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BIPM.EM-K12 (CEM 2025)

Quantum Hall resistance standards and their scaling to other resistance values

KEY COMPARISON

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BUREAU INTERNATIONAL
DES POIDS ET MESURES

On-site comparison of Quantum Hall Effect resistance standards of the CEM and the BIPM

Ongoing key comparison BIPM.EM-K12

Report on the November 2025 on-site comparison

Final report, March 2026

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1. Introduction

The ongoing on-site comparison BIPM.EM-K12 is part of the BIPM program implemented to verify the international coherence of primary resistance standards. It allows National Metrology Institutes (NMIs) to validate their implementations of the Quantum Hall Effect (QHE) for dc resistance traceability by comparison to the reference maintained at the BIPM.

In this comparison, the value of a 100 Ω standard resistor, calibrated using the NMI's quantum Hall resistance standard (QHRS), is compared with the calibration value of the same resistor obtained by the BIPM using its own transportable QHRS. This comparison is completed by measuring two ratios, 100 Ω/10 kΩ and 100 Ω/1 Ω, providing a test of resistance scaling across the central resistance range.

The comparison program BIPM.EM-K12 started in 1993. A first series of five comparisons was carried out from this date until 1999. After a suspension period, the comparison program was resumed in 2013. Since then, nine comparisons have been successfully completed whose results may be consulted on the webpage of the BIPM Key Comparison Data Base (KCDB) [1].

In November 2025 a new BIPM.EM-K12 comparison was carried out at the Centro Español de Metrología (CEM), Spain. It was the first time the CEM participated in this ongoing comparison.

The following sections present the principle of the comparison measurements, the measuring systems being compared and the comparison measurement results.

2. Principle of the comparison measurements

The ohm can be realized from the QHE routinely with an accuracy of the order of 1 part in 10^9 or better. The present comparison is performed on-site in order to eliminate the limitation of transporting transfer resistance standards between the BIPM and the participating institute, which would otherwise result in an increase of the comparison uncertainty by at least a factor of 10.

To this end, the BIPM has developed a complete transportable system that can be operated at the participant's facilities to realize the ohm from a QHE reference at 100 Ω, and scale this value to 1 Ω and 10 kΩ (meaning that not only the QHE systems are covered in this comparison but also the scaling devices).

Practically, the comparison comprises three stages schematized in Figure 1:

(i) The calibration of a 100 Ω standard resistor in terms of the ohm realized from the QHE-based standards of the CEM and the BIPM. In both of these institutes, the ohm was realized in a manner consistent with the SI Brochure – 9th edition (2019) – Appendix 2 [2]. As recommended in this document, the value of the von Klitzing constant R_K = 25 812.807 459 3045 Ω was used (truncated value of h/e^2 with h and e the Planck constant and the elementary charge, respectively). The relative difference in the calibrated values of the standard resistor of nominal value 100 Ω is expressed as $(R_{CEM} - R_{BIPM})/R_{BIPM}$ where R_{BIPM} and R_{CEM} are the values attributed to $R_{100\Omega}$ by the BIPM and CEM, respectively.

(ii) The scaling from 100 Ω to 10 kΩ, through the measurement of the ratio $R_{10k\Omega}/R_{100\Omega}$ of the resistance of two standards of nominal value 10 kΩ and 100 Ω. The relative difference in the measurement of this ratio, hereinafter referred to as K_1, is expressed as $(K_{1,CEM} - K_{1,BIPM})/K_{1,BIPM}$ where $K_{1,BIPM}$ and $K_{1,CEM}$ are the values attributed to K_1 by the BIPM and the CEM, respectively.

(iii) The scaling from 100 Ω to 1 Ω, through the measurement of the ratio $R_{100\Omega}/R_{1\Omega}$ of the resistance of two standards of nominal value 100 Ω and 1 Ω. The relative difference in the measurement of this ratio, hereinafter referred to as K_2, is expressed as $(K_{2,CEM} - K_{2,BIPM})/K_{2,BIPM}$ where $K_{2,BIPM}$ and $K_{2,CEM}$ are the values attributed to K_2 by the BIPM and the CEM, respectively.

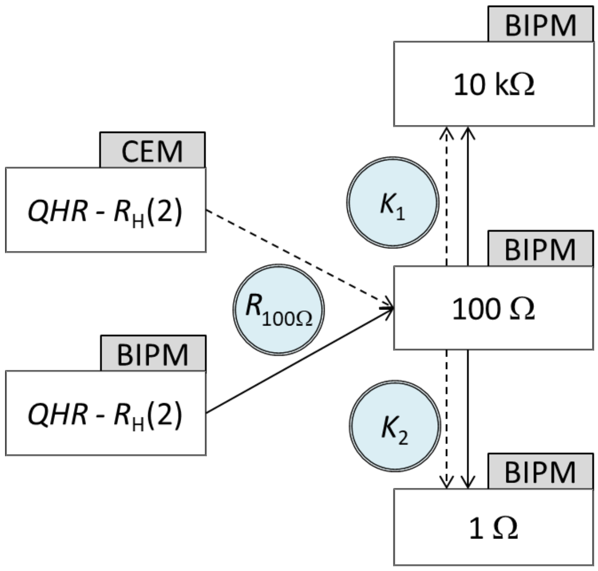

Figure 1: Schematic of the on-site comparison carried out at the CEM in November 2025. Rectangles represent the resistances to be compared, and circles correspond to the resistance $R_{100\Omega}$ or the ratios K_1 and K_2 to be measured. Solid and dashed arrows stand for the measurements with the 1 Hz bridge of the BIPM or with the CCC bridge of the CEM, respectively.

The resistance value of each of the standard resistors used in this comparison is defined as its five- terminal dc-resistance value[1]. This means, unless otherwise specified, that it corresponds to the dc voltage to current ratio once any thermal EMF across the resistor, particularly those induced by the Peltier effect, have reached a stable value. The influence of the Peltier effect on precision resistance measurements has already been discussed in several papers [3-8], in which an extended description of the observed phenomena is provided (in particular regarding 1 Ω resistance measurement).

3. The BIPM measurement system and the transfer standards

3.1. Implementation of the QHE

A complete transportable QHE reference [9] has been developed at the BIPM for the purpose of the BIPM.EM-K12 on-site comparison program. It is composed of a compact liquid helium cryostat equipped with an 11.3 T superconducting magnet and a sample space that can be cooled to 1.4 K with the included vacuum pump. The magnet has an additional support at the bottom of the dewar to allow safe transport.

The separate sample probe can support two TO-8 mounted quantum Hall devices simultaneously (side by side within the magnet), with guarded wiring for eight terminals on each device. For this comparison, BIPM used GaAs heterostructure devices fabricated by PTB. They show an i=2 plateau centered on typical flux density values between 10 T and 10.5 T, which is well quantified for currents of the order of 50 μA at 1.4 K. The cryostat and the QHE devices are suitable for a realization of the ohm meeting all the requirements of the CCEM guidelines [10] for a relative standard uncertainty of the order of 1×10^{-9}.

A transportable resistance bridge is used with the QHE cryostat for the measurement of the different resistance ratios being the subject of the comparison. It is based on a room-temperature low-frequency current comparator (LFCC) operated at 1 Hz (sinusoidal signal), meaning that all resistance or ratio

[1] Ratio of the voltage drop between the high and low potential terminals to the current flowing in the low current terminal, with the case - fifth terminal - maintained at the same potential as the low potential terminal.

measurements are carried out at 1 Hz by the BIPM during the comparison. That way to proceed is preferable to the transport of the BIPM Cryogenic Current Comparator (CCC) bridge on-site since the 1 Hz bridge is a more rugged instrument, simple to operate, and less sensitive to electromagnetic interference and temperature variations. Furthermore, it provides resolution and reproducibility that are comparable to those achievable with the BIPM CCC bridge. However, the performance of the 1 Hz bridge may still depend on the experimental conditions encountered on-site.

The 1 Hz bridge is equipped with two separate LFCCs of ratio 129:1 and 100:1, having turn ratios of 2065:16 and 1500:15, respectively. The construction and performance of these devices are detailed in [11,12].

3.2. Transfer standards

Four transfer resistance standards were used in the comparison: two with a nominal value of 100 Ω, one with 1 Ω, and one with 10 kΩ. The measurands compared in this exercise are the values assigned by the BIPM and the CEM to one of the two 100 Ω resistors in terms of R_K, and to the two ratios 100 Ω/1 Ω and 10 kΩ/100 Ω.

