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The new International System of Units / *Le nouveau Système international d'unités*

The Kibble balance and the kilogram

La balance de Kibble et le kilogramme

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ABSTRACT

Dr. Bryan Kibble invented the watt balance in 1975 to improve the realization of the unit for electrical current, the ampere. With the discovery of the Quantum Hall effect in 1980 by Dr. Klaus von Klitzing and in conjunction with the previously predicted Josephson effect, this mechanical apparatus could be used to measure the Planck constant h. Following a proposal by Quinn, Mills, Williams, Taylor, and Mohr, the Kibble balance can be used to realize the unit of mass, the kilogram, by fixing the numerical value of Planck's constant. In 2017, the watt balance was renamed to the Kibble balance to honor the inventor, who passed in 2016. This article explains the Kibble balance, its role in the redefinition of the unit of mass, and attempts an outlook of the future.

RÉSUMÉ

Bryan Kibble a inventé la balance du watt en 1975 pour améliorer la réalisation de l'unité de courant électrique, l'ampère. Après la découverte de l'effet Hall quantique en 1980 par Klaus von Klitzing, conjointement avec un autre effet quantique prédit par Josephson, cet instrument mécanique peut être utilisé pour mesurer la constante de Planck h. Quinn, Mills, Williams, Taylor et Mohr ont proposé d'utiliser la balance de Kibble pour réaliser l'unité de masse, le kilogramme, en fixant la valeur numérique de la constante de Planck. Depuis 2017, la balance du watt a été renomée «balance de Kibble» pour honorer son inventeur, décédé en 2016. Cet article décrit la balance de Kibble ainsi que son rôle dans la redéfinition de l'unité de masse, et présente de futures perspectives.

1. Introduction

The impending redefinition of the International System of Units (SI for the French acronym *Système international d'unités*) is a great achievement of metrologists working to improve the art of measurements. Many people across the globe have

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refined measurements and have enhanced the state of knowledge to arrive at a point where the foundation of the SI can be changed from base units to fundamental constants, as seen in the article by Terry Quinn and Suzanne Débarbat in this edition [1].

This article focuses on one device that makes a connection between the kilogram and the Planck constant: The Kibble balance. The Kibble balance is one of two possibilities that can be used to realize the unit of mass at the kilogram level with relative uncertainties of approximately 10^{-8}. The other possibility is the X-ray crystal density (XRCD) method which is discussed in an article written by Horst Bettin in this edition [2].

Before we describe the technical details of the Kibble balance, it is worthwhile to revisit the history that led to the redefinition of the unit of mass, and ultimately to the revision of the SI. The following paragraphs are rephrased from an email that Bryan Kibble sent to one of the authors. The adventure started with a collaboration between Dr. Bryan Kibble and Dr. George Briggs, a metrologist from the Australian National laboratory. Kibble and Briggs were weighing a rectangular coil immersed in a magnetic field. At one point during the work in the laboratory, the coil twisted in the magnetic field and almost hit the magnetic poles, which could have been catastrophic for the fragile coil former made from glass. In this situation, Briggs remarked that the energy of a current-carrying coil in a magnetic field is the current in the coil times the magnetic flux threading the coil. And the torques (forces) arise from the gradient of this energy. Kibble was impressed by the simplicity of the picture described by Briggs which seemed to rely solely on a topological argument. Years later, in 1975, Kibble recalled this beautiful relation while working on the Ampere balance and invented the moving mode to measure the geometric factor of the balance. Prior to Kibble's idea, the geometric factor was obtained by tedious calculations [3] using the measured geometric locations of current carrying wires in nested coils [4]. The discovery of the Kibble balance indicates the merit of international collaboration in metrology.

