Practical Quantum Realization of the Ampere

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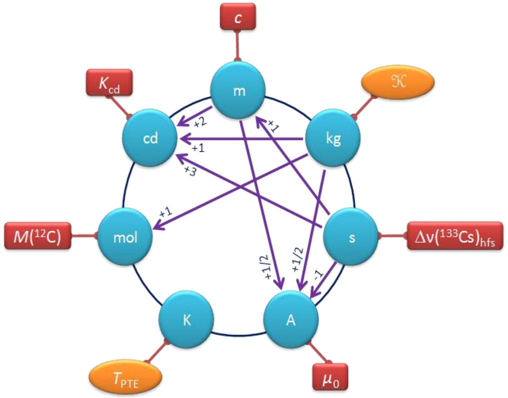
uantΩ Group

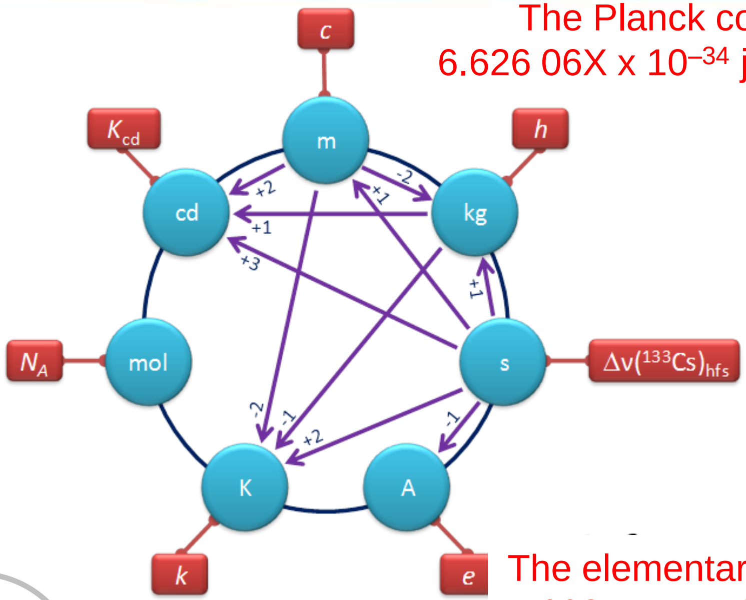
LNE

Le progrès, une passion à partager

CCEM 2017, BIPM, 24/03/2017

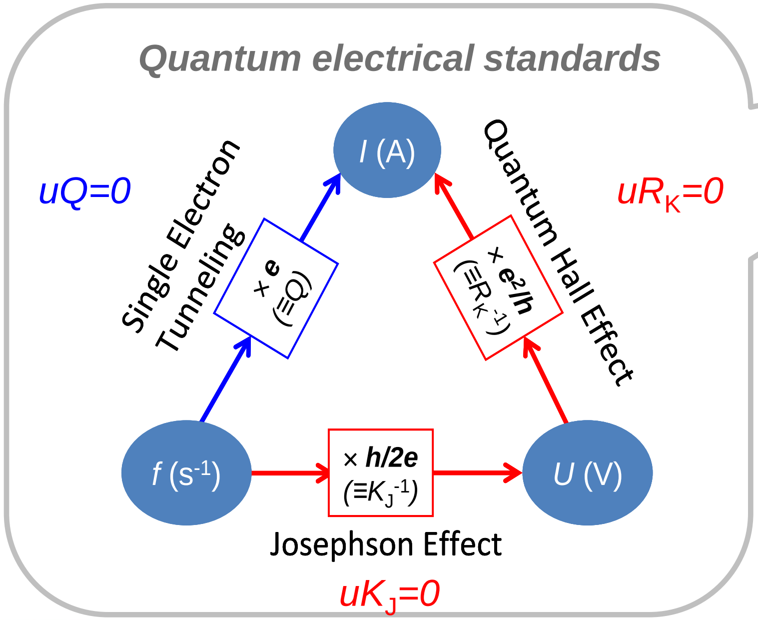
A new *SI* based on defining constants (h,e,c,k_B,N_A) in 2018





The Planck constant *h* is exactly
6.626 06X x 10^{-34} joule second ($kg.m^2.s^{-1}$)

The elementary charge *e* is exactly
1.602 17X x 10^{-19} coulomb (A.s)

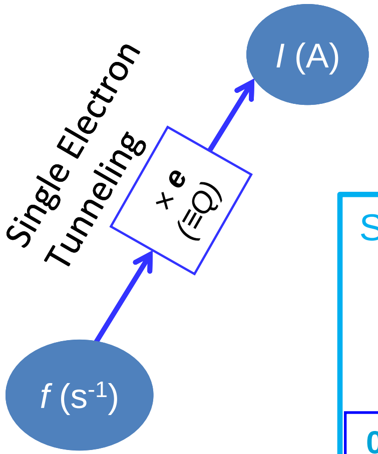


Quantum electrical standards

Need *a mise en pratique* with a
10^{-8} uncertainty

Resolution of the 23/24/25 rd CGPM
…prepare a *mise en pratique for each new definition…*

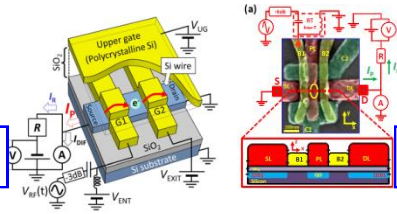
Two ways to realize the ampere from *e* and the frequency *f*



Direct realization of the current from $Q \equiv e$

Quantum devices handling electron one by one at a driven frequency f_P : $I = n_Q Q f_P$
Mesoscopic quantum phenomenon (charge quantization)

Silicium wire NPL National Physical Laboratory

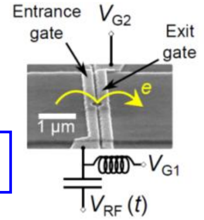


0.9 ppm

0.27 ppm

Yamahata et al. APL 109, 013101 (2016)
R. Zhao et al, ArXiv:1703.04795v1

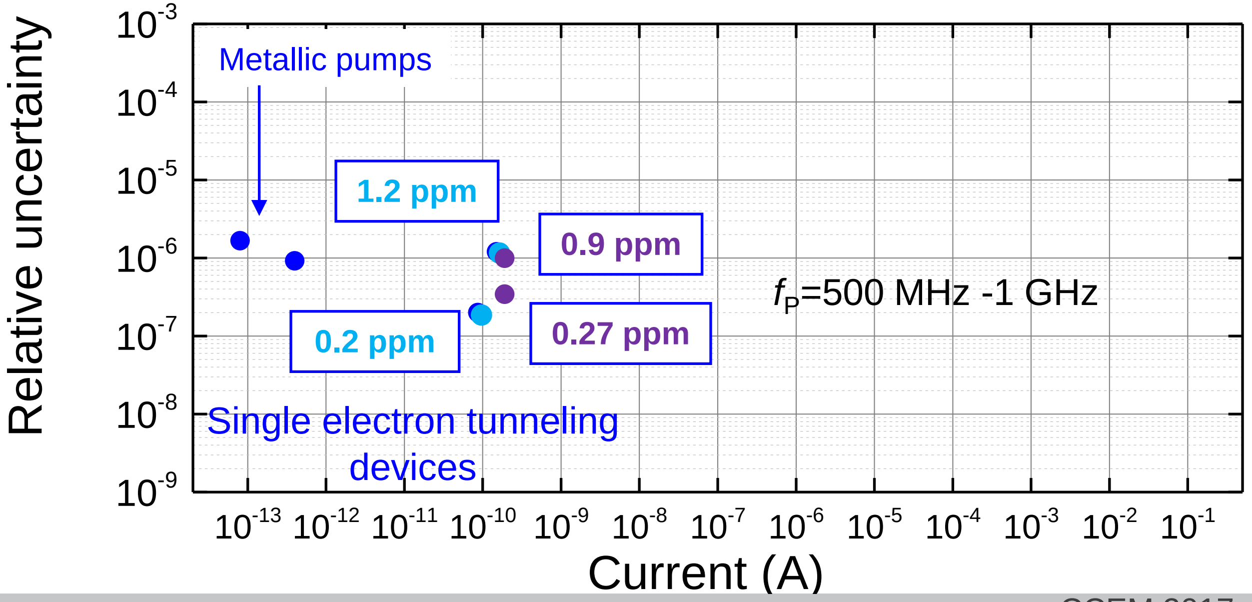
GaAs wire NPL National Physical Laboratory PTB



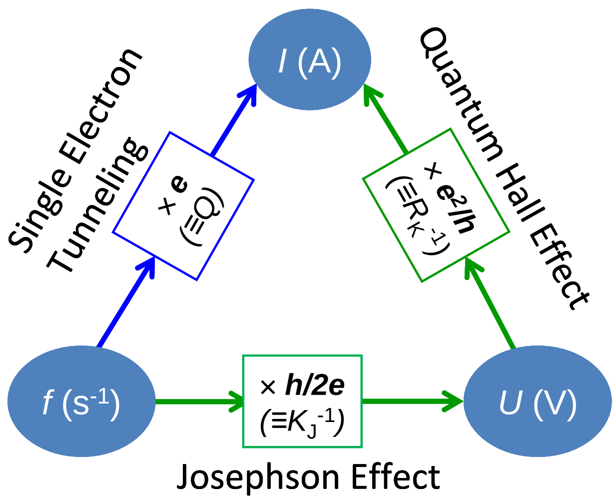
1.2 ppm

0.2 ppm

S. P. Giblin et al. Nature Com. 3, 930 (2012)
F. Stein et al., APL 107, 103501 (2015)



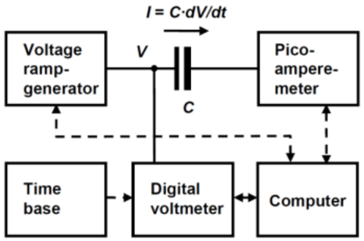
Two ways to realize the ampere from e and the frequence *f*



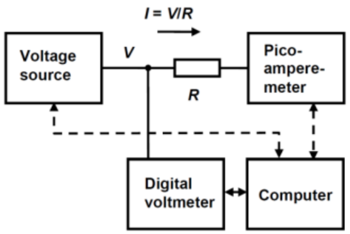
Indirect realization of the current from $2(R_K K_J)^{-1} \equiv e$

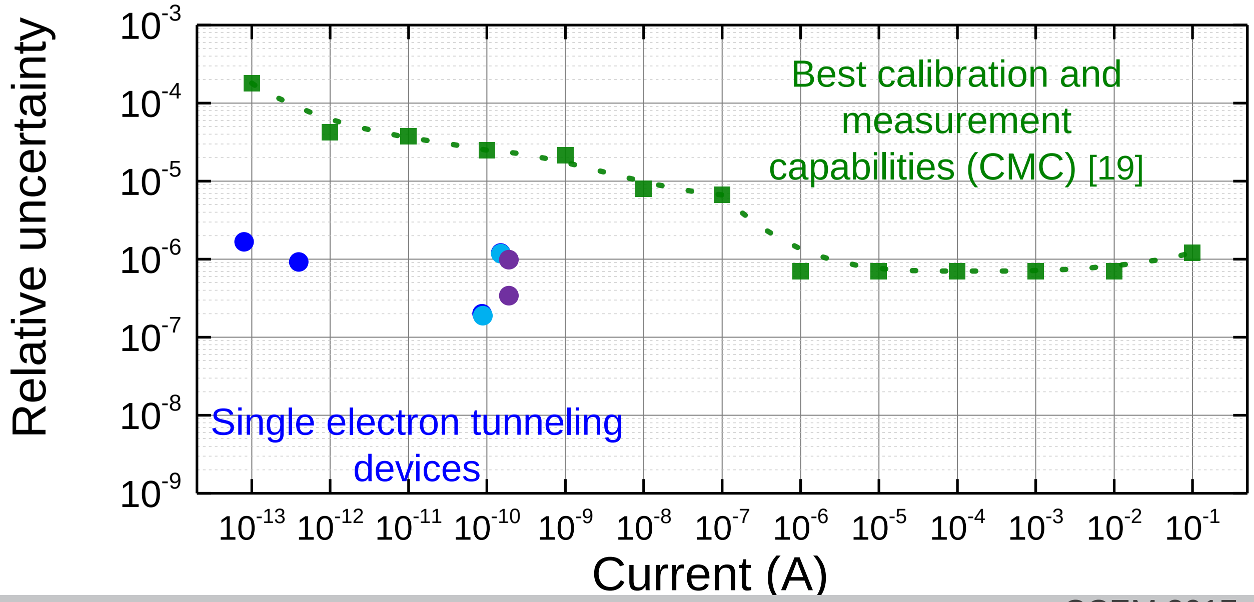
Applying Ohm's law to secondary voltage and resistance (or capacitance) standards calibrated from the JE and the QHE (average current)

