



Report from the BIPM electricity laboratories

M. Stock

CCEM meeting
6-7 March 2025



Staff of the Physical Metrology Department



Dr Michael STOCK
(CCEM, CCU)

Electricity

Impedance
(Resistance, Capacitance)



Dr Pierre
GOURNAY
Principal
Physicist



José Angel
MORENO
Physicist



Benjamin
ROLLAND
Assistant
(Engineer)

Voltage



Dr Stéphane
SOLVE
Principal
Physicist (CCT)



Régis
CHAYRAMY
Principal
Technician

Mass

Kibble balance



Dr Hao
FANG
Principal
Physicist
(CCM)



Dr Franck
BIELSA
Principal
Physicist
(CODATA TGFC)



Adrien
KISS
Assistant
(Engineer)

Mass calibr.
(also pressure, density)



Pedro
CONCEIÇÃO
Principal
Technician

Five BIPM ongoing comparisons



Two on-site comparisons of quantum standards

BIPM.EM-K10	On-site comparison of dc and ac voltages (≤ 1 kHz) from JVSs
BIPM.EM-K12	On-site comparison of QHR standards and resistance scaling

Three bilateral comparisons using conventional BIPM transfer standards

BIPM.EM-K11	voltage at 1.018 V and 10 V
BIPM.EM-K13	resistance at 1 Ω and 10 k Ω
BIPM.EM-K14	capacitance at 10 pF and 100 pF, at 1592 Hz and/or 1000 Hz

Five BIPM ongoing comparisons



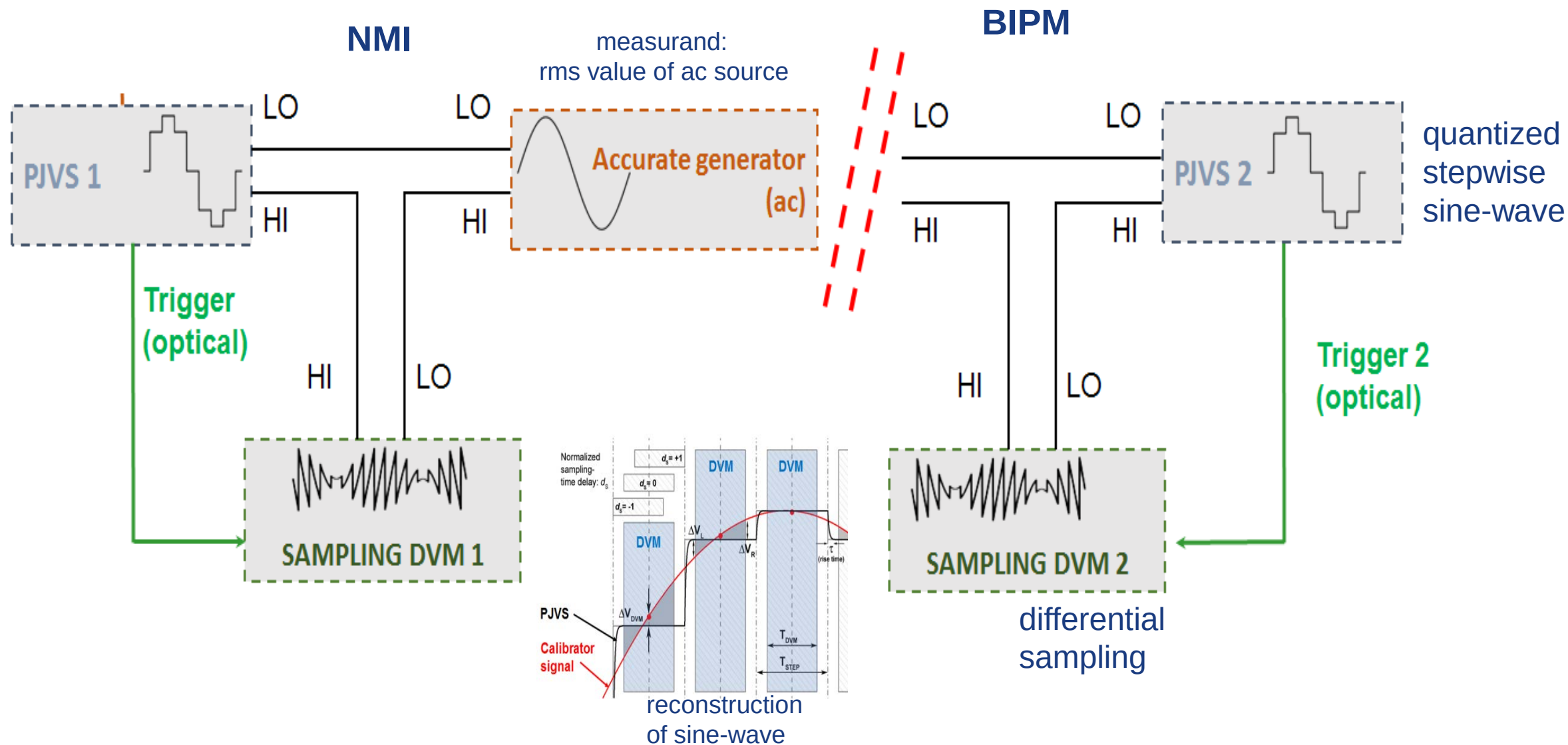
Two on-site comparisons of quantum standards

- | | |
|-------------|--|
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| BIPM.EM-K12 | On-site comparison of QHR standards and resistance scaling |

Three bilateral comparisons using conventional BIPM transfer standards

- | | |
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| BIPM.EM-K11 | voltage at 1.018 V and 10 V |
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| BIPM.EM-K14 | capacitance at 10 pF and 100 pF, at 1592 Hz and/or 1000 Hz |

On-site comparison of ac voltages from JVSs (K10) $\uparrow\downarrow\downarrow$ **BIPM**



Program of Pilot Studies (2015-2024)



NMIJ – 2015

CENAM – 2016

PTB – 2017, 2018, 2021, 2022, 2023, 2024

with the support of KRISS, NMIA and VNIIM

NPL – 2018

KRISS – 2018, 2022, 2023

NIST – 2024

with support of KRISS



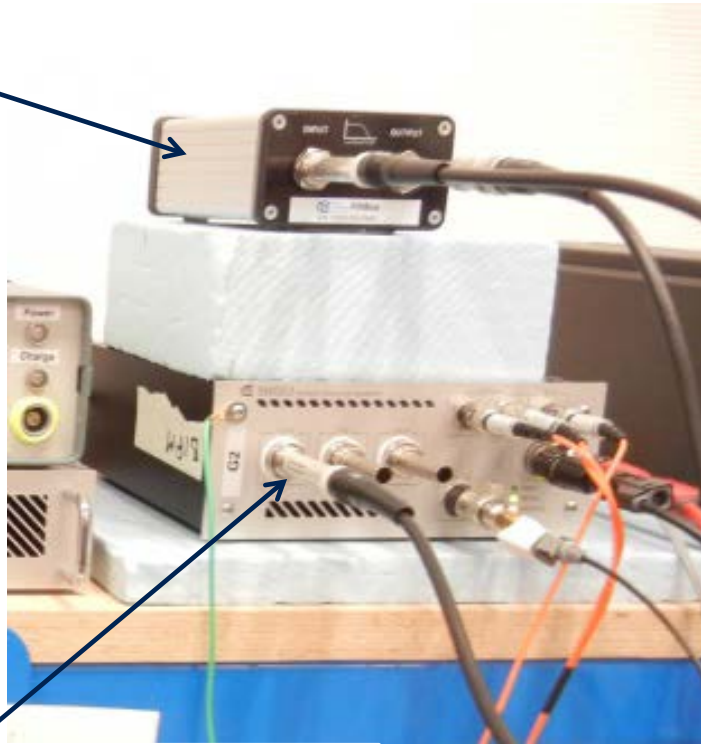
The BIPM Transportable PJVS



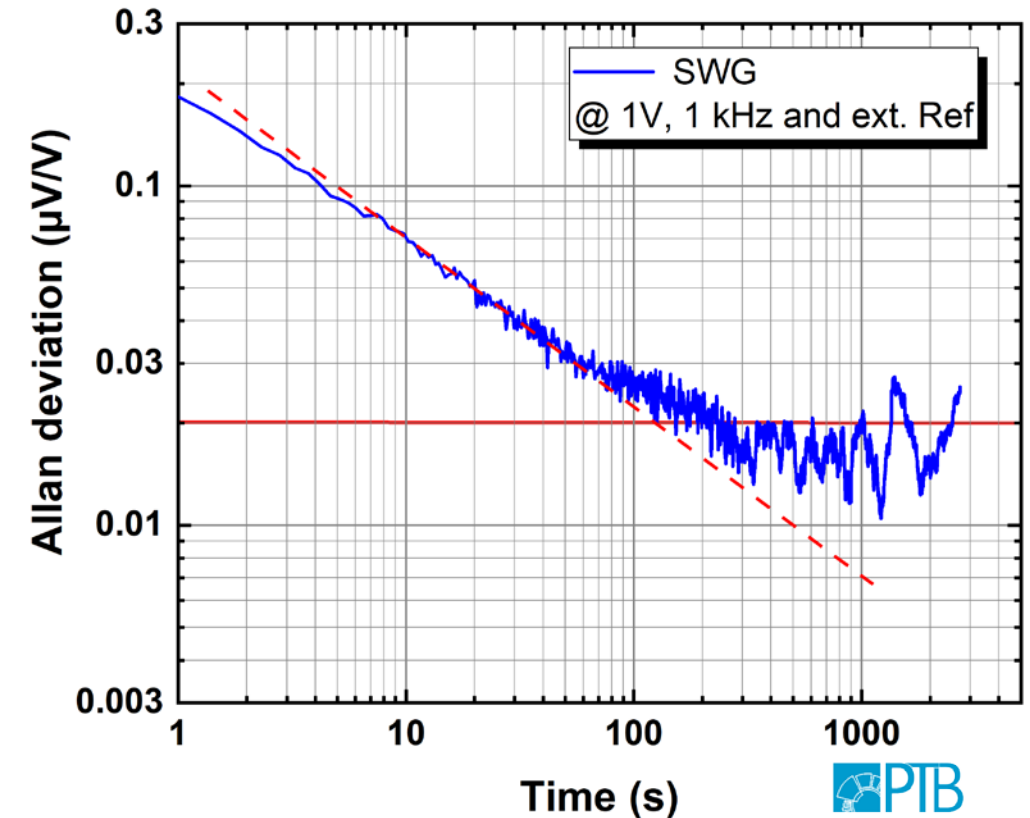
- The BIPM Transportable PJVS is a specially designed compact version of the NIST PJVS (10 V and 2 V) operated in liquid helium
- The array can be biased with **three different bias sources** (NIST, KRISS, Supracon)
- The system is flexible in timing – **can trigger or can be triggered**
- The BIPM differential sampling setup can operate **three different samplers** (Keysight 3458A, Fluke 8588A, NI-PXI 5922)
- The BIPM sampling setup has been **tested with different softwares** (NIST, PTB, KRISS)

