

Advancing Quantum Hall Resistance Standards: Innovations and Applications at PTB

1. Introduction

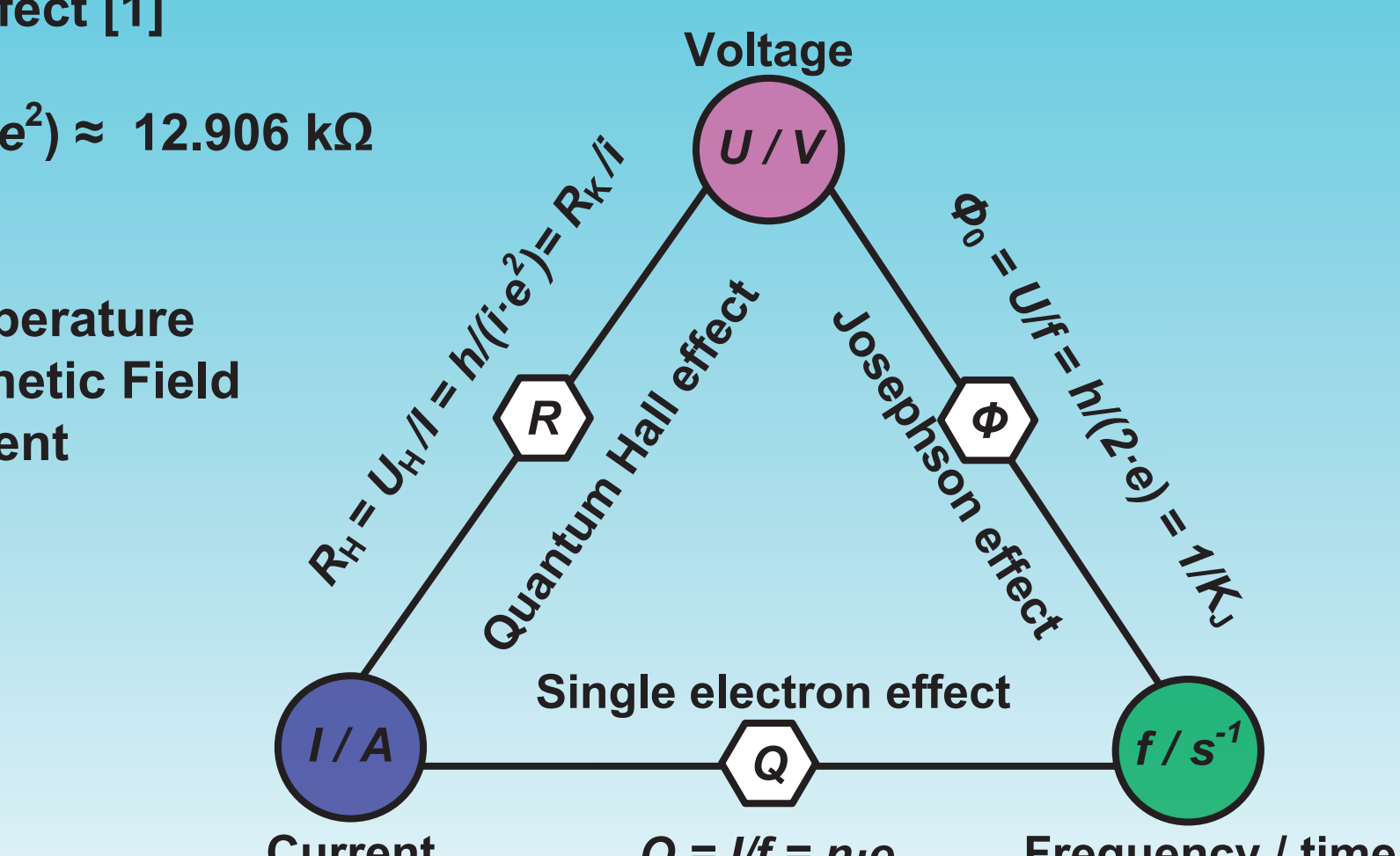
- The Hall resistance plateaus, quantized in terms of the von Klitzing constant " R_K ", provide the realization of the resistance unit 'ohm' based on the Quantum Hall effect [1]

$$R_{\text{Hall}} = R_K/2 = h/(2 \cdot e^2) \approx 12.906 \text{ k}\Omega$$

Critical parameters:

