ABOUT STABILITY OF LEVITATING STATES OF SUPERCONDUCTING MYXINI OF PLASMA TRAPS-GALATEAS

*A.M. Bishaev[1], A.A. Bush[1], M.B. Gavrikov[2], A.I. Denis'uk[1], O.Y. D'yakonitsa[1], K.Y. Kamentsev[1], M.V. Kozintseva[1], T.G. Kolesnikova[1], V.V. Savelyev[2,3], P.G. Smirnov[4], M.M. Shapovalov[1], S.A. Voronchenko[1]***

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

[2]Keldysh Institute of Applied Mathematics RAS, Moscow, Russia;

[3]National Research Nuclear University MEPh, Moscow, Russia;

[4]Moscow Aviation Institute (National Research University), Moscow, Russia

E-mail: kozintseva@mirea.ru

To develop a plasma trap with levitating superconducting magnetic coils it is necessary to carry out the search of their stable levitating states. With this purpose, based upon the superconductor property to conserve the trapped magnetic flux, in the uniform gravitational field the analytical dependence of the potential energy of one or two superconducting rings, having trapped the given magnetic fluxes, in the field of the fixed ring with the constant current from the coordinates of the free rings and the deflection angle of their axes from the common axis of the magnetic system has been obtained in the thin ring approximation. Under magnetic fluxes of the same polarity in coils the existence of the found from the calculations equilibrium levitating states for the manufactured HTSC rings stable relative to the vertical shifts of levitating rings and to the deflection angle of their axes from the vertical has been confirmed experimentally.

PACS: 84.71.-b, 84.71.Ba, 52.55.–s, 52.55.He

INTRODUCTION

Magnetic systems of traps-Galateas consist of several coaxial coils [1]. They form the typical for this type of traps configuration of the magnetic field containing the region of zero field. In the fusion reactor the immersed in the plasma magnetic coils ("myxini" [1]) of such traps must levitate. The equilibrium levitating states of superconducting myxini must have the stability of three types: 1) relative to the vertical shifts of their plane along the common axis; 2) relative to the deflection angle of their axis from the common axis of the magnetic system; 3) relative to the radial shifts of their plane. The developed by the authors approach is in obtaining the analytical dependence of the potential energy of the proposed configurations from the corresponding variables and in the search by the calculations in Mathcad of the local minimums of such dependence corresponding to the stable equilibrium states [2-5].

For experiments with levitation several multiturn short-circuited rings with different diameters (50, 60 and 80 mm) have been made from a high-temperature superconducting (HTSC) wire of the SCS4050-i-AP 2G HTS type (manufactured at SUPER POWER). Their time constants measured from the curve describing the decay of the magnetic field with the time lie in the interval 18…35 min.

The flux trapping by HTSC rings has been carried out by their cooling in the solenoid magnetic field to the liquid nitrogen temperature. Then the field has been switched off, and the coil-ring having trapped the magnetic flux has been moved into the experimental cell for the measuring of the magnetic induction. The experimentally determined maximal values of trapped fluxes are at the level 10^{-3} Wb. The nonsuperconducting coil with the constant current had the following parameters: the middle radius was equal to 4.75 cm, the average radius of the winding cross-section – 0.6 cm, and the number of turns – 400.

1. STATEMENT OF PROBLEM

The given paper is devoted to the search of the equilibrium states of superconducting rings which levitate in the field of the fixed nonsuperconducting ring with the current, stable both to the their shift along the common axis and to the deflection of their axis from the system common axis.

The system under consideration consists of two or three coaxial rings lying in parallel horizontal planes. One of the rings positions scheme is presented in the Fig. 1. The coordinates are measured from the fixed ring. The rings are numbered from top to bottom. It was assumed that the radius (a_k) of the cross-section of each ring is much smaller than the middle radius (R_k) of the corresponding ring.

The derivation of the expression for the potential energy of the system of rings as the function of coordinates of free rings and the deflection angle of their axis from the common axis of magnetic system in the analytical form is analogous to the derivation given in [5] with the only difference that the coefficients of the rings mutual induction $L_{ik}(x,\theta)$ are the functions not only of the coordinate x of the levitating ring but also of the deflection angle θ of its axis from the vertical.

Due to the increase of the number of variables some particular cases have been considered.

