Progress in the realization of the new definition of the kilogram

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NMI Directors and State Representatives Meeting

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Bureau International des Poids et Mesures

Outline

Progress on realization experiments

- Overview of experiments at the level of 1 kg
- Realization of “small” masses << 1 kg

Dissemination of the kilogram

- First key comparison of kilogram realizations
- Internationally coordinated dissemination from “consensus value”

Ongoing Kibble balance and XRCD projects at the level of 1 kg

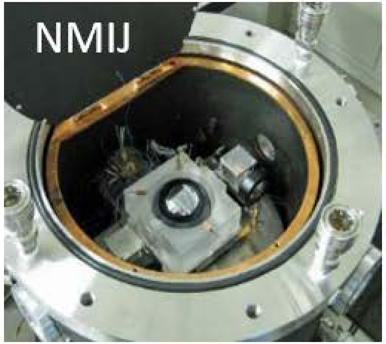
Kibble balance projects:

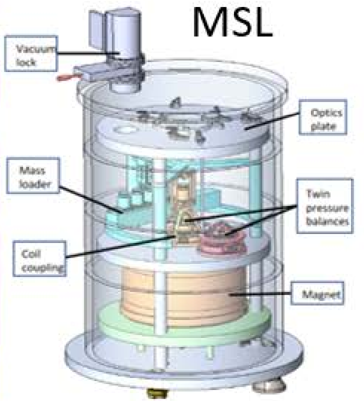
- BIPM (50 µg)
- KRISS
- LNE (< 100 µg)
- METAS (50 µg)
- MSL
- NIM (50 µg) (Joule balance)
- NIST (20 µg)
- NPL (+NMISA, RISE)
- NRC (12 µg)
- UME (150 µg)

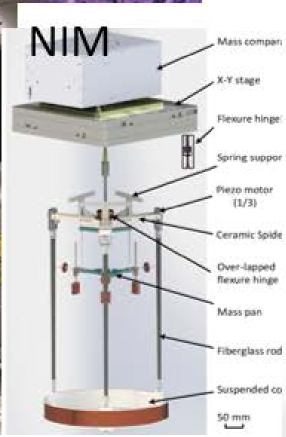
XRCD projects:

- NMIJ (21 µg)
- PTB (15 µg)
- CMS/ITRI (purchased ^{28}Si sphere from PTB)

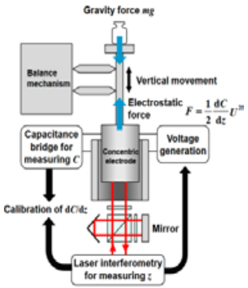
Uncertainties as announced for CCM.M-K8.2021





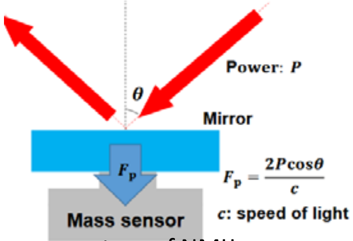


Which new possibilities does the new definition bring?



courtesy of NMIJ

- ➢ In principle any NMI can realize the kilogram (but there is no obligation to do so !)
- ➢ 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.)
- ➢ 2 orders of magnitude lower uncertainties for atomic masses from h/m_u (atomic recoil, H/D-spectr.)
- ➢ 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*)



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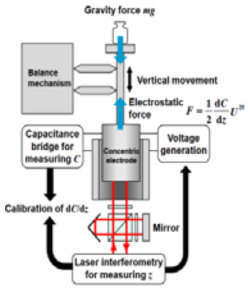

