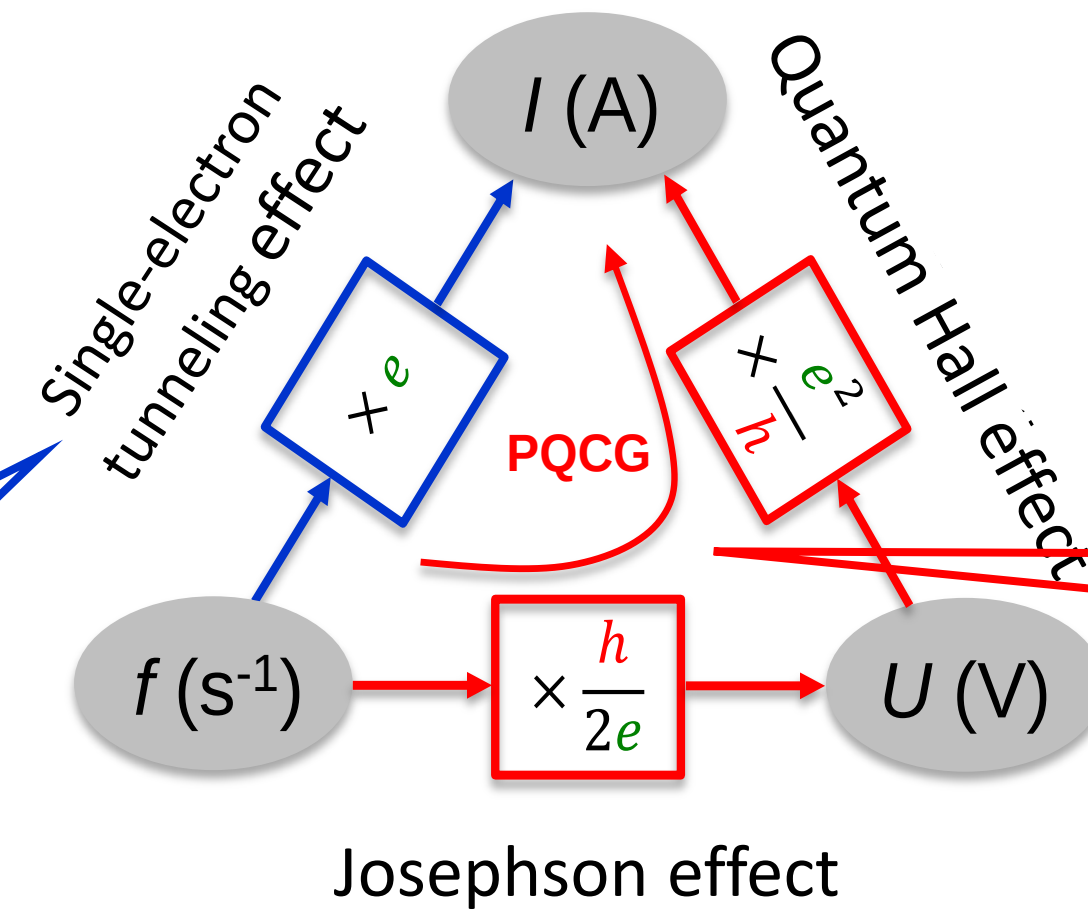


The definition of the ampere from the elementary charge calls for a new realization with a relative uncertainty of 10^{-8}

Single-electron current sources obvious candidates, but the current is still limited to ~ 100 pA with relative uncertainties in the range of 1 part in 10^7 .

