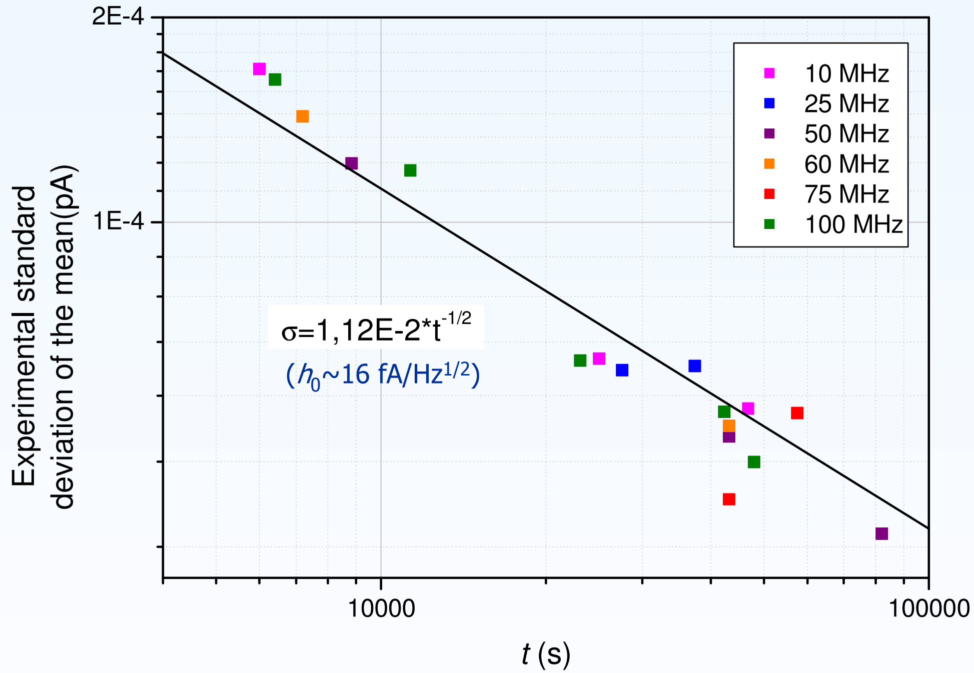
18 fA/Hz$^{1/2}$

Relative uncertainty:

1.5 parts in 10^5

Long term measurements: results





f (MHz)	10	25	50	60	75	100
T (h)	13	7.7	12	12	12	6.5
White noise level ($fA/Hz^{1/2}$)	14	16	14	15	12	12
Relative type A uncertainty (ppm)	33.6	15.3	6.1	5.3	3.3	3.9

Results and limitations of this mode of measurement

- Operating frequency up to <u>100 MHz</u>. No effect of this frequency on the stability of the current at the level of accuracy measured.

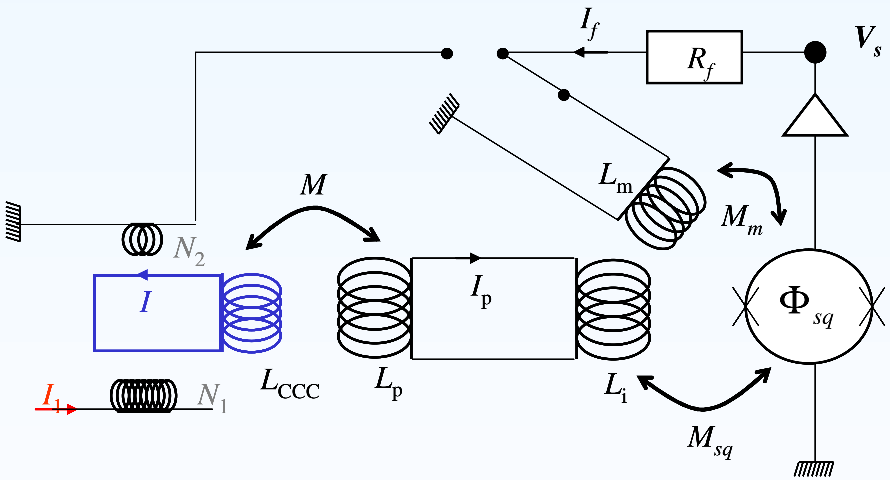
- Stability of the current generated by the pump on long term (up to 12 h) with a relative uncertainty of a <u>few parts in 10^6</u>.

BUT

- No information on the quantization level and on the flatness of the current steps.

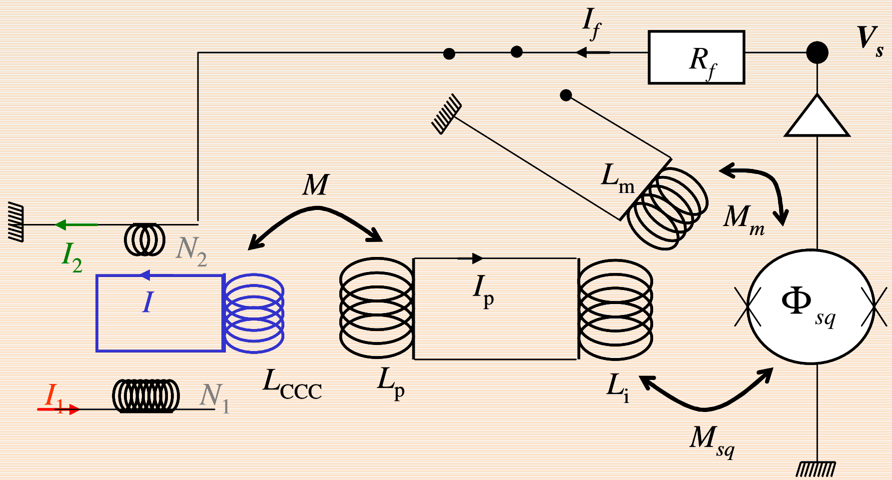
Operating modes of the CCC

Internal feedback mode



$$G_{IFB} = \frac{V_S}{I_1} = \frac{M_{sq}}{M_m}\frac{k}{2}\sqrt{\frac{L_{CCC}}{L_i}}N_1 R_f$$