Limitation: calibration of secondary standards **an absence of true stable and ultra-accurate current standard**

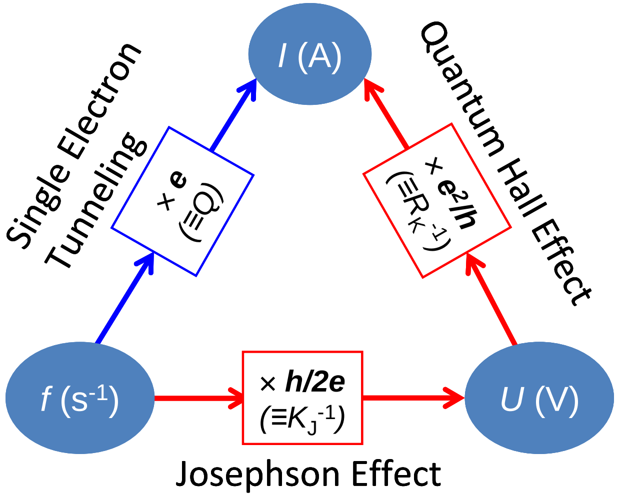


CMC: *u* >10^{-6}





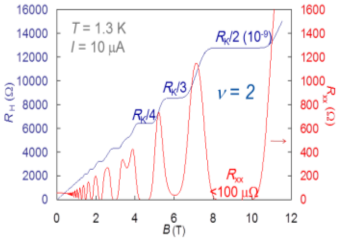
Two ways to realize the ampere from *e* and the frequence *f*

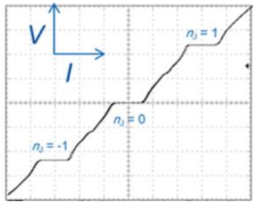


Direct realization of the current from $2(R_K K_J)^{-1} \equiv e$

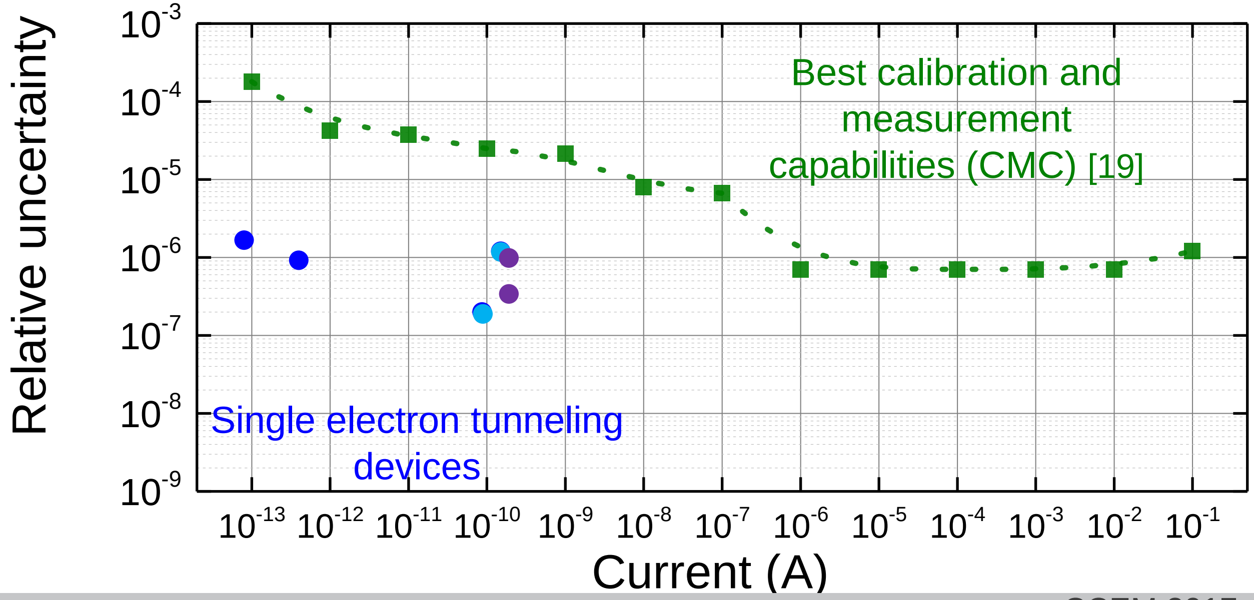
Applying the Ohm's law directly to the quantum Hall and Josephson standards to benefit from:

- high reproducibility (JE: u=10^{-17}; QHE u=3.10^{-11})
- their universality
  - JE: u=10^{-16}
  - QHE :Si-Mosfet/Graphene/GaAs (u=8.10^{-11})
- existence of quick quantization criteria
  - JE: plateau flatness/contacts
  - QHE: R_{xx} value/contacts

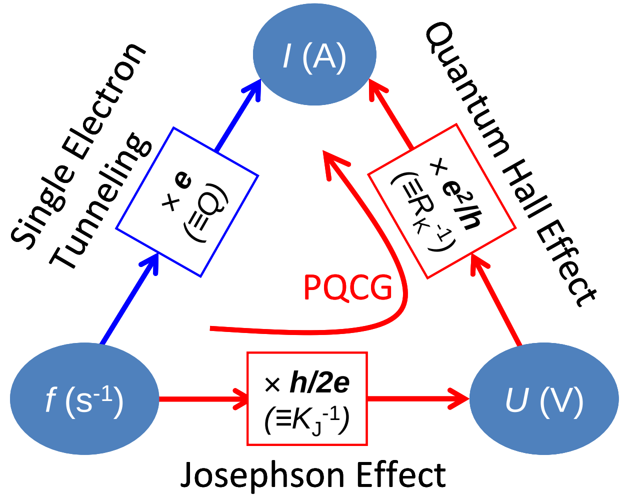




How realizing such a true quantum current standard?



Two ways to realize the ampere from e and the frequence f



I (A)

f (s^{-1})

U (V)

Single Electron Tunneling

× **e** (≡Q)

Quantum Hall Effect

× **e²/h** (≡R_K^{-1})

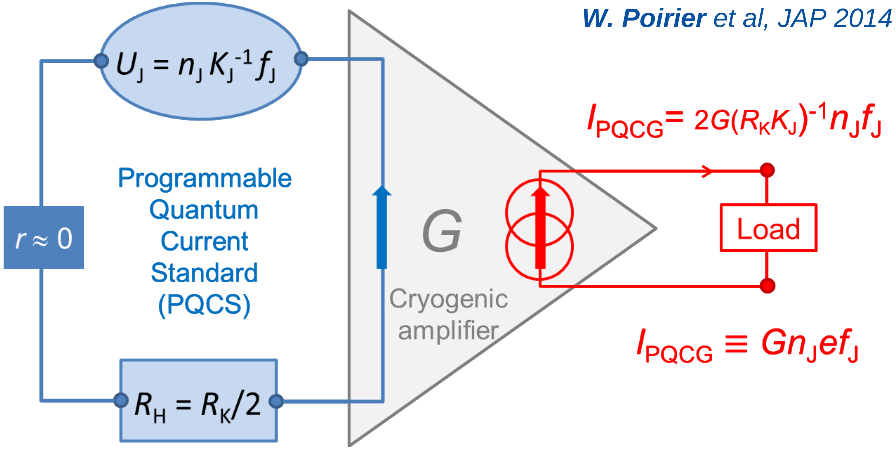
PQCG

× **h/2e** (≡K_J^{-1})

Josephson Effect

A programmable quantum current generator (PQCG)

***W. Poirier** et al, JAP 2014*



$U_J = n_J K_J^{-1} f_J$

$r \approx 0$

Programmable Quantum Current Standard (PQCS)

$R_H = R_K/2$

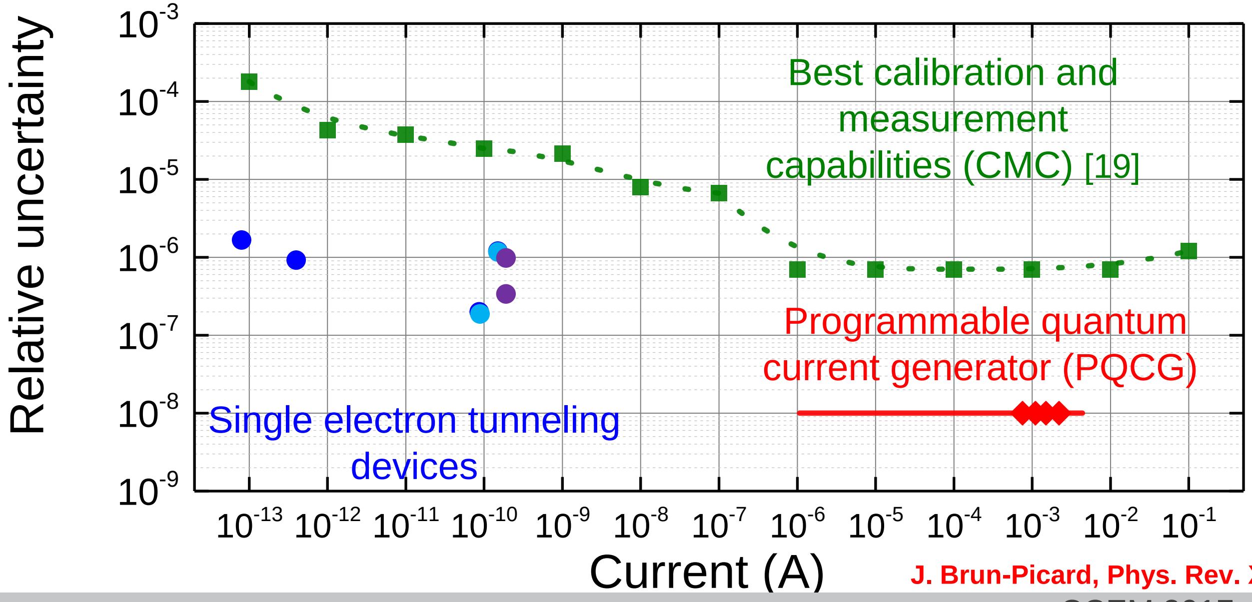
G

Cryogenic amplifier

Load

$I_{PQCG} = 2G(R_K K_J)^{-1} n_J f_J$

$I_{PQCG} \equiv G n_J e f_J$



Best calibration and measurement capabilities (CMC) [19]

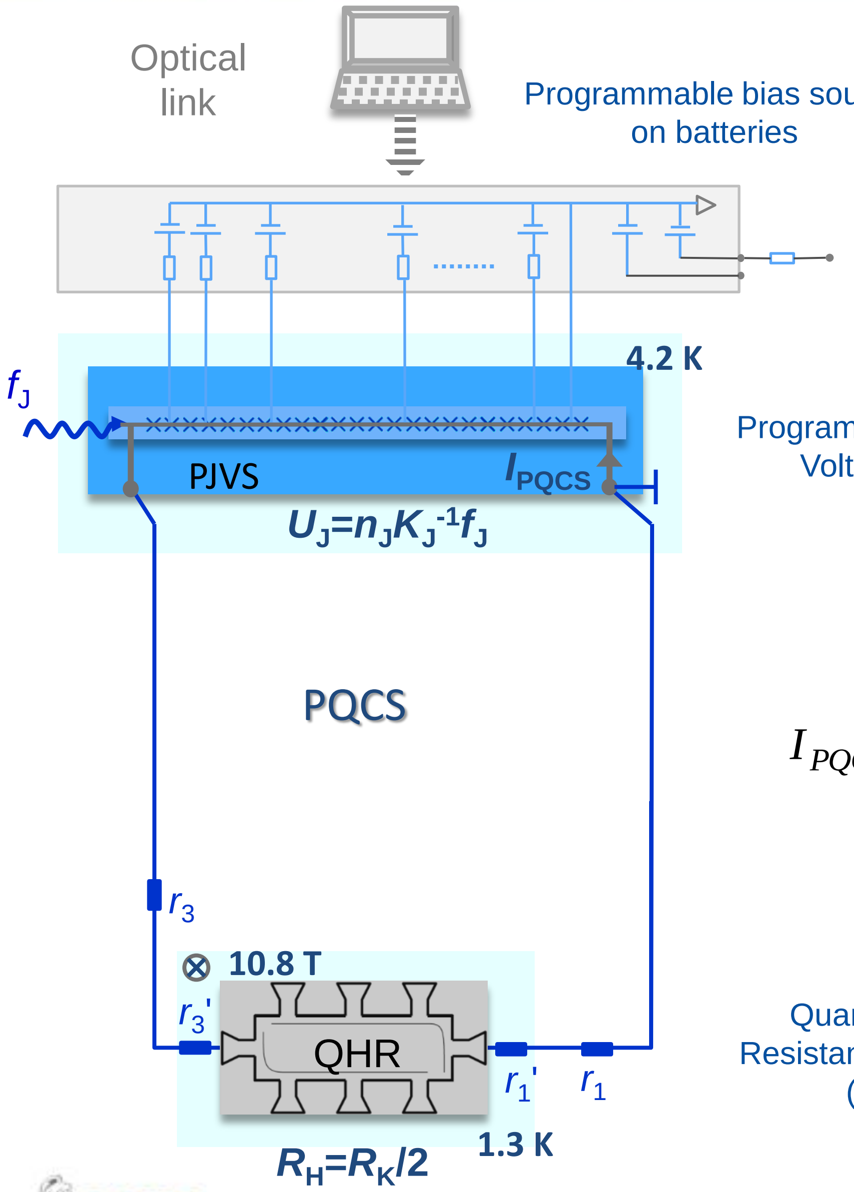
Programmable quantum current generator (PQCG)

