

THE NEW WATT BALANCE EXPERIMENT AT METAS

H. Baumann[◦], *A. Eichenberger*[◦], *B. Jeckelmann*[◦], *Ch. Beguin*⁺, *R. Clavel*[§], *F. Cosandier*[§], *D. Reber*⁺,
D. Tommasini^Δ

◦ Federal Office of Metrology METAS, CH-3003 Bern-Wabern, Switzerland.

E-mail: henri.baumann@metas.ch

+ METTLER TOLEDO, CH-8606 Nänikon, Switzerland

§ Laboratoire de Systèmes Robotiques, LSRO, from the Ecole Polytechnique de Lausanne, EPFL, CH-1015 Lausanne, Switzerland

Δ Centre Europeen de Recherche Nucléaire, CERN, CH-1211 Genève, Switzerland

Abstract: The kilogram is the last unit of the international system (SI) still based on a material artifact, the international prototype of the kilogram (IPK). The comparisons made in the last hundred years have clearly revealed a long term relative drift between the IPK and a set of copies kept under similar conditions. Since the long term stability is one of the major conditions set on the SI base units, this situation is no longer satisfactory and a new definition of the mass unit becomes a priority for the metrology community. A promising route towards a new definition based on fundamental constants is given by the watt balance experiment which links the mass unit to the Planck constant h .

Keywords: Kilogram, Planck constant h , System of units, watt balance.

1. INTRODUCTION

Today, the kilogram is the last unit of the International System of Units (SI) still based on an artifact, the international prototype of the kilogram (IPK), kept at the Bureau International des Poids et Mesures (BIPM). The IPK prototype that has been machined in 1878, is a cylinder of platinum-iridium alloy (Pt 90% - Ir 10% in mass) whose height (39 mm) is equal to its diameter. Six copies were designated as official copies and are kept in the same conditions as the international prototype. At that time, about seventeen other copies were given to the member states of the meter convention to materialize their national prototype. Since then, other countries have joined the meter convention and new national prototypes have been machined and added to the existing set of international prototype copies. To survey the evolution of the different copies relative to IPK three comparisons have been organized since 1880. The results of these comparisons have clearly put in evidence, a relative drift of this set of masses with respect to IPK. The mean drift of the official copies has been evaluated to 0.5 $\mu\text{g}/\text{year}$. Nevertheless, it is clear that the actual definition of mass does not allow attributing the drift to IPK or to the copies. Moreover, variations of the mass unit directly reflect on the ampere definition and therefore on the whole set of electrical units. Since it is now possible to compare two mass standards made out of the same material with an uncertainty of about 1 μg , the instability among the international mass prototypes - including IPK - is a major contribution to the final

uncertainty. Clearly, such a situation is no longer satisfactory for one of the base units of the SI. There is now a general consensus in the metrology community that the time for a redefinition of the kilogram has come. To get a better stability, the new definition should be linked to a physical fundamental constant with a relative uncertainty in the order of 10^{-8} . During the last decades, several experiments have been attempted to realize the new definition [1, 2]. Up to now, the most successful electrical approach has been the watt balance proposed by B. Kibble in 1975 [3]. The principal of this experiment is to link mass to the Planck constant h by a virtual comparison of the mechanical power to the electrical power. With such a definition the SI system will gain in stability and all the units depending on the kilogram such as the ampere, the mole or the candela will no longer depend on the behavior of a material artifact.

Several watt balances are now in operation around the world [4]. In 1997, the development of a watt balance started at the Federal Office of Metrology (METAS). After more than ten years of continuous improvements, systematic characterization and thorough investigations, a final result for the Planck constant has been published [5]. With this result, the apparatus has reached its limits. Additional improvements that should be implemented to reduce the uncertainty significantly become incompatible with the conception of the experimental setup. For this reason, it has been decided to start a new development of a watt balance at METAS, in strong collaboration with industrial partners (METTLER TOLEDO), universities (Laboratoire de Systèmes Robotiques, LSRO, from the Ecole Polytechnique de

Lausanne, EPFL) and research institutes (Centre Europeen de Recherche Nucléaire, CERN)

2. THE WATT BALANCE PRINCIPAL

The concept of the watt balance has been intensely discussed in other places [4]. The experiment is performed in two steps with the same experimental setup: the static or weighing mode and the dynamic or induction mode (Figure 1).