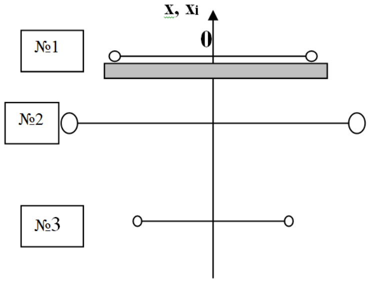


Fig. 1. Rings positions: №1 – fixed ring with the constant current; №2 and 3 – levitating superconducting rings

2. LEVITATION OF MYXINE IN FIELD OF FIXED RING WITH CURRENT

Let the top fixed ring (№1) is not superconducting and has the constant current J_1, the bottom one (№2) is superconducting and free, the trapped by it magnetic flux Φ_2 conserving. Then we may write:

$$J_1 = const;$$
$$L_{21}J_1 + L_{22}J_2 = \Phi_2 = const; \qquad (1)$$
$$L_{12} = L_{21}.$$

Based upon the expression for the interaction force between the contours with current [6] in this case:

$$F_q = -\frac{\partial U}{\partial q} = J_1 J_2 \frac{\partial L_{12}}{\partial q} \qquad (2)$$

(where q is generalized coordinate, differentiation is carried out under constant currents) and taking into account (1), for the potential energy of this system in the uniform gravitational field we obtain:

$$U(x,\theta_2) = \frac{1}{2}\frac{(\Phi_2 - L_{12}(x,\theta_2)J_1)^2}{L_{22}} + m_2 g x\,. \qquad (3)$$

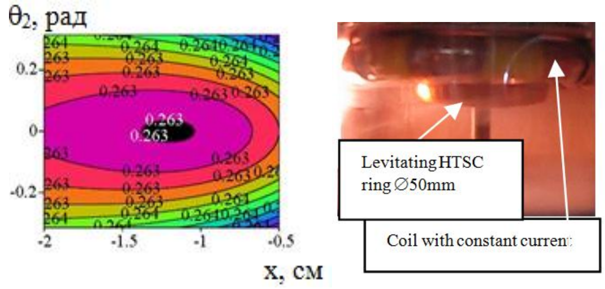
With the help of calculations in Mathcad system of the dependence $U(x,\theta_2)$ the search of such values of the magnetic fluxes, trapped by the ring ∅50 mm from HTSC wire, and the current value in the fixed ordinal coil has been carried out, under which the equilibrium states of the free ring in the 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.

The existence of the determined by calculations equilibrium state for HTSC rings ∅50 mm under fluxes in the rings of the same sign (Fig. 2,a) has been proved experimentally (see Fig. 2,b).

If the bottom ring is fixed and it is not superconducting and has the constant current J_2, the top one is superconducting and free, having trapped magnetic flux Φ_1, then the potential energy of this system in the uniform gravitational field may be written in form:

$$U(x,\theta_1) = \frac{1}{2}\frac{(\Phi_1 - L_{12}(x,\theta_1)J_2)^2}{L_{11}} + m_1 g x\,. \qquad (4)$$

The calculations in Mathcad system of the distribution $U(x,\theta_1)$ have shown that for the fluxes in the rings of the opposite polarity the equilibrium states of the superconducting ring in the field of the ring, fixed

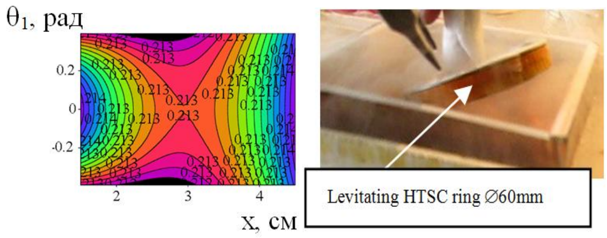


a b

Fig. 2. a) Equipotentials distribution of the system of two rings on the coordinate x of the free superconducting ring and the deflection angle θ_2 of its axis from the vertical (system common axis) in the uniform gravitational field: R_1=4.75 cm, R_2=2.5 cm, a_1=0.6 cm, a_2=0.26 cm, J_1=100 A, $\Phi_2=2\cdot10^{-4}$ Wb, m_2=15.3 g; b) the photo of the stable in x and θ_2 levitating state of HTSC ring in the field of the supporting coil with the constant current, corresponding to the calculated distribution in Fig. 2,a

below, are stable with respect to the shift of the levitating ring plane along the common axis and unstable to the deflection of its axis from the vertical.