Temperature
Magnetic Field
Current

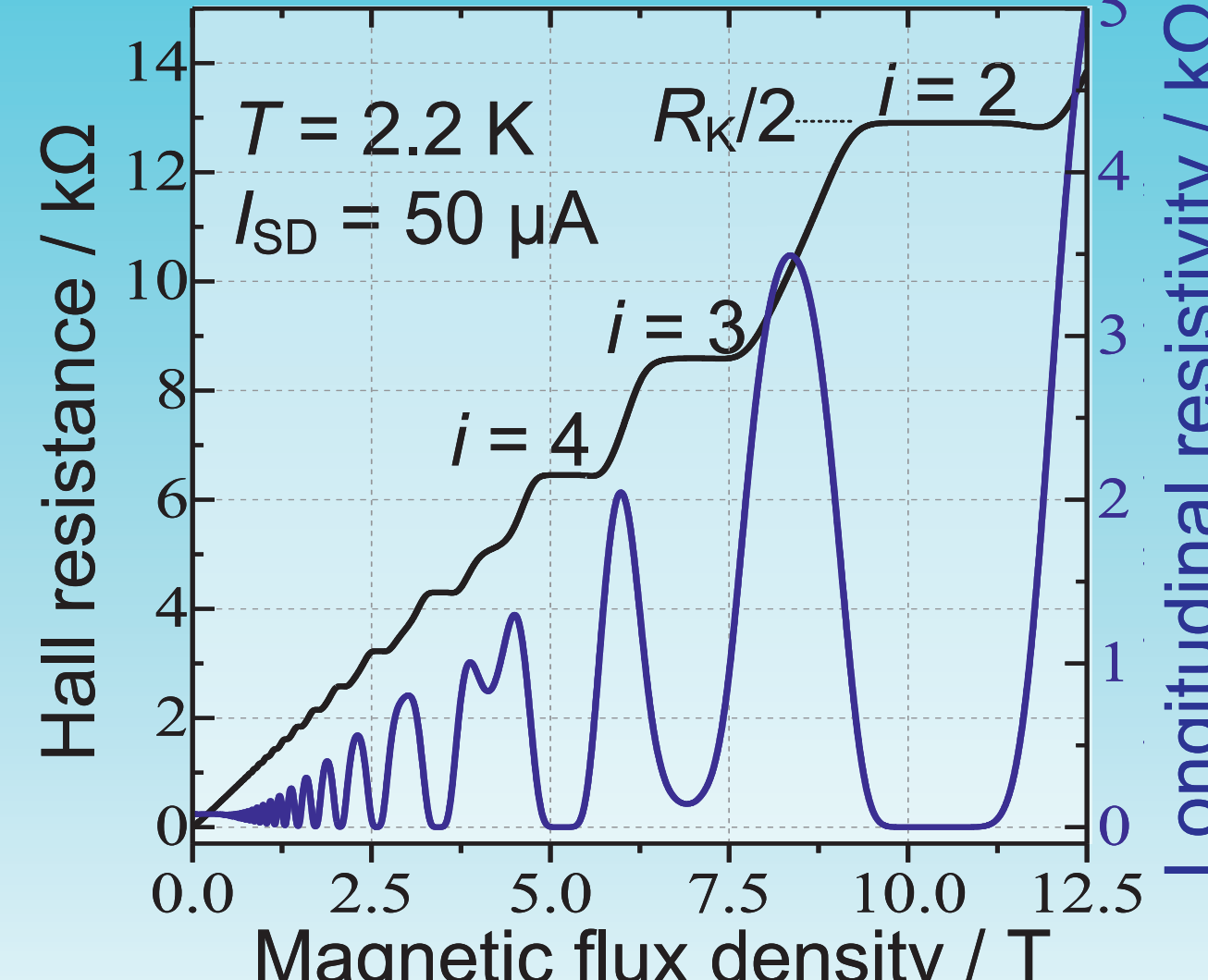
Noble prize laureate
Klaus v. Klitzing



In the quantum metrology triangle [2], three quantum effects define fundamental relations between the quantities el. voltage, el. current and the frequency/time. n and i are integer numbers.

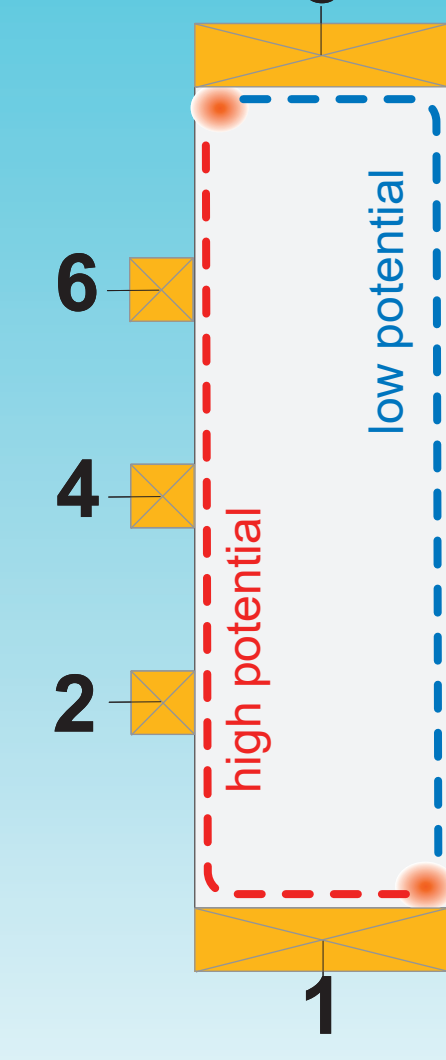
2. The Quantum Hall Effect in GaAs/GaAlAs and Graphene-based Devices [3,4]