BIPM AC voltage transfer standard (sine wave generator)

active filter



AC source transfer standard



Jan Kucera et al. – CPEM 2022

Improvements of CMI's digital synthesizer SWG as an AC voltage transfer standard

Pilot Study PTB – BIPM - 2024 at BIPM



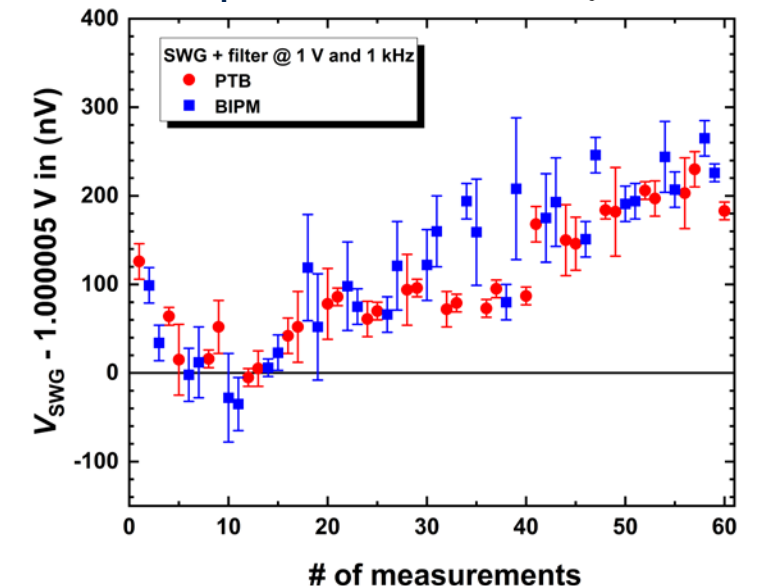
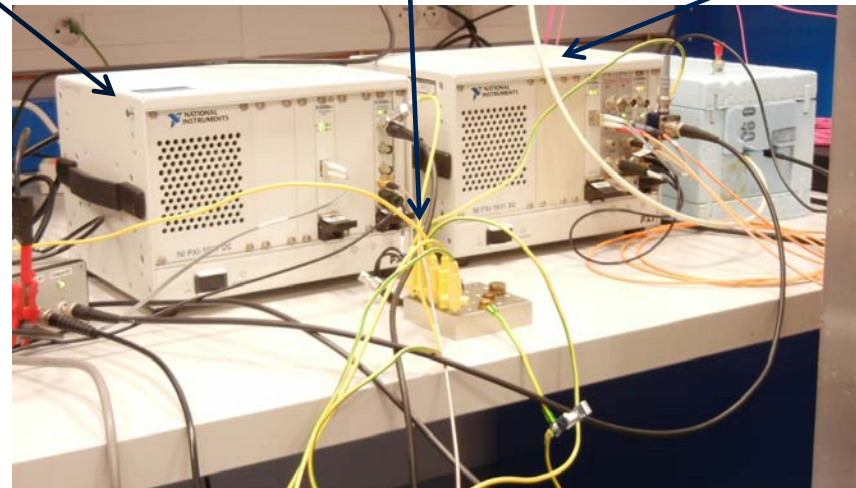
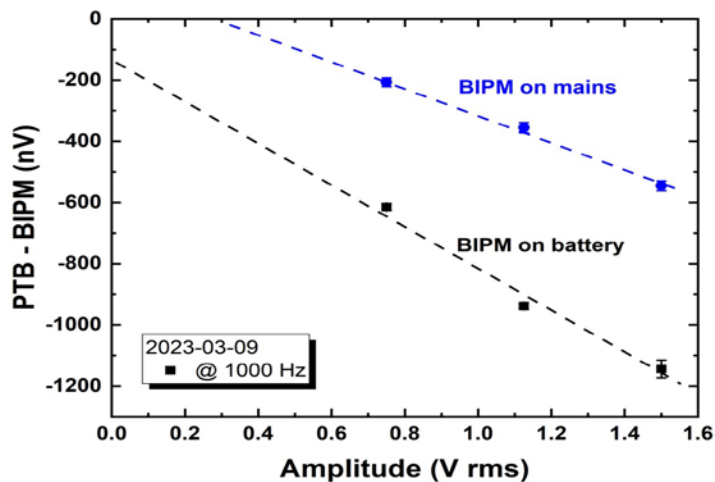
Large discrepancy 2023: Assumption of a leakage effect on the BIPM side

- Repetition of the 2023 exercise using the same NI-5922 sampler and PTB software
- with a **2 V NIST array** on the BIPM system
- Testing two different bias sources on the BIPM system: **NIST and Supracon™ bias source**

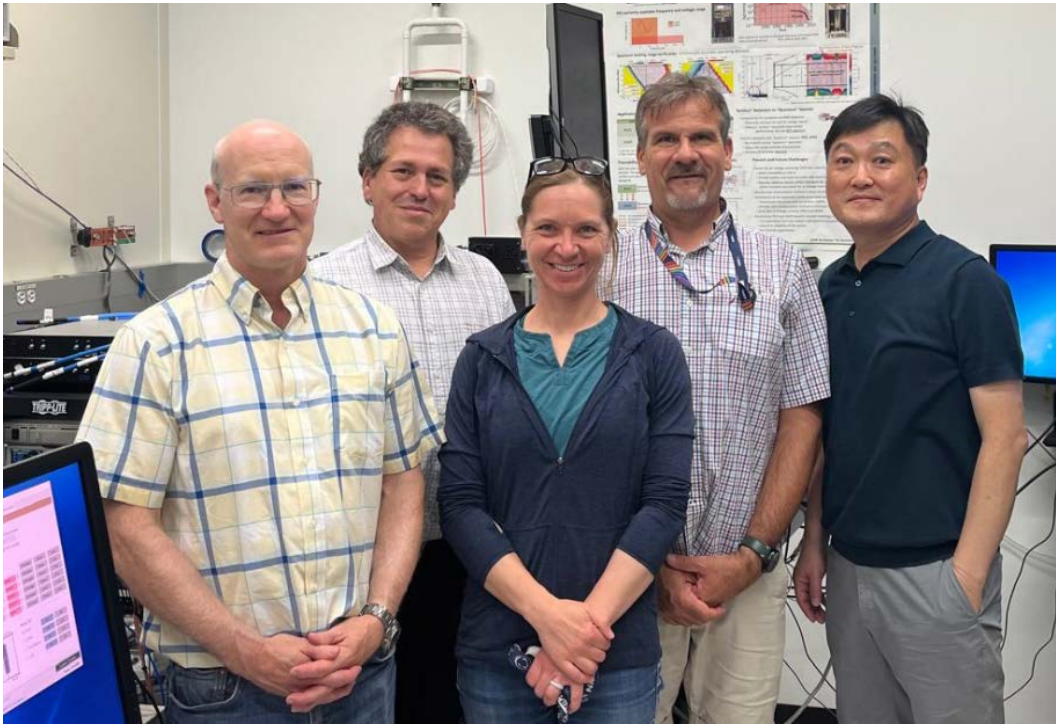
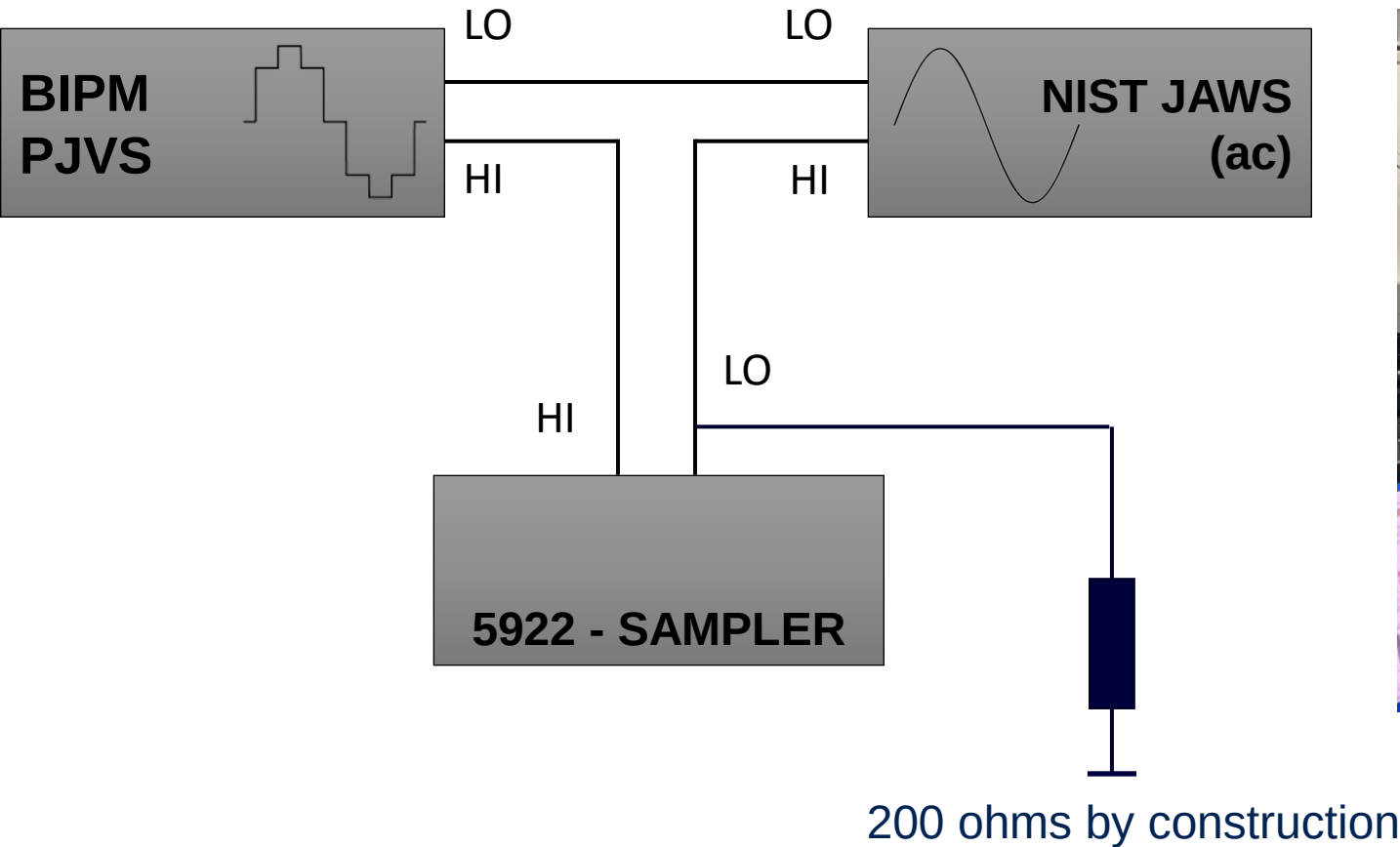
Star Point Voltage Reference Point

BIPM 5922 sampler

PTB 5922 sampler



Pilot Study – NIST – August 2024 at NIST



Very first Measurement at 1 kHz: 0.750 000 019 V !!!!

