



The GIQS project

Graphene Impedance Quantum Standard

... three years in 15 minutes (≈ 10 ppm)

Luca Callegaro 

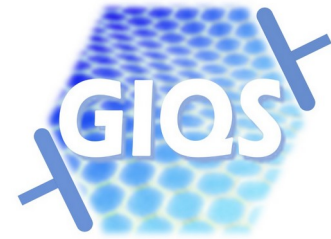
+ a *lot* of people from the consortium!



The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

The GIQS project

GIQS — Graphene Impedance Quantum Standard



Joint Research Project of the
European Metrology Programme
for Innovation and Research



The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

coordinated by the
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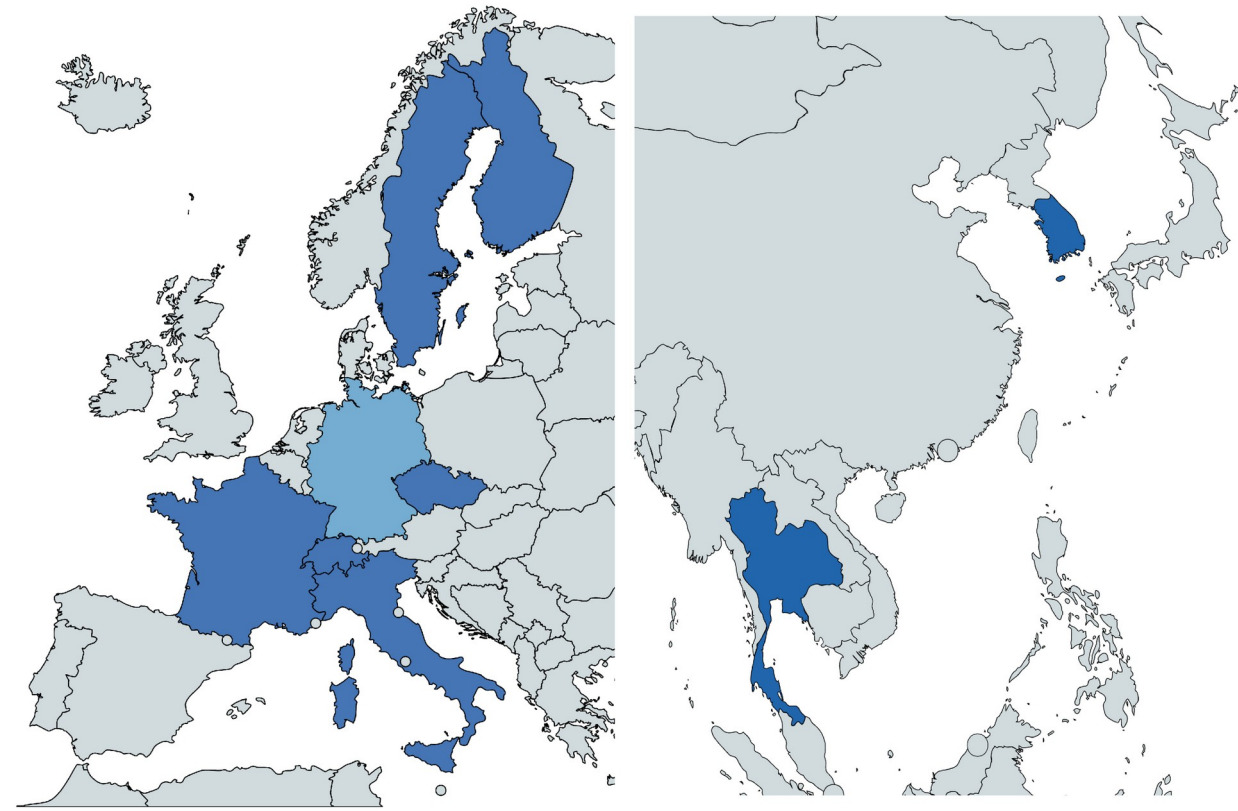
3 year duration (Jul 2019–Jun 2022)

EU contribution: 1560 k€

The project goals

1. Realisation of impedance units (ohm, farad, henry) in the revised SI traceable to fundamental constants
2. Shortening primary traceability chain of calibrations at stakeholder sites
3. Strengthening calibration facilities at smaller NMIs, calibration centres, industry
4. Electrical quantum standards for all metrology institutes
5. Fabrication of robust graphene-based quantum standards
6. Development of cryo-cooler system for all-in-one operation
7. Effective knowledge transfer

The project partners



LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS



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The project implementation

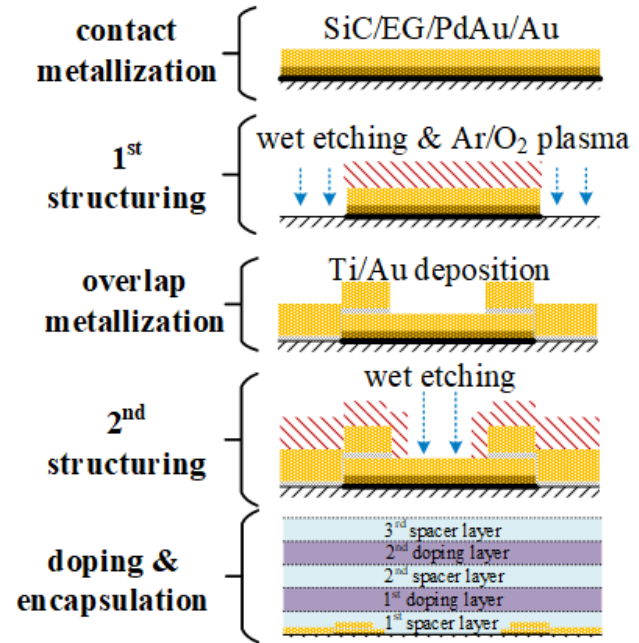
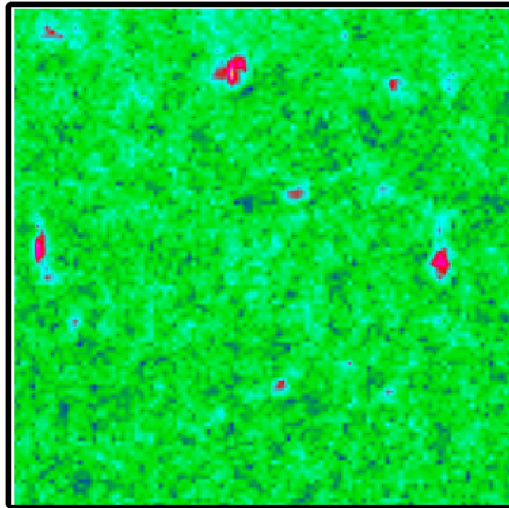
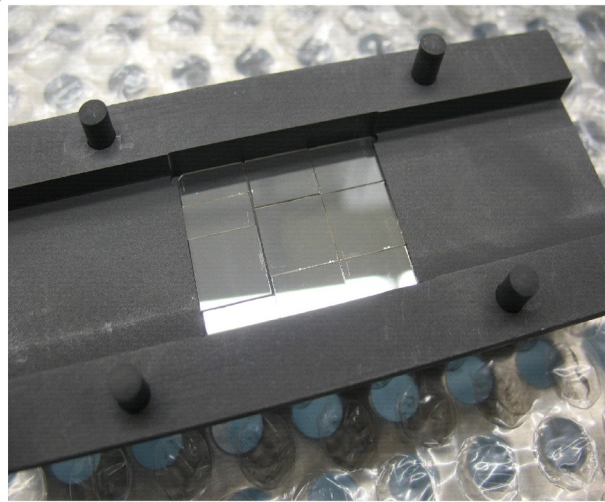
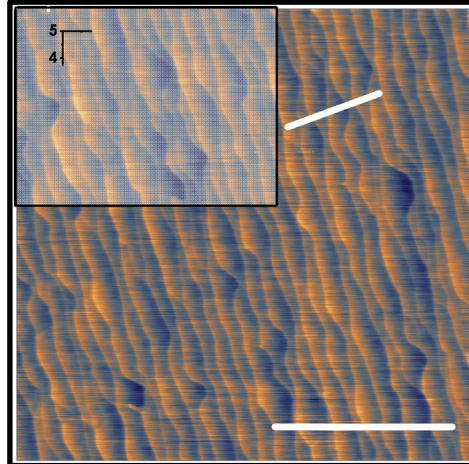
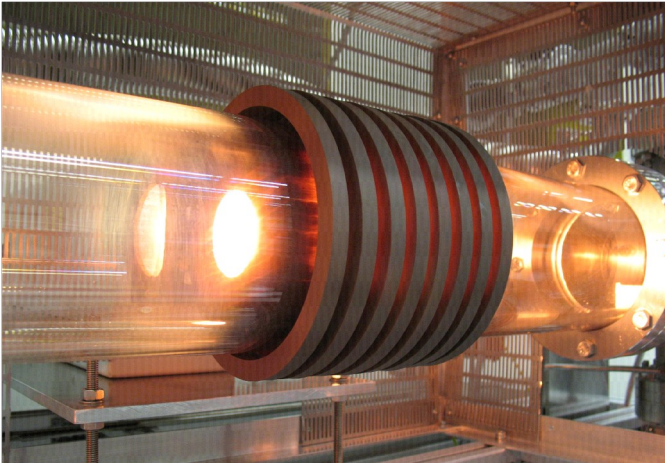
WP1: Graphene devices for AC-QHE applications

