THE METAS WATT BALANCE MARK II: FIRST RESULTS

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Abstract − It is nowadays widely accepted, that the future definition of the kilogram will be based on the Planck constant h [1]. A promising experimental approach is the so called watt balance [2]. The Federal Institute of Metrology METAS is developing the watt balance Mark II apparatus. This paper describes the design of the experiment as well as some experimental results. Considering the experimental progress, first results of the Planck constant, should be available at the time of the conference.

Keywords: Planck constant, Watt balance, Kilogram, International System of Units (SI)

1. INTRODUCTION

One possibility pursued by a number of groups for the determination of the Planck constant is the watt balance. The working principle of this experiment has been described in various publications [2]. It can be decomposed in two phases. In the static phase, or force measurement, 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 (Figure 1a)
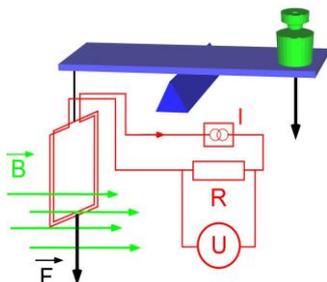
a) Static mode: The electromagnetic force acting on the current carrying coil is balanced against the weight of the test mass.
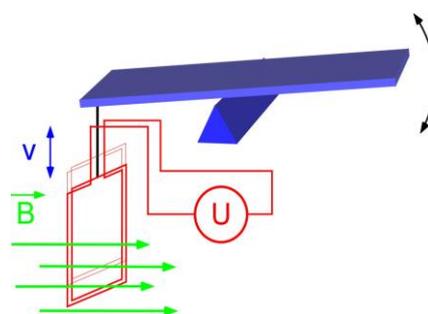
b) Dynamic mode: the coil is moved in the vertical direction through the magnetic field and the induced voltage is measured.

Fig. 1: Principle of the watt balance experiment

The electromagnetic force can be expressed by

$$\vec{F} = I \cdot \oint \vec{dl} \times \vec{B} , \qquad (1)$$

where l is the conductor length of the coil.

In the dynamic phase, or induction 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

$$U = -\oint (\vec{dl} \times \vec{B}) \cdot \vec{v}. \qquad (2)$$

If the magnetic field and the mechanical dimensions of the coil are identical in both modes, and under the hypothesis that the coil passes through its weighing position during the velocity mode with the same orientation, it can be shown that the combination of both phases leads to a virtual comparison between the mechanical and the electrical power. This can be summarized by

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

The experiment thus allows a virtual comparison between the electrical and the mechanical power. Using the

expressions of the quantum Hall and Josephson effects, equation (3) can be rewritten as

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

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.

METAS has chosen the watt balance approach several years ago and published a value of the Planck constant determined with a first experimental setup [3]. Based on the acquired expertise, METAS designed a second version of the experiment in collaboration with external partners. Mettler-Toledo realized a new vacuum compatible mass comparator for this application [4]. The laboratory of robotic from the Ecole Polytechnique Fédéral de Lausanne (EPFL) developed a translation stage and finally, the group of Magnet and Superconductors from CERN designed the magnetic circuit [5]. The performance of the individual elements have been tested before assembling the complete experiment that is now ready for preliminary tests and characterisation measurements.

