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INVESTIGATION OF RF-SQUID AT LIQUID NITROGEN TEMPERATURE

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The results of investigation of two-hole Y–Ba–Cu–O rf squids operating at liquid nitrogen temperatures are reported. The magnetic flux white noise level of 10^{-4} Φ_0 ($\Phi_0 \approx 2.07 \cdot 10^{-15}$ Wb) is determined by amplifier since it is equal to white noise level of low-temperature squid with the same amplifier. Overall 1/f fluctuations develop at frequencies below 20 Hz. The measurement methods and the results of the main parameters measurements are given.

The investigation has been performed at the Laboratory of Neutron Physics, JINR.

Исследование ВЧ-сквида, работающего при температуре жидкого азота

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Описаны результаты исследования двухиндуктивных радиочастотных сквидов из Y–Ba–Cu–O, работающих при температуре жидкого азота. Показано, что уровень белого шума по потоку, примерно равный 10^{-4} Φ_0 ($\Phi_0 \simeq 2{,}07 \cdot 10^{-15}$ Вб), определяется, в основном, шумом усилителя, т.к. точно соответствует белому шуму низкотемпературного сквида с тем же усилителем. Избыточные флуктуации типа 1/f проявляются на частотах ниже 20 Гц. Приведена методика измерения и результаты измерения основных параметров сквида.

Работа выполнена в Лаборатории нейтронной физики ОИЯИ.

In the past year the development of several YBaCuO oxide ceramic squids operating at liquid nitrogen temperatures has been reported. In/1-4/ the encouraging results were obtained: the intrinsic noise of interferometers resulted in less than $5 \cdot 10^{-4}$ $\Phi_0/\mathrm{Hz}^{1/2}$. Which is enough for these devices to be applied in the measurement technique.

Further investigations have shown that the parameters of high-T_c ceramic squids were rather reproducible. Furthermore, the improved technique of ceramic preparation and the advanced methods of the weak link creating have led to better results.

It seems tempting, therefore, to measure these squids characteristics with more care and precision and to compare in more detail the behavior of these devices with that of conventional niobium squids. This is the aim of the present paper.

1. Experimental Technique. Squid Fabrication

In main features of the experimental technique and squid fabrication were described in/2/. Our squids, equally to those described earlier, were made from 2 mm $Y_1Ba_2Cu_3O_{7-\delta}$ ceramic pellets prepared by a standard procedure of solid state reaction/5/. Above 92-93 K a narrow superconductive transition was observed in the ceramic used for our experiment. This ceramic critical current was greater than 30 A/cm^2. Squids were built from the previously tested pellets that did not demonstrate bulk-squid effect.

Two 1-1.6 mm holes situated close one to another were drilled in the pellets, then the region between the holes was filled away and the weak link was created.

The squid was put inside a valve coupled to a measurement tube which in its lower part was sealed in a stainless steel cylinder with a soldered bottom. In this cylinder the gauge pressure of dry gaseous helium was hold and inside it the valve containing the squid was lowered to a liquid nitrogen dewar. All these measures protected squid from moisture throughout several thermal cycles when by filling the bridge in stages the optimal value of its critical current was obtained.

Squid hysteretic parameter

$$\beta = 2\pi L_s I_c/\Phi_0 \qquad (1)$$

was 2-5 at liquid nitrogen temperatures when the bridge with typical size of 10 μm x 10 μm x 10 μm had been made.

2. Squid Parameter Measurement

In fig.1 squid of inductance L_s and a weak link with critical current I_c inductively coupled to a tank circuit L_t C_t is schematically represented. Rf generator G_{rf} pumps the tank circuit at frequency close to tank

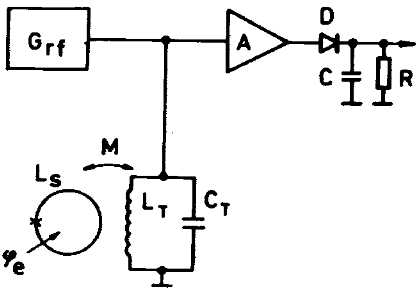

Fig.1. Schematic representation of the squid with L_s inductance and current I_c inductively coupled with tank circuit L_tC_t. G_{rf} – rf-generator. A – low-noise rf-amplifier. D, C – amplitude detector.

circuit resonant frequency $\omega_p = (L_tC_t)^{-1/2}$. Voltage supplied from the circuit is amplificated by lownoise rf-amplifier A and is detected by an amplitude detector assembled from D.C. elements.

