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Cooled ferromagnetic shield as a part hybrid system for isolation of a flux qubit from electromagnetic environment

O.G. Turutanov[1], V.Yu. Lyakhno[1], A.P. Boichenko[1], A.P. Shapovalov[2,3], A.A. Kalenyuk[2,3], I.A. Martynenko[2,3]

turutanov@ilt.kharkov.ua
[1]B.I. Verkin Institute for Low Temperature Physics and Engineering, National Academy of Sciences of Ukraine, 47 Nauky Avenue, Kharkiv 61103, Ukraine
[2]G.V. Kurdyumov Institute for Metal Physics, National Academy of Sciences of Ukraine, 36 Academician Vernadsky Boulevard, Kyiv 03142, Ukraine
[3]Kiev Academic University, 36 Academician Vernadsky Boulevard, Kiev 03142, Ukraine

ORCID: 0000-0002-8673-136X, 0000-0002-2543-1240, 0000-0002-2444-2052, 0000-0002-2181-9416, 0000-0002-7212-434X
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Currently, circuits for quantum informatics, communications and measuring equipment containing superconducting flux qubits in a planar design are being created by quantum engineering techniques. To function, such structures must be cooled in a refrigerator down to about 10 mK. The flux qubits have linear size of superconducting circuit of some tens of micrometers and are very sensitive to external magnetic fields and their variations. The qubit built in the gradiometer-like design has reduced sensitivity to external uniform magnetic fields, but remains quite sensitive to their variations. To protect the qubit from unwanted external magnetic fields, which include the Earth's field, man-made fields, and residual magnetic fields of the cryostat parts, it is necessary to create efficient magnetic shields. Earlier, we proposed a scheme for a single-photon microwave counter, in which a planar flux qubit in a gradiometer version serves as the receiving element. To let it function properly, a 3-layer hybrid magnetic shield composed of two superconducting and one ferromagnetic cylinders, has been designed for installation in a dilution refrigerator at 10 mK temperature. The effectiveness of such a shield depends on the correct design of all three shells. This paper presents the results of calculation and magnetic measurements of a cylindrical ferromagnetic screen made of low-temperature permalloy Cryoperm 10 in dc and low-frequency alternating magnetic fields. Cryoperm 10 keeps high magnetic permeability at liquid helium temperatures and below. It is shown that this shield is able of reducing the absolute value of the magnetic field and its variations by 55-70 dB. Together with superconducting lead magnetic shields, this design will reduce the absolute value of the field by 70 dB, and the field variation by 200 dB, which will provide the necessary conditions for the operation of a single-photon counter based on a flux qubit.
Keywords: magnetic shielding, ferromagnetic shield, low temperatures, permalloy, Cryoperm, flux qubit, electromagnetic environment

Охолоджуваний феромагнітний екран як частина гібридної системи ізоляції надпровідникового потокового кубіту від електромагнітного оточення

О.Г. Турутанов[1], В.Ю. Ляхно[1], А.П. Бойченко[1], А.П. Шаповалов[2,3], О.А. Каленюк[2,3], І.О. Мартиненко[2,3]

turutanov@ilt.kharkov.ua
[1]Фізико-технічний інститут низьких температур ім. Б.І. Вєркіна НАН України, 47 Проспект Науки, Харків 61103, Україна
[2]Інститут металофізики імені Г.В. Курдюмова НАН України, 03142, Київ, бульвар Академіка Вернадського, 36
[3]Київський академічний університет, бульвар Академіка Вернадського, 36, Київ 03142, Україна