GaAs/AlGaAs resistance standard

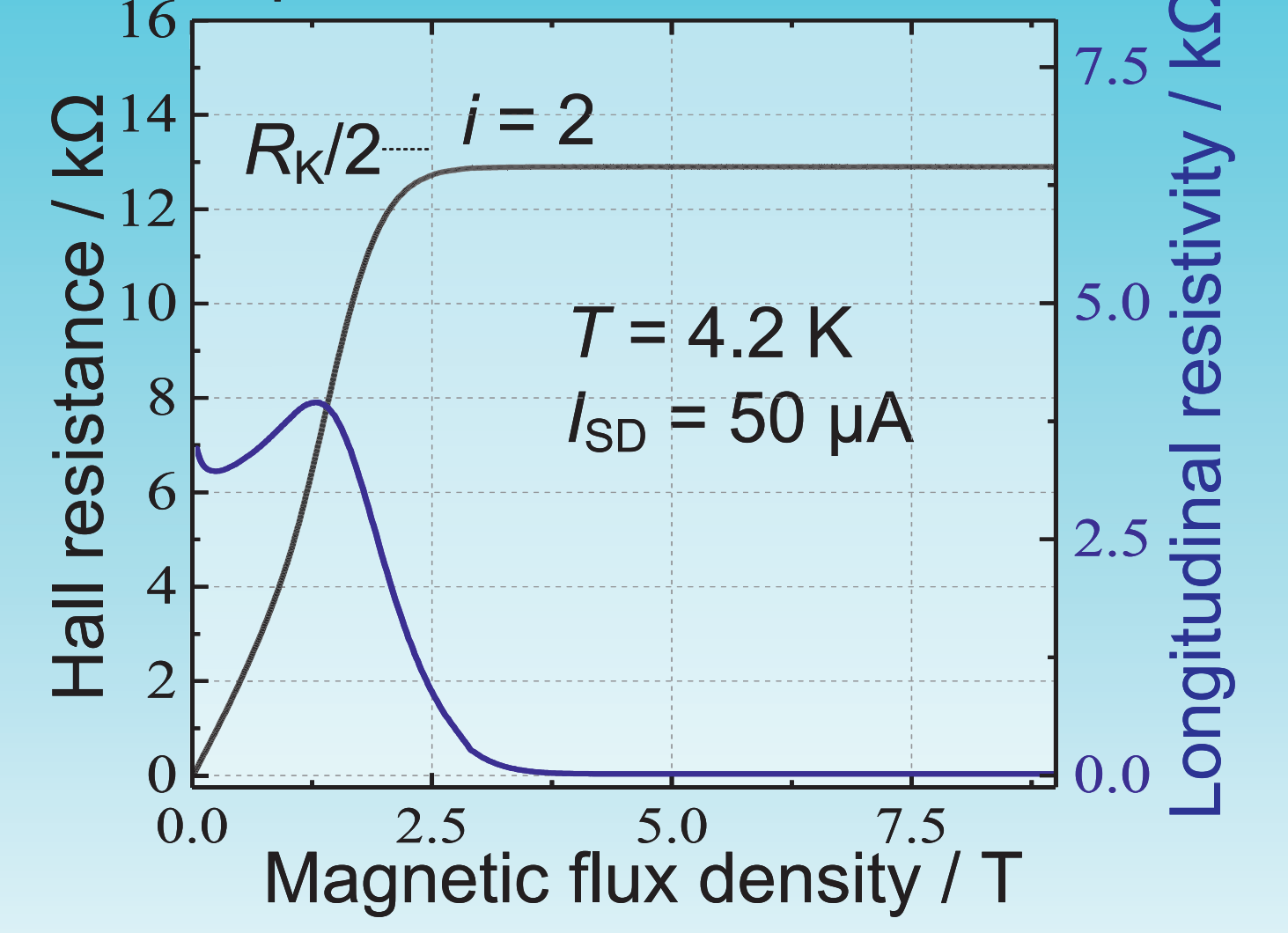


- GaAs/GaAlAs QHR devices require, relatively high magnetic fields B and relatively low temperatures.
- Typical operation conditions are $B = 10.2 \text{ T}$ and $T = 2.2 \text{ K}$.