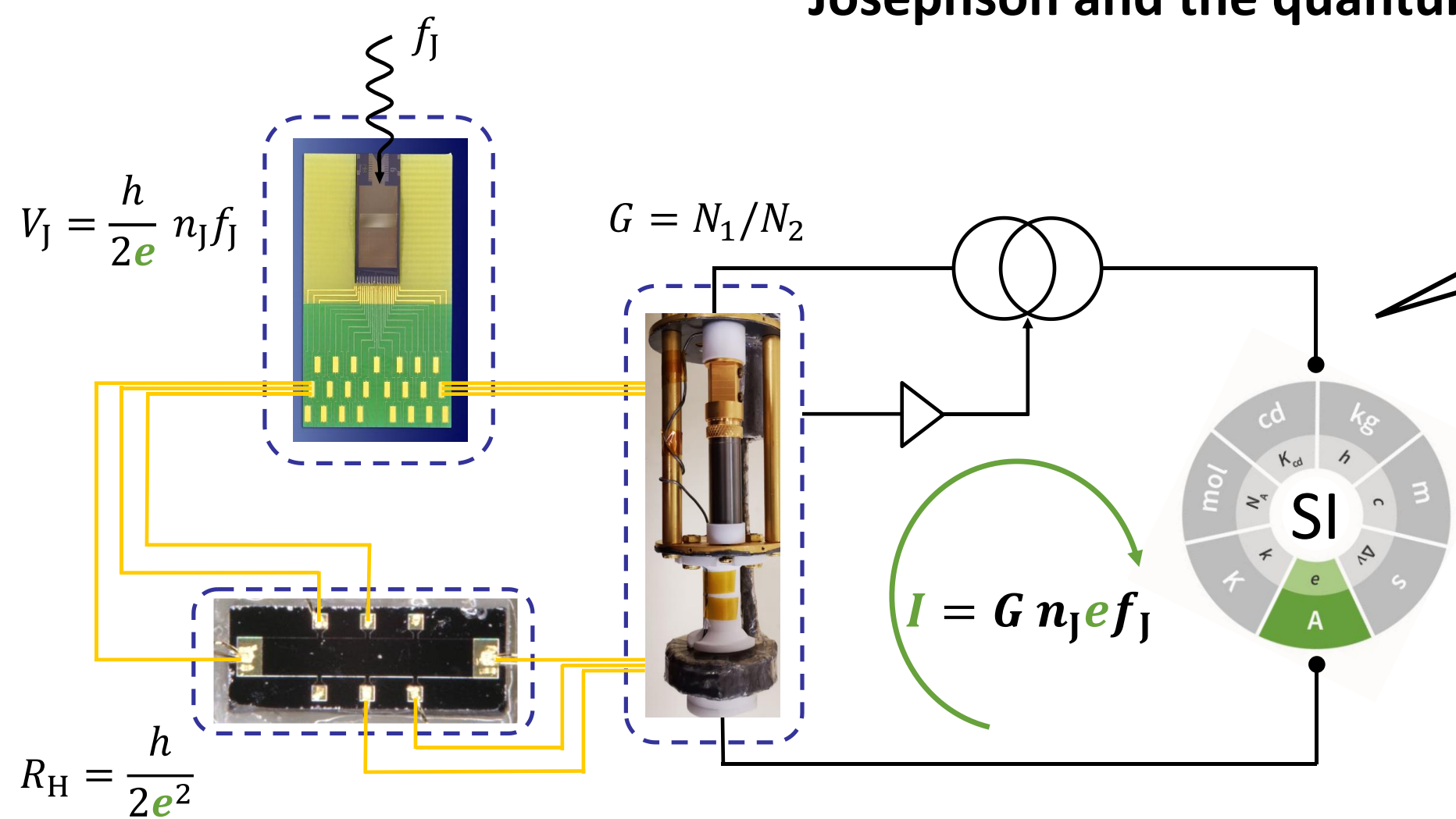


Alternative route : combining the Josephson and the quantum Hall effects [1]

$$I = \frac{(\frac{h}{2e}f_1)}{\frac{h}{2e^2}} = ef_1$$

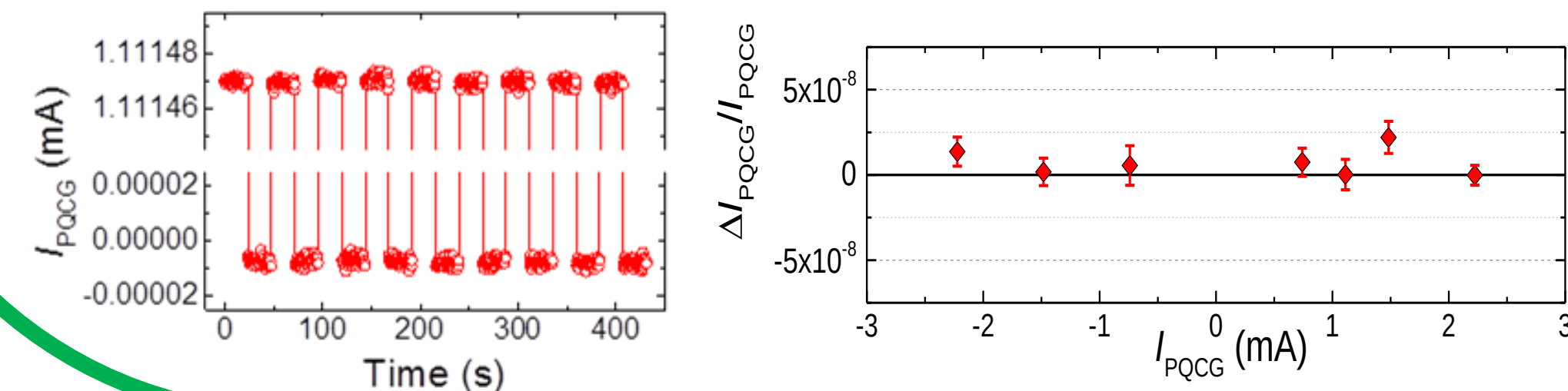
Challenge $\Rightarrow$ Implementing the accurate series connection of the two quantum standards while realizing a true current source.

