Update from CCM WG-M

Dissemination of the kilogram from the Consensus Value of 2023

M. Stock, BIPM

CCEM

8-9 March 2023

Bureau International des Poids et Mesures

The definition of the kilogram in the SI since 20 May 2019

> The kilogram, symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant, h, to be $6.626\,070\,15 \times 10^{-34}$ when expressed in the unit J s, which is equal to kg m^2 s^{-1}, where the metre and the second are defined in terms of c and $\Delta\nu_{Cs}$.

This definition implies the exact relation $h \equiv 6.626\ 070\ 15 \times 10^{-34}\ \mathrm{kg\ m^2\ s^{-1}}$

This shows how the definition defines the kg:

$$h \equiv 6.626\ 070\ 15 \times 10^{-34}\ \mathrm{kg\ m^2\ s^{-1}}$$

the value (or the magnitude) of h is fixed by nature

the numerical value is fixed by this definition

the meter and the second are defined independently in the SI

the effect of this equation is to define 1 kg

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This definition implies the exact relation $h \equiv 6.626\,070\,15 \times 10^{-34}$ kg m^2 s^{-1}

This shows how the definition defines the kg:

$$1 \text{ kg} = (h \,/\, 6.626\,070\,15 \times 10^{-34}) \text{ m}^{-2} \text{ s}$$

Value chosen such that the 'size' of the kg does not change

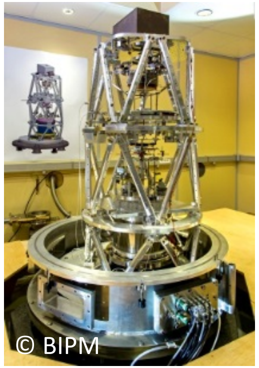
How can the definition of the kilogram be realized in practice ?

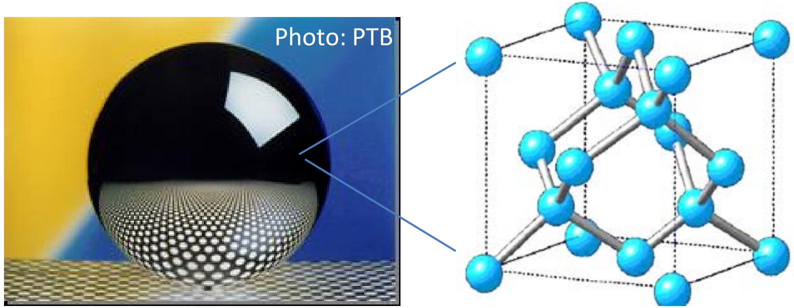
There are currently two primary methods capable of realizing the definition of the kilogram with relative uncertainties within a few parts in 10^8, corresponding to a few tens of micrograms for a mass of 1 kg:

- By comparing electrical power to mechanical power and using macroscopic quantum standards: the Kibble balance
- By determining the number of atoms in a nearly perfect silicon sphere: the X-ray crystal density (XRCD) method

E-learning programme: e-learning.bipm.org

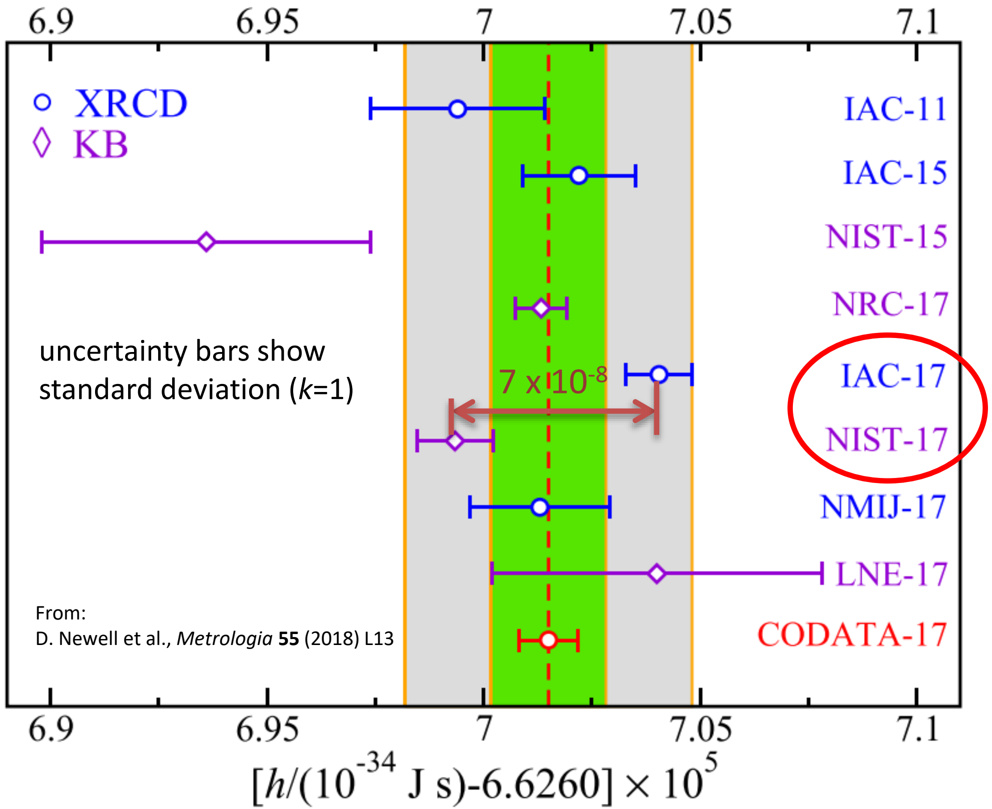
Kibble balances from NRC (Canada, left) and BIPM (right)





