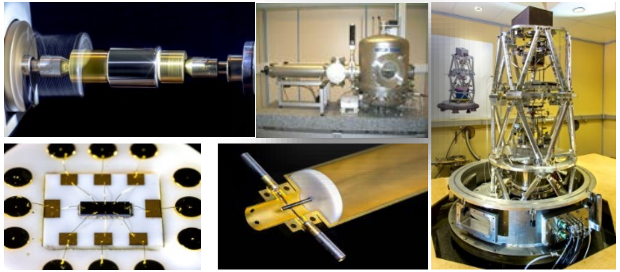
Report from the BIPM mass laboratory

M. Stock

CCM

25-26 May 2023



Staff of the Physical Metrology Department

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(CCEM, CCU)

Electricity

Impedance
(Resistance, Capacitance)

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Principal Physicist

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Voltage

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Kazuaki FUJITA
Secondee (NMIJ)

Mass

Kibble balance

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Assistant

Mass calibr.
(also pressure, density)

Pedro CONCEIÇÃO
Principal Technician

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Activities in Mass Laboratories

Traditional and ongoing tasks

- mass calibrations (Pt-Ir, stainless steel) for NMIs (incl. volume/density, centre of gravity)
- provision of 1 kg Pt-Ir prototypes to Member States

Support for the revised SI

- extraordinary calibrations with respect to the IPK (2014)
- CCM pilot study of kg realizations (2016)
- organization of 2-yearly key comparisons of realizations of the kilogram (2019, 2021, 2023, …)
- contribution to the determination of the "Consensus Value" by CCM TGPfD-kg
- development of an "international" Kibble balance for realization of kilogram
- organization of key comparisons of calibrations of stainless steel standards (2012, 2024 ?)

Guiding principles to ensure a stable BIPM mass unit

- Stable mass unit needed to compare KCRVs of successive KCs of kg realizations and for calculation of Consensus Value
- BIPM working standards calibrated against IPK in 2014
- significant unexpected mass changes since 3rd PV in 1992, attributed to wear
- new hierarchical system of mass standards with 3 significantly different levels of usage introduced in 2015
- significant reduction of the total number of weighings
- regular reports of status to CCM and CIPM

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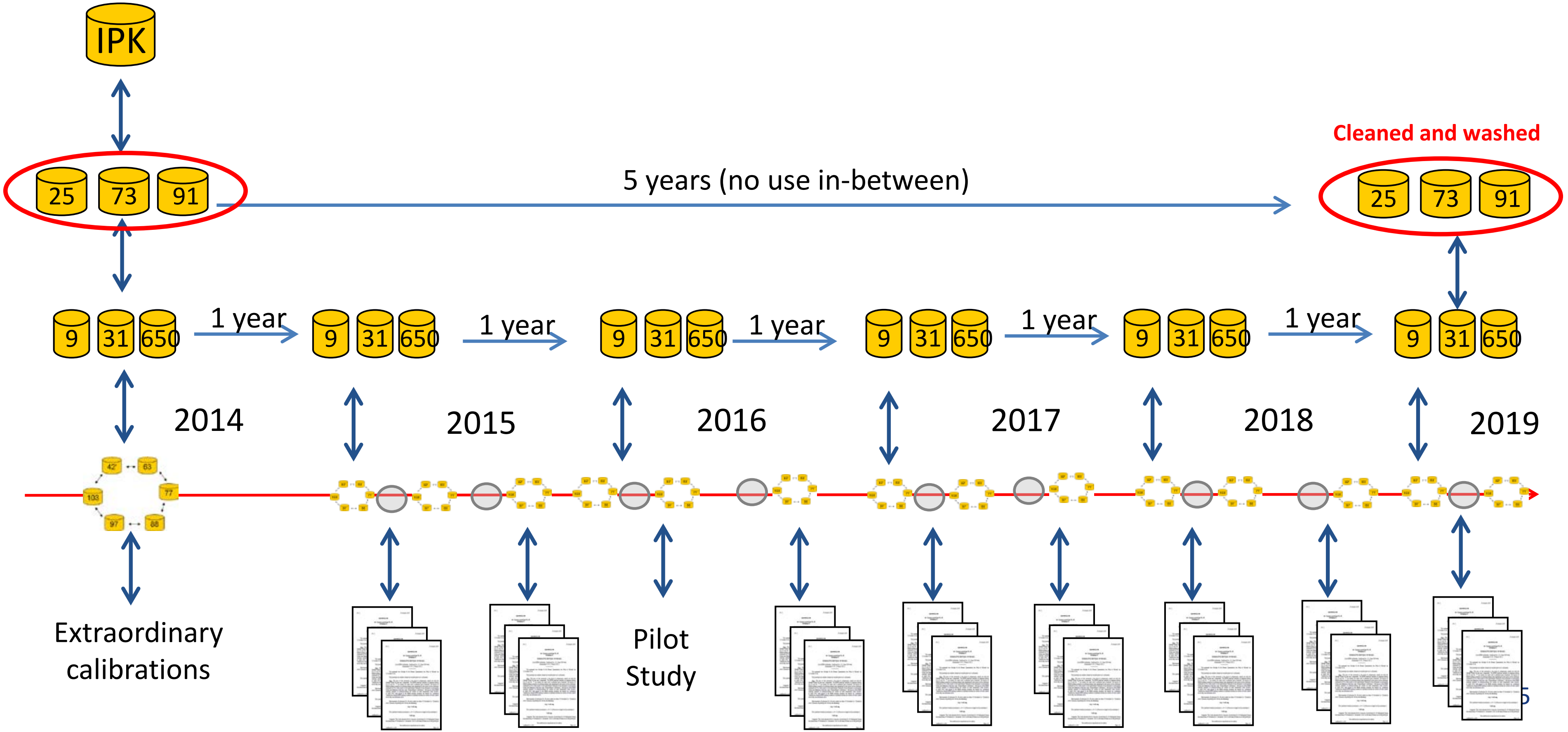
Hierarchy of BIPM Pt-Ir working standards, introduced in 2015



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N°115 24 November 2022

CERTIFICATE

for 1 kg mass prototype No. [redacted]
belonging to

[redacted]

(Last BIPM calibration: Certificate No. 1, 17 January 2011)

The prototype was brought to the BIPM on 12 October 2022. The prototype was neither cleaned nor washed prior to its calibration.