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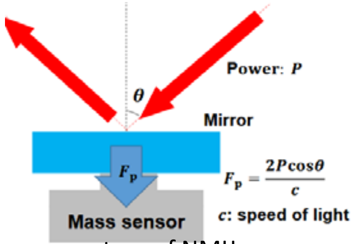
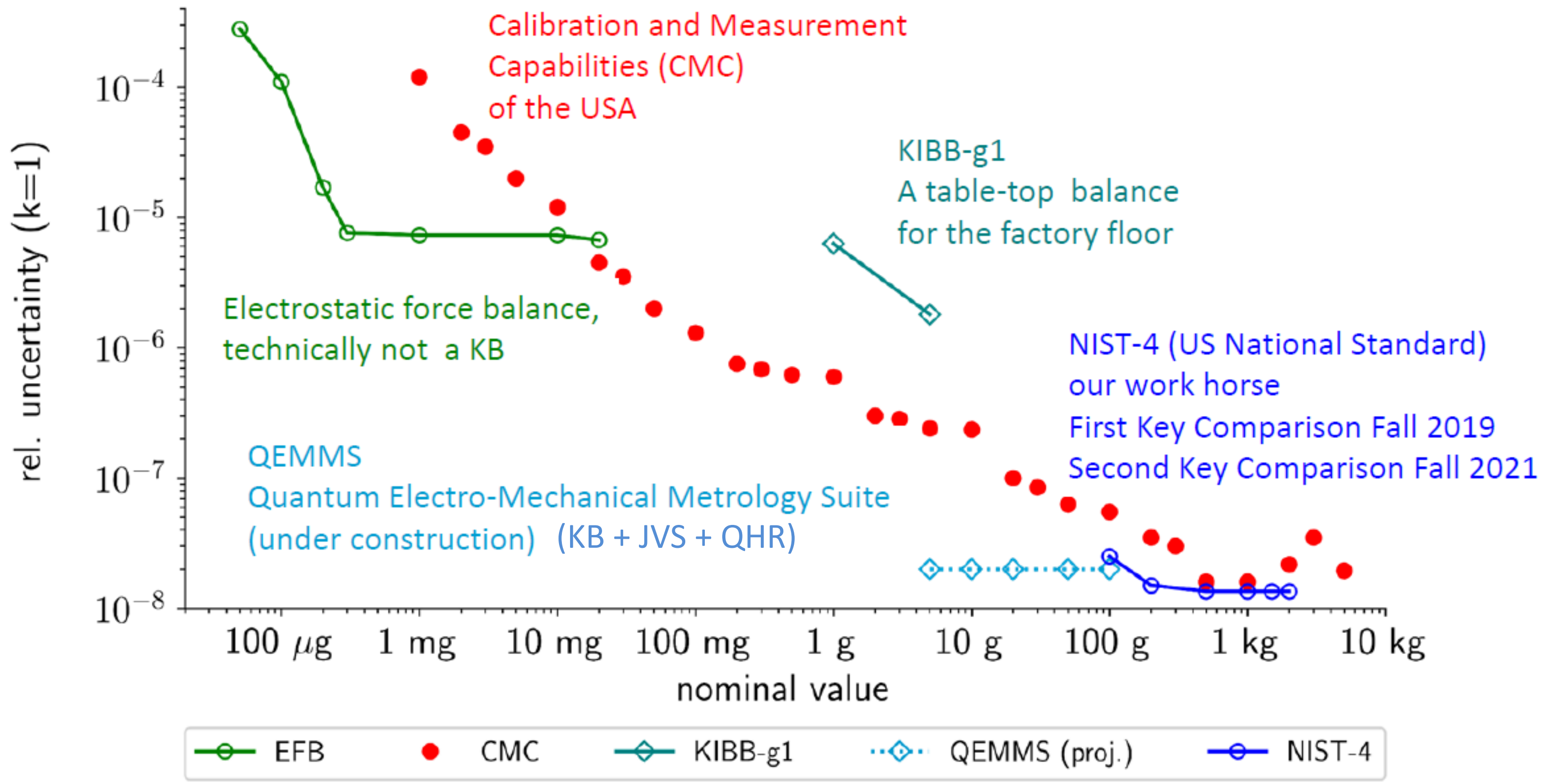


courtesy of NMIJ

National Institute of Standards and Technology
U.S. Department of Commerce

Realization of Mechanical Units of Force, Torque and Mass using the Revised SI

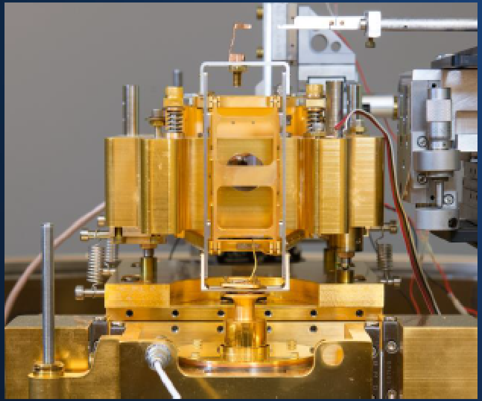


Small Mass and Force Metrology

National Institute of Standards and Technology
U.S. Department of Commerce

Electrostatic Force Balance (EFB)

- Electromechanical balance realizes mass using electrical metrology to provide a link to Planck's constant.
- Primary standard for milligram and submilligram mass with lower uncertainty than conventional calibration.



