Proceedings of the 17th International Conference on Force, Mass, Torque and Pressure Measurements,
IMEKO TC3, 17-21 Sept. 2001, Istanbul, Turkey

Design of a Superconducting Magnetic Levitation System

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Abstract

A preliminary project for the realisation of the kilogram using the “superconducting magnetic levitation method” has been started at MIKES. The work will be carried out in co-operation with VNIIM, Russia. In the levitation method there are still problems, which have to be solved before the final goal, a relative uncertainty of 10^{-8} for the kilogram, can be reached. The main problem at present is energy losses due the incompleteness of the Meissner effect. These losses will be generated if the magnetic flux intrudes into a superconductor. Energy losses can jeopardise the experiment. To measure these losses we are developing a cryogenic calorimeter. The resolution of the device will be about 1 nW. We have also started to optimise the geometry of the levitated body and the coil, which produces the levitating magnetic field in order to minimise the effect of the energy losses.

1. Introduction

The present definition of the kilogram is based on the mass of the international prototype kilogram. This definition is a relic from the past and does not fulfil the requirements of modern metrology. Especially the stability of kilogram is not known.

Several methods have been proposed as candidates for the future realisation of the kilogram. The smallest uncertainty which at present can be reached is obtained with the “Watt balance” method [1-3]. The method links electrical quantities and mechanical quantities together by the use of a coil in a static magnetic field. In this method a vertical force F generated by a known electric current I in the coil is compared with the gravitational force mg due to the mass m . The comparison between the two forces is made with a mass comparator. To avoid the direct determination of the magnitude of the magnetic field or any geometrical factors the coil is moved with a known vertical velocity v. During this motion a voltage U is induced to the coil. This voltage is measured. From the measurements the following equation can be derived *F/I = mg/I = U/v*. From it the mass can be expressed in terms of the other quantities. Different variations of the method have been introduced. Several national metrology institutes are making experiments with this method. A relative standard uncertainty of about 10^{-7} in mass has been achieved [2]. It is also possible to define the kilogram in terms of the Avogadro constant. At present its value can most accurately be determined from single crystals made from silicon [4]. The uncertainty of the Avogadro constant is at present about 0.4 ppm. A new method where gold ions are counted, collected and weighed has been initiated [5]. Also this method is linked to the Avogadro constant. Another method, which resembles the “Watt balance” method, is based on superconducting levitation. [6-9]. The levitation method makes use of low energy losses in magnetic levitation of a superconducting body. It is based on precise measurement of electrical quantities, frequency, height difference and the acceleration of free fall. We have adopted this method. The advantages of a levitation instrument are compact size, lack of mechanical friction and ideal environment for cryogenic standards. The main problem at present is energy losses in superconductors. So far we have made plans for the instrument and we are starting energy loss measurements with a cryogenic calorimeter.

2. Measurement Method

A schematic diagram of a superconducting levitation system is shown in Fig. 1.

The measurement principle has been described in Ref. [8]. The main parts of the system are a superconducting coil and a superconducting levitated body. Other parts are a laser interferometer, a current source and instruments for measuring and/or controlling electrical quantities. Electric current *i* is fed to the coil. The coil generates a magnetic field *B* which is nearly proportional to the current. The superconducting body will extrude this field and it will start floating if the magnetic pressure $B^2/(2\mu_0)$ is high enough. If however the critical field will be exceeded the field will penetrate into the levitating body.

The current to the coil is measured indirectly by measuring with a digital voltmeter (DVM) the voltage across a known resistance. If the current is changed a voltage *U* will be generated across the coil. This voltage is compared with a voltage from a Josephson junction (JJ). The junction is irradiated with microwave radiation of frequency *f*. The coil voltage *U* and the Josephson voltage are kept equal by controlling the rate at which the current is increased.

This is done with the aid of a SQUID which measures any additional current i_s. If the current i_s is zero the coil voltage and the Josephson voltages are equal. The vertical position of the levitated body *z* is measured with a laser interferometer. The position depends on its mass *m* , the acceleration of gravity (free fall) *g* and on the magnetic flux *Φ* linked to the coil.