Si-sphere for the XRCD method (left) and unit cell of the silicon crystal (right)

Agreement between realisation experiments in 2017, just *before* redefinition



If these two experiments were used to determine a mass at the level of 1 kg, the difference would have been 71 μg.

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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 their 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

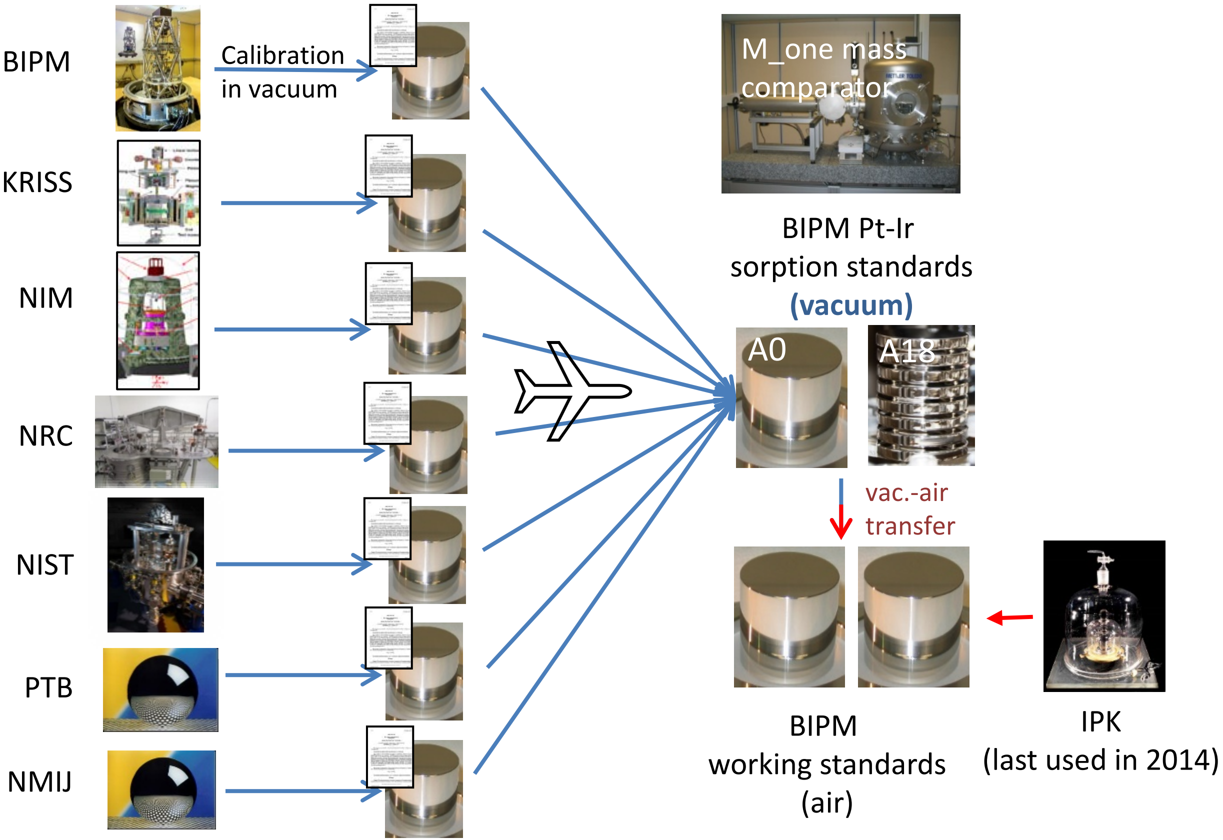
The phases of the dissemination of the kilogram

