

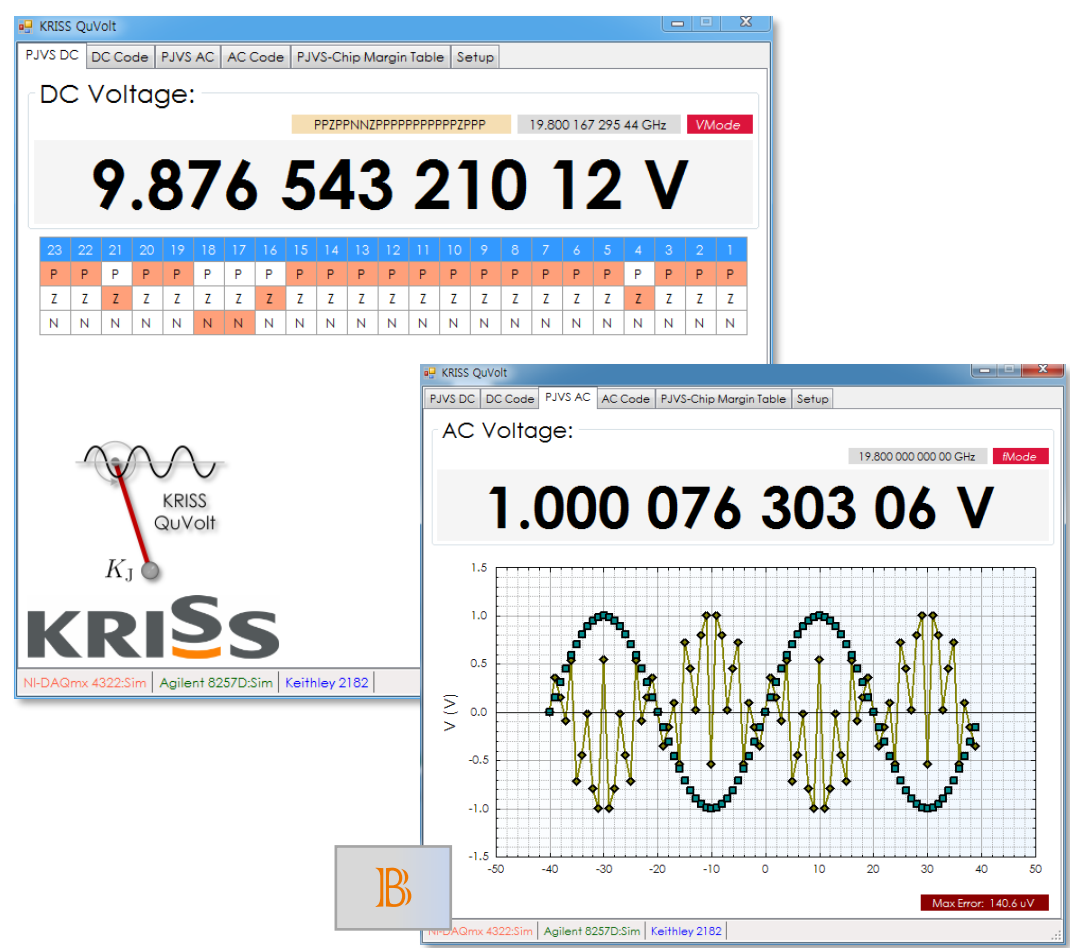
Quantum AC Electrical Standards at KRISS

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Abstract

The Josephson and quantum Hall standards, which represented the SI (International System of Units) volt and ohm based on their exceptional reproducibility, have been promoted in their role to the core of electrical metrology to realize the SI volt and ohm since the 2019 SI redefinition. The standards, established for DC voltage and resistance initially, are now evolving to include AC voltage and impedance. The Korea Research Institute of Standards and Science (KRISS), the National Metrology Institute of the Republic of Korea, has played a significant role in developing quantum electrical standards for both DC and AC measurements. KRISS programmable Josephson voltage standard (PJVS), developed based on the NIST (National Institute of Standards and Technology) superconductor-normal metal-superconductor junction arrays, is not only a standard for DC voltages but is also used as a reference for differential sampling measurements, which can measure AC waveforms in the audio frequency range with the highest accuracy. Its capabilities were recently demonstrated in collaboration with BIPM and NIST during a pilot study for a BIPM key comparison on AC voltages, where KRISS, BIPM, and NIST successfully compared two Josephson-based quantum standards, PJVS and Josephson arbitrary waveform synthesizer. The results showed excellent agreement, with a difference of less than 0.2 $\mu\text{V/V}$ for 1 V at 1 kHz, reaffirming the reliability of Josephson-based quantum voltage standards. In collaboration with PTB (Physikalisch-Technische Bundesanstalt) and CMI (Czech Metrology Institute), KRISS has also realized quantum Hall resistance (QHR) at AC with KRISS-made graphene Hall devices. The Hall quantization was confirmed through a bilateral comparison between KRISS and CMI. The degree of equivalence near 1 kHz is approximately 0.1 $\mu\Omega/\Omega$. KRISS is working to revise its impedance traceability to QHR in graphene. Our ongoing research focuses on the realization of quantum current by leveraging our two quantum standards-KRISS QuVolt (PJVS system) and QHR. Our vision is to implement a quantum calibrator capable of providing quantum-mechanically calculable standards for key electrical quantities in both DC and AC.