The idea of the Kibble balance appeared in print in 1976 in a conference proceeding [5]. The original Kibble balance was used to realize the ampere. The purpose of the Kibble balance changed with the advent of the quantum Hall effect which was discovered in 1980 by Dr. K. von Klitzing [6]. In combination with a quantum effect that was predicted by Dr. B. Josephson almost two decades earlier [7], the Kibble balance morphed from a device that realizes the SI unit of current to an experiment that can measure the Planck constant h with high precision, to an instrument that will be used to realize the SI unit of mass. In the early 90's, scientists were advocating to redefine the unit of mass in terms of fundamental constants [8–11]. Mills, Taylor, Williams, Mohr, and Quinn published a seminal article [12] in 2005 describing the possibility to change the definition of the kilogram from an artifact based definition to one that is based on the Planck constant h.

2. Two quantum effects

The physics of the Kibble balance covers several topics, similar to how a physics textbook has sections, on mechanics, electromagnetism, thermodynamics and much more. The Kibble balance connects classical mechanics to quantum mechanics. However, this span is divided into two separate bridges, one from mechanical quantities to electrical quantities and then from electrical quantities to quantum mechanical effects. In this section, the latter is discussed.

Electrical power, measured in watts, is the product of a voltage U and a current I. With the help of two quantum mechanical effects, electrical power can be measured as a product of two frequencies, f_1 and f_2, the Planck constant h and a known number r,

$$P = UI = rhf_1 f_2 \tag{1}$$

The Josephson effect was predicted by Bryan Josephson in 1962 and measured shortly after. This effect occurs in a superconducting tunnel junction composed of a thin non-super-conducting material sandwiched between two layers of superconducting material. In a superconductor, the Cooper pairs can be described by a single wave function. Two spatially separated superconductors have two different wave functions that are incoherent with each other. By weakly coupling the superconductors with a thin barrier, the phases of the two wave functions become coherent. Furthermore, a supercurrent can tunnel through the barrier layer.

The voltage across the barrier layer is the product of $h/(2e)$ and the time derivative of the phase difference in the wave functions. The current through the barrier is proportional to the sine of the phase difference. Hence, if a DC voltage is applied across the junction, the phase difference grows linearly in time, and the current shows a sinusoidal variation. This phenomenon is called the AC-Josephson effect. Interestingly, the AC-Josephson also works in reverse. By forcing a sinusoidally varying current through the tunnel junction, a DC voltage proportional to an integer multiple of $h/(2e) f_1$ occurs across the junction. The exact multiple depends on the DC content and direction of the applied current, and is usually 1 or 0. This integer is often referred to as the step number. Reversing the direction of the current, changes the sign of the produced voltage. The reciprocal of the proportionality factor is called the Josephson constant $K_J = 2e/h$. Typically, the applied frequencies are in the microwave range; for programmable Josephson voltage systems (PJVS), frequencies around 20 GHz are used. In this case, one junction at step one produces only a DC voltage of 4.13 µV. Hence, to generate a reasonable voltage, several 100 000 Josephson junctions have to be combined.

In a PJVS [13,14], almost any number of junctions can be connected in a series to generate any arbitrary voltage, by slightly adjusting the microwave frequency, within the range of the system. For this purpose, the junctions are organized in cells, which are themselves connected in series. Some cells only have a few dozen junctions, while others have several thousands. The Josephson junctions in each cell share the same bias current which can be individually programmed for each cell. Cells that are not required are set to a bias current of zero, and since junctions with no bias current are superconducting, they generate neither a voltage nor a voltage drop. Hence the junctions in these cells will not contribute to the output voltage. The PJVS has been drastically improved over the last two decades, resulting in systems that can produce any desired voltage between −10 V and 10 V with relative uncertainties of a few parts in 10^{10}. In summary, the voltage generated by the PJVS is

$$U = n\frac{h}{2e}f \tag{2}$$

where the integer n reflects the number of Josephson junctions used and the step number that each junction is on, i.e. the sum of each step number of every junction in the system (zero for inactive junctions). The microwave frequency is given by f.