WP2: Digital- and Josephson impedance bridges for the realisation of capacitance

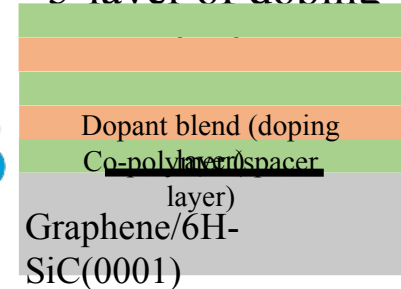
WP3: Graphene AC-QHR with digital and Josephson impedance bridges

WP4: Creating **impact**

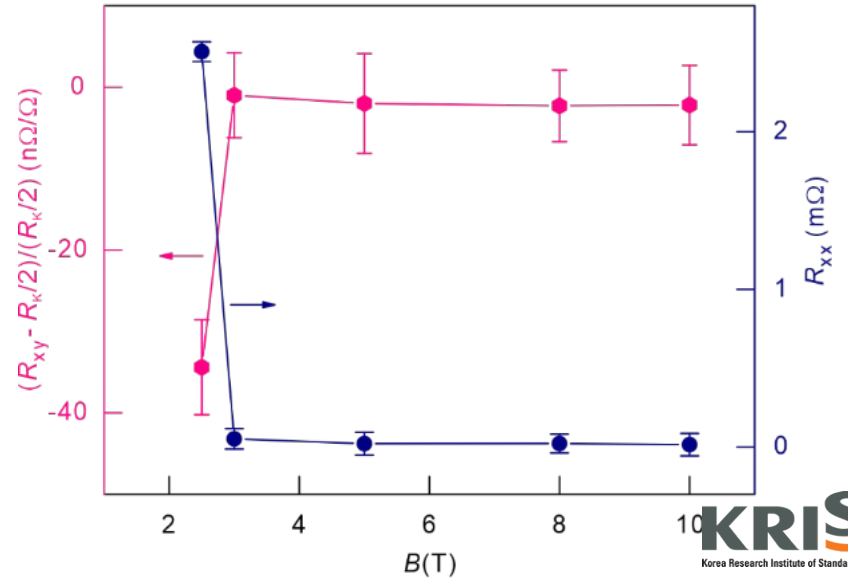
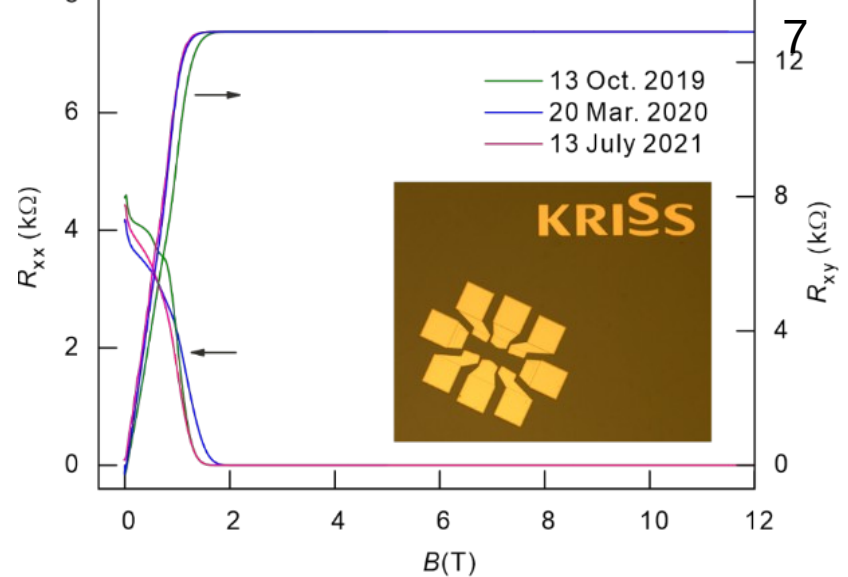
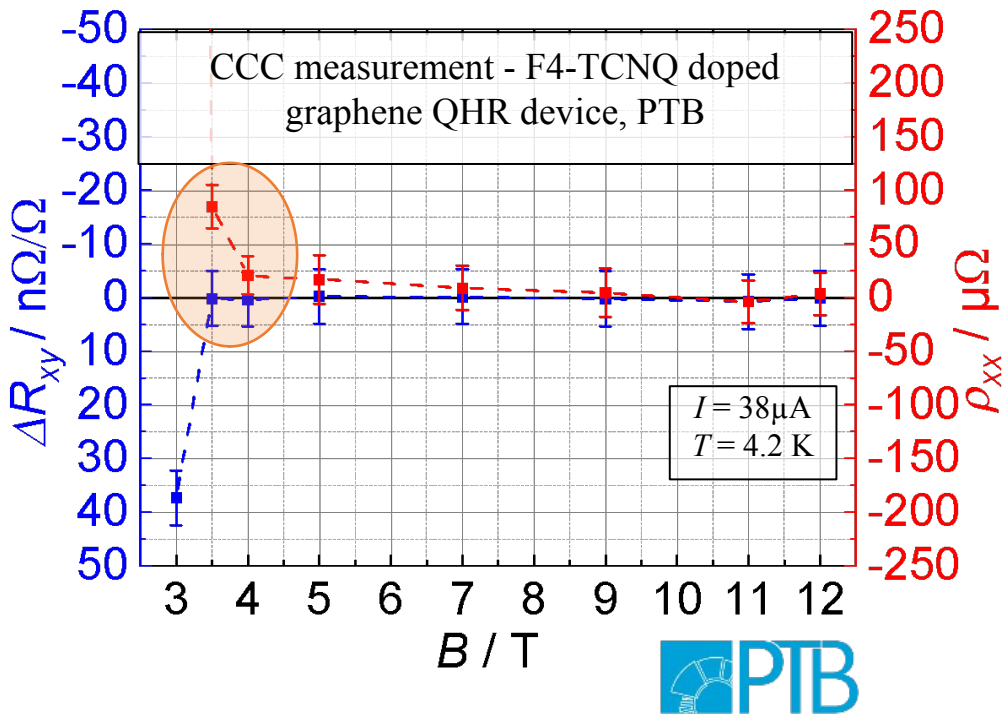
The devices: epigraphene on SiC