The transfer standards were provided by the BIPM. The two 100 Ω standards were a SR102 type resistor from Tegam (s/n: A 2030405SR102) and an HRU-101 type resistor from Alpha Electronics (s/n: F078A). The 10 kΩ standard was a SR104 type resistor from Tegam (s/n: K 201119630104) and the 1 Ω was an HRU-1R0 type resistor from Alpha Electronics (s/n: F112A). All four resistors were fitted in individual temperature-controlled enclosures held at 25 °C. The temperature-regulation system can be powered either from the mains or from external batteries.

For each of these standards, the difference between resistance values measured at 1 Hz and at 'dc' is small but not negligible. Therefore, the same applies to the ratios of standards such as K_1 and K_2. The differences 1 Hz-'dc' for the measurands $R_{100\Omega}$, K_1 and K_2 were determined at the BIPM prior to the comparison. The 'dc' value was measured with the BIPM CCC whilst the 1 Hz value with the transportable 1 Hz bridge (the same as that used for on-site measurements). The differences are applied as corrections to the measurements performed at 1 Hz, meaning that the 1 Hz bridge is used as a transfer instrument referenced to the BIPM CCC.

The frequency corrections (1 Hz-'dc') are reported in Table 1 for $R_{100\Omega}$, K_1 and K_2. The main possible sources contributing to these corrections are the quantum Hall resistance (QHR), the 1 Hz bridge, the transfer standard itself and possibly the measuring cable. Nevertheless, at 1 Hz, the frequency dependence of the QHR is negligible compared to the comparison uncertainty [13], and the characterization of the bridge provides evidence that its error at 1 Hz is below 1 part in 10^9. Consequently, the frequency dependence observed is mainly attributed to the resistance standards themselves (including their conditioning).

Resistance or resistance ratio	100 Ω transfer standard used for the comparison	1 Hz-'dc' correction/10^{-9}	Standard uncertainty/10^{-9}
100 Ω	s/n: A 2030405SR102	6.1	1.0
K_1	s/n: A 2030405SR102	1.1	1.0
K_2	s/n: F078A	-4.7	1.5

Table 1: Value of the 1 Hz to 'dc' corrections applied to the BIPM measurements carried out at 1 Hz (Value('dc')=Value(1 Hz)+Correction). These values are specific to the standards used in this comparison.

For the sake of completeness, it must be noted that the 'dc' resistance value (or ratio) measured with the BIPM CCC bridge results from a current signal driven through the resistors having polarity reversals with a waiting time at zero (36 s) between polarity inversions, cf. Figure 2. The polarity reversal frequency is on the order of 3 mHz (about 340 s cycle period) and the measurements are sampled only during the last 100 s before the change of polarity.

Previous characterization measurements of the $R_H(2)/100\ \Omega$ (where $R_H(2) = R_K/2$ corresponds to the value of the QHR for a filling factor i=2) and 10 kΩ/100 Ω ratios have shown that if the polarity reversal frequency is kept below 0.1 Hz, then any effects of settling or ac behaviour remain on the order of 1 part in 10^9 or less. Regarding the 100 Ω/1 Ω ratio, this is most often not the case due to Peltier effects in the 1 Ω standard.

In order to ensure the best possible comparability of the measurements performed by the BIPM and the participating institute, the measuring system of the latter should be configured to match as closely as possible the reference polarity reversal cycle of the BIPM CCC. In case this is not feasible, a correction must be estimated and applied to the participating NMI's measurements based either on additional characterization of the influence of the polarity reversal rate on the actual measured resistance ratio, or by any other means using the most relevant and reliable information available.

In that respect, in case different current reversal cycles (shape and/or magnitude) would be used by the BIPM and the NMI, an estimation of the difference of the effective powers dissipated in the measured resistance standards should be done and, if necessary, a correction applied considering the power coefficients of those standards.

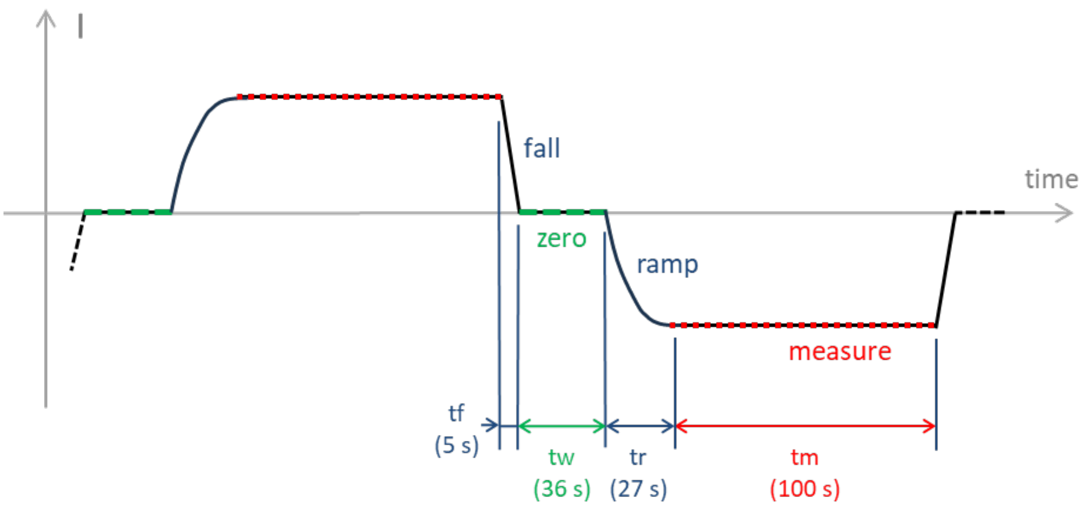

Figure 2: Schematic representation of the reference current cycle with polarity reversals used in the BIPM CCC bridge. Each half-cycle comprises a waiting time at zero current of 36 s, a ramp time of 27 s, a measuring (sampling) time of 100 s and a fall time of 5 s. The complete reversal cycle time is 336 s.

3.3. Uncertainty budget

Table 2 summarizes the BIPM standard uncertainties for the measurement of the 'dc' value of the 100 Ω standard in terms of the von Klitzing constant R_K (as defined section 2), as well as the measurement uncertainties for both the 10 kΩ/100 Ω and 100 Ω/1 Ω ratios (K_1 and K_2, respectively).

Measurement Parameters	*Resistance ratio*		
	$R_H(2)/100\ \Omega$	10 kΩ/100 Ω	100 Ω/1 Ω
Bridge ratio	129/1	100/1	100/1
Currents	40 µA/5.16 mA	50 µA/5 mA	0.5 mA/50 mA
Uncertainty contributions (type-B)	*Relative standard uncertainties / 10^{-9}*		
Imperfect CCC winding ratio	1.0	1.0	1.0
Resistive divider calibration	0.5	0.5	0.5
Leakage resistances	0.2	0.2	-
Noise rectification in CCC	1.0	1.0	1.0
Imperfect realization of the QHR	0.8	-	-
Correction of the 1 Hz-to 'dc' difference	1.0	1.0	1.5
Combined type B standard uncertainty, u_B	**2.0**	**1.8**	**2.1**

Table 2: Contributions to the combined type B standard uncertainty (k=1) for the 'dc' measurement of the three mentioned resistance ratios at the BIPM.

4. The CEM measurement system

4.1. Implementation of the QHE

The quantum Hall resistance standard is operated in a Cryogenic LTD cryogen-free measurement system incorporating a variable temperature insert (VTI) capable of lowering the temperature below 1.5 K, and a 13 T superconducting magnet (maximum flux density). The system is located in the CEM's Quantum Hall laboratory near the Faraday cage in which the CCC is installed.

The GaAs-based QHR device used for the comparison (LEP type #54-7) is the one commonly used for the ohm realization at the CEM. It has been previously characterized according to the guidelines recommended by the CCEM [10].

4.2. Resistance bridge

The resistance bridge used by CEM for the comparison is a commercial Magnicon CCC System. It includes a 12-bit CCC with 18 coils whose binary turn numbers range between 1 and 2048 turns (4647 turns in total), a SQUID sensor and its dedicated electronics, digitally controlled current sources and a low noise chopper amplifier [14-16]. The ratio of the bridge is adjustable over a wide range of values in addition to the usual ratios 1:1, 1:10, 1:100, $R_H(2)/100$ and $R_H(4)/100$. This allows, among other things, the direct comparison of the QHR to resistance values of 100 Ω, 1 kΩ, 10 kΩ, 100 kΩ and 1 MΩ.

The current driven through the primary and secondary resistance standards is reversed periodically as shown in Figure 3. Times t_R, t_W, t_S, and t_{FC} are the ramp time, waiting time, sampling time and full cycle time, respectively. The timing details of the current reversal cycles employed by the CEM during the comparison measurements are summarized in Table 3.