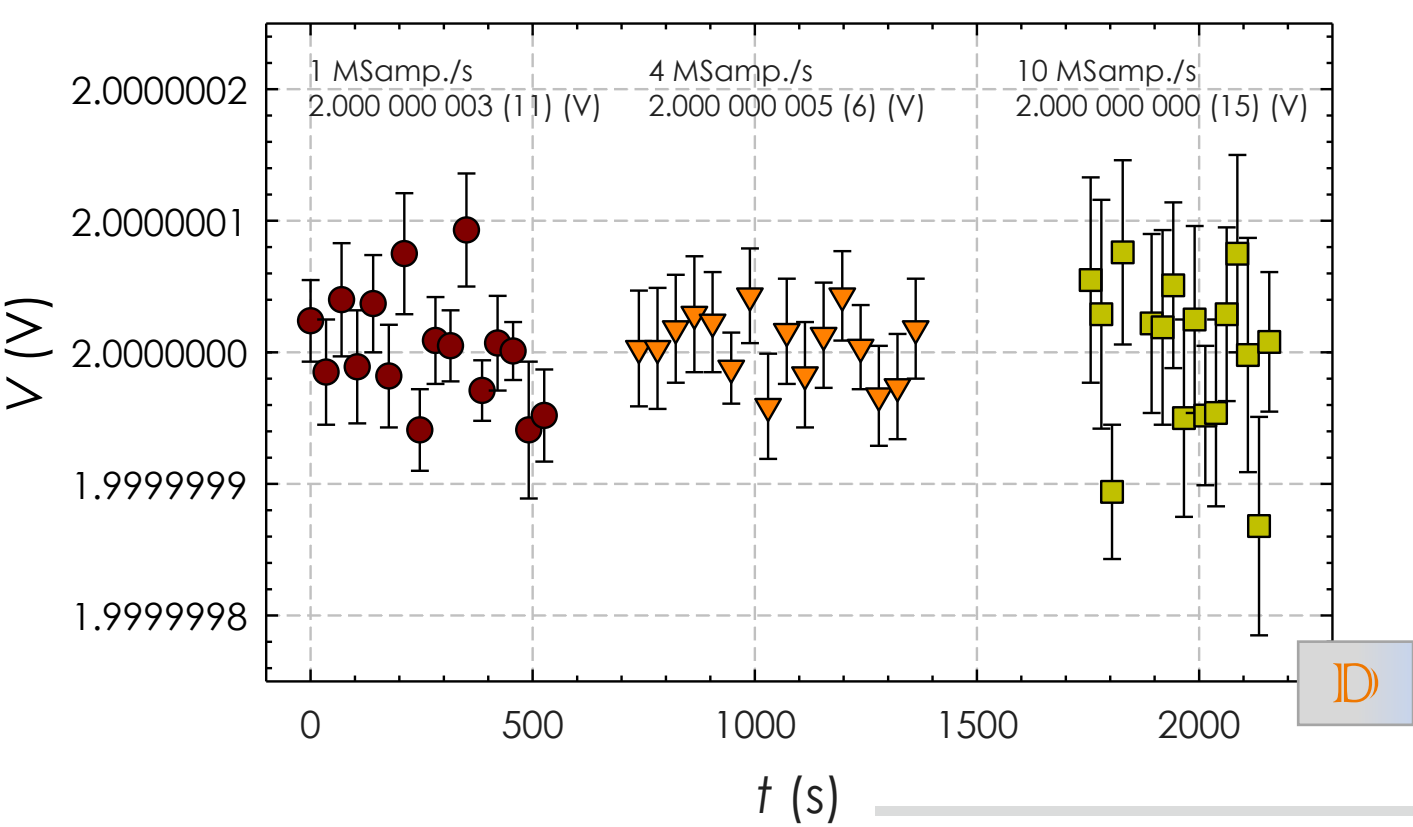
KRISS PJVS



KRISS PJVS:
Since 2006, KRISS has been developing and operating the Josephson Voltage Standard utilizing NIST PJVS arrays (A). The PJVS system, driven by the KRISS bias electronics and operating software (B), can output voltages with quantum mechanical accuracy up to 10V. The PJVS software automatically adjusts the AC bias frequency and DC bias level of each subarray to ensure that the voltage is output with a resolution of 1 nV or less, as long as the output is greater than 100 mV. An (unofficial) comparison with the BIPM, conducted in 2018, confirmed that the difference in DC output voltage (10 V) between the two voltage standards is less than 1 nV (10^{-10} V/V).