Source and Circuit:

PJVS: **External** **On** AC Source: Type II Measurement Circuit:

Server URL: 192.168.100.2 Offset (us): -250

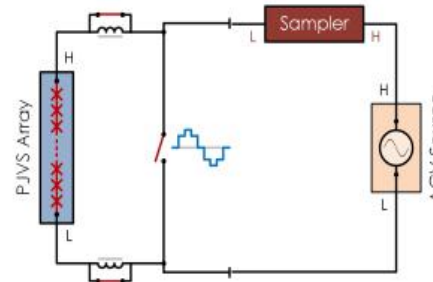
Check

Connected

Clock (F/G): K33500B Measurement Type:

Address: 10

Diff/S Full/S: DUT Full/S: PJVS



RMS Amplitude/Phase referenced to aperture window:

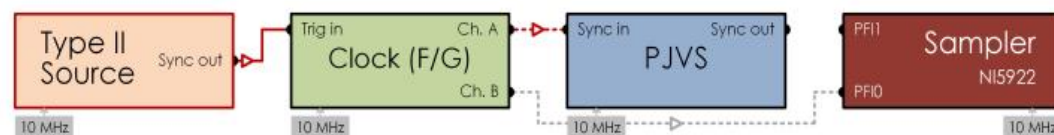
RMS Amp of Fundamental:	Phase:	RMS Voltage:
V (V): 0.750 000 061	Phase (deg): -0.009 084	V (V): 0.750 000 215
Mean (V): 0.750 000 019	Mean (deg): -0.009 112	Mean (V): 0.750 000 146
1s (uV): 0.913	1s (mdeg): 0.077	1s (uV): 0.784
uA (uV): 0.091	uA (mdeg): 0.008	uA (uV): 0.078

Status:

Run: 1/1

Meas: 100/100

Setup:



PJVS and Source:

Frequency (Hz): 1000

RMS Amp (V): 0.75

Steps (SPP): 16

Arm Source DeArm

Sampler: G/F: 0.999924

NI PXI-5922

PXI Slot #: Slot 4

Range: Auto 1 V

Input Channel: Ch0

Rate (MS/s): 10

Configuration:

Mode A: Mode EA:

Mode C: Mode EC:

Mode D: Mode E:

Mode DM: Mode EM:

Delay and Aperture:

Step Width (us): ts 62.500000

Delay/Step (%): 30

Min Delay (us): 0.0

Delay (us): td 18.8

Aperture/Step (%): 39.64

Aperture (us): ta 24.800 000

ta + 2td (us): 62.400

Measurement:

Total Periods: 160

Total Samples: 2560

Initial Pause (s): 0

Interval (s): 0

Stab. Time (s): 0

Run:

Dummy Meas #: 10

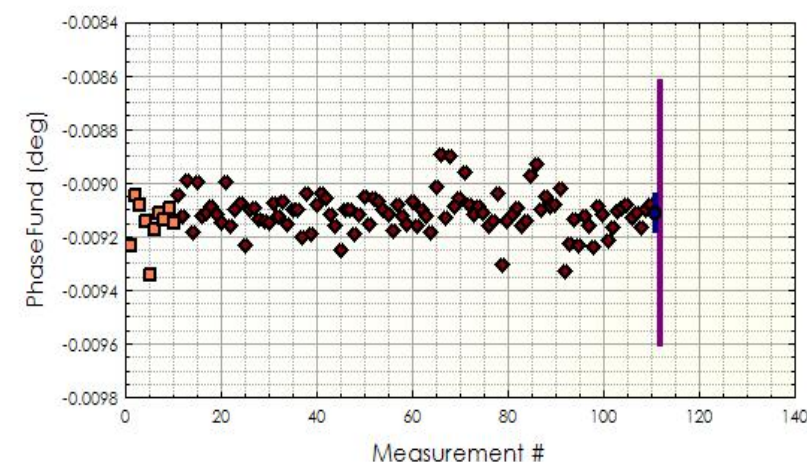
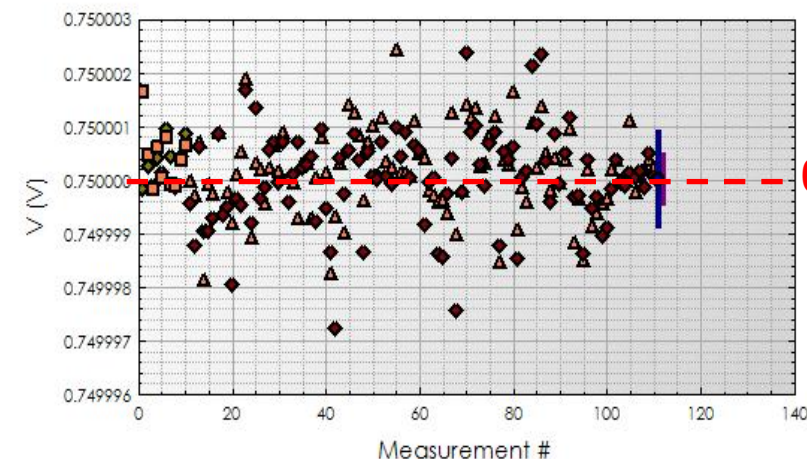
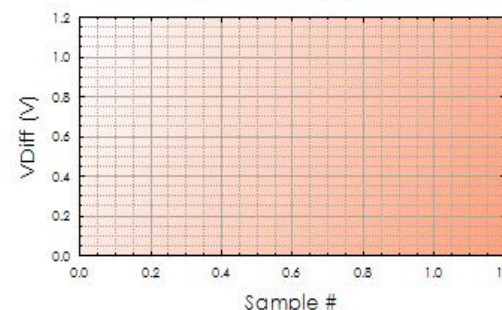
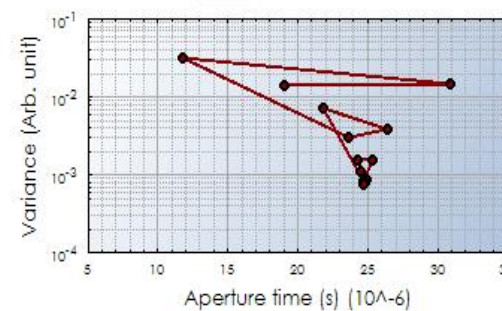
Measurement #: 100

Run #: 1

DeArm source(s) after run:

Do aperture optimization:

Do Sine Fit:

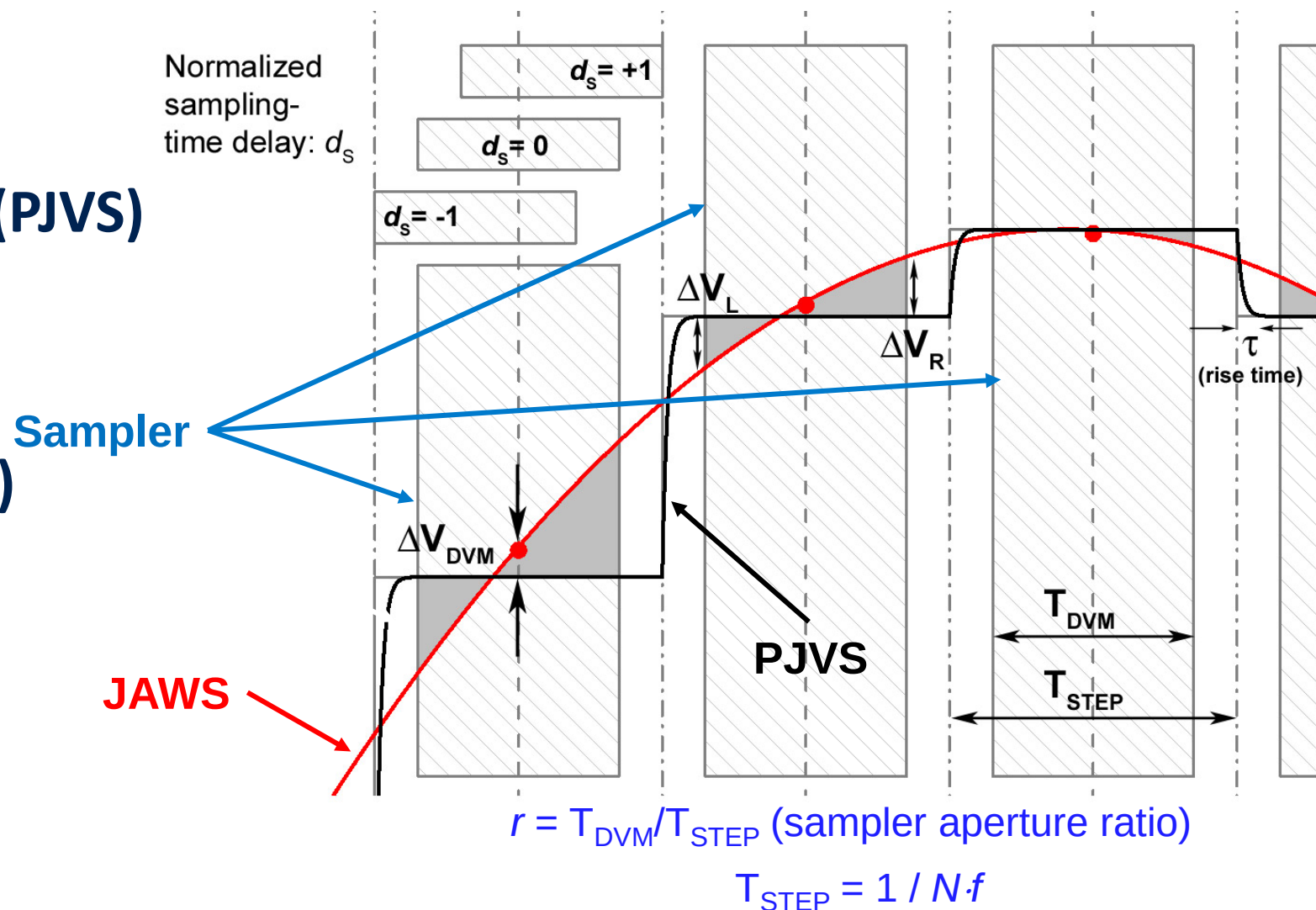


BIPM KRIS

BIPM-NIST Pilot Study - 2024



- Overnight Measurements
- Aperture of the windows (PJVS)
- Delay Time (PJVS)
- Phase shift (JAWS)
- Amplitude changes (JAWS)
- and more...



