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2012 J. Phys.: Conf. Ser. 400 022009

(http://iopscience.iop.org/1742-6596/400/2/022009)

Journal of Physics: Conference Series **400** (2012) 022009 doi:10.1088/1742-6596/400/2/022009

The critical state of a superconducting ring caused by a current

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Abstract. The distribution of a transport current in the branches of a superconducting ring of microwire at achievement of a critical state in one of branch microwire is experimentally investigated. This branch had a "weak" region in the form of local microwire narrowing or in the form of the point contact between microwires. Self-oscillations of a current in a ring with narrowing and their absence in a ring with the point contact are found out. The currents in the branches of a ring with the point contact change in steps when the direct transport current through the point contact exceeds critical value. The role of parametrical inductance of the "weak" region and the microstructure of point contact as quantum interferometer in the formation of critical state of the “weak” regions and features of the distribution of a current in the branches of the rings are discussed.

1. Introduction

The most known superconducting devices are the doubly connected structures. The quantum interferometers (SQUIDs), the shortly closed superconducting coils as the sources of a magnetic field, superconducting magnetic shields are attributed to them. The doubly connected structures are also elementary cells of the complex multiply connected granulated superconductors, in particular, the modern high - temperature ceramics. The definition of properties of the doubly connected superconductors (DCS) is an actual problem. Superconducting ring is the simplest form of DCS. One of the important properties of such ring is the distribution of a transport current on its branches. The Nobel Prize winner M. von Laue was one of the first who studied this property in the completely superconducting ring when currents in branches is less than critical value [1].Thus a magnetic field in a ring and its magnetic energy is remained equal to zero. The distribution of a current in the branches of a ring, one of which is in critical state, was the objective of our researches.

2. Experiments

Two types of the rings have been studied. The ring of the first type with diameter of some centimeters was made of 100 μm in diameter tantalum microwire (Fig.1a). One of the branches of the ring contained a region of narrowing with diameter about 30 μm (form of the region is shown on insert of Fig.1a). The narrowing was made by method of local chemical etching of tantalum. The transport current (I) supply to a ring was executed through points 1-2 with the distance of 1 mm between them.
The inductance of this branch in a normal state was equal to $L_1 \approx 10^{-8}$ H. The current (I_2) in other branch (without narrowing) was defined from the magnetic field value created by the branch current. The part of this branch was executed as a coil having inside detector of a fluxgate magnetometer (FG)

with sensitivity of 10^{-9} T. The general inductance (L_2) of this branch was defined basically by the inductance of the coil and was equal to $5x10^{-6}$ H.

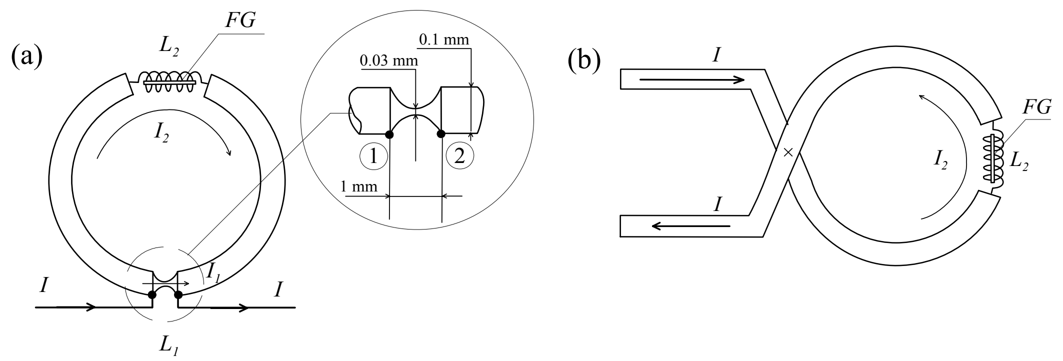

Figure 1. Diagrams of two types of superconducting rings with a narrowing region (a) and with a point contact (b); I – a direct transport current through the rings; I_1 and I_2 – currents in short and long branches of the rings; L_1 and L_2 – inductances of the branches; FG is the fluxgate detector; × is the position of the point contact between niobium conductors.