KRISS Sampling System:

PJVS-based differential sampling (C) is a fast and highly accurate technique for measuring AC waveforms in the audio frequency range. The basic principle of differential sampling is to measure the voltage difference between a stepwise-approximated sine wave synthesized by PJVS and the AC waveform to be measured with a sampler (digitizer). After sampling, the AC waveform is reconstructed based on the calculable step voltages of the Josephson waveform, and the corresponding RMS amplitude is obtained by a discrete Fourier transform analysis or a sine fit. In 2010, KRISS developed a proprietary differential sampling technique and reported results measuring AC waveforms at 50 Hz with an uncertainty of 10^{-7} V/V or less. In 2014, this technique was used as a key element of a quantum-based power standardizer that dramatically improved the accuracy of AC power measurements. Since 2017, KRISS has provided technical support to BIPM for a pilot study on international comparisons of quantum-based AC voltage measurements.

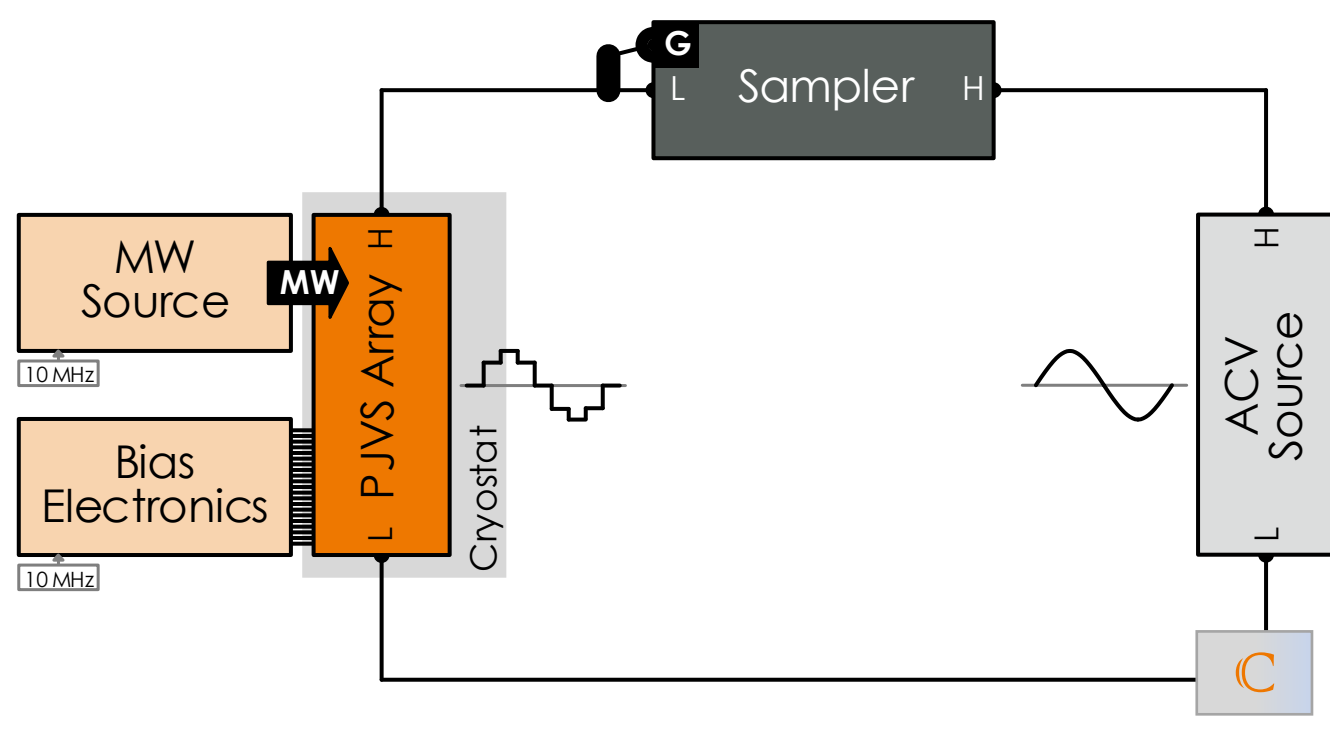