Typical outcome of the most recent pilot studies



Freq./Hz	N	difference/nV	typ. Type A unc./nV
62.5	64	5	30
125	64	7	20
250	32	44	20
625	32	100	20
1250	16	200	30

Type B uncertainty under evaluation

Type A: 2 to 5 parts in 10^8 demonstrated for 0.75 V - 1 kHz

Parameters for the

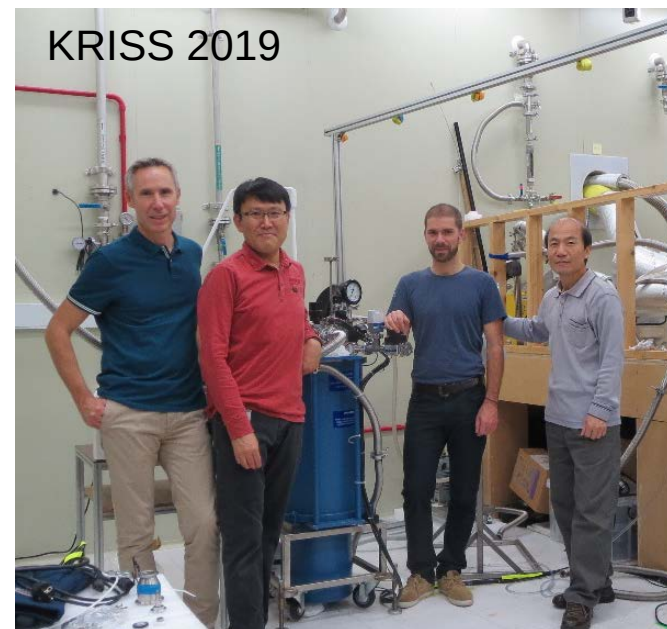
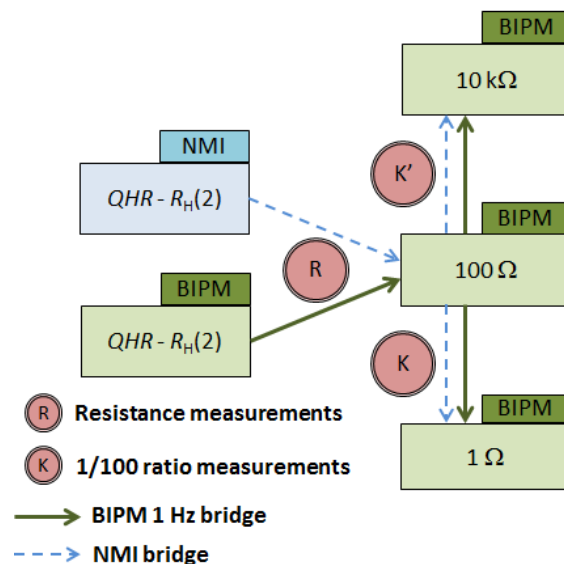
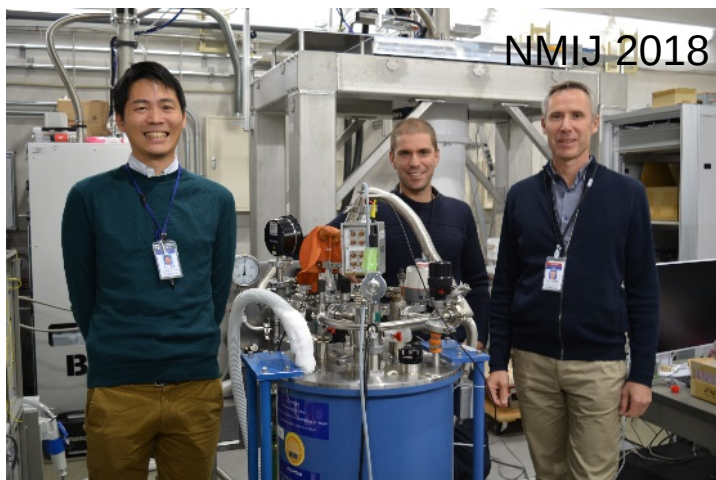
- 0.7 V and 7 V rms
- f/Hz : 10, 50, 60, 62.5, 100, 312.5, 625, 976.5625, 1000, 1250

On-site comparison of ac voltages from JVSs



- For first time agreement at 10 Hz within a few 10^{-9} reached at 2 V_{rms}
agreement at 1 kHz within 2×10^{-7}
- Technical protocol approved by CCEM support group in 2022
- Program of pilot studies now completed, KC officially launched, first two comparisons planned in 2025 with PTB and CENAM, in 2026 with NIM and ...
- Parameters:
 - o 0.7 V and 7 V rms
 - o f/Hz : 10, 50, 60, 62.5, 100, 312.5, 625, 976.5625, 1000, 1250
- Questionnaire on interest (2023): 21 for comparison at dc, 16 for ac

On-site quantum Hall resistance key comparisons (BIPM.EM-K12)



No comparisons 2023-2024 due to liquid He shortage and other problems at NMIs

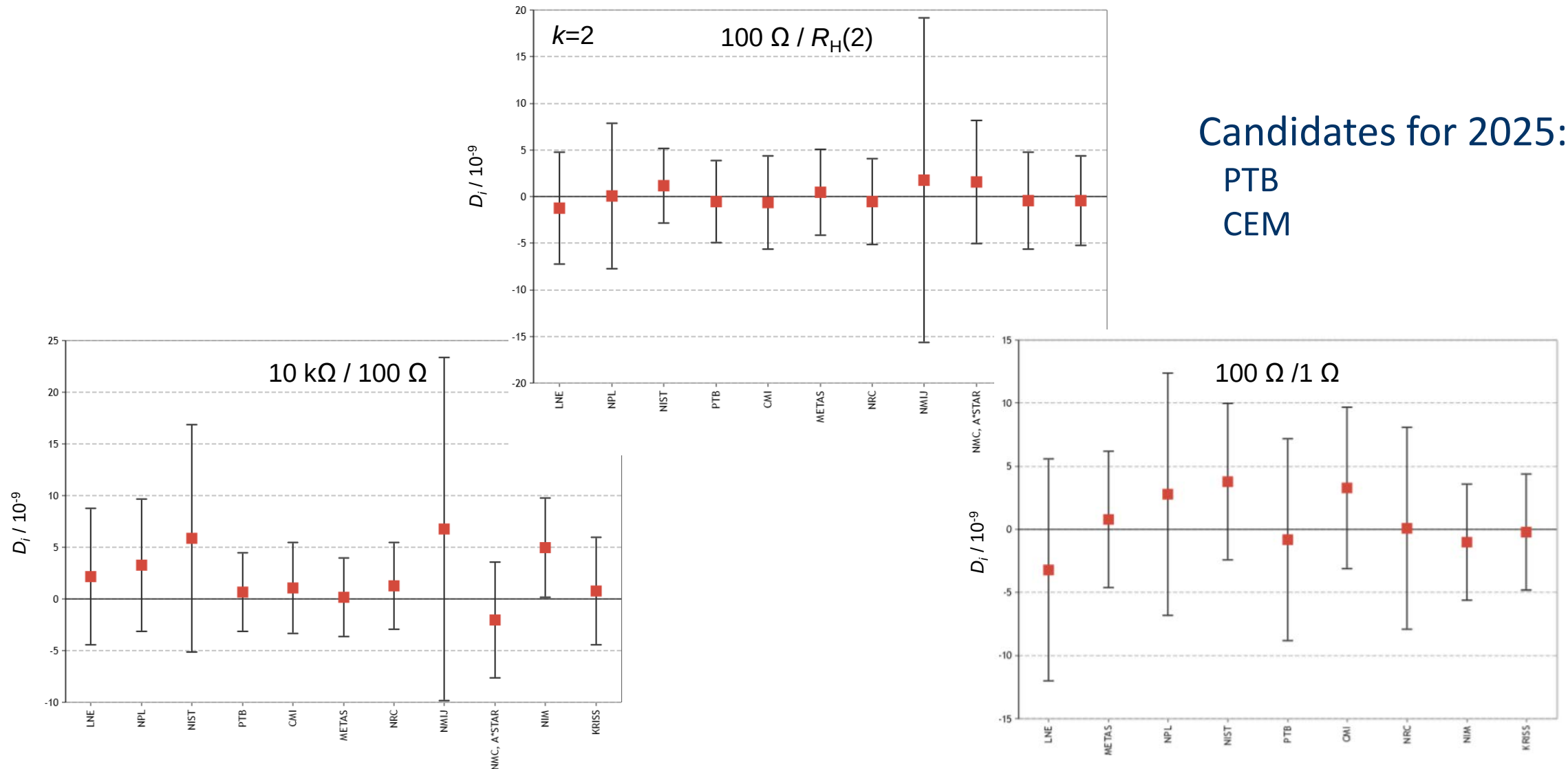
Planned comparisons were cancelled 3 times on request of the NMIs