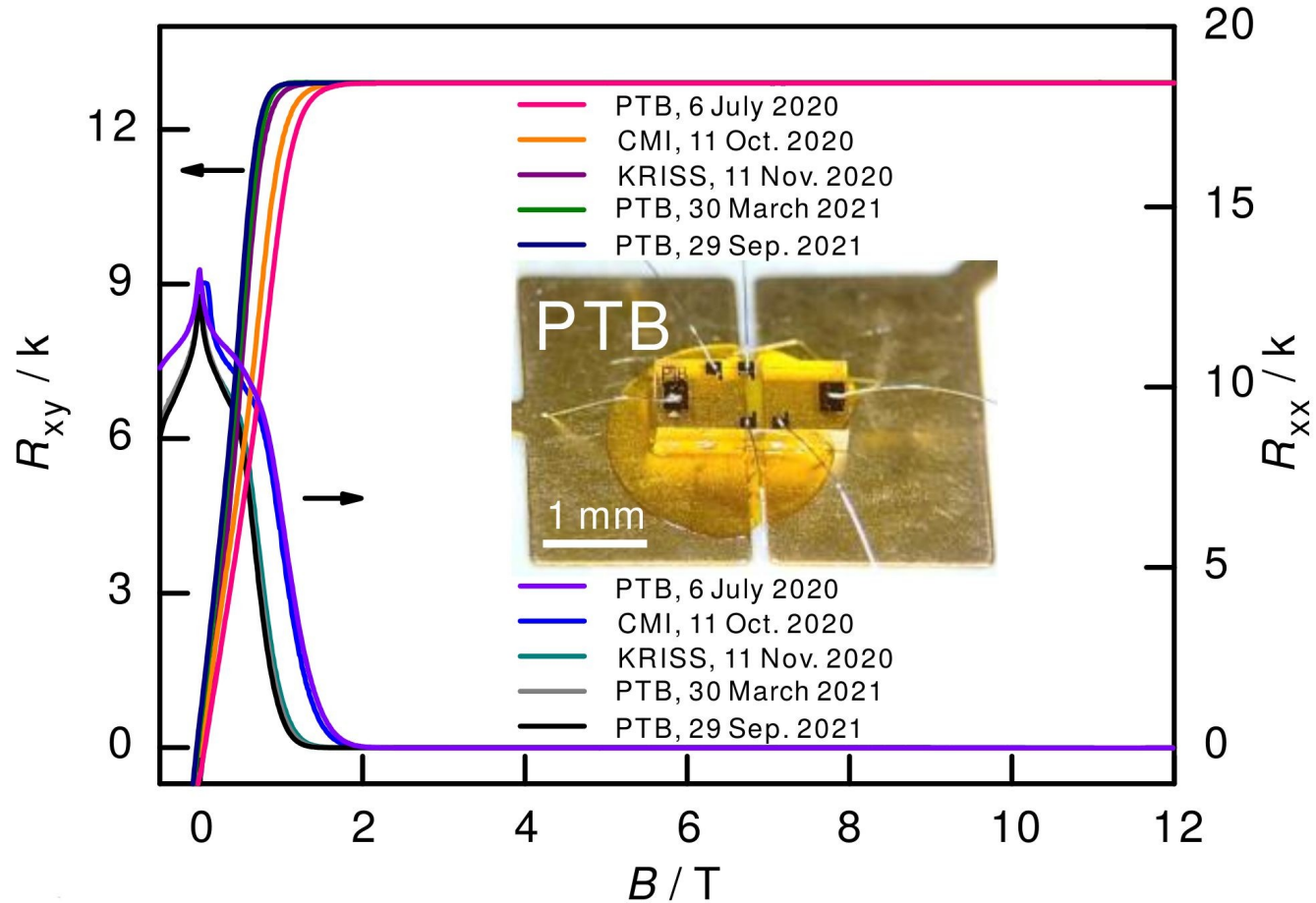
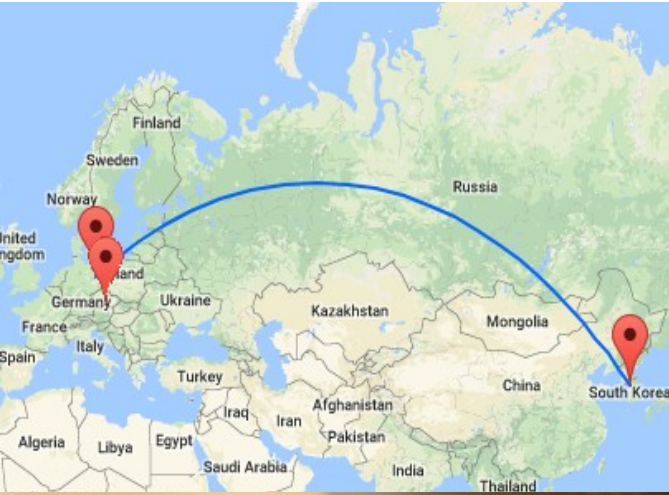
5-layer of doping