As an example, the equipotentials distributions and photo of the corresponding to it levitating state for the ring from HTSC wire ∅60 mm is shown in the Fig. 3.



a b

Fig. 3. a) Equipotentials distribution of the system of two rings on the coordinate x of the free superconducting ring and the deflection angle θ_1 of its axis from the vertical (system common axis) in the uniform gravitational field: R_2=4.75 cm, R_1=3.0 cm, a_2=0.6 cm, a_1=0.35 cm, J_2=200 A, $\Phi_1=-1.8\cdot10^{-4}$ Wb, m_1=32.83 g; b) the photo of the unstable levitating state of HTSC ring in the field of the supporting coil with the constant current (it is fixed on the bottom of container), corresponding to the calculated distribution in Fig. 3,a

The calculations in Mathcad system of the distribution $U(x,\theta_1)$ have shown that for the fluxes in the rings of the same sign the equilibrium states of the superconducting ring in the field of the ring, fixed below, which are stable both 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. The example of the calculation illustrating the existence of minimums for such systems under the definite values of parameters is given in the Fig. 4.

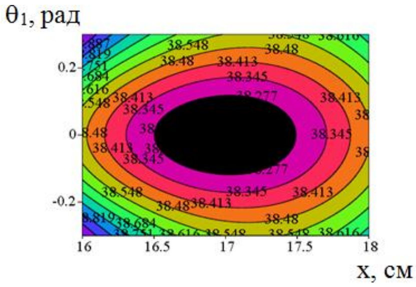


Fig. 4. Equipotentials distribution of the system of two rings on the coordinate x of the free superconducting ring and the deflection angle θ_1 of its axis from the vertical (system common axis) in the uniform gravitational field: R_1=20 cm, R_2=25 cm, a_1=1.5 cm, a_2=0.6 cm, $\Phi_1=5\cdot10^{-3}$ Wb, $J_2=5\cdot10^4$ A, $m_1=2\cdot10^4$ g

3. LEVITATION OF TWO MYXINI IN FIELD OF FIXED RING WITH CURRENT

For the system of three rings, shown in the Fig. 1, besides the deflection angles θ_2 and θ_3 of the levitating rings № 2 and № 3 from the vertical, it is necessary to introduce into the consideration one more variable – the angle φ. It is the angle between the projections of the normals $\vec{n}_2$ and $\vec{n}_3$ to the planes of the rings №2 and № 3 onto the horizontal plane.

Assuming that the magnetic fluxes trapped by the superconducting rings (№2 and 3) remain unchanged, and the current in the nonsuperconducting ring (№1) is maintained constant, by analogy with [5]:

$$J_1 = const;\ L_{ik} = L_{ki};$$
$$L_{21}J_1 + L_{22}J_2 + L_{23}J_3 = \Phi_2 = const, \qquad (5)$$
$$L_{31}J_1 + L_{32}J_2 + L_{33}J_3 = \Phi_3 = const.$$

Now the potential function, formally coinciding with the expression in [5], is the function both the coordinates of the levitating coils x_2 and x_3, and the angles θ_2, θ_3, φ:

$$U(x_2,x_3,\theta_2,\theta_3,\phi)=\frac{1}{2}\left(L_{22}J_2^2+2L_{23}J_2J_3+L_{33}J_3^2\right)+m_2gx_2+m_3gx_3. \qquad (6)$$

In formulae (1)-(6) Φ_i – the magnetic flux trapped by *i*th ring; L_{ik} – coefficients of the self- and mutual induction of the rings; J_k – currents in the rings; m_i – mass of *i*th ring.

In order to carry out the calculations of the potential energy distributions the formulae for the coefficients of the rings mutual induction $L_{12}(x,\theta)$ for the system of two rings and $L_{ik}(x_i,x_k,\theta_i,\theta_k,\varphi)$ for the system of three rings, correspondently, have been deduced (formulae are not represented because they are too cumbersome ones).

