Report from the CCEM working group on electrical methods to monitor the stability of the kilogram

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March 2019

Introduction

- An informal meeting of the working group was held on Friday 6th July 2018 at the time of CPEM 2018 in Paris, France.
- The meeting was held jointly with the CCM working group CCM-WGR-kg.
- The latest version of the report (V1.1) is available as CCEM working document CCEM/19-04-1
- The majority of the report contains information gathered at that meeting but has been updated in March 2019 by e-mail correspondence.

Dr Chris Sutton 1948 - 2018

- Dr Chris Sutton from MSL New Zealand passed away on 13th December 2018
- He worked at MSL for 43 years and invented their novel form of Kibble balance which uses two coupled pressure balances.
- His contributions to the Kibble balance community will be missed.

Redefinition and Maintenance of the kilogram

CCM-WGR-kg

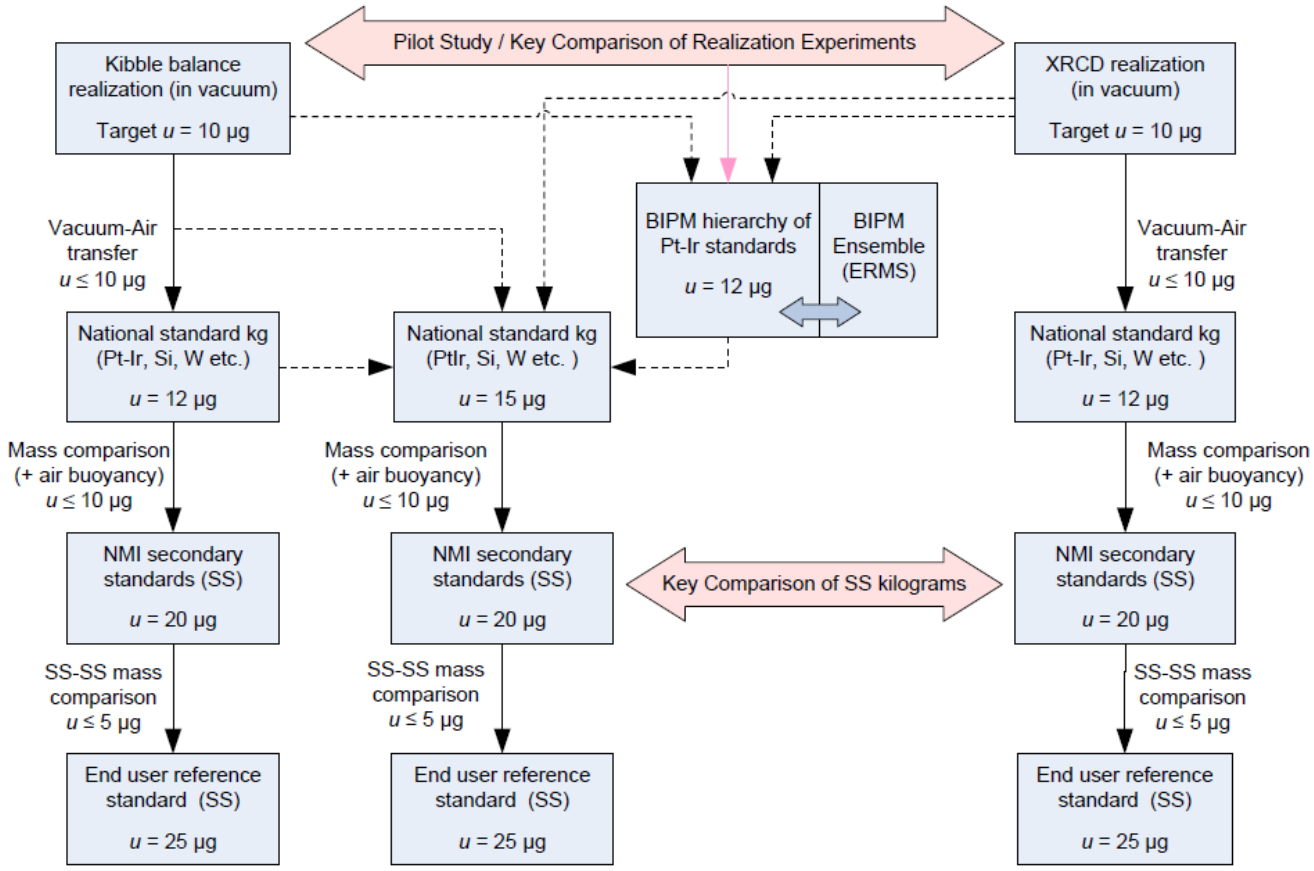
- The meeting started with some general issues for the CCM-WGR-kg.
- The substance of this discussion can be found in the February 2019 report of the CCM-WGR-kg.

Mise en Pratique for the kilogram

- Latest version 11.3 was distributed on the 20th July 2018.
- A Focus Issue of Metrologia was published on the kilogram.
- Open questions:
  - How will the BIPM ensemble of reference mass standards be used?
  - How can the technical protocol of the BIPM.M-K1 comparison be improved?
  - How often should NMIs take part in comparisons to maintain CMCs?
  - How to include Kibble balance measurements of small masses?
- BIPM.M-K1 comparison will occur immediately after the redefinition ($1x10^{-7}$) then every 2-10 years.
- The CCM will disseminate a “Consensus Value” while it is required.

Ensemble of reference mass standards and the Consensus value

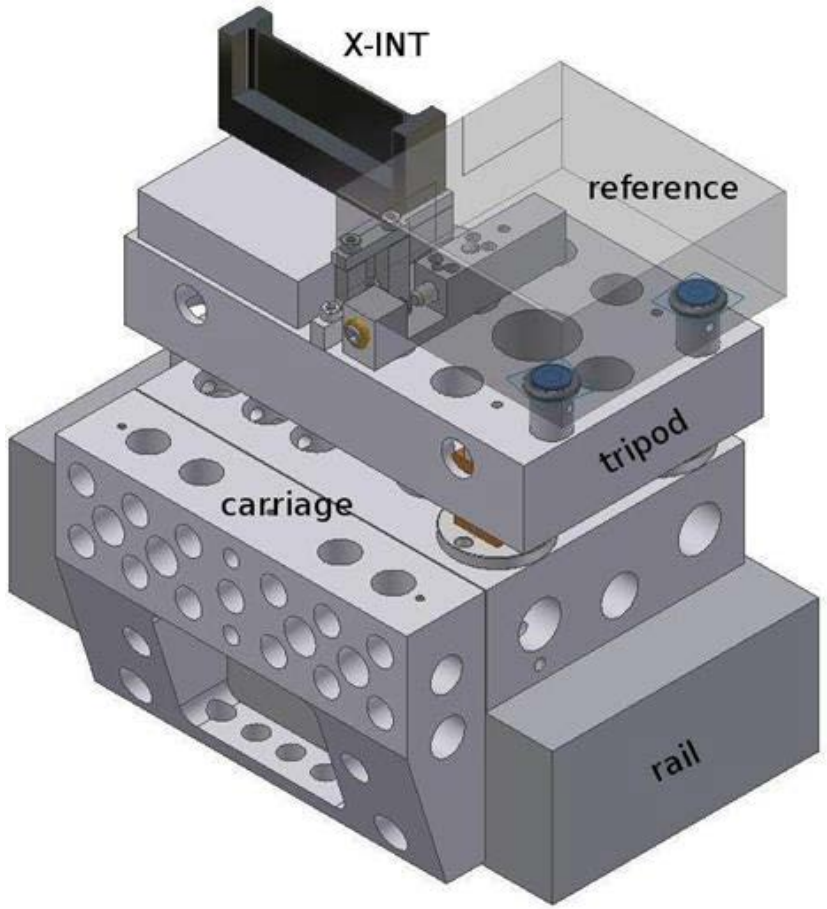
- BIPM ensemble of reference standards
- Placed within hierarchy of reference masses
- Reference masses will be used to help maintain the CCM "Consensus Value"