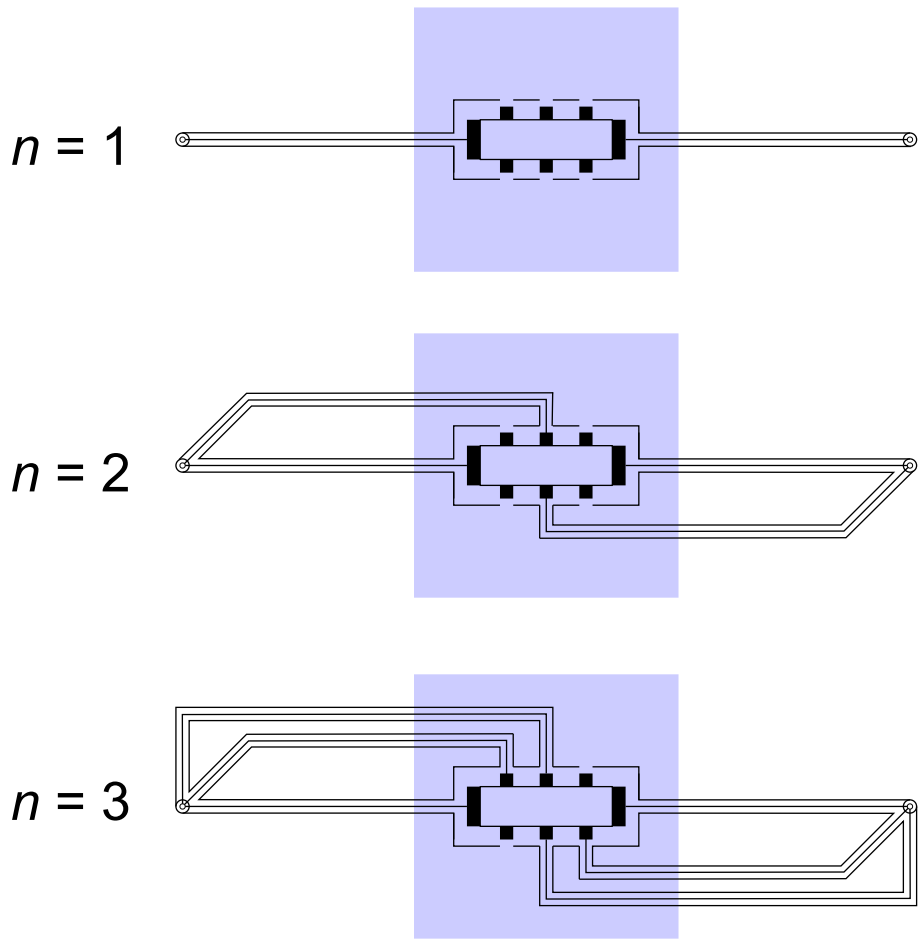
The devices: DC accuracy



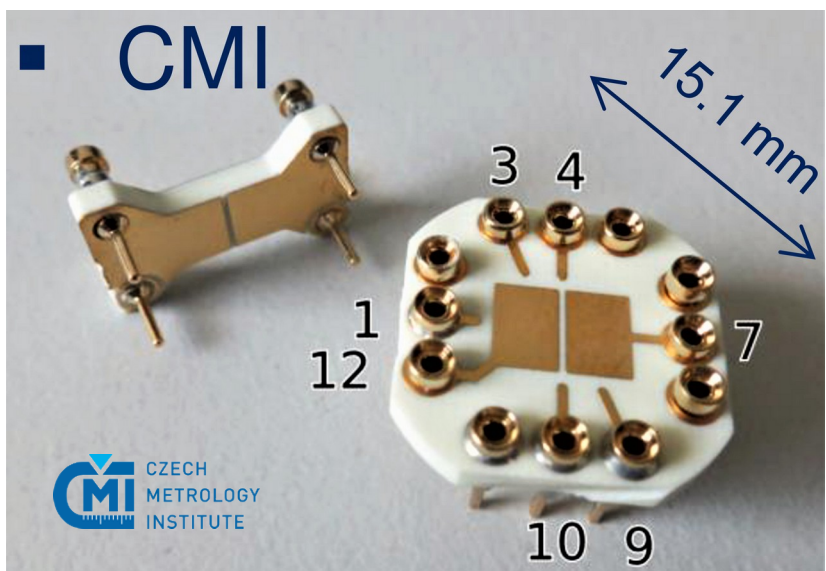
The devices: stability and reliability



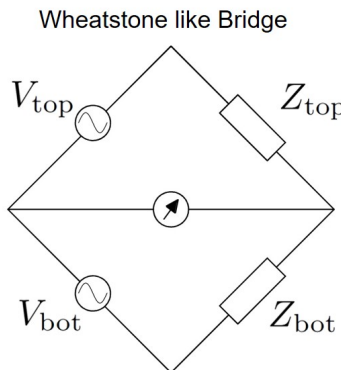
Cryogenic environments



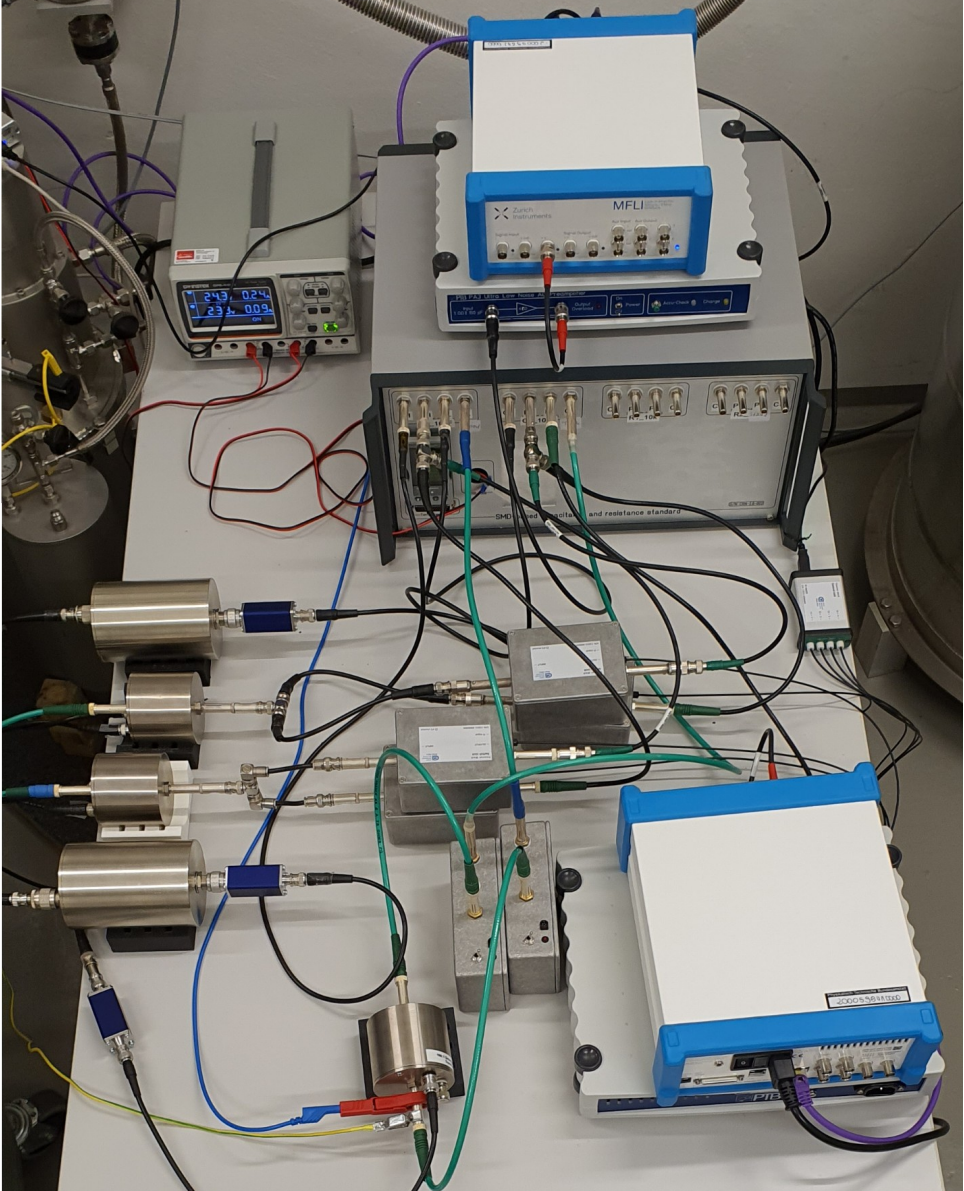
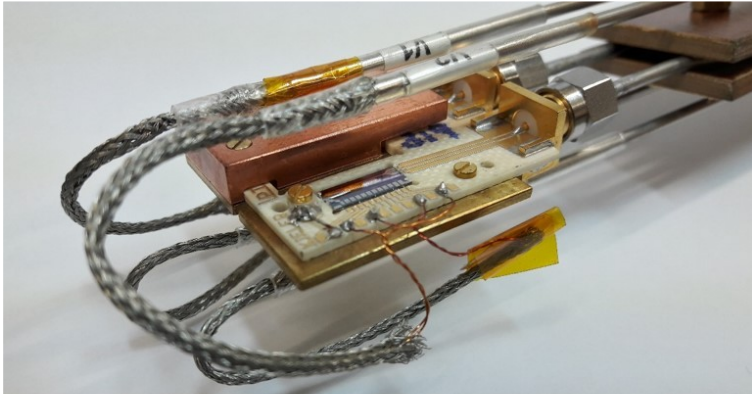
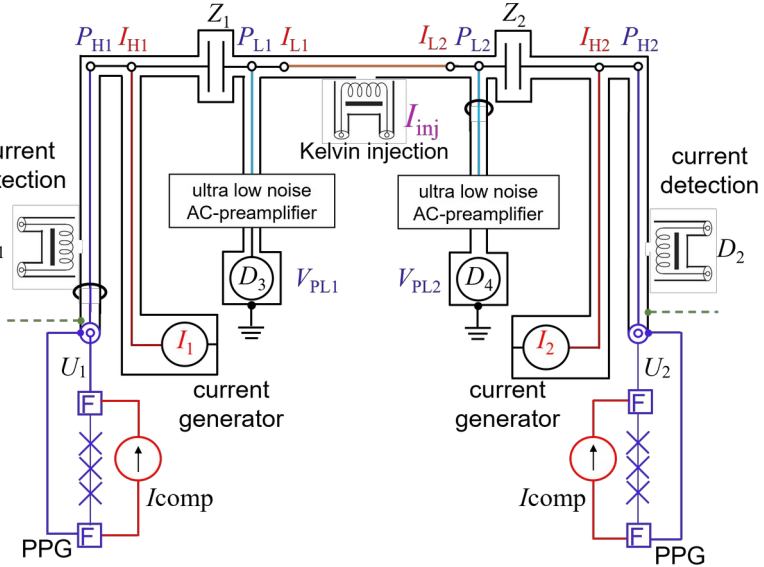
■ CMI