Mass. The mass of prototype No. 58 given in this certificate is based on the definition of the kilogram, which came into force on 20 May 2019. The Consultative Committee for Mass and Related Quantities (CCM) requested in its Recommendation G1 of 2017, that until the dispersion in values becomes compatible with the individual realization uncertainties, the dissemination of the kilogram should be based on the 'consensus value', which would be determined from comparisons between realization experiments. The first consensus value, determined in December 2020, was officially implemented on 1 February 2021[1].

The mass of this prototype is the result of comparisons carried out with the Mettler Toledo Metrotec mass comparator. The BIPM working standards in platinum-iridium No. 88 and No. 97, for current use, were used as reference mass standards. The masses of all BIPM working standards were determined in the course of the calibration performed in 2014 with respect to the International Prototype of the Kilogram (IPK). More recently, in March 2019, the masses of the working standards No. 88 and No. 97 were redetermined with respect to the BIPM working standards for exceptional use.

The mass of the IPK, based on the consensus value, is 1 kg - 2 μg[1].

Measurements of prototype No. 58 were carried out on 02 November 2022. The mass of prototype No. 58, based on the consensus value implemented in 2021, was the following:

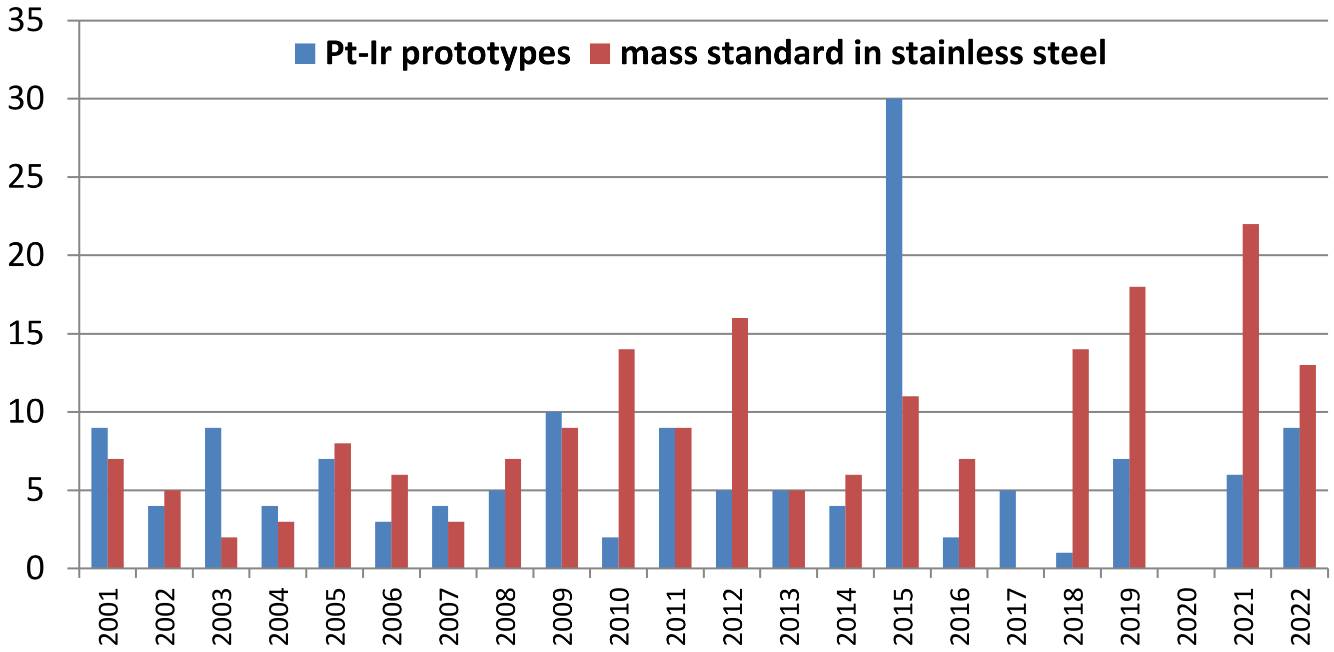
1 kg - 0.175 mg.

The combined standard uncertainty u_c ($k = 1$) of the mass assigned to this prototype is:

$\boxed{\textbf{0.021 mg.}}$

Source of uncertainty	uncertainty / μg
Traceability of working standards for exceptional use, in 2019, wrt IPK 2014	
calibration of 25, 73, 91 against IPK in 2014	3.0
reproducibility of c/w (Pedro 2019 vs. Pauline 2014)	3.0
extrapolation of mass from 2 months after c/w to c/w	2.0
Traceability of working standards for limited use wrt working standards of exc. use	
weighing uncertainty (incl. repeatability) in 2019	1.1
buoyancy correction (using CIPM-2007 formula)	0.5
stability of limited use standards 2019 - 2022 (from within group comp)	1.0
stability of limited use standards 2019 - 2022 (correlated contamination)	2.3
Traceability of working standards for current use wrt working standards of limited use	
weighing uncertainty (incl. Repeatability) in 2022	1.1
buoyancy correction (using formula)	0.5
stability of 2 reference standards during campaign	0.5
stability of 2 reference standards 42 and 103 during campaign	0.8
Calibration of NMI Pt-Ir standards	
weighing uncertainty (incl. repeatability)	1.1
buoyancy (using CIPM-2007 formula)	0.5
Sum (traceability to IPK)	**5.8**
Uncertainty of consensus value wrt IPK (2014)	**20.0**
Sum (tracebility to h)	20.8
rounded up to	**21**

Number of calibrations of mass standards per year



On average per year: 5 Pt-Ir prototypes
10 stainless steel standards

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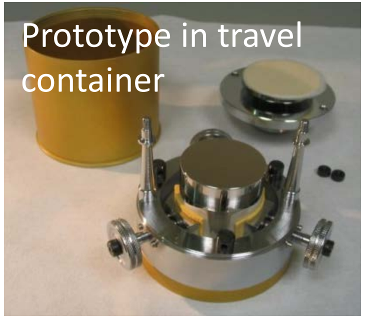
Fabrication of new prototypes

