17th meeting of the CCM

The Kibble balance: measuring mass and related quantities in the revised SI

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Introduction

- History
- Basic theory
- Uncertainties of the principal measurands
- Second order effects
- Alignment insensitivity
- Major forms of the balance
- The future
- NMI level balances
- Wider range - Higher uncertainty
- Conclusion

Invention of the Kibble Balance

NPL National Physical Laboratory

- The Kibble Balance was invented at NPL in 1975 by Dr Bryan Kibble as a different, easier and better way to realise the SI ampere.
- The Current Balance was used for this and was considered to have an error of ~10 ppm.
- The first Kibble Balance in the world: the NPL Mk I was designed, constructed and operated between 1976 and 1988.
- It contributed to the 1990 conventional value of the Josephson constant $K_{\mathrm{J-90}}$ which separated the conventional electrical units from the SI.
- This constant, with the conventional value of the von Klitzing constant $R_{\mathrm{K-90}}$ will be abrogated in 3 days time returning the electrical units to the SI.

Naming of the Kibble Balance

- Bryan's original name for the virtual work/power technique was the falling-coil apparatus.
- We realised that the coil did not really fall so started calling it the moving-coil apparatus.
- Possibly through the influence of NIST it became the moving-coil watt balance or, more simply, the watt balance.
- This persisted until Bryan's death in 2016 when it was renamed the Kibble balance in his honour.
- Other names for this technique exist. For example: Planck and joule balances

David Rollett, Bryan Kibble, Janet Belliss and Ian Robinson in front of the NPL Mk I Kibble Balance in Room 16, Bushy House, NPL, UK.

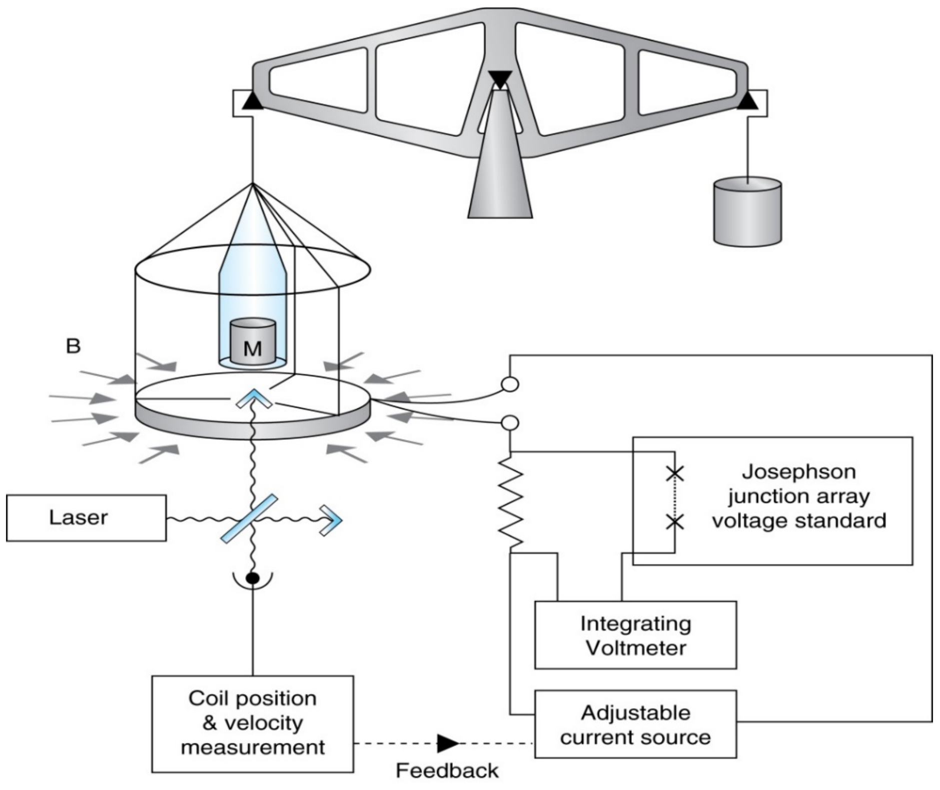
Weighing

- A force F is generated by
  - a current i flowing in
  - a wire of length l in
  - a magnetic flux density B

$$F = Bli$$

- If this balances the weight of
  - mass M with
  - gravitational acceleration g

$$Mg = Bli$$



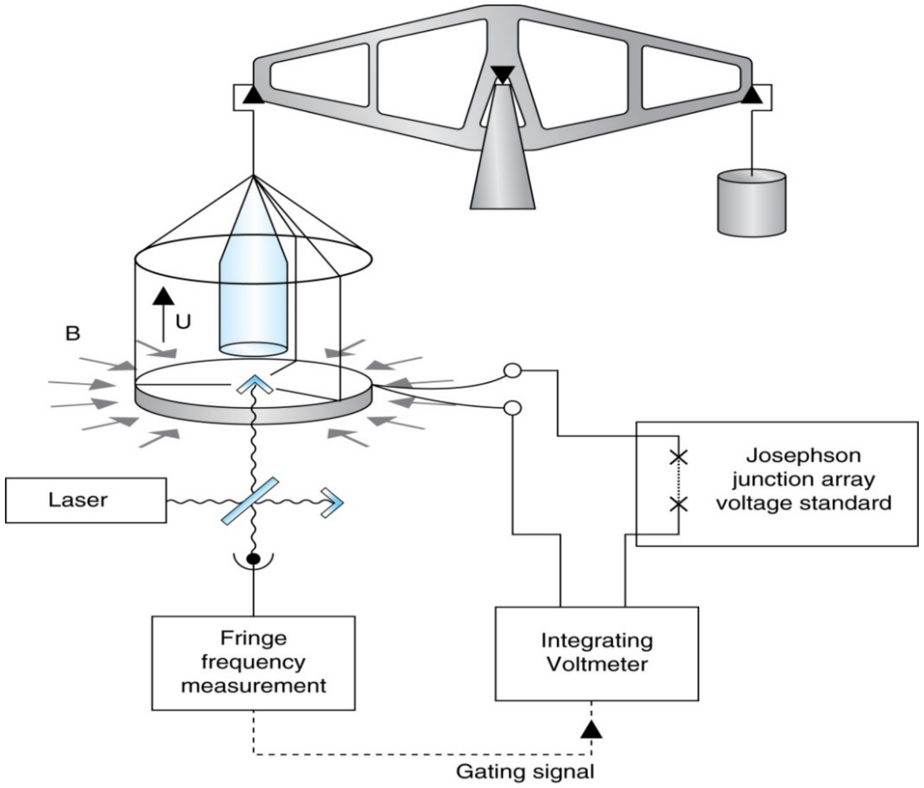
Moving

- If we move the coil in the field
  - with a known velocity *u*
  - a voltage V is generated