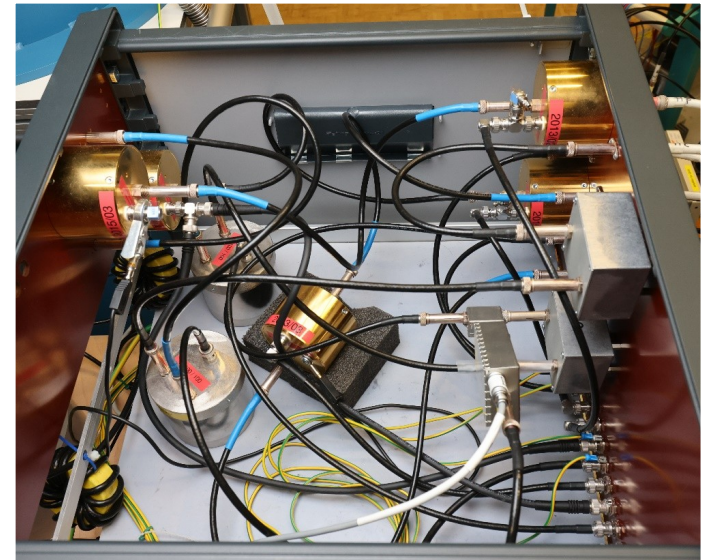
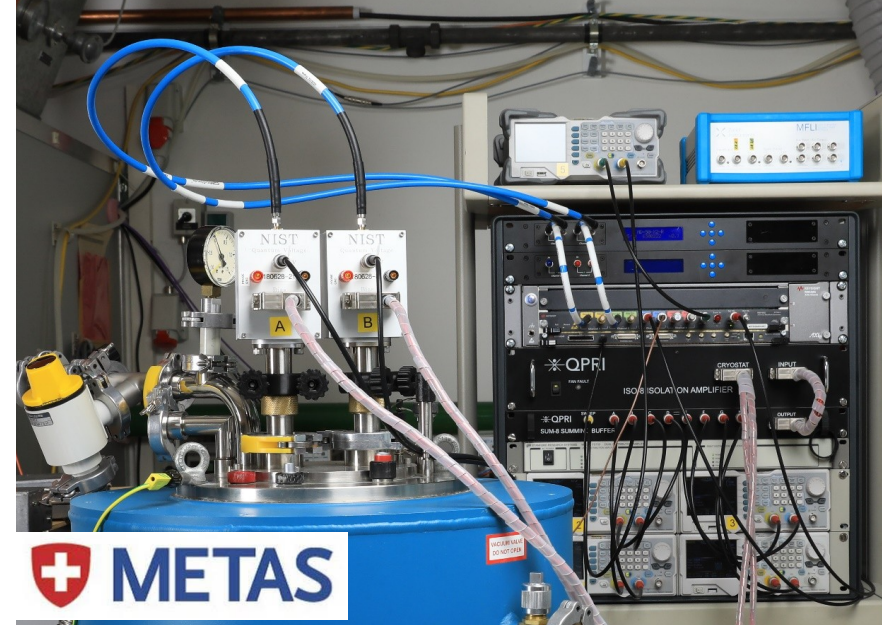
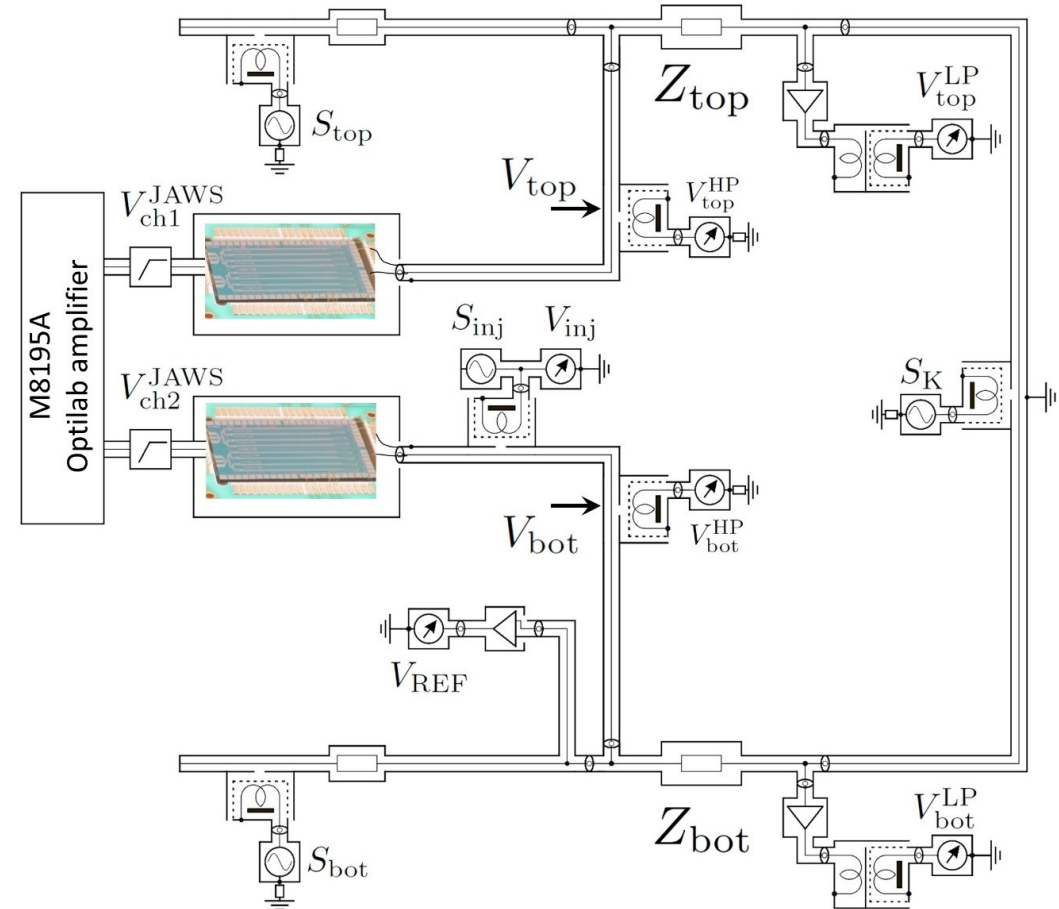
Josephson digital bridges