A Programmable Quantum Current Generator (PQCG) from the Josephson and the quantum Hall effect [2] (2014)



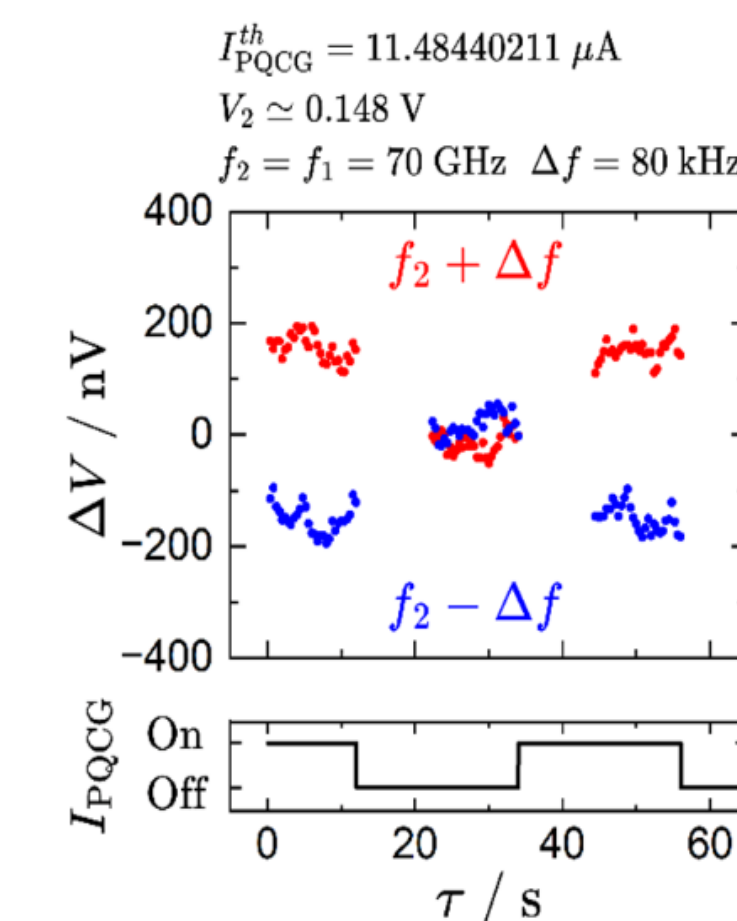
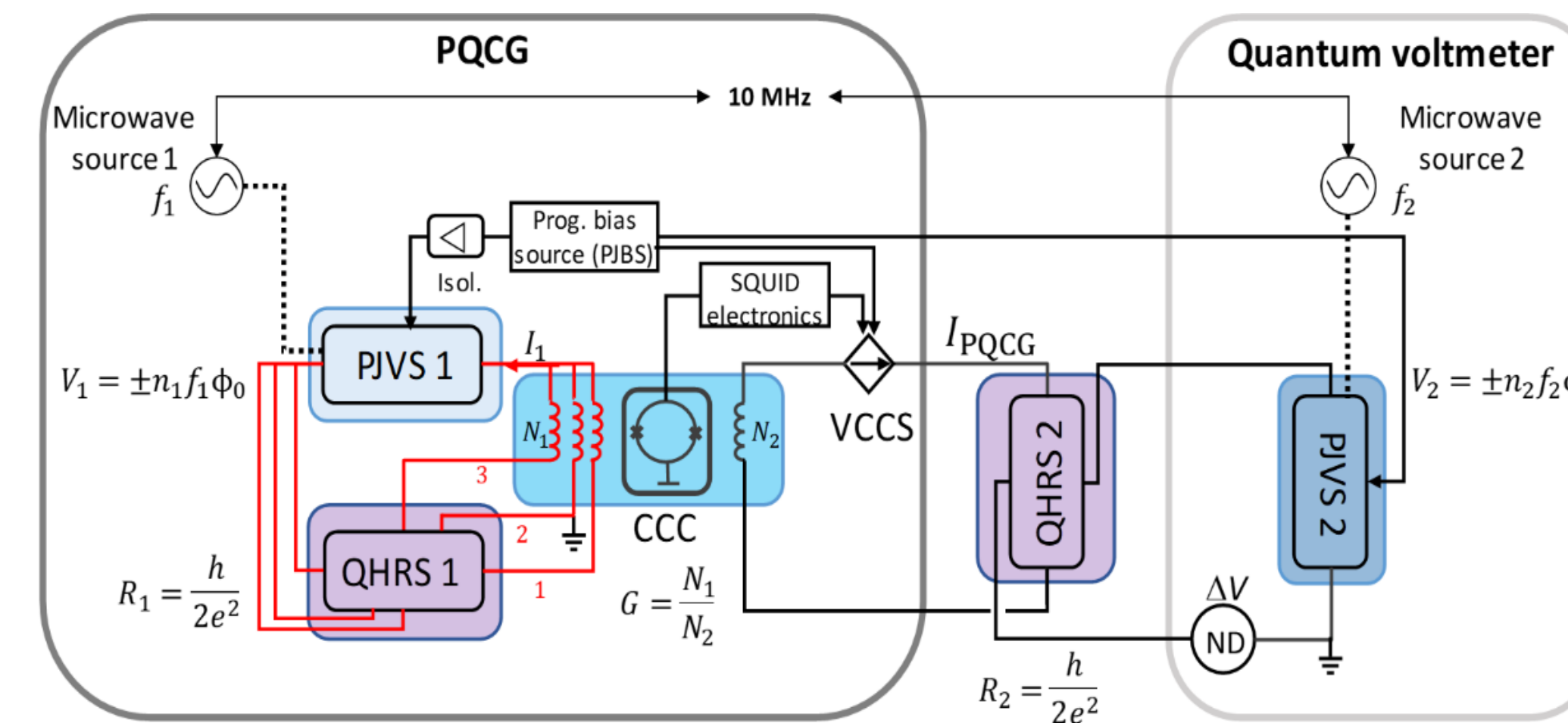
- Josephson voltage standard connected to a quantum Hall resistance.
- Multiple connection technique reduces exponentially the impact of the series resistances.
- Highly accurate cryogenic current amplifier (CCC) scales up or down the quantized current with a gain G.