The integer quantum Hall effect was discovered by Klaus von Klitzing when measuring the relationship between the Hall voltage and current on GaAs MOSFET (metal-oxide-semiconductor field-effect transistor) structures at cryogenic temperatures. In these structures, depending on the applied gate voltage, the electron gas can be seen as two-dimensional. In two dimensions, the Hall resistance, the ratio of the voltage that is perpendicular to the current and the magnetic field to the current is given by

$$R_{\mathrm{H}} = p^{-1}\,h/e^2 \tag{3}$$

where p is an integer. The origin of this beautiful equation is the quantization of the density of states in the so-called Landau levels. The Landau levels describe the discrete cyclotron orbits of the electrons in the magnetic field. Each Landau level can contain $N_{\mathrm{L}} = eB/h$ states, where B is the magnetic flux density of the external field. The Hall conductivity is given by $\sigma_{xy} = Ne/B$. The charge carrier concentration is $N = N_{\mathrm{L}}p$, when all p Landau levels are fully occupied. Combining the two equations causes the magnetic flux density to cancel and yields Eq. (3) as $R_{\mathrm{H}} = p^{-1}R_{\mathrm{K}}$, where $R_{\mathrm{K}} = h/e^2$ is the von Klitzing constant. However, this equation only holds if the Landau levels are fully occupied. In an experimental setting, this can be verified by measuring the transversal resistance, R_{xx}, which has to be zero when the occupied Landau levels are fully occupied.

If only one Landau level is completely filled, the quantum Hall resistance has a very convenient value of about 25.812 kΩ. However, scaling resistance can be done with high accuracy using cryogenic current comparators [15]. Hence, usually in Kibble balance experiments, other resistance values are used. In summary, the resistance values can be expressed as

$$R = r'h/e^2 \tag{4}$$

where r' is a real number that includes the measured resistance ratio and the number p.

The electrical current through a coil, for example, can be measured using both the quantum Hall effect and the Josephson effect. By routing the current through a precision resistor, whose value has been measured according to Eq. 4, a voltage will develop across this resistor. This voltage can be measured against a PJVS operating with a microwave frequency f_1 according to Eq. 2. Combining the two equations yields

$$I = \frac{U}{R} = \frac{n_1 f_1 \frac{h}{2e}}{r'\frac{h}{e^2}} = \frac{n_1}{2r'}ef_1 \tag{5}$$

In addition to the numerical factors, the current depends only on the product of the elementary charge and a frequency. It is easy to see that the unit on the right side of the equation above is charge per second, equal to ampere the unit for current.

To measure electrical power, the current measurement must be combined with a second Josephson voltage measurement. This yields

$$P = UI = n_2\frac{h}{2e}f_2\frac{n_1}{2r'}ef_1 = rhf_1f_2 \tag{6}$$

Here, all the numerical values have been combined into one, r. The electrical power is given by the product of two frequencies, one known number, and the Planck constant. The elementary charge cancels in the equation.

With the quantum standards, current and voltage can be measured with relative uncertainties of 10^{-9}. But, care has to be taken if both quantities are measured simultaneously because of the mutual influence of both measurements. Serendipitously, the Kibble balance experiment is carried out in two modes, the force and velocity mode, see below. In one the current needs to be measured in the other the voltage. The product of current and voltage is just formed numerically in the data analysis. One speaks of virtual power. Measuring virtual power truly decouples the two variables voltage and current and can, therefore, be determined very well. In a well-designed system, with careful experimentation, the virtual power can be measured relative to a few parts in 10^9.

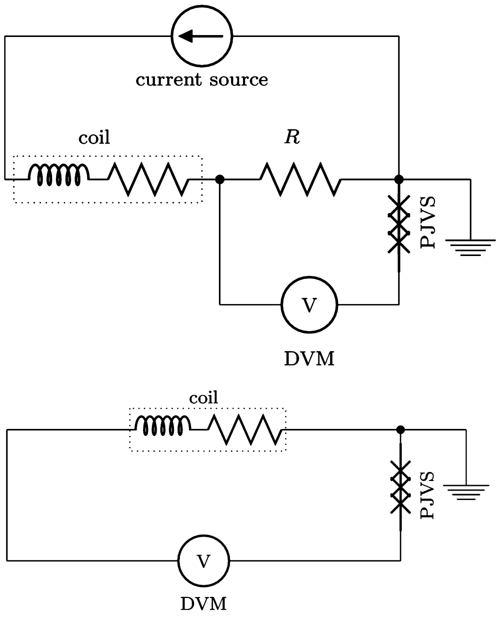

Fig. 1. The circuit diagram of the Kibble balance in force mode (top) and velocity mode (bottom). A digital voltmeter (DVM) is used to measure the small difference between the programmable Josephson voltage standard (PJVS) and the voltage across the resistor (top) or the induced voltage across the coil (bottom).