2016: no. 110 for NIM, China
2017: no. 111 for KRISS, Rep. of Korea
2018: no. 107 for NPSL, Pakistan
2019: no. 112 for SNSU-BSN, Indonesia
2020: no. 113 reserved for a potential buyer
2022: nos. 114 & 115 for NIM, China
2023: request for a quotation received

Final polishing of a Pt-Ir prototype



Prototype in travel container

CCM Recommendation G1 (2017) - For a new definition of the kilogram in 2018

Extract from CCM Recommendation G1 (2017):

Considering

- …that most recent measurement results with relative standard uncertainty below 5×10^{-8} do not pass the standard chi-squared test of consistency, but it is expected that the CODATA value and uncertainty for the Planck constant will be suitable for even the most demanding applications,

requests those National Metrology Institutes having a realization of the kilogram to avail themselves of the consensus value (as determined from the ongoing comparison) when disseminating the unit of mass according to the new definition, until the dispersion in values becomes compatible with the individual realization uncertainties, thus preserving the international equivalence of calibration certificates and in accordance with the principles and agreed protocols of the CIPM Mutual Recognition Arrangement,

→ Internationally coordinated dissemination of kg, based on consensus value ('international mean kilogram')

The calculation of the Consensus Value and its uncertainty

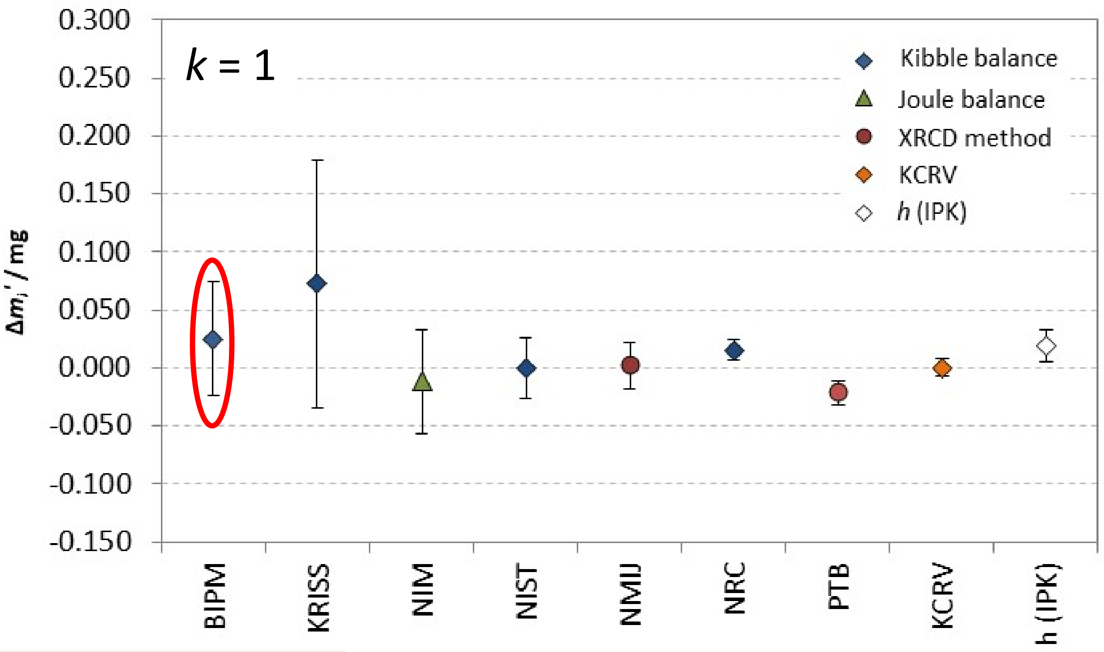
- Determination
  - Key comparisons of the realization experiments take place every 2 years (piloted by BIPM)
  - Consensus value (CV) is calculated as arithmetic mean of the last 3 key comparison reference values (this moving average will ensure temporal stability)
  - initial value will be based on IPK, Pilot study results (2016), reference value of first KC (2019)

- Dissemination
  - CV is maintained and disseminated by the BIPM using its Pt-Ir working standards

- Uncertainty
  - The uncertainty in the Consensus Value has been decided to be 20 µg:
    - This is the typical uncertainty of mature realization experiments
    - It sets the expectation on future uncertainties from realization experiments

CCM.M-K8.2019: Results of the first key comparison of kg realizations

Differences between mass values attributed to a 1 kg weight



- Pilot: BIPM
- 7 participants: 4 Kibble balances, 1 joule balance, 2 XRCD
- Mass of travelling standards of each participant: measured in vacuum
- Final Report published in Oct. 2020
- KCRV calculated as the weighted mean of the participants' results with $u_R(x_R)$ = 7.5 µg

Second key comparison of realizations of the kilogram: CCM.M-K8.2021

Objectives	- test the consistency of realizations based on different realization experiments (Kibble balances, joule balance, XRCD method)	
	- contribute to the second consensus value	
Pilot laboratory	BIPM	
Conditions for participation	$u(m)$ < 200 µg at 1 kg peer reviewed publication incl. detailed uncertainty budget	
Participants (9)	Kibble balances (6):	BIPM, LNE, METAS, NIST, NRC, UME
	Joule balance (1):	NIM
	XRCD method (2):	NMIJ, PTB
Timeline	Technical protocol	September 2021
	BIPM measurements	February-March 2022
	last part. report	25 June 2022
	Draft A-1:	2 August 2022
	Draft B:	3 January 2023
	Final Report published:	26 January 2023
	17 months in total	

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CCM.M-K8.2021: organization of comparison

- Each participant selected 1 or 2 travelling 1 kg standards:

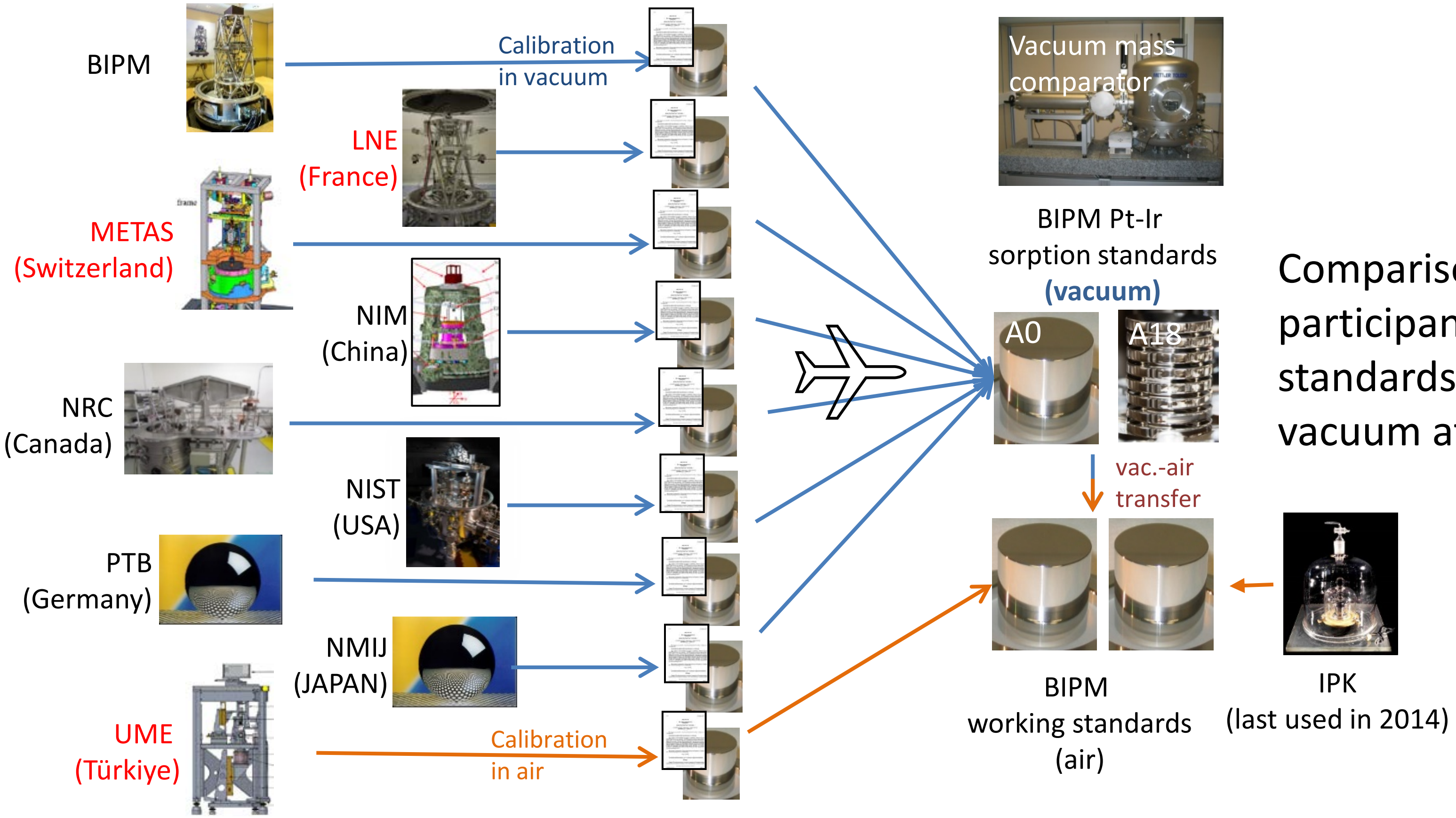
  - Pt-Ir (5), stainless steel (9), tungsten (1), Si-sphere (1)

  for calibration based on realization experiment, under vacuum (UME in air)

  based on : h = 6.626 070 15 x 10^{-34} Js

- NMIs sent travelling standards to BIPM
- At BIPM, all travelling standards compared under vacuum (UME in air) with BIPM reference standard
- The mass of the reference standard under vacuum is known in terms of BIPM as-maintained mass unit (traceable to h via the IPK)

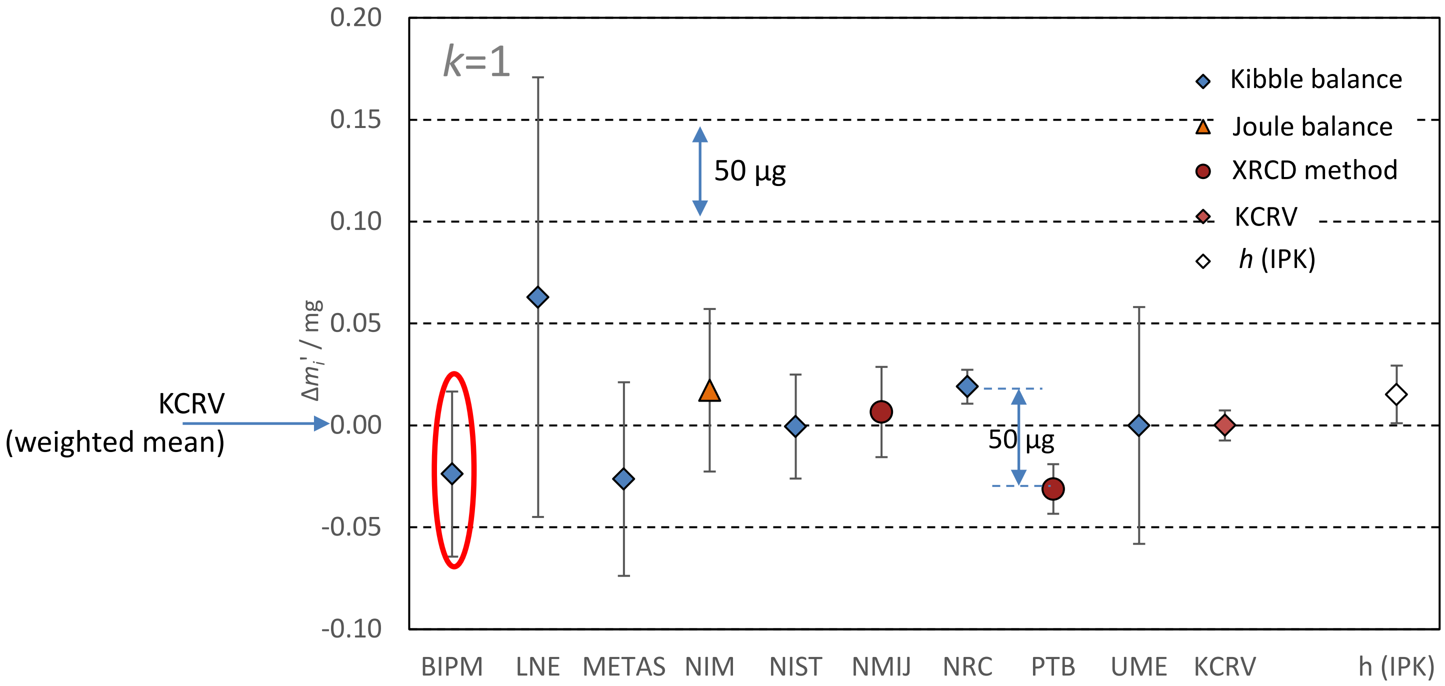
CCM.M-K8.2021, second key comparison of kilogram realizations



