The BNM Watt Balance Project

Gérard Genevès, Pierre Gournay, A. Gosset, M. Lecollinet, François Villar, Patrick Pinot, P. Juncar, A. Clairon, A. Landragin, D. Holleville, Franck Pereira Dos Santos, J. David, Mondher Besbes, Francisco Alves, Luc Chassagne, and Suat Topçu

***Abstract*—A new watt balance project is now in progress at the Bureau National de Métrologie (BNM), Paris, France. In this paper, the general configuration and the main parts of the experimental setup currently in development are presented. The aim is to contribute to the international effort in monitoring the kilogram toward a new definition of the mass unit with a relative accuracy of 10^{-8} or better.**

***Index Terms*—Kilogram, Planck's constant, watt balance.**

I. Introduction

SEVERAL national metrology laboratories are presently working on experiments intended to monitor the stability of the mass unit defined by the international prototype of the kilogram kept at the Bureau International des Poids et Mesures (BIPM).

The weak point of this definition lies in the possible variations of the quantity of matter constituting the artefact, mainly due to surface contamination and bulk outgassing phenomena. These phenomena lead to long-term variations highlighted through comparisons between artefacts [1], which have shown relative variations of about 3×10^{-8} between the international prototype and the mean value of a set of national ones over one century, with scattering between individual artefacts of the order of 1 part in 10^7.

Consequently, the 20th and 21st Conférence Générale des Poids et Mesures issued recommendations encouraging that "national laboratories continue their efforts to refine experiments that link the unit of mass to fundamental or atomic constants with a view to a future redefinition of the kilogram" [2].

At the present time, several methods are studied, including, for example, the determination of the Avogadro constant N_A by means of silicon spheres [3] and gold ion collection [4].

Among them, the watt balance experiment, whose now-well-known principle was proposed in 1976 by Kibble [5], seems one of the most promising. It consists of comparing virtual mechanical and electromagnetic powers from which a link between the mass unit and the Planck's constant is derived. The latter appears through the use of quantum standards employed in the course of the experiment to determine electrical quantities.

The measurement system is mainly composed of a force comparator from which a coil submitted to the induction field of a magnetic circuit is suspended. It is used in a two-mode procedure [6]. During the static (or weighing) mode, the weight of a standard mass is compared with the Laplace force appearing when the coil is driven by a known current, while in the dynamic (or voltage) mode, the electromotive force induced at the terminals of the same coil moved at a known velocity in the same induction field is determined. All electrical quantities are measured by comparison with the Josephson and quantum Hall effects. The magnetic field and the geometric characteristics of the moving coil are transfer parameters between the two operational modes and only need to be constant during the measurements.

Three institutes have already developed experimental systems: first the National Physical Laboratory (NPL, 1977) [7] and the National Institute of Standards and Technology (NIST, 1980) [8] while the third one has been proposed by the Swiss Federal Office of Metrology and Accreditation (METAS) more recently [9].

In order to contribute to the knowledge of the kilogram and to a possible redefinition of the mass unit, the Bureau National de Métrologie (BNM), Paris, France, decided to develop its own experiment. The main characteristics of the project are described hereafter.

II. Dimensions and Structure

With regard to the relative variations between artefacts mentioned previously, the accuracy needed to establish the link between the kilogram and the Planck's constant must be equal to one part in 10^8 or better.

To achieve this goal, several guidelines have been drawn from a preliminary analysis on which the design of the experiment is established. First, the quantities to be measured are kept as close as possible to the values that can be determined with the best uncertainty. Second, the weighing and translation functions are separated. The moving coil is permanently attached to the

Manuscript received June 29, 2004; revised October 26, 2004.

G. Genevès and P. Gournay are with the Bureau National de Métrologie—Laboratoire National d'Essais/Centre de Métrologie Electriques (BNM—LNE/CME), 78197 Trappes Cedex, France.

A. Gosset is with the Bureau National de Métrologie—Laboratoire National d'Essais/Centre de Métrologie et Instrumentation (BNM—LNE/CMI), 75015 Paris, France.

M. Lecollinet, F. Villar, P. Pinot, and P. Juncar are with the Bureau National de Métrologie/Institut National de Métrologie/Conservatoire National des Arts et Métiers (BNM–INM/CNAM), 75003 Paris, France.