8



Graphene resistance standard

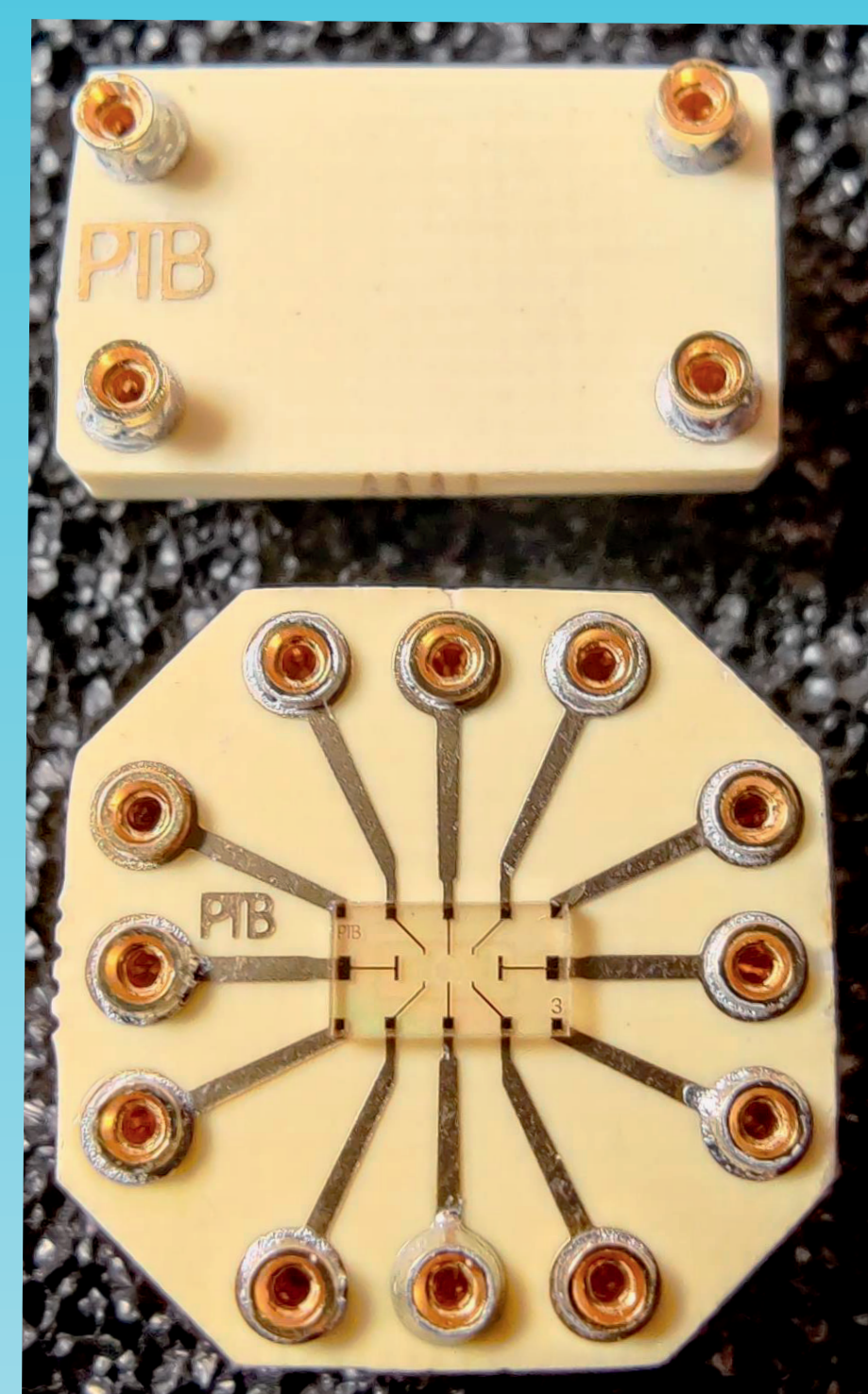


- For QHR devices based on graphene grown on SiC substrate, the resistance plateau for $i = 2$ becomes accessible at $B \leq 5 \text{ T}$ and $T \approx 4.2 \text{ K}$.
- The resistance plateau is comparably wide.

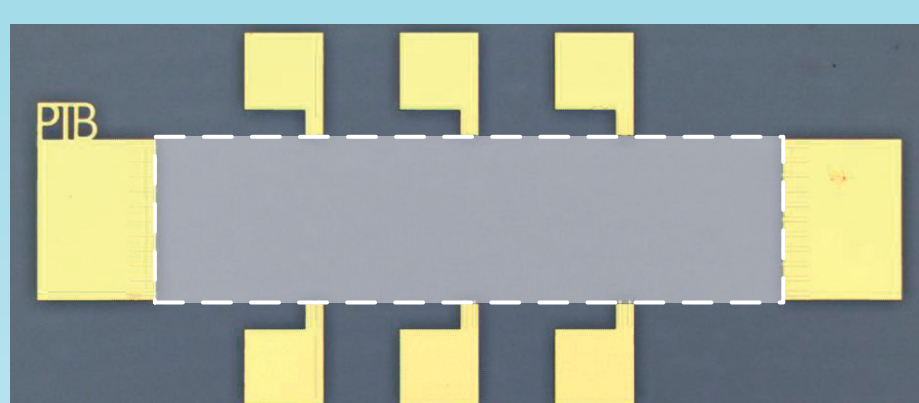
3. Epitaxial Graphene: A New Standard in Quantum Resistance Metrology