Phase	Time scale	Description	Source of traceability	Role of realization experiments	Dissemination of mass from NMIs with realization experiments
0	Until 20 May 2019	Traceability to the IPK	$m_{IPK} \equiv 1$ kg $u_{m_{\mathrm{IPK}}} \equiv 0$	Measurement of *h*	Dissemination from national prototype traceable to IPK
1	20 May 2019 – 1 Feb. 2021	Traceability to the IPK, taking into account the additional uncertainty coming from the (new) definition	$m_{IPK} = 1$ kg $u_{m_{\mathrm{IPK}}} = 10\ \mu g$	Contribute to Key Comparison (KC), improve to resolve discrepancies	Dissemination from national prototype traceable to IPK, with 10 µg added uncertainty
2	1 Feb. 2021 – date 2	**Dissemination via a consensus value (CV)**	**Consensus value (CV)** $\boldsymbol{u_{\mathrm{CV}} = 20\ \mu g}$	contribute to CV (via KC), improve experiments to resolve discrepancies	Dissemination from consensus value with uncertainty ≈ $\sqrt{u_{\mathrm{CV}}^2 + u_{\mathrm{stab.NMI}}^2(t)}$
3	from date 2	**Ultimate target:** **Dissemination by individual realizations**	**Fixed value of *h*** $\boldsymbol{u(h) \equiv 0}$	Realization of the unit of mass, Participation in KCs to demonstrate equivalence	Dissemination from validated realization experiments with the uncertainty of the experiment. The terms of the CIPM MRA are applicable.

redefinition

Now

CCM.M-K8.2019, first key comparison of kilogram realizations



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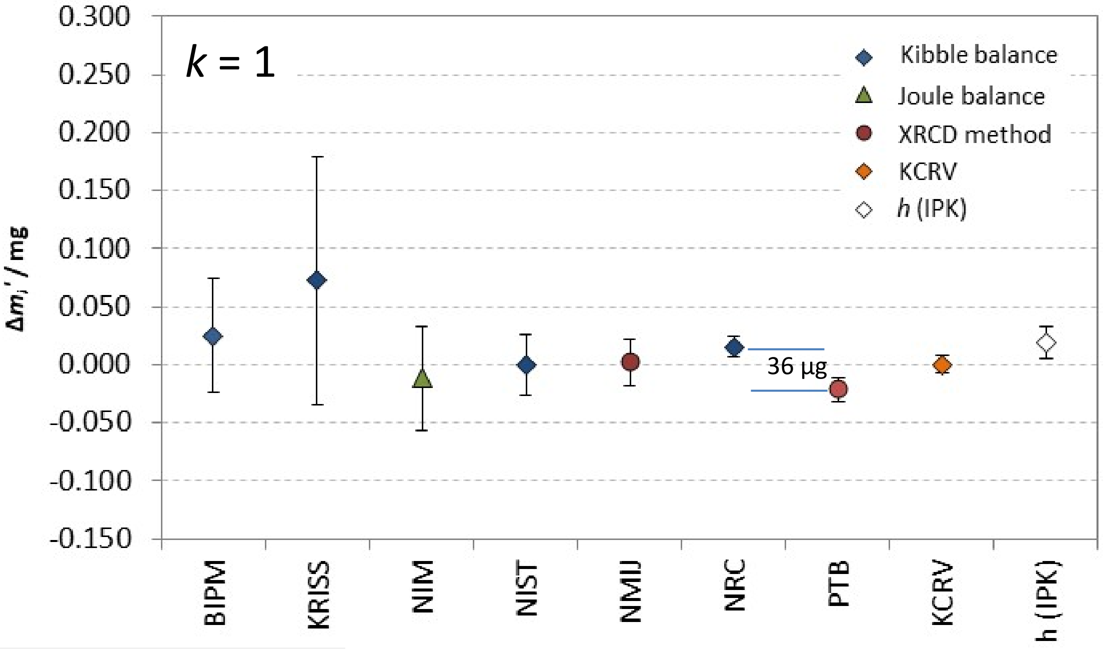
CCM.M-K8.2019: Results of the first key comparison of kg realizations