$$V = Blu$$

- Therefore we have an accurate measure of *Bl* as

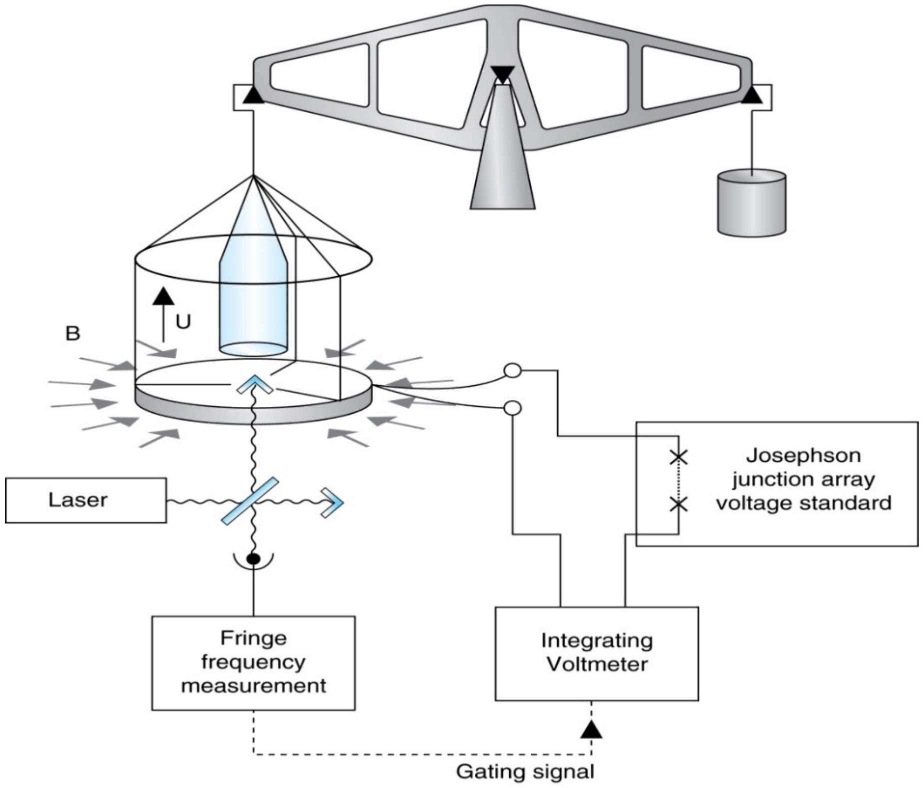
$$Bl = {}^{V}/_{u}$$



Combining the two parts

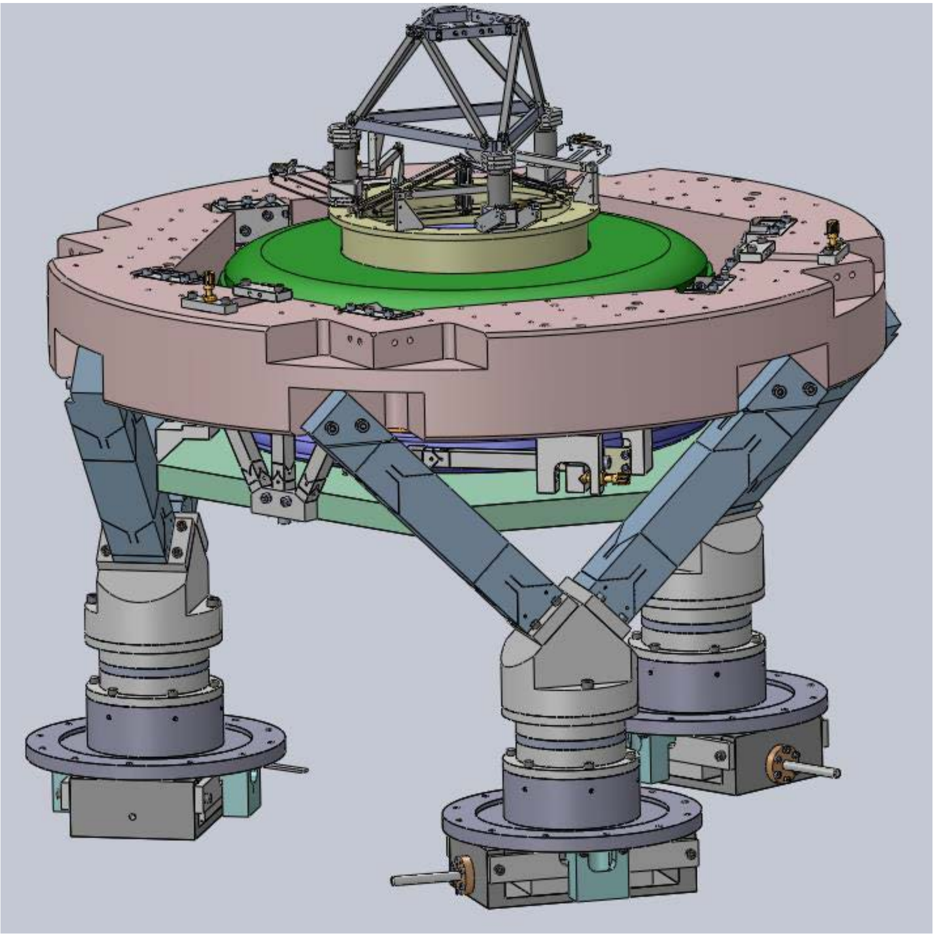
- Weighing: $Mg = Bli$
- Moving: $Bl = {}^{V}/_{u}$

- Virtual Power: $Vi = Mgu$
- Mass $M = \frac{Vi}{gu}$
- A general and purely classical technique involving **virtual** power.
- B. Kibble NPL 1975



Measurements

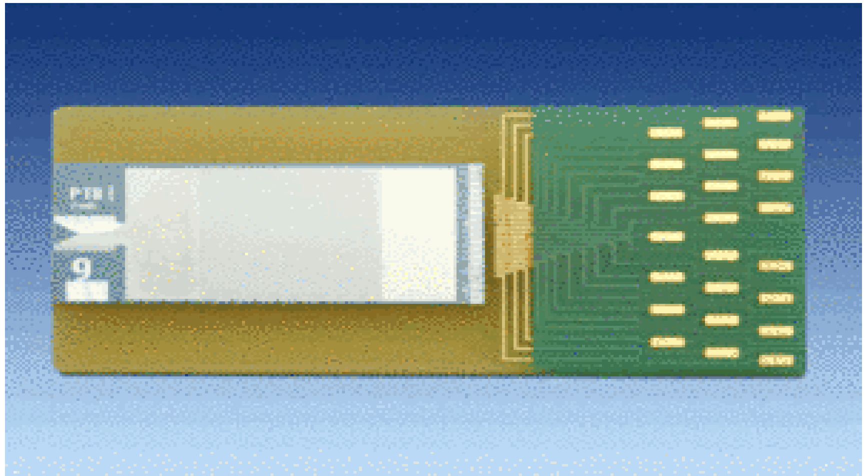
- To measure mass with a Kibble balance 4 different quantities must be measured to an uncertainty commensurate with the desired ultimate uncertainty. These are:
  - Voltage *V* - *Virtual Electrical Power*
  - Current *i* - *Virtual Electrical Power*
  - Velocity *u*
  - Acceleration due to gravity *g*
- If it is desired to realise mass or force using the new definition electrical power must be measured, either directly or indirectly, in terms of the Planck constant.



LNE

Voltage measurement

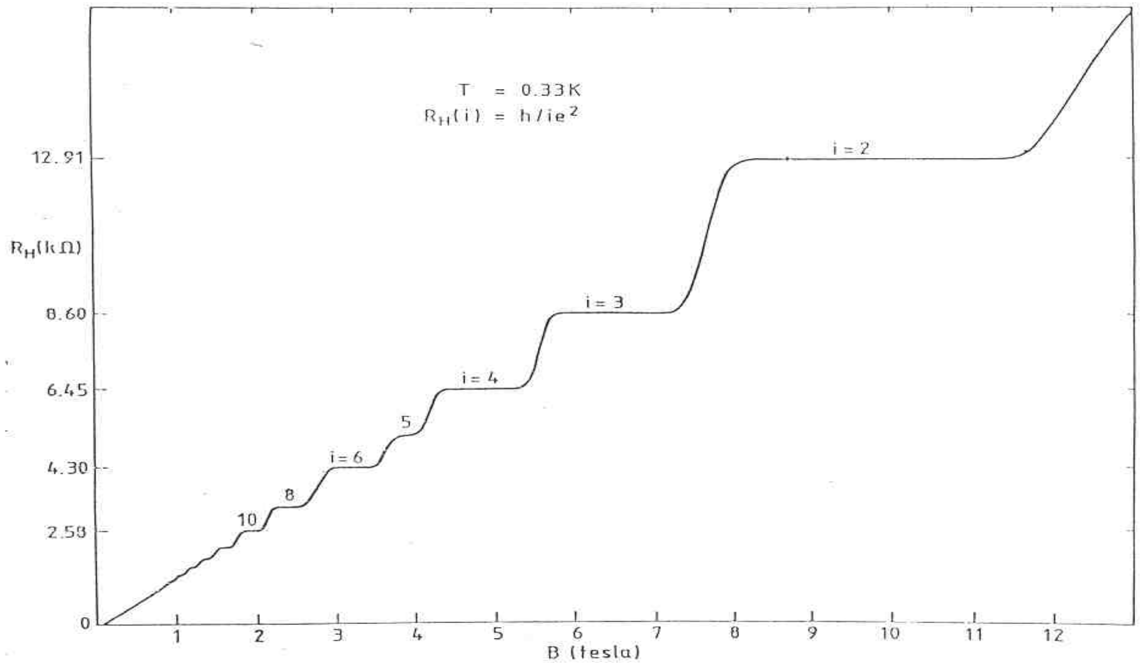
- To relate the mass measurement to the Planck constant voltage is measured using the Josephson effect.
- When an insulating or metal gap of ~1nm is illuminated with microwaves a voltage can appear between superconductors.
- This voltage is proportional to the microwave frequency
- 155 μV at 75 GHz
- Devices now contain arrays of junctions organised to allow the production of fundamentally accurate digital to analogue converters.
- $V = n\,h\,f\,/\,2\,e$
- $V = n\,f\,/\,K_J$