The ring of the second type with same diameter was made of 70 μm in diameter niobium microwire (Fig.1b). This ring contains a clamping point contact (PC) formed by placing and pressing up micro wire ends together. The contact is short branch of the ring. The calculated inductance of the PC in a normal state did not exceed $L_1 = 10^{-11}$ H. The transport current I supply into the ring was executed through the microwire ends. The current I_2 was defined as well as in case of first type ring. The long branch inductance L_2 was equal to $5x10^{-6}$ H. The ratio between the critical currents of the branches in both types of the rings was equal to $I_{c2} / I_{c1} >> 1$.

The rings was immersed in liquid helium at T = 4.2 K. The dependences of the current I_2 of the branch with greater inductance L_2 on the value of a transport current I through the rings of both types have been studied.

3. Results and discussion

The distribution of transport current in branches of first type ring we shall consider in the beginning. The current I_2 is not registered by the fluxgate up to the value of the transport current equal to critical current of the narrowing (I_{c1} = 20 mA). According to [1] such distribution is explained by $L_2 >>L_1$. It is worth to note that the critical current of the second branch was much greater ($I_{c2} \approx 450$ mA) and inductance L_2 is superconducting shunt for the narrowing. At $I = I_{c1}$ there are quasi-harmonic undamped self-oscillations of a current (SO_I) in a branch with the coil and it is kept at $I > I_{c1}$ (Fig.2a). The greatest SO_I amplitude is about of 1 % of I_{c1} value. The amplitude of the SO_I is decreased at I current increase and SO_I frequency was equal to 2 Hz. The possible SO_I reason is influence on the current distribution in branches of a ring not only the initial geometrical inductance of the branches but also the kinetic inductance of the narrowing at $I = I_{c1}$. This narrowing can be considered as volumetric long bridge (with a length, much greater, than a coherence length of tantalum) between sites of the tantalum wire with the diameter of 100 μm at the temperature (T) close to the critical value (T/T_c = 0.95). The periodic transition of a current into the branch with a coil and its return to the branch with the narrowing can be explained by periodic increase of a parametrical kinetic inductance of the narrowing. The increase of a current in the branch with a greater inductance at $I \approx I_{c1}$ causes the increase of magnetic energy of the ring. For its reduction the current return back in an initial position and again reaches the critical value. Further the process is repeated. Whether can weak resistivity of the narrowing arise at self-oscillations of a current? The answer to this question can be received after additional researches. The discussion of other features of the SO_I was made by us in [2].

The distribution of a current in the branches of second type ring is very much different from the first type ring. All transport current exceeding I_{c1} acts in a branch with the inductance L_2 without the occurrence of the SO_I (Fig.2b). The dependence I_2 (I) is in steps modulated. The height of the current steps along axis I_2 and their width along axis I are equal each other. A reduction of a current I from its any value in a range $I_{c1} < I < 2I_{c1}$ up to zero and from its any value in a range $2I_{c1} < I < I_{c2}$ on a value $\delta I = 2I_{c1}$ occurs without change of a current I_2. These areas of the change of the current I can be titled as areas of quasi - freezing values of the current I_2. After switching off the current I exceeding a I_{c1} value current I_2 freezing according to the dependence I_2 (I) is occurred. Thus, simple increase in a current I up to necessary value and its subsequent switching off can allow to adjust a value of the frozen current I_2 and the frozen magnetic field in the coil with the inductance L_2.