Single electron tunneling devices

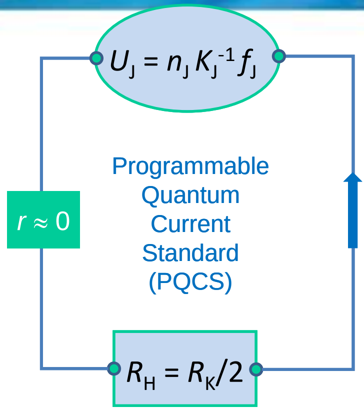
u =1.10^{-8}

J. Brun-Picard, Phys. Rev. X 6, 041051 (2016)

Implementation of the PQCG



Programmable bias source on batteries

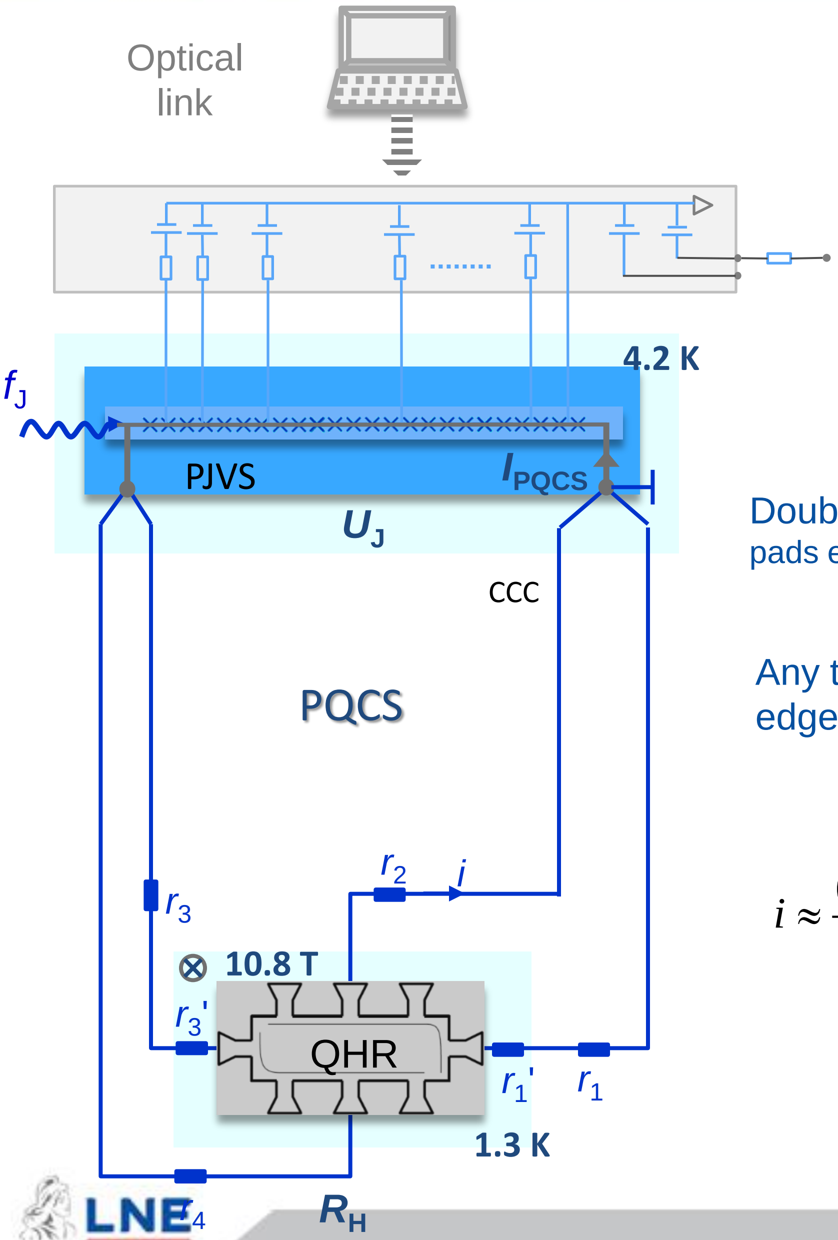


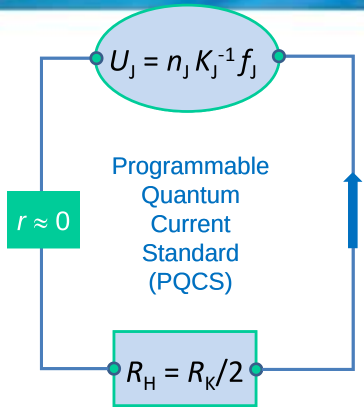
Programmable Josephson Voltage Standard (PJVS)

$$I_{PQCS} \approx \frac{U_J}{R_H}\left(1-\underbrace{\frac{(r_1+r_1'+r_3+r_3')}{R_H}}_{\sim 6.10^{-4}}\right)$$

Quantum Hall Resistance Standard (QHR)

Implementation of the PQCG



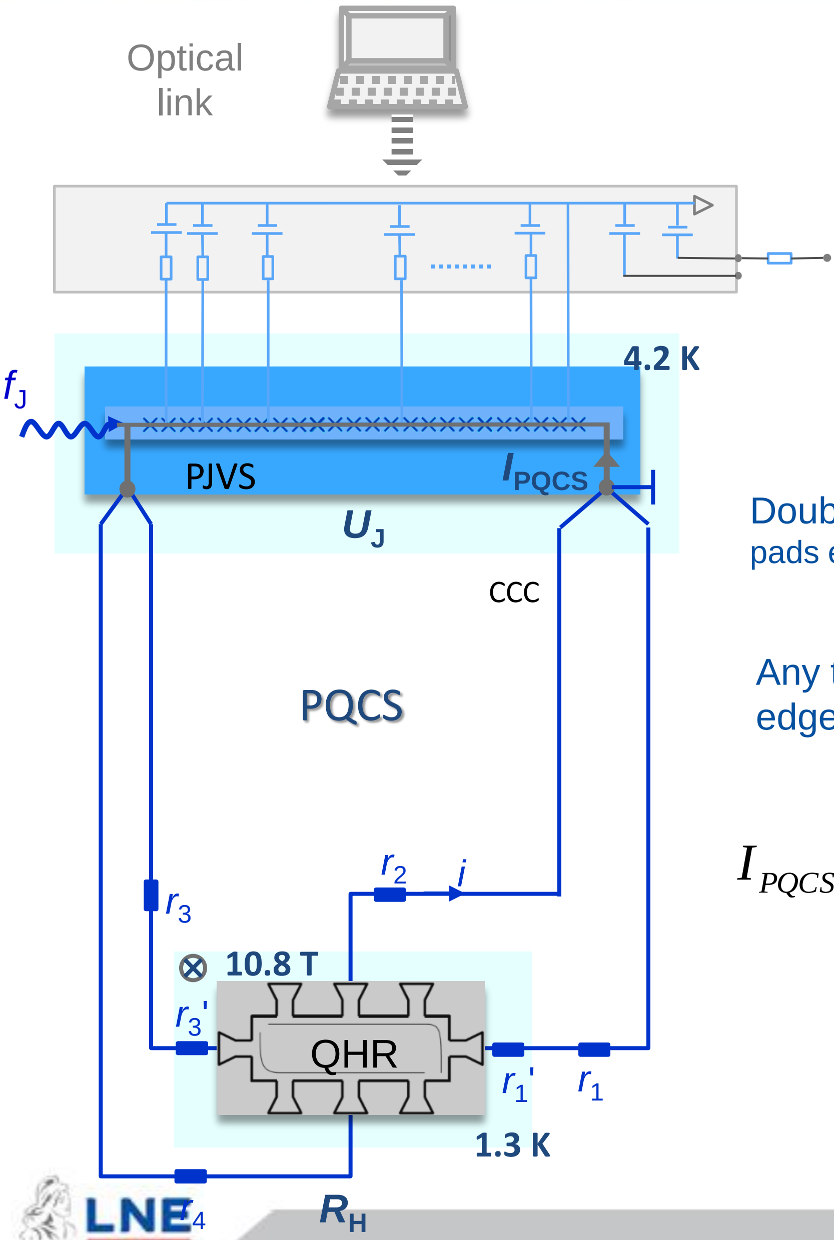


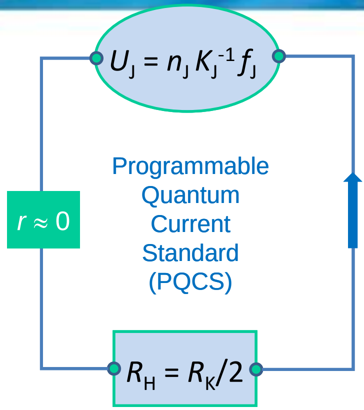
Double connection (two wires are connected to superconducting pads ensuring equipotentiality) F. Delahaye, Metrologia (1993)

Any two-wire resistance is R_H and V_{xx}=0 along an equipotential edge, chirality of edge-states (Landauer-Buttiker)

$$i \approx \frac{(r_1 + r_1')}{R_H} I_{PQCS} \Rightarrow \delta V_H \approx i \times r_2 = \frac{(r_1 + r_1')r_2}{R_H} I_{PQCS}$$