PTB

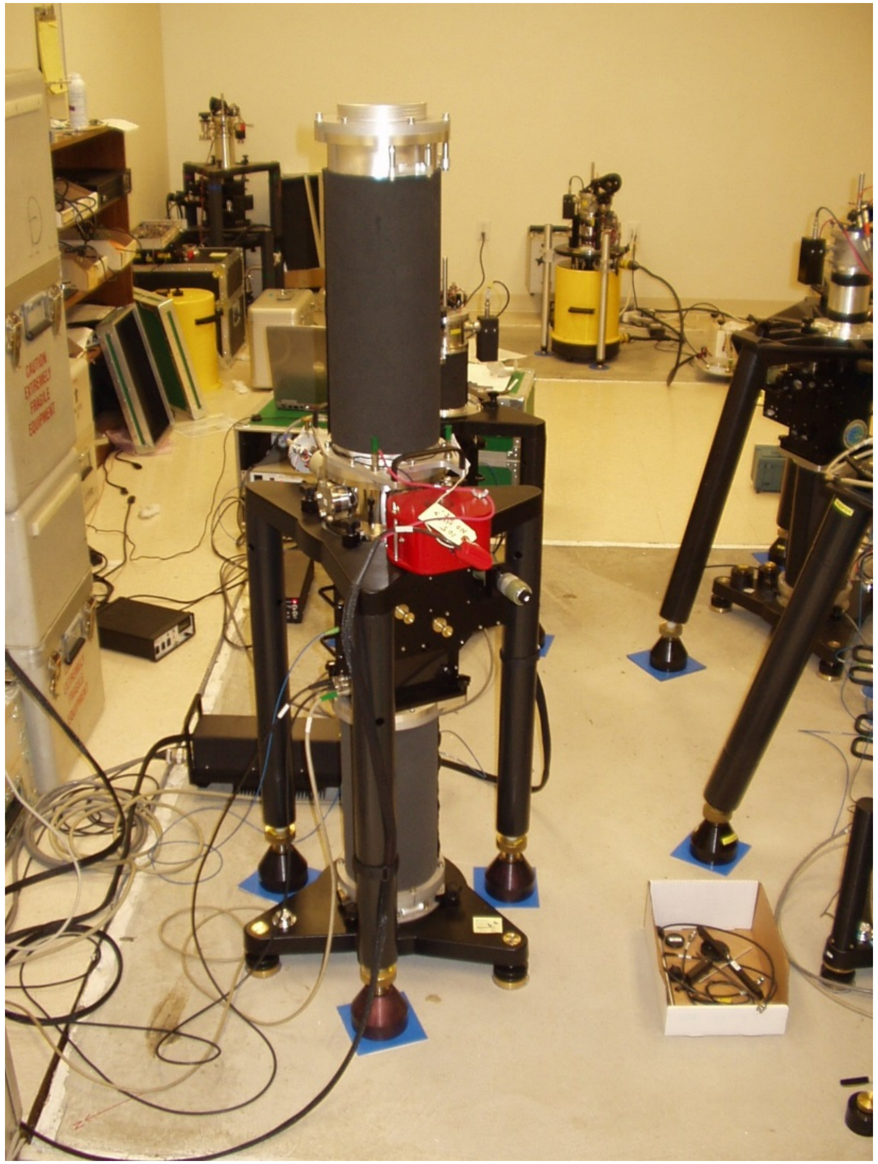
Virtual Electrical Power

- The Josephson effect gives $V_m = hf_m / 2e$
- Current i is obtained by measuring the voltage drop $V_w = hf_w/2e$ across a resistor R known in terms of the Quantum Hall Effect $R = h/ne^2$
- $i = V_w/R = f_w\, n\, e / 2$
- Giving the virtual power as $V_m i = f_m\, f_w\, n\, h / 4$
- Both Josephson and Quantum Hall effects have been verified to much better than 1 part in 10^9 .
- Electrical measurements can provide mass measurements at a level of 1 part in 10^9 or better.
- Improvements in the form of quantum hall arrays which would provide ideal resistors in the range 100-1000Ω and Josephson nanovoltmeters would simplify the work in the future.



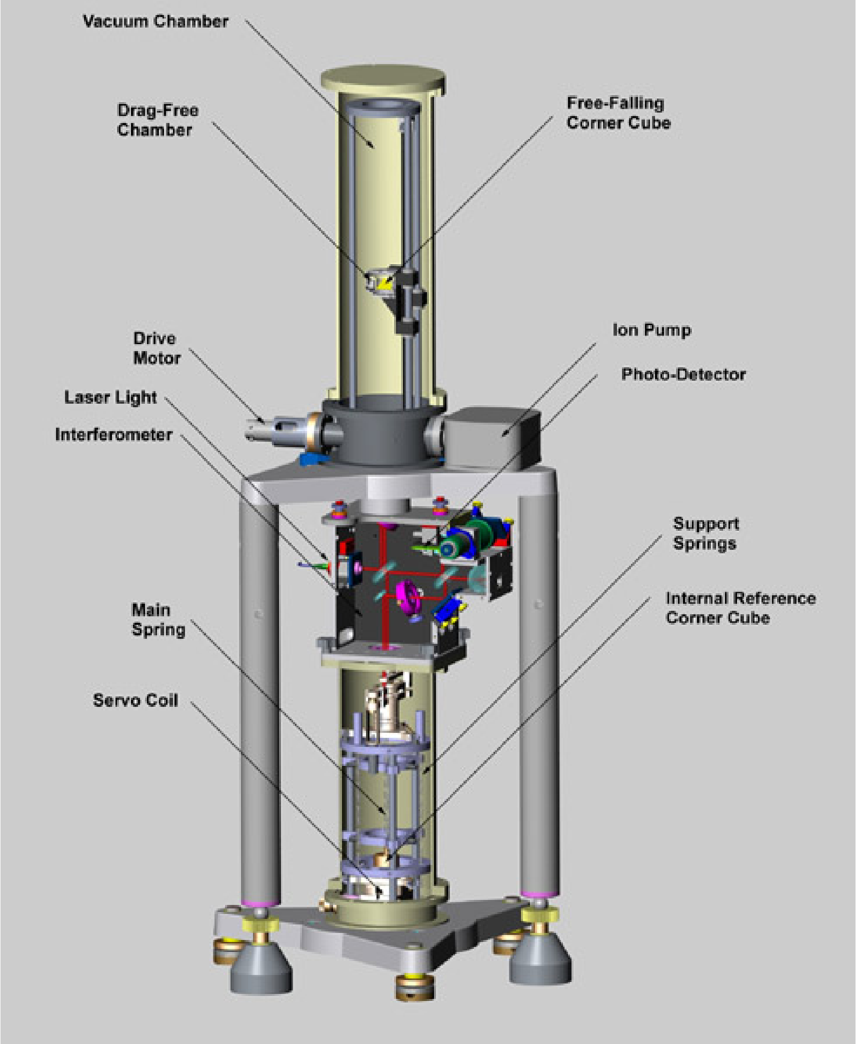
Velocity and *g*

- Both require standards of length and time
- Time can be readily obtained from a variety of sources:
  - Hydrogen maser/caesium clock
  - Calibrated rubidium oscillator
  - Off air standard
    - GPS disciplined oscillator
    - Broadcast time reference
- Length is usually obtained via a laser source whose frequency is stable and known.
  - Iodine stabilised laser
  - Calibrated stabilised laser
- With care uncertainties much better than 1 in 10^9 can be obtained in both cases.