External feedback mode

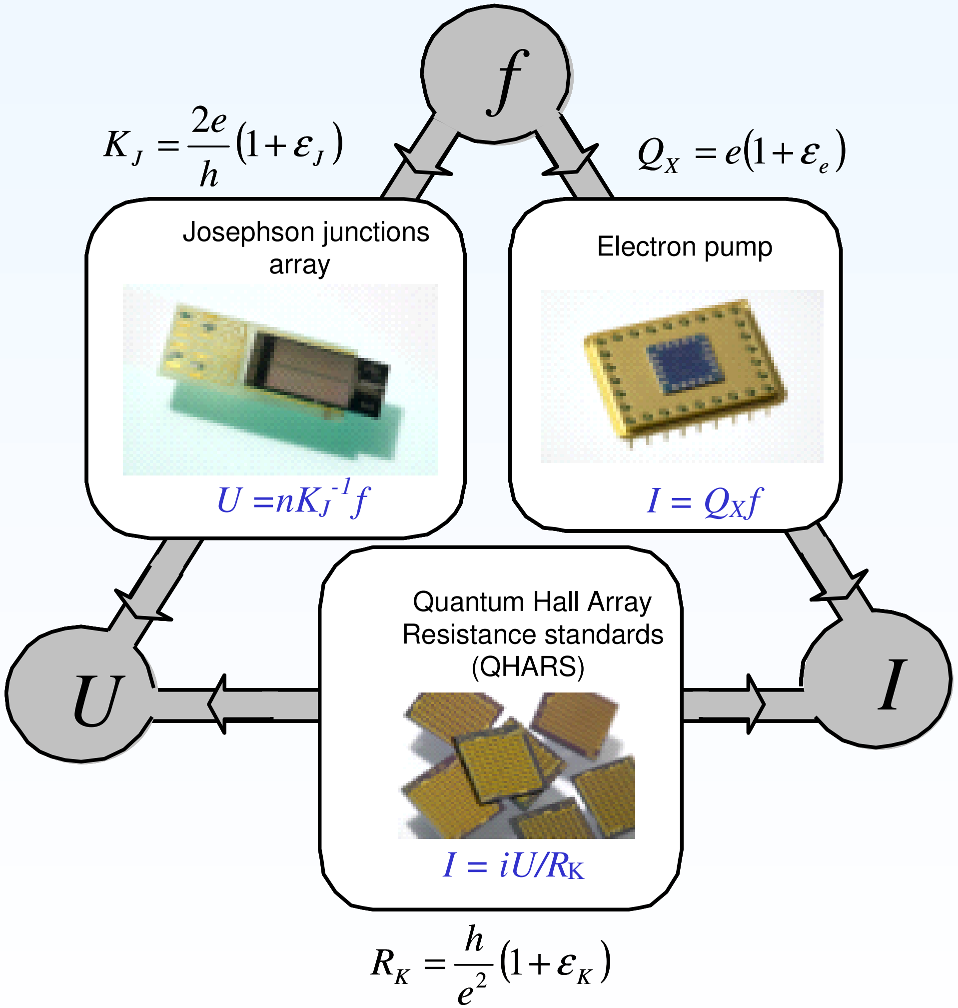


$$G_{EFB} = \frac{V_S}{I_1} = \frac{N_1}{N_2}R_f$$

Outline

- Electrical units
- Single electron pump
- Experimental set-up
- Measurements
- The metrological triangle experiment

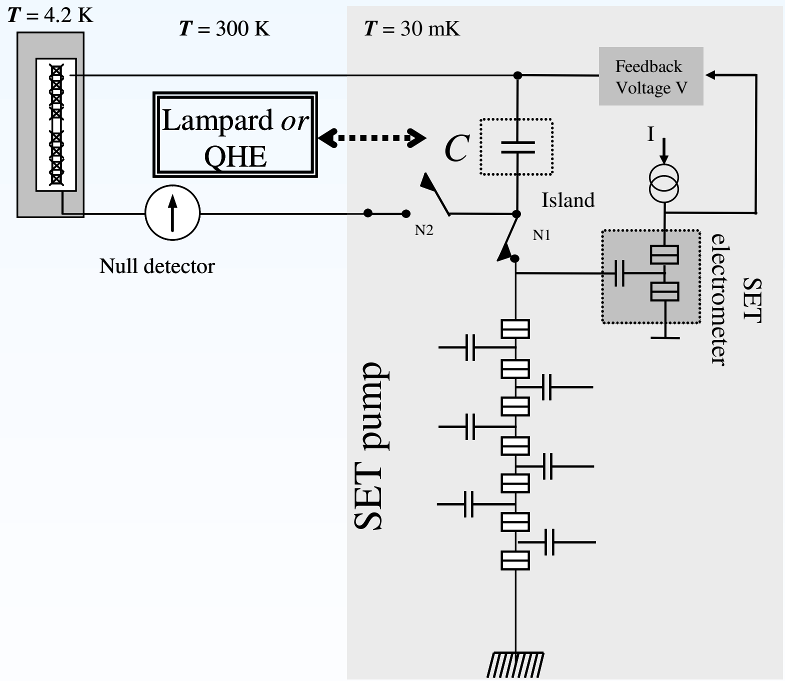
The metrological triangle experiment (MTE)



Realisations of the MTE

Indirect way

$$Q = CV$$



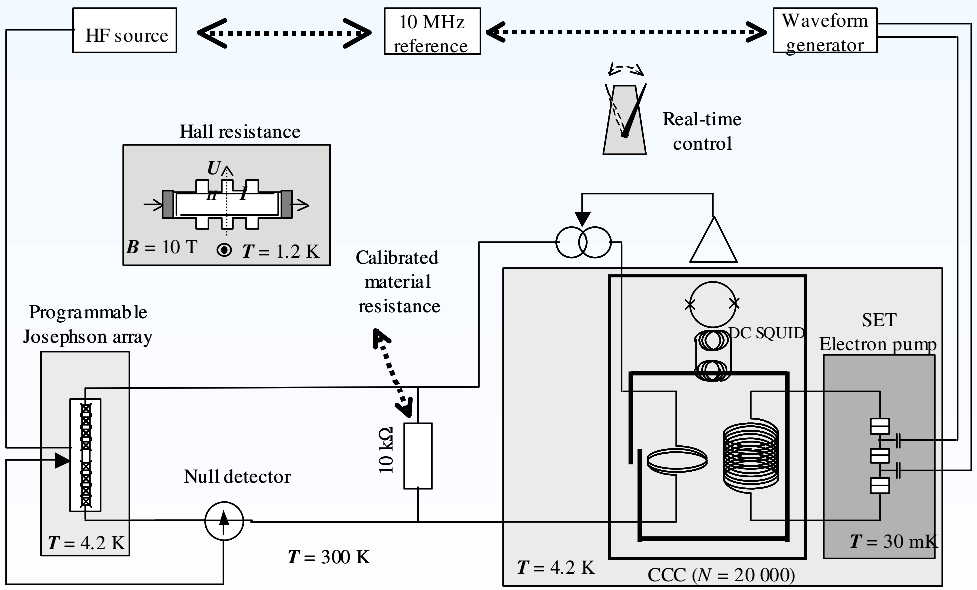
$$R_K K_J Q_X = \frac{in_j}{N} \frac{f_j}{2\pi f_q}$$