A. Clairon, A. Landragin, D. Holleville, and F. Pereira Dos Santos are with the Bureau National de Métrologie—Systèmes de Référence Temps-Espace (BNM—SYRTE), Observatoire de Paris, 75014 Paris, France.

J. David is with the Ecole Nationale Supérieure des Arts et Métiers (ENSAM), 59046 Lille Cedex, France.

M. Besbes is with the Laboratoire de Génie Electrique de Paris, Ecole Supérieure d'Electricité, 91192 Gif sur Yvette Cedex, France.

F. Alves is with the SATIE (Système et Applications des Technologies de l'Information et de l'Energie) Unité Mixte de Recherche, Centre National de la Recherche Scientifique (UMR CNRS 8029), Ecole Normale Supérieure de Cachan, 94235 Cachan Cedex, France.

L. Chassagne and S. Topçu are with the Laboratoire d'InfoRmatique en Image et Systèmes d'Information (LIRIS)—University of Versailles St-Quentin-en-Yvelines, 78035 Versailles Cedex, France.

Digital Object Identifier 10.1109/TIM.2005.843576

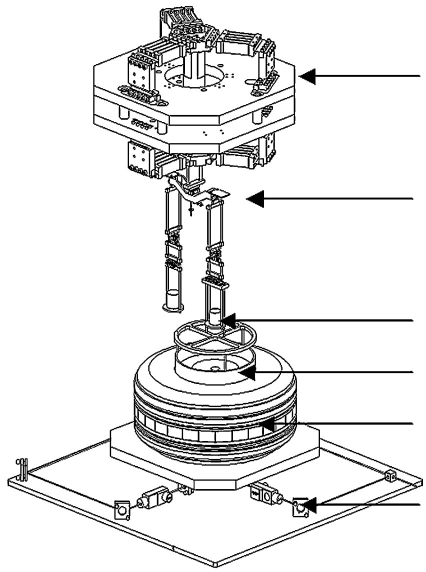

Fig. 1. Schematic diagram of the watt balance demonstrator.

force comparator in order to avoid possible misalignment during the two operating modes and to minimize hysteresis effects in the force comparator. Consequently, the coil and the comparator must be moved together in the dynamic mode, and a guiding translation stage must be added to the setup.

Thermal considerations resulted in choosing an axial geometry for a large-size magnetic circuit providing an induction as high as possible. Among other advantages, this allows a reduction in the coil length, the wire resistance, and, consequently, the heat due to the driving current in the weighing mode. Moreover, in such a geometry, the magnet may be placed away from the influence of the induction generated by the current into the moving coil.

From these considerations, the main dimensions of the apparatus can be determined as indicated hereafter.

A 266-mm-mean-diameter coil of 600 turns submitted to an induction of 1 T and driven by a 5-mA dc current develops a Laplace force of 2.5 N, corresponding to a standard mass of 500 g. The rather low number of turns allows the increase of the diameter of the wire to 0.25 mm and leads to a dissipated power of about 4 mW.

In the weighing mode, the current is measured by means of a 200-Ω resistor calibrated by comparison with the quantum Hall effect. The resulting 1-V EMF is compared with a standard voltage provided by a SINIS Josephson programmable array.

In the dynamic mode, a velocity of 2 mm/s leads again to a voltage drop of 1 V induced at the terminals of the moving coil. The resulting configuration is represented in Fig. 1.

The top part of the experimental setup constitutes a translation stage based on the use of flexure strips. It guides the displacement, along the vertical axis, of a sliding nut from which a force comparator loaded on one arm by a tare mass and on the other by the moving coil and a pan supporting the transfer mass standard is suspended. Specific gimbal assemblies concentrate the weight and the Laplace force on the same point of the suspension. The velocity and the position of the moving coil, situated in the air gap of the magnetic circuit, are controlled by means of an interferometer placed at the bottom of the setup.