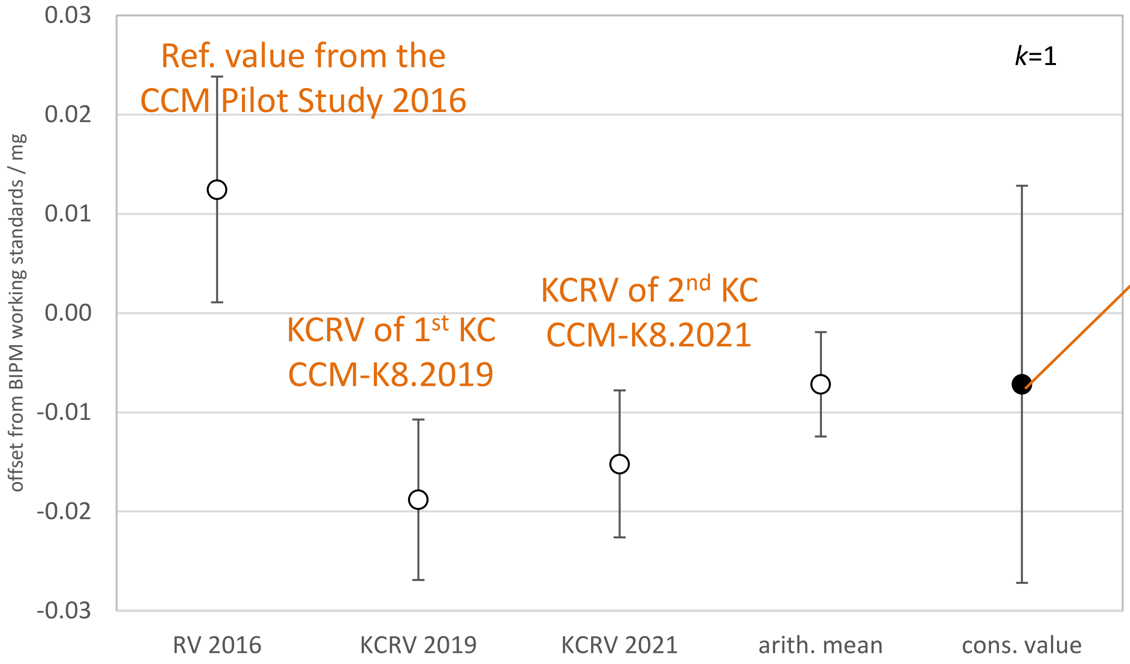
Comparison of the participants' mass standards under vacuum at the BIPM

CCM.M-K8.2021: Results

Differences between mass values attributed to a 1 kg weight (in mg)



CCM.M-K8.2021: second key comparison of kilogram realizations



The mass of the IPK, based on the consensus value is 1 kg - 7 µg with u = 20 µg

Since 1. March 2023, basis for worldwide coordinated mass dissemination

Dissemination from the second Consensus Value

- **Adjustment to the international mass scale of 7 µg needs to be made**
- **No further adjustments of the CMCs is needed**

Calculation of the Consensus Value for the Kilogram 2023

February 2023
CCM Task Group on the Phases for the Dissemination of the kilogram following redefinition
(CCM-TGPfD-kg)

Summary

The 2023 consensus value for the SI unit of mass, the kilogram, has been determined to be:

1 kg - 7 µg with a standard uncertainty of 20 µg

with respect to the mass value of the International Prototype Kilogram (IPK), which is equal to the BIPM as-maintained mass unit. That means that the mass of the IPK, based on the consensus value is 1 kg – 7 µg. (The 2023 consensus value is 5 µg lower than the consensus value of 2021).

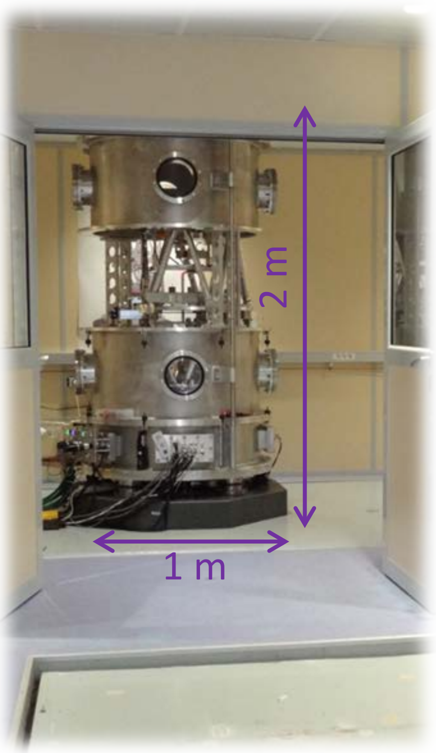
Traceability for the SI unit of mass will be taken from the 2023 consensus value of the kilogram commencing 1st March 2023.