Available as a NIST calibration service via a special test for mass between 30 mg and 100 µg

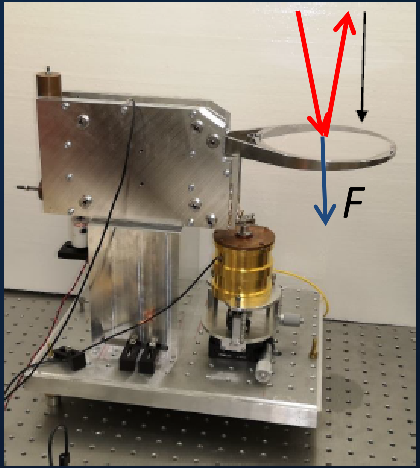
Shaw, et al., Metrologia (2016)
DOI: 10.1088/0026-1394/53/5/A86

TPOC: Gordon Shaw
gshaw@nist.gov

Photonic Force Balance (PFB)

- Electromechanical balance that realizes laser power from photon momentum force using the same traceability as the EFB.

Laser mirror



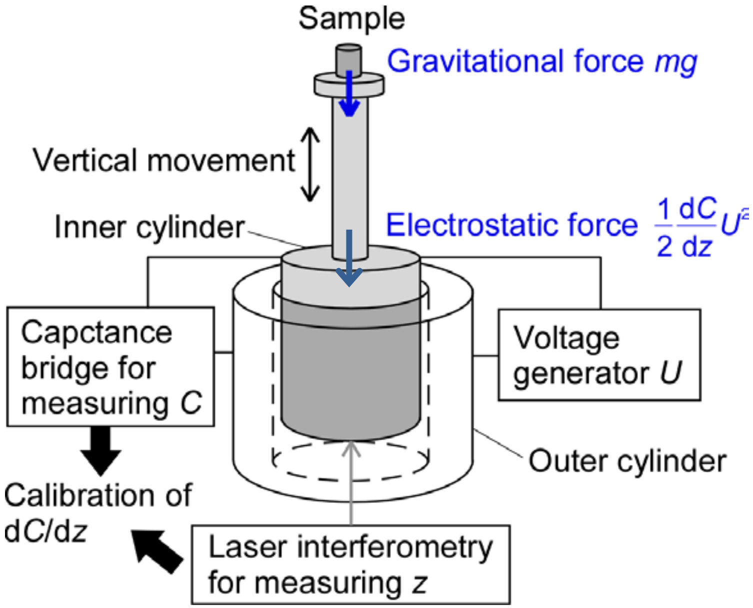
$F=2\,P/c$

100 kW
700 µN
70 mg

Prototype instrument nearing completion. Will be used for laser power realization at NIST. (u_r =1 x 10^{-3})

Keck, et al., IEEE Trans. Instr. Meas. (2021)
DOI: 10.1109/TIM.2021.3060575

Development of electrostatic force balance at NMIJ



- Electrostatic force is generated by applying voltage on a capacitor and is balanced with gravitational force acting on a sample

- Electrostatic force is measured by using electrical standards based on the defining constants in the new SI
  - Josephson voltage standard
  - Quantum Hall resistance standard