The search of the stable levitating states of two myxini in the field of the fixed ring with the current is carried out step by step. The example of this search for the system of HTSC ring with ∅31 mm [4] and the ring from HTSC wire ∅60 mm in the field of the supporting coil with the constant current for the fluxes of the same polarity is represented in Fig. 5. Calculations have been carried out under the following values of parameters: R_1=4.75 cm, R_2=3.0 cm, R_3=1.15 cm, a_1=0.6 cm, a_2=0.35 cm, a_3=0.4 cm, $J_1=1\cdot10^2$ A, $\Phi_2=7\cdot10^{-4}$ Wb; $\Phi_3=3.18\cdot10^{-5}$ Wb, m_2=32.83 g, m_3=9.7 g. At first, having specified the values of the physical parameters, the field of values of the variables x_2 and x_3 is defined, where the equilibrium levitating states of superconducting rings, stable relative to the vertical shifts of their plane along the common axis, are realized (see Fig. 5,a). Then this field of parameters is tested for the stability in θ_2, θ_3 and φ respectively (see Figs. 5,b, c, d). The photo of the stable in x and θ levitating state of the system of HTSC ring with ∅31 mm and the ring from HTSC wire ∅60 mm in the field of the supporting coil with the constant current, corresponding to the calculated distribution in Fig. 5,a, is presented in Fig. 5,e.

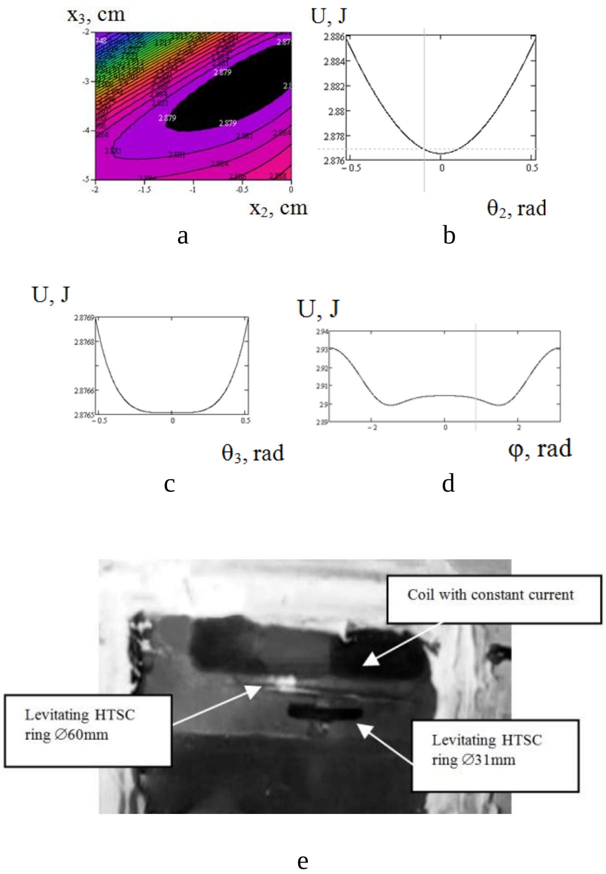


Fig. 5. a) the determination of the field of the stability on coordinates x_2 and x_3; b) the testing of the defined field of stability in coordinates x_2 and x_3 for the stability relative to the deflections of the axis of the top levitating ring by the angle θ_2; c) the testing of the defined field of stability in coordinates x_2 and x_3 for the stability relative to the deflections of the axis of the bottom levitating ring by the angle θ_3; d) the testing of the field of the stability in x_2, x_3, θ_2, θ_3 for the stability relative to the angle φ; e) the photo of the stable in x and θ levitating state of the system, corresponding to the calculated distribution in Fig. 5,a

CONCLUSIONS

Realized earlier experiments in levitation of HTSC rings in the field of the fixed rings with the constant current under the same sign of the fluxes in rings [5] have shown that levitating states both one and two rings in the field of ordinary coil with the constant current, founded by the dependence $U(x)$ of the potential energy only from the coordinate, were stable not only to the shift of their plane along the vertical (along the common axis), but also to the deflection angle θ of their axis from the vertical. The analytical dependencies $U(x,\theta)$ confirm this fact and allow due to their generality to determine the field of stability in x and θ under any values of the physical parameters.