Realisation of the kilogram using the X-Ray Crystal Density method.

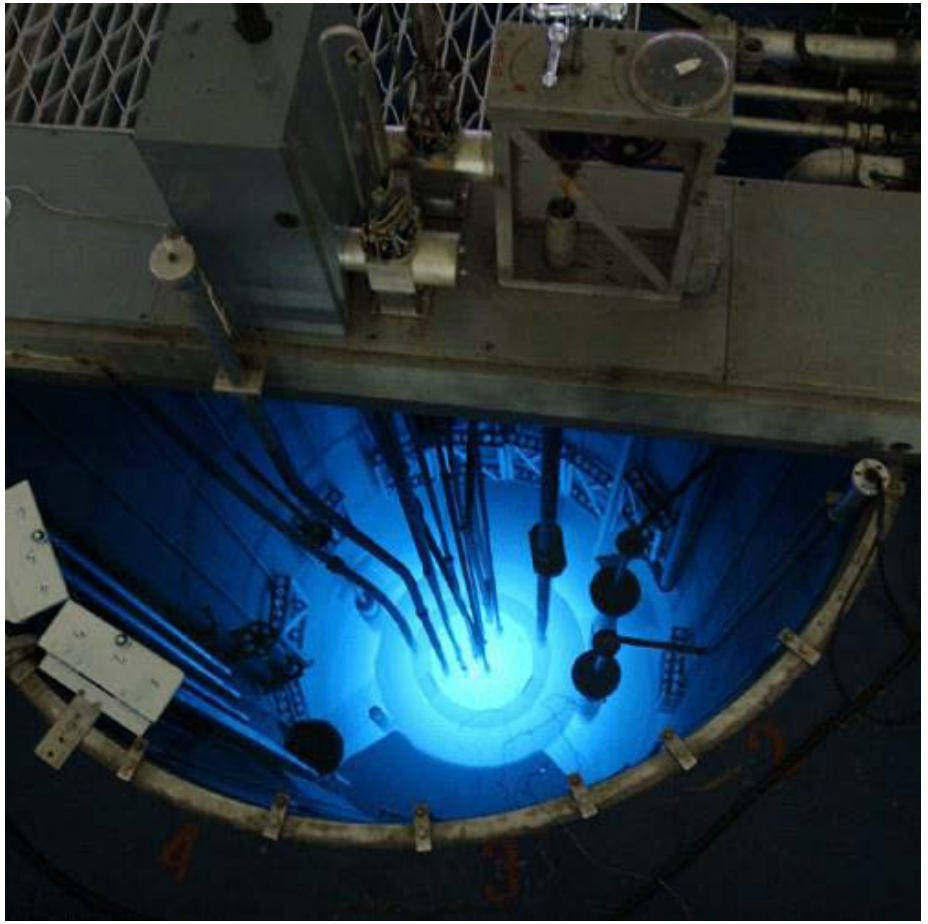
INRIM: silicon lattice spacing measurements

- Improving lattice spacing measurements
  - Diffraction corrections
  - Temperature issues
- Looking at the effects of surface strains resolution at present 1 N/m
- Found scattered light problem near zero path difference. Solved by restricting detector aperture.
- Metrologia: Forward scattering in a two beam laser interferometer.



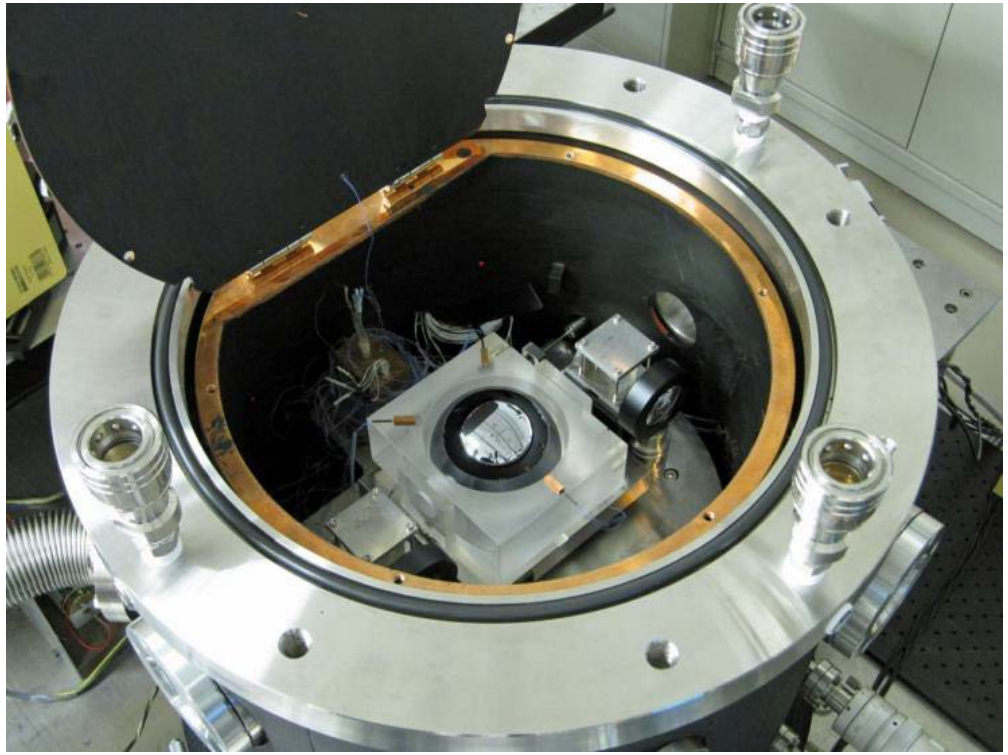
INRIM: Neutron activation analysis and simulation

- They are using neutron activation analysis to look for impurities, voids and vacancies in ^{28}Si crystals.
- They have a digital twin of the sphere supports of the NMIJ optical interferometer
- They have predicted the effects, on the volume measurement, of the distortions produced by gravity.
- Metrologia: Self-weight effect in the measurement of the volume of silicon spheres.