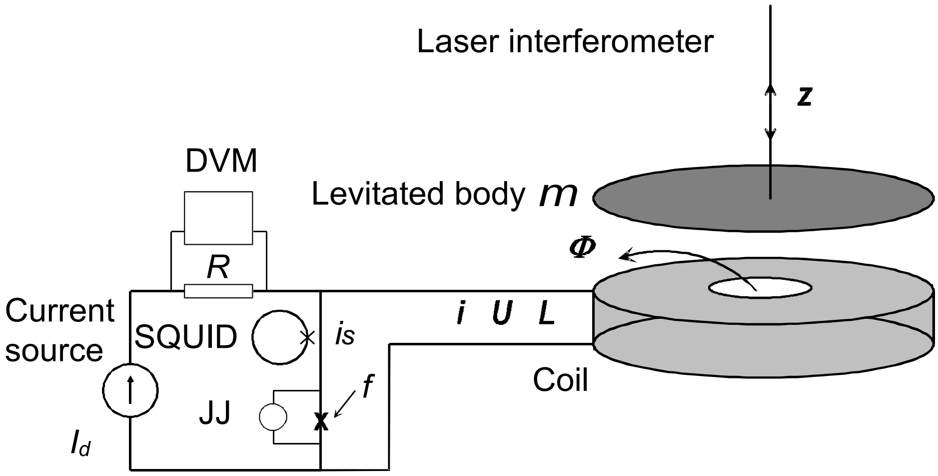


Fig 1. Superconducting magnetic levitation system

The magnetic flux depends on the coil current and on the inductance L . If the current to the coil is constant the height of the levitating body is also constant and the voltage U is zero.

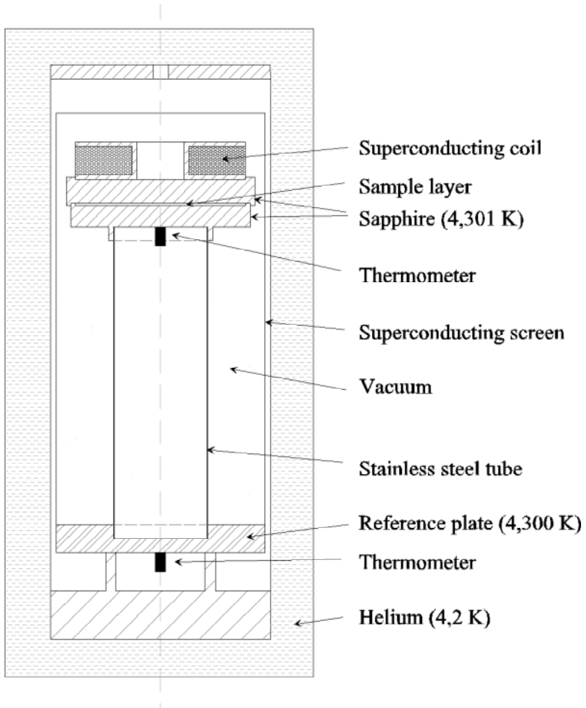
If there are no energy losses the electrical energy fed to the coil is converted to the energy of the electromagnetic field and to the mechanical (gravitational potential) energy of the levitating body:

$$\int_{\Phi_l}^{\Phi_h} i \; d\Phi = \tfrac{1}{2}(\Phi_h i_h - \Phi_l i_l) + mg(z_h - z_l) \quad (1)$$

Subscripts l and h refer the low and high positions of the levitating body. The first term on the right side of Equation 1 is the field energy change and the second term is the potential energy change. Since $U = d\Phi / dt = nf\Phi_0$,

where Φ_0 is the flux quantum and n is an integer. The flux Φ is an integral of the voltage over time. It can be obtained by counting the number of flux quanta.