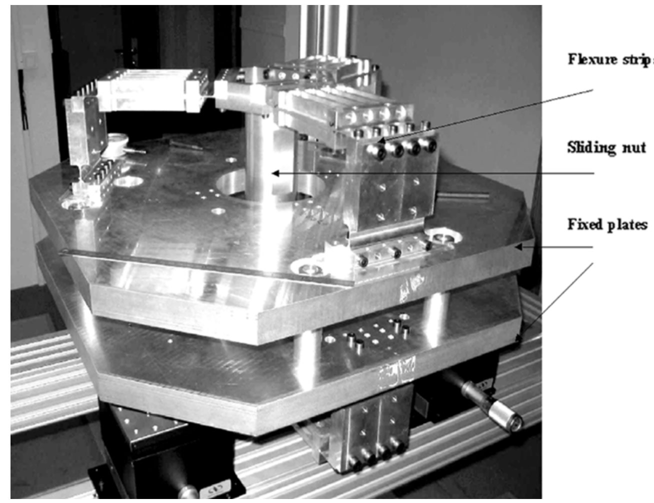

Fig. 2. Photograph of the translation stage.

Currently, the main parts of the proposed experimental device are being developed to demonstrate the validity of the options mentioned previously. The most significant parts are described below.

III. Main Components of the Apparatus

A. The Translation Stage

In the velocity mode, the trajectory of the moving coil must be, in theory, perfectly vertical. Horizontal components of the velocity, together with a noncoplanarity of the magnetic induction and the coil may lead to unexpected voltage components that do not correspond to the field seen by the coil in the weighing mode. Consequently, there is a strong requirement for the translation stage to provide a linear trajectory.

The translation stage is based on the use of flexure strips, chosen because of the absence of noise and wear. The aim is to obtain a stroke of at least 70 mm with a straightness within a few micrometers. The effective displacement range during which the measurements will be made is 40 mm, corresponding to a time interval of 20 s.

A prototype of the translation stage has been developed (Fig. 2). It is composed of two symmetrical nonmagnetic fixed plates, each of them supporting three sets of horizontal and vertical strips oriented at 120° from each other. A sliding nut, from which the force comparator will be suspended, is fixed to the six flexure strip sets, constituting a hyperstatic system constraining the translation along a single degree of freedom. A configuration of six flexure strip sets, instead of five, has been chosen for symmetry and security reasons so that the system can remain isostatic even in case of failure of one of the flexure strips.

Each set of flexure strips is composed of two elements machined in an aluminum alloy. Each of them consists of a rigid body with one or two flexible parts whose thickness are equal to 0.6 and 0.8 mm, respectively, for horizontal and vertical elements.

The initial experimental assembly is designed for a stroke of ±30 mm around the equilibrium position. Straightness measurements have been conducted by means of two micrometric probes scanning the transverse horizontal displacements of the sliding nut. The first results show that a straightness of better than 2 μm is obtained over a displacement range of 30 mm.

The counterpart to the quality of movement is the vertical force needed to move the sliding nut. This force is composed of a constant term (suspended weight about 100 N) and a restoring force proportional to the stiffness of the strips, leading to a component ($\cong$150 N) nearly proportional to their deformation. The use of a low-power actuator is then conditioned by a compensation system that will equilibrate these forces. This compensation system is being designed.

B. The Force Comparator

Considering the advantage of an adequate sensitivity, the best repeatability of equilibrium, and reduced hysteresis effects, it was decided to use a specific flexure strip beam, instead of a classical knife-edge beam. Moreover, the thickness of the strips, and consequently the comparator range, may be adapted to the standard mass and to the weight of the coil. In particular, this reserves the possibility of working at the best sensitivity with mass values differing from 500 g (e.g., 250 g or 1 kg) and to allow future modifications of the coil.

A prototype comparator has been realized and tested. It comprises a symmetrical beam machined in aluminum alloy, with each arm having a length of 10 cm and a width of 20 mm for a total weight of about 200 g. The dimensions of the central and end strips are designed to work with a maximum weight of 2.5 kg suspended at each end of the beam. For a first approach, cramped flexure strips cut in a 10-μm-thick stainless steel foil are used.

For testing and studying this prototype, the equilibrium position of the beam is servo-controlled by a feedback loop, including a proportional–integral–derivative (PID) lock-in amplifier control system. Its optical detection is performed by a two-element photodiode sensitive to the deviation of a laser diode beam reflected by a mirror mounted on one of the balance beam ends. The electromagnetic compensation force is generated by a small coil immersed in the magnetic field of a permanent magnet fixed at one of the balance beam ends and driven by a current driven from the feedback electronics. The servo current is measured via the voltage drop across a precision 100-Ω resistor using a digital multimeter.