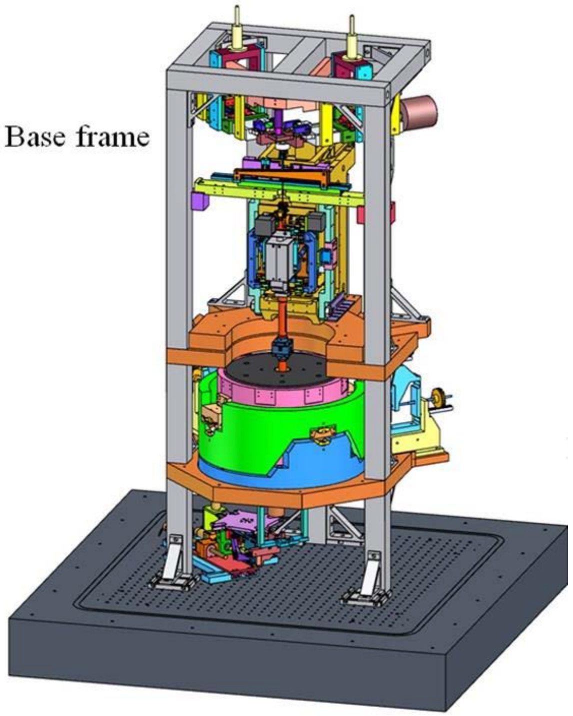
Velocity and *g*

- The principal quantities can be determined at the 1 in 10^9 level but practical issues predominate.
- For velocity - ground vibration can produce noise 1 million times the desired uncertainty.
- As the voltage and velocity are highly correlated this noise can be suppressed by careful measurements taken over the exactly the same time.
- Gravity is measured with a separate instrument: a gravimeter, most commonly a micro-g FG5, but atomic gravimeters are becoming more common.
- There is no reason that both measurements should not pass the 1 in 10^9 barrier but, at present, from the results of comparisons of gravimeters, measurements are limited to around 2-3 in 10^9



Second order effects

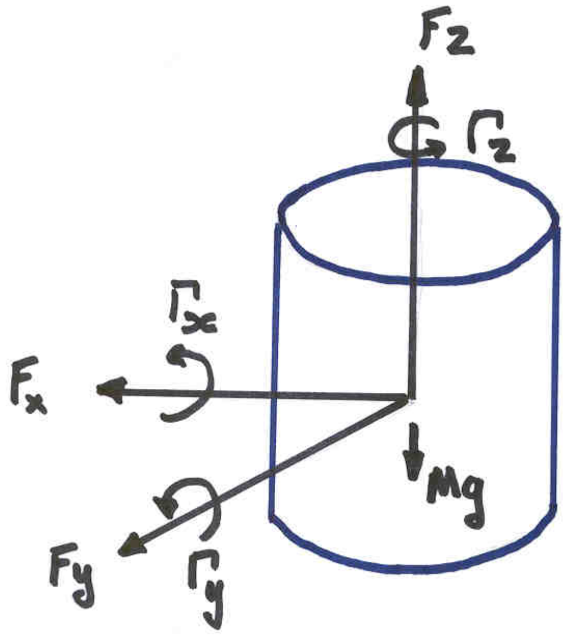
- Whilst, at present, it is theoretically possible to measure the principal quantities to around 2-3 parts in 10^9 a number of other effects in the apparatus must be taken into account.
- The velocity measurement must be made along the gravitational vertical so alignments to ensure this must be made, along with any other necessary alignments.
- However up to a few years ago it was assumed that the coil had to be aligned with the magnetic field of the magnet to ensure that only a vertical force was produced.
- In many cases this is still true; requiring complicated, costly and time consuming alignment techniques
- The recent theory of the balance allows the design of Kibble Balances which do not require such alignments to achieve low uncertainties. This can reduce their cost and simplify their construction and operation.



METAS

Insensitivity to alignment

- The future simplification of the technique depends on extensions to the theory of the Kibble balance derived in 2014.
- In the past it was considered necessary to align the balance to eliminate torques and non-vertical forces acting on the coil and to move it vertically without rotation.
- The new theory shows that under particular conditions this is not necessary.
- It requires the same mechanism to be used for both moving and weighing.
- The alignment of the apparatus must not change significantly between moving and weighing.
- The theory also supports the construction of novel forms of Kibble balance.