2.1. Squid Intrinsic Inductance L_s

It is very important to determine squid intrinsic inductance to be sure that superconducting ring is inside the fabricated hole and not inside some "parasitic" circuit of the sample as in the bulk squid.

The L_s can be evaluated from resonant circuit parameters and the value of current I_0 in a circuit shifting the voltage-flux characteristic of squid at a value of Φ_0.

Being coupled to the squid tank circuit inductance L_t will reduce to

$$L_t' = L_t(1 - k^2), \tag{2}$$

where k is coefficient of coupling between squid and inductance. Tank circuit resonant frequency will increase proportionally. Measuring the frequency shift, L_t being known, one can calculate coefficient of coupling. Beside this, one can evaluate a value of current I_0 by passing direct current through L_t coil and thus determine mutual squid-circuit inductance

$$M = \Phi_0/I_0. \tag{3}$$

By definition

$$M = k(L_t'L_s)^{1/2}, \tag{4}$$

so

$$L_s = M^2 C_t/(\omega_p^{-2} - \omega_p'^{-2}). \tag{5}$$

Here $\omega_p' = (C_t L_t')^{-1/2}$ is resonant frequency of a circuit coupled to the squid.

During the ω_p measurement the squid became nonsuperconductive at temperature above T_c. To avoid an error of capacitance C_t changing with temperature the ω_p measurement was made at a temperature a little higher than T_c.

Measurement of ω_p' was carried out at liquid nitrogen temperatures and at a low pumping level which did not cause dissipative processes in the squid. The current I_0 value was measured by output voltage of amplitude detector.

2.2. Intrinsic Noise Spectrum S_ϕ (ω)

The value of squid magnetic flux resolution $<\Delta\Phi>$ is determined by spectral density of noises S_ϕ (ω). The S_ϕ (ω) was measured by standard procedure at the integrator output in the flux-locked mode. Squid was well shielded from ambient noise and the data were processed by FFT method.

Squid power resolution is

$$\epsilon = S_\phi^2(\omega)/2L_s. \tag{6}$$

3. Squid Parameters at Liquid Nitrogen Temperatures

For our experiment the squid with $\beta = 3$ at 78 K was taken.

The measurements have shown that

$$C_t = (380 \pm 10)\ \mathrm{pF}, \tag{7}$$

$$f_p = (20.82 \pm 0.01)\ \mathrm{MHz}, \quad f_p' = (21.08 \pm 0.01)\ \mathrm{MHz} \tag{8}$$

and

$$I_0 = (3 \pm 0.1)\ \mu\mathrm{A}. \tag{9}$$

The quality of rf tank circuit was $Q = 50$.

Then we have

$$L_t = 0.146 \pm 0.01\ \mu\mathrm{H}, \quad L_t' = 0.142 \pm 0.01\ \mu\mathrm{H} \tag{10}$$

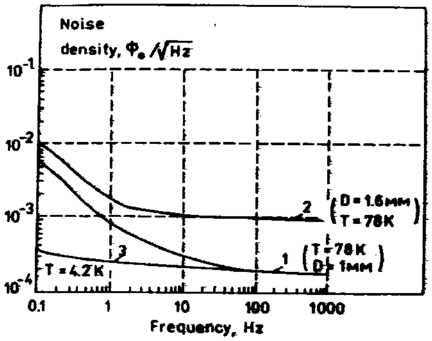

Fig.2. The rf-squid spectral noise density. Curve 1 corresponds to the squid with 1 mm superconducting ring at T = 77 K; curve 2, the squid with 1.6 mm superconducting ring at T = 77 K; curve 3, the standard niobium squid at T = 4.2 K.

$$k = 0.155 \pm 0.01 \tag{11}$$

and

$$L_s = (1.2 \pm 0.1) \cdot 10^{-10}\ \mathrm{H}. \tag{12}$$

Noise spectral density $S_\phi\ (\omega)$ is represented in fig.2. This figure shows that squid magnetic flux resolution in the white noise region in 1Hz bandwidth at liquid nitrogen temperatures is:

$$S_\phi\ (\omega) = 2 \cdot 10^{-4}\, \Phi_0/\mathrm{Hz}^{1/2} \tag{13}$$

Squid energy resolution is:

$$\epsilon = 6{,}6 \cdot 10^{-28}\ \mathrm{J/Hz}. \tag{14}$$

4. Results and Discussion

Our experiments have shown that in main features high-T_c squid behavior is very similar to that of low-T_c one. Being slowly cooled below T_c squid has been found to enter first nonhysteresis state with $\beta < 1$. Squid signal was detected both at positive and negative detuning of generator G_{rf} frequency relatively the ω_p. There was no signal at resonance which is natural in the nonhysteretic mode. At a temperature fall down when β becomes a little more than 1 the maximum signal in the amplitude detector output shifts to a positive tuning and at 78 K enters the normal hysteretic state with maximum signal at a resonant frequency.