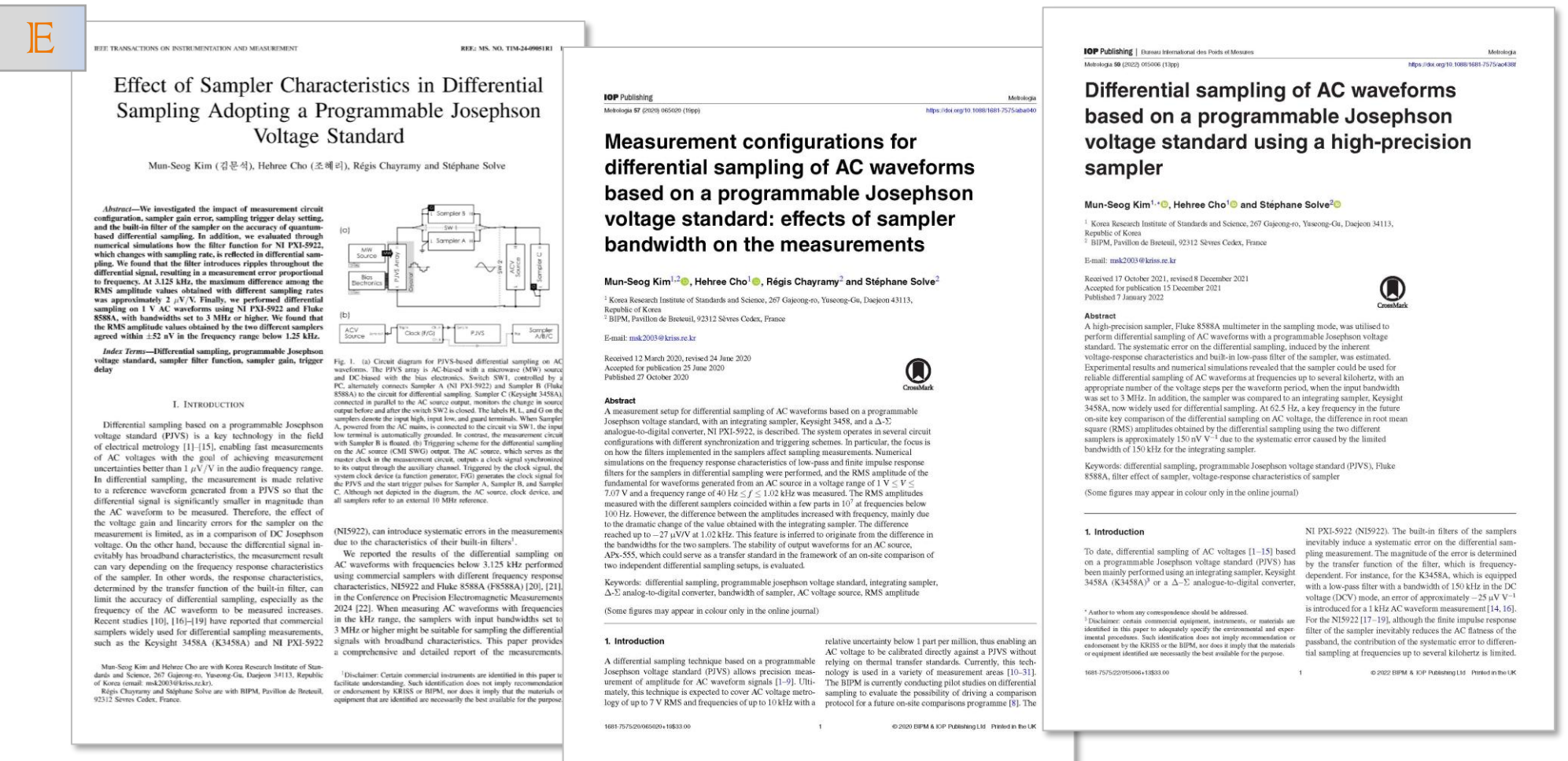


PJVS-JAWS Comparison:

In 2023, KRISS participated in a pilot study for an international on-site comparison of AC voltages based on the Josephson standard to be conducted by the BIPM. For about three weeks at KRISS in Daejeon, comparisons were performed in the frequency range below 1.25 kHz using a KRISS-developed programmable Josephson voltage standard (PJVS) and differential sampling system. The study employed an AC source developed by CMI in the Czech Republic as the transfer standard, and comparisons were performed using two different samplers (NI PXI-5922 and Fluke 8588A). Then, in the summer of 2024, KRISS also participated in another BIPM pilot study at NIST in Boulder. This pilot study, involving BIPM, KRISS, and NIST, was the first to measure AC waveforms synthesized by a Josephson arbitrary wave synthesizer (JAWS) developed by NIST with the BIPM (KRISS and NIST-developed) measurement system. The measurements confirmed the reliability of the BIPM system, achieving a Type A uncertainty of 1 part in 10^9 for a 10 Hz sine wave at 2 V rms (D).