Now planned for 2025:
PTB and CEM

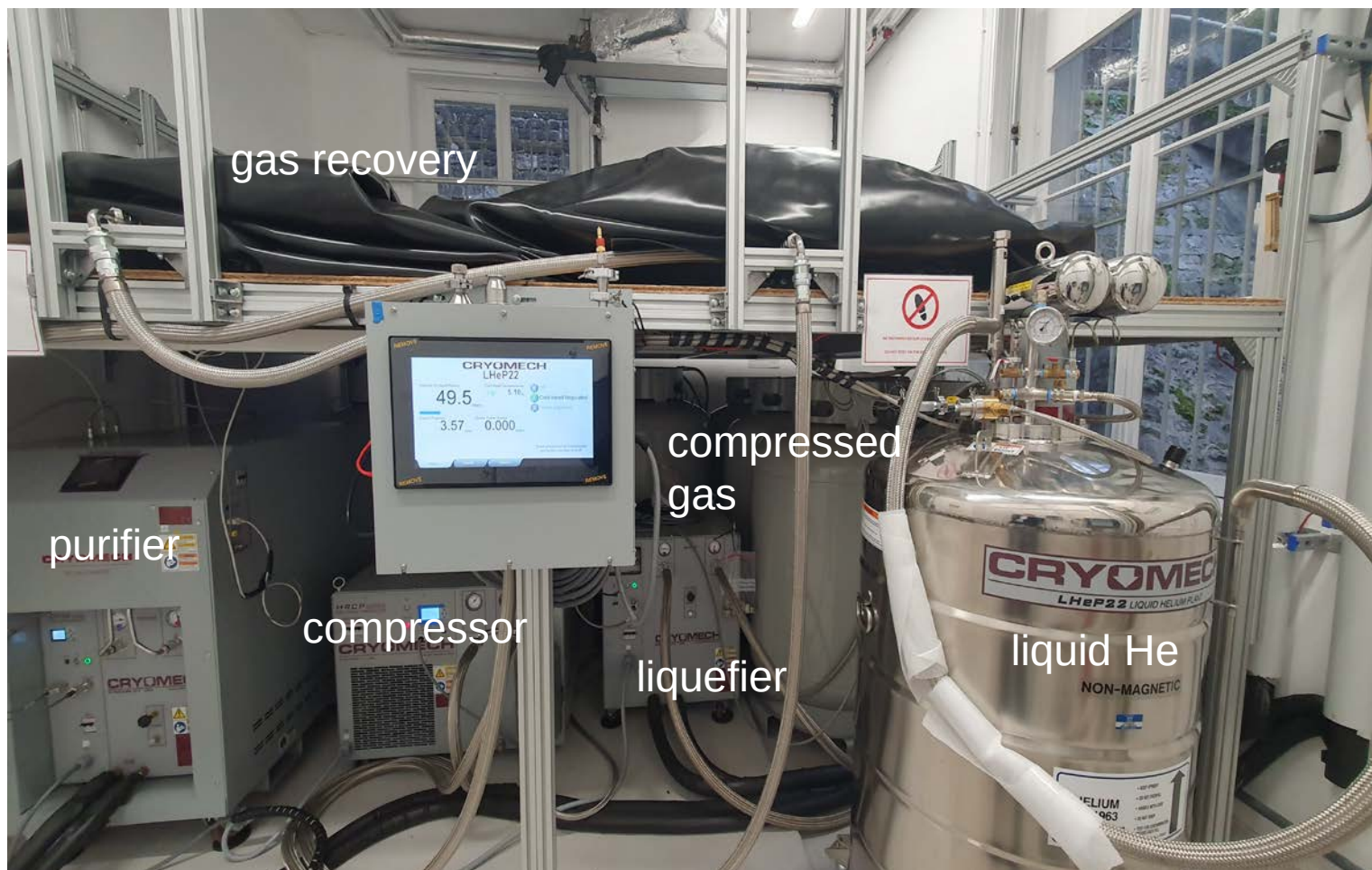
Questionnaire on interest (2023): 14 NMIs interested (until 2030)



On-site quantum Hall resistance key comparisons (BIPM.EM-K12)



Installation of a He liquefier



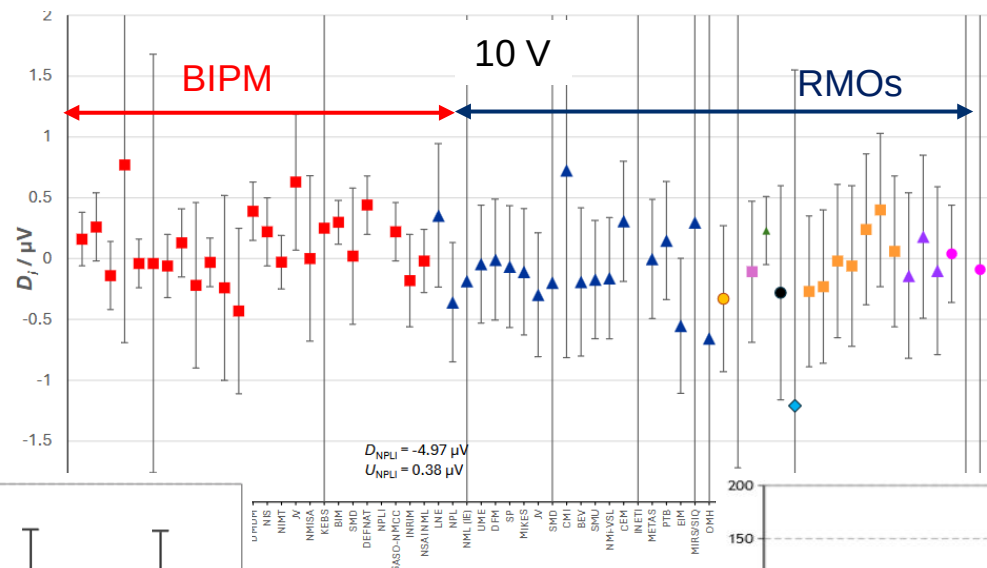
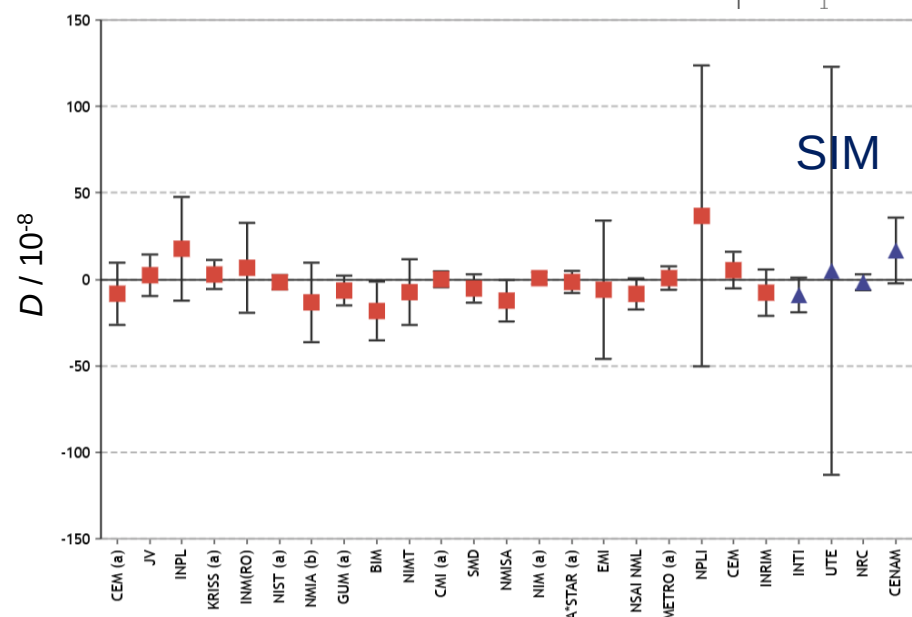
- to provide access to liquid He
- to protect He resources
- to reduce cost
- capacity:
 - 150 liter of liquid He
 - liquefying 25 liters/day

Bilateral comparisons using transfer standards



BIPM.EM-K13

Resistance 1 Ω , 10 k Ω
2023/24: INRIM, UME

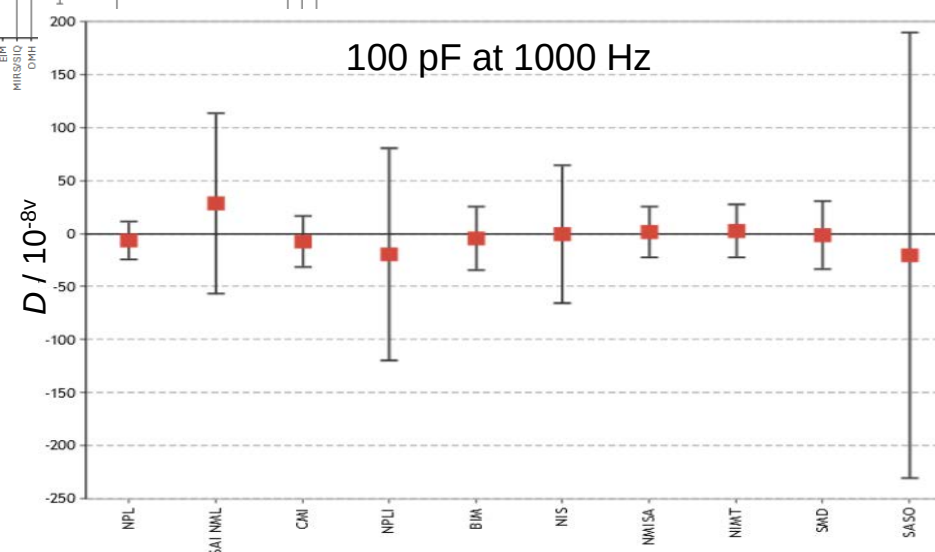


BIPM.EM-K11

Voltage 1.018 V, 10V
2023/24: NSAI, INRIM,
SASO, NSAI, SMD

BIPM.EM-K14

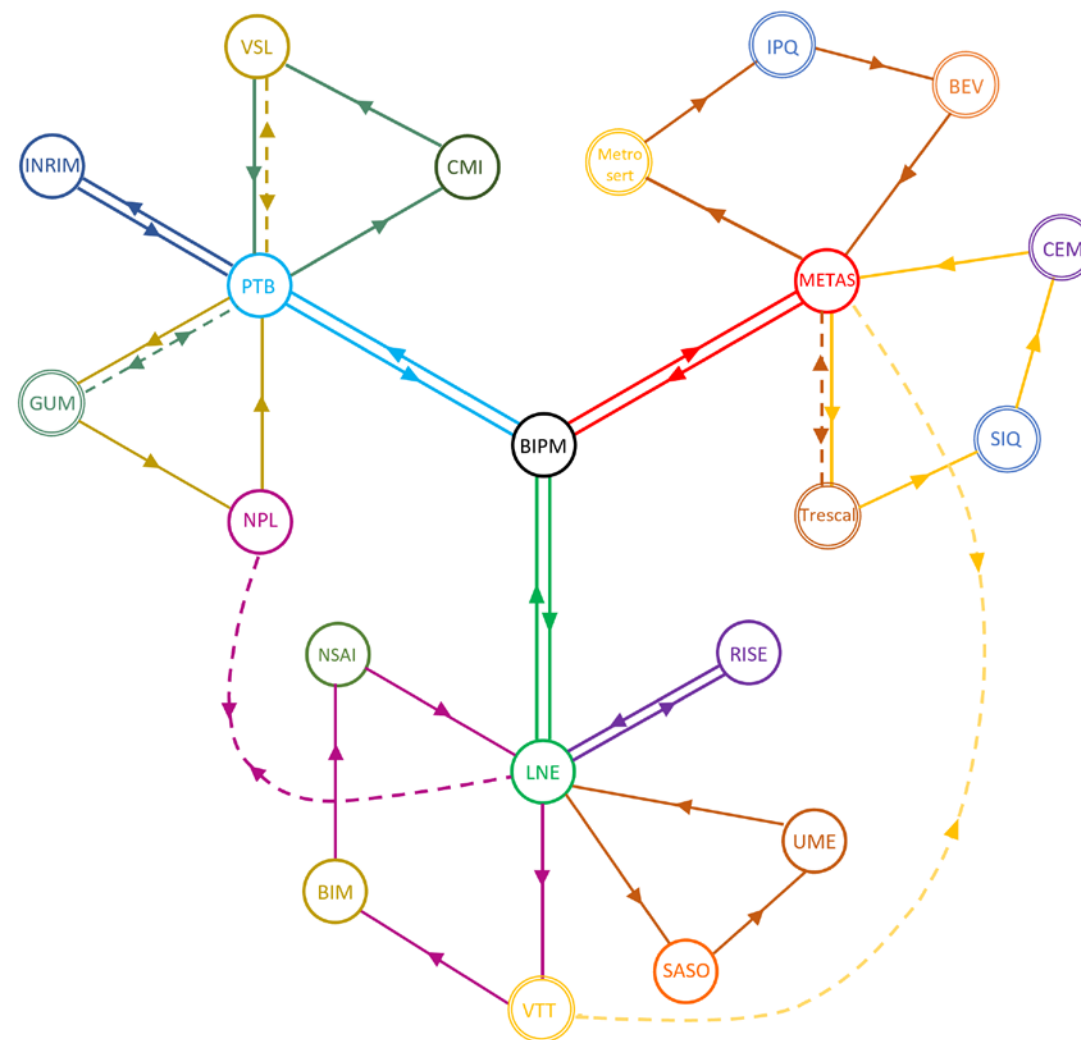
Capacitance 10 pF, 100 pF
2023/24: CENAM



