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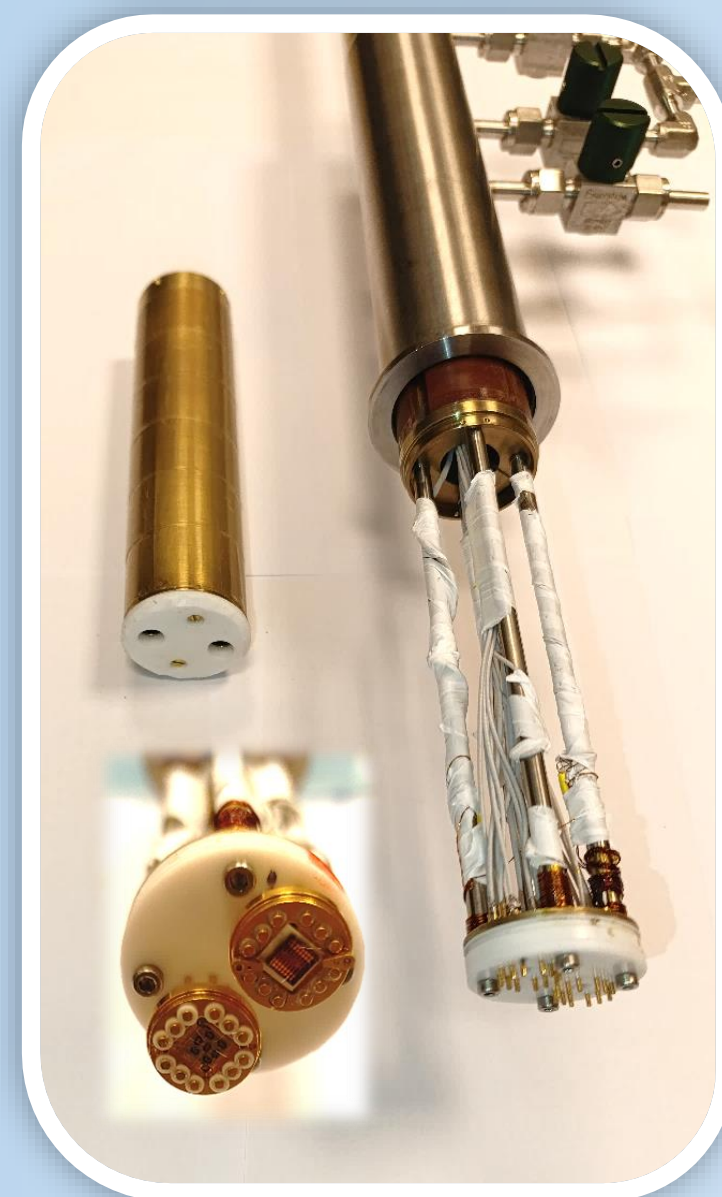
Motivation

LNE aims at the simplification of the traceability chain for the farad realization, currently stemming from quantum Hall resistance standards (QHRS) in the continuous current (DC) regime. For this purpose, two complementary practical realizations are being developed: based on electrostatic laws with the Thompson-Lampard calculable capacitor or on the quantum Hall effect with the QHRS in the alternative current (AC) regime. In parallel to these major developments, LNE is working on two other essential axis. First in the production of graphene-based QHR for operation in relaxed experimental conditions in a cryogen-free cryomagnetic system. The second one is the integration in the chain of digital impedance bridges, potentially with quantum-based AC signal sources such as the Josephson Arbitrary Waveform Synthesizer (JAWS). These progress will allow LNE to compare the two farad traceability chains in the International System of units (SI), with a target relative uncertainty below $1 \cdot 10^{-8}$.