Implementation of the PQCG





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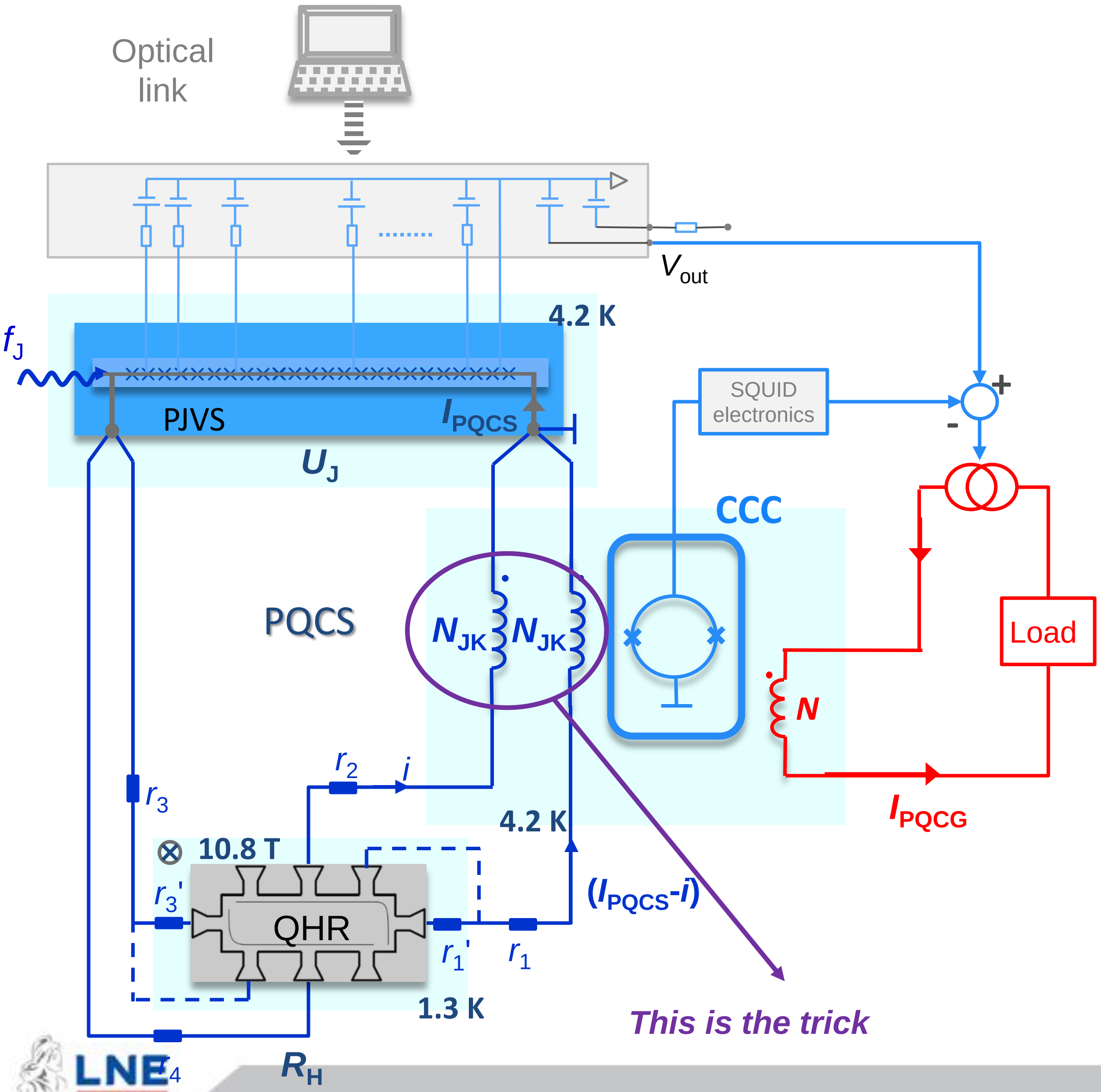
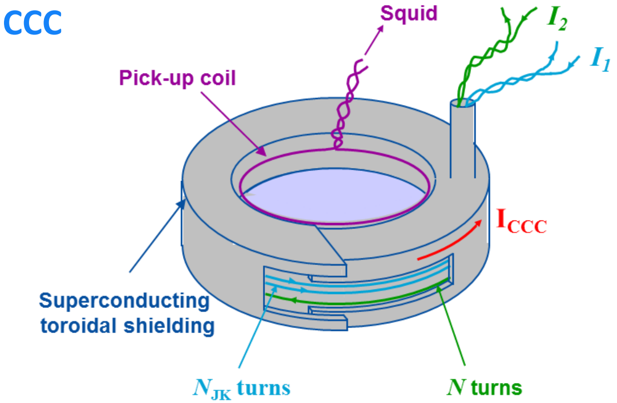
Any two-wire resistance is R_H and V_{xx}=0 along an equipotential edge, chirality of edge-states (Landauer-Buttiker)

$$I_{PQCS} \approx \frac{U_J}{R_H}\left(1-\underbrace{\frac{(r_1+r_1')r_2+(r_3+r_3')r_4}{R_H^{\;2}}}_{\alpha \sim 2.10^{-7} \qquad u\alpha \sim 2.5\text{x}10^{-9}}\right)$$

Implementation of the PQCG



This is the trick

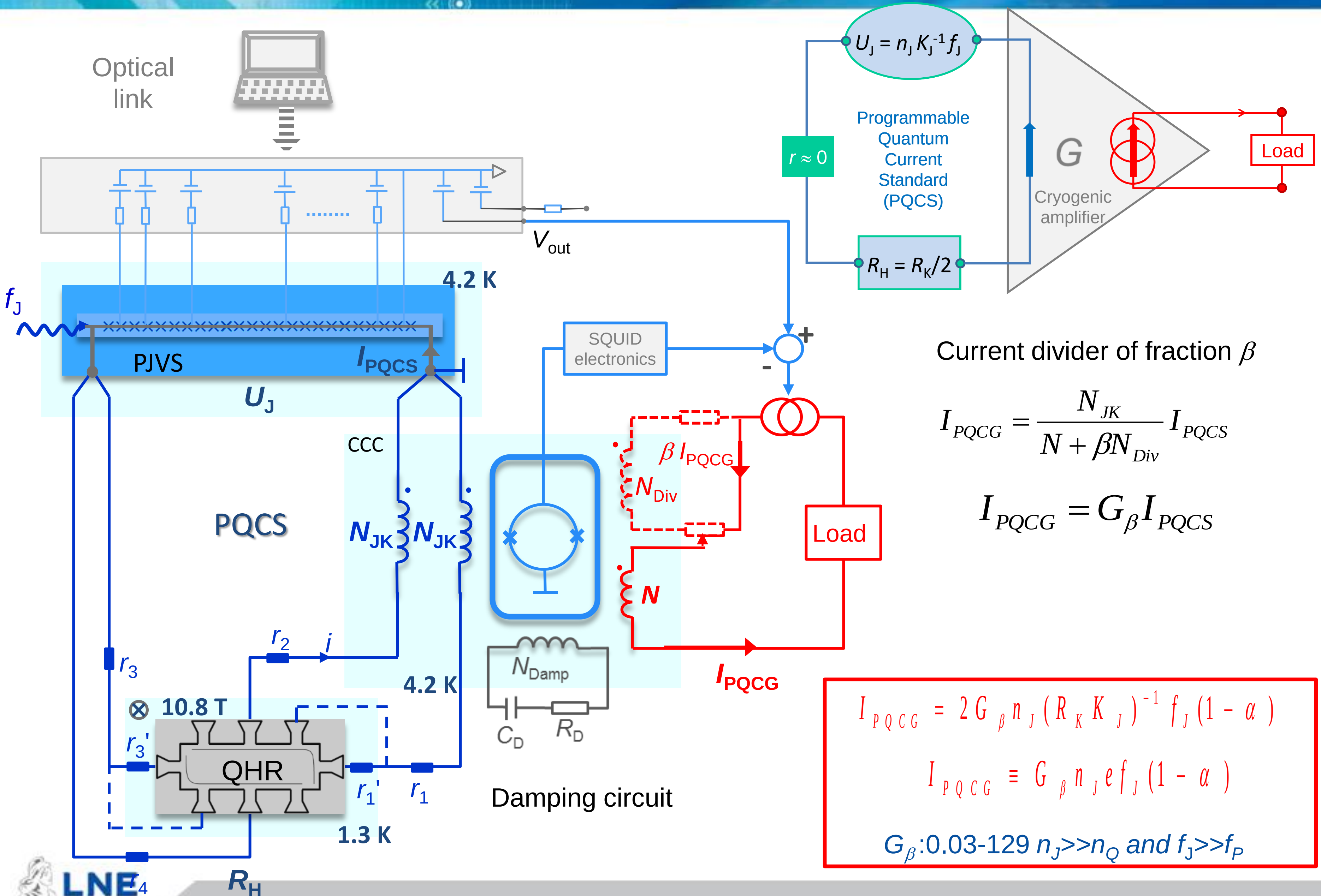


The sum of the current in the two connecting wires is amplified with a CCC of accurate gain (10^{-11})