-> relative uncertainty: **9 parts in 10^7**

Keller et al., CPEM 2006

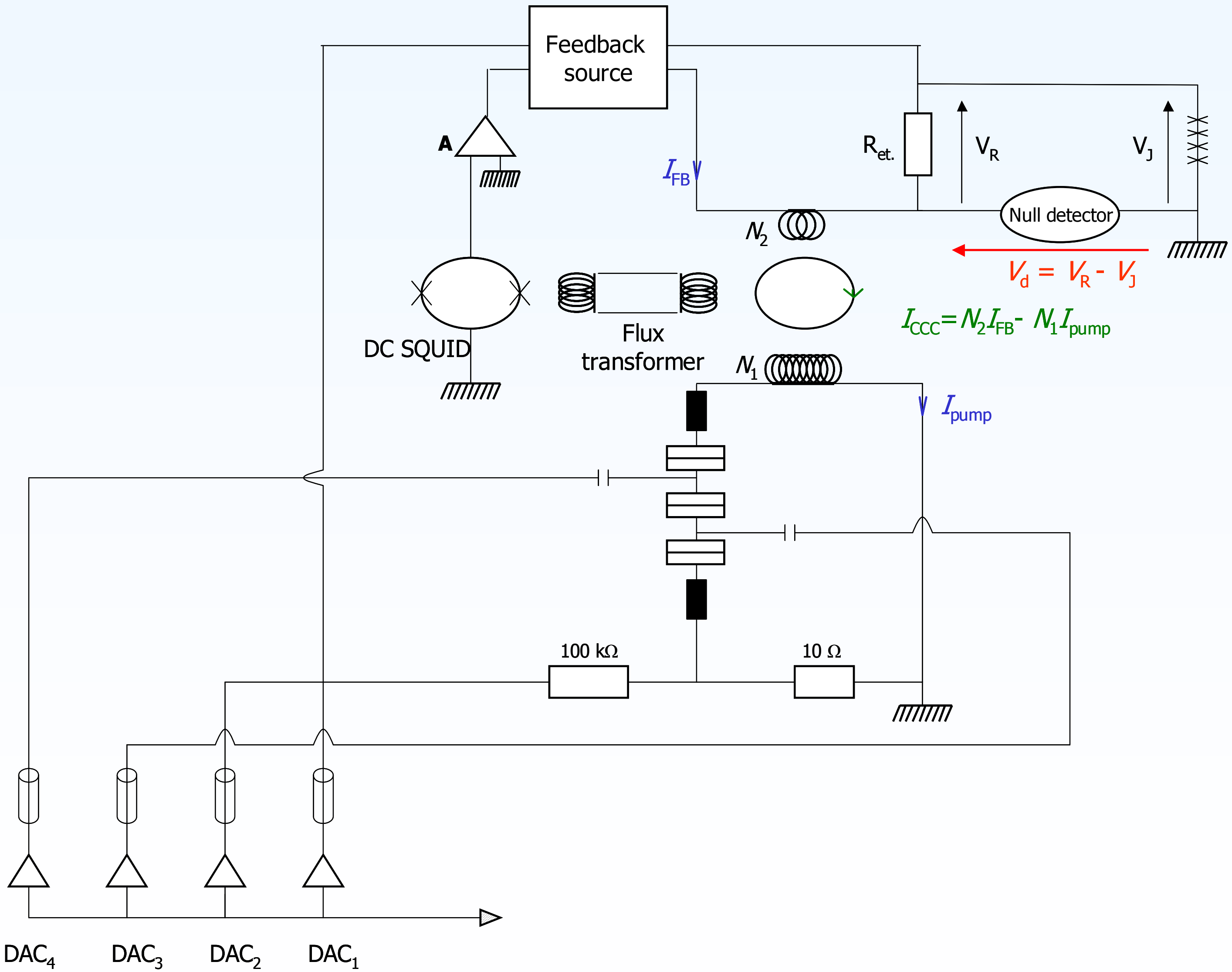
Direct way

$$U = RI$$



$$R_K K_J Q_X = \frac{in_j}{n_s} \frac{f_j}{f_s}$$

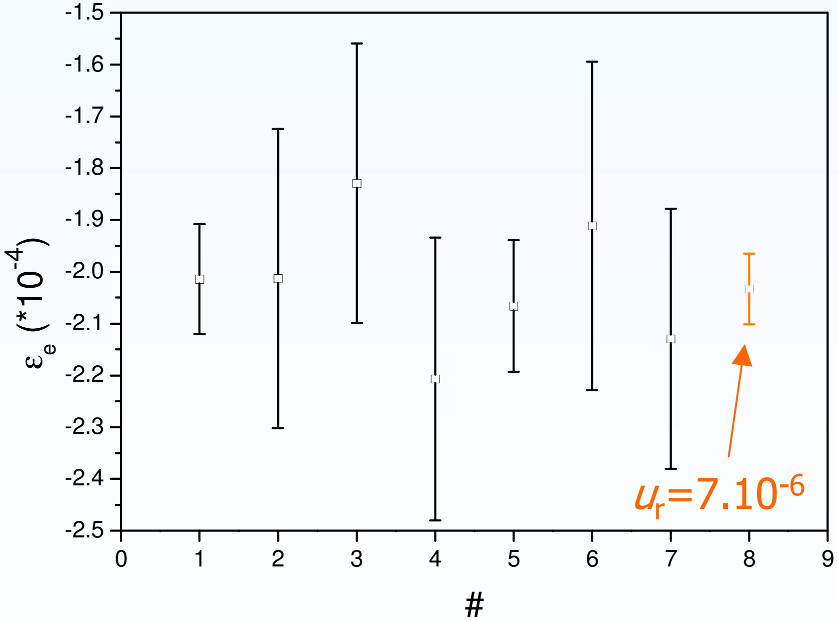
Experimental realisation at LNE



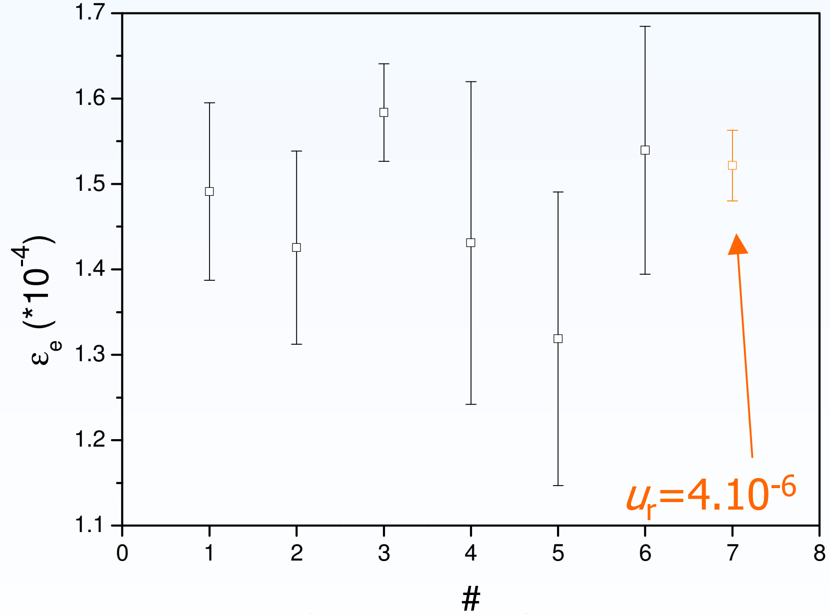
First results

Measurements were performed on long time by reversing voltage and current (modification of current was made by changing the triple point)

$$Q_X = e(1+\varepsilon_e) = \frac{N_2}{N_1}\frac{1}{f_{SET}R_{et}}\left(V_d + \frac{n_j f_j}{K_J}\right)$$



n_j=5, f_j=73 GHz, f_{SET}=23.55 MHz



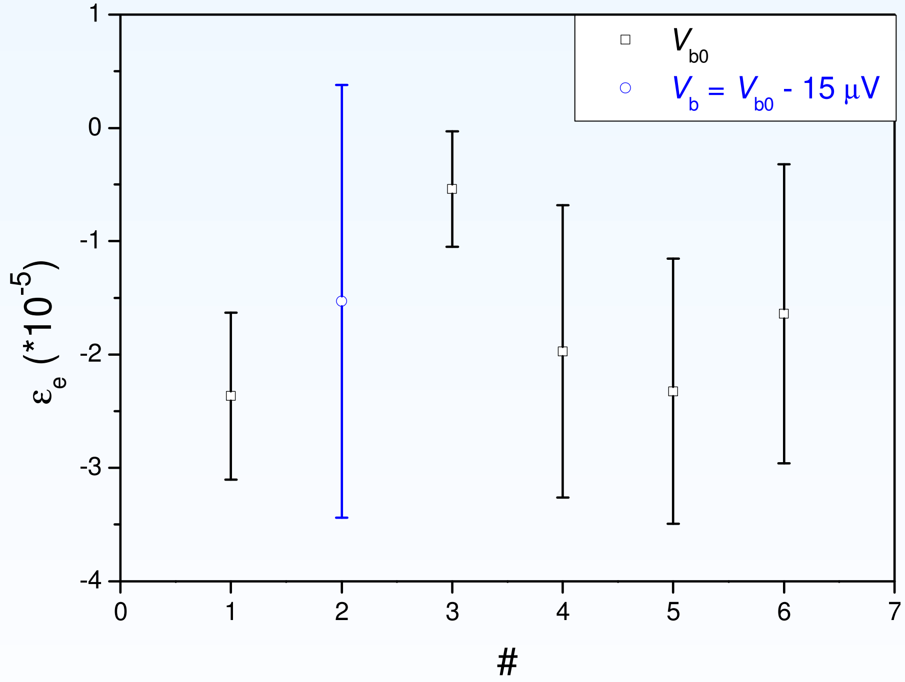
n_j=8, f_j=73 GHz, f_{SET}=37.69 MHz

⇒ there is, at the moment, an irreproducibility **BUT** feasibility of the measurement with a relative uncertainty of a few parts in 10^6 is demonstrated.

Properties of the R-pump

This set-up permits to determine the metrological properties of the R-pump

•Long term measurements made with different bias voltages give the flatness of the current steps.



n_j=8, f_j=73 GHz, f_{SET}=37.69 MHz

•Determination of the quantization level.

•Then this set-up can be used to make comparison between samples and to characterize their metrological properties.

Interests of the MTE

- MTE permits to calculate $R_K K_J Q_X$ then to measure:

$$\varepsilon_K+\varepsilon_J+\varepsilon_e=\varepsilon_m \pm u_r$$

ε_m: measured value
u_r: uncertainty of the measurement

⇒ If $0 \in [\varepsilon_m - u_r, \varepsilon_m + u_r]$, improvement of our confidence in the theoretical relations:

$$R_K = h/e^2,\ K_J = 2e/h,\ Q_X = e$$

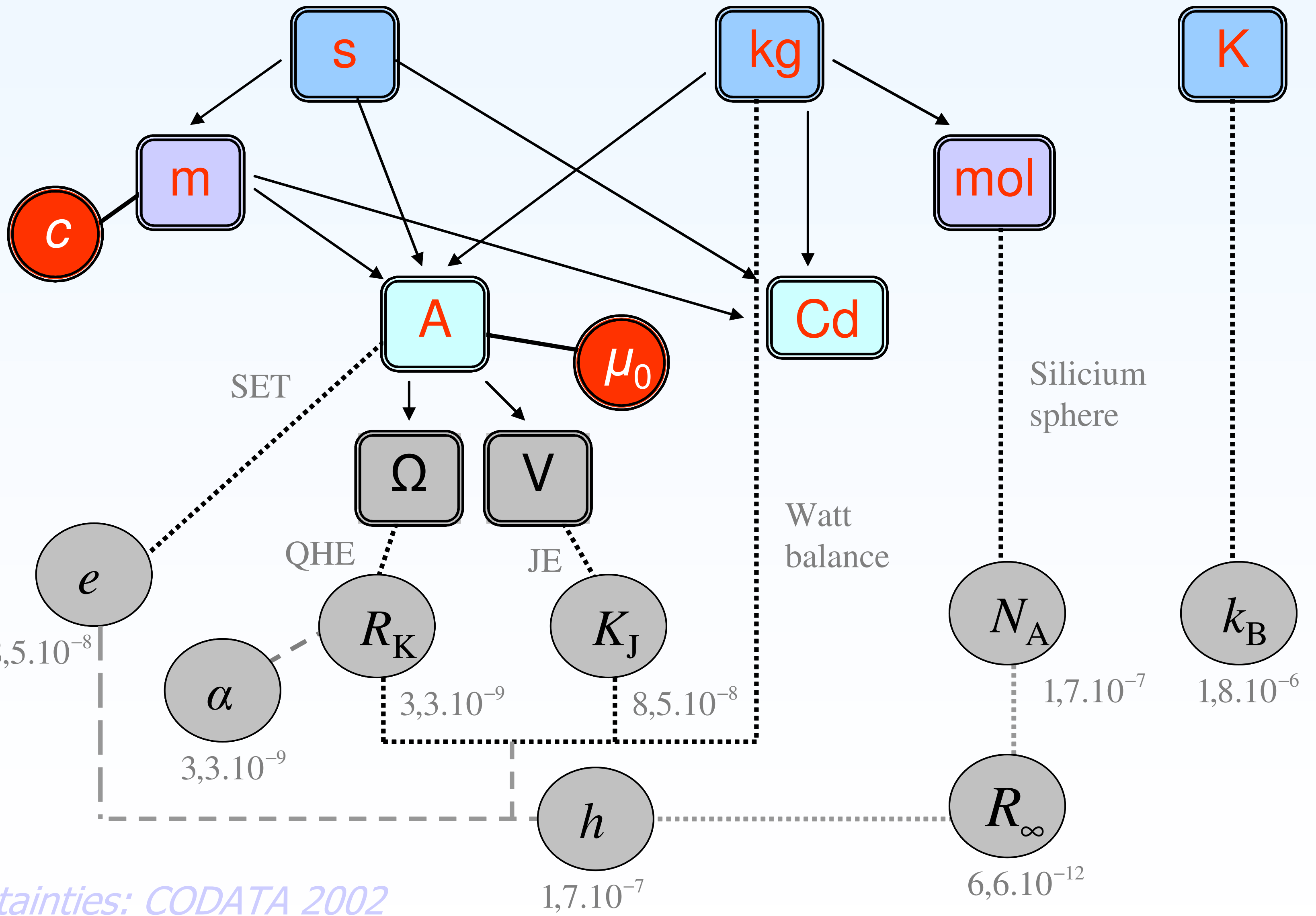
- Thompson Lampard capacitor gives a determination of R_K, then the watt balance gives a determination of K_J

⇒ MTE becomes a determination of Q_X

Système international d'unités (SI)

Base quantity	Unit	Definition
mass	*kilogram* ***(kg)***	The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram. (*3rd CGPM, 1901*)
electric current	*ampere* ***(A)***	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 m apart in vacuum, would produce between these conductors a force equal to 2 .10^{-7} newton per metre of length. (*9thCGPM, 1948*)
thermodynamic temperature	*kelvin* ***(K)***	The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water. (*10th CGPM, 1954*)
time	*second* ***(s)***	The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom. (*13th CGPM, 1967/68*)
amount of substance	*mole* ***(mol)***	1.The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12. 2.When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles. (*14th CGPM, 1971*)
luminous intensity	*candela* ***(cd)***	The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 1012 hertz and that has a radiant intensity in that direction of 1/683 watt per steradian. (*16th CGPM, 1979*)
length	*metre* ***(m)***	The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second. (*17th CGPM, 1983*)

Units and fundamental constants

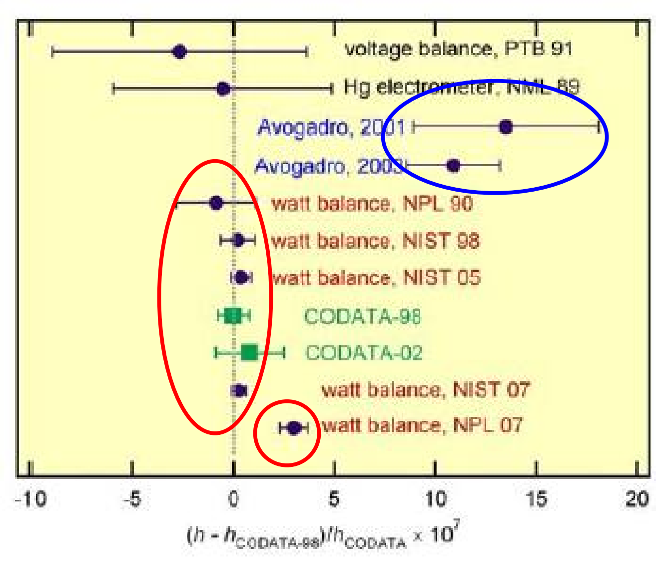


Uncertainties: CODATA 2002

Towards a new SI

- kilogram
  - Microscopic kilogram: *silicium sphere*
    - N_A is fixed
  - Electric kilogram: *watt balance*
    - $K_J^2 R_K$ is fixed

      -> Fixation of h **if** $\begin{cases} R_K = \frac{h}{e^2} \\ K_J = \frac{2e}{h} \end{cases}$



Source: A. Eichenberger, Houches 2007

- kelvin
  - k_B is fixed

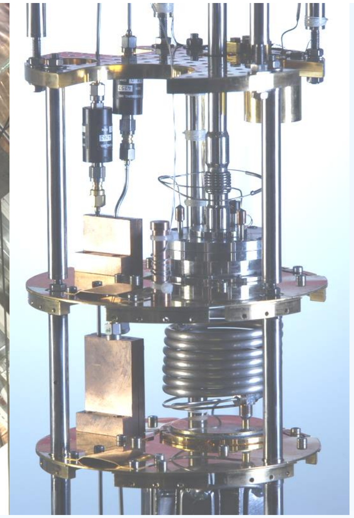
- ampere
  - Z_0 ($=\mu_0 c$) is fixed *=> Thompson Lampard*
  - e is fixed *=> Metrological triangle*