2. MARK II DESIGN

The main components of the METAS Mark II design are presented in Figure 2. The driving stage, placed at the top of the experiment, is based on the principle of a Sarrus linkage. It moves the coil through the magnetic field during the dynamic phase of the experiment. The straightness of movement along the vertical trajectory is ensured by the guiding stage formed by a monolithic 13-hinge stage. The whole suspension holding the coil is attached, to the comparator which is inserted in the driving stage. The behaviour of the complete translation mechanism, composed by the guiding stage, the 13-hinge stage, the comparator, the suspension and the coil has been evaluated. The deviation along the verticality has been evaluated to 200 nm in y and 40 nm in x for a total path of 38 mm. The magnetic circuit in wish the coil is encapsulated can be adjusted in x, y, θ_x and θ_y by the mean of a double gimbal that contains the magnetic circuit. Finally the position of the coil is measured with a laser interferometer. The mass pan is placed at the bottom of the suspension. By placing the mass at the lowest place of the suspension, it can be ensured, that all components will see the same forces during both steps of the static phase of the experiment. The mass exchanger is used to place the test mass on and off the mass pan.
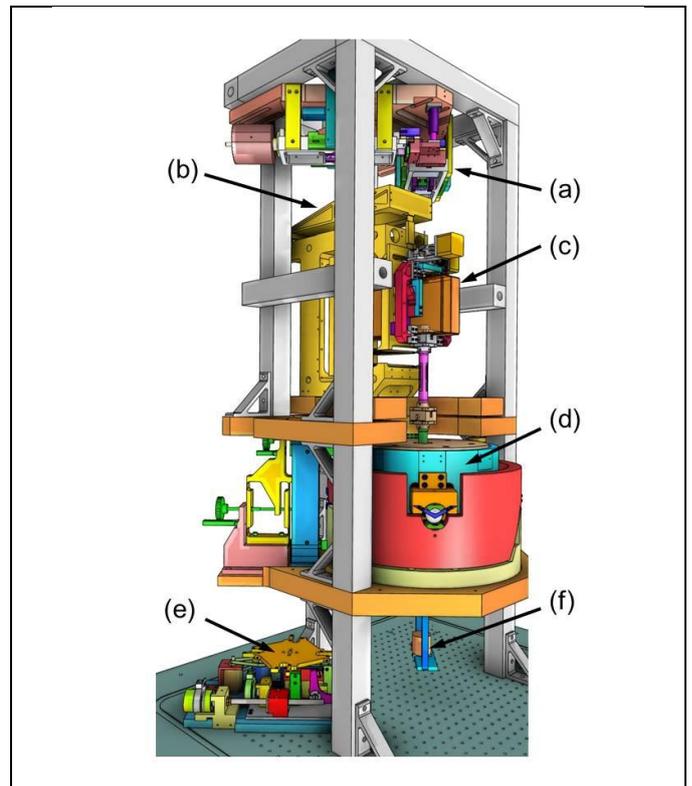

Fig. 2: Schematic view of the METAS watt balance MARK II experiment. The main components are (a) the driving stage, (b) the guiding or translation stage, (c) the mass comparator, (d) the magnetic circuit and its alignment system, and (e) the mass exchanger. The test mass (f) is placed at the bottom of the suspension.

2.1 Suspension

As briefly described in the introduction, it is a fundamental requirement that only the magnetic field, responsible for the vertical electromagnetic force in the static phase, produces an induced voltage in the dynamic phase. Special attention has been paid to this high critical point during the conception of the suspension-coil assembly. To minimise the abbe errors, the main mirror, used for the measurement of the coil position in x, y and z is located at the centre of the coil (Figure 3). Three flat mirrors and three corner cubes placed on the top of the coil are used to determine the orientation of the coil in space (Figure 3). To be able to distinguish lateral forces from torque acting on the coil in the static phase the link between the mass comparator and the coil contains two articulations. The first is located at the output of the comparator and the second one in the middle of the central tube of the suspension [6].
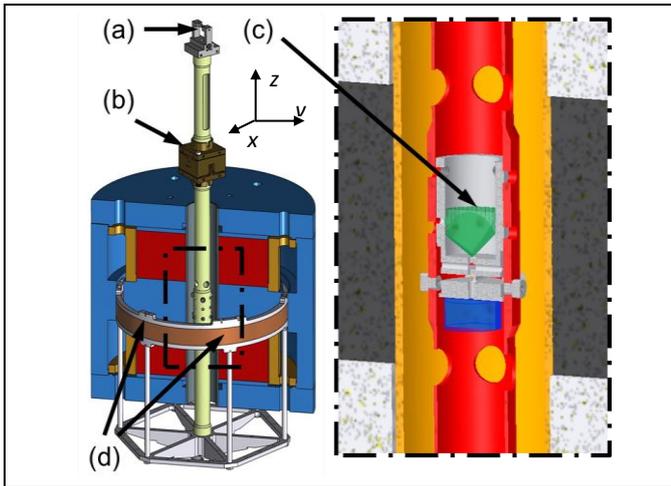
Fig. 3: The suspension-coil assembly is suspended to the comparator by a double cone hook (a). The upper and lower part of the central tube are linked by a monolithic aluminum flexible double gimbal (b). The determination of the position and orientation of the coil in space is measured with help of the main central corner cube (c) and the six optical elements (3 flat mirrors, 3 corner cubes) placed on the mirror structure (d).