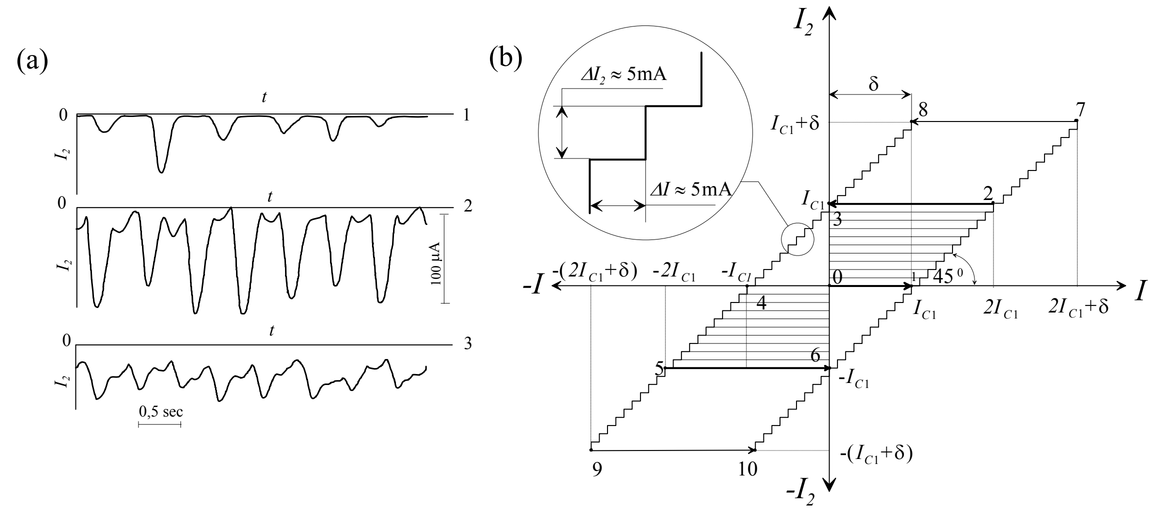

Figure 2. (a) Self-oscillation of the current I_2 in long ring branch (it is shown on Fig.1a) for the different values of the direct transport current I, mA: 20 (1), 20.3 (2), 21.5 (3). (b) Experimental dependence of the current I_2 in the branch with inductance L_2 versus the transport current magnitude I through the ring which is shown on Fig. 1b, δ - value of direct transport current added to $I = 2I_{c1}$ such that the section 7-8 of the "plateau" is shifted relative to the axis I_2 by δ in contrast to similar "plateaus" arising as the current I decreases from $I \leq 2I_{c1}$ (the lines of several "plateaus" in the regions 1-2-3-0 and 4-5-6-0).

The change of the distribution of a current in the branches of this ring at $I = I_{c1}$ corresponds to the achievement of the critical state of the PC shunted by the superconducting inductance L_2. The occurrence of the critical state of the PC can be explained by increase of the parametrical Josephson inductance L_J of a weak region of a branch in the form of the PC at the approach of a transport current to the critical value. A value of the L_J can be estimated under the formula [3]: $L_J = \Phi_0 / (2\pi I_c \cos\varphi)$, where Φ_0 – a quantum of a magnetic flux, φ - a difference of the phases of the wave functions of the Cooper pairs on the boundaries of the PC. A value of φ depends on a current through the PC and at $\varphi = \pi/2$ theoretically can cause the increase of the L_J indefinitely. The form of the dependence I_2 (I) indicates that the parametrical inductance at $I = I_{c1}$ considerably exceeds the inductance of a coil $L_2 = 5 \times 10^{-6}$ H. A property of a ring with the PC to freeze the current excludes an occurrence of the self-oscillations of a current in its branches unlike a ring of the first type.

The current steps of the dependence I_2 (I) can be explained by the complex microstructure of the clamping PC. The several casually formed microcontacts, connected in parallel, form the clamping PC. Such structure is similar to a quantum interferometer with the several Josephson contacts. The current I creates a magnetic field acting on the interferometer. In particular, a critical current of interferometer with two micro contacts is changed periodically at the change of this current. It causes the periodic change of its parametrical inductance L_J. The modulation of the L_J leads in this case to the

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periodic change of conditions for the passage of a transport current to the greater branch of a ring containing the coil. As a result the periodic current steps are appeared. More detailed analysis of the occurrence of the current steps is made by us in [4].]. For explanation of the regular steps periodicity of the I_2 (I) dependence in the case of the interferometer with many various micro contacts the additional researches are needed.

4. Summary

The critical state of one of the branches of a superconducting ring can be caused by the increase of the kinetic or the Josephson inductance of a branch "weak" region at the transport current value close to the critical value. The narrowing in a superconducting conductor or the clamping point contact between the superconductors are such "weak" regions. This critical state is shown differently depending on the extent of a “weak” region. Besides, the direct transport current is frozen in the ring with point contact in the form of the portions (quantums) at the reduction of the current from values exceeding critical current of the contact. This phenomenon can be the reason of the occurrence of a frozen magnetic field in the granulated superconductors and the superconducting cables with multiply connected cores at a cycle variation of a transport current and can be put in a basis of the advance of a new type of the shortly closed coil with the point contact in the form of an adjustable source of a magnetic field without a thermal switch.

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