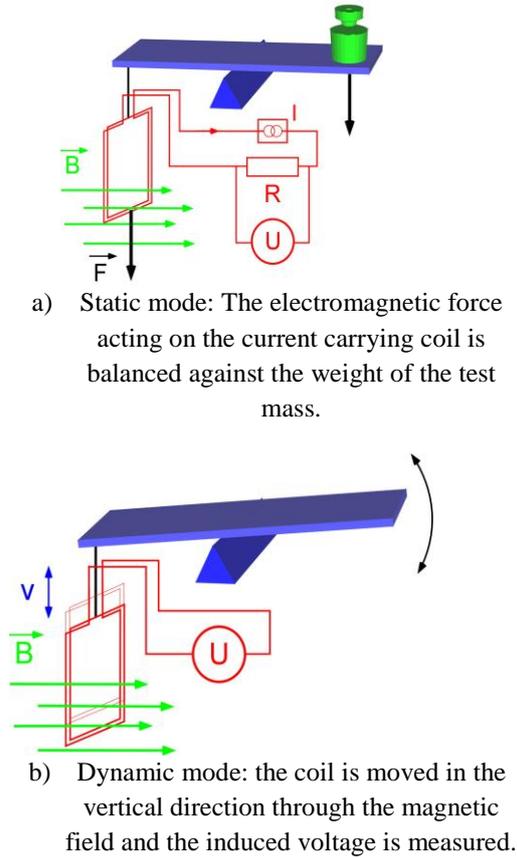


Figure 1: Principle of the watt balance experiment

In the static mode, the force generated by a mass m placed in the local gravity field g , is balanced by the vertical component of the electromagnetic force produced by a current I flowing in a coil immersed in a magnetic field B . The electromagnetic force can be expressed by

$$\vec{F} = I \cdot \oint d\vec{l} \times \vec{B}, \quad (1)$$

where l is the conductor length of the coil.

In the dynamic mode, the coil is moved vertically at a velocity v through the magnetic field B . This motion induces a voltage U across the coil that can be expressed by

$$U = -\oint (d\vec{l} \times \vec{B}) \cdot \vec{v}. \quad (2)$$

If the mechanical dimensions of the coil and the magnetic field are strictly identical in both modes, and under the hypothesis that the coil passes through its weighing position during the velocity mode, the combination of both modes leads to the expression

$$U \cdot I = m \cdot g \cdot v. \quad (3)$$

The experiment thus allows a virtual comparison between the electrical and the mechanical power. Using the expressions of the Josephson and quantum Hall effects, equation (3) can be rewritten as

$$m = C \cdot \frac{f_j \cdot f_j'}{g \cdot v} \cdot h, \quad (4)$$

where C is a calibration constant, f_j and f_j' are the Josephson frequencies used during the static and the dynamic phase and h the Planck constant. The watt balance experiment allows therefore relating the unit of mass to the meter, the second and the Planck constant.

3. THE NEW METAS DESIGN

The first watt balance developed and operated at METAS during the 10 last year showed its metrological limits. Based on this experience, the main components of the METAS watt balance experiment have been newly designed in collaboration with different partners. A new translation stage has been developed in association with the laboratory of robotics of the EPFL, a completely new monolithic load cell has been realized by METTLER TOLEDO and a high precision magnetic circuit has been constructed in cooperation with the group of Magnets and Superconductors of the CERN. A general view of the new design is presented in figure. 2

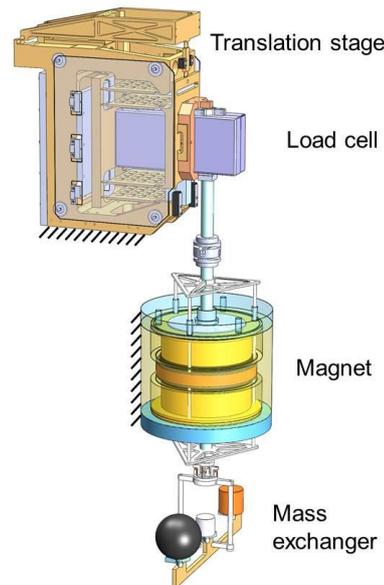


Figure 2: General view of the new design of the METAS watt balance.