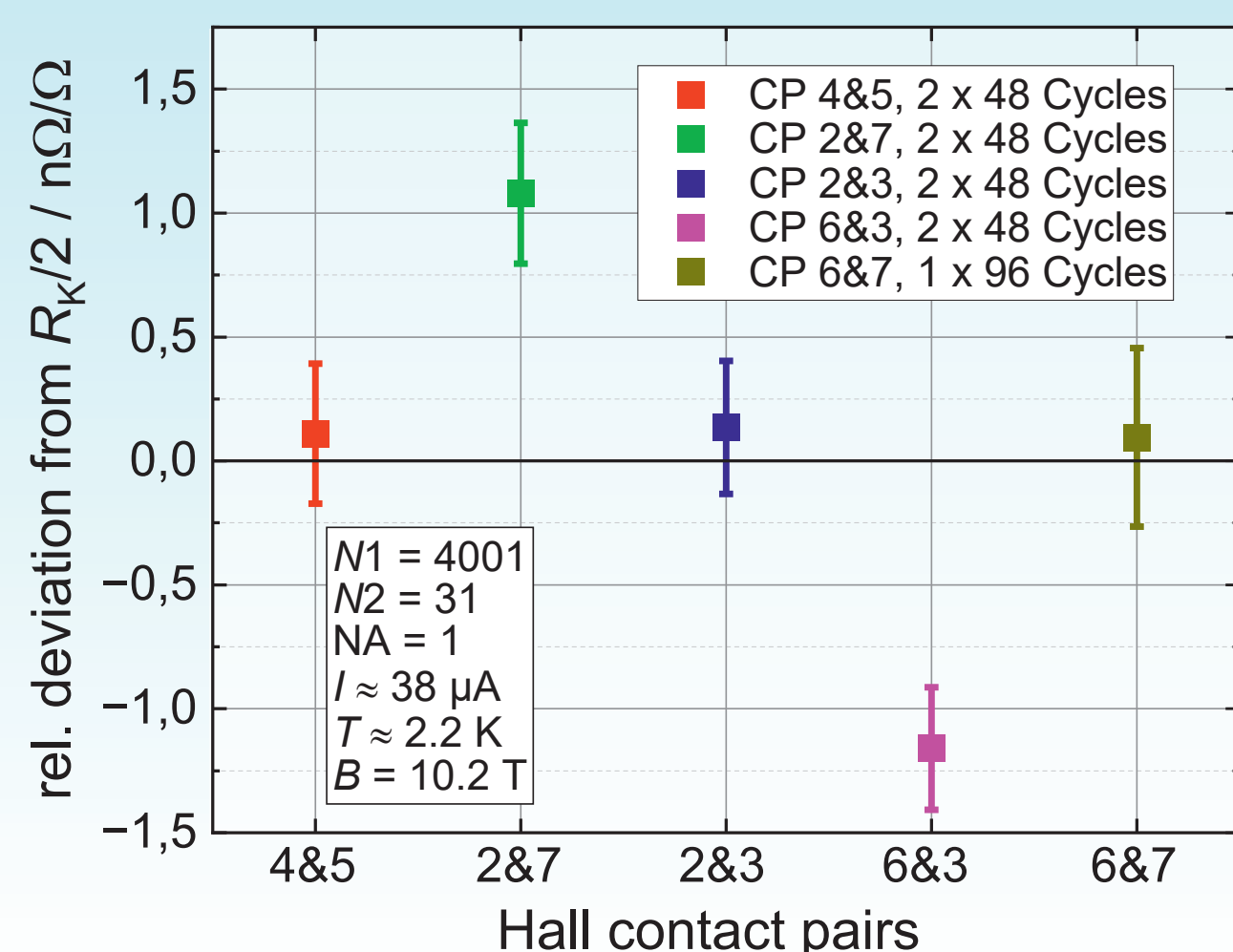
Image of a tabletop cryocooler system that is used for graphene-based quantum Hall resistance (QHR) measurements at PTB.



Graphene quantum Hall device from PTB mounted on a T0-8 sample holder [4]