For the comparison measurements of the ratio $R_H(2)/100\ \Omega$ and the K_1 ratio 10 kΩ/100 Ω, a full cycle time of 20 s was used which is the standard cycle used routinely at CEM. No corrections related to the cycle time were applied to these ratios.

For the K_2 ratio 100 Ω/1 Ω, the influence of the full cycle time was investigated for the cycle times 6 s, 10 s, 20 s, 40 s, 80 s and 340 s, the time parameters of which are described in detail in Table 3. This preliminary study was conducted because similar investigations carried out during previous comparisons showed that K_2 ratio could depend on the cycle time. This could in turn lead to significant differences between CEM and BIPM measurements, their CCC bridges operating with quite different cycle times.

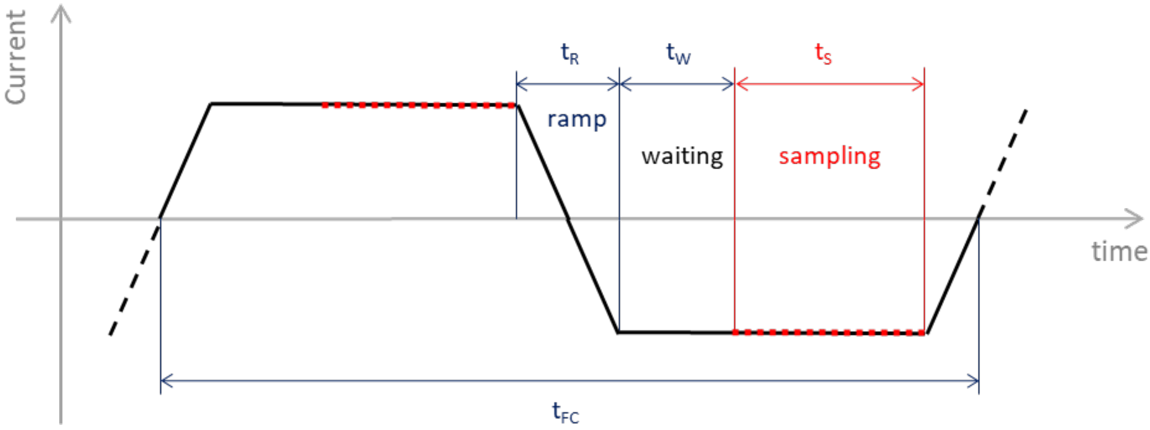

Figure 3: Current reversal timing of the CEM measurement. t_R, t_W, t_S, and t_{FC} are the ramp time, waiting time, sampling time, and full cycle time, respectively.

Cycle /s	t_{FC} /s	t_R /s	t_W /s	t_S /s
340	340	1.02	8.98	160
80	80	1.01	18.99	20
40	40	1.02	8.98	10
20	20	1.02	3.98	5
10	9.92	0.64	1.84	2.48
6	6.08	0.64	0.96	1.44

Table 3: Timing details of the current reversal cycles used during K_2 ratio measurements.

4.3. Measuring environmental conditions

Throughout the duration of the comparison measurements – from 27 November to 3 December 2025 - the laboratory maintained an ambient temperature at (22.4±0.6) °C and a relative humidity at (46±5) %. The atmospheric pressure remained within 931 hPa and 942 hPa with a mean value of 936.5 hPa.

4.4. Uncertainty budget

Table 4 lists the measurement parameters, typical type A uncertainties, and type B uncertainty contributions in the CEM uncertainty budget for the three resistance ratios mentioned.

The estimation of uncertainty sources related to the CCC bridge is mainly based on the calibration of its compensation unit, tests of winding ratio errors, grounding currents effects (common mode effects) and channel symmetry.

	Resistance ratio		
Measurement parameters	$R_H(2)$/100 Ω	10 kΩ/100 Ω	100 Ω/1 Ω
Number of turns N_1/N_2	2065/16	2000/20	2000/20
Number of turns N_A	1	1	1
DUT voltage (V)	0.5	0.5	0.05
Compensation ratio	12040.77	1656.06	873.57
Type A contributions	Relative standard uncertainties/10^{-9}		
Mean value of the standard deviations of the mean of individual measurements	2.0	1.0	2.5
Type B contributions	Relative standard uncertainties/10^{-9}		
CCC winding ratio	1	1	1
CCC electronics and SQUID	0.6	0.6	0.6
Compensation ratio	0.5	0.5	0.5
Bridge voltage measurement	<0.1	<0.1	<0.1
Measurement of the DUT voltage	<0.1	<0.1	<0.1
Leakage resistance	0.5	1.5	2.5
Imperfect realization of the QHR	1.2	NA	NA
Combined type B standard uncertainty, u_B=	**1.8**	**2.0**	**2.8**

Table 4: Measurement parameters, typical type A uncertainty of individual measurements, and type B uncertainty contributions (k=1) to the uncertainty budget of measurements performed by CEM.

5. Measurement of the 100 Ω transfer standard in terms of $R_H(2)$

5.1. BIPM measurements

5.1.1. Preliminary tests

The GaAs-based quantum Hall device used by the BIPM for this comparison is of PTB-type. It was characterized at BIPM prior to the comparison and has shown equivalence with a LEP514-type device within the uncertainty of measurement of the BIPM QHE system. It was operated on the i=2 plateau at a temperature of 1.4 K and with a rms current of 40 μA.

The magnetic flux density corresponding to the center of the plateau was determined by recording the longitudinal resistance R_{xx} as a function of magnetic flux density and was found to be about 10.4 T. The two-terminal Hall resistance of the four-terminal pairs device was checked before and after each series of measurements, showing that the contact resistance always remained below a few ohms (considering the 5 Ω resolution of the handheld multimeter used and the resistance of the two device connecting wires of approximately 1.2 Ω each).

The absence of significant longitudinal dissipation along both sides of the device was tested as described in [10] section 6.2, by combining the measurements obtained from four different configurations of the voltage contacts (orthogonal and diagonal configurations between the voltage contact pairs at both sides of the device). The absence of dissipation was demonstrated within about 2×10^{-10} in relative terms with a standard uncertainty of the order of 5×10^{-10}. No correction was applied to compensate for possible imperfect quantization, but an uncertainty component for imperfect QHR realization is considered in Table

2. The difference between measurements made using orthogonal pairs of voltage contacts in the center and on either side of the sample was also found to be uniform within 5×10^{-10}, significantly below the uncertainty of each individual measurement of 2×10^{-9} (see Table 2).

The series of measurements performed subsequently for the purpose of the comparison were taken from the central pair of contacts only.

5.1.2. BIPM results

On November 27, 2025, the QHE systems of the BIPM and CEM were operational to perform the 100 Ω comparison based on $R_H(2)$. The 100 Ω standard (Tegam s/n: A 2030405SR102) was connected alternately to the CEM and BIPM bridges for a total of seven CEM measurements interleaved with six BIPM measurements. After each change, at least 10 minutes were allowed for thermal stabilization of the connections, with measurement current applied. As mentioned earlier, a rms current of 40 µA was applied to the BIPM quantum Hall standard which corresponds to a current in the 100 Ω transfer standard of 5.16 mA.

The values of the 100 Ω standard measured by the BIPM at 1 Hz are shown in Table 5 as well as the 'dc' corrected values (using the 1 Hz-'dc' correction from Table 1). Both are expressed as the relative difference from the 100 Ω nominal value: (R_{BIPM}/100 Ω) - 1. Each of the measurements reported in the table is the average value of a series of six individual measurements and corresponds to a total measurement time of about 22 minutes.

Time	(R_{BIPM}/100 Ω)-1 /10^{-6}		Dispersion /10^{-6}
	1 Hz measurements	'dc' corrected (with 1 Hz-'dc' correction)	
27/11/25 11:10	-0.158 29	-0.152 19	0.000 70
27/11/25 12:24	-0.158 86	-0.152 76	0.000 32
27/11/25 13:56	-0.156 72	-0.150 62	0.00045
27/11/25 15:17	-0.158 06	-0.151 96	0.000 44
27/11/25 16:41	-0.157 67	-0.151 57	0.000 38
27/11/25 17:59	-0.156 12	-0.150 02	0.000 37
	Mean value	**-0.151 52**	
	Standard deviation, u_A	**0.001 02**	

Table 5: BIPM measurements of the 100 Ω standard in terms of $R_H(2)$ on November 27, 2025. Results are expressed as the relative difference from the nominal 100 Ω value. Each measurement is the average value of a series of six individual measurements. Time corresponds to the mean time of this measurement series and the dispersion to the standard deviation of the mean.