Comparison of capacitance EURAMET.EM-K4



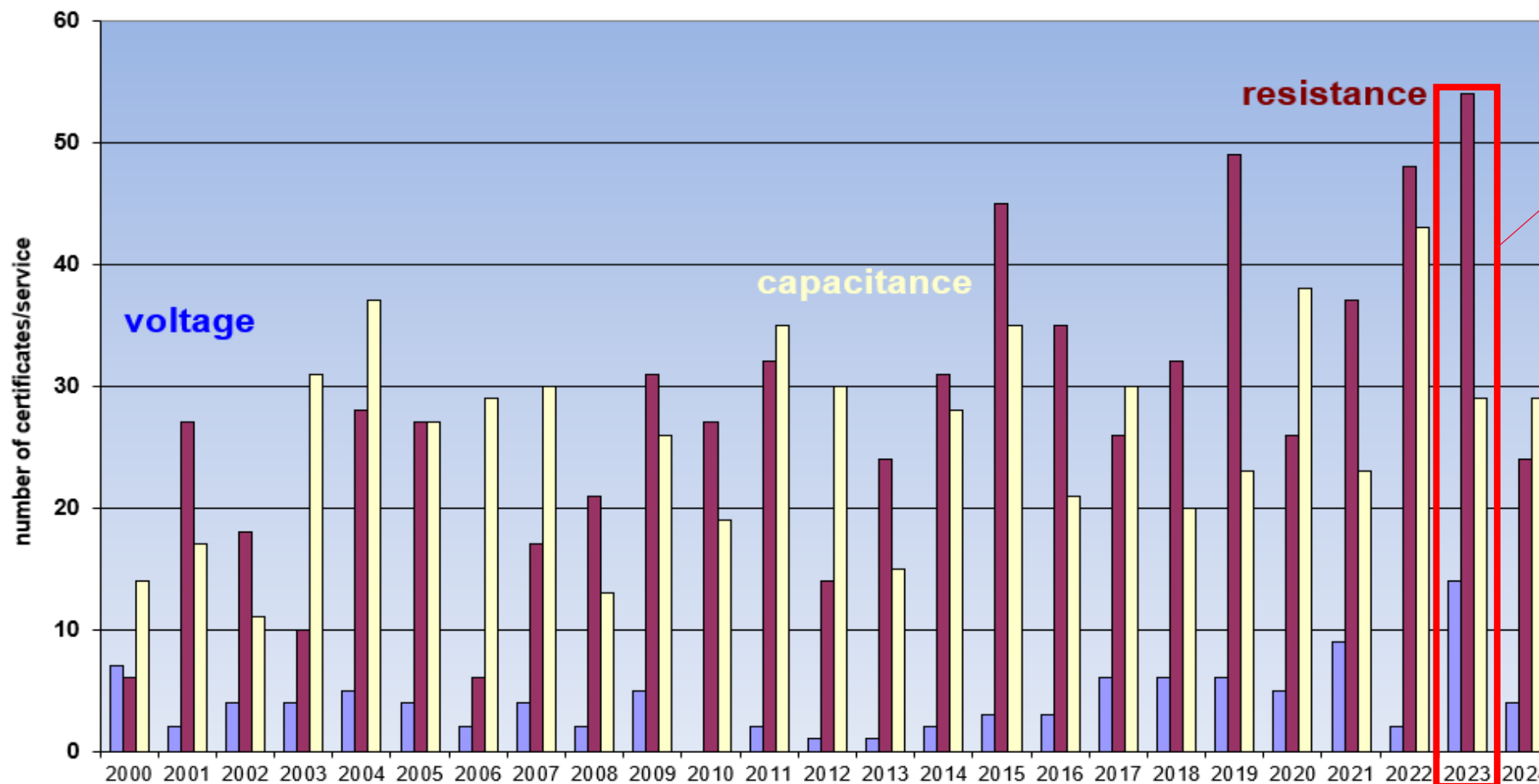
- Coordinator: PTB
- Measurand:
 - 10 pF at 100 V and 1592 Hz
 - 100 pF at 10 V and 1592 Hz
- High number of participants (21)
- Organized in one inner loop and three outer loops
- BIPM participates as:
 - Member of the support group
 - Center of the inner loop with the three sub-pilots of the comparison
- Measurements of 12 capacitors simultaneously from middle April 2025 for four weeks.



Calibrations



voltage:	1.018 V, 10 V	on average	6 per year
resistance:	1 Ω , 100 Ω , 10 k Ω		38 per year
capacitance:	1 pF, 10 pF, 100 pF		30 per year



Largest number of calibrations ever (97)

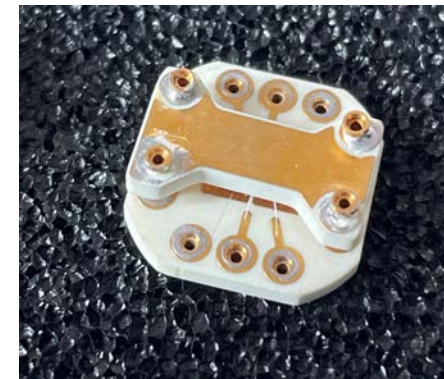
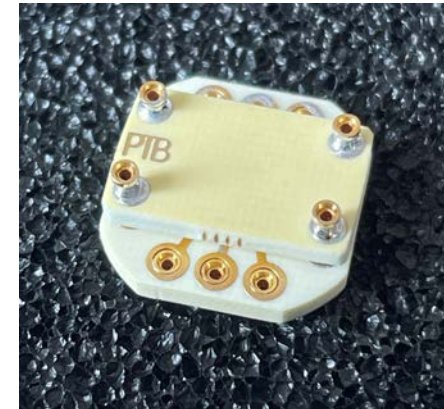
4 new NMIs as customer

Trend towards more calibration requests due to more Member States

Study of the stability and performance of graphene devices

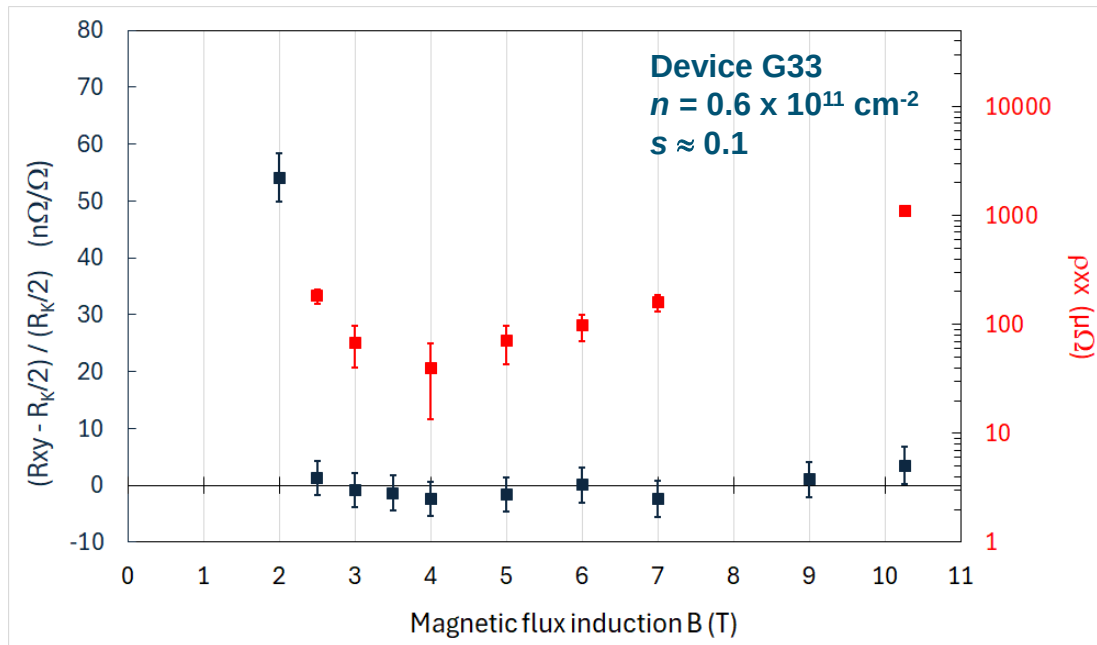
The use of a graphene-based quantized Hall resistor would simplify the BIPM.EM-K12 comparison and reduce its cost

- ⇒ Preparation to the transition from GaAs-type QHR to graphene-type QHR by characterizing devices and study their long-term stability
- ⇒ This work is carried out in collaboration with the PTB, providing epitaxial graphene-based devices to the BIPM
- ⇒ BIPM is a member of CCEM TG-Graphene