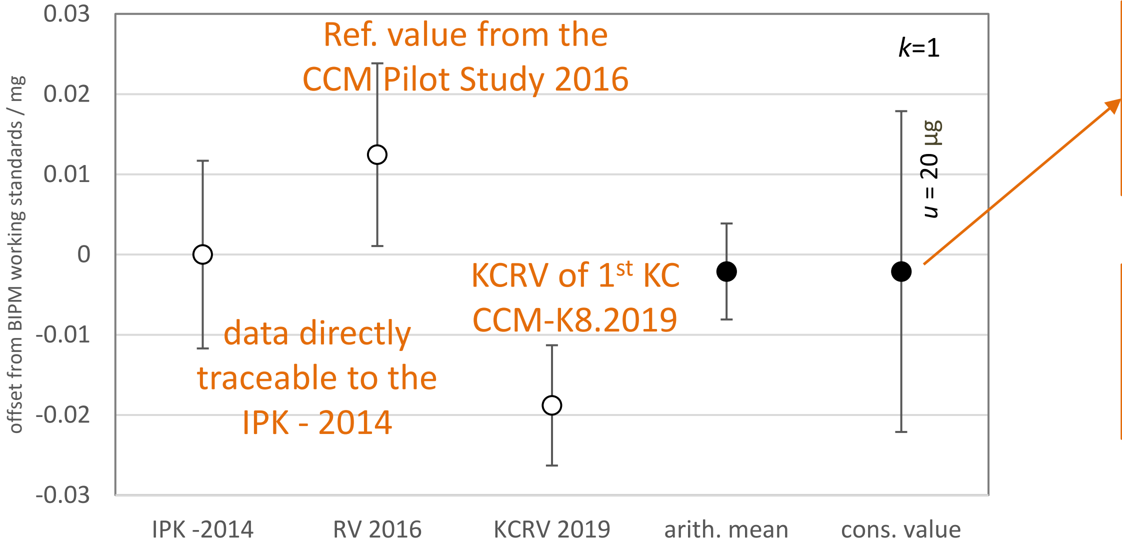
Differences between mass values attributed to a 1 kg weight



- 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

Calculation of the first Consensus Value of 2021

- The consensus value is the arithmetic mean of 3 sets of data, with an uncertainty of 20 µg
- The 3 data sets are linked together by the BIPM Pt-Ir working standards
- The CV is expressed as an offset from the BIPM mass unit, maintained on the working standards
- Implemented on 1 February 2021



The mass of the IPK, based on the consensus value is 1 kg - 2 µg with u = 20 µg

Since 1. Feb. 2021, basis for worldwide coordinated mass dissemination

Dissemination from the first Consensus Value

- **no adjustment to the international mass scale needed to be made**, since the offset of 2 µg is much smaller than its uncertainty of 20 µg.
- **adjustments to the CMCs** of some National Metrology Institutes were necessary to take into account the increased uncertainty in the CV relative to the previous uncertainty.
- As a consequence of the introduction of the consensus value, the uncertainty of BIPM mass calibrations has increased to 21 µg (compared to 5 µg wrt IPK).

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

The second key comparison of kg realizations has been launched at the end of 2021.