SI-traceable mass measurements without using reference weights

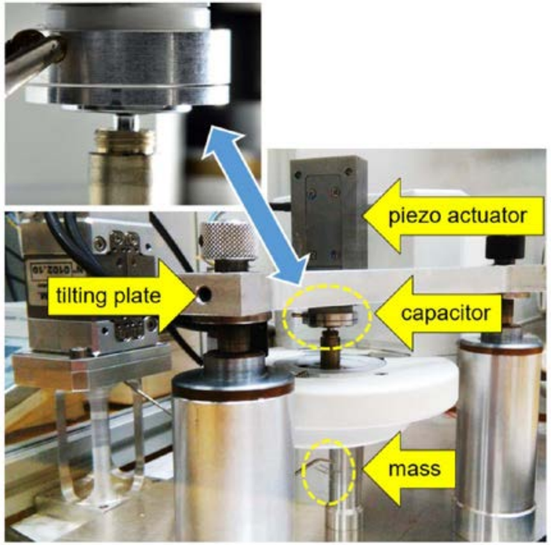
Target

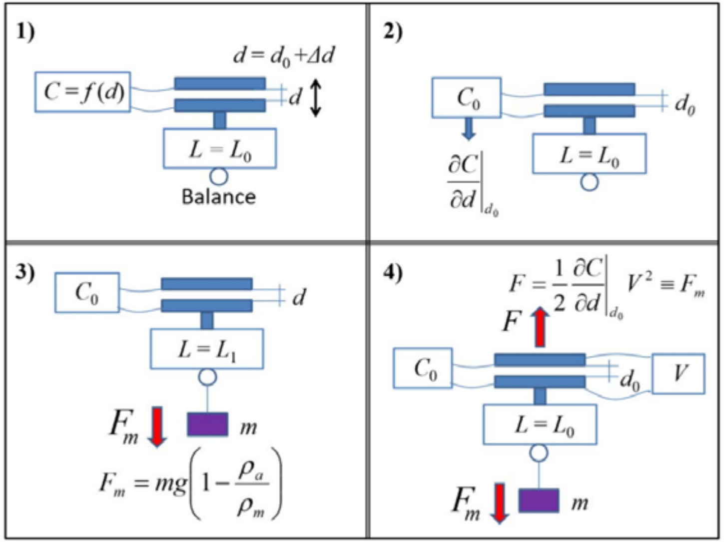
- u_r(mass) = 10^{-5} for mg range realized by small weights
- u_r(mass) = 10^{-2} for µg range realized by radiation pressure of laser

1 W -> ~1 µg

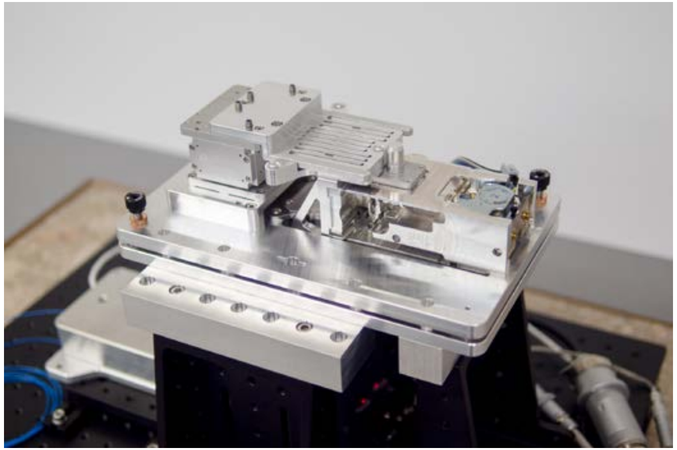
INRIM's electrostatic balance

- Simple approach with parallel plates/low voltage
- Encouraging preliminar results in the milligram range
- Novel set-up to be realized in 2022 with internal financing
- Maximum range 1 g





Calibration of mass standards below 10 g with Planck-Balance



Project start in 2022:

- Compact and user friendly Kibble balance based on standard load cell Sartorius WZA 26-HC (specified standard deviation: 2 µg)
- Continuous mass range: < 1 mg to 10 g
- Sinusoidal coil excitation for determination of geometric factor (*Bl*)
- Desired accuracy: For calibration of mass standards up to class E1 (i.e. 3.3×10^{-7} @ 10 g)
- Automated uncertainty evaluation by Monte-Carlo Method („Virtual Planck-Balance“, digital twin)