Наразі квантові схеми для квантової інформатики, комунікаційного та вимірювального обладнання, що містить надпровідні потокові кубіти в планарному дизайні створюються методами квантової інженерії. Для нормальної роботи такі конструкції мають бути охолодженими у рефрижераторах розчинення до температури близько 10 мК. Потокові кубіти мають лінійні розміри надпровідного контуру в кілька десятків мікрометрів і дуже чутливі до зовнішніх магнітних полів і їх варіацій. Кубіт, що побудований за градієнтометричною схемою, має знижену чутливість до зовнішніх однорідних магнітних полів, але збережує досить велику чутливість до їх варіацій. Для захисту кубіта від небажаних зовнішніх магнітних полів, включаючи поле Землі, рукотворні поля і залишкові магнітні поля в конструкції кріостата, необхідно створити ефективні магнітні екрани. Раніше ми запропонували схему однофотонного лічильника мікрохвильового діапазону, в якій приймальним елементом є планарний потоковий кубіт в градієнтометричному виконанні. Для забезпечення його роботи був розроблений тришаровий гібридний магнітний екран, що складається з двох надпровідних і одного феромагнітного циліндрів та призначений для установки в рефрижератору розчинення при температурі близько 10 мК. Ефективність такого екрану залежить від правильної конструкції всіх трьох оболонок. У даній роботі представлені результати розрахунку і магнітних вимірювань в постійних і низькочастотних змінних магнітних полях циліндричного феромагнітного екрану з низькотемпературного пермалою Cryoperm G10, який підтримує високу магнітну проникність при температурах рідкого гелію і нижче. Показано, що він здатний зменшити абсолютне значення поля і його варіацій на 55-70 дБ. Разом з надпровідними свинцевими магнітними екранами ця конструкція дозволить знизити абсолютне значення магнітного поля на 70 дБ, а варіації поля на 200 дБ, що забезпечить необхідні умови для роботи однофотонного лічильника на основі потокового кубіту.

Ключові слова: магнітне екранування, феромагнітний екран, низькі температури, пермалой, Cryoperm, потоковий кубіт, електромагнітне оточення

INTRODUCTION

The rapid development of quantum informatics and quantum engineering requires the creation, by means of modern lithographic technologies, of the key elements of quantum circuits - qubits [1] to provide their stable operation. Superconducting qubits are often called "artificial macroscopic atoms", since they, having macroscopic dimensions of tens and hundreds of micrometers, obey quantum laws and have a discrete energy spectrum. One of the most common types of superconducting qubits is the flux qubit, which consists of one or three Josephson junctions incorporated in a superconducting loopt. A single-Josephson-contact qubit is topologically similar to an RF SQUID loop (superconducting quantum interferometer device). The state of such a qubit is determined by the magnitude of the magnetic flux penetrating the loop. The energy levels of the qubit are extremely sensitive to changes in the external magnetic flux at a level of $0.001\Phi_0$, where $\Phi_0 = h/2e \approx 2.07 \cdot 10^{-15}$ Wb is the superconducting magnetic flux quantum (h is Planck's constant, e is the electron charge). Thus, to let the qubit exhibit its quantum behavior, it is necessary, in addition to low temperatures ~10 mK, to provide low enough and stable magnetic fields, i.e. the question arises of the magnetic shielding and, generally speaking, of the isolation of the qubit from the electromagnetic environment [2].

Earlier, we proposed [3] a scheme for a single-photon counter in the microwave range based on a flux qubit. In this design, the qubit is manufactured in the form of a planar gradiometer (Fig. 1) with the loop area of 80×(80+80) μm. This solution significantly reduces the influence of uniform magnetic fields, but the suppression of spatial variations (gradient) of the magnetic field remains an important issue.

The main methods of passive reduction of the magnetic field in a certain space region are the use of ferromagnetic and superconducting shields.

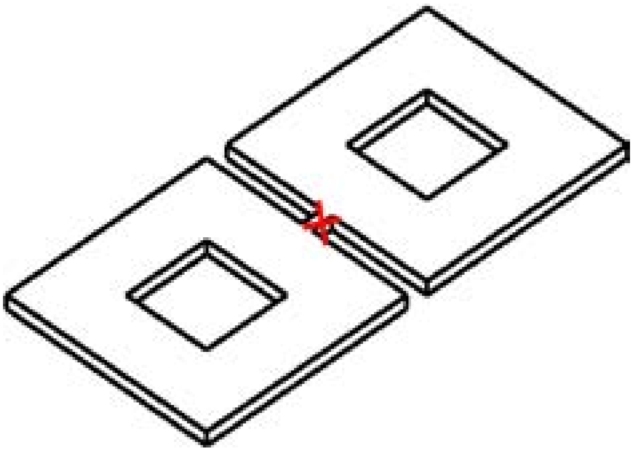

Fig. 1. Configuration of a planar (thin film) superconducting flux qubit with one Josephson contact (RF SQUID configuration), made in the form of a gradiometer.