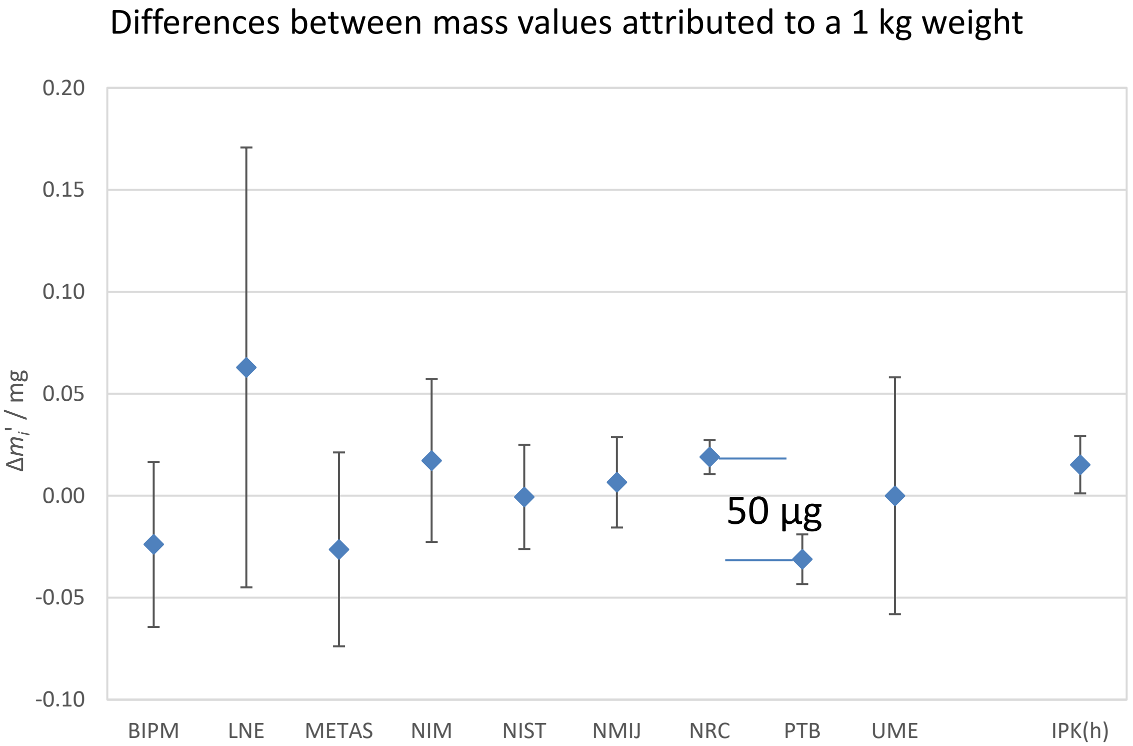
9 Participants: BIPM (also pilot laboratory), LNE (France), METAS (Switzerland), NIM (China), NIST (USA), NMIJ (Japan), NRC (Canada), PTB (Germany), UME (Turkey)

The measurand to be compared is the mass in vacuum of a 1 kg mass standard, calibrated using the realization experiment.

Very similar protocol to CCM.M-K8.2019.

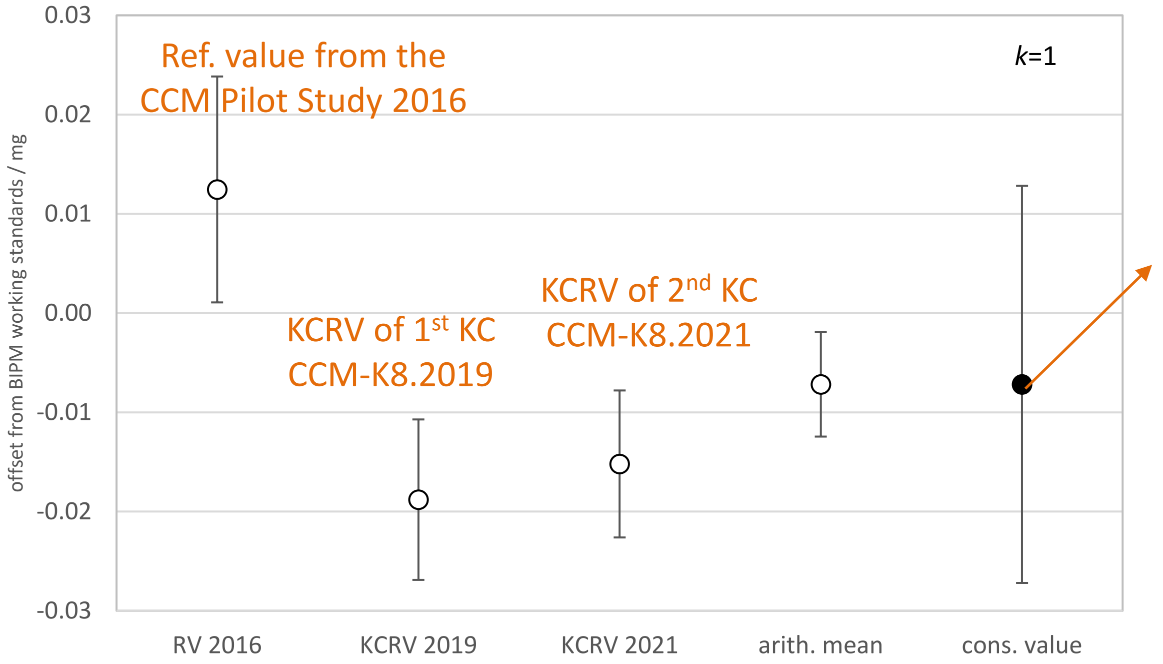
The results of the comparison will be used to calculate the second consensus value.