In 2016, first realization of the ampere in the mA range with a 10^{-8} relative uncertainty

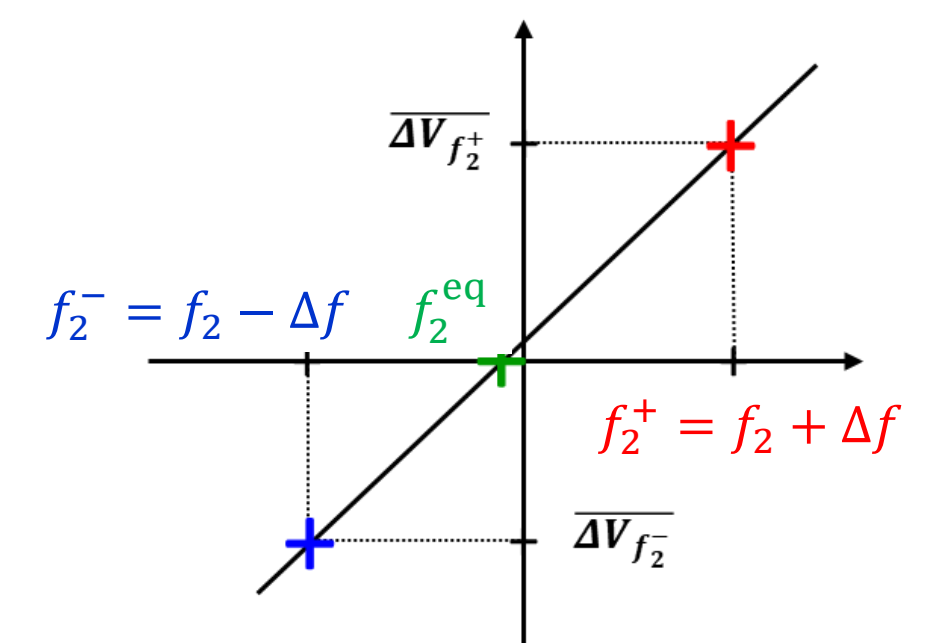


BUT the ideal current was obtained after a 10^{-7} -correction due a double connection only.

A primary quantum current standard at the heart of a full quantum instrumentation



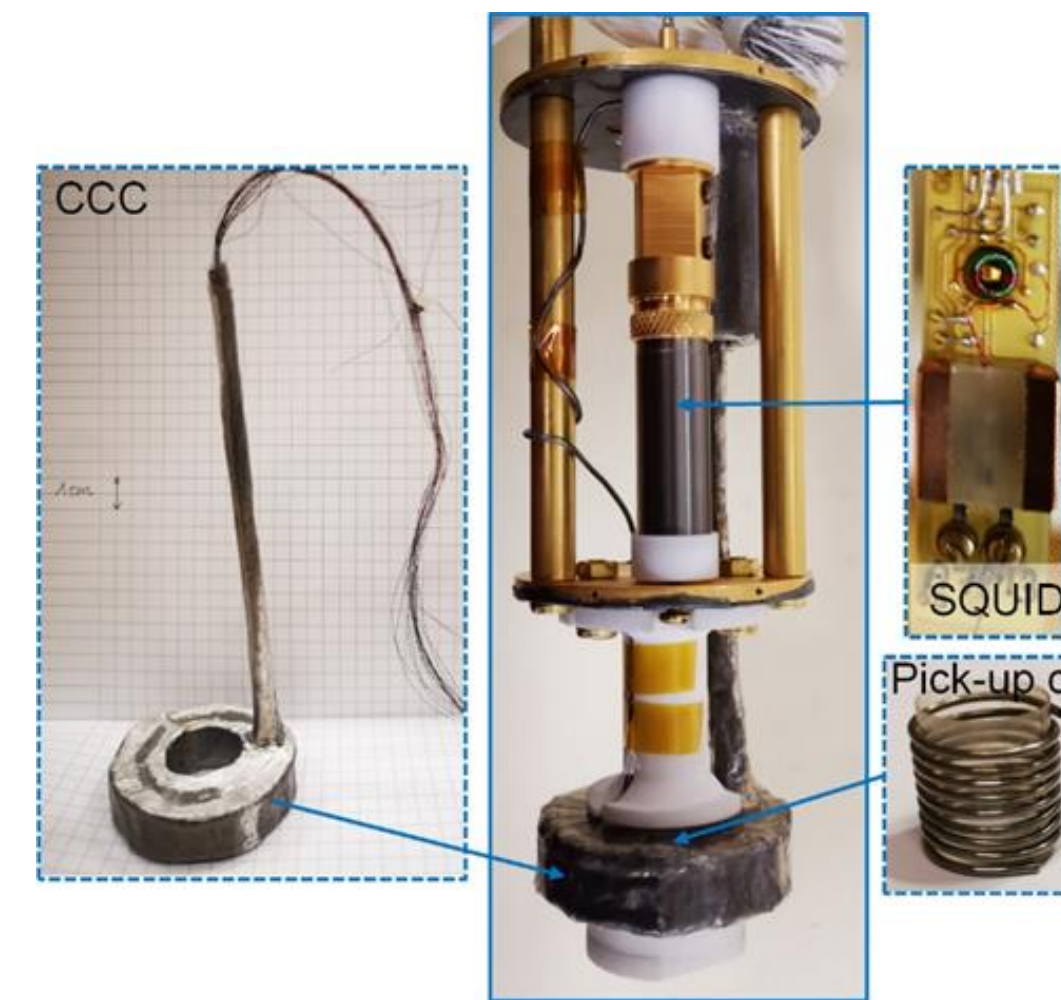
$$I_{PQCG} = n_2 e f_2^{eq} (\Delta V = 0)$$



