ABOUT LEVITATION OF SUPERCONDUCTING RINGS FOR MAGNETIC SYSTEM OF MULTIPOLE PLASMA TRAP

A.M. Bishaev[1], A.A. Bush[1], M.A. Behtin[1], M.B. Gavrikov[2], I.S. Gordeev[1], A.I. Bugrova[1], K.Ye. Kamentsev[1], M.V. Kozintseva[1], V.V. Savel'ev[2], A.A. Safronov[1], M.I. Shaposhnikov[1], P.G. Smirnov[1]

[1]Moscow State Technical University of Radio Engineering, Electronics and Automation, Moscow, Russia;

[2]Keldysh Institute of Applied Mathematics of Russian Academy of Sciences, Moscow, Russia

E-mail: kozintseva@mirea.ru

In order to continue works on creation of the plasma trap with levitating magnetic coils the analytical function of the potential energy $U(x,\theta)$ of the system of two coaxial superconducting rings (and the upper ring is fixed at that), which trapped given fluxes of the same sign, in the homogeneous gravity field versus the coordinate x of the free ring and the deflection angle θ of its axis from the vertical has been obtained under approximation of thin rings. For manufactured HTSC rings, which trapped fluxes of the same sign, with the help of calculations of the dependence $U(x,\theta)$ in Mathcad system, such values of magnetic fluxes trapped by rings have been obtained under which equilibrium states of the free ring in the field of the fixed ring, stable to the shift of the levitating ring plane along the common axis and to the deflection of its axis from the vertical, exist. The existence of the determined by calculations equilibrium state for HTSC rings under trapped fluxes of the same sign, stable to the vertical shifts of the levitating ring and to the deflection of its axis from the vertical, has been proved experimentally.

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In researches devoted to the development of magnetic systems of multipole traps-galateas [1] with levitating superconducting coils (so named "myxini") the analytical expression for the potential energy of the system of several coaxial superconducting coils-rings (and one of them is fixed at that), which trapped the given magnetic fluxes, in the homogeneous gravity field versus the coordinate x of free ring has been obtained under approximation of thin rings [2]. The dimensions of superconducting coils, the sign and values of trapped fluxes, levitating coils masses are the parameters of this dependence. Using calculations in Mathcad system it has been shown that under definite values of parameters there are equilibrium states of such a system.

However obtained relations allow to determine equilibrium levitating states which are stable only to the shift of levitating ring plane along the common axis. In a real experiment, it is important to provide stability of the ring levitating state with respect to its displacements in the horizontal plane and to its rotation around an arbitrary horizontal axis.

The derivation of the analytical formula for the potential energy of the given system as a function of both coordinate along the axis and deflection angle θ of levitation ring axis from the vertical is the next stage on the way of the determination of the stable equilibrium states of the indicated above system of superconducting rings.

As the first step, let us consider a system of two coaxial superconducting rings lying in the parallel horizontal planes, and the upper ring is fixed at that (Fig. 1). The coordinate x is counted off from the fixed ring. Rings are numbered from top to bottom. It is assumed that the cross-section radius of each coil-ring (a_k) is much less than the mean radius of the corresponding ring (R_k). The potential energy for such system of two superconducting rings which trapped

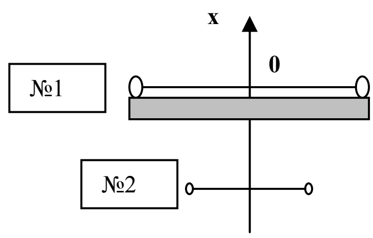

Fig. 1. Location of superconducting rings

magnetic fluxes Φ_1 and Φ_2 , respectively, in the homogeneous and Φ_2 , respectively, in the homogeneous gravity field, by analogy to [2], will be written in form:

$$U(x,\theta) = \frac{1}{2}\left[\Phi_1 J_1(x,\theta) + \Phi_2 J_2(x,\theta)\right] + m_2 g x , \quad (1)$$

where x is the coordinate of the free ring, J_i are the current in rings, m_2 – is the mass of the free coil-ring. Assuming that the fluxes trapped by superconducting rings, remain constant we obtain the system of equations for the determination of the dependences $J_1(x, \theta)$ and $J_2(x, \theta)$ [3]:

$$\begin{aligned} &L_{11}J_1 + L_{12}(x,\theta)J_2 = \Phi_1 , \\ &L_{21}(x,\theta)J_1 + L_{22}J_2 = \Phi_2 , \\ &L_{12}(x,\theta) = L_{21}(x,\theta) . \end{aligned} \quad (2)$$

Here L_{ik} are self-induction and mutual induction coefficients of rings.