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
- Final Report published in Jan. 2023
- KCRV calculated as the weighted mean of the participants' results with $u_R(x_R)$ = 7.4 µg

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).

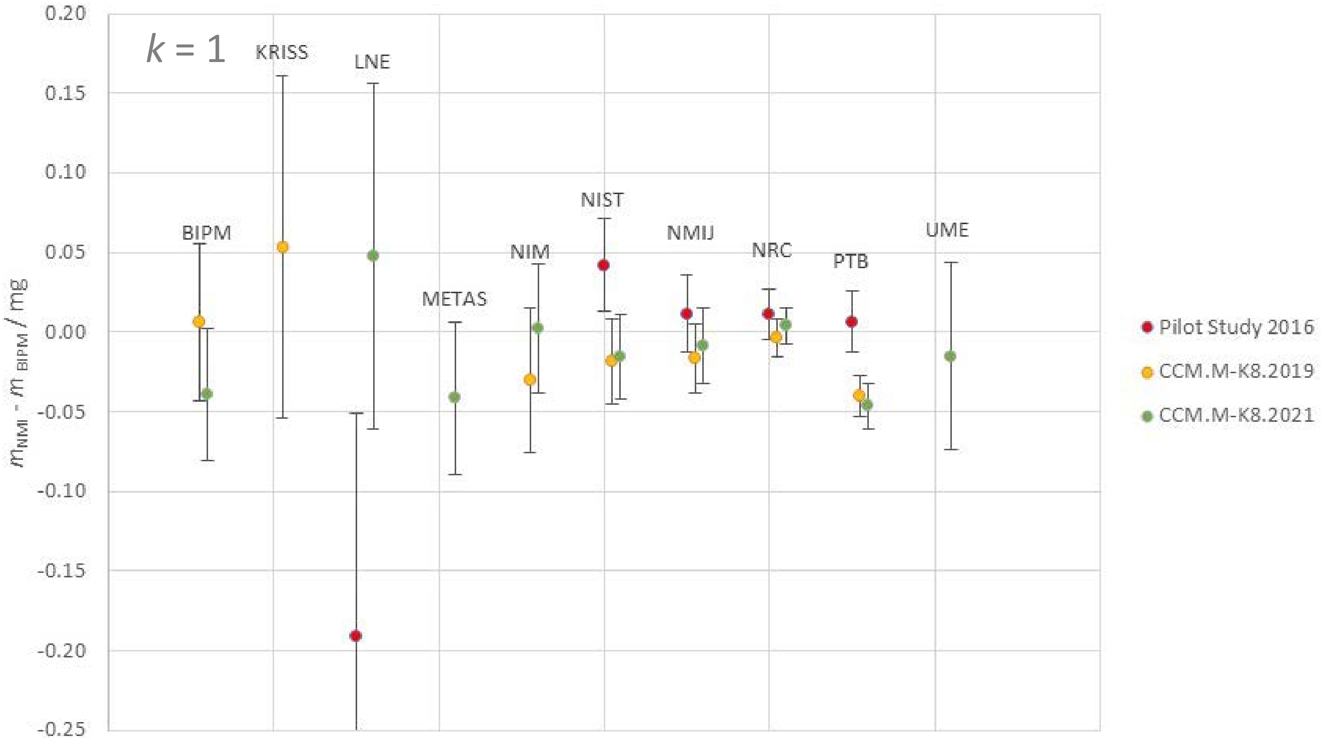
Traceability for the SI unit of mass will be taken from the 2023 consensus value of the kilogram commencing 1st March 2023.