In fig.3 the volt-current characteristic obtained at liquid nitrogen temperatures is shown. Squid volt-oersted characteristic at the same temperature in a bandwidth 10 kHz is given in fig. 4.

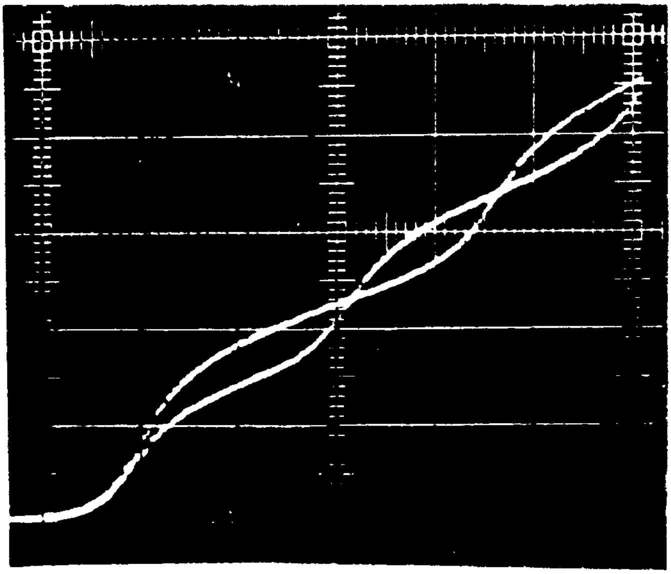

Fig.3. Volt-current characteristic of the squid with 1 mm holes at T = 77 K in bandwidth 1 kHz.

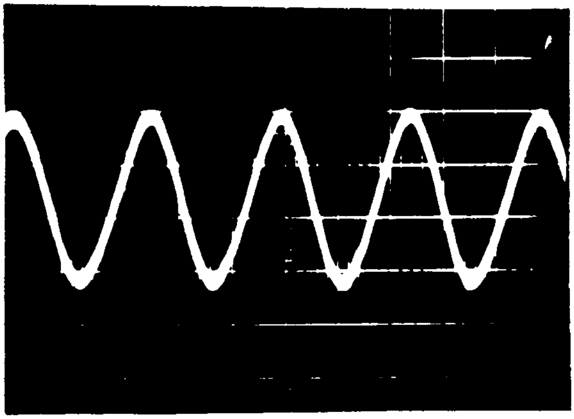

Fig.4. Volt-oersted characteristic of the squid with 1 mm holes at T = 77 K in a bandwidth 10 kHz.

During our investigation a typical property of rf squid was noted: I_0 value changing with temperature. In figures 5a and 5b output signals of amplitude detector when squid was influenced by homogeneous linearly increasing with time magnetic field are represented. The response in Fig.5a belongs to the squid operating at liquid nitrogen temperatures. In fig. 5b the squid response at elevated temperature in the evaporated liquid nitrogen near T_c can be seen. These figures illustrate that when