The program of calculation of the dependence $U(x,\theta)$, written in Mathcad system for two coils-rings, the upper of them is fixed and the lower one is free, which trapped magnetic fluxes of the same sign, allows to determine the equilibrium states of such configuration which are stable both with respect to the shift of the levitating ring plane along the common axis and with respect to the deflection of levitating ring axis from the vertical.

For experiments with levitation, HTSC[1] samples in the form of rings made from preliminary synthesized powder HTSC phase $YBa_2Cu_3O_y$ with the help of melt textured growth (MTG) method [4] have been used. In such samples, high critical currents with a density up to $j_c=(10^3…10^4)$ A/cm^2 can be achieved at the temperature T=77 K [5]. The external diameter of HTSC rings was equal to 35 mm, the internal diameter was equal to 16mm, the thickness was equal to 8mm and the mass was equal to 40 g.

The search for levitating states of HTSC rings by relationships (1), (2) presupposes that the values of the magnetic fluxes which can be trapped by theses rings are known. The flux trapping by the HTSC ring has been carried out by its cooling down to the temperature of the liquid nitrogen in the magnetic field of solenoid. Then the field was deactivated and the ring which trapped the magnetic flow was displaced to the experimental cell to measure the magnetic induction. According to the magnetic induction values measured at a 1-mm-height from the ring surface, the magnetic fluxes trapped by the HTSC rings for the different currents in the magnetizing solenoid turns have been calculated. The magnetic flux trapped by the HTSC ring with a diameter of 35 mm increases proportionally to the current growth in the solenoid turns and achieves the maximal value of $6.55\cdot10^{-5}$ Wb at 50 A current in its winding.

For HTSC rings of diameter ∅35 mm, which trapped the fluxes of the same sign, with the help of calculations in Mathcad system of dependence $U(x,\theta)$, the search of such values of the magnetic fluxes, trapped by rings, has been carried out under which the equilibrium states of the free ring in the field of the fixed ring, stable with respect to the shift of the levitating ring plane along the common axis and to the deflection of its axis from the vertical, exist.

One of the possible equilibrium state of the free HTSC ring ∅35 mm in the field of fixed and located above the same HTSC ring ∅35 mm is achieved if the free ring has trapped the flux $6.6\cdot10^{-5}$ Wb and the fixed one has trapped the flux $2.6\cdot10^{-5}$ Wb. There is shown the distribution of the equipotentials for the given case in the Fig. 2. It is seen from Fig. 2, the local minimum is achieved at the coordinate $x=-1.3$ cm (i.e. at the distance 13 mm between the central cross-sections of the rings) and at the angle $\theta=0$ (the levitating ring axis is parallel to the axis of the fixed ring).

We should note that the sizes of the real HTSC rings, used for carrying out the experiment, did not satisfy the assumption made during the derivation of the formulas for self-induction and mutual induction coefficients of rings: the cross-section radius of each ring (a_k) was only a few times smaller than the mean radius of the corresponding ring (R_k), instead of much less, as we had assumed. Therefore, its equilibrium state coordinates obtained from calculations may differ from those which are realized experimentally.

The demonstration device has been developed and

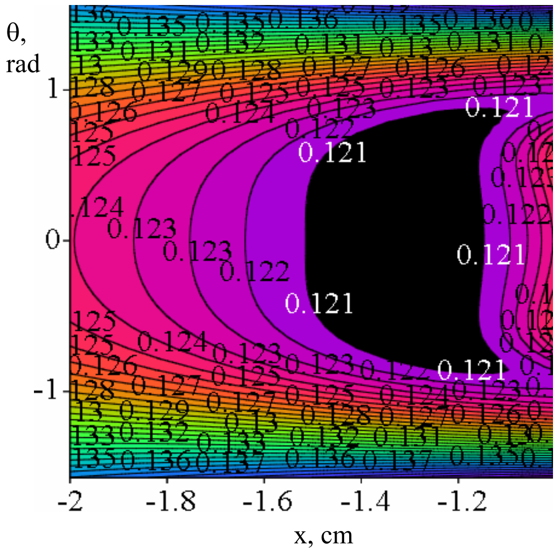

Fig. 2. Distribution of equipotentials for two superconducting rings, which trapped the fluxes of the same sign, as a function of the coordinate x of the free ring and the deflection angle θ of its axis from the vertical

manufactured to carry out the experiments on the levitation of the superconducting ring in the field of the supporting superconducting ring. Its main units are the lower container, in which bottom centre the copper rod is fixed for the system centering, and the removable upper container with the copper tube soldered in the bottom centre. Installed in the lower container lifting mechanisms allow to move superconducting rings in height with the help of the brass tenons.