The operation of superconducting devices requires cryogenic temperatures. The levitated body must repel the magnetic field, that is, the Meissner effect must be complete. It is possible only if the magnetic field is below the (first) critical field throughout the superconducting surfaces. This is a very serious limitation. In practise only niobium and lead are relevant materials. The operating temperature of the instruments can not be much higher than about 4.2 K. Most of the electrical parts of Fig. 1 can or must be operated at these low temperatures. Only the current source and the voltmeter are operated at room temperature. One problem at low temperatures will be the comparison of the mass



of the levitated body with a mass standard at room temperature. This may require a transfer of the mass to room temperature.

3. Material Studies

One of the most difficult problems will be to find the proper superconducting material for the coil and for the levitated body. There should be

Fig. 2. Calorimeter for energy loss measurements

no energy losses when the field is changed. In practise this is equivalent to the requirement that the magnetic field should not penetrate into the material. The penetration starts from sharp corners.

For small magnetic fields the penetration is not significant. The field should however be as high as possible. Otherwise the magnetic pressure is too low and mass of the levitated body is too small to be measured accurately. A lower limit for the mass is about 100 g. The magnetic field on the surface of the levitated body does not change very much during the levitation whereas the magnetic field on the surface of the coil increases when z is increased. This limits the maximum height difference because the critical field must not be reached. For accurate dimensional measurements the height difference should be 5-8 mm [10].

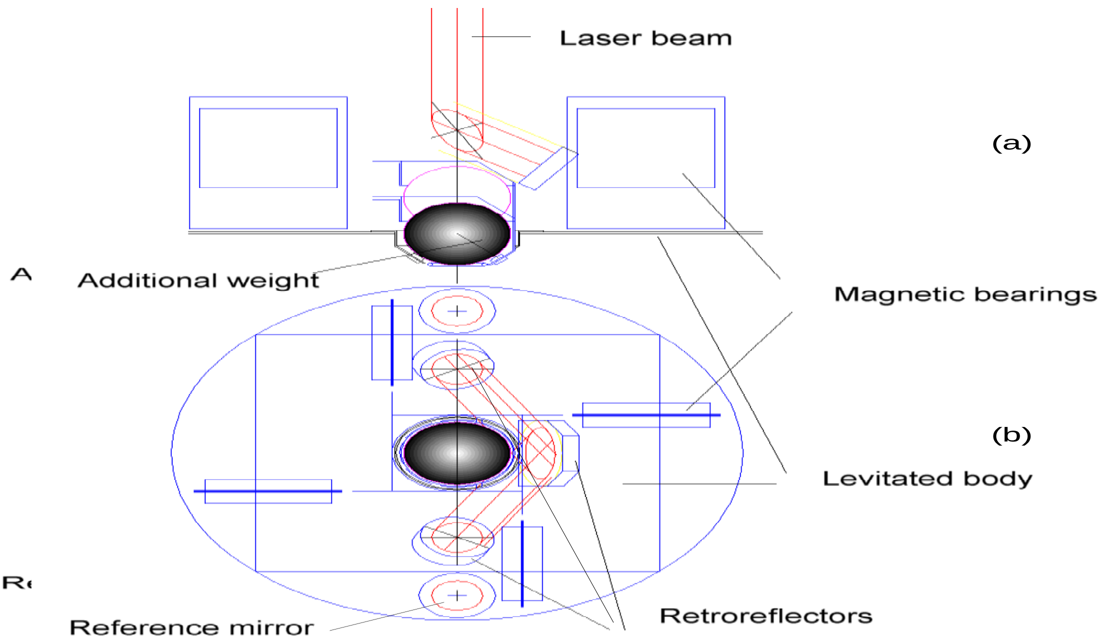
At present we are studying Niobium as a candidate both for the coil and for the levitating body. Niobium is a type II superconductor. The critical superconducting temperature is about 9.25 K. The first critical field $\mu_0 H_{c1}$ is about 140 mT. In practise, however, flux migration has been observed at fields as low as 30 mT [11]. The quality, purity and form of the Nb sample affects its superconducting properties. It is difficult to find very pure Nb wires or sheets. One possibility would be to use hetero-epitaxial $Nb/\alpha{\cdot}Al_2O_3$ structures [12]. In such a structure Nb forms a single crystal layer on a sapphire crystal. The thickness of the layer can be as much as 1 µm. The structure is limited to flat surfaces.