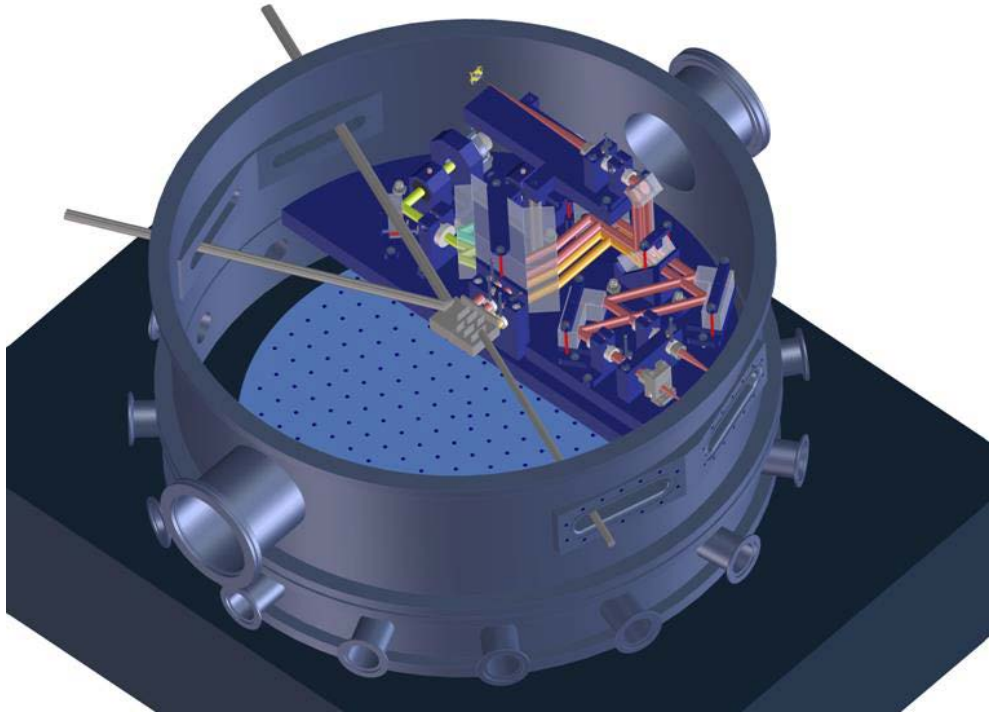
NMIJ: X-Ray Crystal Density (XRCD) measurements.

- NMIJ published an independent measurement of the Avogadro constant with a relative standard uncertainty of 2.4×10^{-8} in 2017.
- They have improved interferometer temperature control by improving their radiation baffle.
- They have made further comparisons of silicon lattice spacing.
- They are using EPR techniques to look at impurity concentrations and check mass deficit corrections.
- They have improved their ellipsometry equipment for characterising the materials adsorbed on the sphere surface.



PTB: X-Ray Crystal Density (XRCD) measurements.

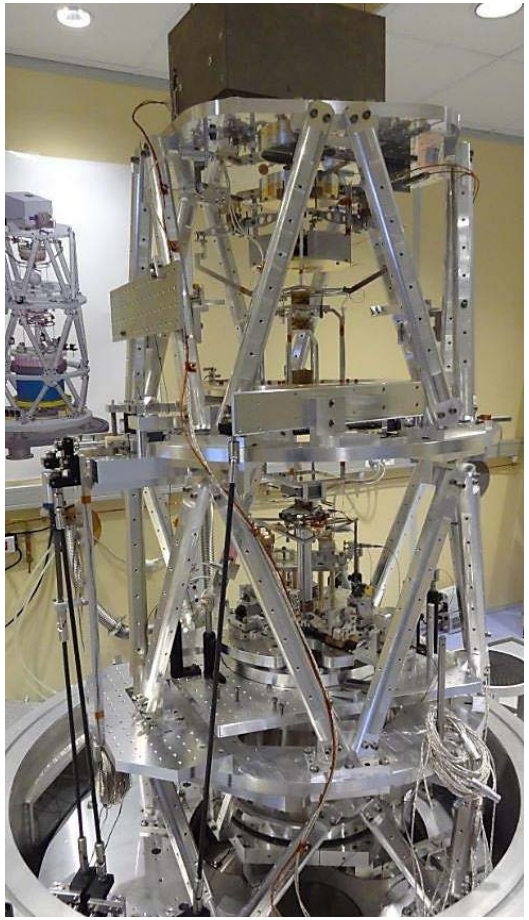
- The IAC measured the Avogadro constant in 2017 with an uncertainty of 1.2×10^{-8}.
- 3 new silicon crystals, giving 6 new spheres.
- Checked temperature uncertainties with INRIM results to better than 0.1 mK contributing less than 1×10^{-9} on volume.
- They have an XRF/XPS apparatus allowing the spheres to be transferred under vacuum to the balance.
- They are investigating alternatives to the use of the expensive ^{28}Si spheres.



Realisation of the kilogram using Kibble balance techniques.