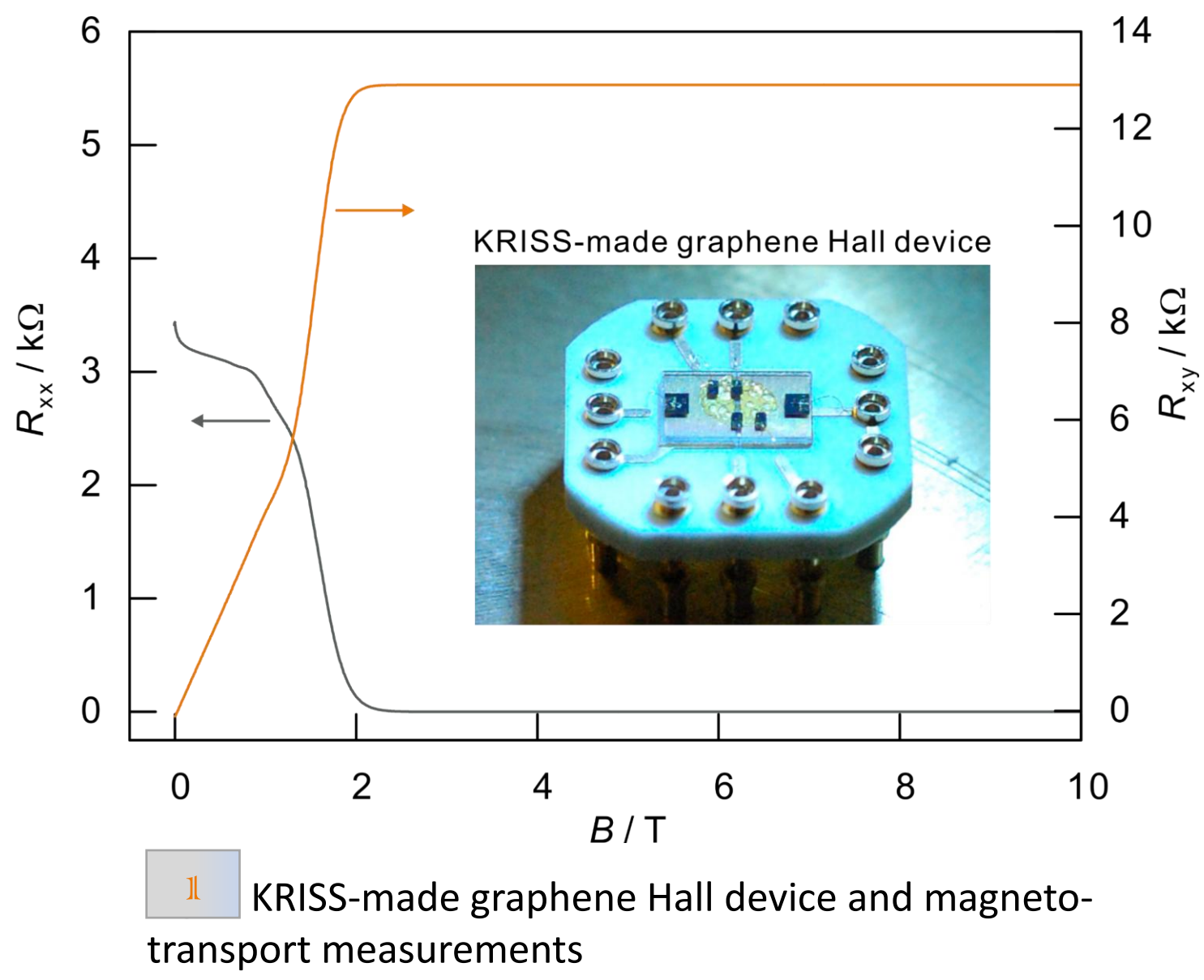
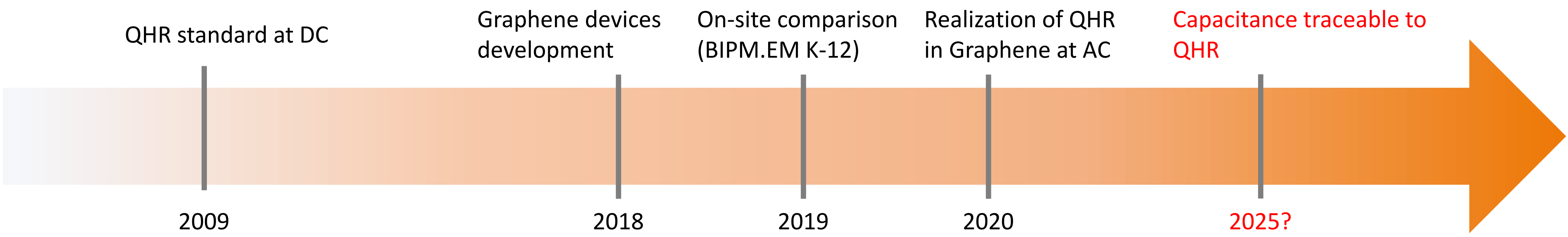
Effect of Sampler Characteristics in Differential Sampling:

In 2025, KRISS will publish a paper titled "Effect of Sampler Characteristics in Differential Sampling Adopting a Programmable Josephson Voltage Standard" in the IEEE Transactions on Instrumentation and Measurement (accepted for publication), which reports on the effect of the filter functions of the NI PXI-5922 on the differential sampling based on a PJVS. This publication completes a series of three papers by KRISS and BIPM investigating the impact of samplers, including the Keysight 3458A ("Measurement configurations for differential sampling of AC waveforms based on a programmable Josephson voltage standard: effects of sampler bandwidth on the measurements", Metrologia, vol. 57, no. 6, p. 065020, 2020) and Fluke 8588A ("Differential sampling of AC waveforms based on a programmable Josephson voltage standard using a high-precision sampler", Metrologia, vol. 59, no. 1, p. 015006, 2022), on differential sampling (E).

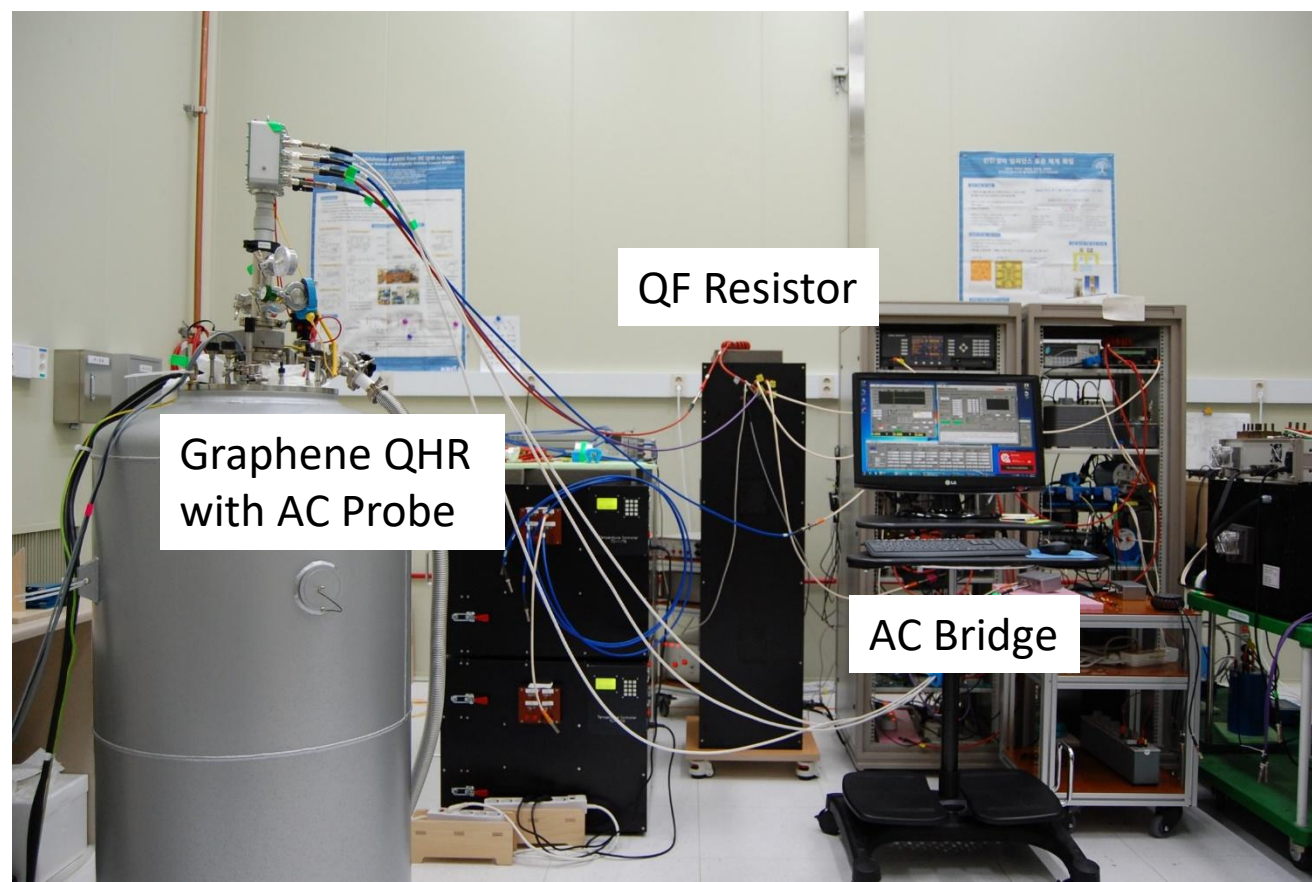