Figure 4 represents a measurement of the orientation of the coil in space around the x (upper graph) and y (lower graph) axes when the coil is moving up and down. The orientation of the coil along the path varies from -10 µrad to 10 µrad around the x axes and from -5 µrad to 5 µrad around the y axes, what is significantly lower than the required limit of some tens of µrad [3].
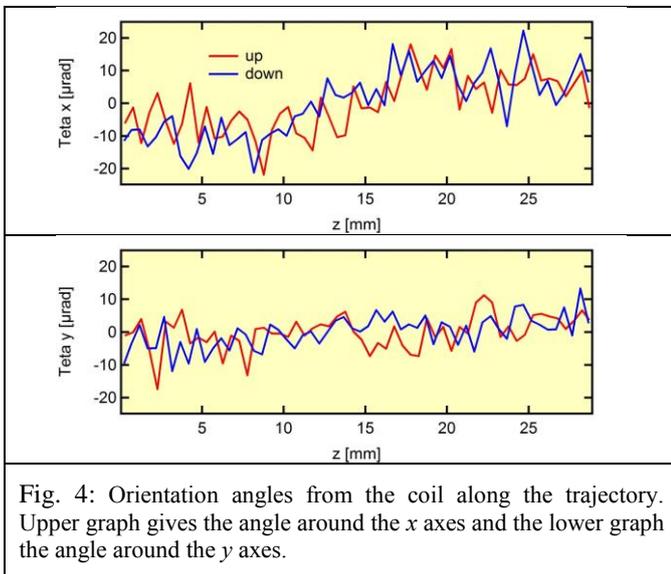

Fig. 4: Orientation angles from the coil along the trajectory. Upper graph gives the angle around the x axes and the lower graph the angle around the y axes.

2.1 Magnetic field profile

The magnetic field is generated by two SmCoGd permanent magnets placed in a closed magnetic circuit. The temperature dependence of the magnetic circuit is drastically reduced by the physical properties of the used magnets and by the 'magnetic shunt', made of a Fe-Ni alloy. With this configuration, a magnetic flux density of 0.65 T with a

vertical homogeneity in the order of 10^{-5} and a temperature coefficient better than -5 ppm/K can be expected.

A ppreliminary evaluation of the quality of the magnetic field has been performed by induction measurements which correspond to the dynamic phase of the experiment. In this phase the ratio between the induced voltage and the velocity is calculated. This ratio, called the geometrical factor G, gives information about the magnetic field and the mechanical behaviour of the coil. During these tests the coil was moved at a velocity of 1.3 mm/s to generate a voltage of about 1 V.

To measure the velocity of the coil, an in-house developed inline interferometer is used. The working principle of the interferometer is schematically represented in Figure 5. The incoming beam passes through a half wave (l/2) plate used to equilibrate the two arms of the interferometer. After the half wave plate, the beam is divided into two signals by a polarised splitter (BS1). The first beam goes straight to the photo detector (PD). The second one goes through the quarter wave plate (l/4) down to the moving corner cube (MCC). After the reflexion the beam travels to the second beam splitter (BS2) where one part of the signal is directed to the x-y position detector (PSD), and the second part to the reference corner cube (RCC). Then the beam moves back to the first splitter where it is reflected to the photo detector (PD). With this interferometer design, it is possible to measure the position of the coil in the x-y plan with the information obtained with the PSD, and it position along the z axis with the interference signal measured by the photo detector (PD).
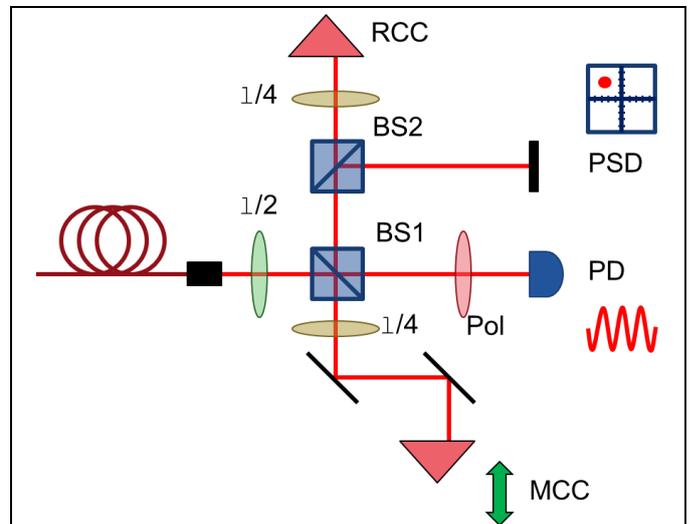

Fig. 5: Schematic view of the inline interferometer. The incoming laser beam is divided in two. The first beam goes through the splitter (BS1) to the detector (PD). The measuring beam travels from the first splitter to the moving corner cube (MCC). After reflection it moves back to the second splitter (BS2) where one part of the signal is directed to the x-y position detector (PSD) and the other part goes to the reference corner cube (RCC). From the reference corner cube the signal goes back to the first splitter where it is reflected to the photo detector (PD).