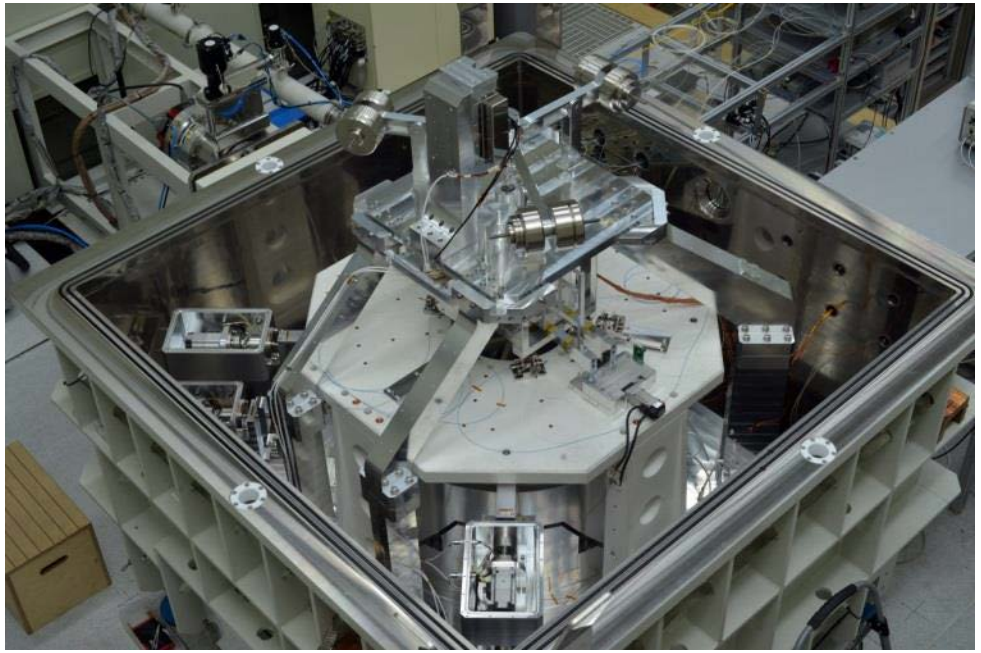
BIPM: Kibble Balance measurements

- The balance is working in vacuum and is using the 1 mode and 2 measurement phase operating scheme using a bifilar coil at room temperature.
- Weighing noise improved by 100 times and the repeatability is now a few parts in 10^7.
- Two papers in Metrologia one on the effect of the weighing current on the magnet.
- Many improvements including alignments.
- Planning to publish measurements in 2019



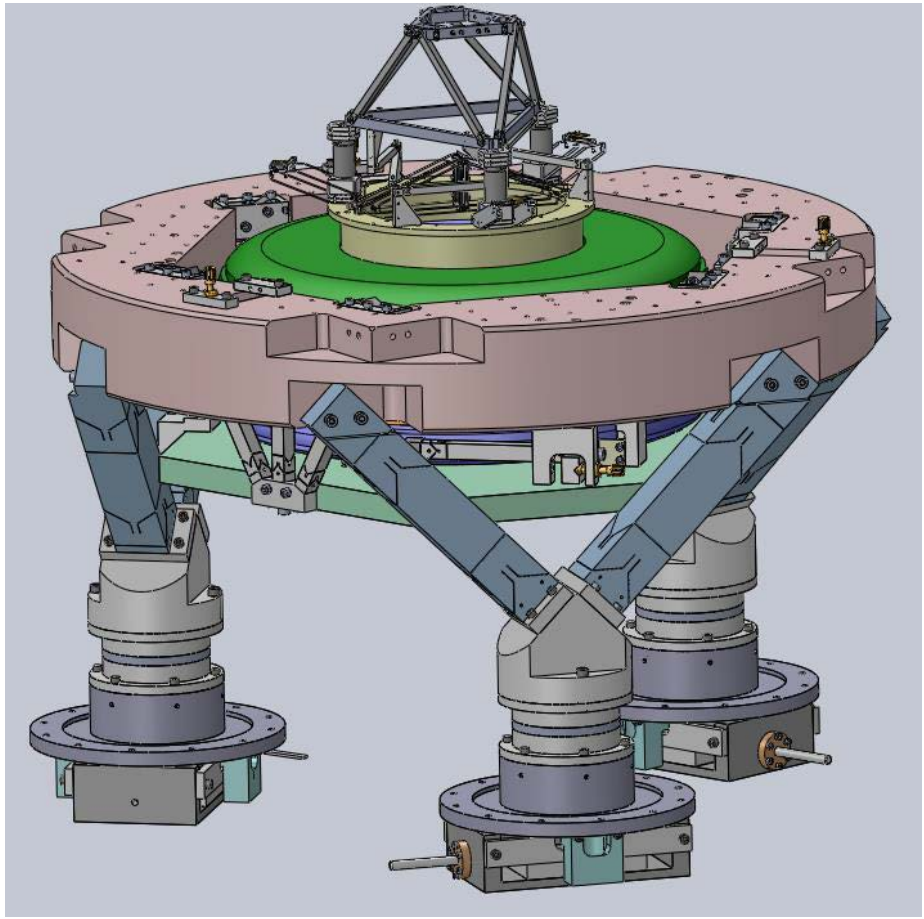
KRISS: Kibble Balance measurements

- They are aiming for an uncertainty of between 1-2 parts in 10^7 in 2019, improving to 5 parts in 10^8 by 2020
- They intend to contribute to the comparison BIPM.M-K1 in 2020.
- They are improving techniques both for the alignment of the apparatus and the synchronisation of the acquisition of moving data.
- They are starting work on a micro Kibble balance for use in the range between 1 mg and 2 g.



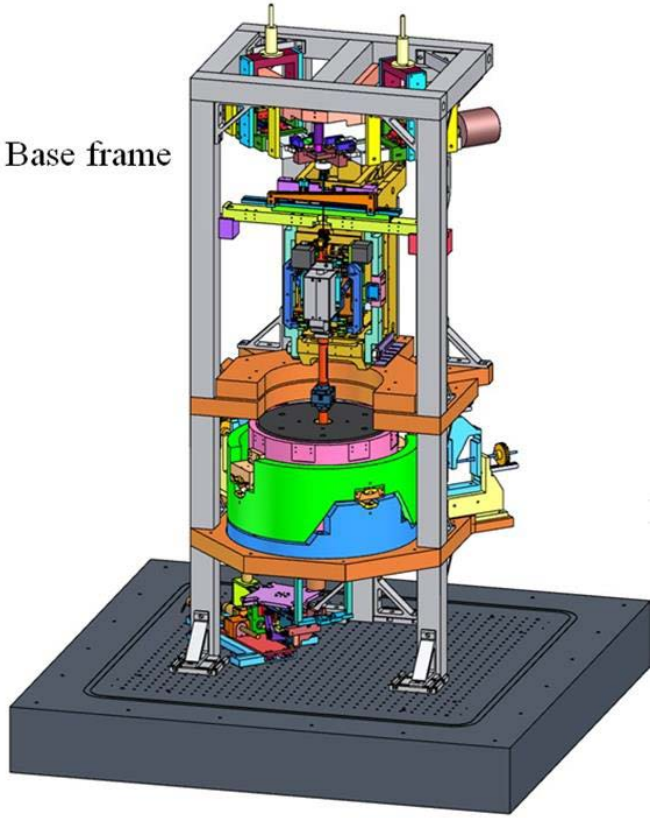
LNE: Kibble Balance measurements

- LNE produced a measurement of the Planck constant in 2017 with a relative standard uncertainty of 57 x 10^{-9}.
- Factor of 1000 reduction of movement on evacuation allows vacuum operation.
- Modifications to balance and support slab have greatly reduced type A uncertainty.
- Aiming to contribute to the comparison BIPM.M-K1 with a relative standard uncertainty of below 50 x 10^{-9}.
- Will realise the mass unit.
- Work on a traceable method to measure small forces and masses.