KRISS QHR

Timeline of Quantum Resistance Standard Development at KRISS



1 KRISS-made graphene Hall device and magneto-transport measurements



2 Experimental setup for QHR in graphene at AC with a digital impedance bridge

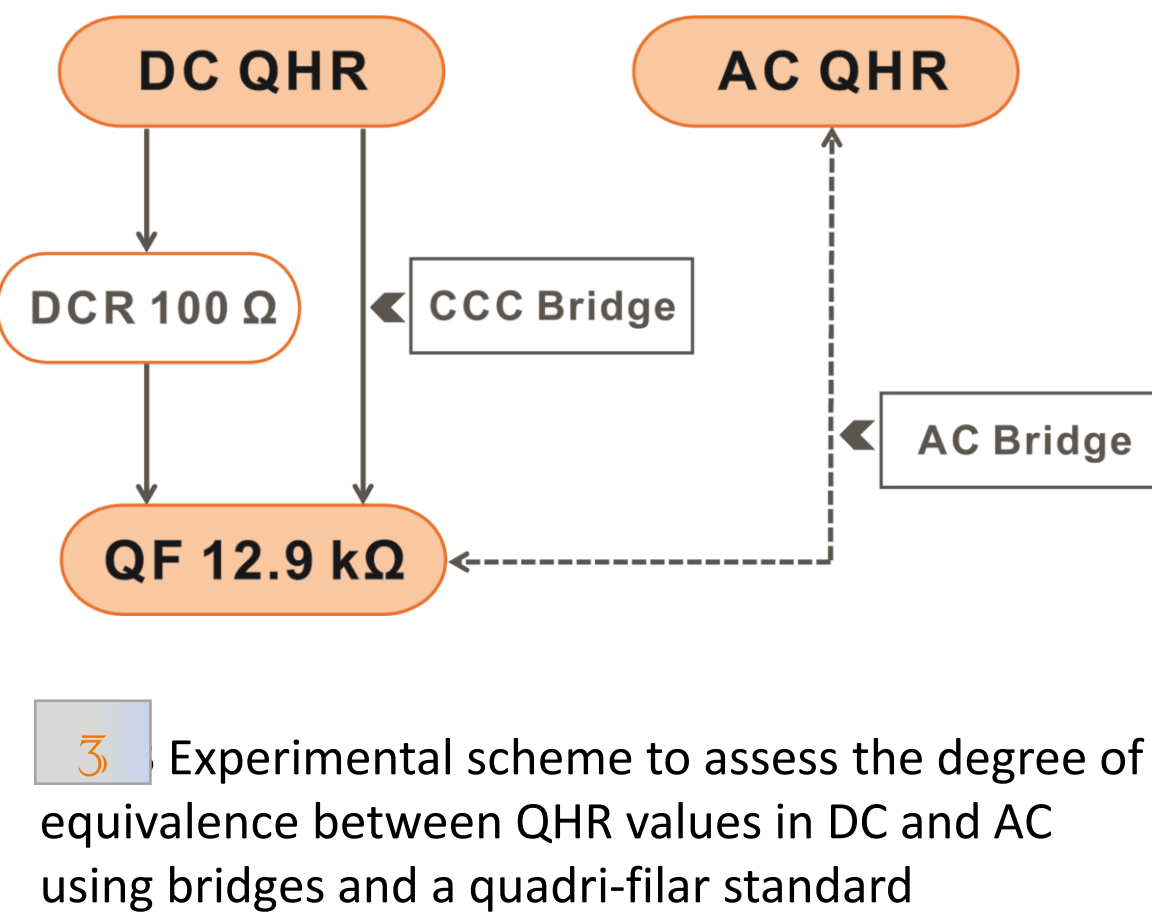
KRISS-made graphene Hall device:
KRISS developed a graphene Hall device and demonstrated its quantum Hall resistance at 4.2 K (J). The Hall resistance starts to be quantized at the nominal value of $h/2e^2$ for filling factor 2 above a perpendicular magnetic field of 2 T at 4.2 K. The longitudinal resistance is correspondingly suppressed above the magnetic field due to the quantum Hall state.

The experimental setup for QHR in graphene at AC is equipped with a CMI digital impedance bridge (2). A toploading probe was homemade with coaxial cables for measurements at AC. The graphene Hall device was connected to the bridge via a triple-series connection scheme.