The cryogenic setup

Commercial top-loading ^4He variable temperature insert (VTI) (1.25 K to 300 K) with a 14 T magnet:

- Extremely high temperature stability
- Pulse-tube technology
- No liquid helium consumption
- Separated remote motor



Home-made AC-probe:

- Operation from DC to 50+ kHz

→ Coaxial cables:

- Cu-based inner conductor
- Stainless steel shielding
- PTFE insulation

- SMA to LEMO connectors at the top (flexibility)

- SSMCX connectors at low temperature to maintain coaxiality down to the sample holders

- Two TO-8 compatible sample holders

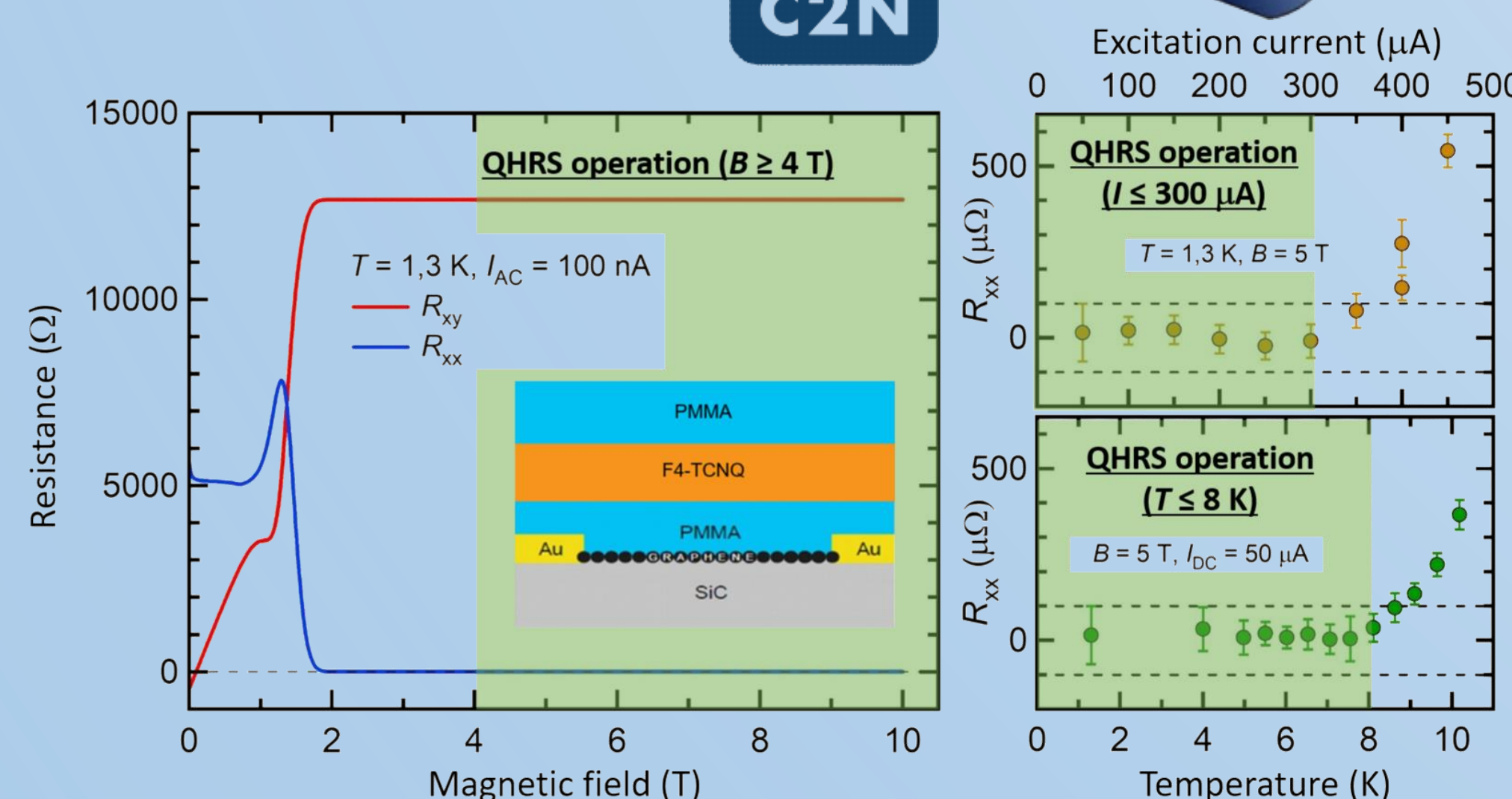
Graphene-based QHRS

- Quantization of the Hall resistance in quantum Hall effect regime, with $R_H = R_K/n = \frac{h}{ne^2}$, $n \in \mathbb{N}$