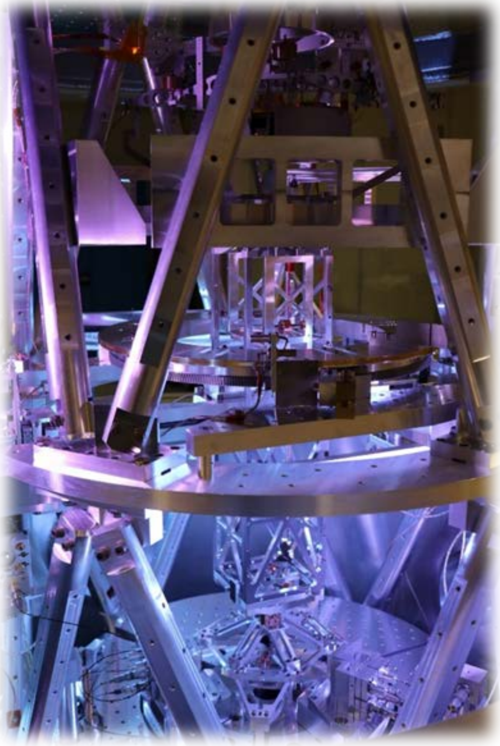
Action required

To achieve consistency with the 2023 consensus value, **all NMIs would need to reduce the mass value of their national as-maintained mass unit by 7 µg with respect to the mass value based on the IPK or by 5 µg with respect to the consensus value of 2021**. It is recommended to all NMIs to state clearly on their certificates the traceability to the Consensus Value 2023, for example, using the following sentence "The calibration results stated in this certificate are based on the Consensus Value of the kilogram commencing 1st March 2023." **The adoption of the consensus value of 2023 requires no further adjustment to the published CMCs of NMIs.**

Note to all CCM members and BIPM calibration customers (NMIs)

The BIPM Kibble balance (started in 2005)





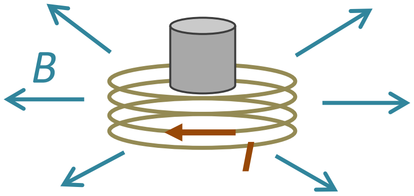
- magnetic flux density 0.47 T
- bifilar coil (each 26 layers & 1100 turns)
- current 10 mA for a 1 kg mass
- standard resistor 100 Ω
- voltage drop 1 V
- velocity 1 mm/s
- induced voltage 0.5 V

Measurement scheme

One-mode two-phase scheme

weighing phase

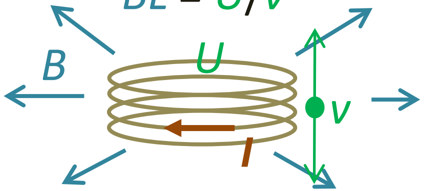
mg = *BLI*



$$\frac{m}{h} = \frac{n_1 n_2}{4r} \frac{f_1 f_2}{gv}$$

moving phase

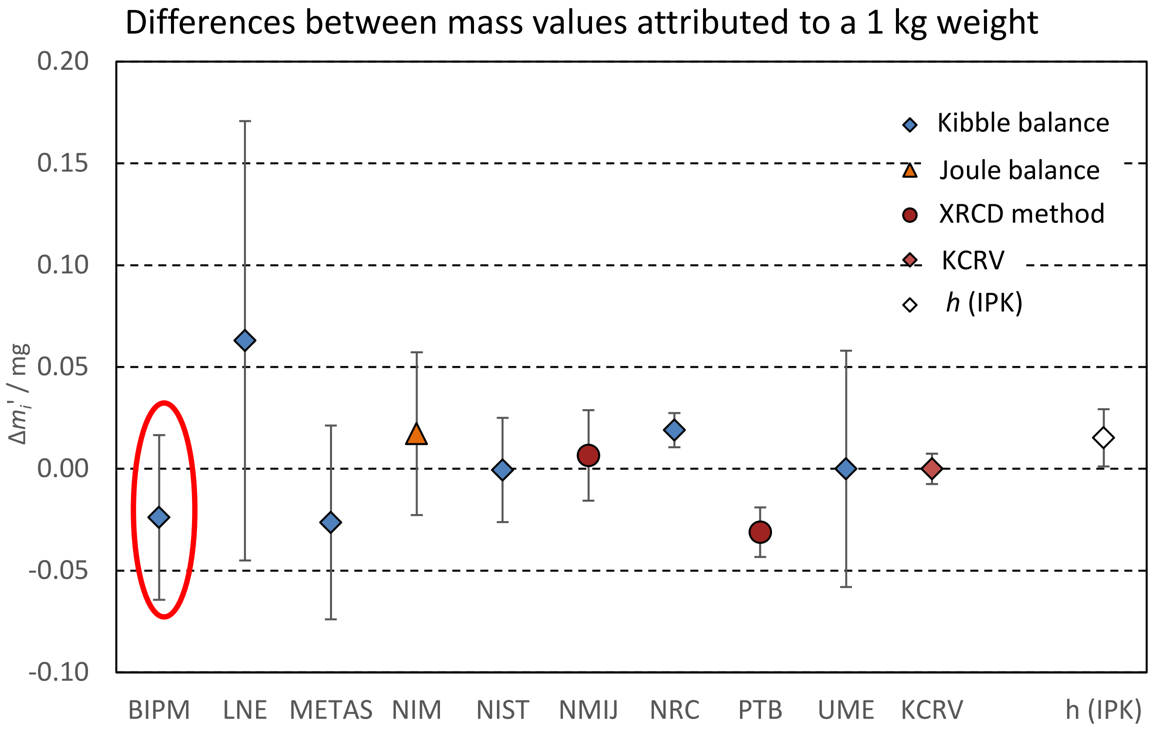
BL = *U*/*v*



n: integer number
f: frequency
r: calibration factor

- Constant Joule heating of the coil (60 mW) -> better temperature stability
- Same alignment for both phases
- Allows faster measurement sequence