3.1 MAGNETIC CIRCUIT

The homogeneity and the stability of the magnetic field during the two modes is a crucial issue for the watt balance experiment. In the frame of the project, a close collaboration with the group of Magnets and Superconductors of the CERN has been started. The goal of this collaboration is to build a magnet circuit with temperature stability better than 5 ppm/K and homogeneity along the vertical trajectory better than 10^{-5} . The adopted design is a closed cylindrical circuit (figure 3). Theoretically, this circuit should deliver in the gap a magnetic field of 0.6 T with a vertical homogeneity of 10^{-6} .

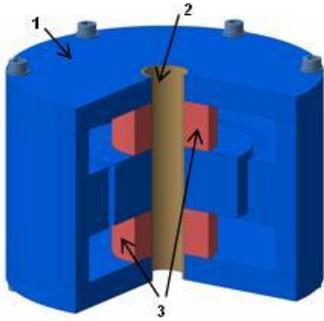


Figure 3: New magnetic circuit. (1) iron yoke (2) magnetic shunt, (3) permanent magnets.

The temperature coefficient of common magnets is around 300 ppm/K and represents a major source of systematic error and uncertainty contribution. By introducing a well dimensioned ‘magnet shunt’ with low Curie temperature, it is possible to drastically reduce the temperature coefficient. To evaluate this possibility, a first demonstrator has been designed and characterized. It has been possible to show that by ‘shunting’ the permanent magnet with a well dimensioned Fe-Ni cylinder, the temperature dependency of the circuit can be inverted (figure 4). Based on this approach the temperature coefficient of the circuit could be theoretically eliminated.

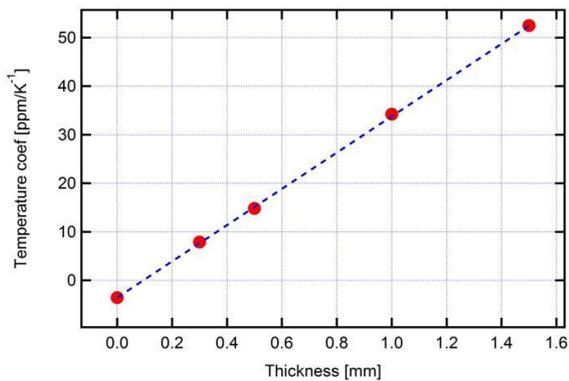


Figure 4: Temperature coefficient as function of the shunt thickness.

3.2 TRANSLATION STAGE

One of the central points of any watt balance experiment is the translation stage. This part of the experiment determines the quality of the dynamic mode, but also the reproducibility needed for the static mode. The straightness requirement along the movement is better than $1 \mu\text{m}$. In the frame of collaboration between the laboratory of robotics of the EPFL and METAS, a 13 hinge translation stage has been developed. The working principle of such a translation system is sketched in figure 5. The mobile output stage is linked to an intermediate stage by a coupling lever. By an appropriated design, the circular motion of the output stage can be compensated by the asymmetric motion of the intermediate stage. A detailed description of the translation stage can be found in [6].

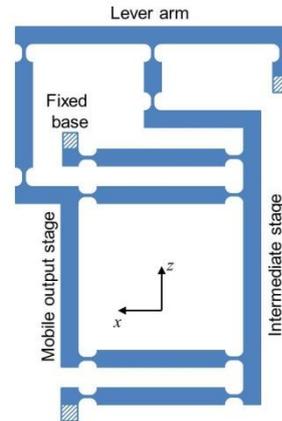


Figure 5: Schematic representation of the 13-hinge translation stage.

Figure 6 shows the first prototype that has been developed and manufactured. The hinge thickness is $155 \mu\text{m}$ with a radius of 50 mm and a total output stroke of 40 mm. The deformation angle of the hinges is $\pm 4.8^\circ$.