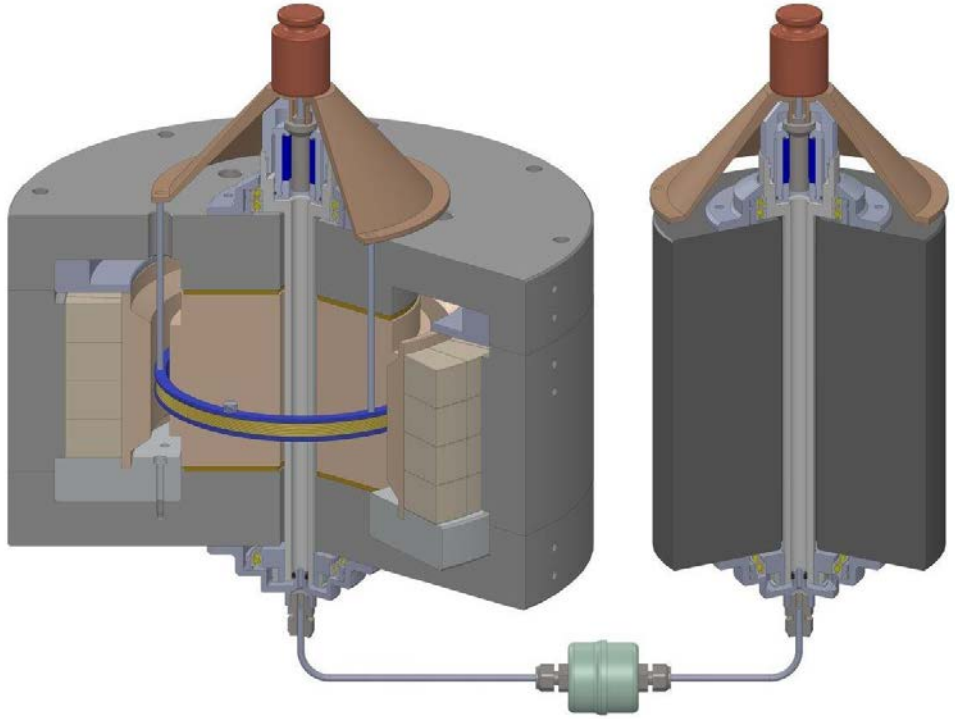
METAS: Kibble Balance measurements

- Replaced “crossed cone” alignment system.
- They are using a green laser to improve velocity and displacement measurements
- New method to align mass comparator to vertical.
- About to test Abbe error elimination method.
- Apparatus is showing reproducible alignment and will be operational in vacuum.
- They intend to transfer the apparatus to their mass lab.
- Aim to participate in the comparison BIPM.M-K1.



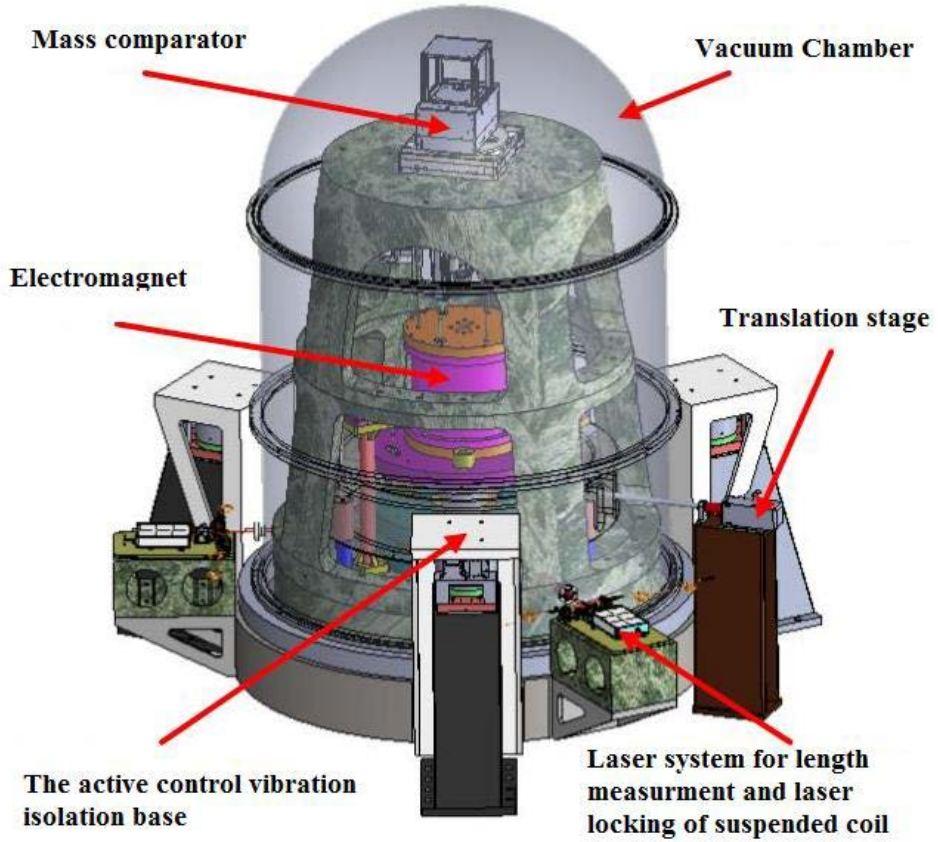
MSL: Kibble Balance measurements

- Piston and cylinder modelled, tilt and eccentricity are critical, but variations < 2 parts in 10^9.
- Magnet designed: 0.6 T, 20 ppm/K, uniformity better than ±20 ppm over a ±20 mm span.
- Laboratory constructed, *g* measured.
- Construction and characterisation of ancillary equipment under way.
- They intend to operate in air in 2021 with vacuum operation later.
- Intend to participate in BIPM.M-K1.