The resistance value $\boldsymbol{R_{BIPM}}$ reported below corresponds to the mean of the corrected measurements carried out by the BIPM on November 27, 2025:

Mean value: $\boldsymbol{R_{BIPM} = 100 \times (1 - 0.151\,52 \times 10^{-6})\ \Omega}$

Relative standard uncertainty: $\boldsymbol{u_{BIPM} = 2.2 \times 10^{-9}}$

where u_{BIPM} is calculated as the root sum square of $u_A = 1.0 \times 10^{-9}$ (Table 5) and $u_B = 2.0 \times 10^{-9}$ (Table 2).

5.2. CEM measurements

5.2.1. Preliminary tests

The CEM Resistance laboratory participated in 2022 in the bilateral comparison BIPM.EM-K13 (a and b) of travelling standards of values 1 Ω and 10 kΩ. For the 10 kΩ value, the difference between the CEM and the BIPM was 20 nΩ/Ω with a relative standard uncertainty of 34 nΩ/Ω. For the 1 Ω value, the difference was a bit higher but still very acceptable for this resistance value.

With such differences close to the lower limits achievable with traveling standards, the only way to further reduce the CEM-BIPM difference and improve the CEM's Calibration and Measurement Capabilities (CMCs of the CIPM MRA[2]) was to perform an on-site comparison BIPM.EM-K12. The relevance of making such a comparison was reinforced by the fact that the implementation of a new QHR system and a new CCC bridge at CEM was planned for early 2025.

Following the installation of this equipment, the new CEM ohm traceability chain was tested by measuring the resistors of the historic reference group composed of three 10 kΩ standards (ESI SR104). Measurement results were compared to those obtained with the old QHE system and DCC bridge, and showed that the difference between the two systems was consistent with the CEM-BIPM difference measured in 2022 during the BIPM.EM-K13 comparison. In figure 4, which presents the measurement history of one of the resistors of the reference group, the measurement made with the new QHE system and CCC bridge does indeed show a good agreement with the historical trend.

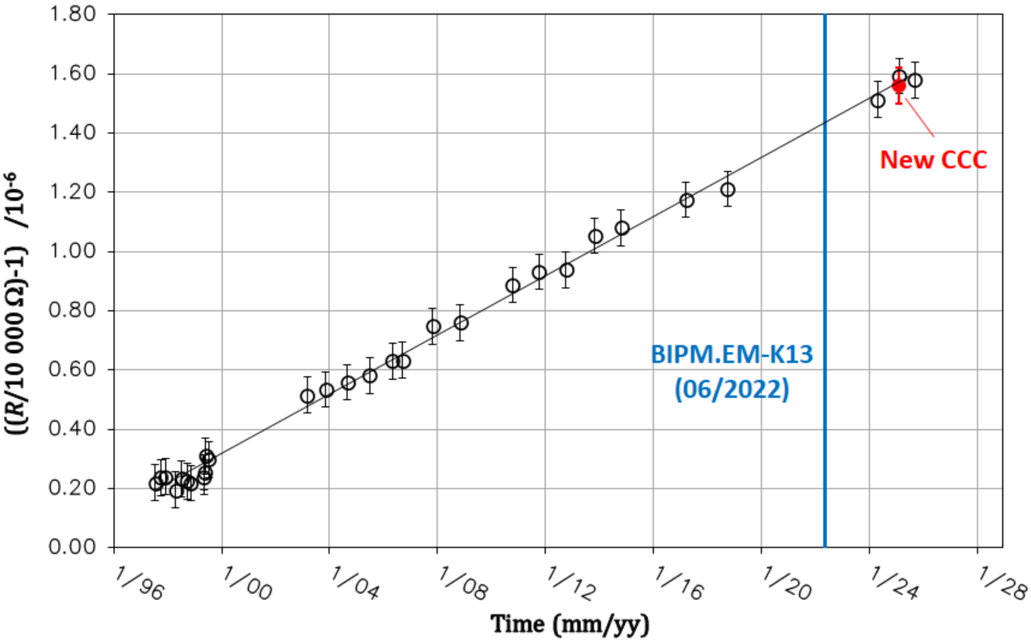

Figure 4: History of measurement of the resistance *R* of one of the 10 kΩ resistors of the CEM reference group. The measurement made with the new QHE system and CCC bridge is reported in red and shows a good consistency with the historical trend.

As mentioned earlier, the QHR device used for the comparison was a LEP device referenced 54-7. It was cooled to 1.52 K and the magnetic flux density at the center of the plateau corresponding to the filling factor i=2 was 10.27 T. Prior to the comparison measurements, the contact resistances and quantization of the device was checked according to the guidelines recommended by the CCEM [10].

[2] Mutual Recognition Arrangement of the Comité international des poids et mesures

5.2.2. CEM results

CEM measurements of the 100 Ω resistance standard based on $R_H(2)$ were carried out using a cycled current of 38.739 µA in the QHR (i.e. 5 mA in the 100 Ω) with a reversal rate of 20 s. Each CEM measurement consisted of a set of 96 consecutive cycles but only the last 60 were used to compute the measurement result. This means that each 20-minute measurement (60 cycles) was preceded by a warm-up time of around 12 minutes.

Seven measurements interleaved with the six BIPM measurements were performed by the CEM. However, the second measurement was not included in the final calculation of the comparison result as it clearly appeared to be an outlier. Indeed, a difference greater than 22 nΩ/Ω was observed between this outlier and the average of the six other CEM measurements, which all six remain within a standard deviation of about 1.4 nΩ/Ω around this average value. The most likely reason for this outlier, given that there have been no changes to the CCC bridge electronics settings following the first measurement, is a poor contact between one or more voltage and/or current wires of the CEM measurement cable and the corresponding voltage and/or current terminals of the 100 Ω resistor.

The cable ends of the current and voltage wires are equipped with fork connectors, and the resistor's input terminals are screw terminals. Contact between the voltage and current wires is therefore achieved by tightening. Imperfect tightening can indeed lead to this type of measurement error.

At the time of measurement, the significant discrepancy between the second CEM measurement and the initial measurements made by the CEM and the BIPM could not be interpreted without a new measurement being made by the BIPM to confirm or refute the observed jump. The latter could indeed have been caused by a failure of the 100 Ω standard resistor. As Figure 5 shows, the second BIPM measurement and all subsequent measurements carried out by the BIPM and the CEM do not indicate such a jump in resistance of the 100 Ω standard, but clearly that only the second CEM measurement is erroneous.

The raw and corrected measurement results of the CEM are reported in Table 6 along with the starting time of measurement and dispersion (standard deviation of the mean). The 'corrected' measurements correspond to the raw measurements corrected for the difference in power dissipated in the 100 Ω by CEM and BIPM. This difference results from the difference in the waveform of the reversal current cycles used by CEM and BIPM (see Figures 2 and 3), and from the small difference in the applied currents. The correction was estimated to $(+0.29\pm0.08)\times10^{-9}$ as detailed in section 5.2.3 below.

Time	$(R_{CEM}/100\ \Omega)-1\quad /10^{-6}$		Dispersion $/10^{-6}$
	Raw measurements	Corrected measurements	
27/11/25 9:25	-0.151 88	-0.151 59	0.003 46
27/11/25 11:38	**Outlier**		
27/11/25 13:02	-0.149 45	-0.149 16	0.002 20
27/11/25 14:28	-0.147 22	-0.146 93	0.001 70
27/11/25 15:49	-0.145 80	-0.145 51	0.001 56
27/11/25 17:09	-0.149 50	-0.149 21	0.001 62
27/11/25 18:28	-0.146 64	-0.146 35	0.001 85
	Mean value	**-0.148 12**	
	Standard deviation, u_A	**0.002 26**	

Table 6: CEM measurements of the 100 Ω standard in terms of $R_H(2)$ on November 27, 2025. Results are expressed as the relative difference from the nominal 100 Ω value. Time corresponds to the starting time of measurement and the dispersion to the standard deviation of the mean of the measurement considered.

The resistance value R_{CEM} reported below corresponds to the mean of 100 Ω measurements carried out by the CEM, corrected for the difference in power dissipated in the resistor, on November 27, 2025.

Mean value: $R_{CEM} = 100 \times (1 - 0.148\ 12 \times 10^{-6})\ \Omega$

Relative standard uncertainty: $u_{CEM} = 2.9 \times 10^{-9}$

where u_{CEM} is calculated as the root sum square of: $u_A = 2.3 \times 10^{-9}$ (Table 6), $u_{power} = 0.1 \times 10^{-9}$ the standard uncertainty on power correction and $u_B = 1.8 \times 10^{-9}$ (Table 4).