Theoretically, superconducting shields could have an extremely high shielding factor of up to 10^{43} (a completely closed superconducting sphere) due to the Meissner-Ochsenfeld effect (pushing out the magnetic flux from the superconductor volume). However, in most cases, they are cylindrical in shape, have holes for the input electric lines and, when cooled, can capture and even concentrate the magnetic flux due to inhomogeneities of the superconducting material and improper cooling procedure. Therefore, the attenuation coefficients of the longitudinal and transverse fields do not exceed 1000 and several tens, correspondingly [5]. Superconducting shields have no equal in unique experiments on obtaining the ultimate magnetic vacuum [4], but in practical applications [6] it is advisable to combine them [7] with shields made of ferromagnetic materials that concentrate the magnetic field in their volume. Coaxially located ferromagnetic and superconducting screens not only have a higher magnetic field attenuation coefficient than taken alone, but also significantly reduce the spatial field variations. In subtle experiments with superconducting interferometers and qubits during quantum measurements, this is of decisive importance, along with careful filtering of the input circuits, and provide necessary isolation of the quantum object from the electromagnetic environment [2].

For the single microwave photon counter proposed by us [3] which is based on a flux qubit, a hybrid shield is developed [8], consisting of alternating layers of superconducting and ferromagnetic cylindrical shells. This paper presents the calculation and the data of magnetic measurements of a low-temperature ferromagnetic shield, which, in the design described above, is to be placed between two superconducting lead shells.

SAMPLE AND MEASURING TECHNIQUES

The ferromagnetic shell-under-test was a cylinder with a bottom, with the length of 115 mm, inner diameter of 26.5 mm and the wall thickness of 1 mm, made of low-temperature permalloy Cryoperm® 10 from Vacuumschmelze (Germany). The choice of the material is dictated by the fact that the magnetic permeability in low-temperature permalloy (including Cryoperm® 10) increases when lowering the temperature due to a special heat treatment, while for ordinary permalloy 79NM, 80NM it drops sharply.

According to the information from website of MuShield company [9], “Cryoperm is a soft magnetic nickel-iron alloy with about 80 % nickel, 4.2 – 5.2 % molybdenum, a saturation induction of approx. 8000 Gauss, the highest technically obtainable permeability, (Max > 350,000) and a very low coercive force. Cryoperm exhibits very high permeability at very low induction, yielding superior magnetic shielding attenuation of low flux density magnetic fields. In addition, Cryoperm is the magnetic shielding alloy of choice for cryogenic applications. Cryoperm exhibits very high permeability at 4.2 – 10 degrees Kelvin.”

The magnetic field was measured using an MF-20 fluxgate magnetometer with sensors of the longitudinal and transverse field components. The maximum and minimum measurement limits of the magnetometer were 20 G and 2 mG, correspondingly, with a measurement error of 0.2 mG. The device has an analog voltage output, which was used to control the field amplitude with an S1-83 oscilloscope when measuring in low-frequency alternating fields. The dc and ac fields were created by a 300 Oe/A solenoid, powered by a direct current source or sinusoidal voltage from the 600-ohm output of the G6-33 generator. Measurements with the solenoid were made in a two-layer permalloy screen with a diameter of 200 mm and a height of 740 mm and attenuation factor for the Earth’s field of at least 1000 (the measured residual field is less than the measurement error of the magnetometer). The shield-under-test was oriented vertically during measurements; the magnetometer sensor was located on a nonmagnetic rod made of fiberglass and moved using a screw feed with a graduation of 0.02 mm.

CALCULATIONS

The calculation procedure, based on the magnetostatic approach, of a finite-length cylindrical ferromagnetic shell, made of a high magnetic permeability material, is briefly summarized in [10]. For a cylindrical shield of finite length with a bottom, the attenuation coefficient S of the external field H_0 perpendicular to the cylinder axis is expressed by the formula

$$S = H_0 / H_i \approx (4NS_0 + 1) / (1 + D / 2L),$$

where H_0 is the field intensity outside, H_i is the field intensity inside, at the center of the shield, S_0 is the shielding factor for a cylinder of infinite length with axis perpendicular to the field, $S_0 = \mu d / D$ for $\mu >> 1$, $d << D$, and $\mu d / D >> 1$ (d is thickness of the wall of the shield, D is diameter of the shield, and N is the demagnetizing factor of an ellipsoid with the dimensional ratio $p = L / D$ (L is length, D is diameter of the shield):

$$N = [1/(p^2-1)]\{p/(p^2-1)^{1/2} \ln[p + (p^2-1)^{1/2}] - 1\}.$$

Note that the attenuation factor S is calculated at the center of the cylinder open at both ends. The field value decreases exponentially inside the cylinder along its axis [10, 11] with increasing distance from the open ends, until it reaches a minimum value. Due to the bottom, the required length of the cylindrical shell can be reduced by almost half, but close to the bottom the field increases again.