The existence of the determined by calculations equilibrium state for HTSC rings ∅35 mm under trapped

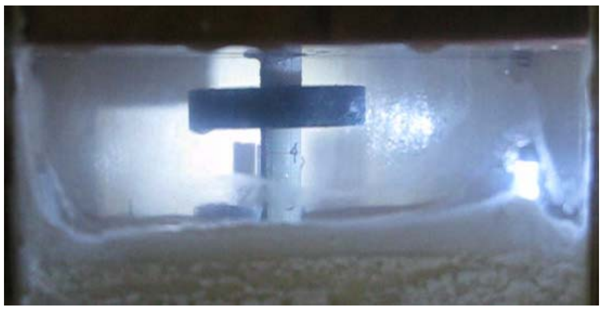

Fig. 3. The stable levitating state of HTSC ring ∅3 5mm ($\Phi_2=6.6\cdot10^{-5}$ Wb) in the field of located in upper container fixed HTSC ring ($\Phi_1=2.6\cdot10^{-5}$ Wb) under trapped by them fluxes of the same sign

fluxes of the same sign (see Fig. 2) has been proved experimentally.

There is presented the photograph of the stable levitating state of HTSC ring ∅35 mm, which is in the lower container of the demonstration device, in the field of the fixed HTSC ring ∅35 mm, located in the upper container, in the Fig. 3. The levitating state of HTSC ring has been stable, in accordance with the calculations, with the respect to the vertical shifts and to the deflection of its axis from the vertical. Besides, the stability of the

[1] *High –temperature superconductivity*

levitating state of HTSC ring with the respect to its horizontal shifts has been experimentally observed.

The obtained results show that it is possible to create a magnetic system with several levitating coils [6].

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О ЛЕВИТАЦИИ СВЕРХПРОВОДЯЩИХ КОЛЕЦ ДЛЯ МАГНИТНОЙ СИСТЕМЫ МУЛЬТИПОЛЬНОЙ ПЛАЗМЕННОЙ ЛОВУШКИ

А.М. Бишаев, А.А. Буш, М.А. Бехтин, М.Б. Гавриков, И.С. Гордеев, А.И. Бугрова, К.Е. Каменцев, М.В. Козинцева, В.В. Савельев, А.А. Сафронов, М.И. Шапошников, П.Г. Смирнов

В продолжение работ по созданию плазменной ловушки с левитирующими магнитными катушками в приближении тонких колец получено аналитическое выражение для потенциальной энергии $U(x,\theta)$ системы из двух коаксиальных сверхпроводящих колец (причем, верхнее из них закреплено), захвативших заданные потоки одного знака, в однородном поле силы тяжести как функции координаты x свободного кольца и угла отклонения θ его оси от вертикали. Для изготовленных ВТСП-колец, захвативших потоки одного знака, с помощью расчетов в системе Mathcad зависимости $U(x,\theta)$ были найдены такие значения захваченных кольцами магнитных потоков, при которых существуют равновесные состояния свободного кольца в поле закрепленного кольца, устойчивые по отношению к смещению плоскости левитирующего кольца вдоль общей оси и к отклонению его оси от вертикали. Существование найденного из расчетов равновесного состояния для ВТСП-колец при захваченных потоках одного знака, устойчивого по отношению к вертикальным смещениям левитирующего кольца и к отклонению его оси от вертикали, было подтверждено экспериментально.

ПРО ЛЕВІТАЦІЮ НАДПРОВІДНИХ КІЛЕЦЬ ДЛЯ МАГНІТНОЇ СИСТЕМИ МУЛЬТИПОЛЬНОЇ ПЛАЗМОВОЇ ПАСТКИ

А.М. Бішаєв, А.А. Буш, М.А. Бехтін, М.Б. Гавріков, І.С. Гордеєв, А.І. Бугрова, К.Є. Камєнцев, М.В. Козінцева, В.В. Савельєв, А.А. Сафронов, М.І. Шапошніков, П.Г. Смірнов

У продовження робіт зі створення плазмової пастки з левітуючими магнітними котушками в наближенні тонких кілець отримано аналітичний вираз для потенційної енергії $U(x, \theta)$ системи з двох коаксіальних надпровідних кілець (причому, верхнє з них закріплено), що захопили задані потоки одного знаку, в однорідному полі сили тяжіння як функції координати x вільного кільця і кута відхилення θ його осі від вертикалі. Для виготовлених ВТНП-кілець, які захопили потоки одного знаку, за допомогою розрахунків в системі Mathcad залежності $U(x, \theta)$, були знайдені такі значення захоплених кільцями магнітних потоків, при яких існують рівноважні стани вільного кільця в полі закріпленого кільця, стійкі по відношенню до зміщення площини левітуючого кільця уздовж загальної осі та до відхилення його осі від вертикалі. Існування знайденого з розрахунків рівноважного стану для ВТНП-кілець при захоплених потоках одного знаку, стійкого по відношенню до вертикальних зсувів левітуючого кільця та до відхилення його осі від вертикалі, було підтверджено експериментально.