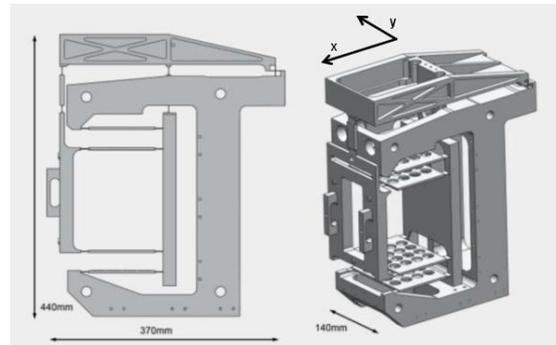
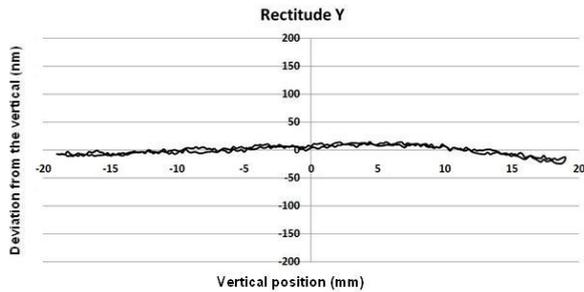
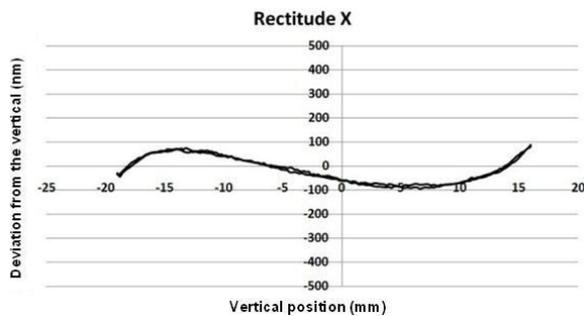


Figure 6: Monolithic 13-hinge translation stage.

The straightness measurement was performed with an interferometer by measuring the lateral position of the outlet when the table was displaced vertically. The results of these measurements, illustrated in figure 7, show a peak to peak straightness of 190 nm in x and 40 nm in y for a displacement of 40 mm.



a) Straightness in y direction



b) Straightness in x direction

Figure 7: Straightness measurement of the 13-hinge translation stage.

3.3 FORCE CELL

In the new concept the rest force that has to be determined in the static phase will be measured with a load cell integrated in the translation stage (figure 8)



Figure 8: Load cell integrated in the translation stage.

Since the mass comparator is not decoupled for the dynamic phase of the experiment, severe requirements in terms of mass made it impossible to use existing comparators. In close collaboration with METTLER TOLEDO, numerous challenges in designing a specific load cell had to be resolved. The low mass, a new interface to the motion mechanism, the vacuum capability, the robustness of the control loop and the low sensitivity to external disturbances were among the most important requirements.

After a pre-study with simulation of different solutions, a monolithic load cell approach, identified as most promising, was pursued. The result of an intensive design phase was a complete new innovative load cell design. By using proven components, and the Monobloc approach, a prototype of the comparator was manufactured. The first comparator prototype behaved close to the expected simulation results and with some optimization the expectations have been fulfilled. The load cell impressed with speed, sub-microgram repeatability at 1.2 kg load with the typical measurement procedure, low hysteresis and very repeatable thermal behavior. Figure 9 shows an example of the high repeatability ($\sigma = 0.29 \mu\text{g}$) of the load cell after 1 kg load step.

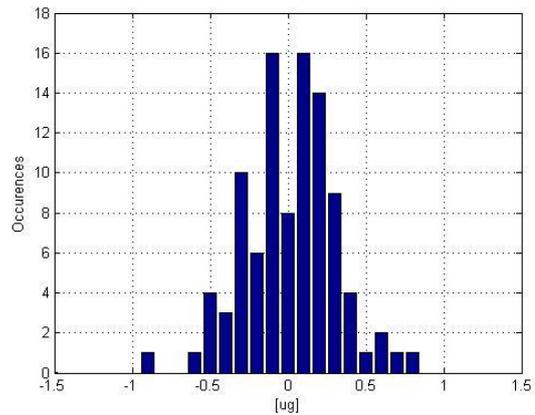


Figure 9: Repeatability curve of the new monobloc load cell from METTLER TOLEDO after 1 kg load step ($\sigma = 0.29 \mu\text{g}$).

3.4 CONCLUSION

The basic requirement for a new definition of the kilogram is a reliable evaluation of the Planck constant h . The origin of the discrepancies between the published values can be due to systematic errors in the experimental setups. To solve this problem new experiments with different approaches have to be developed around the world involving the best experts for each part of the conception. The new approach taken at METAS is to develop a new watt balance in close collaboration with industrial partner, universities and

research institutes. METTLER TOLEDO for the development of a new monobloc load cell, the Laboratoire de Systèmes Robotiques (LSRO) from the Ecole Polytechnique de Lausanne (EPFL) for the conception of a translation stage and the Centre Européen de Recherche Nucléaire (CERN) for the realization of the magnetic circuit. The preliminary results obtained for the main parts of the experiment are very promising and should allow, in a near future to

5. REFERENCES

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