3. The principle of the Kibble balance

While the previous section gave a description of the relationship between electrical power and the Planck constant, this section will give a detailed account of the connection between electrical and mechanical power. This connection is facilitated with a balance that is used to compare an electromagnetic force produced by a coil in a magnetic field to the weight of a test mass,

$$F_z = mg = -IN\frac{\partial \Phi}{\partial z} \tag{7}$$

where m is the mass of a test mass, g the local gravitational acceleration, I the current in the coil with N turns, and Φ the magnetic flux through the area of the coil.

Before Bryan Kibble's discovery, the flux was calculated by integrating the magnetic flux density over the coil area, $\int \boldsymbol{B} \cdot \mathrm{d}\boldsymbol{A}$, which required absolute measurements of the coil physical dimensions, and the magnetic field. These measurements were impossible to carry with uncertainties significantly below 10^{-6} [16].

Kibble's idea avoids the cumbersome calculation of $\partial\Phi/\partial z$. It can be obtained with the same setup by moving the coil through the magnetic field and observing the induced electromotive force U. This yields

$$U = -N\frac{\partial \Phi}{\partial t} = -N\frac{\partial \Phi}{\partial z}\frac{\partial z}{\partial t} \tag{8}$$

Here, the last equation is strictly true only if the other components, for example, $\partial\Phi/\partial x \cdot \partial x/\partial t$, are zero. This can be achieved within the uncertainties required in the Kibble balance experiment by aligning the coil motion with respect to the magnetic flux.

The expression $\frac{\partial z}{\partial t}$ is the vertical velocity of the coil v_z, which is identical to the velocity of the mass pan when they are rigidly coupled. By dividing Equation 7 by Equation 8, the flux gradient and the number of turns drop out on the right side, obtaining

$$\frac{mg}{U} = I/v_z \implies mgv_z = UI \tag{9}$$

The equation on the right is named the Kibble equation or watt equation since the quantities on both sides of the equation are measured in units watt. The product on the left is mechanical power, and the one on the right is electrical power. Again, the concept of virtual power is essential in the Kibble balance. As it is the case with the voltage and current, the force (mg) and the velocity v_z are not measured simultaneously, but in two separate modes, named force mode and velocity mode. As a consequence, friction does not matter in the velocity mode, and motion does not matter in the force mode.

To measure the currents and voltages, the electrical connections must be changed between the two modes. Fig. 1 gives an example for two circuits that may be used in force and velocity mode in the top and bottom of the figure, respectively.

Combining the Kibble equation with Equation 6 yields to the connection of mass and the Planck constant

$$mgv_z = rhf_1 f_2 \implies m = \frac{rf_1 f_2}{v_z g} h \tag{10}$$

3.1. Variations in the principle

The explanation given above followed the original description by Kibble. Two separate modes are necessary for the measurement. The mass is weighed in force mode, and the flux gradient of the coil-magnet assembly is determined in velocity mode. Over the years several proposals to combine both modes into a single one have been made. One could imagine moving a current carrying coil through the magnetic field, i.e. the force generated by the current is supporting the weight of the test mass, and the geometric factor is measured simultaneously as the coil moves through the field. While such a simultaneous measurement is possible, it destroys the principle of virtual power. Suddenly both factors on each side of the Kibble equation have to be measured simultaneously, and great care must be taken that the two elements do not influence each other. For example, the current in the coil will produce a resistive voltage drop in the coil that adds to the induced electromotive force.