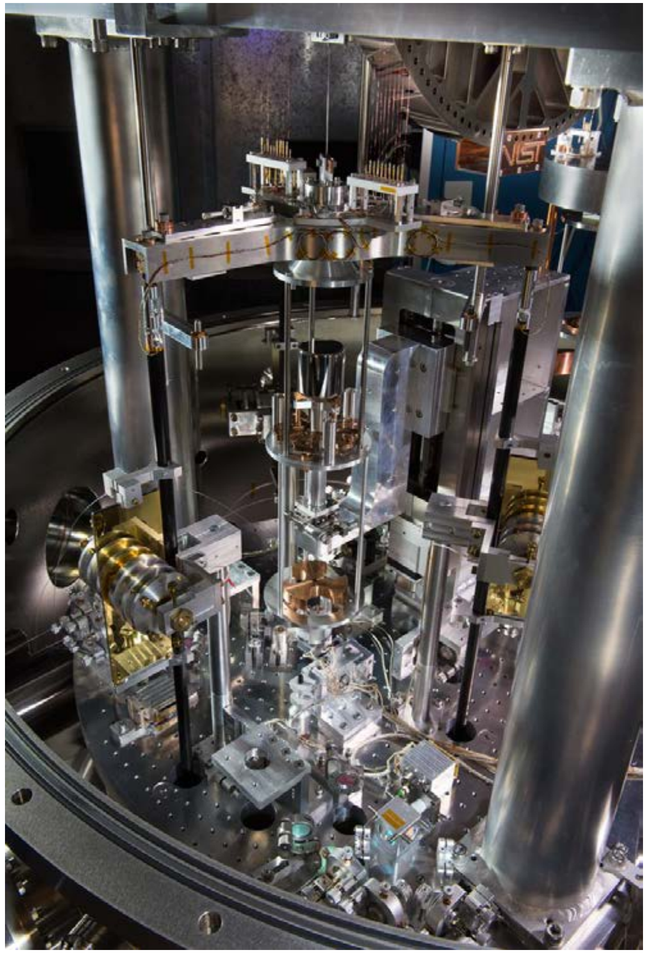


Metrologia **51** (2014) S132-139

Forms of Kibble balance

NPL
National Physical Laboratory

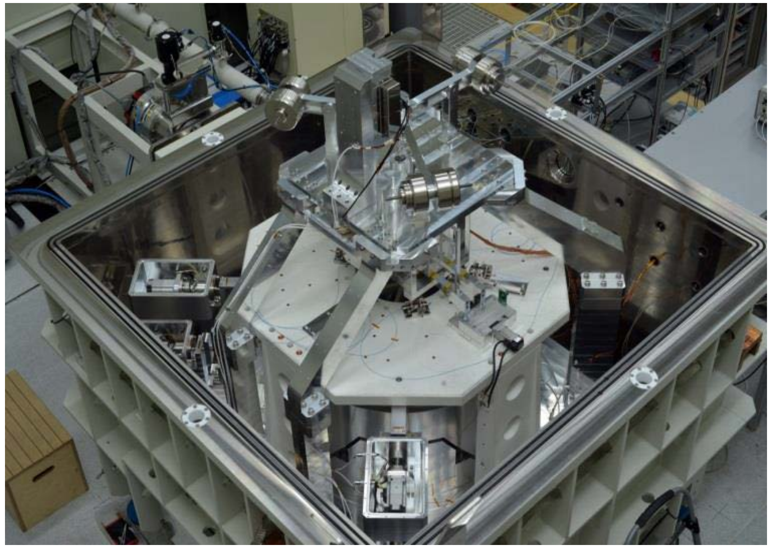
- The original form of Kibble balance employed two modes: a weighing mode and a moving mode and two associated measurement phases: a weighing phase and a moving phase.
- Later the BIPM proposed a modification whereby the modes and phases were combined, making use of a superconducting coil to make both measurements simultaneously giving a 1 mode 1 phase balance.
- Some advantages can be gained from operating in a single mode with the weighing current present at all times but retaining 2 separate measurement phases.
- Both BIPM and NPL use variants of this one-mode two-phase technique.



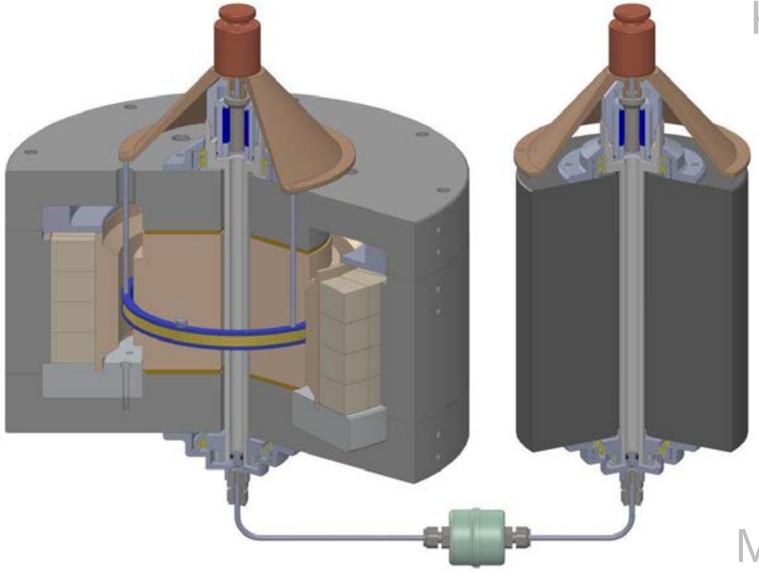
NIST

2 mode 2 phase

- 2 mode 2 phase balances are operated by:
    - KRISS
    - LNE
    - METAS
    - MSL (coupled pressure balances)
    - NIM
    - NIST
    - NPL Mk I and II,
    - NRC
    - PTB (Planck)
- For various reasons most of these balances need coil alignments to achieve low uncertainties.



KRISS



MSL

1 mode 1 phase

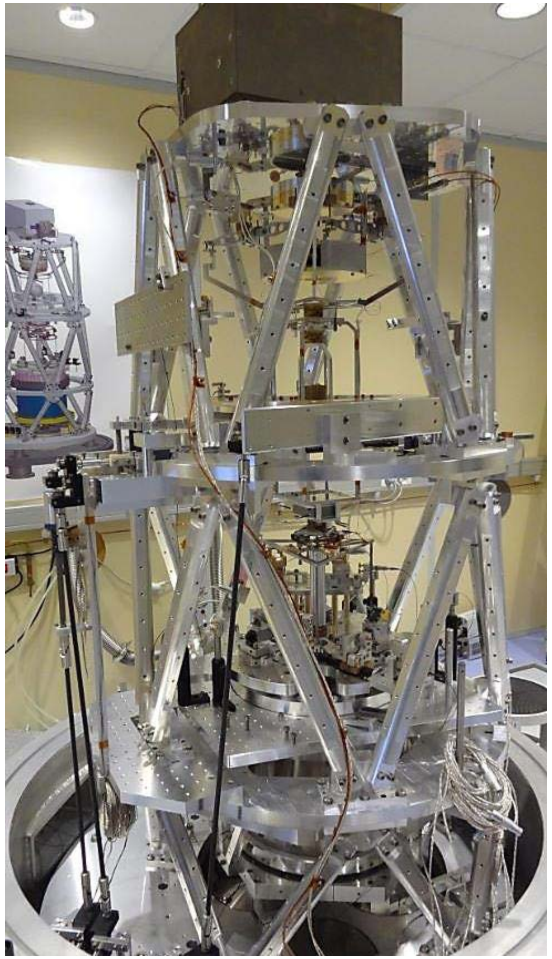
- The BIPM proposed a modification to the Kibble technique whereby the modes and phases were combined, making use of a superconducting coil.
- In 2012 NPL proposed a modification to this technique whereby a bifilar coil could be used to allow correct operation at room temperature.
- Whilst making both measurements simultaneously has the advantage that the apparatus is insensitive to changes in the magnetic field; coupling between the two measurements can give rise to excessive noise.
- UME have had success in using this technique with an oscillating magnet. With care the resulting dc weighing signal and ac moving signal can be separated.

UME

1 mode 2 phase

- This form of operation was identified as a way of ensuring that coil alignment effects could be eliminated despite systematic motions of the coil.
- The balance adopts two alignments caused by differing force and torque vectors in mass up and mass down states of the balance.
- If these two states are associated with their own moving measurements alignment issues are eliminated.
- This technique was proposed by NPL and is being tested.

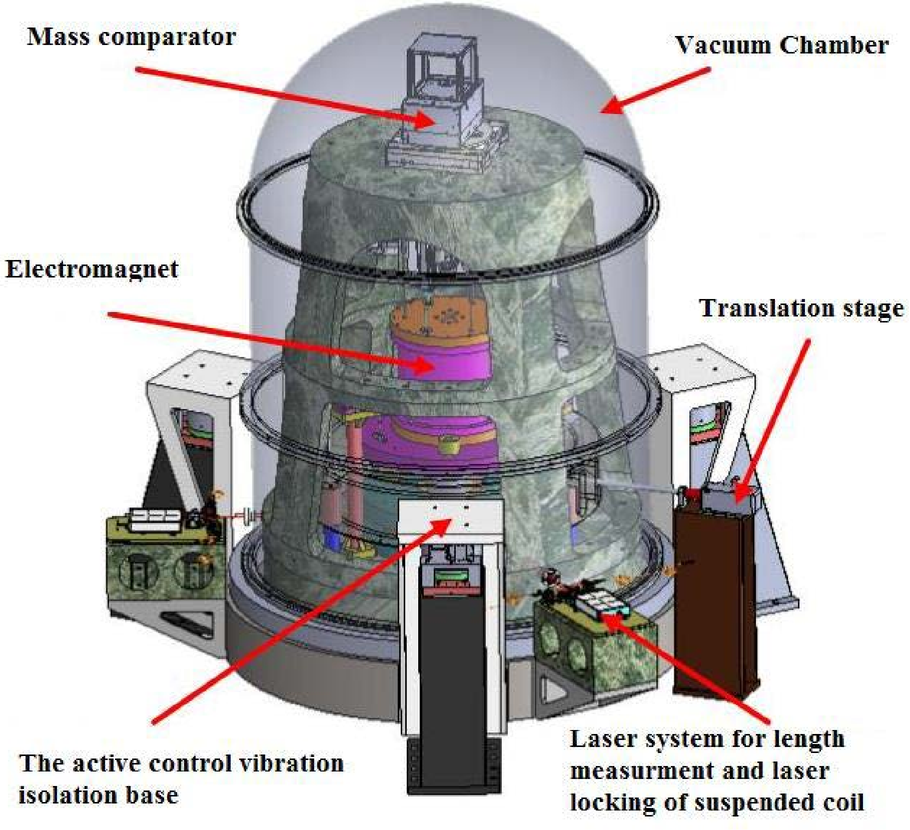
- As the BIPM balance has to be aligned to eliminate motion of the coil on current reversal there is no need for the added complexity of the NPL technique.
- The adoption of this mode of operation has reduced weighing noise considerably from that encountered in 1 mode 1 phase operation.