- The **new generation PQCG** is based on implementing the **triple connection** technique (3 windings of the CCC detect the quantized current). The PQCG delivers current at values $G n_1 e f_1$ **without correction**.
- The **accuracy of the PQCG** is determined from the measurement of the voltage at the terminals of QHRS₂ using a quantum voltmeter made of PIVS₂ and a null detector (ND).

$$\frac{\Delta I}{I} = \frac{I_{PQCG} - G n_1 e f_1}{I} = \frac{f_2^{eq}}{f_1} - 1$$

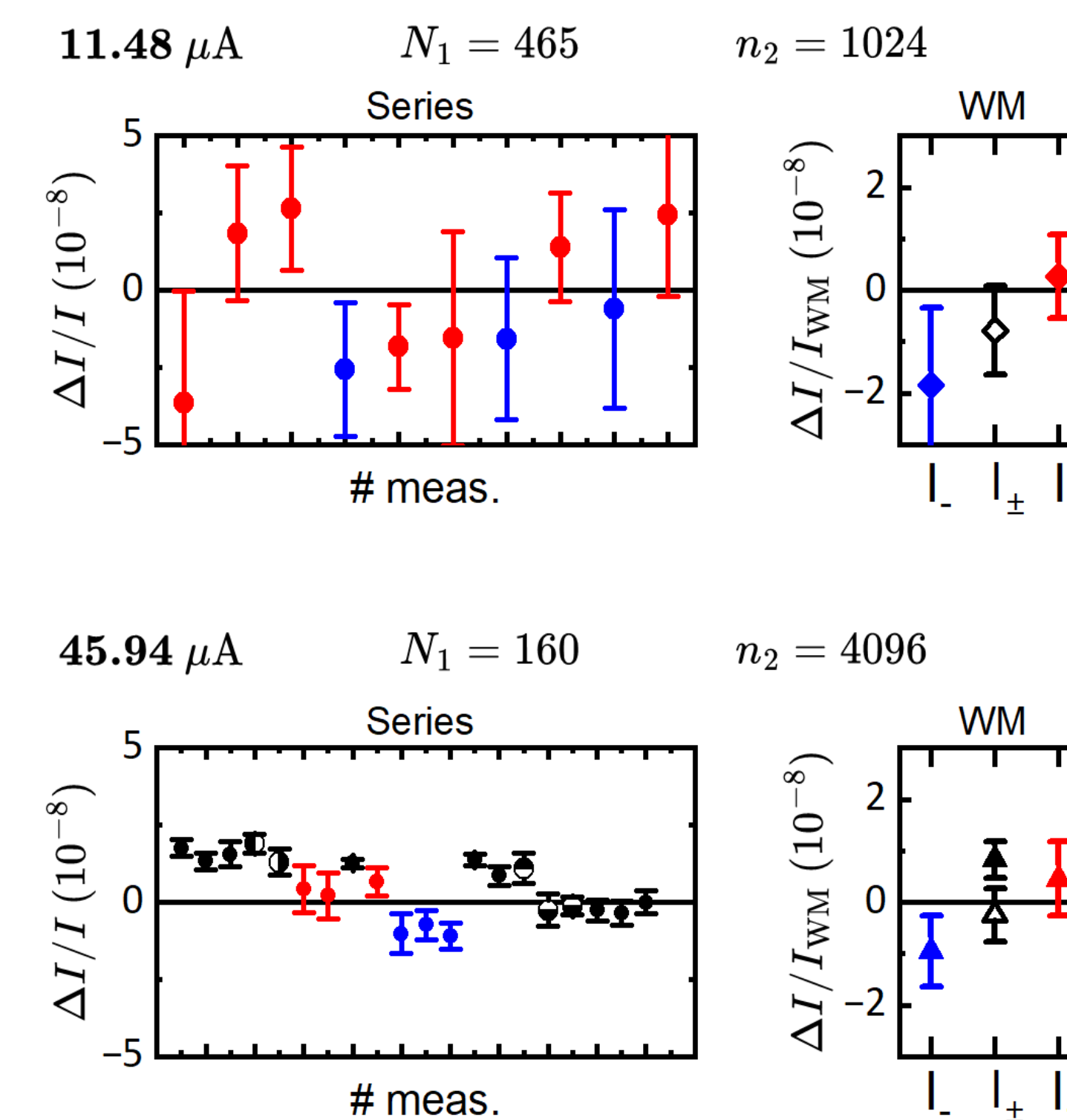
- The relative deviation of the current from its quantized value is determined from the ratio of two Josephson frequencies.
- f_2^{eq} is obtained from linear extrapolation of voltage measurements at two detuned frequencies.