A few ideas exist to mitigate the side effects of the simultaneous measurements. The Kibble balance group at the Bureau International des Poids et Mesures (BIPM) proposed the use of a superconducting moving coil to avoid the resistive voltage drop in the force mode. However, the idea was too complex, and such a Kibble balance was never built. As a good workaround, the researchers at BIPM are employing a bifilar coil, i.e. two coils with nearly identical flux gradients. One coil carries the weighing current, while the other is used to measure the induced EMF. Attention has to be paid to the transformer coupling between the two coils [17].

An entirely different idea was put forward by a researcher at the Turkish Metrology Institute, Ulusal Metroloji Enstitüsü (UME) [18]. Here the two modes are separated in frequency space and the magnet is moved instead of the coil. The motion is carried out at 0.5 Hz. The induced voltage will be produced at this frequency, while the resistive losses are at DC.

The Joule balance, an experiment that is very similar to the Kibble balance, was put forward by the National Institute of Metrology (NIM) in China in 2006 [19]. The core idea of the Joule balance circumvents a challenging measurement problem in the Kibble balance: The measurement of voltage and velocity have to be synchronized very well. Instead of measuring the voltage and the velocity, both quantities are integrated with respect to time. The coil is moved from position z_1 to position z_2 (the integral of the velocity). While the coil completes the trajectory, the induced voltage is integrated over the time it takes to get from z_1 to z_2.

To date, the classical Kibble balances produce the best results [20]. They take advantage of the virtual power concept and use the same mechanism for moving the coil and for performing the weighings. However, these type of balances had about 30 years more development time than the newer ideas. It will be exciting to watch the balances based on the new ideas improve in the future.

4. Existing Kibble balances

In the first twenty-five years after the invention of the Kibble balance in 1975, only two laboratories pursued the idea: the National Physical Laboratory (NPL) in the United Kingdom and the National Institute of Standards and Technology (NIST) in the United States of America. At the turn of the century, three European laboratories, two located in France and one in Switzerland, joined the effort. A few years later, the national laboratory in China started working on a variation of the Kibble balance, the Joule balance. In 2009, the Kibble balance research at NPL was temporarily suspended, and the Kibble balance was sold to the national metrology institute of Canada. The move of the Kibble balance from the UK to Canada will turn out to be the tipping point that ultimately led to the redefinition of the unit of mass. National metrology institutes of several more countries, e.g., Korea, New Zealand, and Turkey, have started to work on Kibble balances after 2009. Since 2014 [21], the idea of building table-top versions of the Kibble balance is getting more popular. NIST [22], Germany's national metrology institute [23], and NPL [24] are currently working on table-top systems. The masses used in the table-top Kibble balances are ranging from 1 g to 1 kg with relative uncertainties ranging from 10^{-7} to 10^{-6}.

To date, no two Kibble balances are identical. All Kibble balances are unique in their design and operation. The pursuit of many different ideas could be an expression that the optimal configuration for a Kibble balance has not yet been discovered.

While the optimal overall design of the balance is still unclear, there seems to be convergence on what is the best source of the magnetic field. The very first balance built by B. Kibble used a conventional electromagnet [25]. A balance made later at NIST featured a superconducting magnet to avoid heating caused by the current in the field generating coil [26]. The superconducting coils were designed to produce a radial magnetic flux density whose strength was inversely proportional to the radius [27]. This geometry offers a substantial advantage: The flux gradient is independent of the radius of the moving coil. Hence, possible changes of the radius of the moving coil due to heating in the force mode will not affect the result. Today, all operating Kibble balances employ permanent magnet systems with a radial $1/r$ field. Samarium–cobalt is often used as the magnetic material. Samarium–cobalt has a high energy density, but has a temperature coefficient that is an order of magnitude smaller than that of neodymium–iron–boron magnets.

Less consensus exists on the mechanical design to move the coil. The contemporary thinking can be divided into two schools of thought: On the one side, researchers believe in using the same device for moving the coil and for weighing. It can be shown [21] that as long as the position of the coil in space is dependent on a single parameter, the non-vertical motion of the coil during velocity mode does not contribute a measurement bias. If the coil is suspended from the end of a beam balance, then the angle describing the angle between a plane and the beam is the single parameter from which the vertical and horizontal position of the coil can be calculated. Hence, although the coil moves on a parabolic trajectory, the Kibble equation holds.