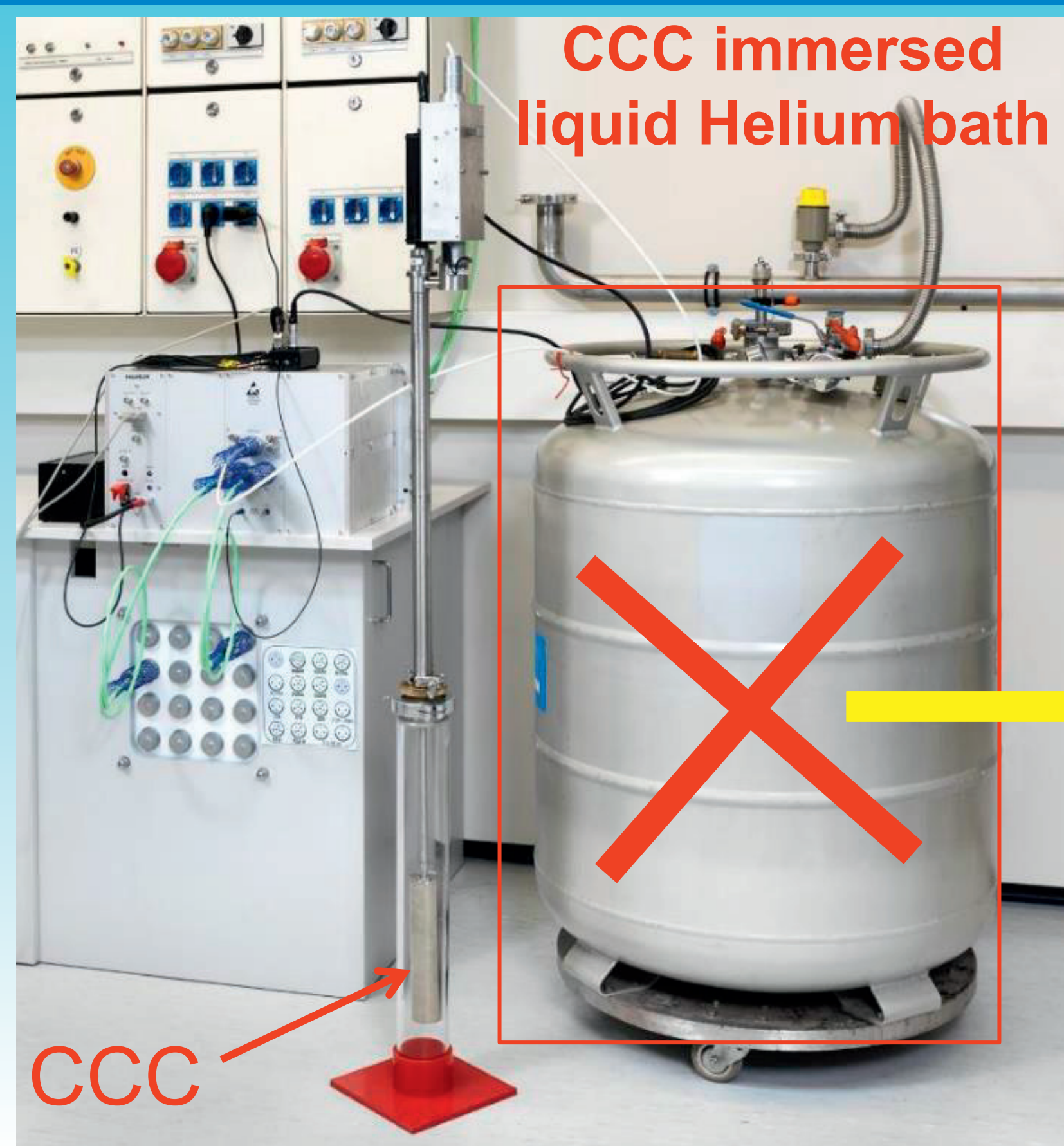


Optical image of a graphene QHR device in Hall bar geometry, fabricated in the PTB's clean room centre



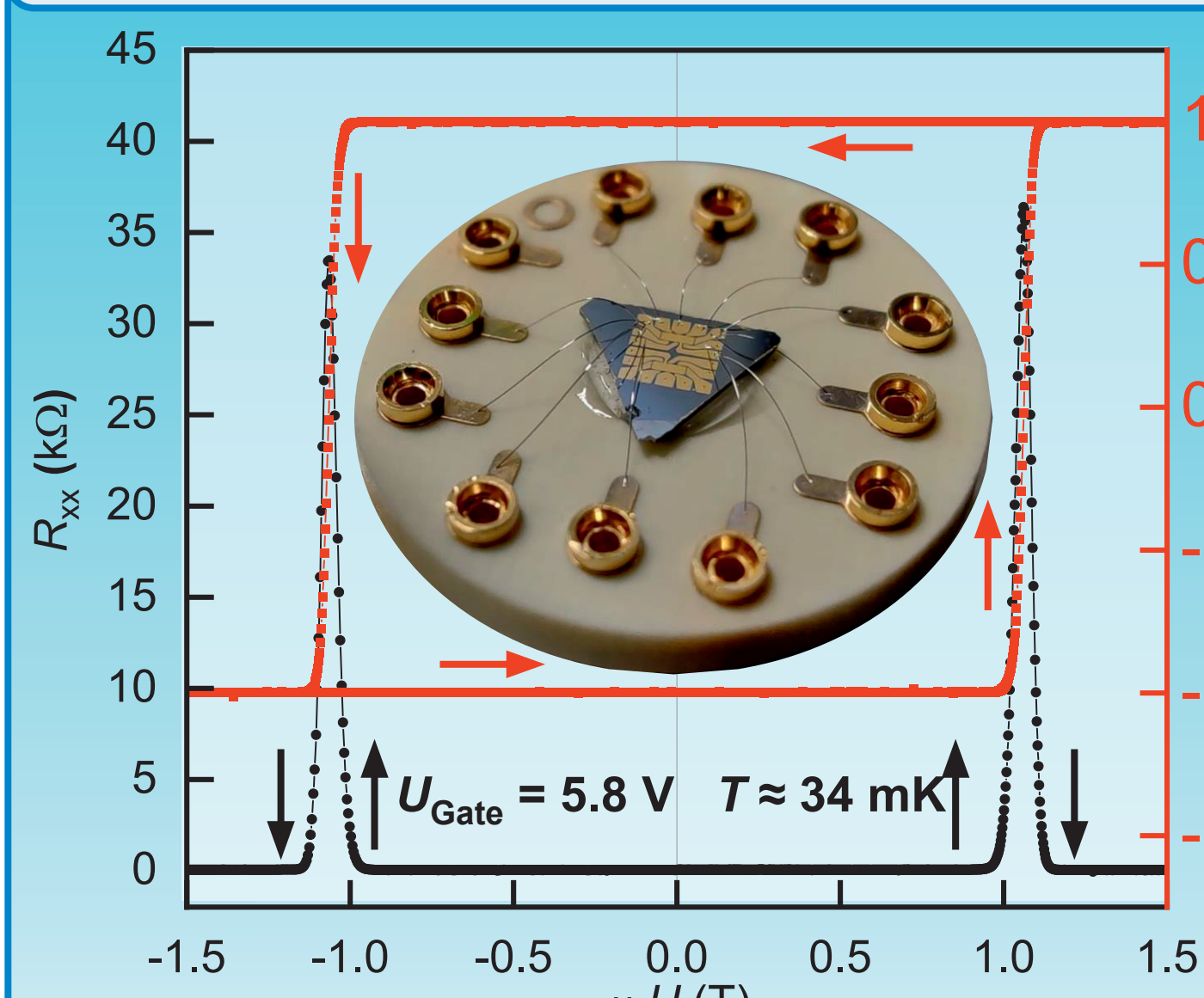
Results from Hall resistance measurements performed with a cryogenic current comparator (CCC) measurement bridge [5] on diagonal and orthogonal voltage contact pairs. The measured values are plotted as relative deviation from $R_K/2$.