A specific cryogenic current comparator (CCC) made of 20 windings with numbers of turns between 1 and 2065, having a sensitivity of 80 pA.turns/ Φ_0 . It allows implementing the triple connection for 1, 2 16, 128, 160, 465, 1600 turns.

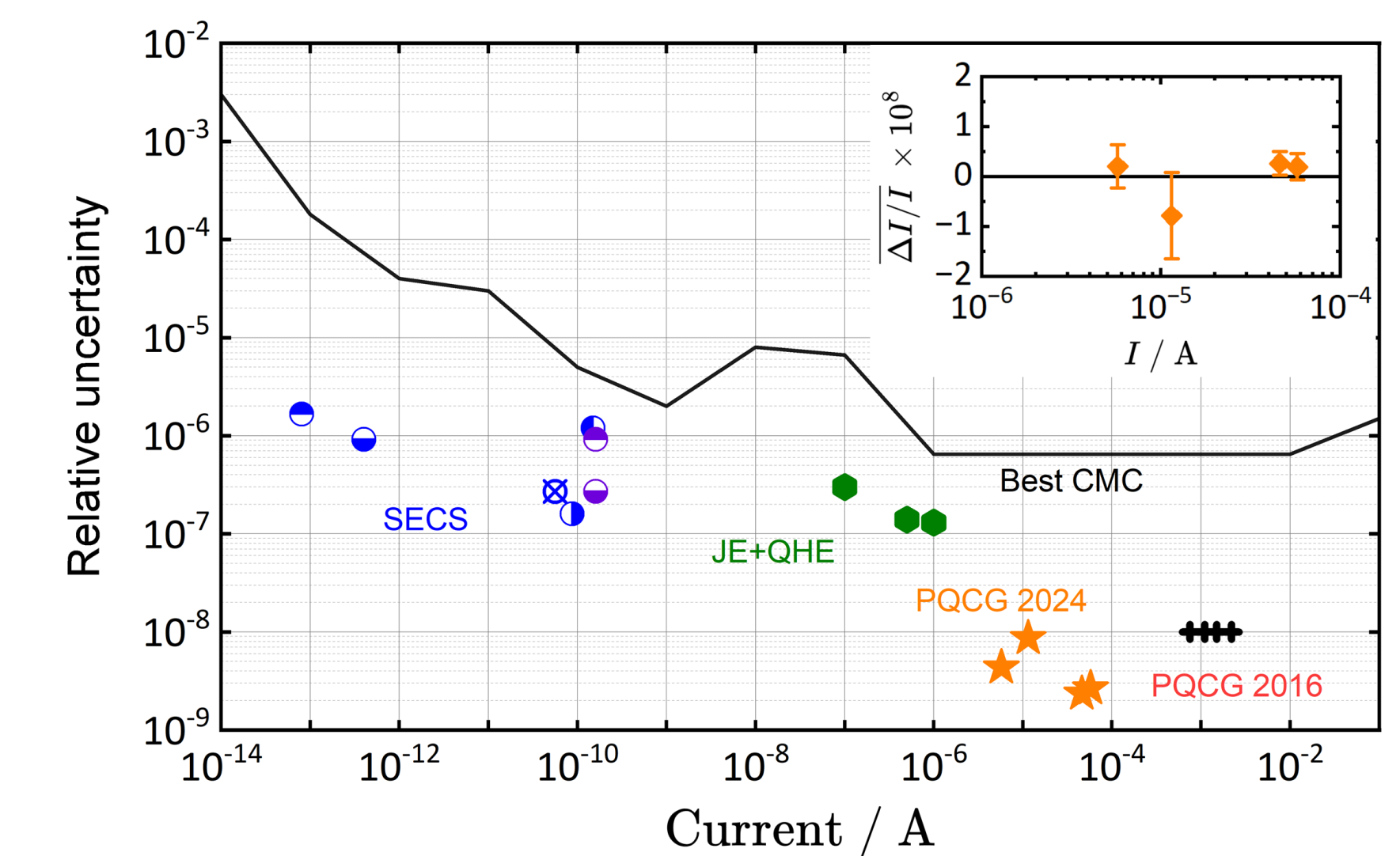
Type B uncertainty	$u_B (10^{-9})$
PQCG	2
Quantum voltmeter	0.5
Accuracy test	2.1