The second school of thought believes that the weighing and moving can be decoupled and treated as two different problems. In this rationale, a convenient solution is to use a commercial mass balance for the weighing and built a dedicated device that moves the balance with the coil attached or only the coil. The advantage is that for one hard problem, i.e. precise weighing, proven and existing solutions can be employed.

A brief discussion of existing Kibble balances gives the reader a unique insight into the complexity, beauty, and richness of the field. The list below is sorted in alphabetical order of the acronyms used by the laboratories. Unique features of each balance are pointed out, but space constraints forbid an appropriate discussion of each system. For a deeper understanding of the balances, the reader is encouraged to follow the provided citations.

- ‘Bureau international des poids et mesures’ (BIPM). The Kibble balance was designed to perform the velocity and force mode measurements simultaneously. The original idea was to use a superconducting coil to avoid a resistive voltage drop over the coil. This idea has been discarded in favor of a bifiliar coil. The two coils, of which one carries the current, and in the other, the electromotive force is induced, have nearly identical geometric factors and can be interchanged [28].
- Korean Research Institute of Standards and Science (KRISS). Similar to the BIPM instrument, a weighing cell from a mass comparator is used for the force mode. For the velocity mode, the weighing cell with the coil attached is moved. Noteworthy is the piston-cylinder assembly that ensures straight up-and-down motion of the balance [29].
- ‘Laboratoire national de métrologie et d’essais’ (LNE) in France. Similar to the procedure used in two Kibble balances described above, a balance with a coil connected to it is moved by an external mechanism [30]. Here, a dedicated flexure strip beam balance was designed and built [31].
- Swiss Federal Institute for Metrology (METAS). In the second-generation METAS balance, a weighing cell with the coil attached is moved by an external mechanism. The straightness of the trajectory is ensured by a 13 hinge translation stage. METAS was the first to introduce thermal compensation in their magnet system to reduce the temperature coefficient of the permanent magnet system [32]. The idea to use a flux shunt to compensate the temperature coefficient was proposed by LNE in 2005 [33].
- Measurement Standard Laboratory (MSL) of New Zealand. In contrast to the balances discussed above, the same device is used for weighing and guiding in the velocity and force mode, respectively. The device used here seems like an unusual choice, two connected pressure balances. However, researchers at MSL have shown the feasibility of this design [34,35].
- National Research Council (NRC) of Canada. Here, a traditional beam balance, employing knife edges, is used to accomplish the moving and weighing. The NRC balance is the only working balance that was designed by B. Kibble. It holds the world-record for the measurement of Planck’s constant with the smallest uncertainty [36].
- National Institute of Metrology (NIM) in China. The second generation Joule balance uses a commercial mass comparator to suspend the coil [37]. According to the Joule balance principle, the induced voltage is integrated while here the permanent magnet, not the coil, is moved.
- National Institute of Standards and Technology (NIST) in the USA. A pulley balance, resting on a central knife edge, provides the mechanics for moving and weighing [38]. The pulley is a precision-turned wheel, and the coil and mass-pan are suspended via Titanium bands. Fig. 2 shows a photograph of the current Kibble balance at NIST. Researchers at NIST are also working on a table-top Kibble balance.
- National Physical Laboratory (NPL) in the UK. In recent years, the national laboratory of the United Kingdom has started to design and build smaller (100 g) Kibble balances. The NPL design also utilizes a scheme where weighing and moving coincide via a bifilar coil. However, the measurement is carried out in two phases, mass-on and mass-off. The design heavily relies on the fact that the same mechanical system, a seismometer suspension, will be used for weighing and guiding of the motion [21,39].
- ‘Physikalisch-Technische Bundesanstalt’ (PTB), the national metrology institute of Germany. The PTB project aims to build two Kibble balances with different specifications. The first version aims to realize masses up to 100 g with relative uncertainties below 3×10^{-7}. The moving mode is performed at 4 Hz [23]. The core component of the PTB Kibble balance is a commercial weighing cell.
- ‘Ulusal Metroloji Enstitüsü’ (UME), the national metrology institute of Turkey. UME was the first laboratory to implement a Kibble balance continuous sinusoidal excitation. An oscillatory excitation was proposed by Sutton [40] in 2009. In the UME balance, the weighing and velocity mode are performed simultaneously, but the results can be separated in frequency space [18]. Different from Sutton’s proposal, the magnet and not the coil is moved, and the weighing is carried out simultaneously.