$$N_{JK}(I_{PQCS}-i)+N_{JK}i=NI_{PQCG}$$

$$I_{PQCG}=\frac{N_{JK}}{N}I_{PQCS}=GI_{PQCS}$$

Implementation of the PQCG



Current divider of fraction β

$$I_{PQCG} = \frac{N_{JK}}{N + \beta N_{Div}} I_{PQCS}$$

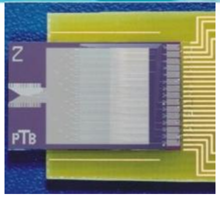
$$I_{PQCG} = G_\beta I_{PQCS}$$

$$I_{PQCG} = 2 G_\beta n_J (R_K K_J)^{-1} f_J (1 - \alpha)$$

$$I_{PQCG} \equiv G_\beta n_J e f_J (1 - \alpha)$$

G_β:0.03-129 $n_J >> n_Q$ and $f_J >> f_P$

Implementation of the PQCG: equipment

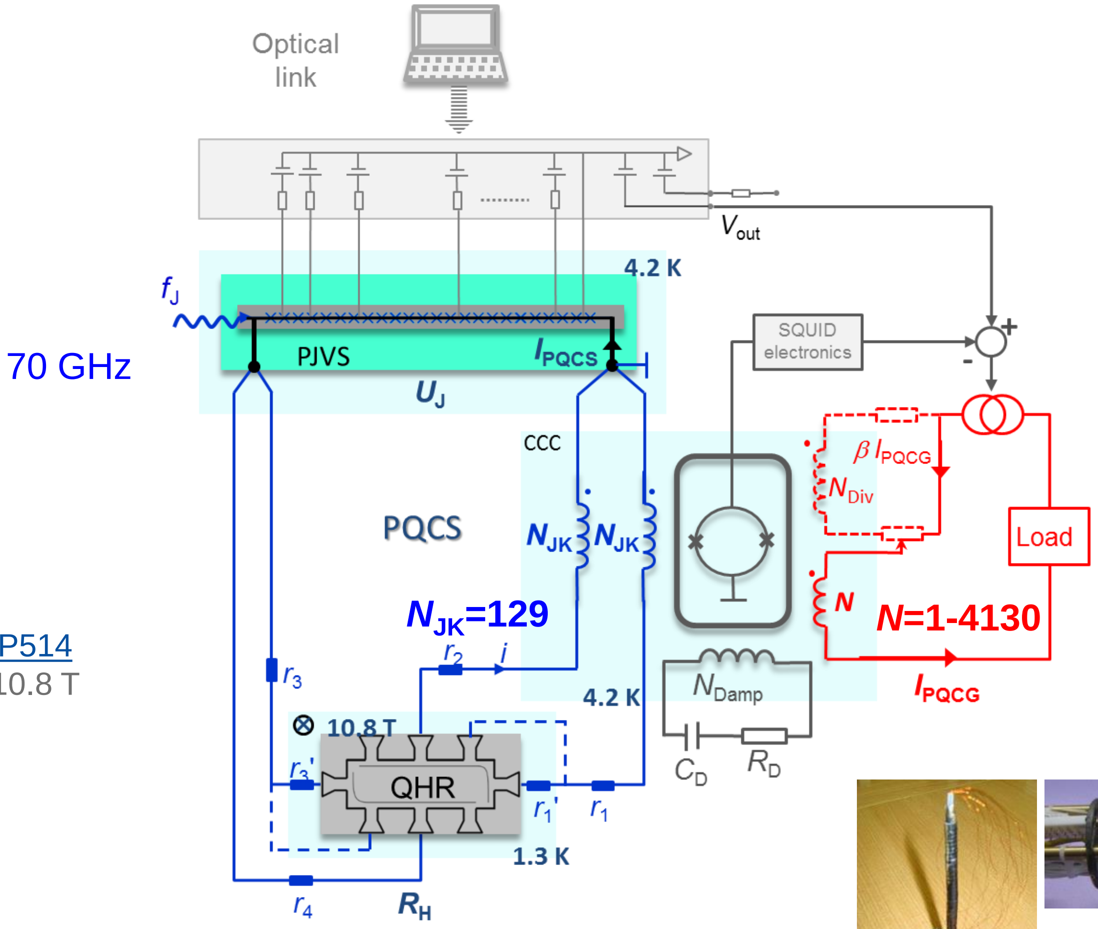


PTB SINIS arrays

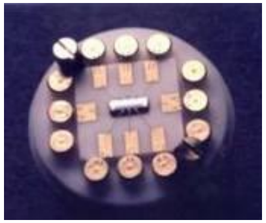
n_J = 7168 – 8192 jj,

f = 70 GHz,

14 segments



Current source of the QHR bridge

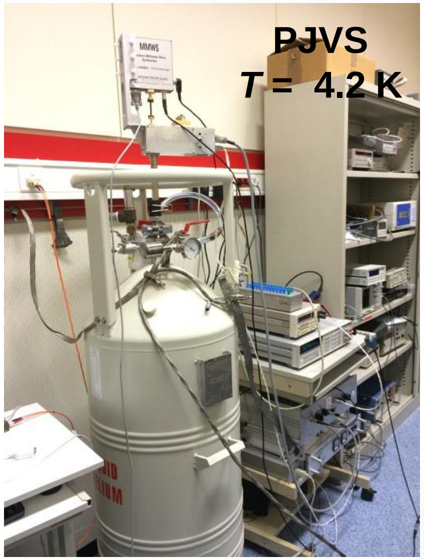


LEP514

B=10.8 T

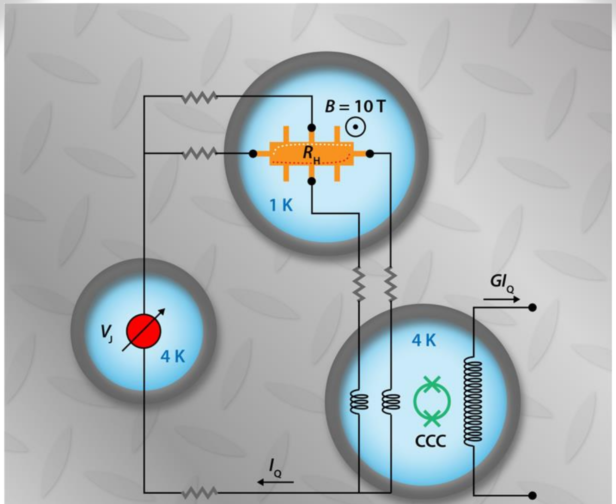
S=80 pA.turn/Hz$^{1/2}$

Three cryogenic setups

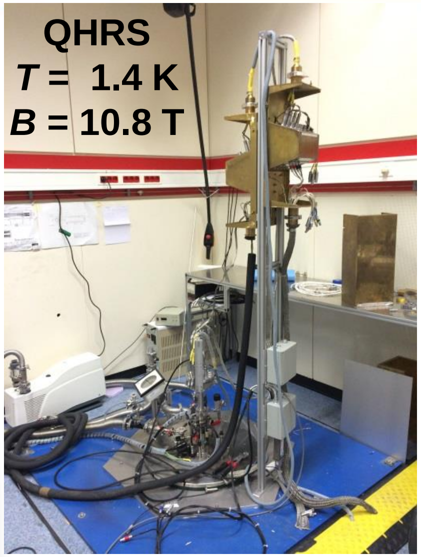


PJVS
T = 4.2 K

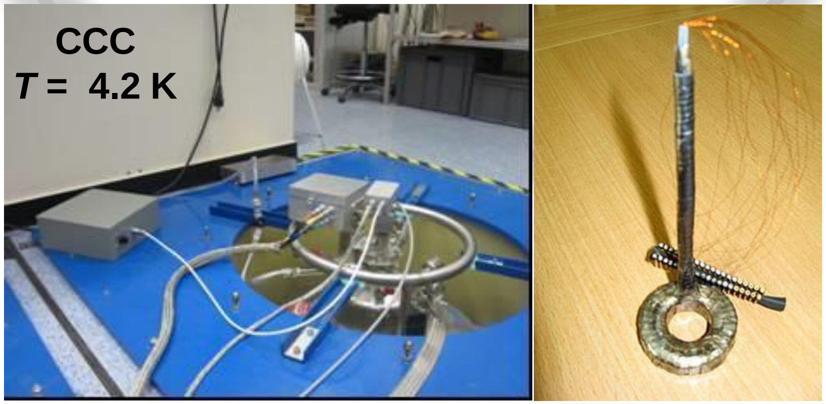
Usual devices available in Lab



M. W. Keller and Joe Aumentado, «A New ERA for the Ampere», Physics 9, 144 (2016)

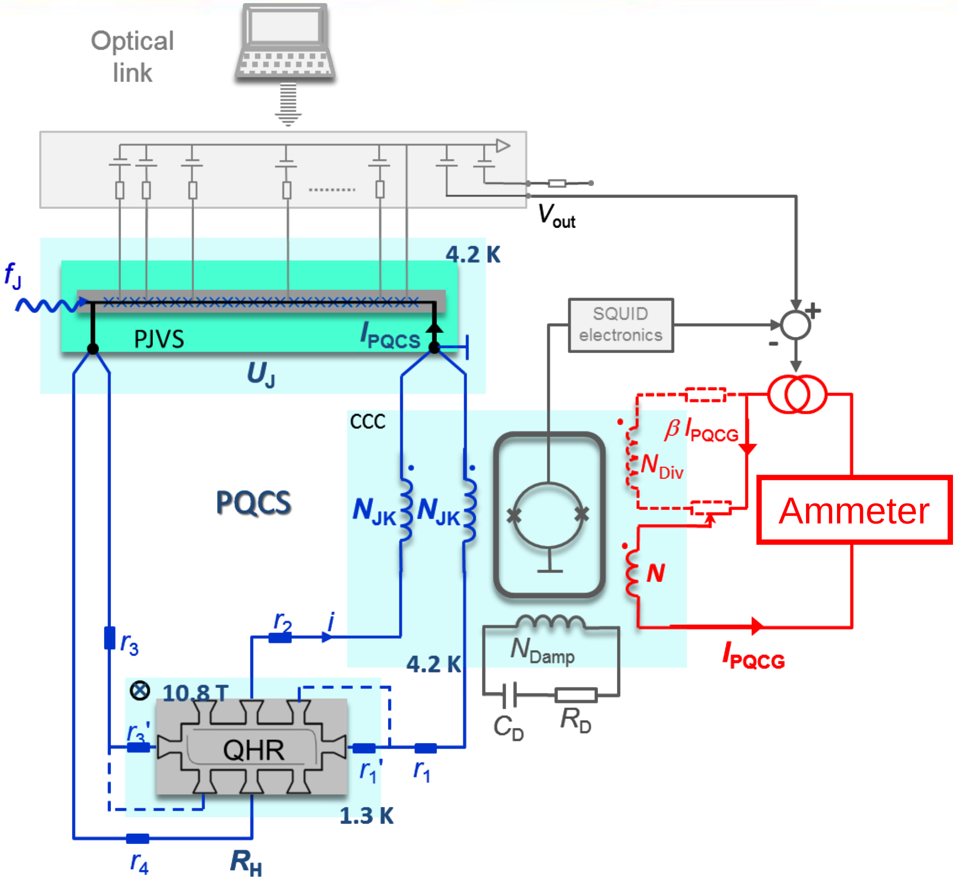


QHRS
T = 1.4 K
B = 10.8 T

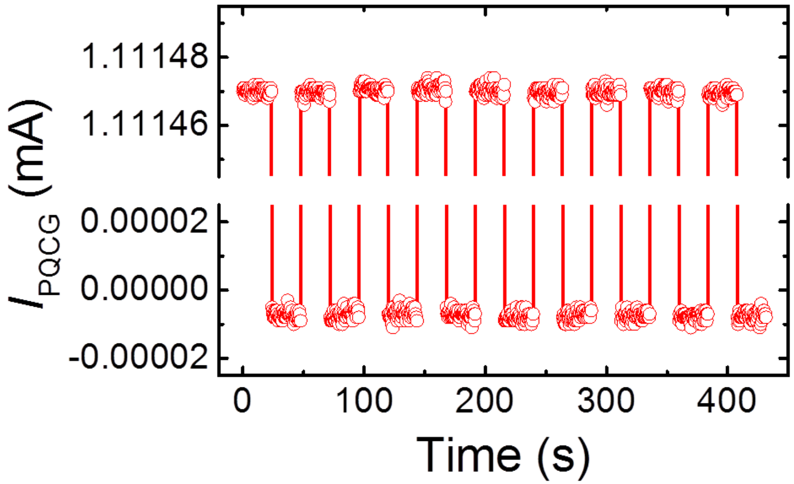


CCC
T = 4.2 K

Implementation of the PQCG: equipment

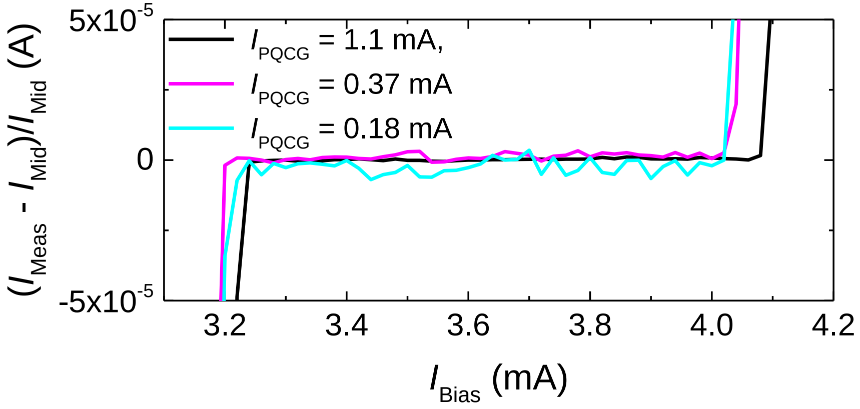


n_J=3073; N_{JK}=129; N=4: I_{PQCS}=34 µA

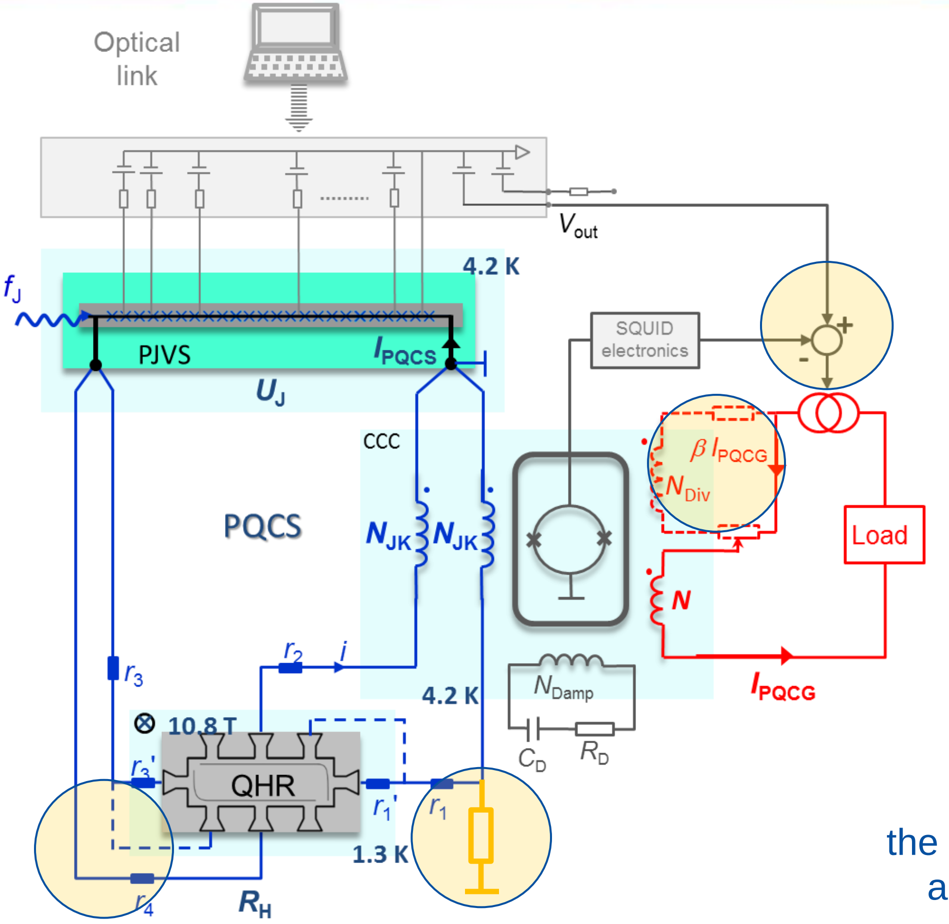


Stability and low noise

Current steps



PQCG: uncertainties



$$I_{PQCG} = 2G_\beta n_J \left(R_K K_J\right)^{-1} f_J (1-\alpha)$$

- **Type B relative Uncertainty**

Current Leakage
$u \sim (r_1+r_1')/R_L \sim 4.10^{-12}$

Feedback electronics
$u \sim 2.5\times10^{-10}$

Double connection
$u_\alpha \sim 2.5\times10^{-9}$

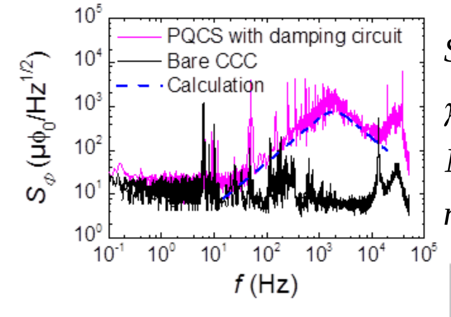
Current divider calibration

$u_\beta \sim 0.5\times10^{-9}(N_{Div}/N)$
(from 0 to 8×10^{-9})