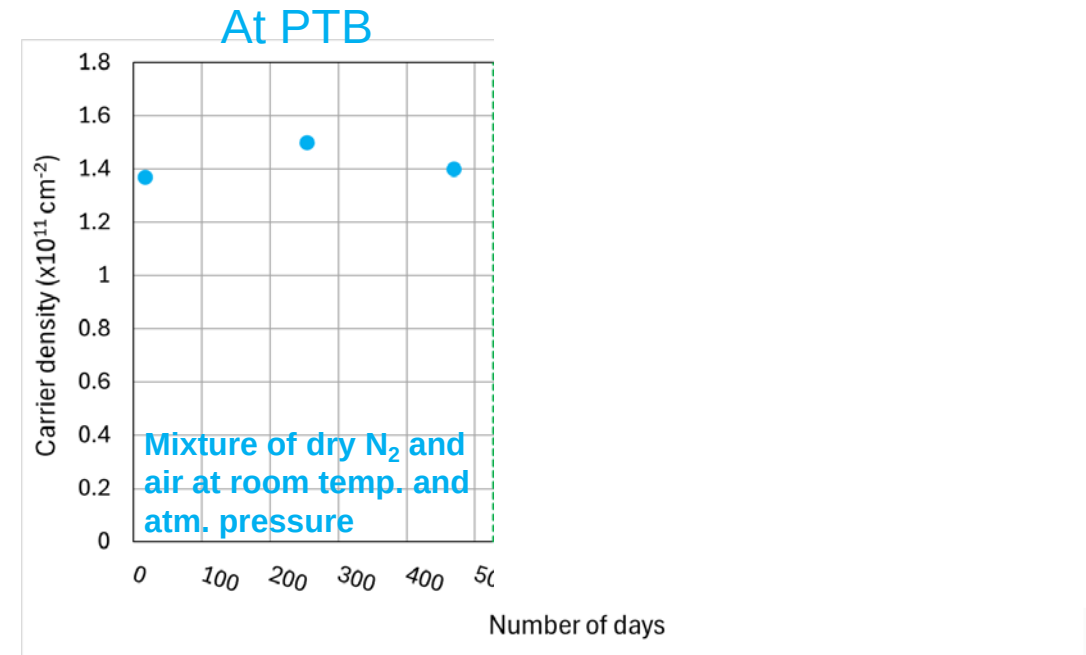


Study of the stability and performance of graphene devices

Characterization of PTB's graphene devices and study of their long term stability



Quantization of graphene-based device G33 within $2 \text{ n}\Omega/\Omega$ with low carrier density n and low s parameter



Study of long-term stability of the carrier density to be continued ...

Investigation of frequency dependence of 1 Ω resistors



Objective: find a 1 Ω standard with low or negligible frequency variation at low frequency, between 1 Hz and dc typically, which could be used for **BIPM.EM-K12** comparisons.

- Previous study in 2014 with most used wire wound resistance standards of type: CSIRO, L & N, Tinsley, Thomas and MI9210A.
- This study was repeated for the recently commercialized Alpha resistors only – model HRU-1R0 - including prototypes having different internal wiring configuration

Collaborative work between the NMIJ , PTB and BIPM

- Alpha HRU-1R0 resistance standards were provided by NMIJ
- The measurements were carried at BIPM using both PTB and BIPM CCC bridges and BIPM 1 Hz bridge

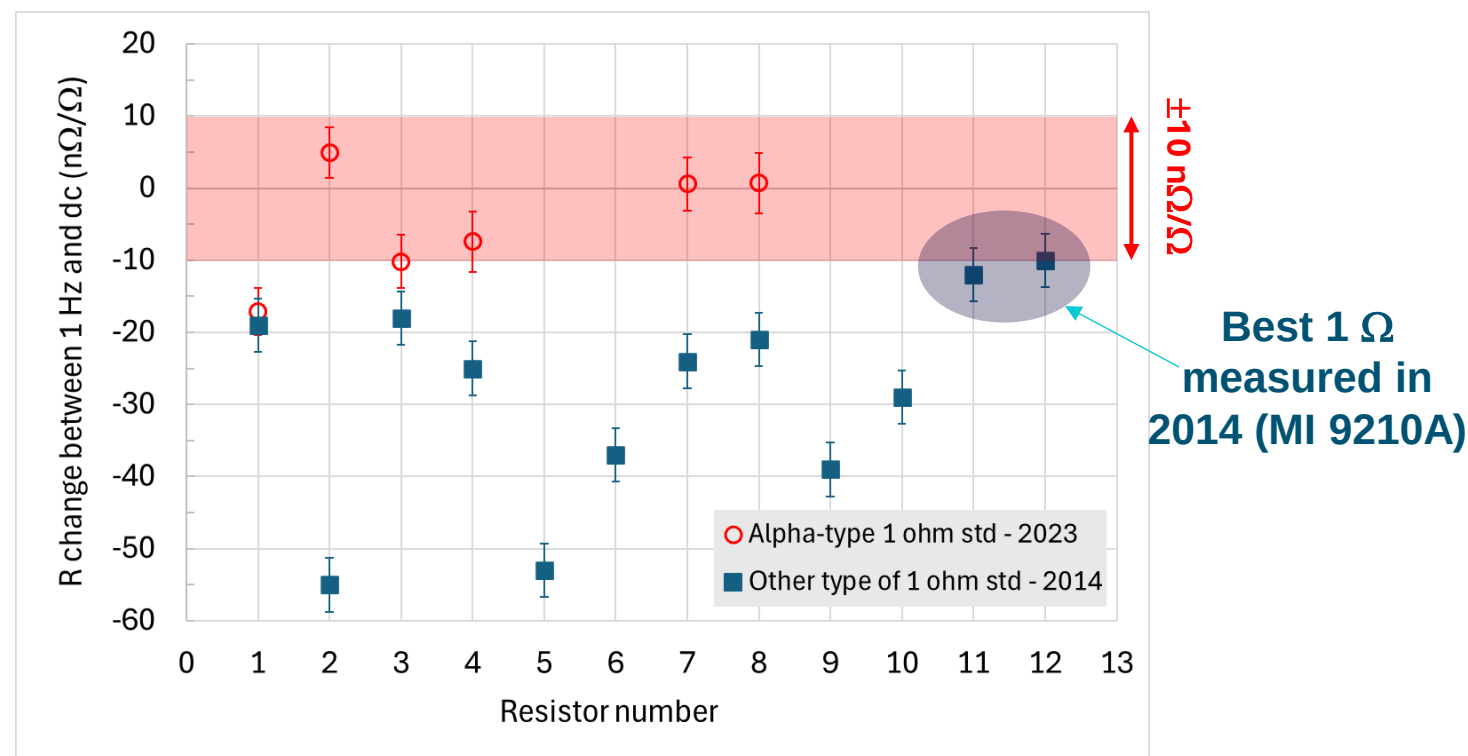
Investigation of frequency dependence of 1 Ω resistors



Comparison of the 1 Hz-dc differences of the wire wound and Alpha resistance standards

2023 study

R #	Type / SN
1	F067A
2	F068A
3	F069A
4	F112A
5	Prototype – T002
6	Prototype – T004
7	Prototype – T006
8	Prototype – T007



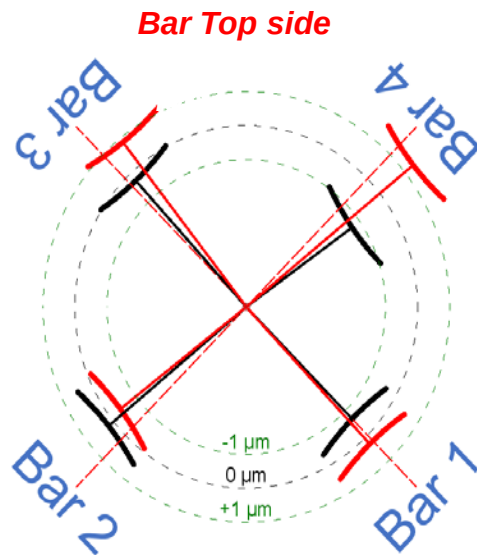
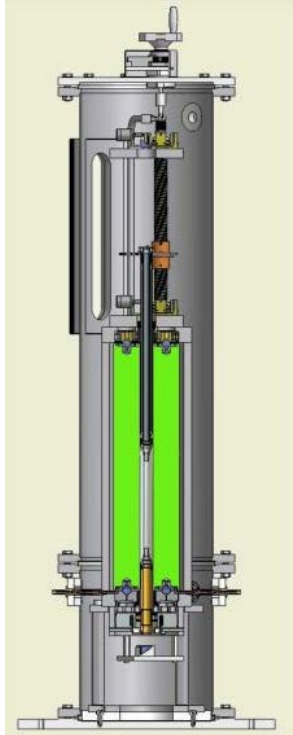
2014 study

R #	Type
1	L & N 4210
2	L&N 4210
3	L&N 4210
4	CSIRO
5	CSIRO
6	CSIRO
7	CSIRO
8	CSIRO
9	Thomas NBS
10	Tinsley
11	MI 9210A
12	MI 9210A
13	MI 9210A

With the exception of one, all the 1 Ω Alpha resistors we tested have a 1 Hz-dc difference lower or equal to the best resistor measured in 2014

⇒ possibility of selecting resistors with a frequency dependence close to zero difference.

Calculable capacitor



- Diagonal distances within $\pm 1 \mu\text{m}$ on average.
- Angles adjusted at 90° within $\pm 0.3 \text{ mrad}$.

In collaboration with Dr.
Almazbek Imanaliev of LNE

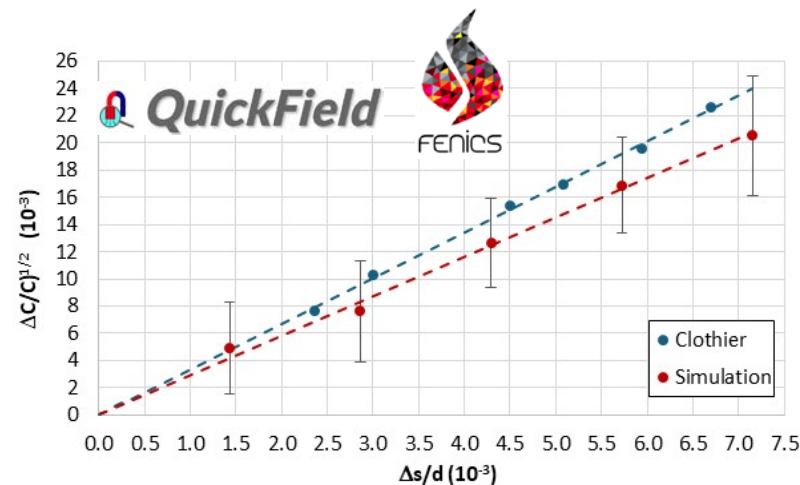


2D and
3D modeling



Cavity
Meshing

Introduction of
defects
+
Computation
of effects on C



Diagonal displacement of one electrode

To do:

- Investigation of other important defects (on progress)
- Accuracy versus time consuming optimization

Overview of the modernization of the equipment



Recently done:

- *new low frequency RT current comparator*
- *new CCC*
- *new QHR and CCC cryoprobes*
- *renewal of oil-bath for reference capacitors*

On progress:

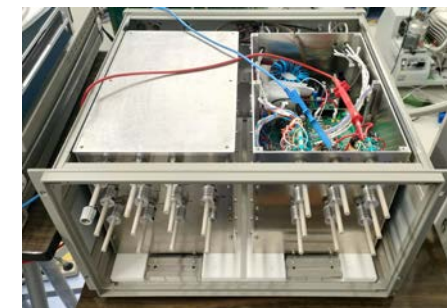
- *final characterization of a new 1 Hz bridge for the BIPM.EM-K12 comparison*

Planned:

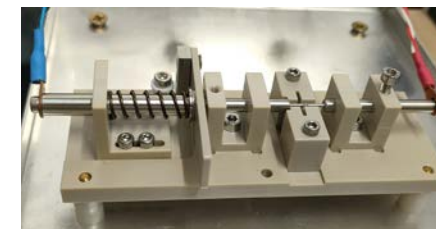
- *dual digital current source to equip a new CCC bridge*
- *R and C standards for quadrature bridge*
- *quadrature bridge including an ac-QHR*



Renewed oil-bath

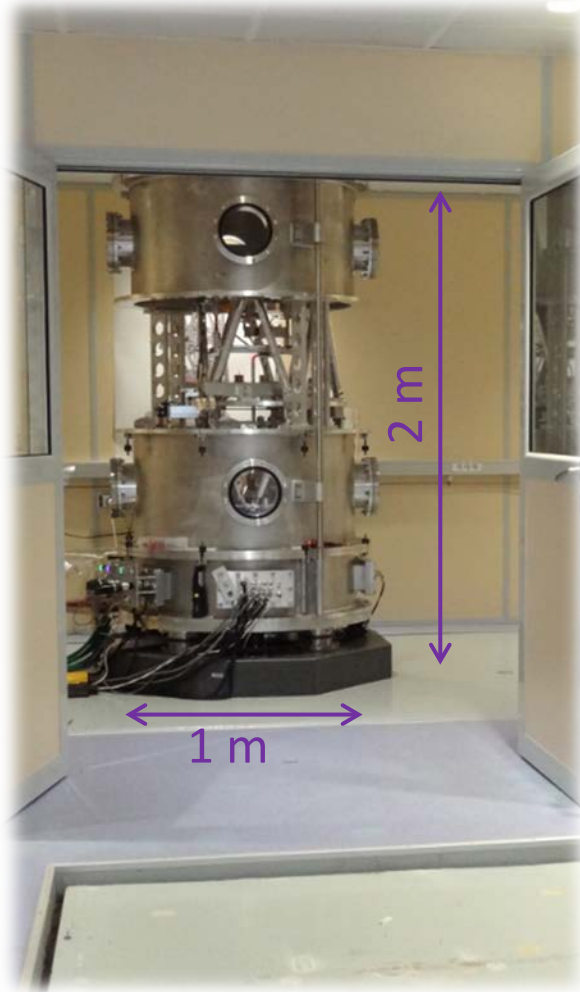


New 1 Hz bridge

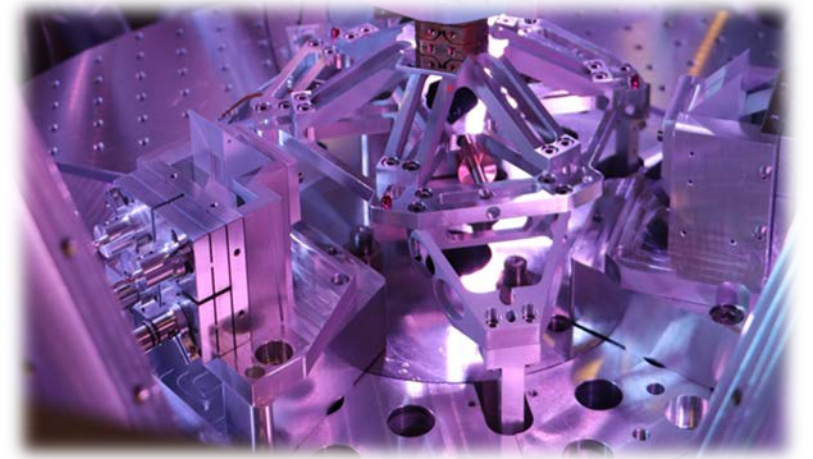


Characterization of ceramic capacitors

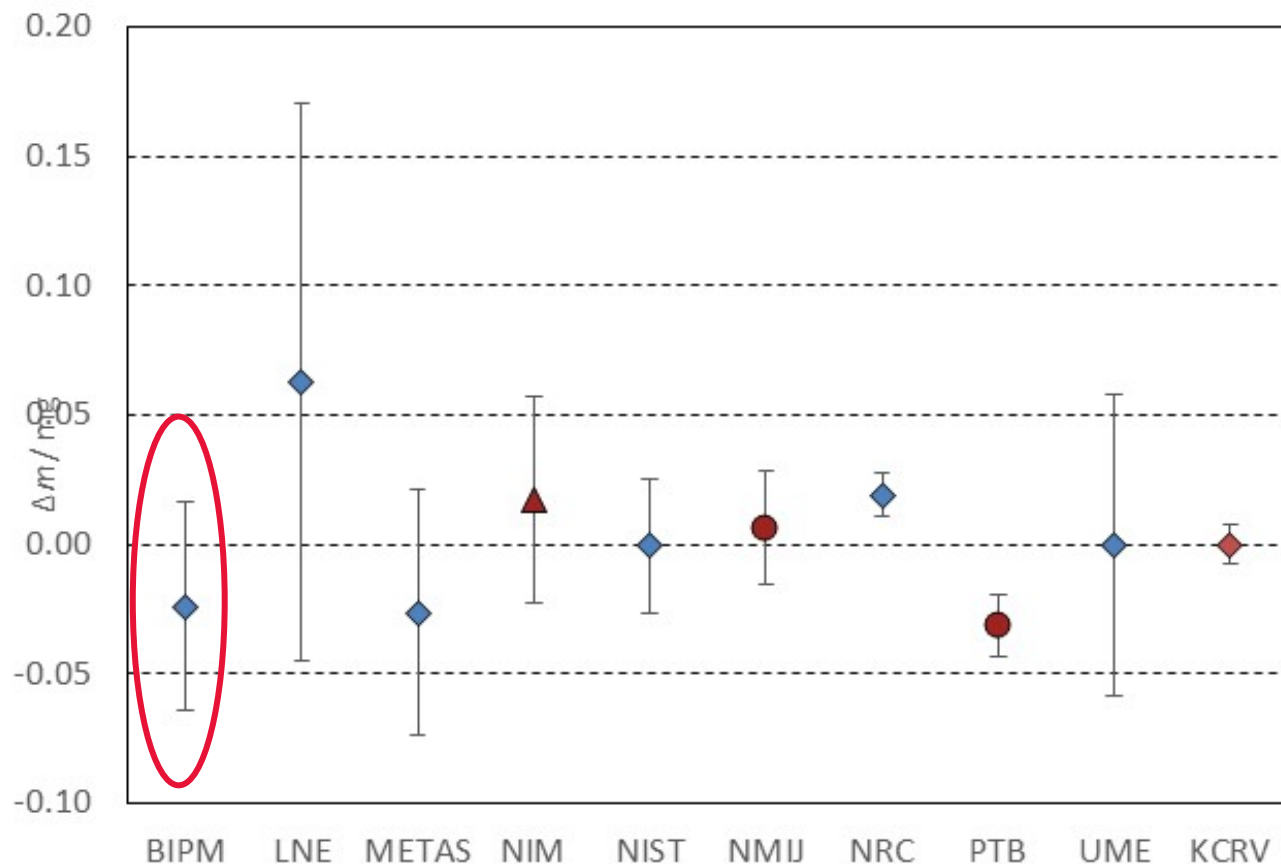
The BIPM Kibble balance



- magnetic flux density 0.47 T
- bifilar coil (each 26 layers & 1400 turns)
- current 10 mA for a 1 kg mass
- standard resistor 100 Ω
- voltage drop 1 V
- velocity 1 mm/s
- induced voltage 0.5 V



Participation in CCM.M-K8.2021 – KC of kg realizations (completed 2023)

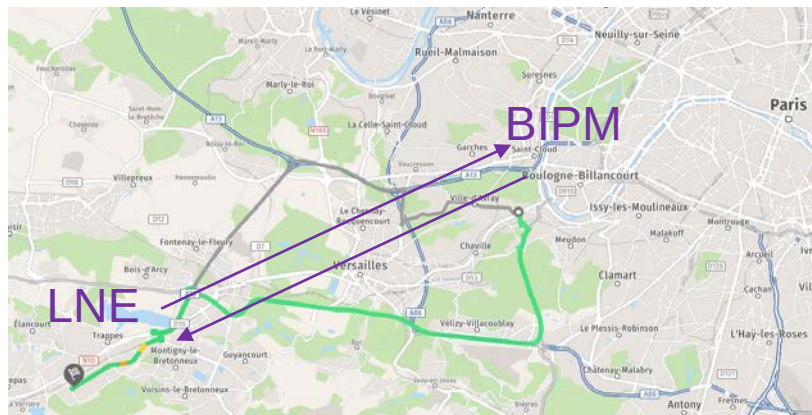


Uncertainty budget in parts in 10^9 ($k = 1$).

Type A	10
Alignment	33
Velocity	7
Voltage (mainly electrical grounding)	14
Standard resistor	9
Free-fall gravity acceleration	7
Others	10
Total	41

- Standard uncertainty 4.1×10^{-8} dominated by parasitic coil motion in velocity mode → new beam mechanism
- At present preparing for participation in CCM.M-K8.2024

Other Kibble balance developments



- Determination of gravity difference between LNE and BIPM in 2024
- At present confirmation with an absolute atomic gravimeter at BIPM



Development of new beam mechanism:

- Performance improvement of existing KB
- Prototype for a compact KB



- Development of a home-made voltmeter, optimized for KB operation (one single device instead of three, voltage in sub-mV range)

Outlook into next PoW 2028-2031



Guiding principles:

- Maintain continuity with present program so that NMIs can rely on program of comparisons and calibrations
- Adapt program to new developments

Proposed activities:

- Continue the new program of comparisons of PJVSs at ac
- Launch/continue comparisons of QHR standards using graphene samples
- Development of acQHR as primary standard for impedance, for reduced uncertainty in capacitance
- Continue the provision of calibration services for voltage, resistance, capacitance for NMIs without quantum standards
- Any new ideas ?
 - Other resistance values?
 - ...her resistance values?

Thank you