Figure 6 represents the geometrical factor $G = U/v$ along the vertical path of the coil. The mean value (solid line) is an average of 44 curves taken in 15 minutes. It shows a flat region of almost 15 mm wide with a standard deviation of

the order of 10^{-5}. The residual slope over a region of 5 mm around the weighing position is well below 1 ppm/mm. Even though the velocity regulation and the synchronization of the different instruments are not yet optimized, this curve shows that the homogeneity of the magnetic field satisfies the requirements of the experiment.
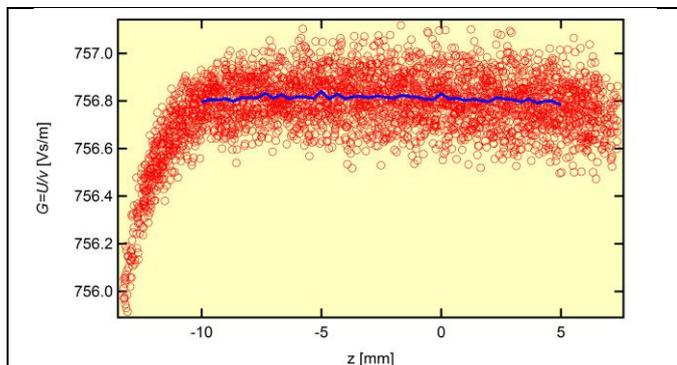

Fig. 6: Geometrical factor G = U/v estimated along the gap. The solid line shows the mean value of 44 curves. The field profile is flat over a region of almost 15 mm.

2.2 Determination of the gravitational acceleration

The determination of the local value from the gravity acceleration g is measured synchronously with a commercial absolute gravimeter FG5X [7]. Since more than 10 years, the reference station, WANA, in the METAS watt balance laboratory is measured approximatively once a month. The variation from the gravity over all these years it represented in Figure 6. The standard deviation of these measurements is 2.6 μGal (1 Gal = 10^{-5} m/s^2).
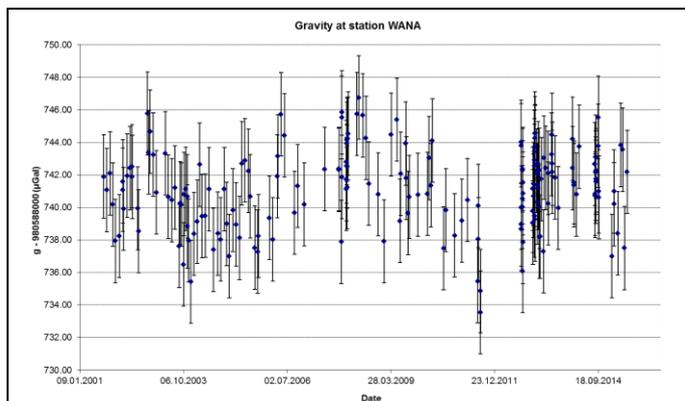

Fig. 7: Variation from the gravity measured on the watt balance reference station WANA.

The reference station WANA is placed beside of the experiment. To evaluate the gravity felt by the reference mass in the watt balance experiment, the value measured by the absolute gravimeter has to be transferred from the absolute gravity station to the location of the reference mass. Different approaches have been described for the transfer [8,

9]. In all these methods, a number of models had to be used to estimate for instance the influence of the experiment itself onto the gravity at the position of the reference mass. In the present experiment the transfer will not include any model but will be based on measurements made inside the experiment with closed vacuum chamber. For this a direct tie from the gravity station WANA to the interior of the experiment with closed vacuum chamber, will be performed with a LRC relative gravimeter.

4. CONCLUSIONS

The METAS watt balance Mark II experiment is assembled. First experimental tests have shown a very promising behaviour of the whole magnetic circuit. Complete measurement cycles, dynamic and static phase are currently investigated. First preliminary results will be available at the time of the conference.

ACKNOWLEDGMENTS

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