$$\boxed{u_B(I_{PQCG}) < 10^{-8}}$$

- **Type A relative Uncertainty**

the Johnson-Nyquist noise of the QHR, the SQUID noise and some extra external noise (ex: damping circuit)



$$S_\phi \approx 20\,\mu\phi_0 / Hz^{1/2}$$

$$\gamma_{CCC} = 8\,\mu A.turn/\phi_0$$

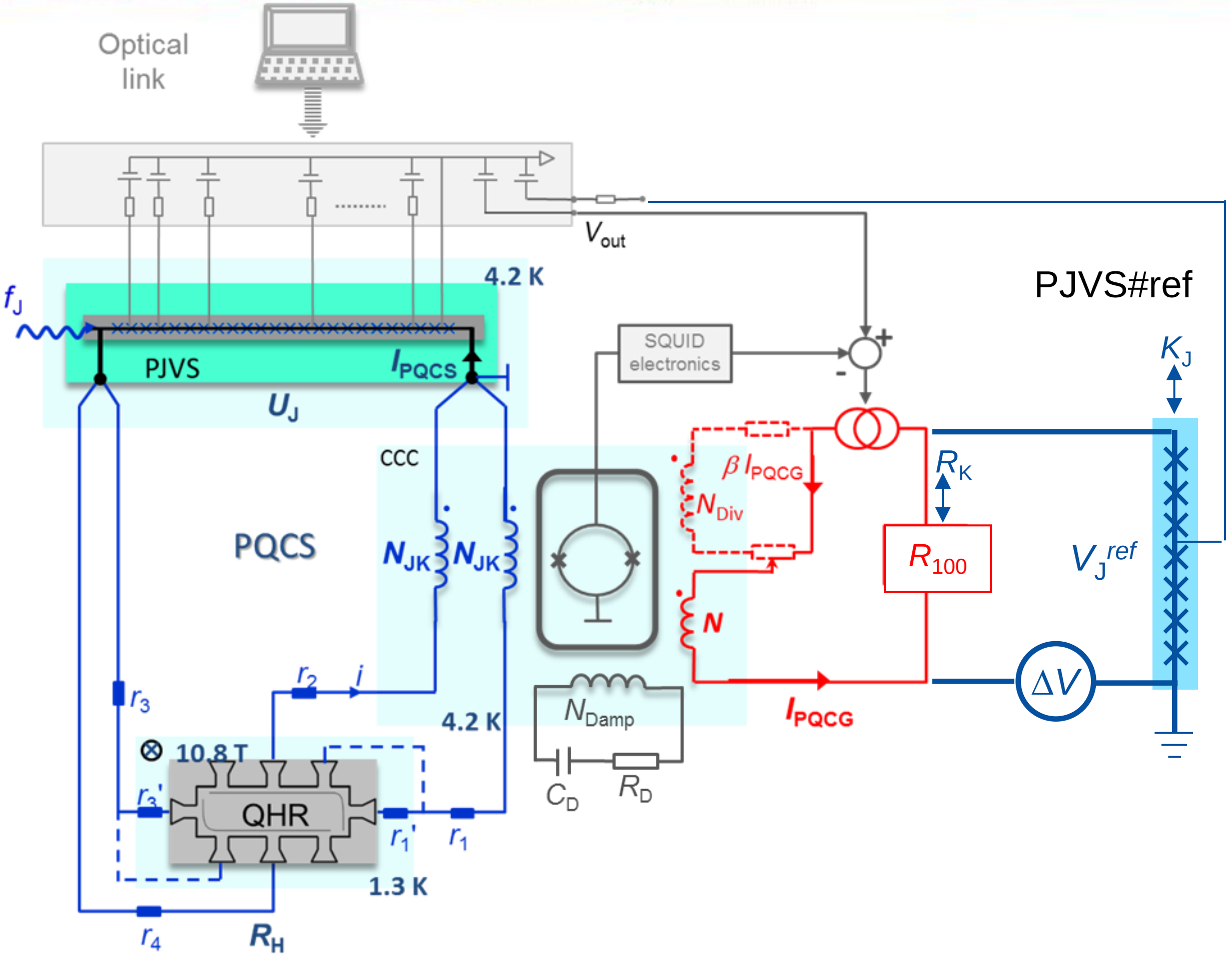
$$N_{JK} = 129$$

$$n_J = 3072$$

$$S_A(I_{PQCG}) = \frac{1}{n_J e f_J} \frac{\gamma_{CCC}}{N_{JK}} S_\phi$$

$$\boxed{S_A(I_{PQCG}) \approx 3.6\times10^{-8} / Hz^{1/2}}$$

Quantization tests : is I_{PQCG} equal to $G_{\beta}n_J(R_KK_J)^{-1}f_J(1-\alpha)$?



Comparison of I_{PQCG} to the reference quantized current V_J^{ref}/R_{100}

⇔

Comparison of R_{GaAs} and $R_{Graphene}$

Adjusting β_0 so that ΔV=0

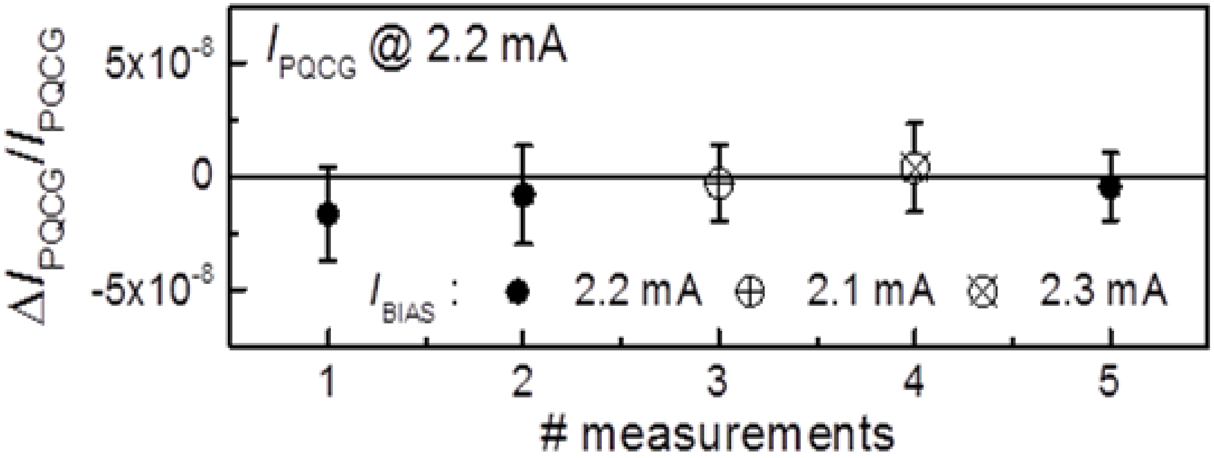
$$\frac{V_J^{ref}}{R_{100}} = I_{PQCG}$$

$$\boxed{\Delta I_{PQCG} = I_{PQCG} - G_{\beta_0} I_{PQCS}}$$

Quantization tests : reproducibility *vs time and* I_{Bias}

Five successive time series (τ_{series}=792 s) over four hours

n_J = 3074, N = 2, N_{JK} = 129

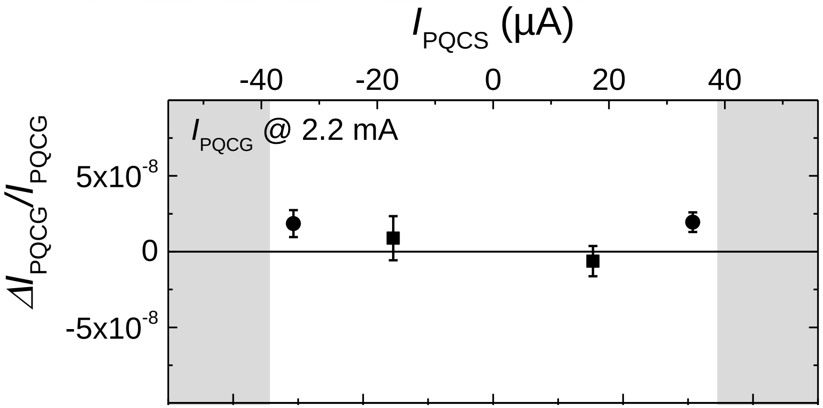


Accurate

Reproducible

Independent of the bias current I_{Bias} of the Shapiro steps
=> 1th Quantization criterion

Quantization tests : reproducibility *vs* with I_{PQCS} and *N*

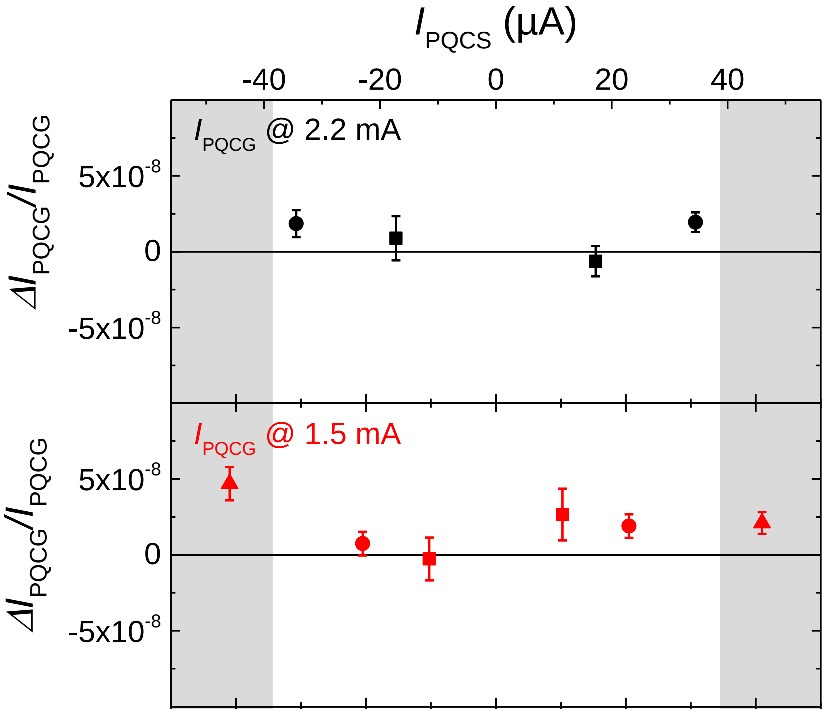


☐ *N* = 1
○ *N* = 2
△ *N* = 4

I_{PQCG} : accurate to within u~2×10^{-8}

independently of I_{PQCS} circulating
in the primary loop while $I_{PQCS} \leq 35$ µA
($n_J \leq 3074$)