Given the parameters of our shield D=26.5 mm, L=115 mm, d=1 mm, the maximum permeability value for permalloy [9] μ=350000, we get:

$$p = L / D = 115 / 26.5 \approx 4.34, \quad D / 2L \approx 0.23,$$

$$S_0 = 350000 \cdot 1 / 26.5 \approx 13200, \quad N \approx 0.069$$

and, thus, the upper estimate for the shielding factor for the transverse field is $S \approx 2960$. According to the nomographic chart [10], the shielding factor for the longitudinal field should be 4 times less.

RESULTS AND DISCUSSION

Fig. 2 shows the axial (vertical) and transverse (horizontal) components of the Earth's magnetic field, weakened by the shield-under-test, vs. the depth coordinate of the sensor inside the shield. The coordinate is measured from the edge at the open end. The inclination of the Earth's magnetic field in this place was about 55°. If not taking into account the strong field distortion near the open end, due to which the field at the opening is approximately 2 times greater than the external one, the field attenuates by an exponential law with the depth in accordance with [10,11]. The plateau is due to two reasons, the sensitivity limit of the magnetometer and a small residual magnetization of the shield (about 0.2-0.3 Oe).

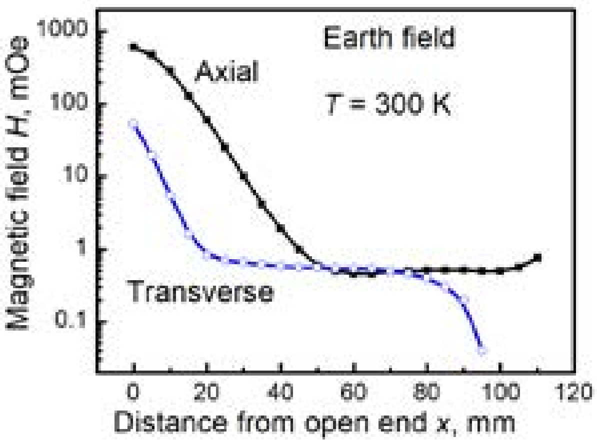

Fig. 2. Axial and transverse components of the magnetic field inside a cylindrical shield with a bottom vs. the distance from the open end. The bottom is at a distance of 115 mm. The details are in the text.

Since the cryostat, into which the shield should be placed, may have some residual magnetization of structural materials, we checked the attenuation of the external field as a function of its value H_{ext}. Fig. 3 shows the attenuation of the external longitudinal (axial) field $K_A = H / H_{ext}$ vs. the immersion depth x into the shield, normalized to the cylinder diameter $2r$. It can be seen that these values are the same within the specified fields. The discrepancy in the plateau region is caused by the sensitivity limitation of the magnetometer. Note that there is a strong distortion and concentration of the external magnetic field close to the opening, so the "attenuation" is greater than unity.

To check the operation of the shield at low temperatures, the same dependence of the field attenuation at room temperature and at liquid nitrogen temperature was measured (Fig. 4). The magnetometer sensor was protected by non-magnetic thermal insulation. It can be

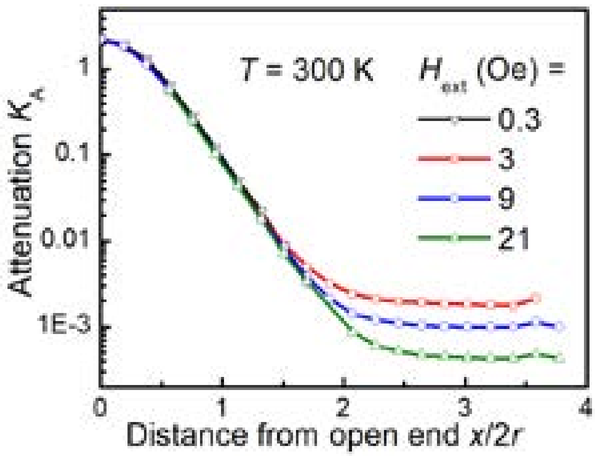

Fig. 3. Attenuation K_A of the axial component of the magnetic field inside a cylindrical shield with a bottom vs. the distance from the open end x normalized to the diameter $2r$ in various external fields. The external field is created by a solenoid. The details are in the text.

seen from Fig. 4 that the shielding properties improve by about a factor of 2 when cooled to 77 K deep inside the screen, which is in good agreement with the increase in the magnetic permeability of Cryoperm® 10 from 25,000 to 50,000 at 77 K [9] (Fig. 5).