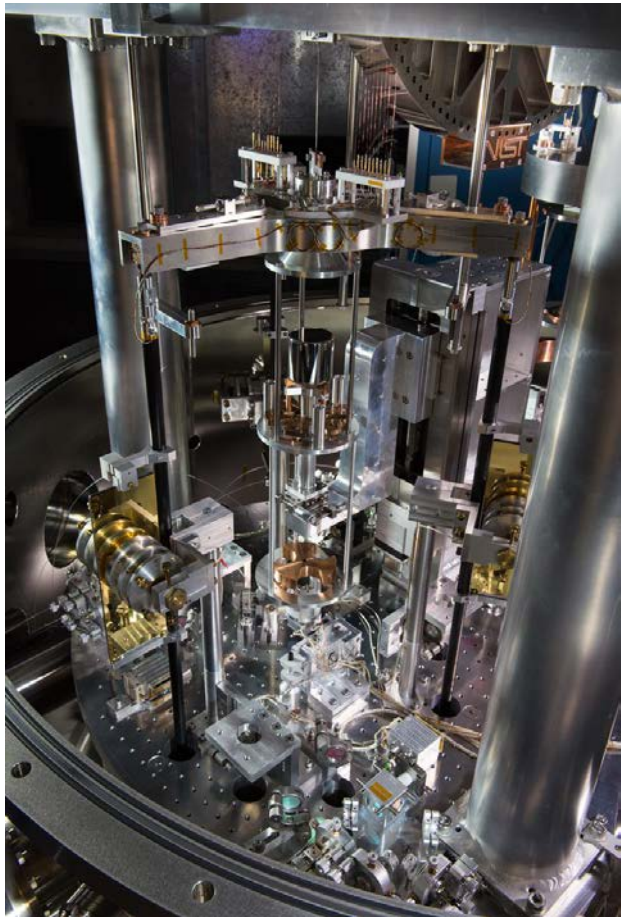
NIM: Joule Balance measurements

- NIM-2 produced a measurement of the Planck constant with an uncertainty of 2.4×10^{-7}.
- shielded permanent magnet, with a factor of 6 improvement in flux density (0.49 T), replaces their electromagnet. This has reduced the Type-B uncertainty arising from external magnetic fields to 1.4×10^{-8}.
- the type-A uncertainty of the apparatus has been decreased to 3×10-8.
- improvements to reduce this uncertainty towards several parts in 10^8.
- Their long term aim is to realise the redefined kilogram in vacuum and transfer it to the mass group of NIM.



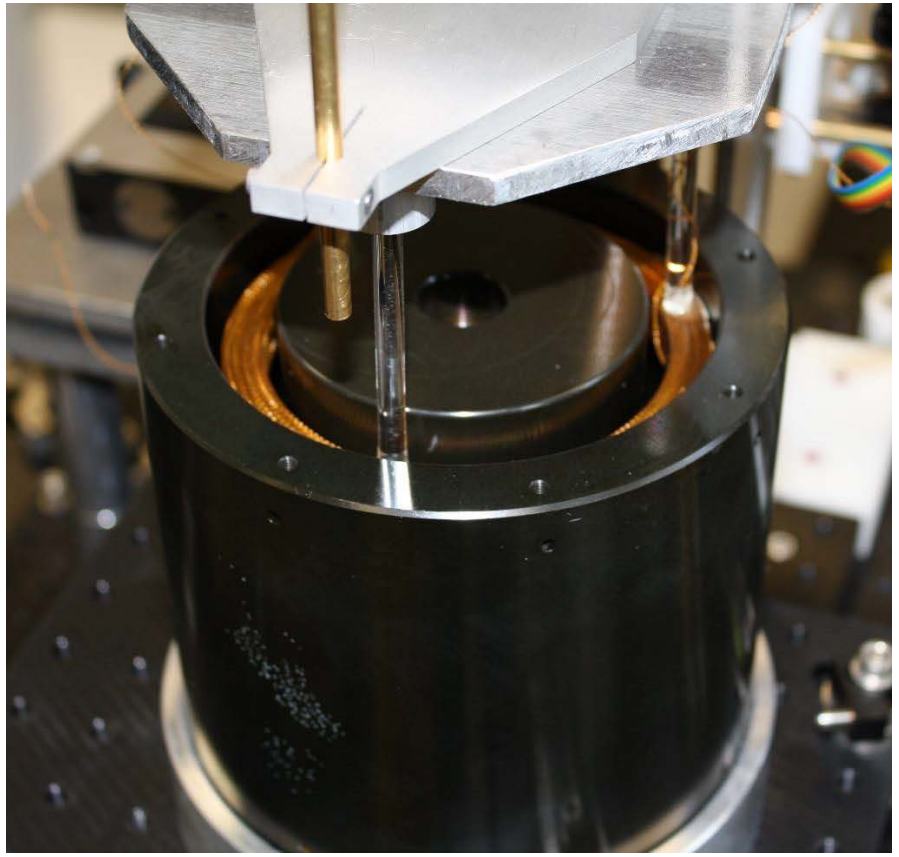
NIST: Kibble Balance measurements

- NIST measured the Planck constant in 2017 with an uncertainty of 13 x 10^{-9}.
- They have worked on many improvements
- An accident involving the coil, plus a laboratory flood, have delayed work.
- They are working on a table-top Kibble balance with a range from 1 g to 10 g with a target uncertainty in the region of 10^{-6}.
- They are also designing a 1 g - 100 g in-vacuum Kibble balance.



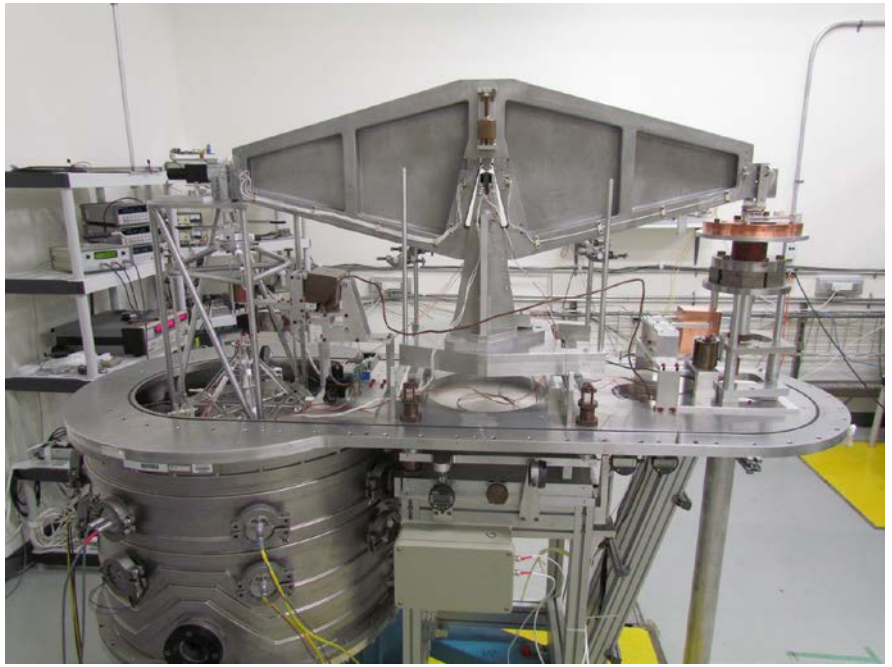
NPL: Kibble Balance measurements

- NPL are developing a next generation Kibble Balance to measure from 100 g – 250 g.
- Six demonstration balances have been built for SI publicity.
- Electronics updated: modern ring control computer and updated isolated low-noise electronics.
- Aiming to produce results with an uncertainty < 1 x 10^{-6} by the end of 2019



NRC: Kibble Balance measurements

- The NRC measured the Planck constant in 2017 with an uncertainty of 9.1×10^{-9}
- They described critical techniques used: some from NPL, some from NRC.
- They are investigating, characterising and reducing sources of uncertainty.
- The drift in their measurements of *h* over 3.2 years is $(-0.51 \pm 2.3) \times 10^{-9}$/year.
- New gravity transfer measurements should allow a reduction of the associated uncertainty to 3×10^{-9}.