BIPM

Moving magnet balances

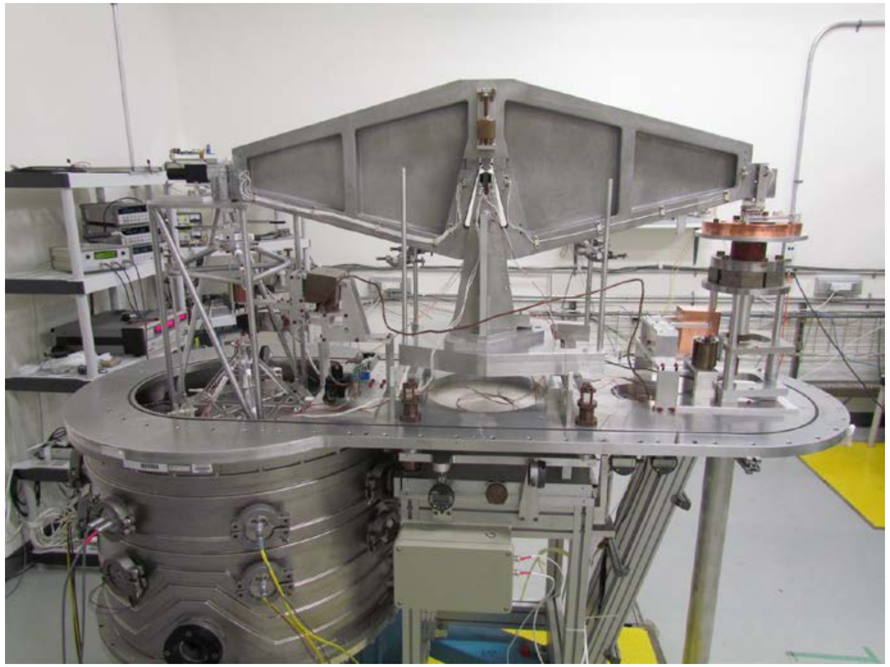
- At present two Kibble balances move the magnet to determine the Bl product: the joule balance and the UME oscillating magnet balance.
- Moving the magnet can be subject to additional uncertainties as the weighing is sensitive to static magnetic fields such as that of the earth. The Bl determining phase would only be sensitive to the field of the moving magnet producing an error.
- Experiments which adopt a moving magnet need to take steps to ensure that the effects of static fields are eliminated and their magnets are designed carefully to reject such fields.



NIM

The future

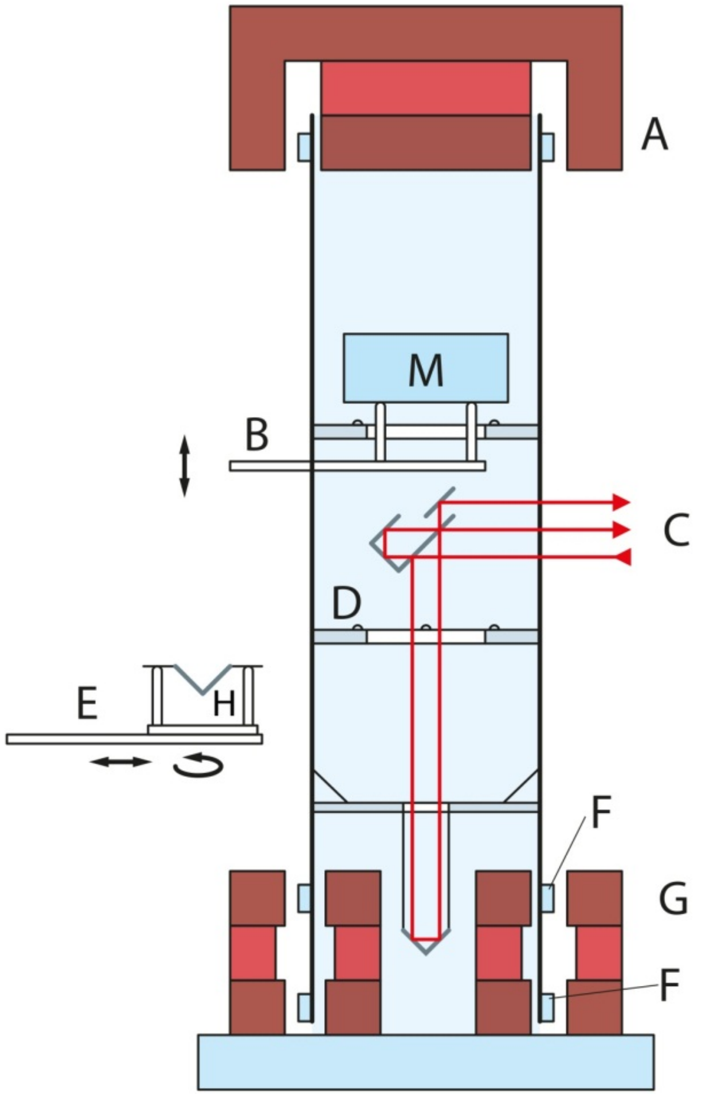
- In three days time the Kibble balance will become a method for realising mass in the revised SI
- The Kibble balance allows an NMI to realise mass independently of any other laboratory.
- All of the existing contributions to the determination of the Planck constant use balances which are physically large and have taken considerable times to develop and are not simple to operate.
- In general laboratory budgets are not increasing significantly and it is difficult for many to justify the expense of developing a Kibble balance.
- To generate further independent Kibble balances they must be made smaller, simpler and must be capable of being replicated.