After adjusting the beam, the sensitivity of the prototype under a load of 10 N at each end has been measured in air and was of the order of 0.25 mrad $\cdot$ mg^{-1}. This result is fully compatible with the theoretical sensitivity in the same conditions, calculated to be 0.2 mrad $\cdot$ mg^{-1}, determined from the well-known theory of the flexing of a strip under a tensile load and from a previous description of flexure strips used as pivots in mass comparators [10].

Moreover, the repeatability after raising and lowering a 1-kg standard mass on the pan several times appears to be better than 10^{-8}. Based on the experience gained with this first prototype, a new flexure strip beam is currently under development with the aim of approaching the theoretical sensitivity limit of order 4 mrad $\cdot$ mg^{-1} and reaching a repeatability better than 1×10^{-9}, requested for the watt balance experiment.

In addition, flexure strips made from Cu–Be alloy and machined by BIPM are being tested on this first beam prototype.

C. The Magnetic Circuit

The main element of the magnetic circuit is a ring of 60 individual Sm_2Co_{17} magnets inserted between two steel plates. This part is completed with two pure iron yokes, with the inner one including a FeCo cylinder. The design and the profile of the air gap, defined with the help of finite-element (FE) calculations, give a radial field of about 1 T. FE calculations show that the latter is constant within 1×10^{-4} in relative value for a distance of 60 mm. To achieve such a value, the air gap has to be machined with a precision of few micrometers. More details on the magnetic circuit currently in construction are available in [11].

D. The Interferometer

One possible way to reduce the voltage noise due to the velocity noise in the dynamic mode is to control the velocity and the position of the moving coil. The method of velocity control is based on the use of a heterodyne Michelson interferometer, a two-level translation stage, and a home-made high-frequency phase-shifting electronic circuit. It is presently tested in the form of a prototype device to be adapted to the final mounting.

A commercial heterodyne interferometer is used. The difference between the two optical components is equal to 20 MHz. The first level of the translation stage is based on a high-precision linear brushless servo motor designed to have a velocity control at the 10^{-5} accuracy level on a total travel of about 100 mm. The second level is a piezoelectric translator supporting the moving reflector of the interferometer. The maximum travel range of the piezoelectric element is 3 μm for an applied voltage of 100 V. The velocity control of this level is performed using the method described in [12]. It is based on an electronic loop, including a signal generation board fixing the set value of the velocity. This board is made from high-speed and low-phase-noise logic components and a high-frequency clock (640 MHz). To quantify the stability of the velocity, the output of the interferometer is sent to a frequency counter, and the Doppler frequency shift corresponding to a velocity of 2 mm $\cdot$ s^{-1} is recorded (i.e., $\sim$12 kHz). For this purpose, the useful signal is first mixed with a reference signal at a frequency of 20 MHz. The Allan standard deviation has been used to calculate the stability, and a $\sigma_y(\tau)$ of about 2.2×10^{-9} over 400 s has been obtained (Fig. 2).

E. The Gravimeter

Recent advances in manipulating atoms by laser make possible high-sensitivity cold atom inertial sensors. A cold atom gravimeter is now being developed with an expected accuracy of a microGal, equivalent to that of the best free-fall gravimeters. A description of the device is given in [13].

Among the advantages of such a device is the repetition rate of 3 Hz. Moreover, the gravimeter will be transportable and will allow participation in international comparisons.

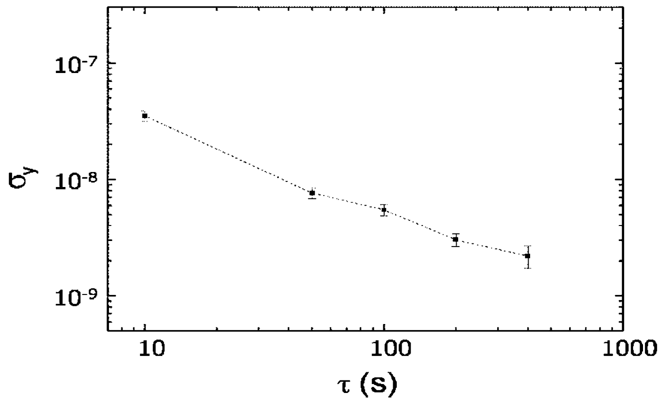

Fig. 3. Allan standard deviation of the Doppler shift induced by the moving mirror of the interferometer.