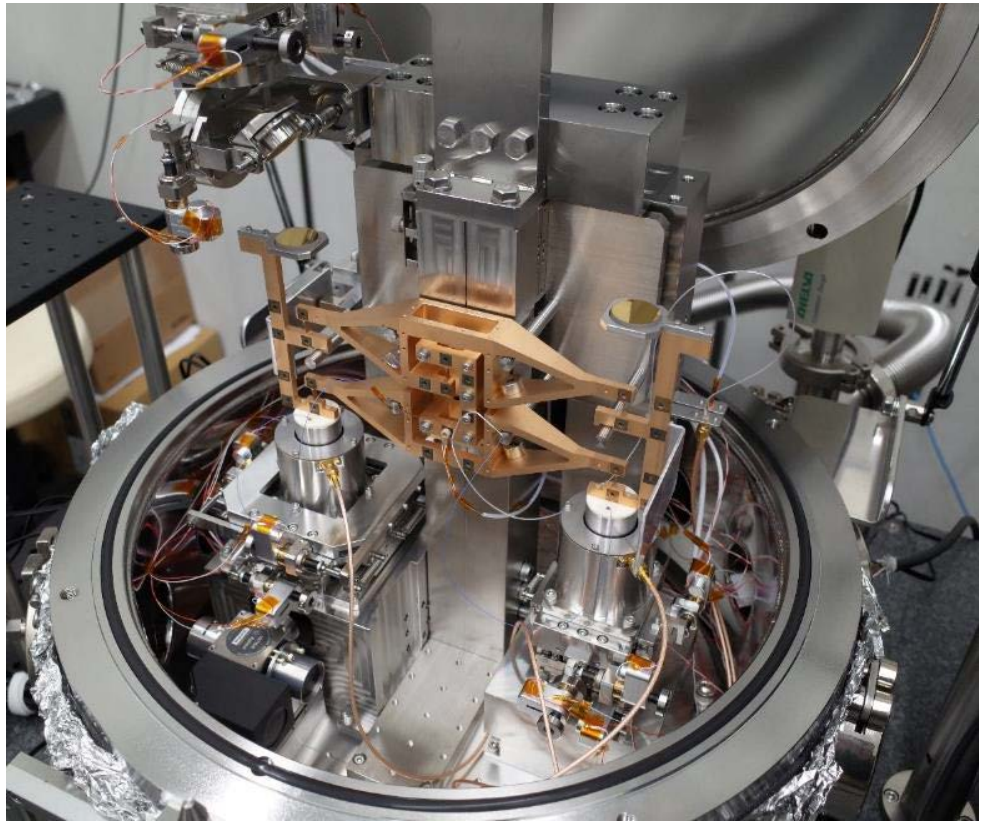
UME: Kibble Balance measurements

- The first UME oscillating magnet Kibble balance (UME KB-I) has achieved an uncertainty of 6 ppm.
- UME KB-II was constructed to provide a lower uncertainty than UME KB-I.
- They have developed optimization procedures for the apparatus and have achieved a repeatability of 0.3 ppm.
- They are integrating a PJVS into the measurement system.
- UME KB-III is being designed with a target uncertainty is 0.05 ppm within two years.

Related Topics.

NMIJ: Small mass measurements

- NMIJ are working on a voltage balance for measurements of small masses.
- They have also built a MEMS based voltage balance to measure small masses and their work to measure small torques is proceeding well.
- They are also making force measurements between 10 nN to 10 pN using radiation pressure using laser powers varying from 1.5W to 1.5 mW.
- They are currently investigating some discrepancies in the system.



Gravitation

- Uncertainties of Kibble balances are decreasing and their influence in maintaining mass globally is going to increase
- The validity of measurements made with absolute gravimeters will have an increasing effect on the uncertainty of the Kibble balance.
- The CCM-WGG are responsible for the treatment of results from key comparisons in gravity.
- It is important that a dialogue exists between the CCM-WGG and the appropriate CCM Kibble balance working group to ensure that any formal mechanisms proposed for the handling and propagation of comparison results are acceptable to the Kibble Balance groups.

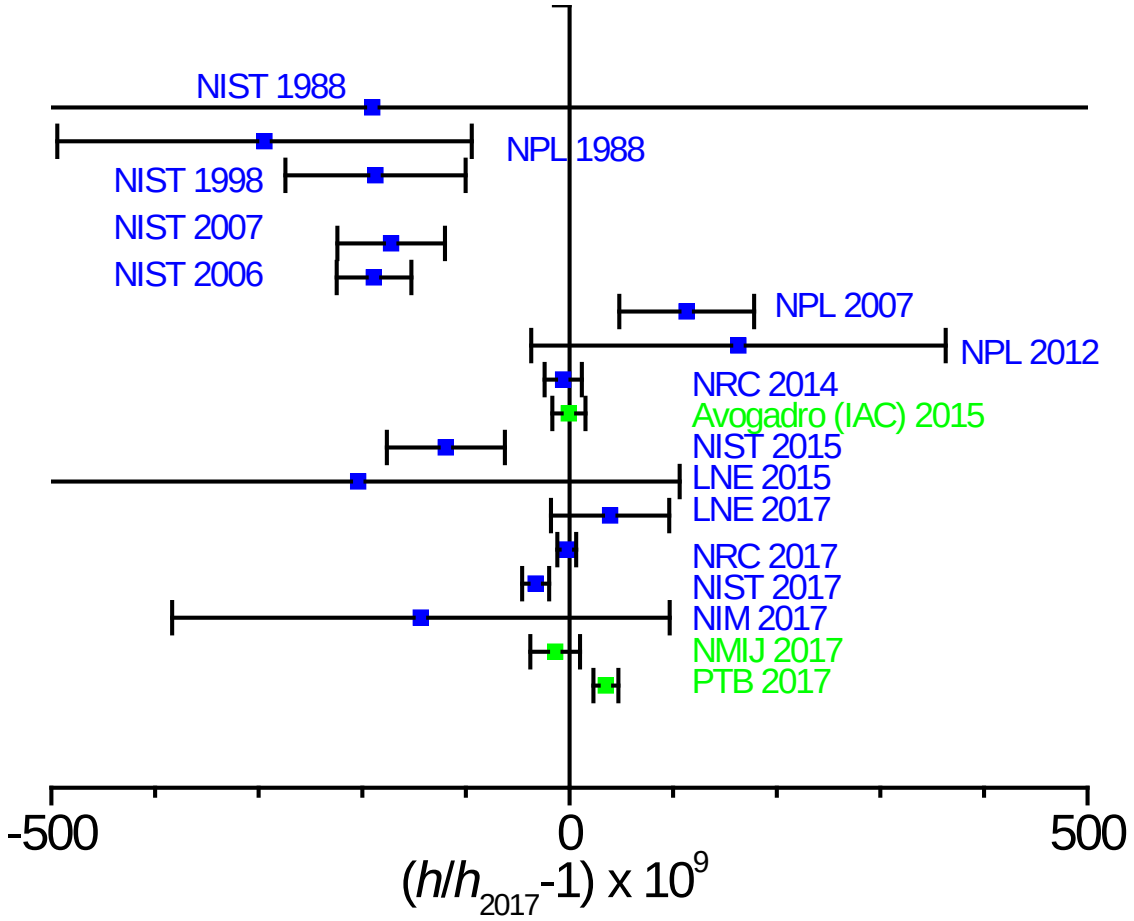
Future Kibble Balance technical meetings