Quantization tests : reproducibility *vs* with I_{PQCS} and *N*

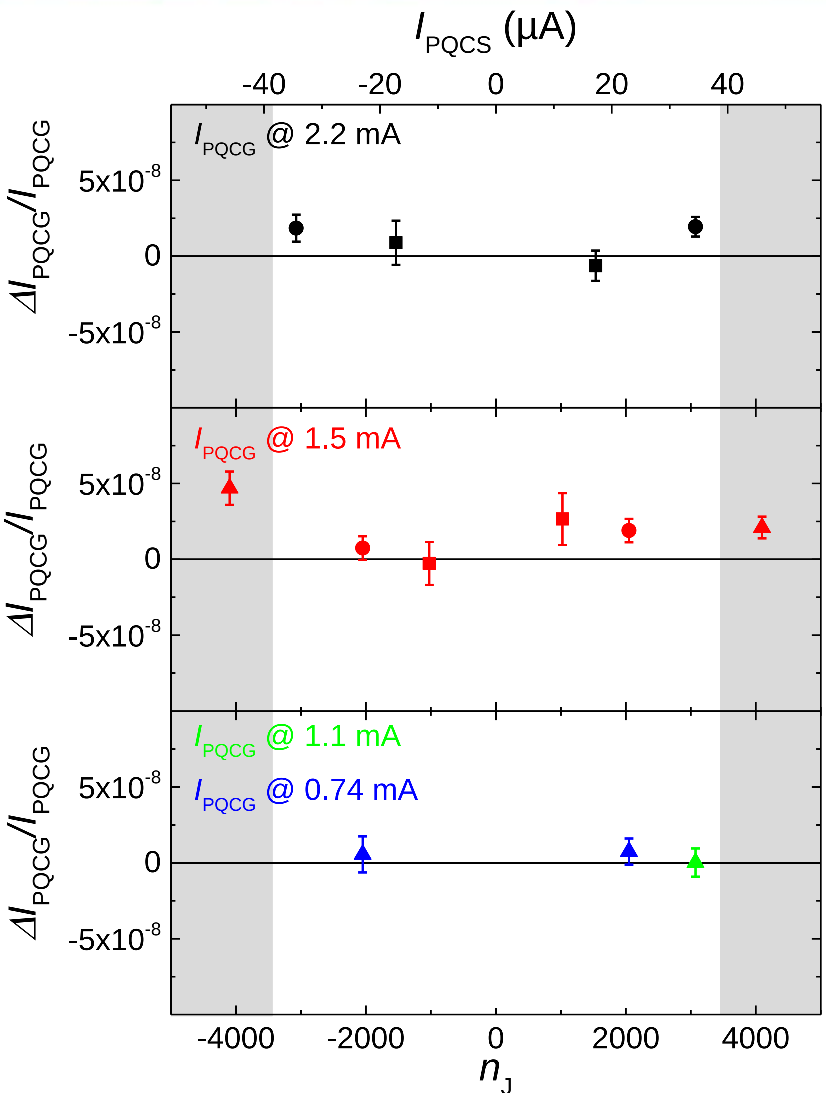


I_{PQCG} : accurate to within $u\sim2\times10^{-8}$

independently of I_{PQCS} circulating in the primary loop while $I_{PQCS} \leq 35$ µA ($n_J \leq 3074$)

….whatever the current generated from +/- [0.74 to 2.2] mA

Quantization tests : reproducibility *vs* with I_{PQCS} and *N*



I_{PQCG} **:** accurate to within u~2x10^{-8}

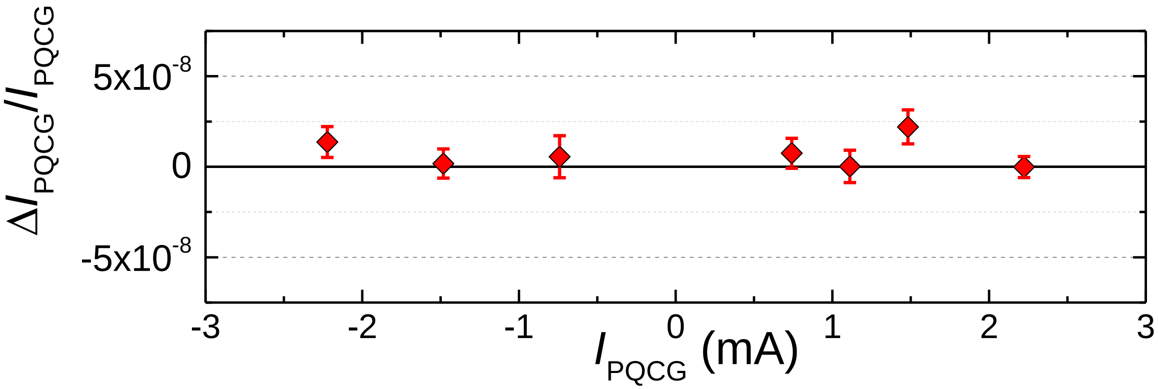
independently of I_{PQCS} circulating in the primary loop while $I_{PQCS} \leq 35$ µA ($n_J \leq 3074$)

….whatever the current generated from +/- [0.74 to 2.2] mA

=> 2th Quantization criterion

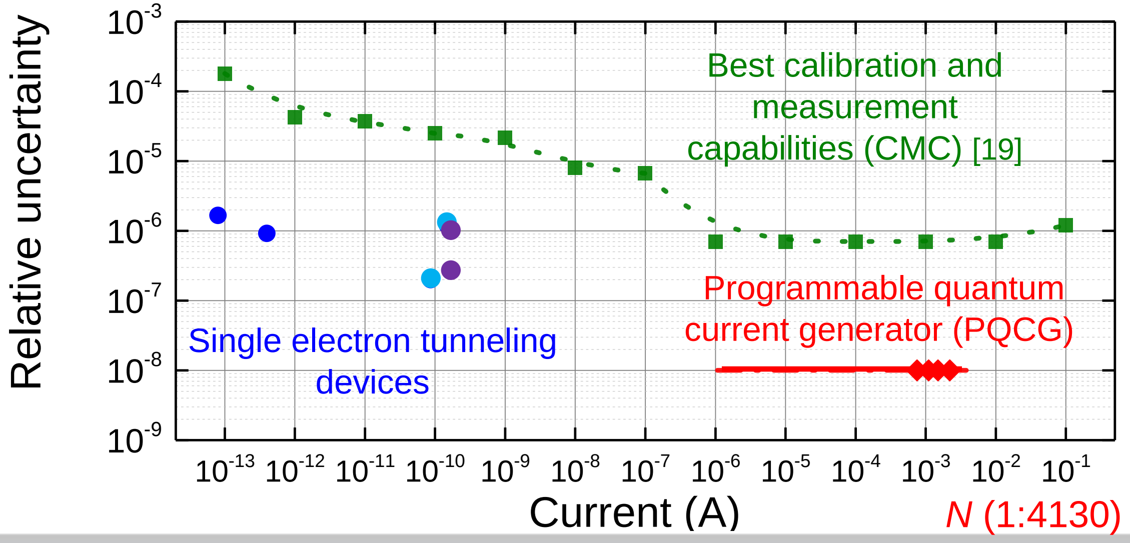
Quantization tests : PQCG is 10^{-8}-accuarte

=> ***A***veraging of data for $n_J \leq 3074$



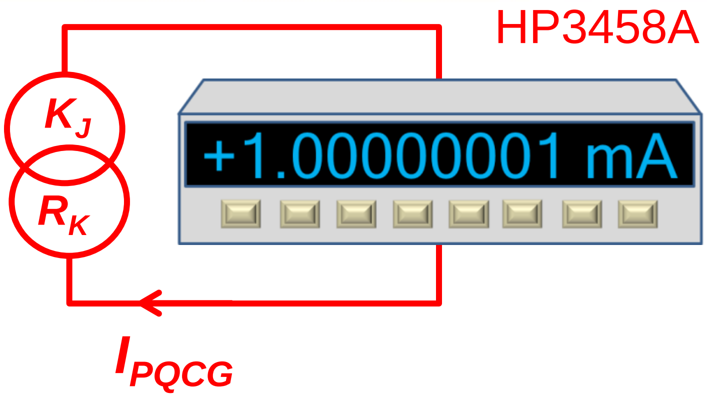
- No significant deviation within a measurement uncertainty of 10^{-8}
- Weithed mean : $(6 \pm 6) \times 10^{-9}$

=> Validation of the Type B uncertainty budget (independent of I_{PQCG} value)

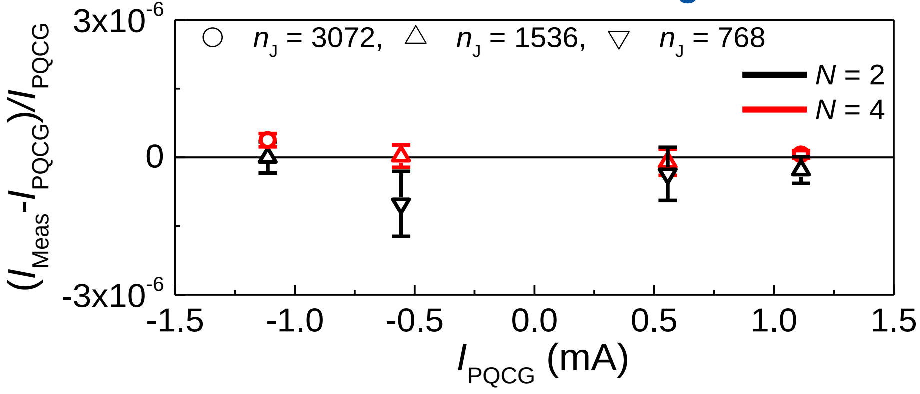


From the uncertainty budget, 10^{-8} -accurate down to µA range

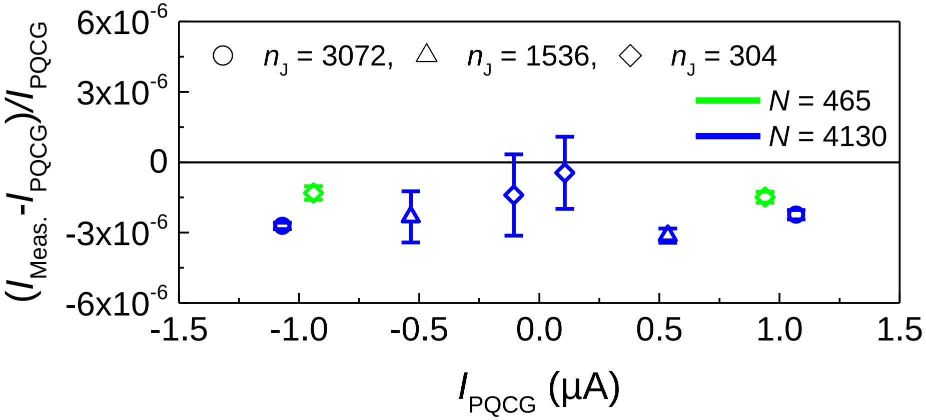
Digital ammeter calibration



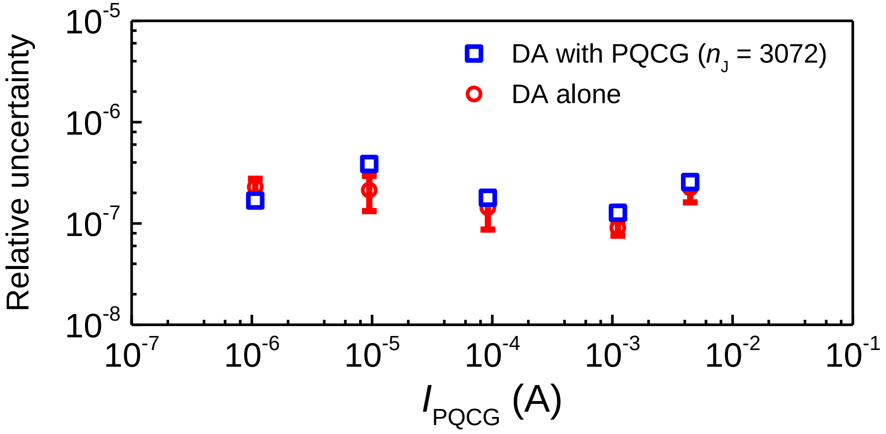
Calibration in mA range



Calibration in μA range



Calibration uncertainties over 4 decades



- 10^{-7} uncertainty: limited by the DA

Conclusions

- A true quantum current standard :

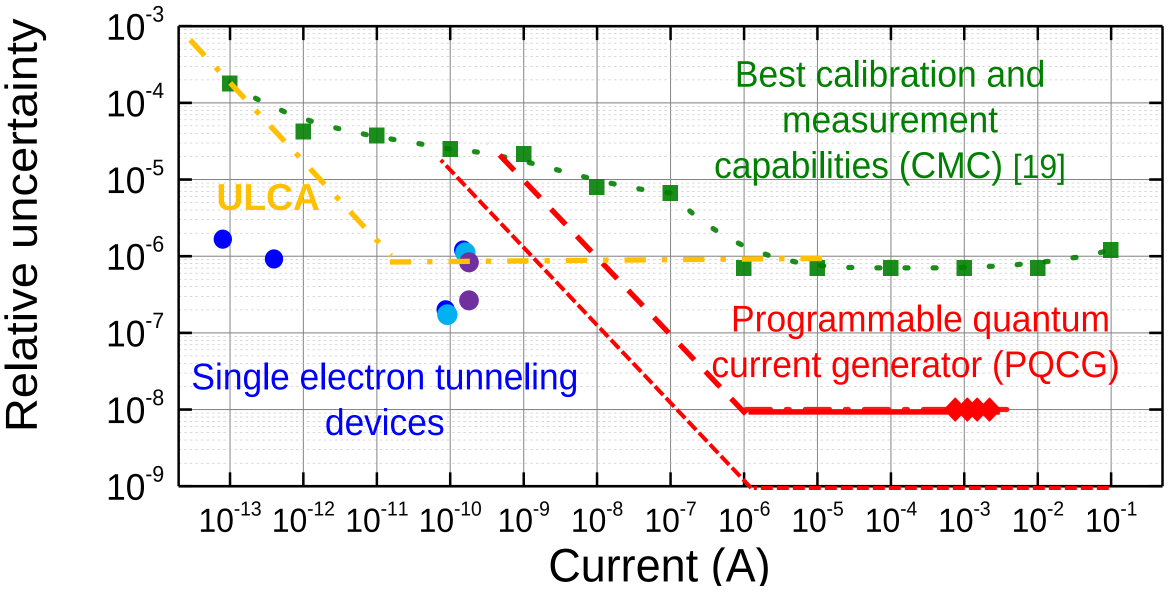
  Accurately quantized (10^{-8}) in terms of *e*, Reproducibility, Uncertainty budget
  Identification of Quantization criteria, calibration of DA tested

=>The PQCG realizes the first quantum « mise en pratique » of the ampere from *e* within a **10^{-8}** uncertainty in the current range from 1 µA up to 10 mA

- Uncertainty improvement and current range extension (10^{-9}/1 µA, 10^{-8}/100 nA, 10^{-7}/10 nA)

  (Damping at low temperature, triple connection….)