This study was supported by the Ministry of Education and Science of the Russian Federation and in part by the Russian Foundation for Basic Research (project nos. 13-08-00717 and 12-01-00071).

REFERENCES

1. A.I. Morozov, V.V. Savel'ev. On Galateas – magnetic traps with plasma-embedded conductors // *Physics-Uspekhi*. 1998, v. 41, № 11, p. 1049-1089.

2. A.M. Bishaev, A.A. Bush, et al. The Potential Energy of a Superconducting Ring System Locking Magnetic Flows in a Gravity Field // *Technical Physics Letters*. 2012, v. 38, № 10, p. 880-883.

3. A.M. Bishaev, M.V. Kozintseva, et al. About Levitation of Superconducting Rings for Magnetic System of Multipole Plasma Trap // *Problems of Atomic Sciences and Technology. Series "Plasma Physics" (19).* 2013, № 1, p. 48-50.

4. A.M. Bishaev, M.V. Kozintseva, et al. Equilibrium of a System of Superconducting Rings in a Uniform Gravitational Field // *Technical Physics*. 2013, v. 58, № 5, p. 684-691.

5. A.M. Bishaev, M.V. Kozintseva, et al. Levitating States of Superconducting Rings in the Field of a Fixed Ring with Constant Current // *Technical Physics*. 2014, v. 59, № 6, p. 940-943.

6. L.D. Landau and E.M. Lifshitz. *Course of Theoretical Physics.* Vol. 8: *Electrodynamics of Continuous Media*. Pergamon, New York, 1984.

Article received 10.12.2014

ОБ УСТОЙЧИВОСТИ ЛЕВИТИРУЮЩИХ СОСТОЯНИЙ СВЕРХПРОВОДЯЩИХ МИКСИН ПЛАЗМЕННЫХ ЛОВУШЕК-ГАЛАТЕЙ

А.М. Бишаев, А.А. Буш, М.Б. Гавриков, А.И. Денисюк, О.Ю. Дьяконица, К.Е. Каменцев, М.В. Козинцева, Т.Г. Колесникова, В.В. Савельев, П.Г. Смирнов, М.М. Шаповалов, С.А. Воронченко

Для разработки плазменной ловушки с левитирующими сверхпроводящими магнитными катушками нужно выполнить поиск их устойчивых левитирующих состояний. С этой целью, исходя из свойства сверхпроводников сохранять захваченный магнитный поток, в однородном поле силы тяжести в приближении тонких колец получена аналитическая зависимость потенциальной энергии одного либо двух сверхпроводящих колец, захвативших заданные магнитные потоки, в поле закрепленного кольца с постоянным током от координат свободных колец и углов отклонения их осей от общей оси системы. При совпадающих по знаку потоках в кольцах существование найденных из расчетов равновесных левитирующих состояний для изготовленных ВТСП колец, устойчивых по отношению к вертикальным смещениям левитирующих колец и к отклонению их осей от вертикали, было подтверждено экспериментально.

ПРО СТІЙКІСТЬ ЛЕВІТУЮЧИХ СТАНІВ НАДПРОВІДНИХ МІКСИН ПЛАЗМОВИХ ПАСТОК-ГАЛАТЕЙ

А.М. Бішаєв, А.А. Буш, М.Б. Гавріков А.І. Денісюк, О.Ю. Дьяконіца, К.Є. Камєнцев, М.В. Козінцева, Т.Г. Колеснікова, В.В. Савєльєв, П.Г. Смірнов, М.М. Шаповалов, С.А. Воронченко

Для розробки плазмової пастки з левітуючими надпровідними магнітними котушками потрібно виконати пошук їх стійких левітуючих станів. З цією метою, виходячи з властивості надпровідників зберігати захоплений магнітний потік, в однорідному полі сили тяжіння в наближенні тонких кілець отримана аналітична залежність потенційної енергії одного або двох надпровідних кілець, які захопили задані магнітні потоки, у полі закріпленого кільця з постійним струмом від координат вільних кілець і кутів відхилення їх осей від загальної осі системи. При співпадаючих за знаком потоках у кільцях існування знайдених з розрахунків рівноважних левітуючих станів для виготовлених ВТНП кілець, стійких по відношенню до вертикальних зміщень левітуючих кілець і до відхилення їх осей від вертикалі, було підтверджено експериментально.