Energy losses due to ac-magnetic field have been measured in superconductors. Most of the measurements have been made at high frequencies. The results are not quite adequate for our purposes. To study energy losses in superconductors we are constructing a cryogenic calorimeter. A draft of the instrument is shown in Fig. 2. The measurements will be made with similar samples and coils as in the levitation experiment. Several materials will be investigated.

The construction of the calorimeter is similar to that in Ref. [13]. In Fig. 2 a weak thermal link between the sample unit and a reference plate is obtained with a thin walled stainless steel tube. The temperature of the reference plate will be stabilised to about 4.3 K with an electric heater and a heat link to ^{4}He bath.

The temperature of the sample unit is kept constant by another electric heater fixed to it (not shown in the figure). If there are energy losses in the coil or in the sample the electrical power is reduced. The power reduction is measured. The instrument will be constructed in such a way that the uncertainty of power measurement will be about 1 nW. A temperature difference of 1 mK along the tube corresponds a power loss of about 50 nW.

Figure 3. The The view is from one side (a) and from top (b). additional weight and laser interferometer mirrors.



4. Design of the Levitation System

The geometry of the coil and the levitated body should be optimised. The maximum field at any point on the superconducting coil should be less than about 100 mT . Numerical calculations of magnetic fields and lifting forces at different geometry have been made. The profile of the magnetic field can be modified with a superconducting shield. Because the maximum allowed magnetic field for Nb is low the area of the levitated body has to be relatively large. It also is very difficult to have a long vertical lift without exceeding the critical field at the surface of the coil. If the maximum vertical displacement is limited to about 10 mm the levitated body can be a relatively thin circular plate. An ideal form for the coil is also a flat ring with an outer diameter less than the diameter of the levitated body. A possible construction for the levitated body is shown in Fig. 3. The levitated mass is made from four rectangular Nb coated Sapphire plates. The size of the structure is about 8 x 8 cm^2. The coils are not shown in the picture. They can also be manufactured from Nb coated Sapphire plates using photolithography methods.

Because it is difficult to determine the mass of the levitated body (includes bearings, reflectors etc.) accurately an additional weight of more convenient shape should be added to the plate as shown in Fig. 3. The mass of the additional weight can be determined from levitation measurements made with the weight and without the weight. It is important that the centre of gravity of the plate and the additional mass are coincident and that the laser interferometer measures the vertical displacement of the centre of gravity as shown in Fig. 3. The levitation system will not be operated in absolute vacuum. The effect of He pressure to the index of reflection has to be taken into account.

The motion of the levitated body should be restricted to vertical raise or fall. Movements in other directions or any rotation of the body can consume energy and complicate the measurement of the vertical displacement. The restriction to vertical movements can be achieved with magnetic bearing as shown in Fig. 3. It is composed of a superconducting plate which is placed between two coils. It is important that the bearings do not produce any vertical forces.

The acceleration of gravity should be determined. It can be measured with an absolute gravimeter. In principle it is also possible to determine it from oscillations of the levitated body [14].

5. Conclusions

A preliminary project for realising the kilogram using the “levitation method” has been started. The final goal is to reach a relative uncertainty of 10^{-8} in mass. This will take many years and several problems has to be solved before the required uncertainty is reached.

In the near future energy losses in different superconducting materials will be tested with a cryogenic calorimeter. From the results of these measurements the best material and an optimal configuration will be chosen. The design of the superconducting levitation system has been started. The following restrictions have been set. The mass of the additional weight should be about 100 g and its vertical displacement should be 5-10 mm.

6. References

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