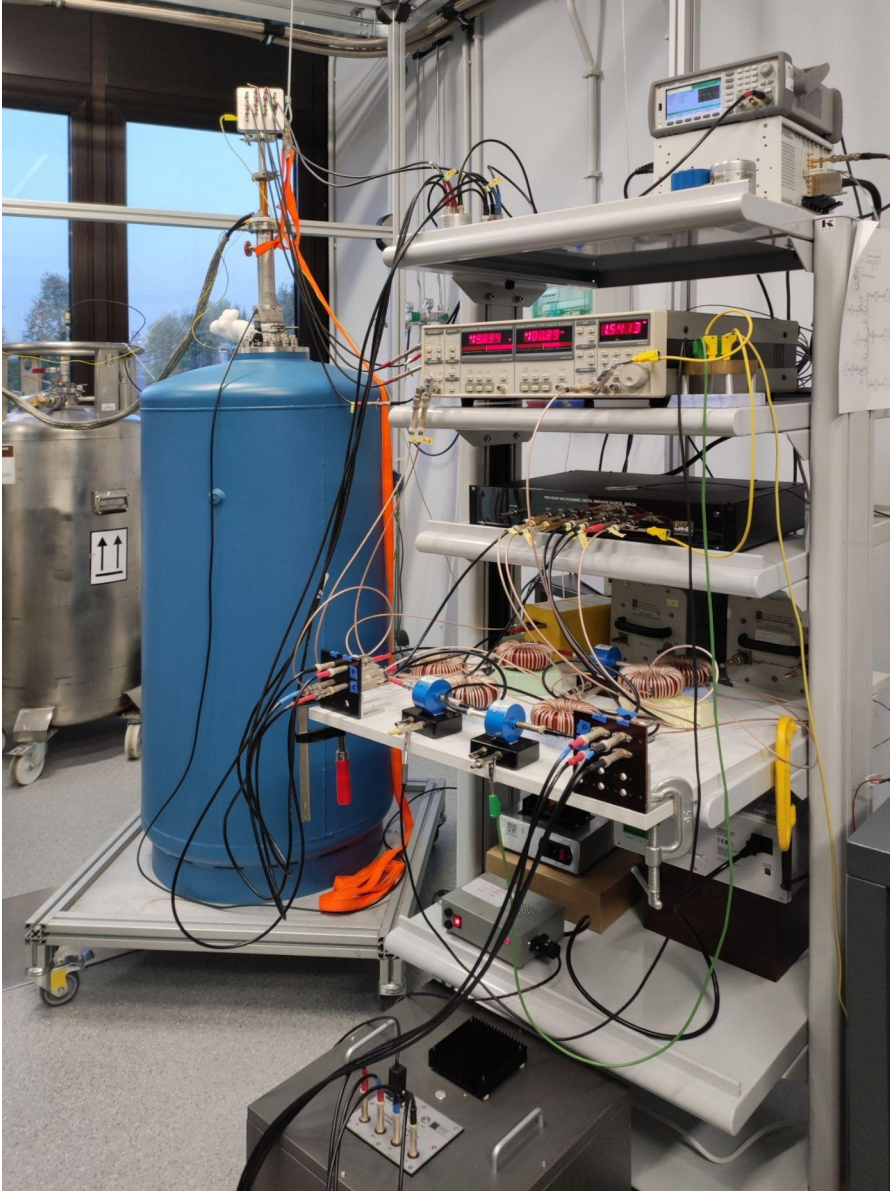
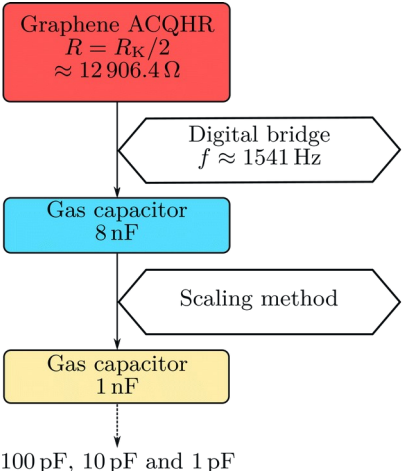
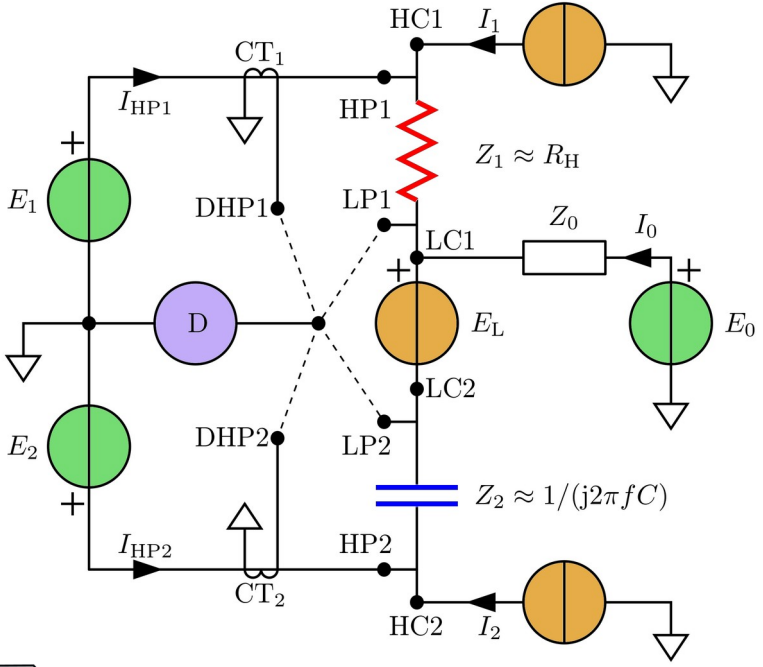
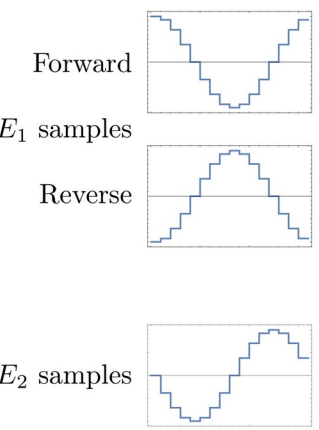
$$\frac{V_{top}}{V_{bot}} = -\frac{Z_{top}}{Z_{bot}}$$