NRC

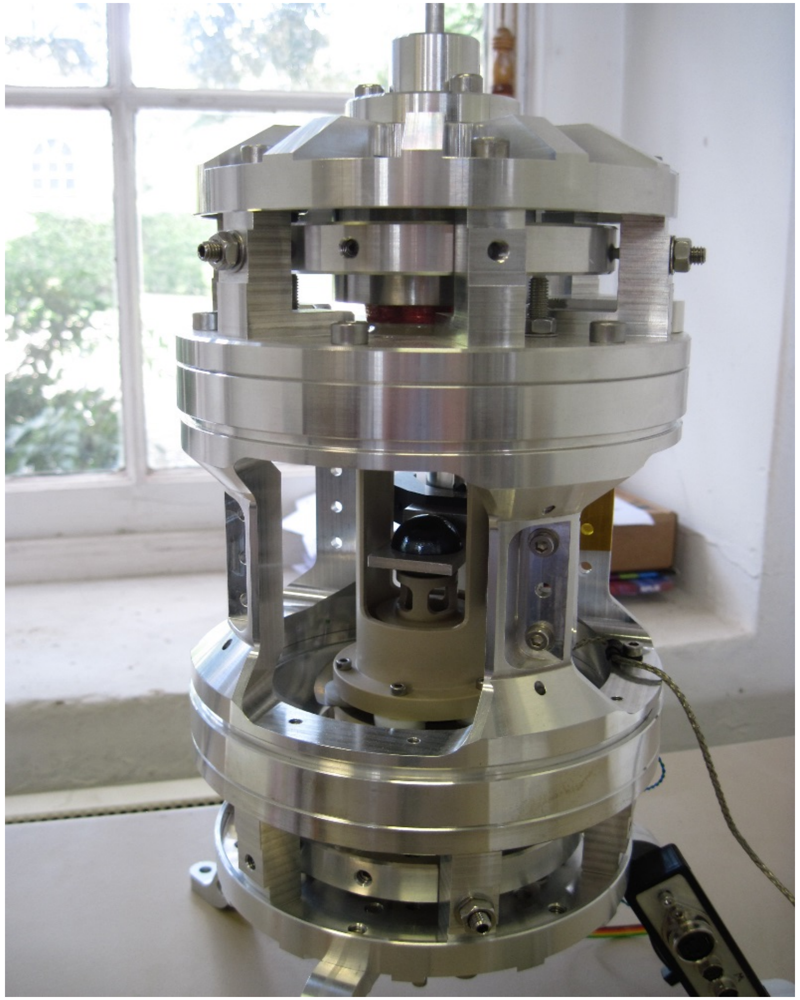
The future

- Recent advances, and the recognition that the lowest uncertainties are not always needed, are driving development in this area.
- There are three main areas of development:
  - Provision of simpler and cheaper Kibble balances to NMI level institutions to support maintenance of the mass scale at the highest level: around 1 part in 10^8.
  - Production of much smaller, simpler and cheaper Kibble balances for use over a range of masses at uncertainties around 1 ppm.
  - Production of Kibble balances for possible industrial use around 1 mg to reduce downtime and eliminate calibration which uses extremely delicate mass standards.



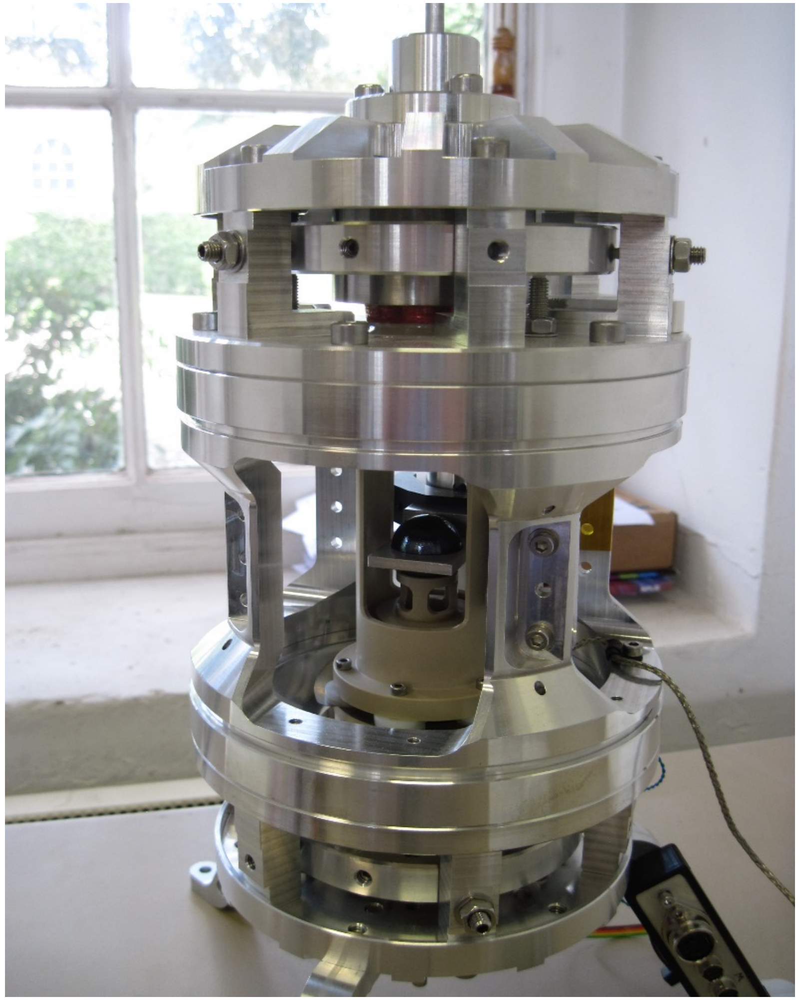
Producing NMI level balances

- They will need to be affordable both to acquire and run.
- They will need to be relatively easy to manufacture and maintain..
- The balances will need to operate in vacuum using a full range of Quantum standards
- To reduce their size/cost they will need to operate in the region around 100g
- They may make use of novel standards such as Quantum Hall arrays to eliminate difficult to characterise uncertainties in the system.
- NIST, NPL and UME are developing balances of this type.



Using NMI level balances

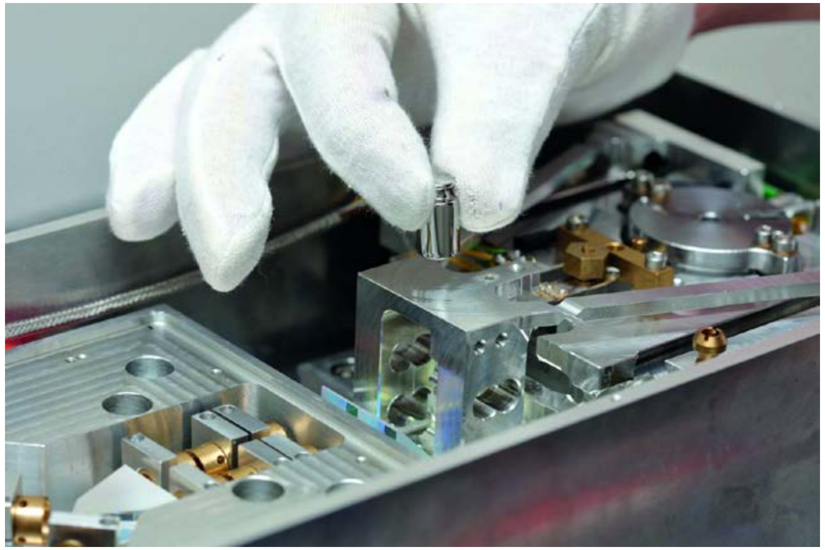
- Each balance could be used to provide a “sovereign” mass realisation for its country.
- However this is not the best use of such a balance.
- The balances could contribute to a mass scale generated by circulating a transfer mass, either via the BIPM or independently.
- It would only take four collaborators to halve the uncertainty associated with a single balance.
- The more balances the lower the uncertainty, as long as the contributing devices are statistically independent.
- Initial testing would give some confidence of this.
- A balance with an open, accessible, architecture would allow individual NMIs to investigate their instrument providing another level of randomisation.



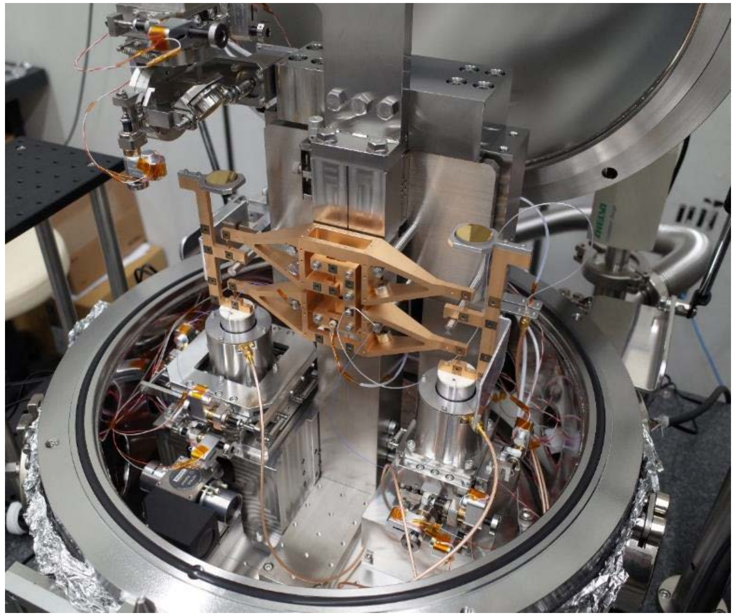
Balances at ppm levels or greater

- Larger balances for operation around 1 g
  - These would be aimed at low cost operation using no quantum standards and operating in air.
  - PTB, NIST and UME are working in this area.
  - The unique advantages of wide-range with electrical and dimensional calibration may avoid possible competition from conventional mass standards.