- The next technical meeting on the Kibble balance, KBTM2019, will be hosted by NPL in the UK on the 25th and 26th of October 2019 in Bushy House.
- Further details can be obtained from Ian Robinson (ian.robinson@npl.co.uk)

Closure of the CCEM working group on electrical methods to monitor the stability of the kilogram

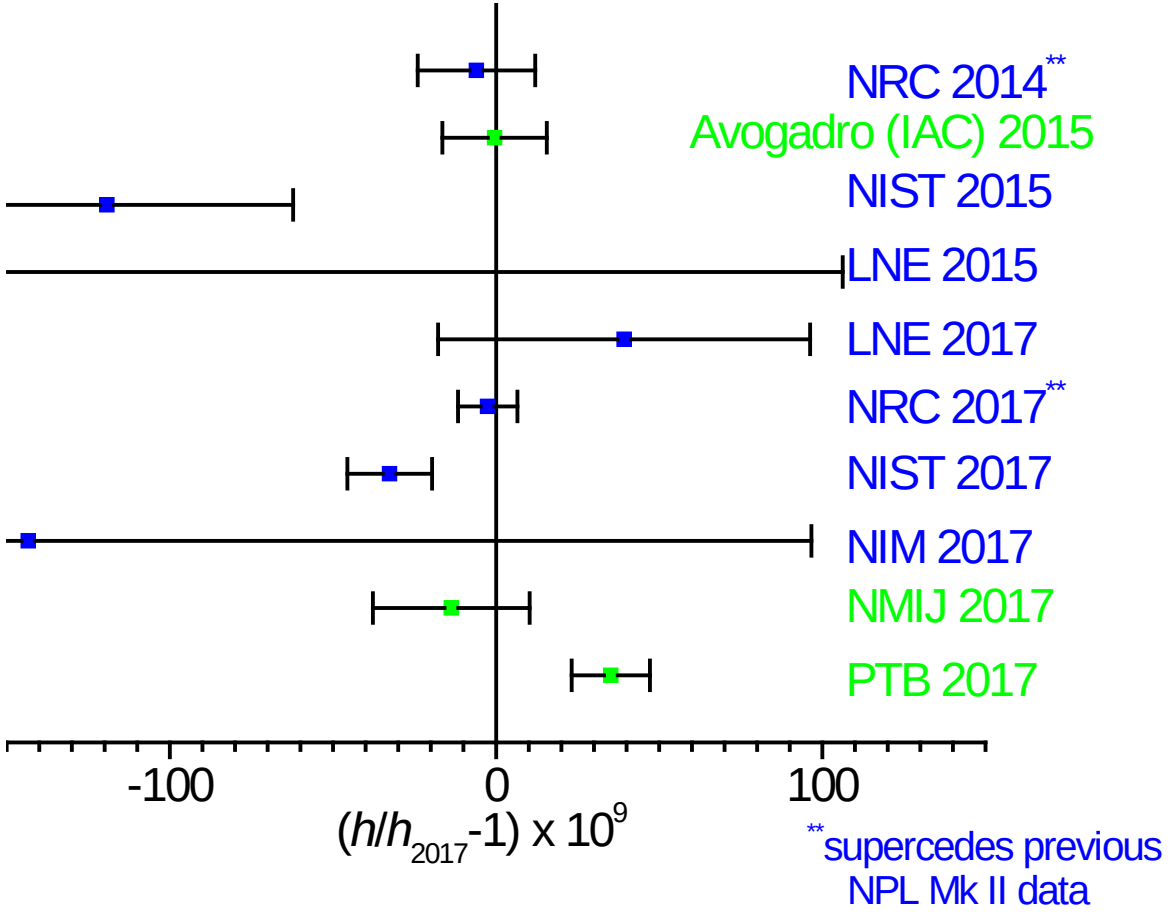
Measurements of the Planck Constant

- At their meeting in November 2018 the CGPM resolved to revise the SI and fix the numerical values of both the Planck constant and the elementary charge.
- This change will take place on the 20th May 2019.
- Once the SI has been so revised the electrical units will no longer depend on the kilogram.
- All the members of this group have encouraged and contributed to this change.
- The figure shows selected historical measurements of the Planck constant.



Recent measurements of the Planck Constant

- This figure shows more recent data which led to the redefinition of the kilogram.
- This achievement, by its members, represents a successful conclusion to the work of the group
- Future activities will be the responsibility of the CCM.
- The chair of this working group and the President of the CCEM have agreed that the group will be disbanded at this meeting.



Electrical innovations for Kibble Balances

- Kibble balance work would benefit from improvements in electrical measurements:
  - conventional resistors with improved robustness, stability and reduced temperature and power coefficients,
  - compact QHR arrays
  - novel conventional voltage references / precise integrating voltmeters
  - novel quantum voltage references/voltmeters – preferably operating at LN2 temperature.

Electrical innovations for Kibble Balances

- Quantum standards, operating at helium temperatures, will be required for Kibble balances operating at the lowest uncertainties
- Industrial applications of Kibble balance are being investigated by many NMIs.
- These will require cheaper but still accurate standards and instruments, operating at room temperature, so there will be a need for innovation in this area.

Chairman’s remarks

- I would like to thank all the members of the group, both past and present, who have contributed to our work and its successful conclusion; it has been a privilege to work with all of them.
- The group was started under the chairmanship of Bryan Kibble and I have been honoured to have been associated with it since its inauguration.
- Our discussions, and the actions of both the membership of the group and the CCEM, have helped steer and enable the process of redefinition over more than 20 years.

Conclusion

- I am proud to have chaired this group and I intend to continue to drive progress in this exciting field.
- I hope to see a world-wide mass scale maintained by an ensemble of independent Kibble Balances.
- I would like to see this powerful technique applied to solve problems in a range of industrial applications.
- The real work of the groups, specialising in the Kibble balance technique, is just starting. It is up to everyone in the field to ensure that the world obtains maximum benefit from their efforts.