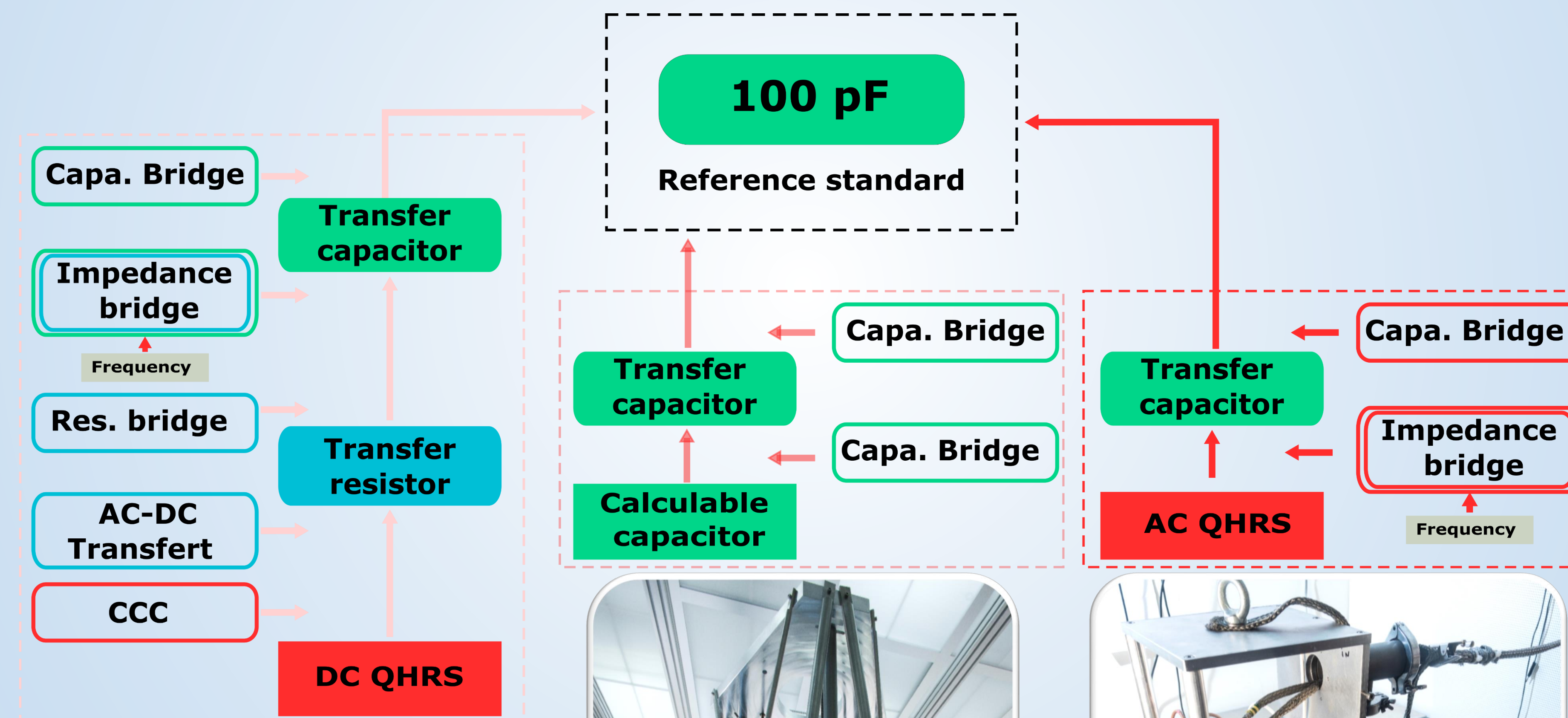
(R_K and h the van Klitzing and Planck constants, e the elementary charge)

- Epitaxial graphene grown by propane-hydrogen chemical vapor deposition at CRHEA/CNRS

- Hall bars processing at C2N/CNRS with molecular doping (F4-TCNQ) process to reach targeted carrier density and mobility