5.2.3. Estimation of the power correction applied on the CEM 100 Ω measurements

The 100 Ω resistance standard has a non-zero power coefficient that has been previously determined at the BIPM. The differences in shape and magnitude of the reversal current cycles used by CEM and BIPM for the comparison therefore induce a difference of the effective powers dissipated in the 100 Ω resistor during the measurements.

From the magnitude and shape differences of the current cycles used by the BIPM and CEM CCC bridges, it was estimated that the effective power dissipated in the resistor by CEM is (0.35 ± 0.05) mW higher than that dissipated by BIPM. Considering the power coefficient of the 100 Ω standard, estimated as (-0.82 ± 0.26) parts in 10^9 per mW, a power correction was computed and applied to the CEM measurement results. This correction was estimated as (0.29 ± 0.08) parts in 10^9.

5.3. 100 Ω measurements comparison

Figure 5 presents the corrected interleaved measurements from CEM and BIPM on November 27, 2025. Error bars correspond to the dispersion observed for each measurement.

The red arrow indicates that the second CEM measurement is outside the graph with a value of more than 25 nΩ/Ω compared to the first CEM measurement. As explained above in section 5.2.2, this measurement can be considered as an outlier as its value differs considerably from all the other CEM and BIPM measurements. This outlier is not taken into account for the calculation of the CEM-BIPM difference below.

Excluding the outlier, no significant instabilities of the 100 Ω transfer resistor were observed within the limit of the dispersion of the results and therefore no additional uncertainty component was included in the final comparison results.

The difference between CEM and BIPM was then calculated as the difference between the corrected means of the series of measurements carried out by both institutes on November 27, 2025 (from Tables 5 and 6):

Relative difference CEM-BIPM: $(R_{CEM} - R_{BIPM}) / R_{BIPM} = 3.4 \times 10^{-9}$

with a relative combined standard uncertainty: $u_{comp} = 3.6 \times 10^{-9}$

where u_{comp} is calculated as the root sum square of $u_{BIPM} = 2.2 \times 10^{-9}$ and $u_{CEM} = 2.9 \times 10^{-9}$.

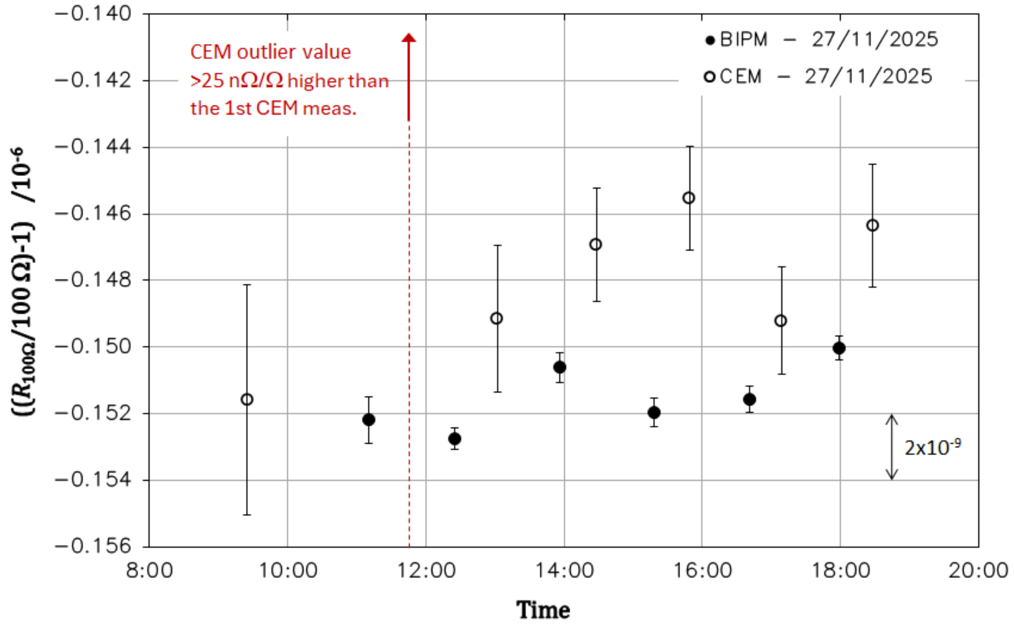

Figure 5: CEM (open circles) and BIPM (black dots) corrected measurements of the 100 Ω resistance $R_{100\Omega}$ in terms of $R_H(2)$ on November 27, 2025. The error bars correspond to the dispersion observed for each measurement. The red arrow indicates that the second CEM measurement (outlier) is outside the graph with a value of more than 25 nΩ/Ω compared to the first CEM measurement.

6. Measurement of K_1 ratio (10 kΩ/100 Ω)

6.1. BIPM measurements of K_1

For the measurement of K_1 ratio, the 129:1 LFCC equipping the BIPM 1 Hz bridge for the $R_H(2)$/100 Ω ratio measurement was replaced by a 100:1 LFCC. The 100 Ω and 10 kΩ standards referenced s/n: A 2030405SR102 and s/n: K 201119630104, respectively, were used. The rms current in the 10 kΩ standard was 50 µA corresponding to 5.0 mA in the 100 Ω standard.

On December 1, 2025, the 10 kΩ and 100 Ω standards were connected alternately to the BIPM and CEM bridges and seven BIPM measurements were interleaved with six CEM measurements. After each bridge change, at least 10 minutes were allowed for thermal stabilization of the connections, with measurement current applied.

The raw and corrected BIPM measurements are reported in Table 7 (relative difference from nominal ratio 100). Each of the raw measurements is the mean value of seven individual measurements corresponding to a total measurement time of about 26 minutes. The corrected measurements correspond to the raw data to which the 1 Hz–'dc' correction reported in Table 1 was applied. The associated dispersion is estimated by the standard deviation of the mean of the seven individual measurements.

The K_1 ratio value reported below corresponds to the mean of the corrected ratio measurements carried out by the BIPM on December 1, 2025.

Mean value: $\mathbf{K_{1,BIPM} = 100 \times (1 + 1.660\,41 \times 10^{-6})}$

Relative standard uncertainty: $\mathbf{u_{BIPM} = 1.9 \times 10^{-9}}$

where u_{BIPM} is calculated as the root sum square of $u_A = 0.5 \times 10^{-9}$ (Table 7) and $u_B = 1.8 \times 10^{-9}$ (Table 2).

Time	$(K_{1,\text{BIPM}}/100)$-1 /10^{-6}		Dispersion /10^{-6}
	1 Hz measurements	'dc' corrected (with 1 Hz-'dc' correction)	
1/12/25 8:29	1.659 29	1.660 41	0.000 55
1/12/25 10:12	1.659 69	1.660 81	0.000 64
1/12/25 11:53	1.659 95	1.661 06	0.000 52
1/12/25 13:30	1.659 19	1.660 31	0.000 69
1/12/25 15:07	1.658 68	1.659 80	0.00026
1/12/25 16:42	1.658 77	1.659 89	0.000 47
1/12/25 18:18	1.659 47	1.660 59	0.000 37
	Mean value	**1.660 41**	
	Standard deviation, u_A	**0.000 46**	

Table 7: BIPM measurements of the ratio K_1 on December 1, 2025. Results are expressed as the relative difference from the nominal ratio value 100. Each measurement is the mean value of a series of seven individual measurements. Time corresponds to the mean time of this measurement series and the dispersion to the standard deviation of the mean.

6.2. CEM measurements of K_1

For K_1 ratio measurements, the currents through the 100 Ω and 10 kΩ resistance standards were 5 mA and 50 µA, respectively. A current reversal cycle time of 20 s was used.

As mentioned earlier, six CEM measurements were interleaved with seven BIPM measurements. Each CEM measurement consisted of a set of 110 consecutive full cycles, but only the last 75 were used to compute the measurement result (25-minute measurement preceded by a warm-up time of around 12 minutes).

As with the $R_{100\Omega}$ measurement, a correction was made to account for the difference in dissipated powers between BIPM and CEM in the 100 Ω and 10 kΩ standards. This correction was estimated from the power coefficient of the ratio K_1 and from the effective difference of power dissipated in the resistors between the CEM and the BIPM. The latter was computed from the current magnitudes and cycle timing parameters used by each of the institutes and considering that the power was only dissipated in the 100 Ω standard (negligible dissipation in the 10 kΩ standard). It was estimated that the power dissipated by CEM in the 100 Ω was (0.47 ± 0.03) mW higher than that dissipated by BIPM. Thus, using the power coefficient (1.35 ± 0.37) × 10^{-9} per mW of the ratio K_1 – determined by the BIPM prior to the comparison – the power difference correction of the K_1 ratio was in turn estimated to be (-0.63 ± 0.13) × 10^{-9}.