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

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,

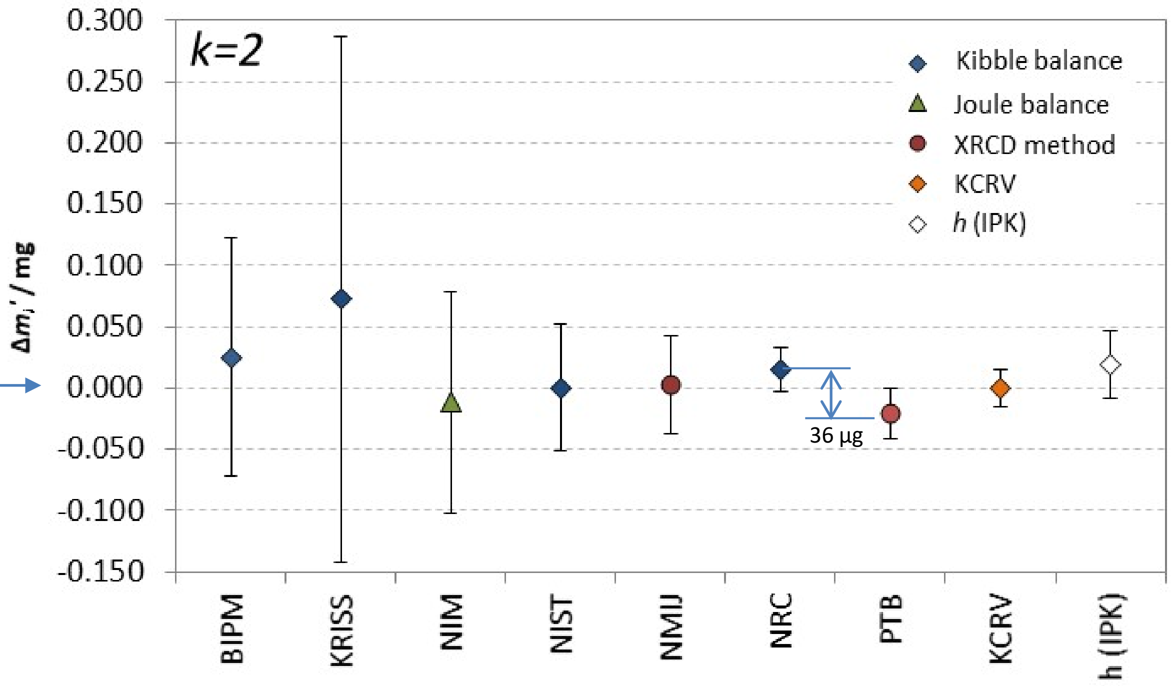
requests those National Metrology Institutes having a realization of the kilogram to avail themselves of the consensus value (as determined from the ongoing comparison) when disseminating the unit of mass according to the new definition, until the dispersion in values becomes compatible with the individual 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')

First key comparison of kilogram realizations (CCM.M-K8.2019)