Besides the citations given in the paragraphs to the individual balances, several review articles are available. [41–44]

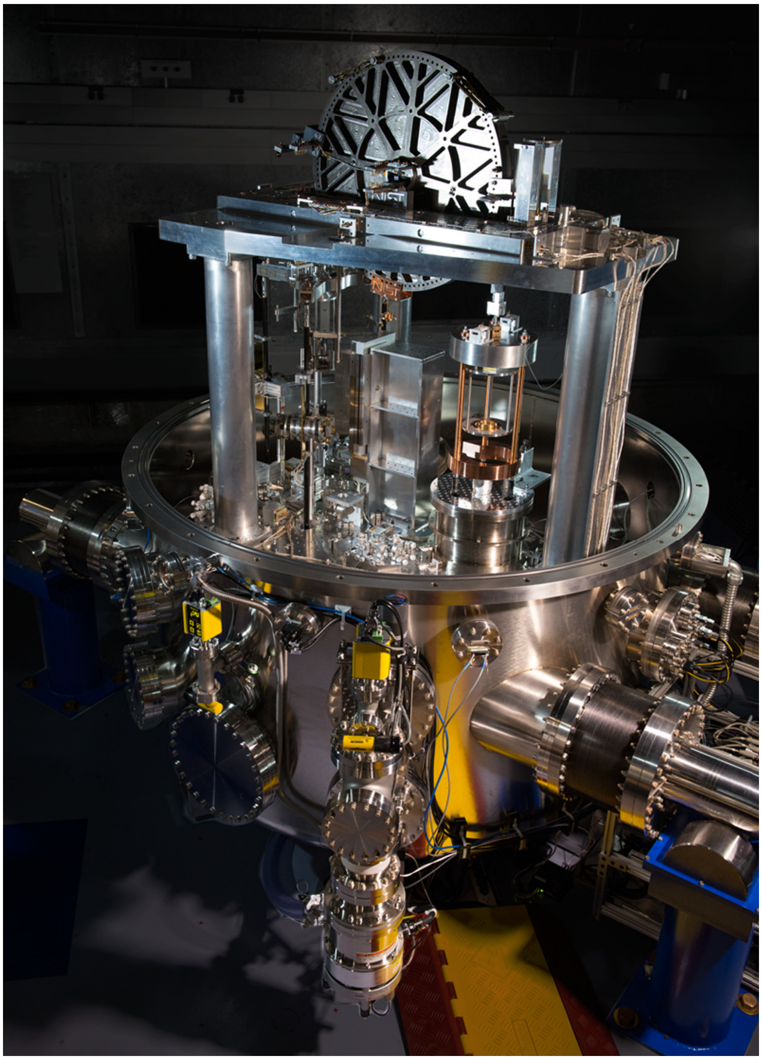

Fig. 2. A picture of the NIST-4 Kibble balance. Photo: NIST.

5. Outlook

Up to July 2017, Kibble balances were used to determine the Planck constant using the mass of the international prototype of the kilogram (IPK) as an input quantity. With the data accepted for publication before July 1st 2017, the Task Group on Fundamental Constants within the Committee on Data for Science and Technology, calculated a recommended value for $h = 6.626\,070\,15 \times 10^{-34}\,\mathrm{Js}$ [20,45]. This value will be used to define the kilogram in the revised SI. Note that in order to realize the unit of mass, the speed of light, c, and the hyperfine transition frequency of $^{133}\mathrm{Cs}$ must be used, as well. The latter defining the unit of time interval, the second, and the former defining the unit of length, the meter. Both are needed to measure the gravitational acceleration g and the coil's velocity v_z.