Accuracy tests : $\leq 10^{-8}$ (2024)



Measured currents for positive/negative values agree with quantized values with uncertainties $\leq 10^{-8}$ in the μ A range [5].

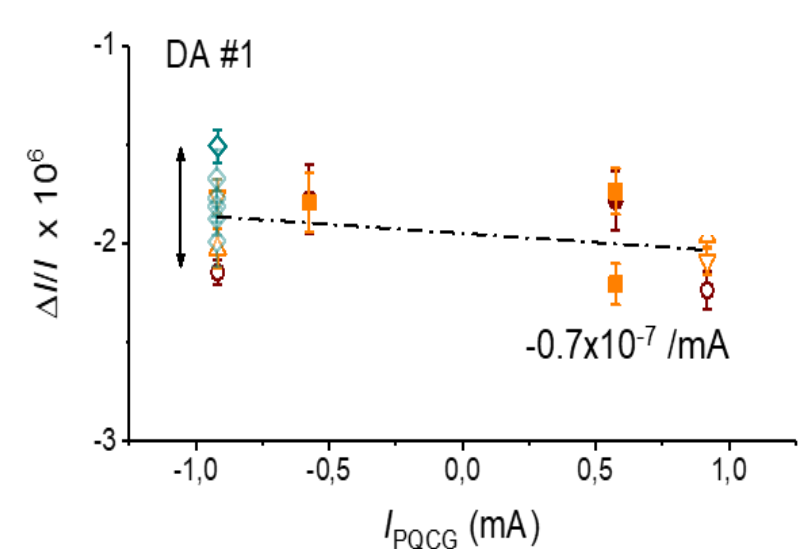
Quantum current generation: state-of-the-art



The PQCG is able to generate current at quantized values with uncertainties $\leq 10^{-8}$ over a range extending from μ A to mA [5].

Ammeter calibration

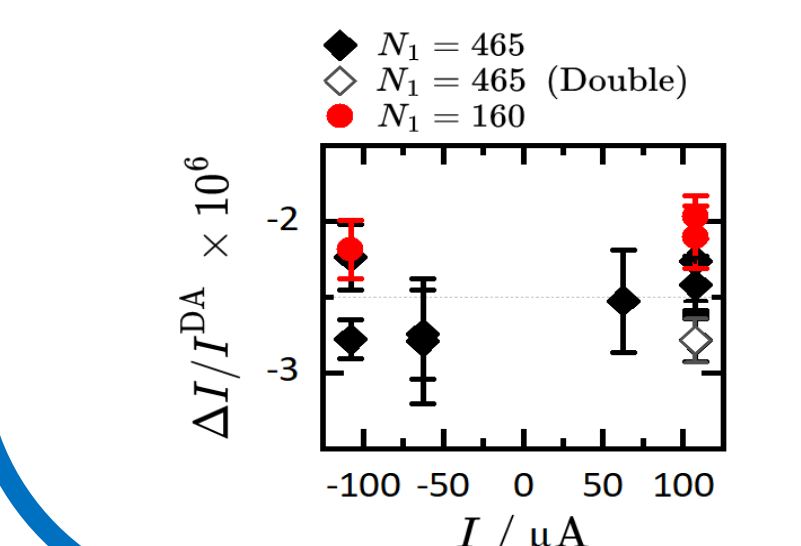
mA range (ref. [4])



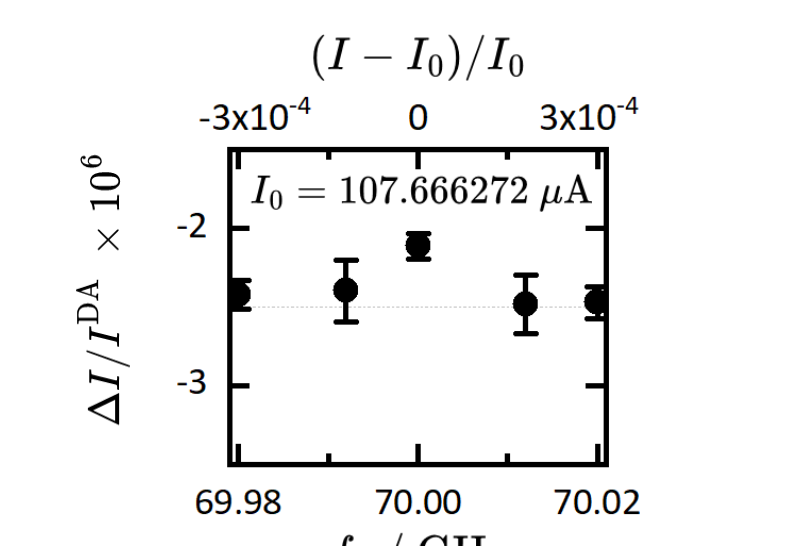
Calibration over several current ranges with uncertainties (10^{-7}) limited by devices under test by simply replacing QHRS₂ by ammeter.