4. Cryogenic Current Comparators operated in „dry“ cryocoolers

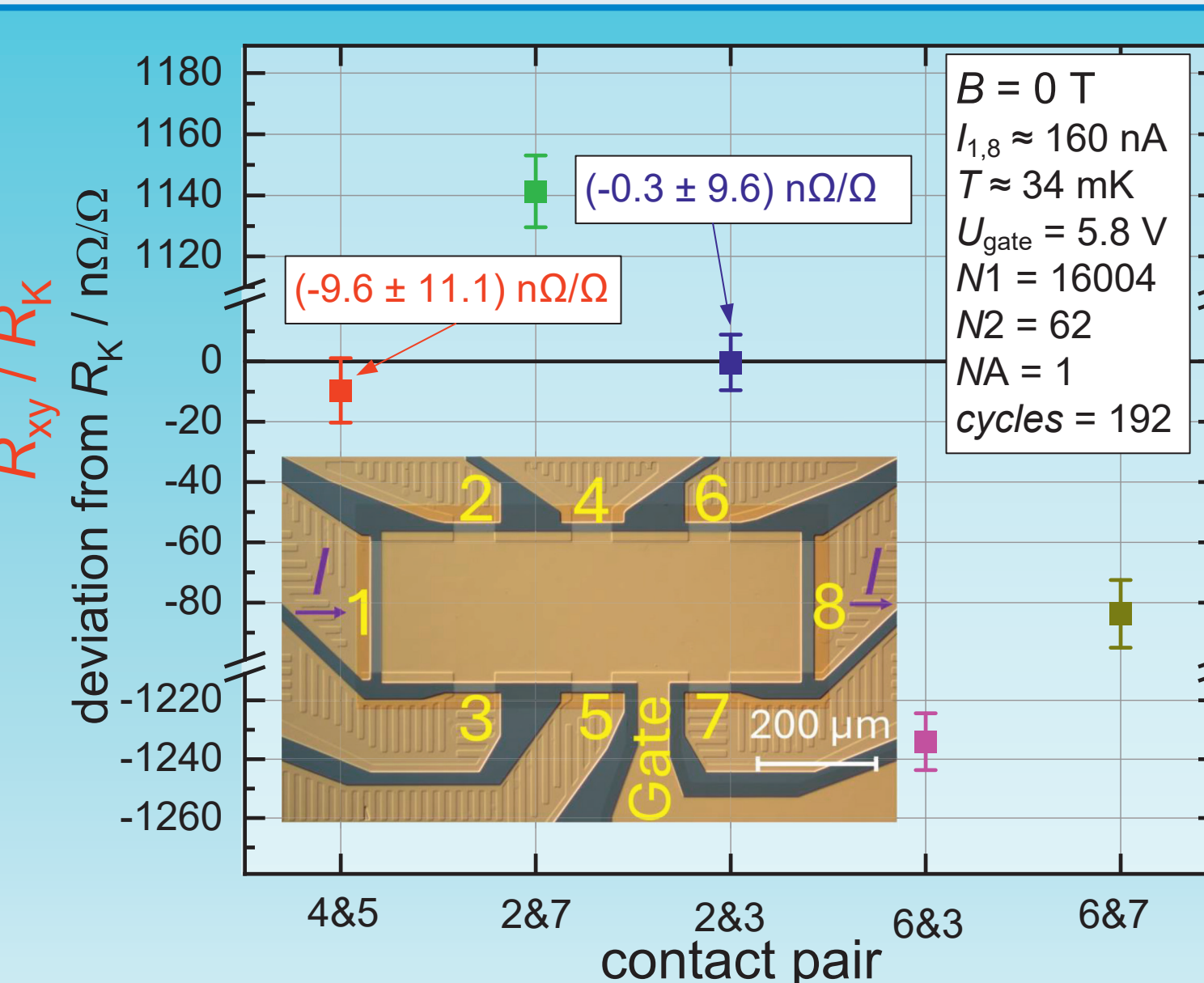


- Traditional CCC systems rely on liquid He^4 , which is costly and increasingly scarce.
- A cryocooler-based CCC is being developed as a more sustainable and industry-friendly alternative, eliminating the need for liquid helium.
- PTB is supporting the development of a cryocooler-integrated CCC prototype in collaboration with industry partners, as part of a newly launched project.
- This new setup will simplify industrial quantum resistance measurements, balancing precision with operational ease.
- Such setup enables economic quantum resistance standard applications in calibration laboratories and in industry, balancing accuracy and precision with ease of operation.