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**

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

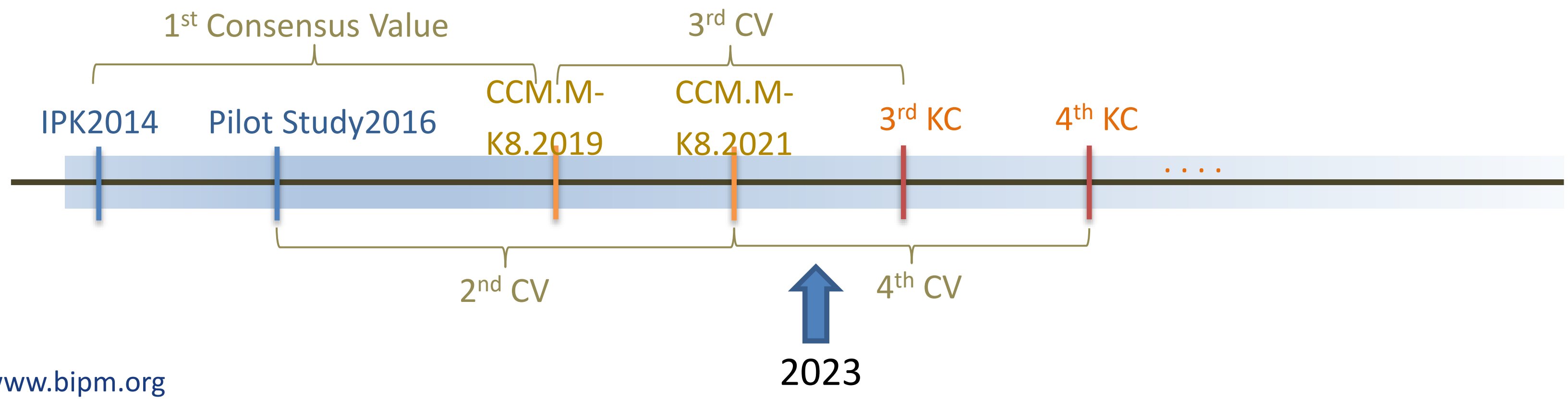
Evolution of kg realizations 2016 to 2021



Next steps

- Organization of the 3rd key comparison CCM.M-K.2023 (to be agreed by CCM in May)
- Determination of the 3rd Consensus Value
- Iteration until the decision of the CCM to allow dissemination from local realizations

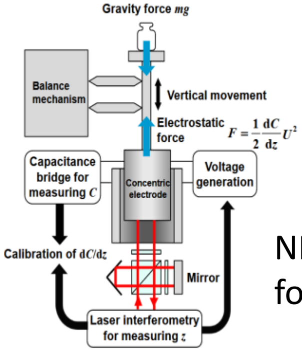
(sufficient level of agreement between independent realizations: CCM has established set of criteria)



The way forward: opportunites offered by the new definition

- In principle any NMI can realize the kilogram (but there is no obligation to do so !)
- Simplification of Kibble balances, commercial instruments for the shop floor
- The mass unit can be realized at any particular value, 1 kg no longer has special status
- Lower uncertainties for “small” masses (mg-range) than before (electrostatic force bal.)