The raw and corrected measurement results of CEM are reported in Table 8. They are expressed as the relative difference from the nominal ratio value 100 with a dispersion corresponding to the standard deviation of the mean of the individual measurements.

The K_1 ratio value reported below corresponds to the mean of the ratio measurements carried out by the CEM on December 1, 2025.

Mean value: $\boldsymbol{K_{1,\text{CEM}} = 100 \times (1 + 1.658\,46 \times 10^{-6})}$

Relative standard uncertainty: $\boldsymbol{u_{\text{CEM}} = 2.4 \times 10^{-9}}$

where u_{CEM} is calculated as the root sum square of: u_{A} = 1.4 × 10^{-9} (Table 8), u_{power} = 0.1 × 10^{-9} the standard uncertainty on power difference correction and u_{B} = 2.0 × 10^{-9} (Table 4).

Time	$(K_{1,\text{CEM}}/100)$-1 /10^{-6}		Dispersion /10^{-6}
	Raw measurements	'power' corrected measurements	
1/12/25 9:12	1.659 66	1.659 03	0.001 10
1/12/25 10:58	1.657 49	1.656 86	0.001 00
1/12/25 12:35	1.657 96	1.657 33	0.000 97
1/12/25 14:09	1.660 20	1.659 57	0.001 10
1/12/25 15:48	1.658 22	1.657 59	0.000 83
1/12/25 17:35	1.660 97	1.660 34	0.000 97
	Mean value	**1.658 46**	
	Standard deviation, u_A	**0.001 39**	

Table 8: CEM measurements of the ratio K_1 on December 1, 2025. Results are expressed as the relative difference from the nominal ratio value 100. Time corresponds to the starting time of measurement and the dispersion to the standard deviation of the mean of each individual measurement.

6.3. Comparison of K_1 measurements

Figure 6 presents the interleaved corrected measurements from CEM and BIPM on December 1, 2025. Error bars correspond to the dispersion observed for each measurement.

No clear drift or significant instability was detected in the K_1 measurements within the limit of the comparison uncertainty and therefore no specific additional uncertainty component was included in the final comparison results.

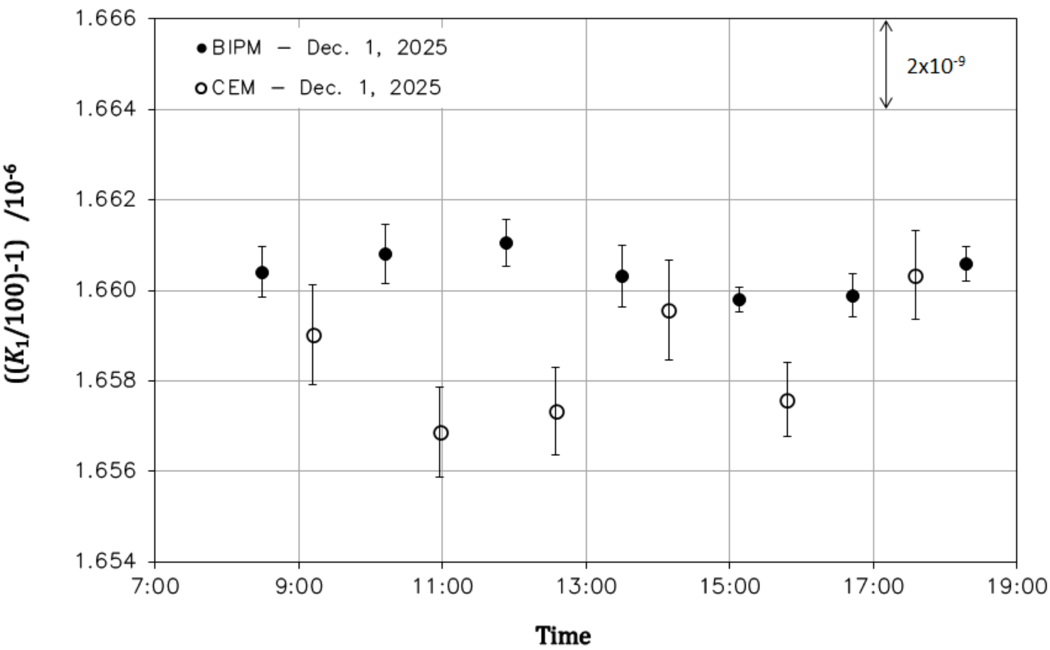

Figure 6: CEM (open circles) and BIPM (black dots) corrected measurements of the ratio K_1 on December 1, 2025. Error bars correspond to the dispersion observed during each measurement.

The relative difference between CEM and BIPM was calculated from the difference of the means of the measurement series carried out by both institutes on December 1, 2025 (from Tables 7 and 8):

Relative difference CEM-BIPM: $(K_{1,\mathrm{CEM}} - K_{1,\mathrm{BIPM}}) / K_{1,\mathrm{BIPM}} = -2.0 \times 10^{-9}$

with a relative combined standard uncertainty: $u_{\mathrm{comp}} = 3.1 \times 10^{-9}$

where u_{comp} is calculated as the root sum square of $u_{\mathrm{BIPM}} = 1.9 \times 10^{-9}$ and $u_{\mathrm{CEM}} = 2.4 \times 10^{-9}$.

7. Measurement of K_2 ratio (100 Ω/1 Ω)

7.1. Preliminary measurements: influence of the current reversal cycle time

Previous studies [3-8] have shown that close attention must be paid to the influence of the Peltier effect in the 1 Ω standard when measuring the K_2 ratio. In particular, it has been shown in [3,5,6,8] that the Peltier effect induces a decrease in the K_2 value as the current reversal cycle time increases (at least up to the usual BIPM CCC cycle time of about 340 s), preventing the true "dc" value of this ratio from being reached. However, it was also observed that it exists a threshold cycle time (typically of the order of 10 s to a few tens of seconds) below which K_2 measurements remain stable within the usual best measurement uncertainties as those that can be reached in the present comparison.

This is why, in previous BIPM.EM-K12 comparisons since 2013, the K_2 measurements were carried out using short cycle times, for which the error due to Peltier effect – and possibly cable influence – is limited or null. Preliminary measurements are therefore necessary to determine the threshold value of the reversal cycle time below which the K_2 ratio remains stable. Below this threshold value, the measurement made by the participating NMI can be directly compared with the BIPM measurement performed with its 1 Hz bridge (1 s period sinusoidal reversal cycle).

In this comparison, we used a new type of 1 Ω standard resistor – model HRU-1R0 manufactured by Alpha Electronics on the basis of an AIST-NMIJ design – which is expected to have reduced cycle time dependence. This expectation is based on a study of the influence of cycle time on this type of resistance, carried out in collaboration with the PTB and the NMIJ, which is summarised in [17].

The HRU-1R0 type 1 Ω resistor we measured during this comparison (s/n: F112A) was already used for the first time in a previous BIPM.EM-K12 comparison at PTB in May 2025 [18]. Preliminary characterization measurements made on this occasion effectively showed that the cycle time dependence of this 1 Ω standard is quite small. They were repeated at CEM, using CEM's CCC bridge, in order to confirm this result.

The preliminary measurements were carried out over several days. They began with a long-term measurement with a cycle time of 340 s during the night of December 1 to 2, 2025. This was followed on December 2 by successive measurements with cycle times of 6 s, 10 s, and 20 s. Measurements were then interrupted due to a problem on the CCC bridge, which was not resolved until the end of the day. Measurements resumed on December 3, 2025, with a sequence of cycle times of 20 s, 6 s, 40 s, and 80 s. For all these measurements, the current magnitude in the 100 Ω and 1 Ω standards were 0.5 mA and 50 mA, respectively. All the other experimental conditions were the same as those used for the measurement of K_1 ratio. Care was taken that CEM and BIPM use similar measuring cables.

Figure 7 shows the results of the preliminary K_2 ratio measurements performed by CEM. These results are represented by the open circle symbols. Error bars correspond to the combined uncertainty of measurements. As in the previous comparison at the PTB, it can be seen that, within the limits of measurement uncertainty, the K_2 ratio (i.e., the resistance of 1 Ω) remains stable when the cycle time varies between 6 s and 340 s. However, the dispersion of measurements is somewhat higher.

The comparison of the K_2 ratio could again be carried out in the same way as for K_1, by comparing the CEM measurements for a cycle time of 20 s with the BIPM measurements for the cycle time of 336 s of its CCC bridge (i.e., the 1 Hz measurements corrected with the "1 Hz-dc" correction from Table 1). Nevertheless, as in all previous comparisons since 2013, it was decided to continue comparing the BIPM measurements at 1 Hz with the CEM measurements for a short cycle. A full cycle time of 10 s was chosen by the CEM.