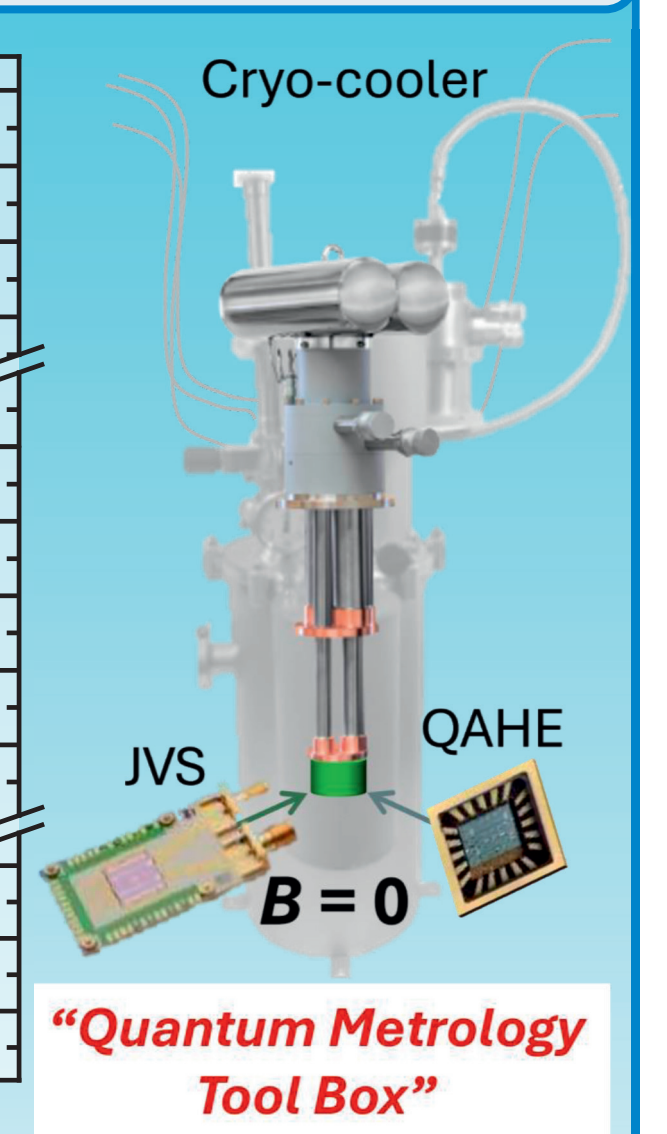
5. Topological Quantum Materials and the Quantum Anomalous Hall Effect



- Longitudinal (R_{xx} , in black) and Hall (R_{xy} , in red) resistance plotted vs. external magnetic field (at optimal gate voltage). Inset: Photograph of a chip with two QAHE devices made from V-doped $(\text{BiSb})_2\text{Te}_3$, mounted on a T08 sample holder
- Once the device is magnetized, R_{xy} is quantized in terms of R_K at $B = 0 \text{ T}$.



- Results from Hall voltage measurement performed with the CCC setup, demonstrating resistance quantization at zero external magnetic field with accuracy and uncertainty on levels of better than $10 \text{ n}\Omega/\Omega$ [6]. Inset: Optical image of the QAHE device in Hall bar geometry.
- Inset picture is the optical image of a V-doped $(\text{BiSb})_2\text{Te}_3$ QAHE device.



The QAHE enables realizing the combination with Josephson-based quantum voltage standards in a single cryo-cooler. [7]

6. Summary

- QHE devices based on GaAs/GaAlAs and graphene provide precise resistance standards, with graphene offering wider plateaus at lower fields and higher temperatures.
- Epitaxial graphene is a leading candidate for the material basis of next-generation quantum resistance standards, providing relaxed operation conditions that can be realized in compact cryocooler systems.
- PTB is collaborating with industry partners on the development of a cryocooler-based CCC prototype to eliminate the need of liquid helium, making precision quantum measurements accessible also for industrial use.
- Topological materials enable the realization of the Quantum Anomalous Hall Effect (QAHE), providing resistance quantization without external magnetic field.

7. References & Acknowledgements

- von Klitzing K et al., New Method for High-Accuracy Determination of the Fine-Structure Constant Based on Quantized Hall Resistance, Phys. Rev. Lett., Volume 45, pp. 494-497, 1980, doi: 10.1103/PhysRevLett.45.494
- K. K. Likharev und A. B. Zorin, „Theory of the Bloch-wave oscillations in small Josephson junctions“, J. Low Temp. Phys. 59, 347 1985, doi: 10.1007/BF00683782
- M. Kruskopf and R. E. Elmquist, “Epitaxial graphene for quantum resistance metrology,” Metrologia, vol. 55, no. 4, pp. R27–R36, 2018, doi: 10.1088/1681-7575/aacd23
- Y. Yin et al., „Graphene quantum Hall resistance standard for realizing the unit of electrical resistance under relaxed experimental conditions“, Phys. Rev. Applied, 2025, DOI: 10.1103/PhysRevApplied.23.014025
- M. Götz, E. Pesel and D. Drung, “A compact 14-bit cryogenic current comparator,” CPEM 2014 Conf. Digest, pp. 684-685, Oct. 2014, doi: 10.1109/CPEM.2014.6898570
- D. K. Patel et al., “A zero external magnetic field quantum standard of resistance at the 10^{-9} level”, Nat. Electron. 2024, doi: 10.1038/s41928-024-01295-w
- Rodenbach L. K. et al., “Realization of the quantum ampere using the quantum anomalous Hall and Josephson effects,” arXiv e-prints, 2023, doi: 10.48550/arXiv.2308.00200

Acknowledgements: The project (23FUN07 QuAHMET) has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States. PTB gratefully acknowledges the support by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC-2123 QuantumFrontiers – 390837967.