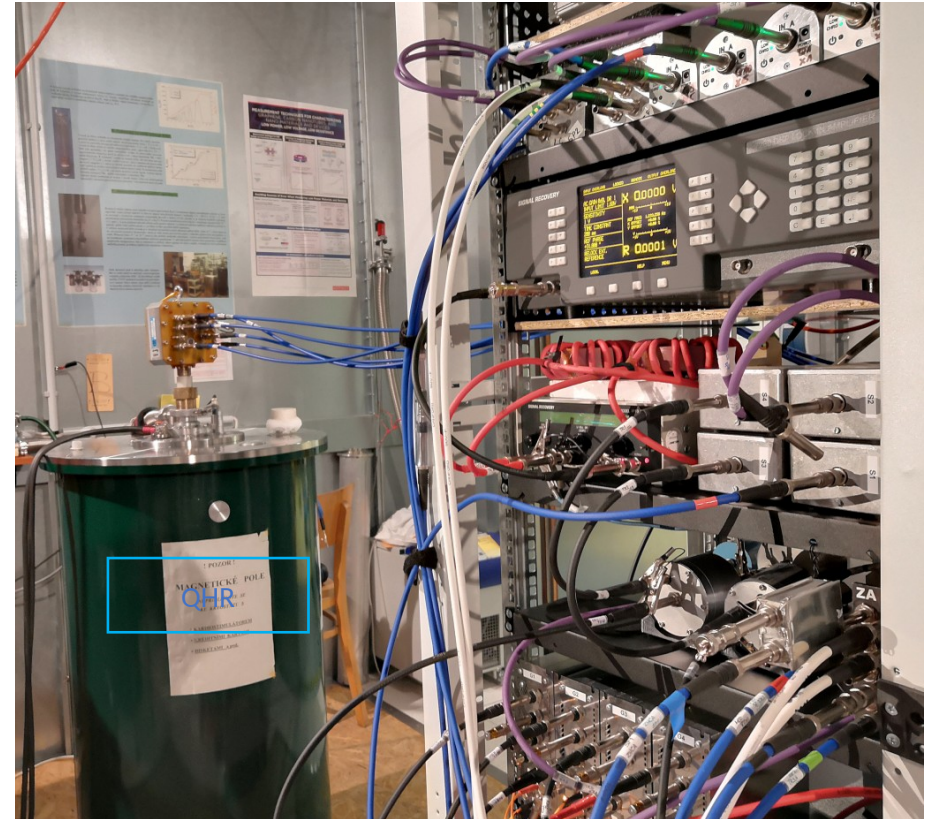
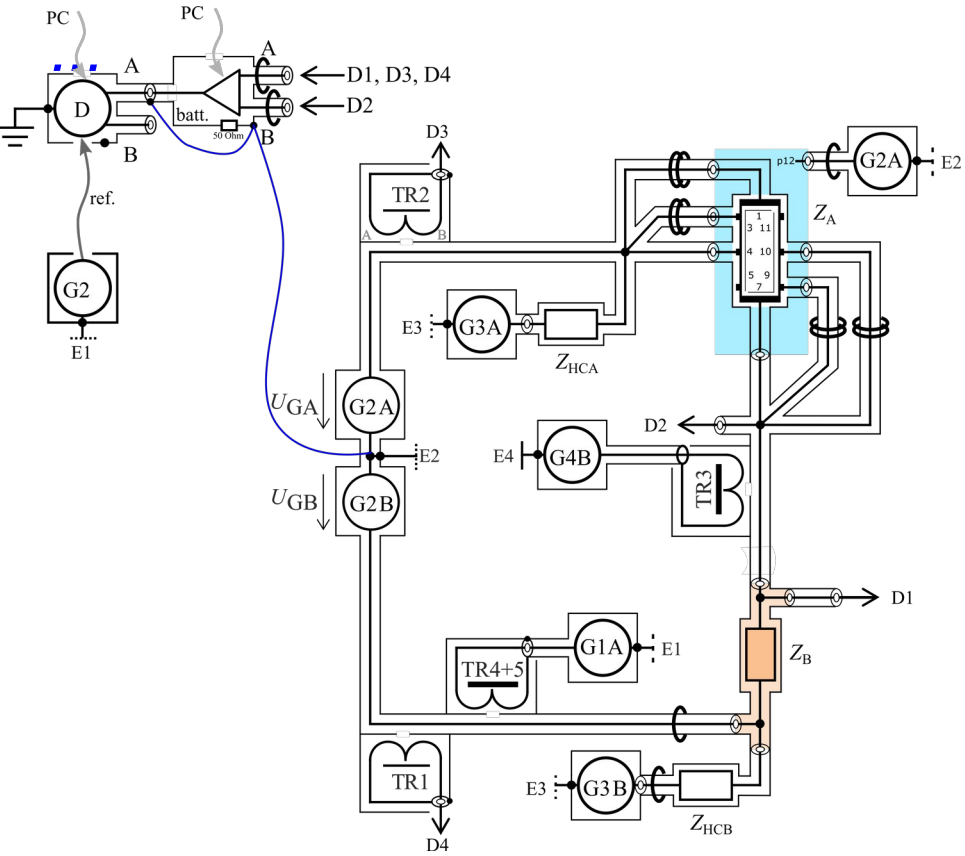
Josephson digital bridges



Electronic digital bridges



Electronic digital bridges

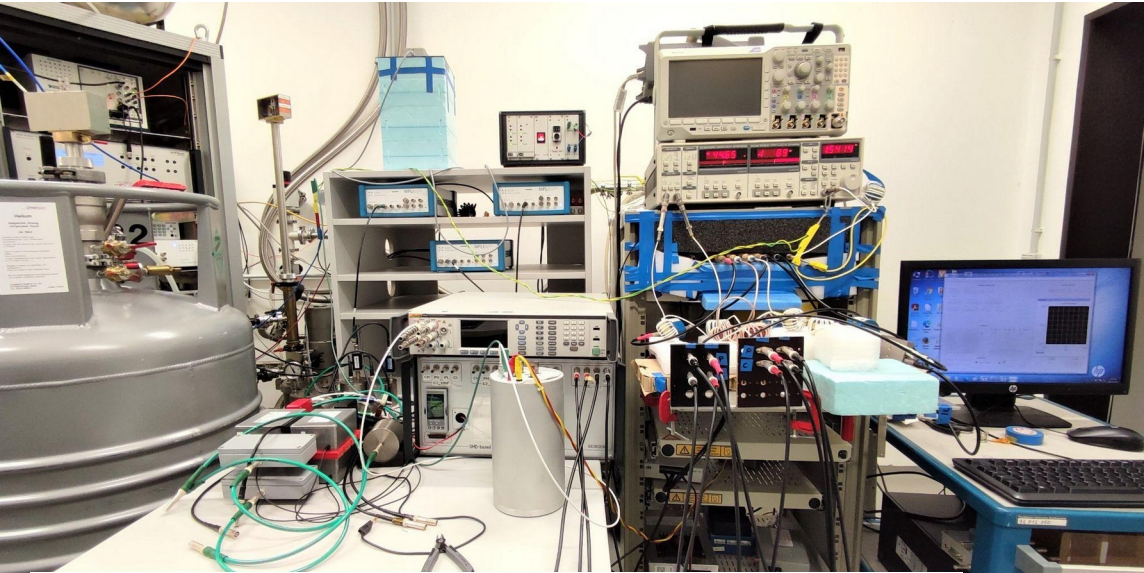


+QHR

FD DigiBridge

+DA

Assessment of digital impedance bridges



- ▶ $R_1 = \text{PTB } 12.9\text{ k}\Omega$
- ▶ $R_2 = \text{INRIM } 12.9\text{ k}\Omega$
- ▶ C_1 and $C_2 = \text{two PTB } 10\text{ nF}$

All the uncertainties are reported with a coverage factor $k = 1$.