Outlook

- Obtaining of an uncertainty of 1 part in 10^6 is a first step important in the framework on a new definition of units and in characterization of R-pump

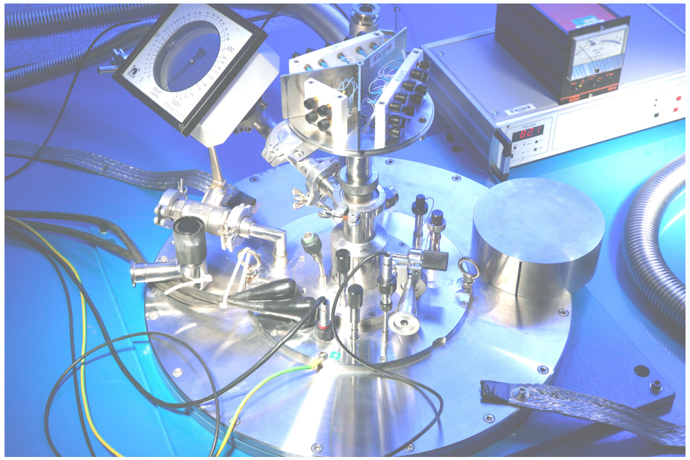
- Such a step permits to validate the measurement principle

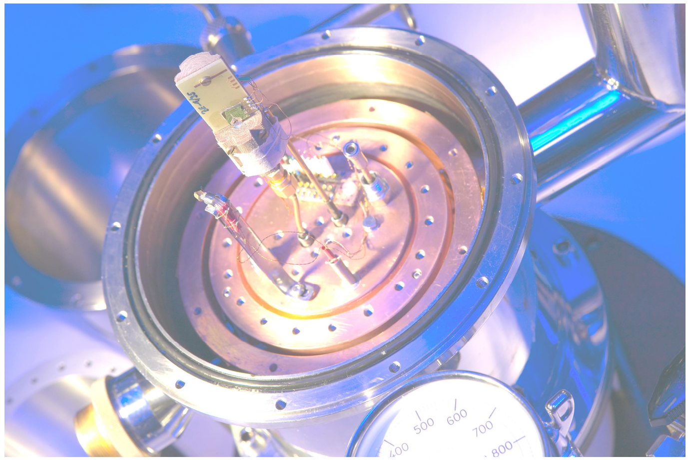
- This set-up could then be used to test other devices which generate more current



Thanks for your attention

and special thanks to the quantum metrology group at LNE

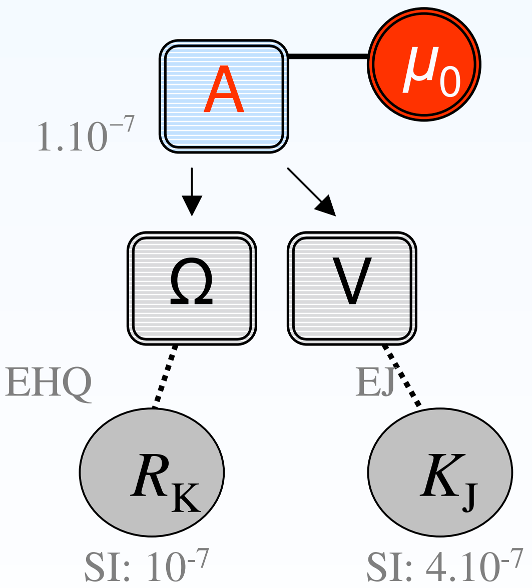




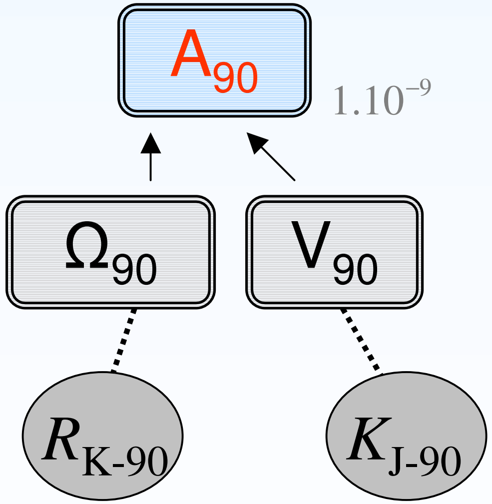
Electrical units : the "90" system

- CIPM recommendations (1988)

  set exact values for the Josephson and von Klitzing constants, and called for laboratories to base their standards on these values from 1 January 1990. These values are noted $K_{J\text{-}90}$ and $R_{K\text{-}90}$.



$$\begin{cases} V_{90} = \dfrac{K_{J-90}}{K_J} V_{SI} \\ \Omega_{90} = \dfrac{R_K}{R_{K-90}} \Omega_{SI} \end{cases}$$



Reproducibility:

-> QHE ohm: 10^{-10}

-> JE volt: 10^{-9}

$K_{J\text{-}90}$ = 483 597.9 GHz/V

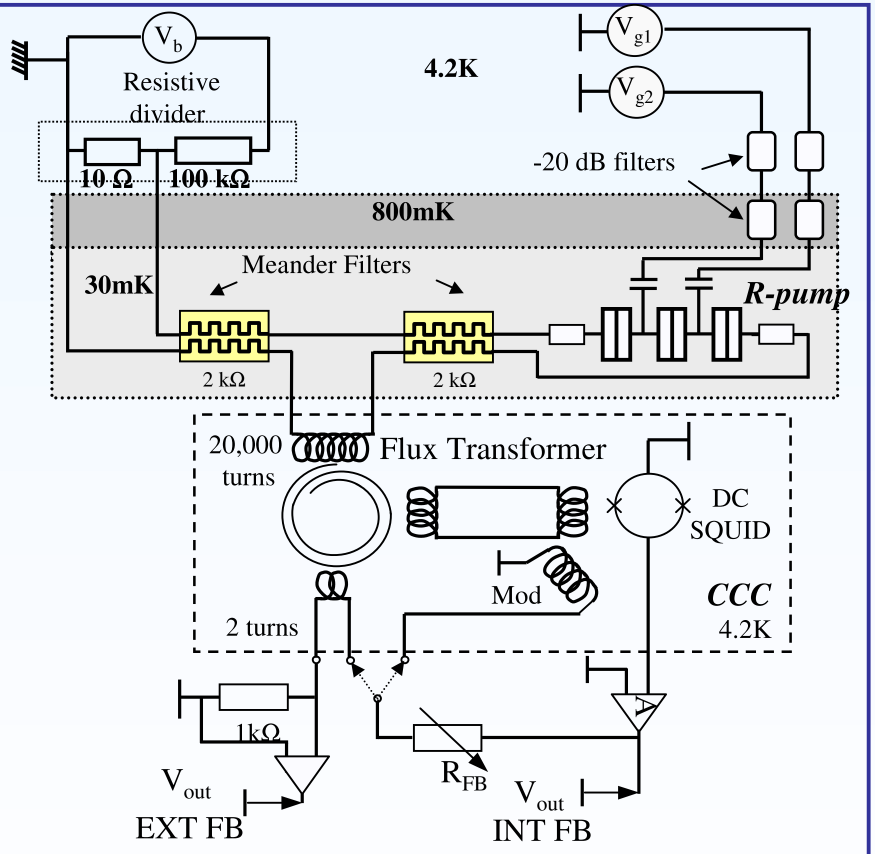
$R_{K\text{-}90}$ = 25 812.807 Ω

CODATA 2002:

$K_J = K_{J\text{-}90}(1 - 4.3.10^{-8} \pm 8.5.10^{-8})$

$R_K = R_{K\text{-}90}(1 + 1.74.10^{-8} \pm 0.33.10^{-8})$

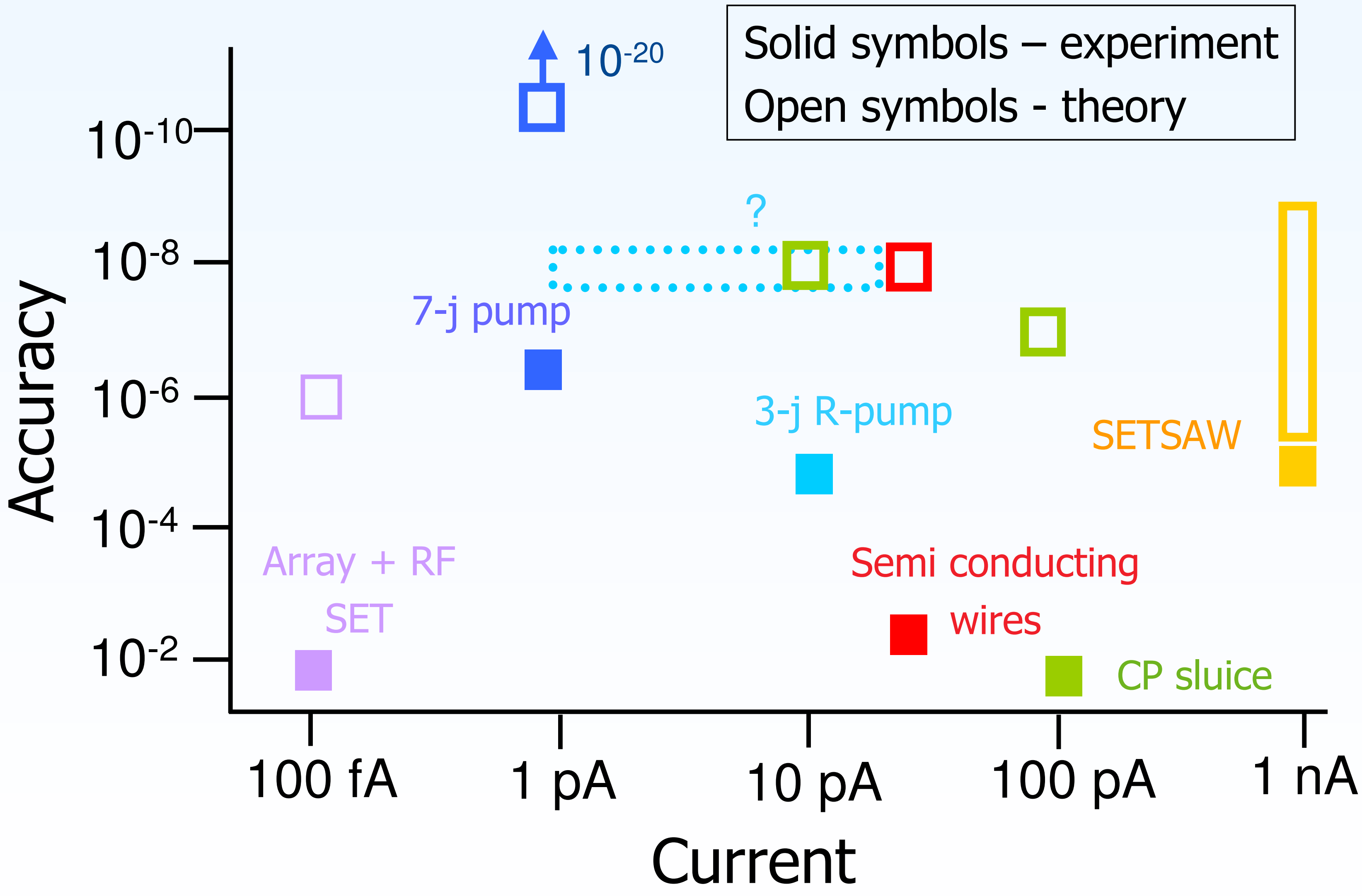
Electrical schematic view of the set-up



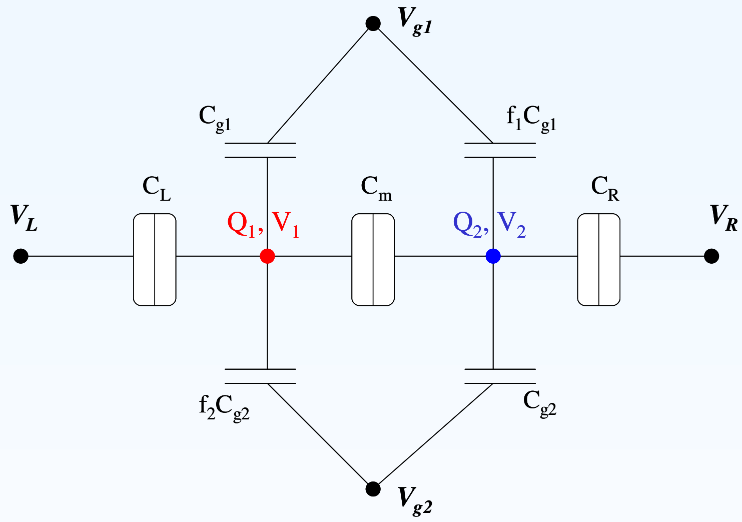
Schematic view of the set-up wiring with meanders filters and resistive divider