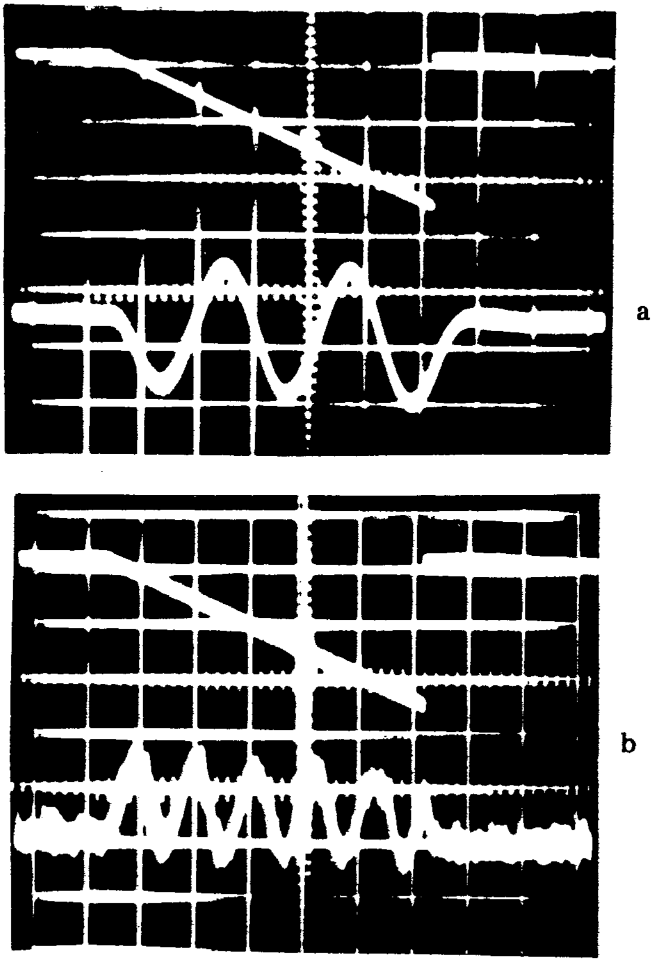

Fig. 5. The output signal of amplitude detector when squid was influenced by homogeneous linearly increasing magnetic field. a – squid signal at liquid nitrogen temperature; b – the signal of the same squid operating in evaporated liquid nitrogen near T_c.

temperature increases I_0 value becomes approximately 2 times greater.

We have found that the above-mentioned I_0 increment is connected with increasing squid inductance which in turn may be caused by breaking of superconductive switches between superconductors grains in the ceramics with a consequent increasing of superconducting ring. Probably it is connected with doubled period of squid volt-oersted characteistic in nonhysteretic mode.

The inductance L_s of squid with response (see fig. 5b), which at liquid nitrogen temperature has L_s given in (12), at a temperature close to T_c is $3.8 \cdot 10^{-10}$ H.

To estimate squid sensitivity we have noise current caused by normal resistance of Josephson contact R:

$$<I_n^2> = 4kT\Delta f/R. \tag{15}$$

Here Δf is the noise bandwidth of the squid, R is the Josephson junction normal resistance.

Reliability of the system requires

$$<I_n^2>^{1/2} L_s << \Phi_0. \tag{16}$$

Taking account of (15) we have

$$L_s^2 << \Phi_0^2 R/4k_b T\Delta f, \tag{17}$$

as the squid bandwidth is

$$\Delta f = (R/2\pi L_s)\pi/2 = R/4L_s \tag{18}$$

and the constant of time characteristic of the squid is

$$\tau_s = L_s/R \tag{19}$$

we'll get

$$L_s << L_{max}, \tag{20}$$

where

$$L_{max} = \Phi_0^2/k_b T. \tag{21}$$

At T = 77 K, we'll have

$$L_{max} = 4 \cdot 10^{-9} \text{ H}. \tag{22}$$

According to (8) inductance of squid with 1.6 mm holes is $6 \cdot 10^{-10}$ H.

Thus, high-T_c superconductors use practically does not limit the squid inductance. One can roughly estimate high-T_c squid intrinsic noise making an assumption about the squid contact resistance value.

If we suppose the ceramic impedance to be

$$\rho = 1\ \mathrm{m\Omega\ cm}$$

and contact size to be about 10 μm x 10 μm x 10 μm, then the contact resistance is

$$R = 1\,\Omega.$$

In this case according to equation (15) in a $L_s = 10^{-10}$ H inductance squid in a bandwidth 1 Hz a noise flux will arise

$$\Phi_n = 10^{-5}\ \Phi_0,$$

i.e. here like in the low temperature squids circuit and amplifier noises which are usually by an order of magnitude higher must play the main role. The performed high-T_c squid noise measurements agree with this conclusion.

In fig.2 the noise spectrum $S_\phi\ (\omega)$ of HTS squid operating at liquid nitrogen temperatures (curve 1) is shown. One can see that the white noise level of about $10^{-4}\ \phi_0$ is in fact determined by the amplifier noise because it is identical to the low-T_c squid white noise with the same amplifier (curve 3).

We explain the excessive 1/f fluctuations by random switching of several Josephson contacts which varies the superconducting ring area.

It should be noted that the described squids emanated 1/f noises at frequencies below 20 Hz but not 100 Hz as described earlier in our previous paper/2/. It may be connected, we suppose, with the improved ceramics quality.

Recently in our Laboratory the squids from ceramics with high critical current density ($J_c > 150$ A/cm^2) were built. Though it turned out more difficult to fabricate Josephson contacts in such devices, they have demonstrated, however, high operating characteristics: stable operation without shielding which permits its practical use.

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