→ QHRS operation for $B \geq 4$ T, $T \leq 8$ K, $I \leq 300$ μA



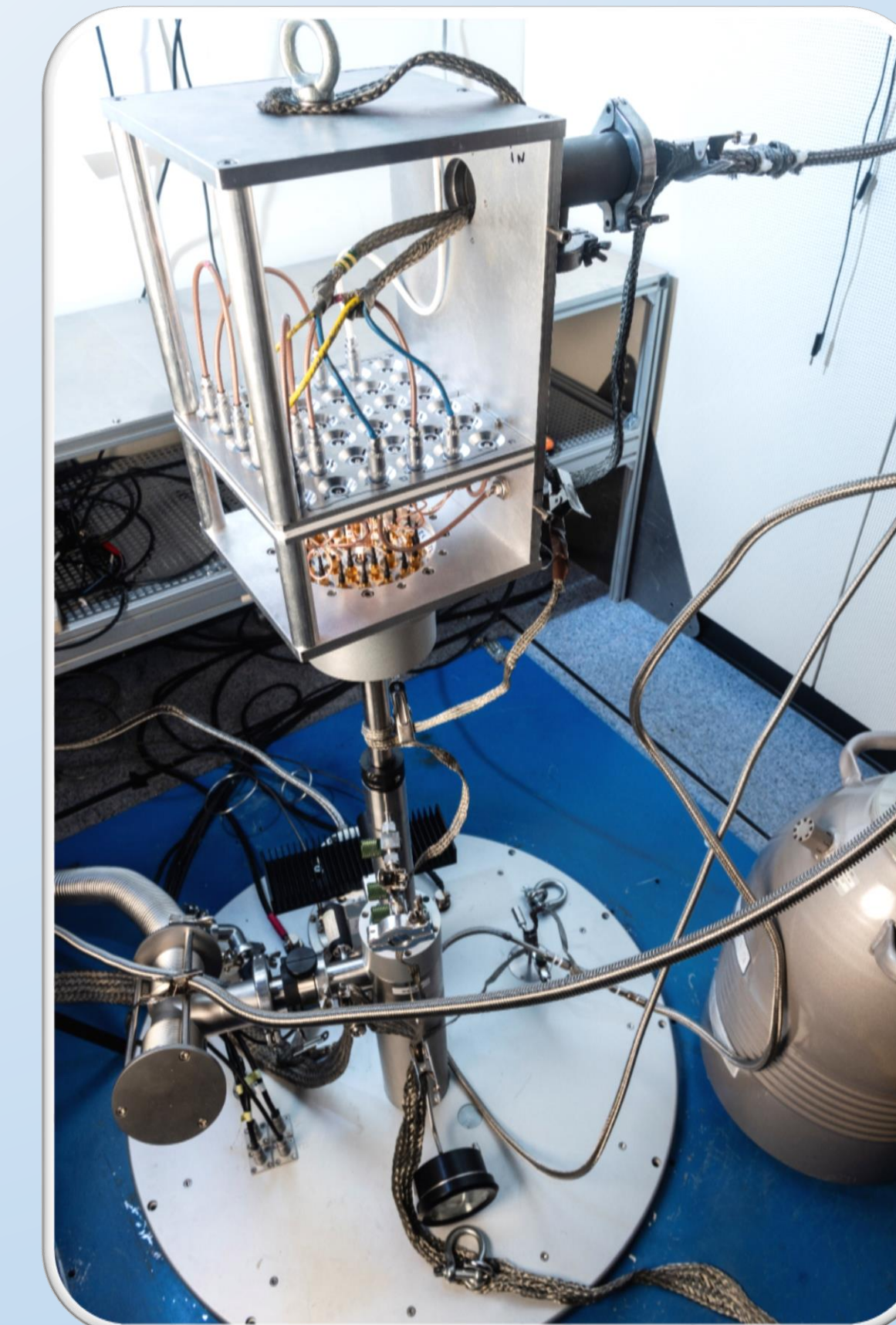
1

Current traceability chain



2

Final characterization on-going



3

Under development

The Thompson-Lampard calculable capacitor

- Movable guard within a five-electrode system, following the Thompson-Lampard theorem:

$$e^{(-\pi/\epsilon)\gamma_{1-3+4}} + e^{(-\pi/\epsilon)\gamma_{2-5}} = 1$$

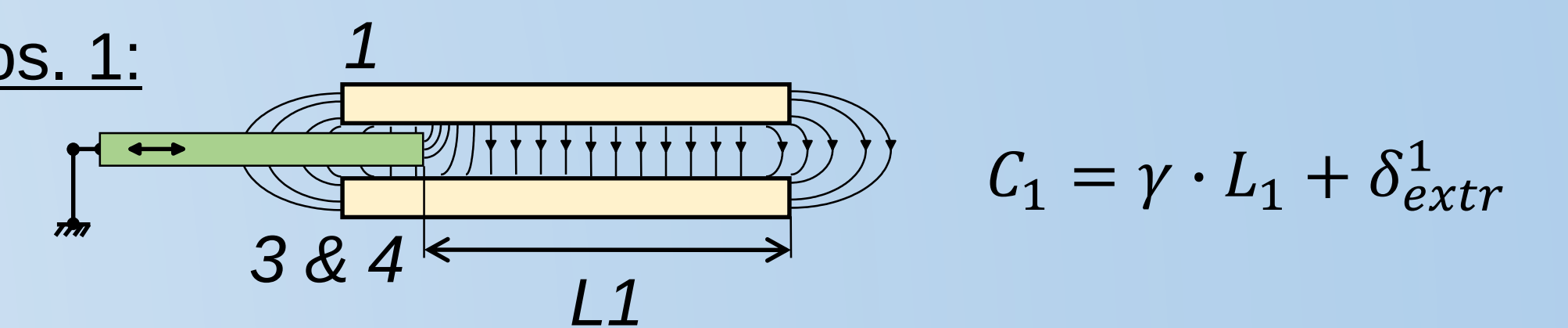
(γ_{i-j} the lineic capacitances and ϵ the electric constant)

- If symmetric: $\gamma_{i-j} = \gamma = \frac{\pi}{\epsilon} \ln \left(\frac{2}{\sqrt{5}-1} \right)$

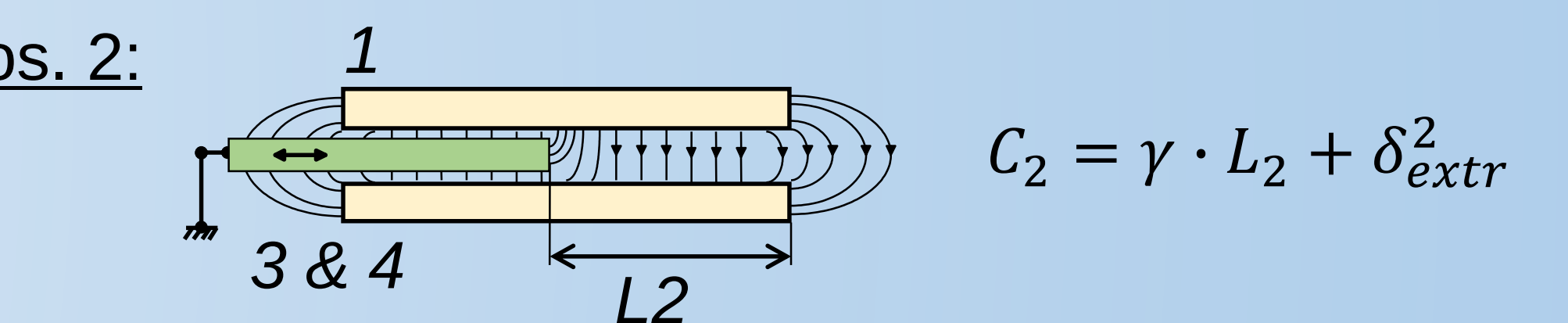
- Measurements at two positions, with

$\delta_{extr}^1 = \delta_{extr}^2$ the extremity effects supposed identical

Pos. 1:



Pos. 2:

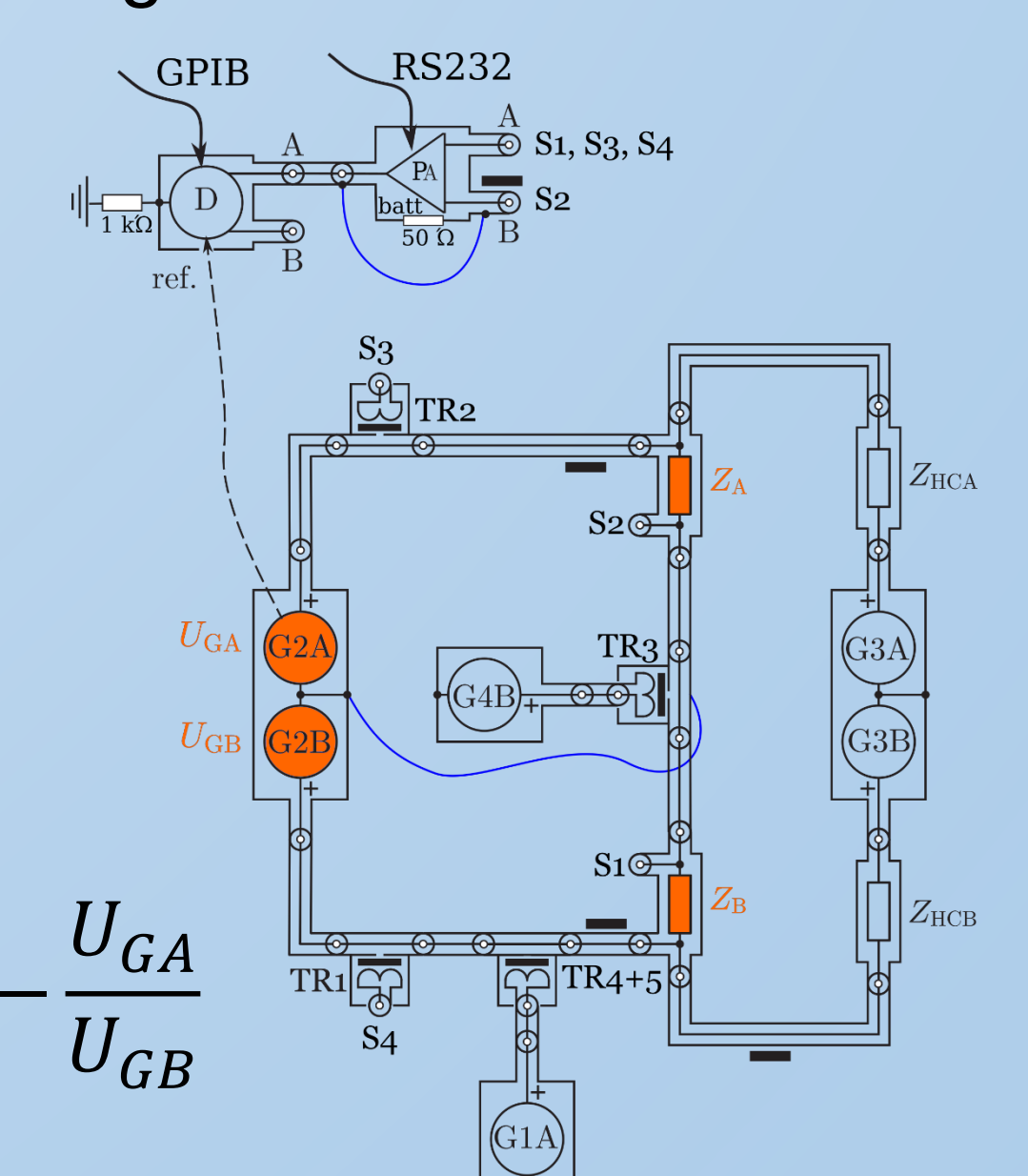


Resulting capacitance:

$$\Delta C = C_1 - C_2 = \gamma \cdot (L_1 - L_2)$$

The digital impedance comparison bridge

- Arbitrary impedance measurements (R , L , C)
- Arbitrary amplitude and phase ratios
- Continuous operation frequency (60 Hz to 20 kHz)
- Automatized
- Moderate uncertainty ($\sim 10^{-7}$, mainly on U_{GA} and U_{GB}), can be reduced to 10^{-8} using quantum-based voltage sources



$$\frac{Z_A}{Z_B} = -\frac{U_{GA}}{U_{GB}}$$