PTB
D. Drung et al,
IEEE TIM (2016)



J. Brun-Picard,
Phys. Rev. X 6, 041051 (2016)

- Can be implemented in any NMIs equipped with a QHR and a PJVS setup (no additional cost)

Perspectives

- Pulse-driven JVS

PQCS

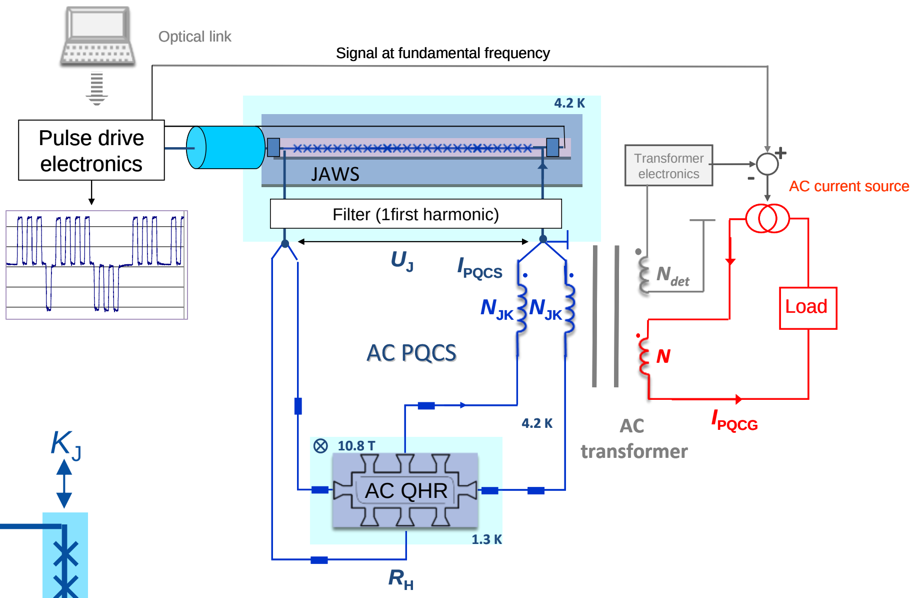
voltage pulse is quantized

$$\int V\mathrm{d}t = n_\mathrm{J} K_\mathrm{J}^{-1} \Rightarrow \int I\mathrm{d}t = Q = n_\mathrm{J} e$$

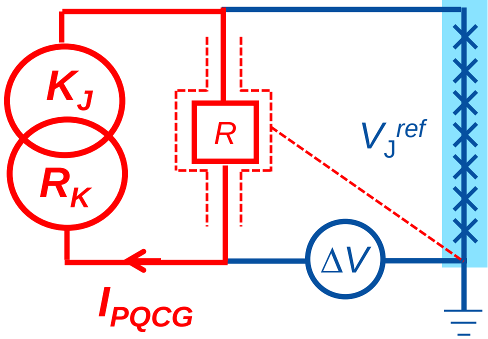
current pulse is quantized

The PQCG is fundamentally a multi-electron pump synchronized by the external Josephson micro-wave signal
=> Potential application in charging capacitances: Quantum capacitance standard

- AC PQCG = Pulse-driven JVS +
  AC QHE +
  AC transformer



- Resistance calibration

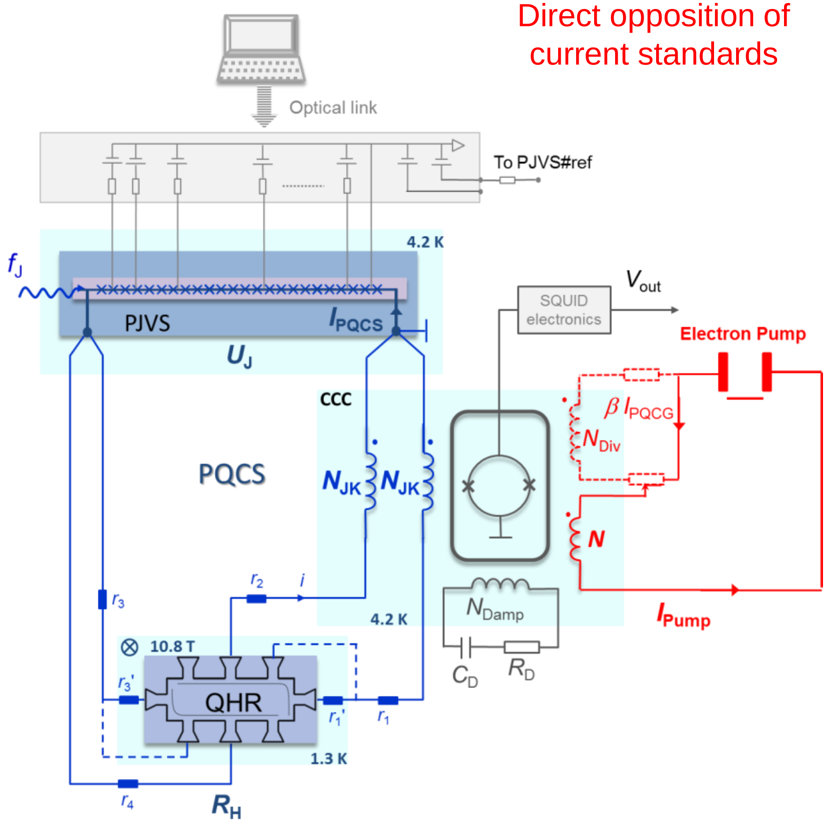


W. Poirier et al, JAP 2014

Perspectives

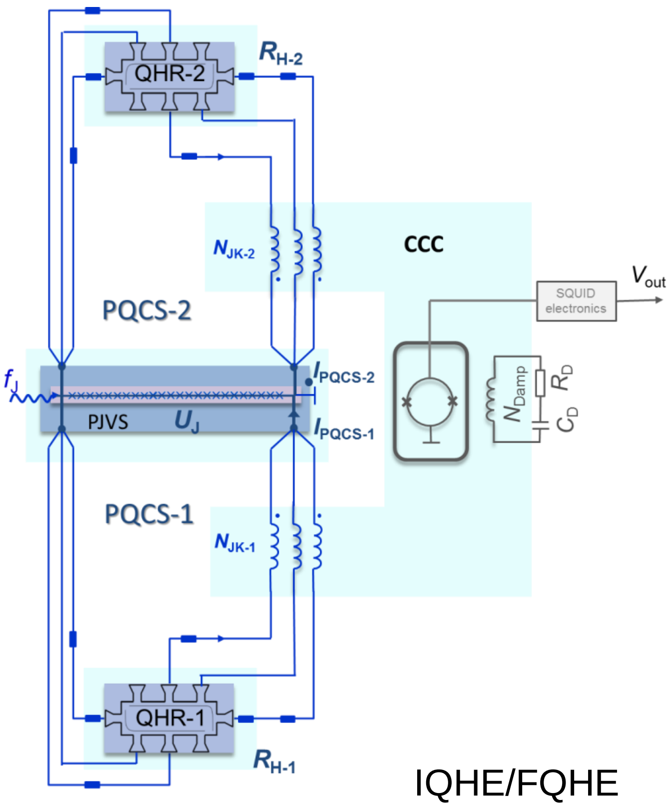
- Quantum Ammeter:

Direct opposition of current standards



Simplifying the metrological triangle experiment

- Ultra-accurate comparison of QHRS

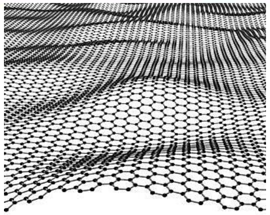


IQHE/FQHE

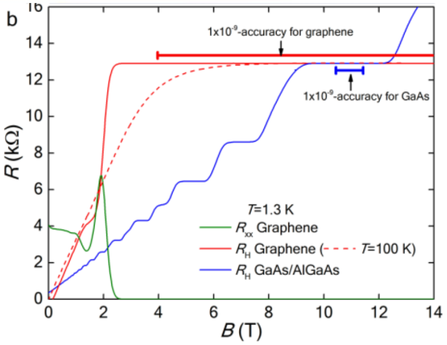
Ahlers et al, ArXiv:1703.05213

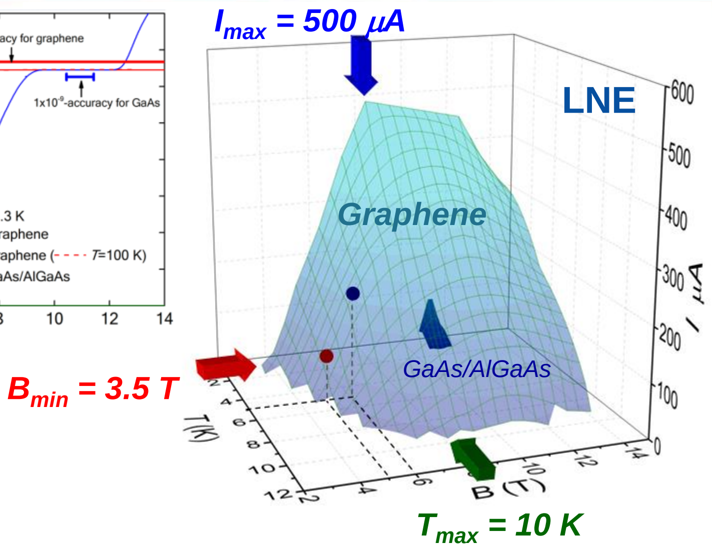
W. Poirier et al, JAP 2014

Perspectives: graphene-based resistance standard



Operation under relaxed experimental conditions !





In DC: *R. Ribeiro-Palau et al, Nat. Nanotech. 10, 965 (2015)*
F. Lafont et al, Nat. Commun., 6, 6805 (2015)

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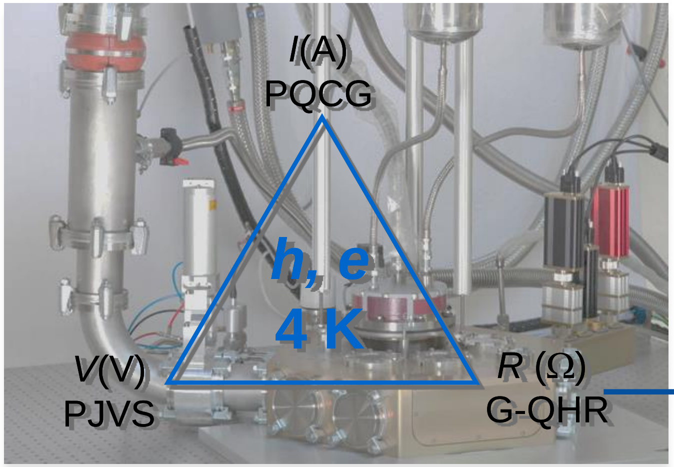
T.J.B.M. Janssen et al.,2D Materials (2015)

In AC: *C. C. Kalmbach et al, Appl. Phys. Lett., 105, 073511 (2014)*

Towards a quantum calibrator/multimeter



C (F)

Acknowledgments

J. Brun-Picard *et al*, «Practical Quantum Realization of the Ampere from the Elementary Charge», Phys. Rev. X 6, 041051 (2016)

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W. Poirier et al, J. Appl. Phys. 115, 044509 (2014)