Comparison coordinator: BIPM

KCRV
weighted mean

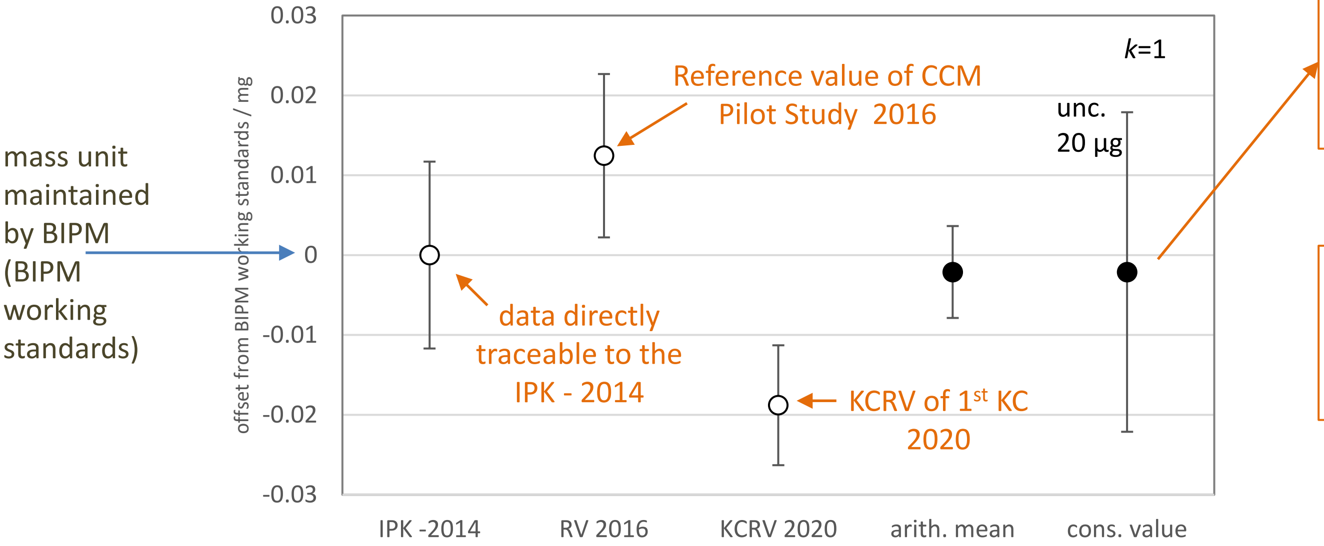


Input for the calculation of the first CCM consensus value for the internationally coordinated dissemination of the kilogram

Bureau International des Poids et Mesures

Calculation of the first CCM Consensus Value for the kilogram

- Consensus Value based on an arithmetic mean of 3 sets of data
- All 3 data sets obtained from work organized by BIPM mass laboratory
- Data sets linked together by BIPM Pt-Ir mass standards



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

Basis for worldwide coordinated mass dissemination

2nd KC being started

Dissemination of the Consensus Value

- **no adjustment to the international mass scale needs to be made**, only the uncertainty needs to be increased
- **adjustments to the CMCs** of some NMIs are necessary to take into account the increased uncertainty in the CV relative to the previous uncertainty in the IPK
- draft adjustments calculated by an ad-hoc TG of the CCM WGM and circulated to the affected NMIs for approval, then updated in KCDB

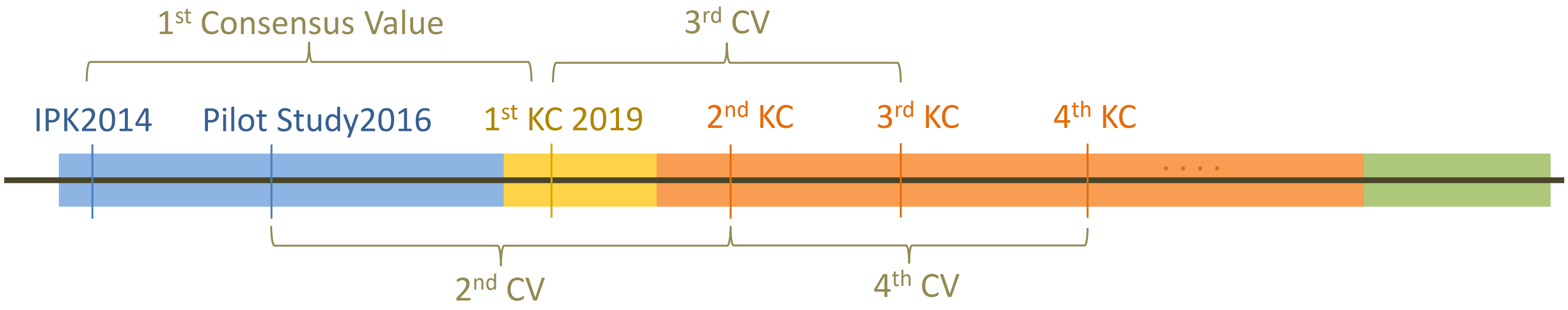
BIPM

Note on the impact of the beginning of Phase 2 of the kilogram dissemination process on BIPM mass calibrations

Next steps

- Repeat the CCM.M-K8 (scheduled to take place every 2 years)
- Determination of the 2nd Consensus Value
  - based on results of CCM Pilot Study, KCRVs of the 1st KC and of the 2nd KC
  - check of the temporal stability of the CV
- Dissemination of the 2nd Consensus Value

- Iteration until the decision of the CCM to go into Phase 3 (independent dissemination)



Thank you for your attention !