For the sake completeness, we also added in Figure 7 all the subsequent interleaved comparison measurements made on December 3 by CEM for a cycle time of 10 seconds (cross symbols). All the 1 Hz comparison measurements made by BIPM were also added as well as the corresponding equivalent 336 s cycle measurements of the BIPM CCC bridge (full circle and triangle symbols). The latter equivalent measurement value is obtained by correcting the 1 Hz measurement for the 1 Hz-'dc' difference from Table 1, and for the power difference in the 1 Ω resistor associated with the difference in shape of the CCC bridge reversal cycles of the BIPM and CEM (see figures 2 and 3). The error bars correspond to combined uncertainties of the measurements. The CEM measurements for the 10 s cycle time and BIPM measurements at 1 Hz give an idea of the reproducibility of the measurements.

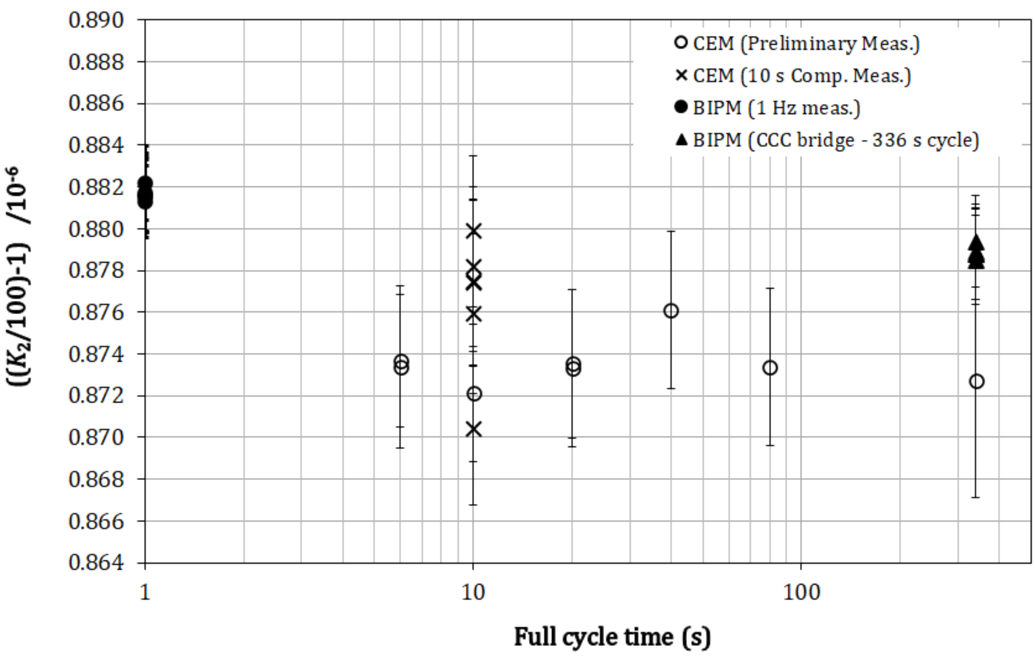

Figure 7: Preliminary measurements of the K_2 ratio performed by CEM when the current reversal cycle time is varied between 6 s to 340 s (open circles). For comparison, all the interleaved comparison measurements made by CEM for a 10 s cycle time (crosses) and by the BIPM at 1 Hz (full circles) are also reported. The data points indicated by the triangles show the calculated equivalent dc values of BIPM's CCC bridge (336 s cycle time), which correspond to the 1 Hz measurements corrected for the 1 Hz-'dc' difference of K_2 ratio and for the power difference resulting from the difference in shape of BIPM's and CEM's CCC reversal cycles.

7.2. Influence of comparing measurements at 1 Hz on the BIPM uncertainty budget

When the 1 Hz bridge of the BIPM is no longer used as a transfer instrument referenced to its CCC bridge, one has to consider the uncertainty associated with the accuracy of its room temperature current comparator and resistive divider [11]. The uncertainty budget for the use of the BIPM 1 Hz bridge for the measurement of the ratio K_2 is reported in Table 9.

Furthermore, although no significant influence of the Peltier effect is expected in measurements between cycle times of 1 s and 10 s, its influence is still considered as possible within the limit of ± 1x10^{-9}. A relative standard uncertainty of $u_{\text{Peltier}} = 1 \times 10^{-9}$ is therefore also considered in this table.

Relative standard uncertainties for the measurement of the resistance ratio K_2 (100 Ω/1 Ω)		
Source	**Uncertainty component**	**Value /10^{-9}**
1 Hz bridge	*Ratio error of the room temperature current comparator*	1.5
	Resistive divider calibration of the secondary current source	0.5
	Finite gain of servo of the bridge balance	0.5
Peltier effect	*Estimated residual Peltier effect*	1.0
	Combined type B standard uncertainty, u_B	**1.9**

Table 9: Uncertainty budget for the measurement at 1 Hz of the K_2 ratio using the BIPM 1 Hz bridge (the 1 Hz bridge being no longer used as a transfer instrument referenced to the BIPM CCC bridge).

7.3. BIPM measurements of K_2

For the measurement of K_2, two resistance standards from Alpha Electronics were used. The 100 Ω was of type HRU-101 (s/n: F078) and the 1 Ω of type HRU-1R0 (s/n: F112A). The rms current in the 100 Ω standard was 0.5 mA corresponding to 50 mA in the 1 Ω standard.

On December 3, 2025, the 100 Ω and 1 Ω standards were connected alternately to the BIPM and CEM bridges and five BIPM measurements at 1 Hz were interleaved with six CEM measurements. After each bridge change, at least 5 minutes were allowed for the thermal stabilization of the connections, with measurement current applied.

The BIPM measurements at 1 Hz, expressed as the relative difference with respect to the nominal ratio of 100, are shown in Table 10. Each of the raw measurements is the mean value of six individual measurements corresponding to a total measurement time of about 22 minutes. The associated dispersion is estimated by the standard deviation of the mean of the six individual measurements.

Time	$(K_{2,\mathrm{BIPM}}/100)-1$ /10^{-6}	Dispersion /10^{-6}
	1 Hz measurements	
3/12/25 12:21	0.882 20	0.000 51
3/12/25 13:25	0.881 72	0.000 82
3/12/25 14:29	0.881 58	0.000 36
3/12/25 15:34	0.881 30	0.000 32
3/12/25 16:53	0.881 61	0.000 59
Mean value	**0.881 68**	
Standard deviation, u_A	**0.000 33**	

Table 10: BIPM measurements of the ratio K_2 carried out on December 3, 2025. Results are expressed as the relative difference from the nominal ratio value 100. Each measurement is the mean value of a series of six individual measurements. Time corresponds to the mean time of this measurement series and the dispersion to the standard deviation of the mean.

The K_2 ratio value reported below corresponds to the mean of the 1 Hz ratio measurements carried out by the BIPM on December 3, 2025.

Mean value: $\boldsymbol{K_{2,\mathrm{BIPM}} = 100 \times (1 + 0.881\,68 \times 10^{-6})}$

Relative standard uncertainty: $\boldsymbol{u_{\mathrm{BIPM}} = 1.9 \times 10^{-9}}$

where u_{BIPM} is calculated as the root sum square of $u_{\mathrm{A}} = 0.3 \times 10^{-9}$ (Table 10) and $u_{\mathrm{B}} = 1.9 \times 10^{-9}$ (Table 9)

7.4. CEM measurements of K_2

For K_2 ratio measurements, the currents through the 100 Ω and 1 Ω resistance standards were 0.5 mA and 50 mA, respectively. As explained in section 7.1, a current reversal cycle time of 10 s was used by CEM.

Six CEM measurements were interleaved with five BIPM measurements. Each CEM measurement consisted of a set of 150 consecutive cycles but only the last 120 were used to compute the measurement result (20-minute measurement time preceded by a 5-minutes warm-up period).

As with the $R_{100\Omega}$ and K_1 measurement, a correction was applied to account for the differences in power dissipation in the two resistors (100 Ω and 1 Ω standards) due to the different bridge current excitations used by BIPM and CEM. This correction was estimated from the power coefficient of the ratio K_2 and from the effective difference of power dissipated in the resistors between the CEM and the BIPM. The latter was computed from the current magnitudes and cycle timing parameters used by each of the institutes and assuming that the power was only dissipated in the 1 Ω standard (negligible dissipation in the 100 Ω standard).