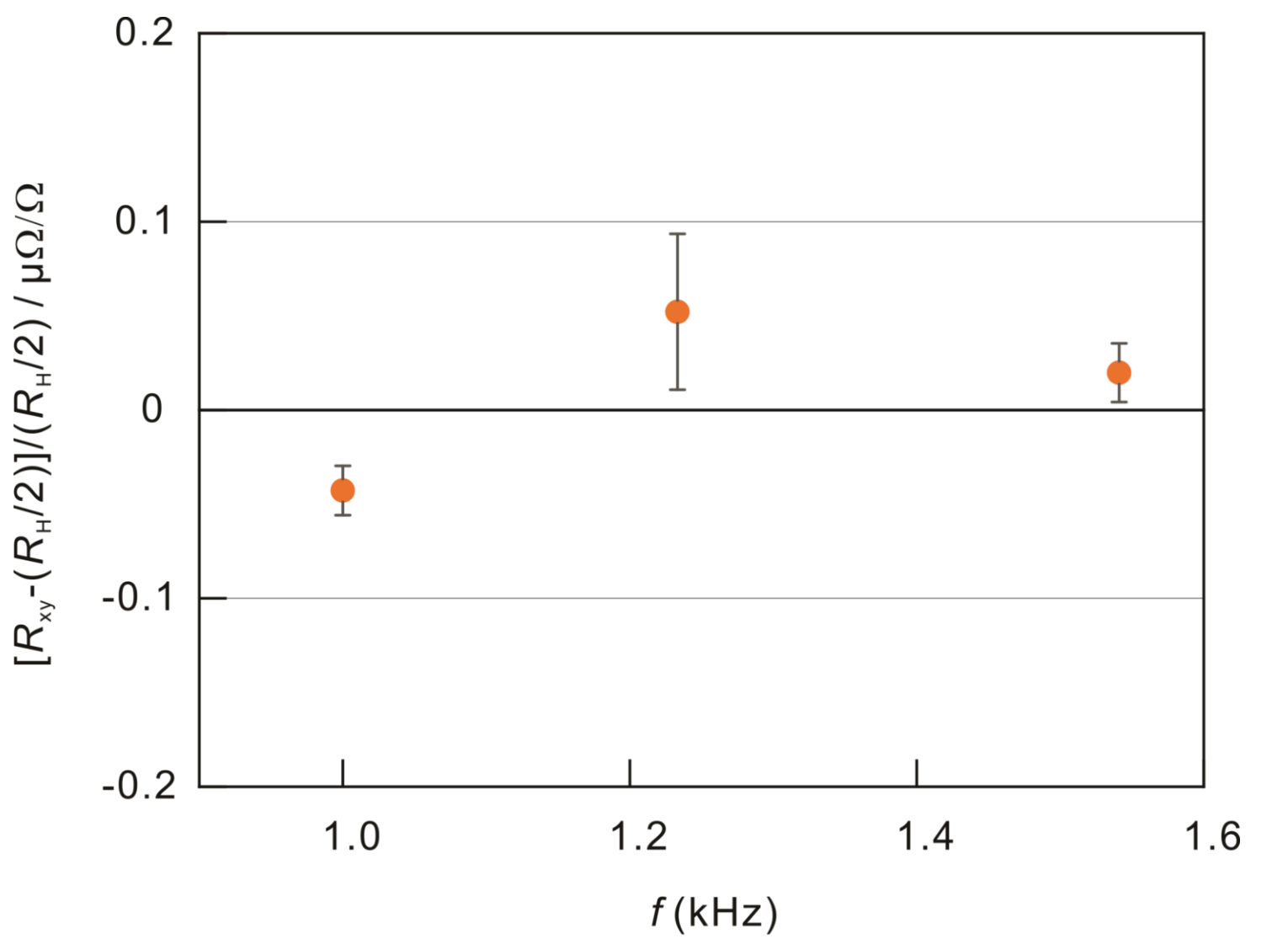
Realization of QHR in Graphene at AC:

The degree of equivalence between the DC and the AC QHR values was confirmed using a quadri-filar resistor as a transfer standard. The 12.9 kΩ quadri-filar standard resistor was first calibrated against the QHR standard at DC using a cryogenic current comparator. Then, two standards were compared again at AC using a 4-terminal-pair digital bridge (3).

The AC measurement results showed that the measured AC QHR values agreed with the nominal value on level of 10^{-8} (4). Based on the successful results, further studies are being carried on, including the frequency extension and the capacitance calibration against the AC QHR [1].



3 Experimental scheme to assess the degree of equivalence between QHR values in DC and AC using bridges and a quadri-filar standard



4 The relative deviation of AC QHR values from the nominal value, measured using a digital impedance bridge

Reference
[1] D. -H. Chae, M. Kruskopf, J. Kucera, J. Park, N. T. M. Tran, D. B. Kim, K. Pierz, M. Götz, Y. Yin, P. Svoboda, P. Chrobok, F. Couëdo, and F. Schopfer, "Investigation of the stability of graphene devices for quantum resistance metrology at direct and alternating current," in Meas. Sci. Technol., vol. 33, no. 6, pp. 065012, Mar. 2022.