μ A range (full range)



μ A range (short range)



Paradigm shift in the resistance calibration

The accuracy test experiment can be used to calibrate an unknown resistance R_2 (replacing QHRS₂) once the PQCG is assumed accurate.

$$R_2 = \frac{h}{2e^2} \frac{N_2 n_2 f_2^{eq}}{N_1 n_1 f_1}$$

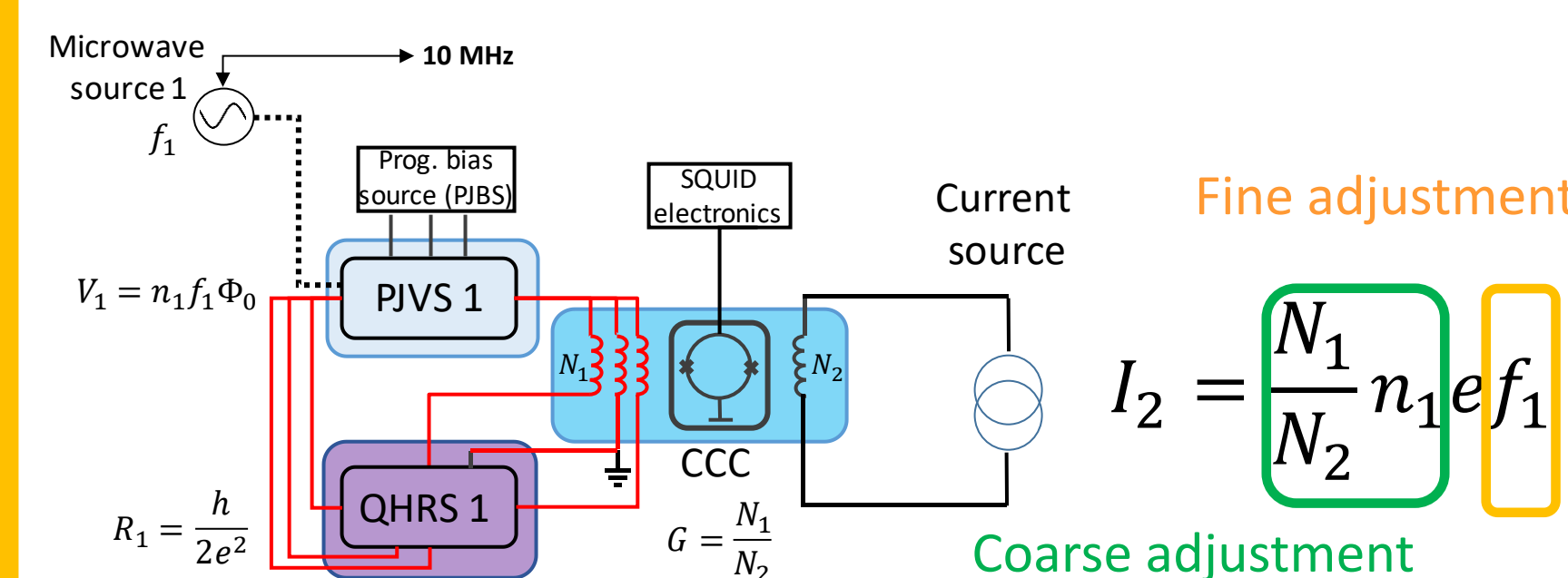
Coarse adjustment Fine adjustment

Demonstration with 100 Ω (2016-ref[3]) and 12,9 k Ω (2024-ref[5])

The PQCG should allow one step calibration of large resistance (1 M Ω) from $h/2e^2$ (current leakage strongly reduced).

Quantum Ammeter

The quantized reference current can be used to calibrate an unknown current source using the CCC as a comparator.



A 10 nA current could be measured with a relative uncertainty of 5×10^{-8} within 12 hours data acquisition: towards comparison with other quantum current sources (SET devices...).

Conclusions

The primary quantum current standard :

- $\Rightarrow$ provides a realization of the ampere definition with a relative uncertainty of 10^{-8} over a wide of current values.
- $\Rightarrow$ can be extended towards lower currents to bridge the gap with other quantum current sources (Set devices...).
- $\Rightarrow$ will foster development of new secondary standards such as ammeters.

The full quantum instrumentation :

- $\Rightarrow$ forms the basis of a universal quantum realization of electrical units (volt, ampere, ohm) in a single experiment: **a DC quantum calibrator/multimeter.**