IV. Conclusion

A new setup for a watt balance experiment has been proposed with the aim of linking the kilogram to the Planck's constant. In particular, it includes a translation stage allowing the force comparator and the moving coil to remain attached during both parts of the measurement.

The development of the main parts of the device is now in progress in the form of prototype elements. It is expected that the dimensions and the structure of the experimental setup will allow a relative accuracy better than one part in 10^8 in order to contribute to a possible redefinition of the mass unit. It is planned that the present developments will lead to an operational device by the end of 2006.

Acknowledgment

The authors would like to thank Physikalisch–Technische Bundesanstalt (PTB) for kindly providing a programmable Josephson Junction Array dedicated to the watt balance.

References

[1] G. Girard, "The third periodic verification of national prototypes of the kilogram (1988–1992)," *Metrologia*, vol. 31, pp. 317–336, 1994.
[2] *Definition of the Kilogram*, Oct. 1999. Resolution 7, 21st CGPM, BIPM.
[3] P. Becker, H. Bettin, H.-U. Danzebrink, M. Gläser, U. Kuetgens, A. Nicolaus, D. Schiel, P. De Bièvre, S. Valkiers, and P. Taylor, "Determination of the Avogadro constant via the silicon route," *Metrologia*, vol. 40, pp. 271–287, 2003.
[4] M. Gläser, "Tracing the atomic mass unit to the kilogram by ion accumulation," *Metrologia*, vol. 40, pp. 376–386, 2003.
[5] B. P. Kibble, "A measurement of the gyromagnetic ratio of the proton by the strong field method," in *Atomic Masses and Fundamental Constants 5*, J. H. Sanders and A. H. Wapstra, Eds. New York: Plenum, 1976, pp. 545–551.
[6] A. Eichenberger, B. Jeckelmann, and P. Richard, "Tracing Planck's constant to the kilogram by electromechanical methods," *Metrologia*, vol. 40, pp. 356–365, 2003.
[7] I. Robinson and B. P. Kibble, "The NPL moving coil apparatus for measuring Planck's constant and monitoring the kilogram," *IEEE Trans. Instrum. Meas.*, vol. 46, no. 2, pp. 596–600, Apr. 1997.
[8] E. R. Willams, R. L. Steiner, D. B. Newell, and P. T. Olsen, "Accurate measurement of the Planck constant," *Phys. Rev. Lett.*, vol. 81, pp. 2404–2407, 1998.
[9] W. Beer, B. Jeanneret, B. Jeckelmann, P. Richard, A. Courteville, Y. Salvadé, and R. Dandliker, "A proposal for a new moving-coil experiment," *IEEE Trans. Instrum. Meas.*, vol. 48, no. 2, pp. 192–195, Apr. 1999.
[10] T. J. Quinn, "The beam balance as an instrument for very precise weighing," *Meas. Sci. Technol.*, vol. 3, pp. 141–59, 1992.
[11] P. Gournay, G. Genevès, F. Alves, M. Besbes, F. Villar, and J. David, "Magnetic circuit design for the BNM watt balance experiment," in *Dig. Conf. Precision Electromagnetic Measurements (CPEM) 2004*, London, U.K., Jun. 2004, pp. 510–511.
[12] S. Topcu, L. Chassagne, D. Haddad, Y. Alayli, and P. Juncar, "Heterodyne interferometric technique for displacement control at the nanometric scale," *Rev. Sci. Instrum.*, vol. 74, no. 11, pp. 4876–4880, 2003.
[13] P. Cheinet, F. Pereira Dos Santos, T. Petelski, A. Clairon, N. Dimarq, D. Holleville, and A. Landragin, "Cold atom absolute gravimeter for the watt balance," in *Dig. Conf. Precision Electromagnetic Measurements (CPEM) 2004*, London, U.K., Jun. 2004, pp. 60–61.