- Smaller balances aimed at operation around 1 mg
  - These would also be aimed at low cost operation using no quantum standards and operating in air.
  - KRISS PTB NIST NMIJ and NPL are working in this area.
  - These will be covered in detail in another talk in this workshop



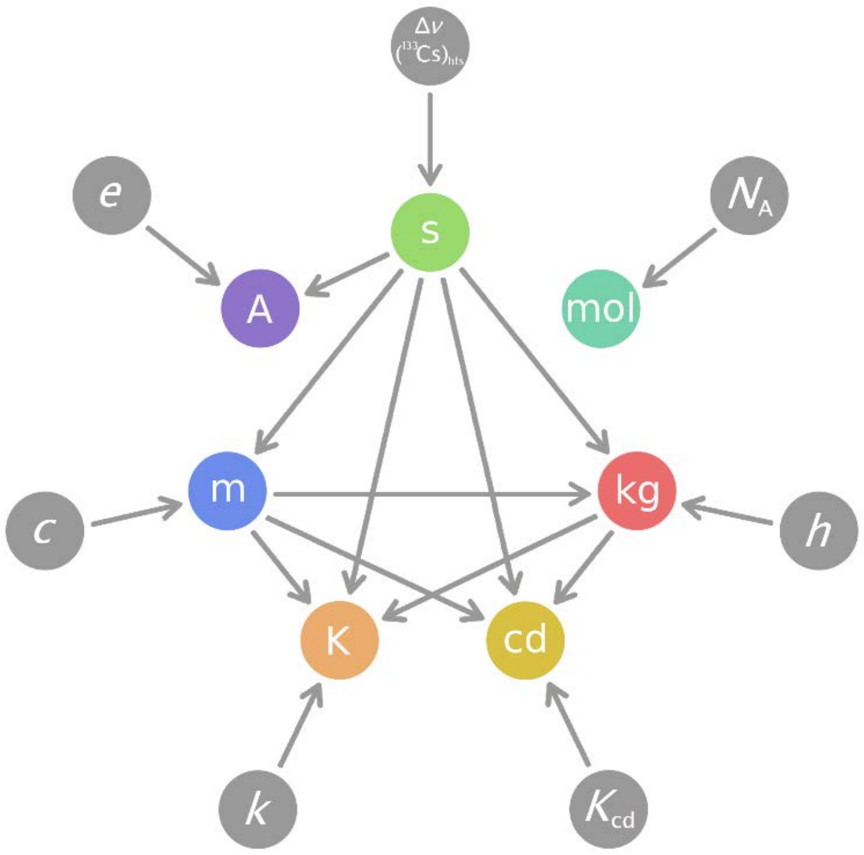
TU Ilmenau



NMIJ

Conclusion

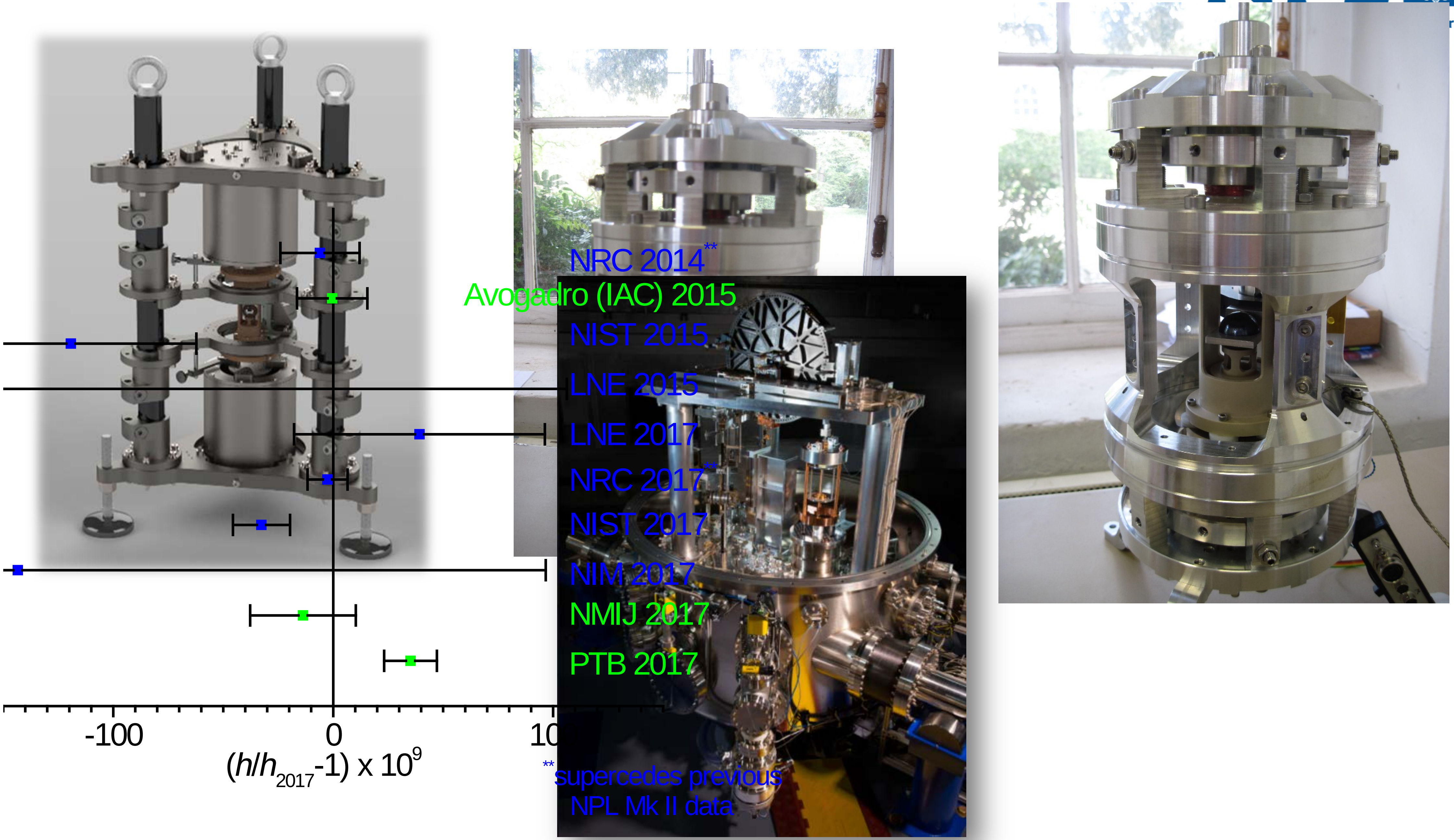
- The redefinition of the kilogram in the revised SI opens many opportunities in the long term but comes with challenges in the short term.
- A single point of failure has been removed from the system.
- We would like better consistency and smaller uncertainties from the existing realisation experiments plus further balances to ensure the world develops a robust mass scale.
- Simplified, high quality, Kibble balances can be built to realise mass at the highest level. If enough of these collaborate they could produce an ensemble scale having a very low uncertainty.
- The Kibble balance can be used for industrial applications in the range from µg to g and for force and dynamic force measurements.
- The redefinition represents a new beginning for the Kibble balance.



THANK YOU

Ian A. Robinson

National Physical Laboratory


NRC 2014**
Avogadro (IAC) 2015
NIST 2015
LNE 2015
LNE 2017
NRC 2017**
NIST 2017
NIM 2017
NMIJ 2017
PTB 2017
-100
0
10
$(h/h_{2017}-1) \times 10^9$
** supercedes previous
NPL Mk II data