Quantity	f/Hz	PTB	INRIM-POLITO	δ	Unit
$C_1/C_2 - 1$	1233	2.506(7)	2.731(111)	-0.225(114)	$\mu\text{F}/\text{F}$
$C_1/C_2 - 1$	2466	3.265(9)	3.292(221)	-0.027(221)	$\mu\text{F}/\text{F}$
$R_2/R_1 - 1$	1233	-21.633(9)	-21.564(102)	-0.069(103)	$\mu\Omega/\Omega$
$R_2/R_1 - 1$	2466	-21.808(11)	-21.772(108)	-0.036(109)	$\mu\Omega/\Omega$
$2\pi f R_1 C_1 - 1$	1233	10.311(9)	10.322(121)	-0.011(121)	$\mu\Omega/\Omega$
$R_{\text{QHR}}/R_1 - 1$	1233	-7.734(9)	-7.773(102)	0.039(103)	$\mu\Omega/\Omega$
$1/(2\pi f R_{\text{QHR}} C_2) - 1$	1233	0.266(9)	0.129(137)	0.137(116)	$\mu\Omega/\Omega$
$2\pi f R_1 C_2 - 1$	1233	7.504(9)	7.620(118)	-0.116(118)	$\mu\Omega/\Omega$
Triangle	1233	0.036(16)	0.024(194)	0.012(195)	$\mu\Omega/\Omega$

EURAMET Project #1501

Technical assessment of novel digital impedance bridges



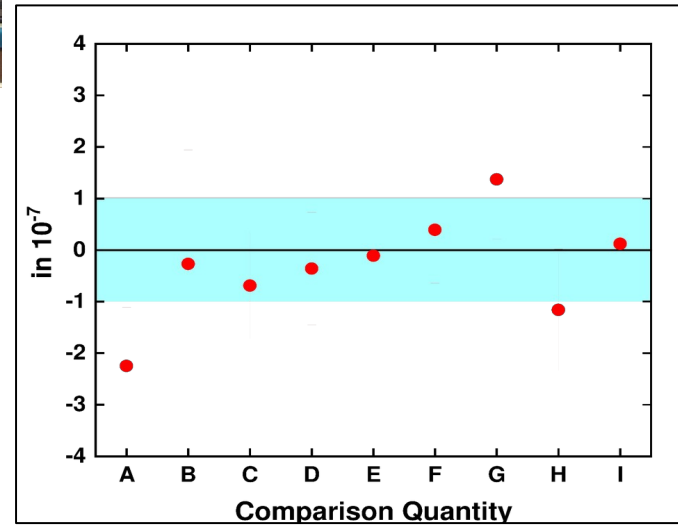
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Outlook: specialised cryostats



INRiM
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DI RICERCA METROLOGICA

KRISS
Korea Research Institute of Standards and Science



Josephson + QHE
In the same cryostat



**RI
SE**

VTT
MIKES METROLOGY

The Good Practice Guide

EMPIR Joint Research Project
18SIB07 GIQS
Graphene Impedance Quantum Standard



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40 pages

83 references

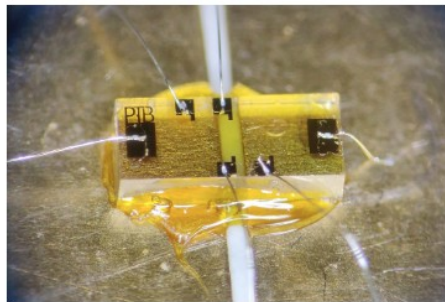
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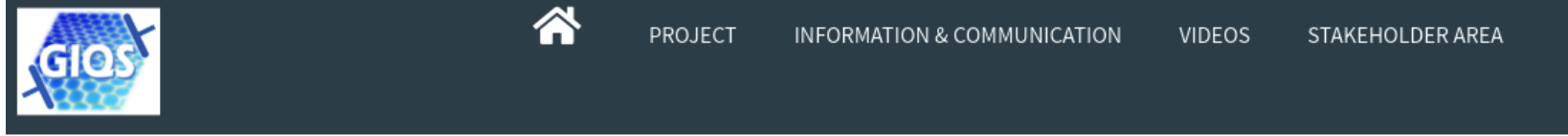
Graphene-based AC-QHE
realization of the farad

“The transition from the actual GaAs-based QHR reference to a compact graphene-based reference, allowing relaxed operational conditions, is now underway at the BIPM and is planned to be effective in a few years’ time.”

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Preparing for the transition from a GaAs to a graphene-based quantum Hall resistance reference at the BIPM

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Scientific publications

Design and development of a coaxial cryogenic probe for precision measurements of the quantum Hall effect in the AC regime, M. Marzano et al., ACTA IMEKO 10 (2021)

Graphene quantum Hall effect devices for ac and dc electrical metrology, Kruskopf et al., IEEE TEM 68 (2021)

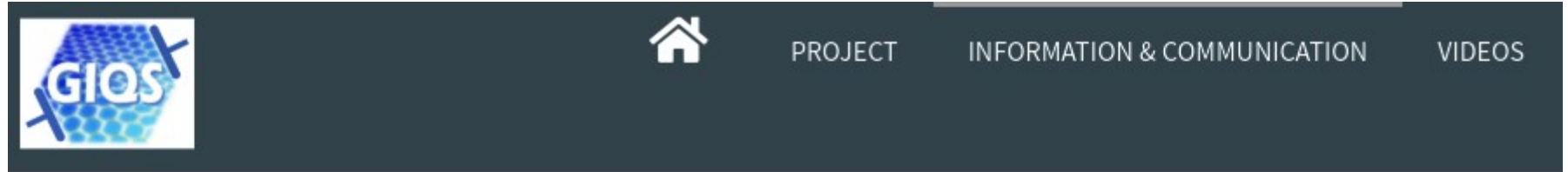
A four-terminal-pair Josephson impedance bridge combined with a graphene quantized Hall resistance, Bauer et al., Meas. Sci. Technol. (2021))

A fully digital bridge towards the realization of the farad from the quantum Hall effect, M. Marzano et al., Metrologia (2020)

Silicon Carbide Stacking-Order-Induced Doping Variation in Epitaxial Graphene, D. Momeni Pakdehi, Adv. Funct. Mater. (2020)

Realization of $5h/e^2$ with graphene quantum Hall resistance array, J. Park et al., Appl. Phys. Lett. (2020)

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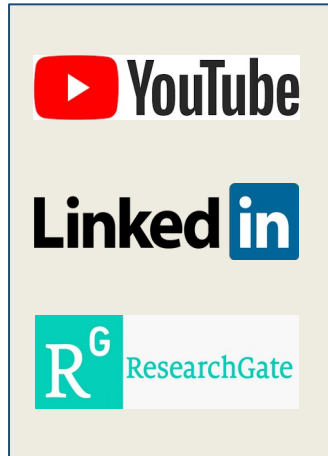
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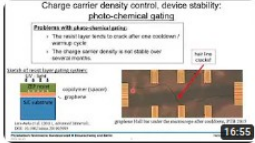
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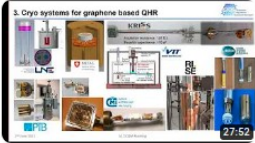
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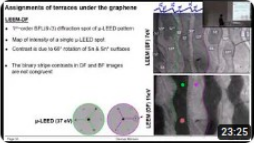
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Thanks to:

- the **people** of the consortium!
- the **collaborators and stakeholders!**

Thank you!