5.1. Realizing mass in a new SI

In the revised SI, the role of the Kibble balance is to realize the unit of mass based on the fixed value of h. The realization is simply performed by putting a mass on the Kibble balance and using Eq. 10.

The advantage of the revised SI is that a measurement of mass can be made at any mass value and not only at cardinal points, as is the case in the present SI. Here the unit of mass is only realized at 1 kg in the form of the IPK. This is the difference between an artifact, that defines a point on a scale, and a fundamental constant, that is scale invariant.

While h is scale invariant, the instrument used to convert h to a mass will only be able to cover a given mass range. The authors estimate that with a single instrument masses over a factor of 20 can be measured with low uncertainty. Hence, several dedicated instruments have to be built to cover a larger mass range. However, this may not be necessary, since the established procedures in mass metrology to subdivide and add masses can still be used.

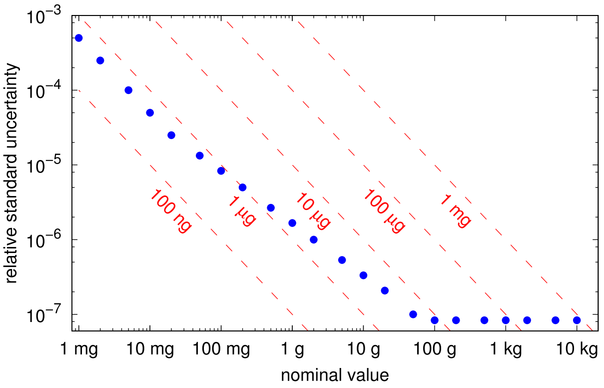

Fig. 3. Required relative uncertainties for the calibration of E_1 masses according to OIML R111-1 [46]. The dashed lines indicate values of constant absolute standard uncertainties. For small nominal mass values, the required relative uncertainties are given by approximately constant absolute uncertainty.

5.2. Table-top Kibble balances

In the present SI, mass is defined at 1 kg and different values are obtained by subdividing and adding. Fig. 3 shows the required uncertainties for masses in the E_1 class of the International Organization of Legal Metrology (OIML) according to their recommendation R111-1. The smallest 1-sigma relative uncertainty of 8.3×10^{-8} is required at the nominal value of 1 kg. At higher nominal mass values, the relative uncertainty stays at this level. To smaller nominal mass values, the relative uncertainty increases due to the limited resolution of the balances.

Obviously the current OIML requirements have been written around the existing system, a definition of the mass unit at 1 kg. The question that should be asked is: Are these requirements conducive for industry? Where are the most precise mass measurements required? One could argue that the more precious the material, the more precise weighings are required. Typically precious materials are rare and measured in grams rather than kilograms. This line of reasoning would argue for more precise measurements at the gram level. An argument in a similar direction, albeit for even smaller masses, can be made with the new developments of personalized medicine. For personalized medicine, drugs are mixed together for each person rather than in larger batches for entire populations.

Table top Kibble balances are aiming at this market. These devices operate typically in the gram range with uncertainties comparable to E_2 weights which are allowed to have relative standard deviations about three times higher than those of E_1 weights. Several laboratories are working on table top Kibble balances: NIST, NPL, and PTB [23,24].

6. Conclusion

The Kibble balance is a device that is a little over 40 years old. But in this short time it found many uses: defining the unit of current, the ampere, measuring the Planck constant, and in the future, realizing the kilogram. In the last decade, there has been an explosion of ideas, activities, and articles on the Kibble balance. It is a vibrant field. In (national) laboratories, the Kibble balance can act as a focal point for different disciplines: mechanical, electrical, and optical. This article, due to its length, could only provide a glimpse at the surface of a rich and deep research field. The reader is encouraged to follow up the more comprehensive sources in the bibliography.

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