It was estimated that the power dissipated by CEM in the 1 Ω was (0.16 ± 0.05) mW lower than that dissipated by BIPM. Thus, using the power coefficient $(2.68 \pm 0.48) \times 10^{-9}$ per mW of the ratio K_2 – determined by the BIPM prior to the comparison – the power difference correction to be applied to the K_2 ratio was in turn estimated to be $(0.43 \pm 0.12) \times 10^{-9}$.

The raw measurement results of CEM as well as those corrected for the difference in power dissipation are reported in Table 11. They are expressed as the relative difference from the nominal ratio value 100 with a dispersion corresponding to the standard deviation of the mean of the individual measurements.

Time	$(K_{2,\mathrm{CEM}}/100)-1$ /10^{-6}		Dispersion /10^{-6}
	Raw measurements	Corrected measurements	
3/12/25 11:43	0.877 38	0.877 81	0.002 80
3/12/25 12:47	0.877 44	0.877 87	0.002 80
3/12/25 13:49	0.879 89	0.880 32	0.002 30
3/12/25 14:53	0.870 43	0.870 86	0.002 40
3/12/25 16:05	0.875 91	0.876 35	0.002 60
3/12/25 17:17	0.878 20	0.878 63	0.002 60
	Mean value	**0.876 97**	
	Standard deviation, u_A	**0.003 26**	

Table 11: CEM measurements of the ratio K_2 carried out on December 3, 2025. Results are expressed as the relative difference from the nominal ratio value 100. Time corresponds to the starting time of measurement and the dispersion to the standard deviation of the mean of each individual measurement.

The K_2 ratio value reported below corresponds to the mean of the corrected ratio measurements carried out by the CEM on December 3, 2025.

Mean value: $\boldsymbol{K_{2,\mathrm{CEM}} = 100 \times (1 + 0.876\,97 \times 10^{-6})}$

Relative standard uncertainty: $\boldsymbol{u_{\mathrm{CEM}} = 4.3 \times 10^{-9}}$

where u_{CEM} is calculated as the root sum square of $u_{\mathrm{A}} = 3.3 \times 10^{-9}$ (Table 11), $u_{power} = 0.1 \times 10^{-9}$ the standard uncertainty on power difference correction and $u_{\mathrm{B}} = 2.8 \times 10^{-9}$ (Table 4).

7.5. Comparison of K_2 measurements

The interleaved measurements of the BIPM and CEM, carried out at 1 Hz and for a full cycle time of 10 s respectively, are reported in Figure 8.

For an undetermined reason, the fourth CEM measurement is significantly lower than the other five it performed. This obviously increases the CEM-BIPM difference for the measurement of the K_2 ratio, but also the type A uncertainty of the series of the six CEM measurements (standard deviation). The combined uncertainty of the mean K_2 value for CEM and that of the CEM-BIPM difference (noted u_{comp} below) are therefore both noticeably increased.

If we disregard the fourth measurement of the CEM, no drift or instabilities is observed in the series of measurements of the CEM and the BIPM, and no additional uncertainty component related to these effects was included in the final results of the comparison.

Therefore, the difference between the CEM and the BIPM was computed as the difference of the means of the measurement values provided in Table 10 and Table 11:

Relative difference CEM-BIPM: $\boldsymbol{(K_{2,\mathrm{CEM}} - K_{2,\mathrm{BIPM}}) / K_{2,\mathrm{BIPM}} = -4.7 \times 10^{-9}}$

with a relative combined standard uncertainty: $\boldsymbol{u_{\mathrm{comp}} = 4.7 \times 10^{-9}}$

where u_{comp} is calculated as the root sum square of $u_{\mathrm{BIPM}} = 1.9 \times 10^{-9}$ and $u_{\mathrm{CEM}} = 4.3 \times 10^{-9}$.

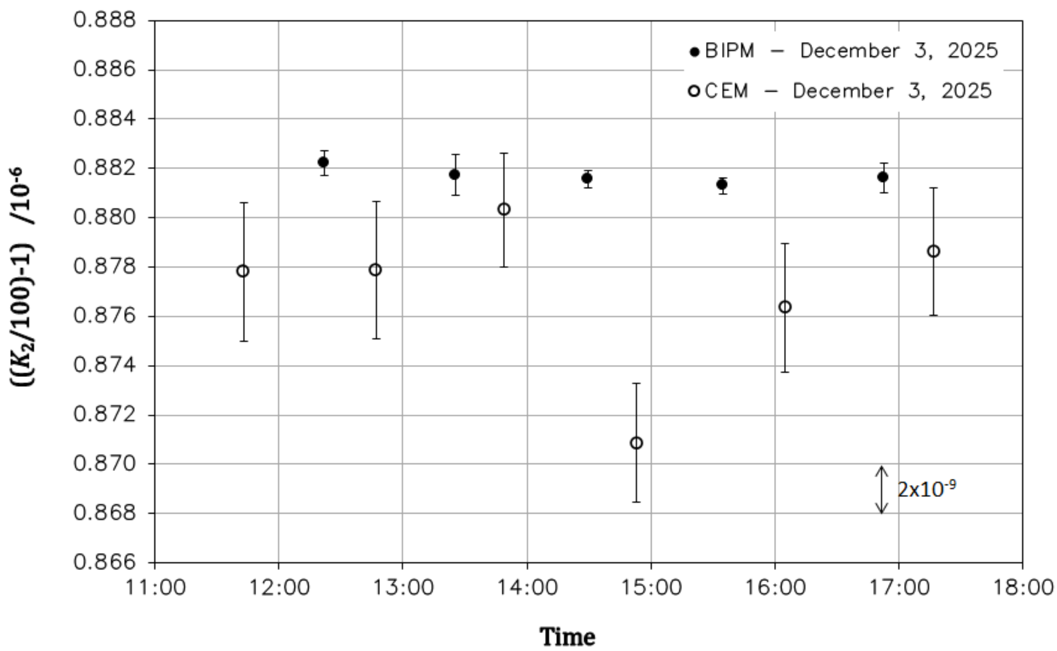

Figure 8: Measurement results for K_2 ratio on December 3, 2025: BIPM at 1 Hz (black dots) and CEM for a 10 s cycle time (open circles). Error bars correspond to the dispersion observed for each measurement.

8. Conclusion

The on-site key comparison BIPM.EM-K12 carried out from 27 November to 3 December 2025 between the CEM and the BIPM showed an agreement within a few parts in 10^9 in the measurements of a conventional 100 Ω resistor in terms of the quantized Hall resistance ($R_H(2)$), and in the determination of the resistance ratios K_1 (10 kΩ/100 Ω) and K_2 (100 Ω/1 Ω).

The comparison results for the measurement of $R_{100\Omega}$ in terms of $R_H(2)$ and of K_1 and K_2 ratios are summarized in Table 12 and will be reported in the BIPM KCDB.

$R_{100\Omega}$ in terms of $R_H(2)$	$(R_{CEM} - R_{BIPM}) / R_{BIPM}$ = **3.4×10^{-9}**	u_{comp} = **3.6×10^{-9}**
$K_1 = R_{10k\Omega}/R_{100\Omega}$	$(K_{1,CEM} - K_{1,BIPM}) / K_{1,BIPM}$ = **-2.0×10^{-9}**	u_{comp} = **3.1×10^{-9}**
$K_2 = R_{100\Omega}/R_{1\Omega}$	$(K_{2,CEM} - K_{2,BIPM}) / K_{2,BIPM}$ = **-4.7×10^{-9}**	u_{comp} = **4.7×10^{-9}**

Table 12: Summary of the results of the CEM-BIPM on-site comparison BIPM.EM-K12 carried out from 27 November to 3 December 2025, and associated relative standard uncertainties. The measurement of K_2 ratio was carried out at 1 Hz by the BIPM without applying the 'dc' correction, and with a cycle time of 10 s by the CEM.

The comparison results will also appear as Degree of Equivalence (DoE) in the BIPM KCDB. The DoE of the participating institute with respect to the reference value is given by a pair of terms: the difference D from the reference value and its combined expanded uncertainty for k=2, i.e. U=2u. The reference value of the on-going comparison BIPM.EM-K12 was chosen to be the BIPM value.

The comparison results expressed as DoEs are summarized in Table 13.

	Degree of equivalence D /10^{-9}	**Expanded uncertainty U /10^{-9}**
$R_{100\Omega}$ in terms of $R_H(2)$	**3.4**	**7.2**
$K_1 = R_{10k\Omega}/R_{100\Omega}$	**-2.0**	**6.2**
$K_2 = R_{100\Omega}/R_{1\Omega}$	**-4.7**	**9.4**

Table 13: Summary of the comparison results expressed as degrees of equivalence (DoEs): difference from the BIPM reference value and expanded uncertainty U (k=2).

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