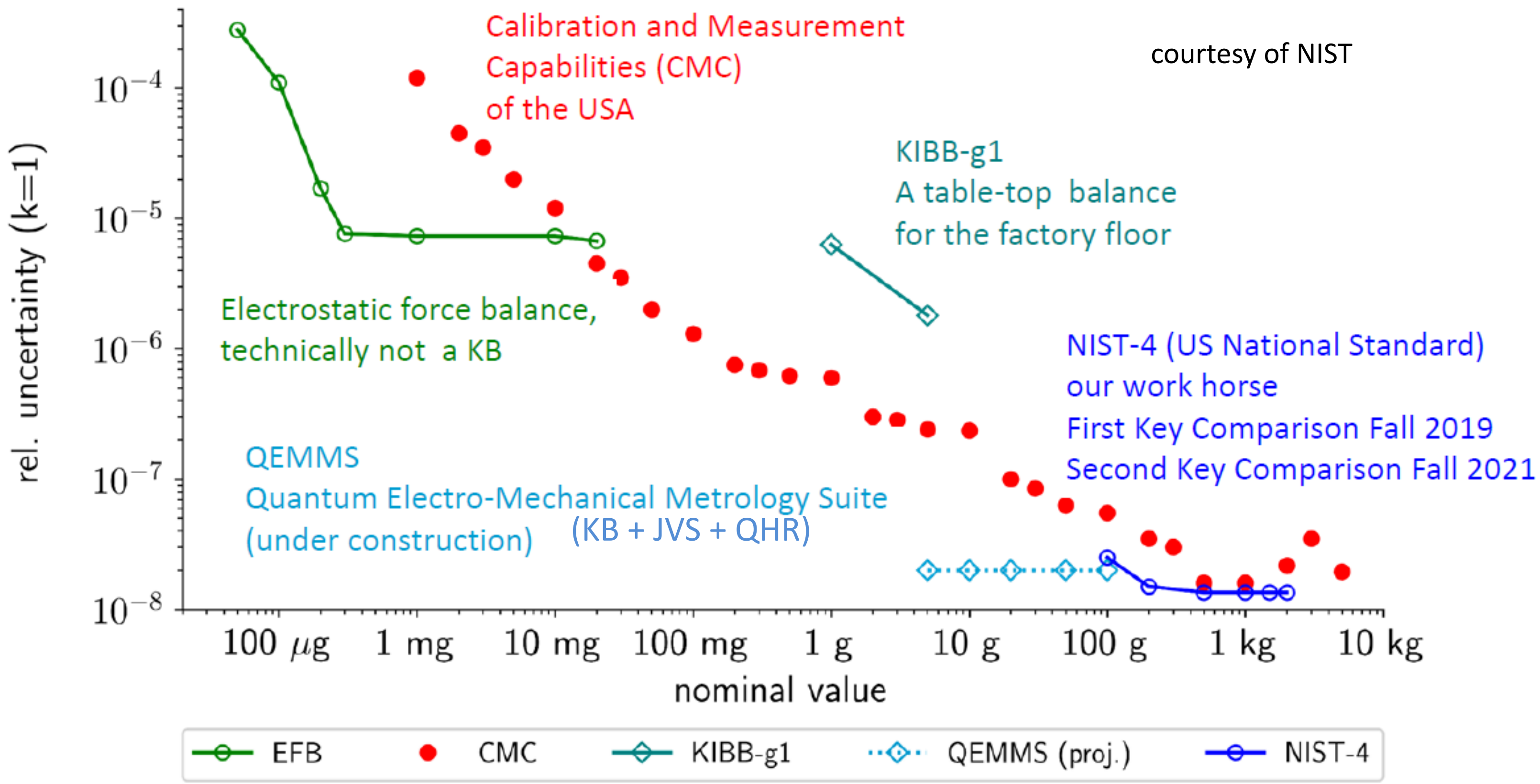
NPL KB demonstrator
10^{-7} level



courtesy of NMIJ

NMIJ electrostatic
force balance

Direct realization of mass below 1 kg



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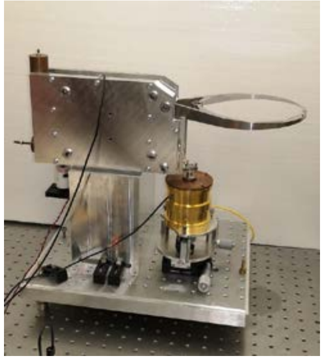
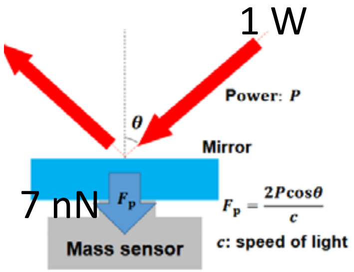
- Optical radiation pressure for (very) small mass measurement: 1 W –> 7 nN –> 0.7 µg



Photonic force balance, NIST



courtesy of NMIJ

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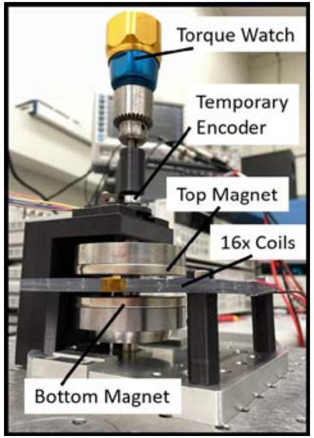
- Optical radiation pressure for (very) small mass measurement: 1 W –> 7 nN –> 0.7 µg
- Force, torque, pressure can be derived from electrical quantities instead of mass, with potentially smaller uncertainty (independent on *g*)



Electronic NIST torque realizer, prototype, up to 3 in-ozf (0.02 Nm)

Thank you for your attention !

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