CCM.M-K8.2021: second key comparison of kilogram realizations

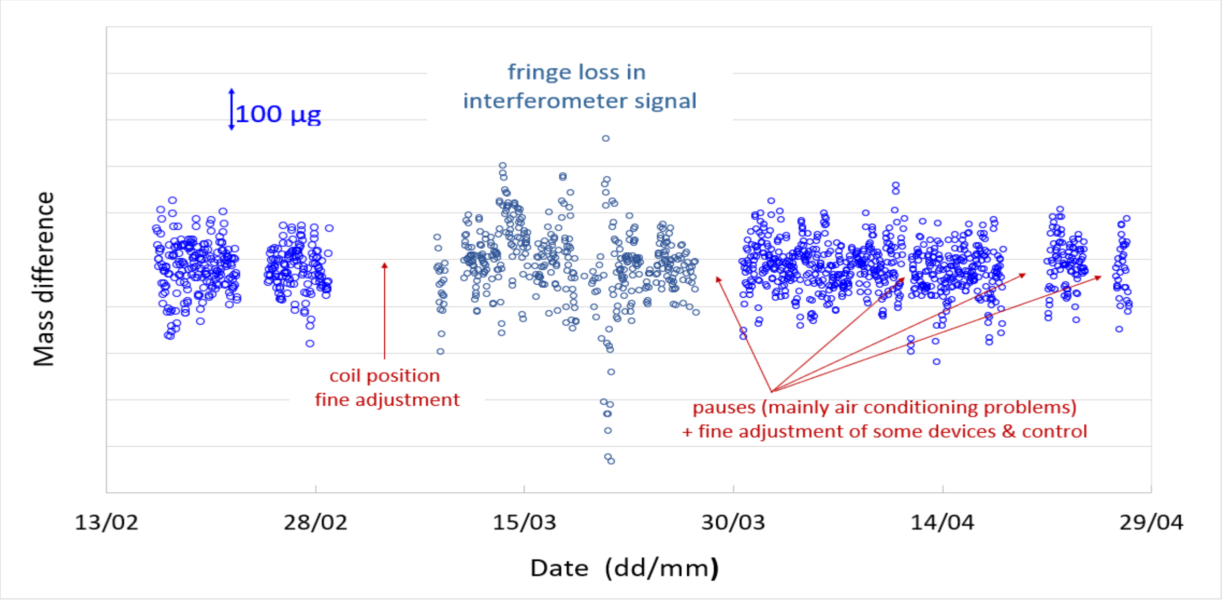


- Pilot: BIPM
- 9 participants: 6 Kibble balances, 1 joule balance, 2 XRCD
- Mass of travelling standards of each participant: measured in vacuum
- Comparison at BIPM during Feb./ Mar. 2022
- Final Report published in Jan. 2023
- KCRV calculated as the weighted mean of the participants' results with $u_R(x_R)$ = 7.4 µg

KB will be maintained for future comparisons

Main changes since 2nd KC

- use of a cryo-cooler for cooling PJVS array (new 2 V PJVS array, kindly supplied by NIST)
- first characterization and comparison against 2nd array last year
- comparison against PJVS system belonging to BIPM voltage metrology service under way