Meander filters supplied by CEA (Saclay)

Others devices



Characterization of a pump: determination of the parameters



$$E(n_1,n_2)=\frac{e}{C_1C_2-C_m^2}\Big[\frac{e}{2}\left(C_2n_1^2+C_1n_2^2\right)+eC_mn_1n_2$$
$$-V_{g1}C_{g1}\left(\left(C_2+f_1C_m\right)n_1+\left(C_m+f_1C_1\right)n_2\right)$$
$$-V_{g2}C_{g2}\left(\left(C_m+f_2C_2\right)n_1+\left(C_1+f_2C_m\right)n_2\right)\Big]$$
$$+\text{termes indépendants de }(n_1,n_2)$$

$$\begin{cases} C_1 = C_L + C_m + C_{g1} + f_2C_{g2} \\ C_2 = C_R + C_m + f_1C_{g1} + C_{g2} \end{cases}$$

- Determination of the boundaries of the domain where *(0,0)* is stable

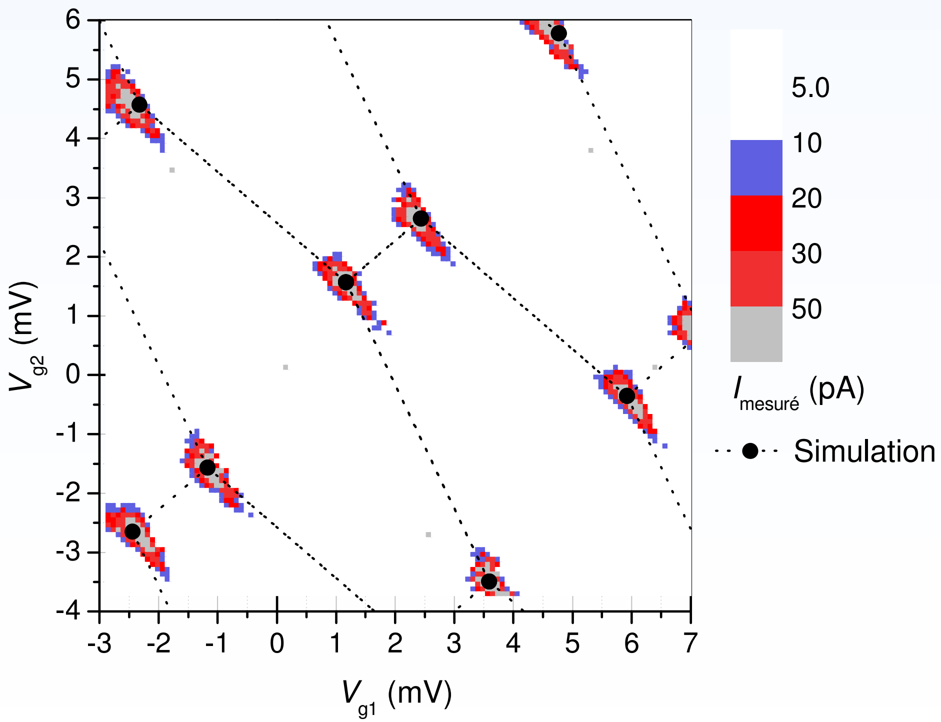
-> 6 segments delimit this domain, the positions of the 6 triple points are function of the capacitor parameters of the pump.

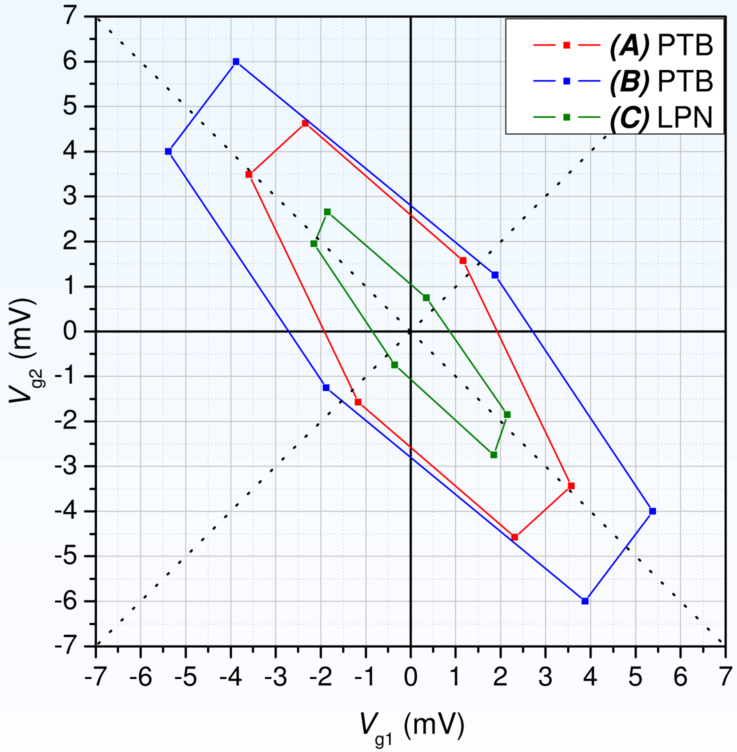
- Measurements of the stability diagram **and** of the threshold voltage permit to determine the 7 parameters unknown:

C_L, C_m, C_R, C_{g1}, C_{g2}, f_1, f_2

Characterization of a pump: determination of the parameters

Pump	C_{g1} (aF)	C_{g2} (aF)	f_1	f_2	C_L (aF)	C_m (aF)	C_R (aF)	T_C (K)
(A)	35	30	0.30	0.25	75	85	60	7
(B)	25	25	0.4	0.3	55	120	75	5.5
(C)	80	60	0.35	0.60	95	215	135	3





Pump	C_L/C_m (%)	C_R/C_m (%)	C_L/C_R (%)
(A)	90	70	125
(B)	45	60	75
(C)	45	60	70