New beam mechanism

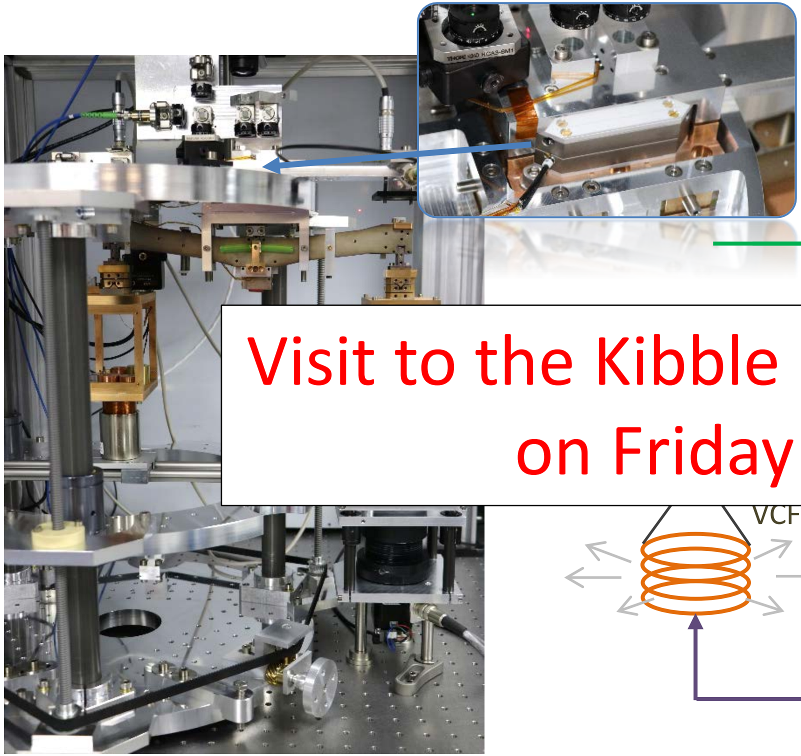
Design

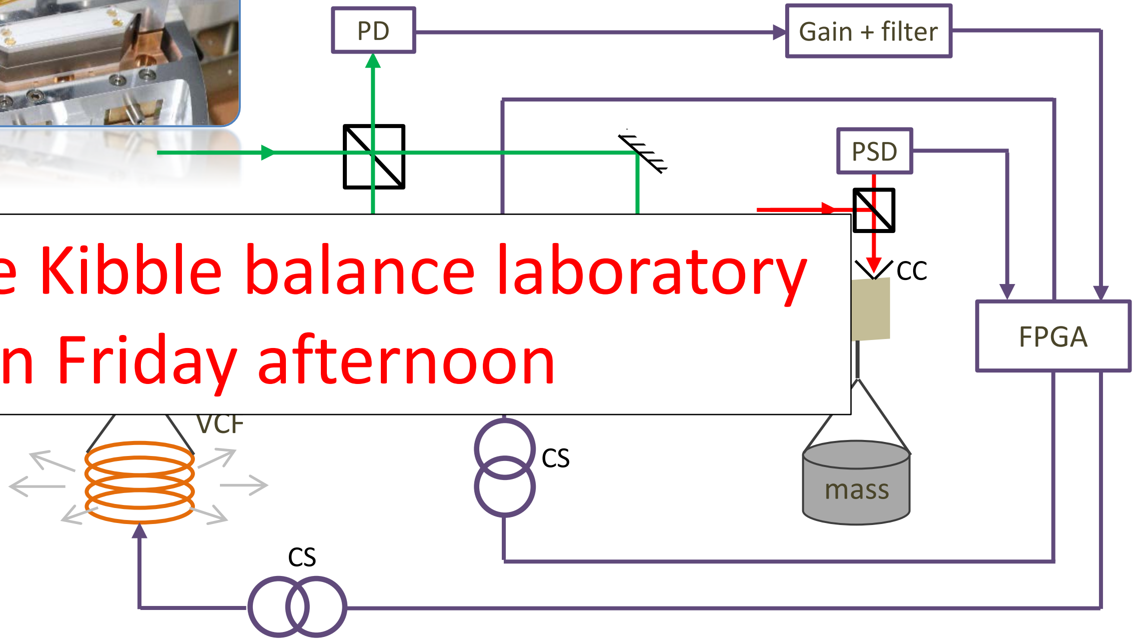
- an equal-arm beam mechanism using flexure hinges for pivots
- serve as zero-force detector in force phase and as coil vertical displacement generator in velocity phase
- use of a translation stage for correcting coil horizontal displacement (due to beam arc-motion) in velocity phase

Objectives

- evaluate the performance improvement to the present set-up in order to reach a target uncertainty of 2 parts in 10^8 at the 1 kg level
- develop a prototype apparatus that implements the beam mechanism design as the basis for a compact Kibble balance at masses of 500 g and below

Experimental test bench





Visit to the Kibble balance laboratory
on Friday afternoon

Kazuaki FUJITA
Secondee (NMIJ)

Liquid helium shortage

- Since early 2022, the cost for liquid helium has more than doubled from 13 €/l to close to 30 €/l, which we expect to continue
- In other countries the cost is already around 80 €/l.
- At the same time, the quantity available from our supplier has decreased significantly (about 40-50 %)

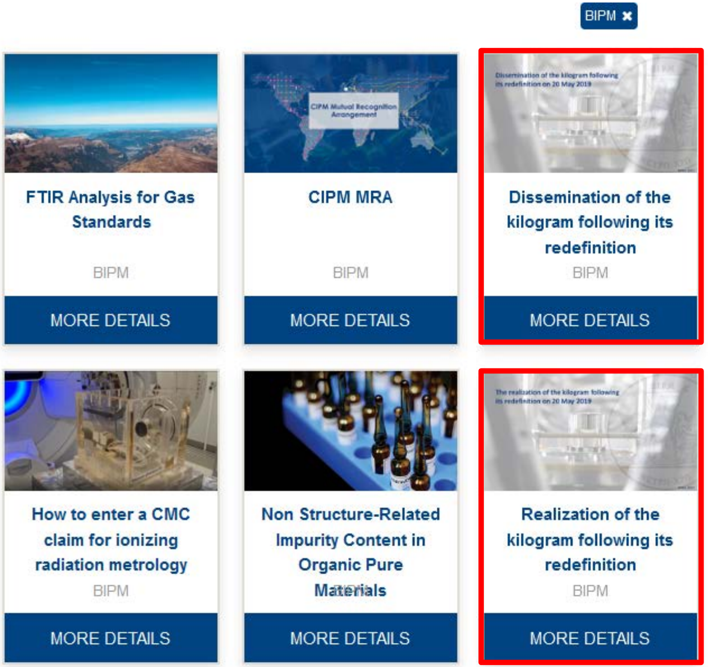
➡ PJVS of Kibble balance now operated inside a cryocooler, use of cold water of the air conditioning of the building for cooling down the compressor

Comparison between PJVS in cryocooler and PJVS in dewar being carried out this week.

Physical metrology		
Detailed strategy	**Plans (2022-2023)**	**Long Term (2024-2029)**
Support the comparison programme of the CCEM to demonstrate the capabilities of the NMIs and for knowledge transfer through travelling scientists by providing on-site comparisons using dedicated travelling quantum standards.	– *Operate a programme of on-site comparisons of electrical quantum standards:* – *Josephson voltage standard* – *Quantum Hall resistance standard* – *Develop more efficient and versatile quantum standards to be used for on-site comparisons.*	– *Deliver a programme of on-site comparisons using a new generation of more efficient and versatile quantum standards to increase the impact of the service with NMIs.* – *Provide knowledge transfer services to NMIs that are developing new quantum standards capabilities.*
Support NMIs that have no access to quantum standards by providing calibrations for electrical quantities and by knowledge transfer.	– *Maintain the portfolio of highest-accuracy calibration services for the most fundamental electrical quantities that exploits past investments.*	– *Adapt the portfolio of calibration services to the NMIs needs.* – *Implement a digital calibration certificate system.* – *Provide knowledge transfer on electrical quantum standards for emerging NMIs.*
Support the *mise en pratique* of the kilogram by coordinating CCM key comparisons of primary realizations held by NMIs.	– *Organize 2-yearly key comparisons of realizations of the kilogram to support the internationally coordinated dissemination of the kilogram.* – *Determine the CCM consensus values for the dissemination of the kilogram.* – *Contribute to the CCM consensus value with the BIPM Kibble balance.*	– *Coordinate key comparisons of primary realizations of the kilogram and of secondary mass standards according to the mise en pratique.* – *Maintain the BIPM Kibble balance for realizing the kilogram.*
Support the dissemination of the kilogram by providing calibrations of mass standards to NMIs that have no access to a primary realization.	– *provide mass calibrations for NMIs that do not have access to their own primary realization.*	– *Implement digital calibration certificates and provide knowledge transfer in the fields of the realization (Kibble balance) and dissemination of the kilogram.*

E-learning courses on realization and dissemination of the kilogram

- e-learning.bipm.org



66 participants

40 participants

Thank you for your attention !