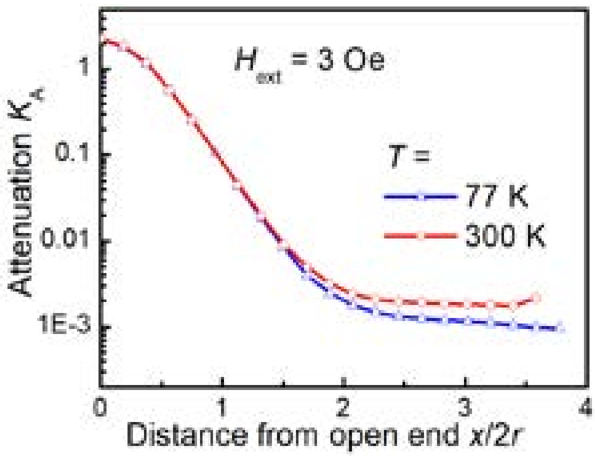

Fig. 4. Attenuation K_A of the axial component of the magnetic field inside the shield vs. the distance from the open end for various temperatures.

Although the fluxgate magnetometer is designed to measure dc and slowly changing fields, we made an attempt to evaluate the change in the shielding properties of the tested permalloy cylinder when it is placed in a low-frequency ac magnetic field. Fig. 6 shows comparison of the attenuation factors of the amplitude of an external ac sinusoidal field for "almost" stationary field (frequency 1 Hz) and industrial frequency (55 Hz) field in a shield cooled down to the temperature of liquid nitrogen. Despite the low measurement accuracy, the tendency of improving the shielding with frequency rise is well pronounced. This trend is consistent with the results of measurements on

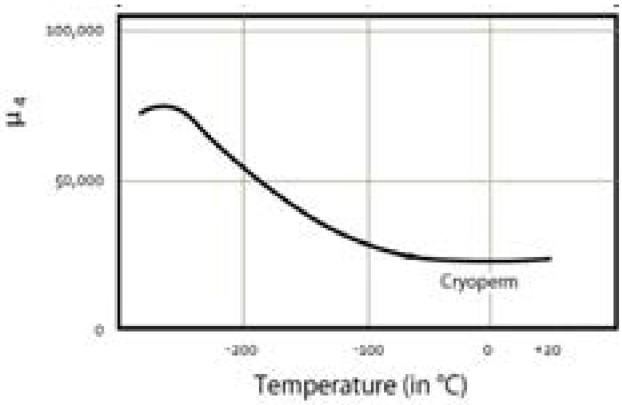

Fig. 5. Magnetic permeability of Cryoperm® 10 vs. temperature. Adapted from the site [9].

another permalloy, Mumetall, at higher frequencies [11]. We will continue frequency measurements of the shield in further works at higher frequencies using another method.

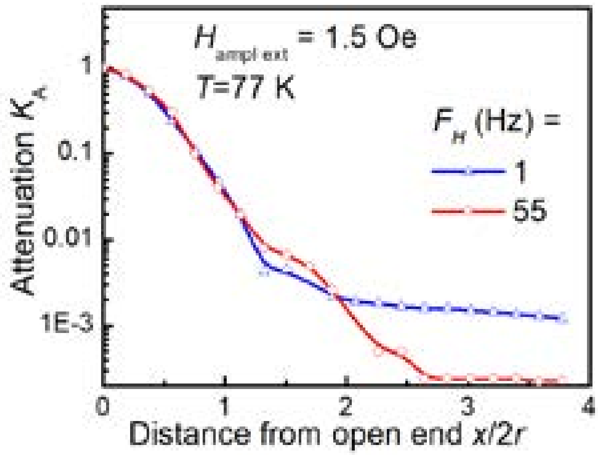

Fig. 6. Attenuation of the amplitude of the longitudinal component of the ac magnetic field inside the shield vs. the distance from the open end at various low frequencies and temperature 77 K.

Summarizing, we can say that the measured shielding factors $1/K_A \approx 600-4000$, which corresponds in logarithmic units to ~55-70 dB, are consistent with the estimation, taking into account the large spread and temperature dependence of the magnetic permeability of the cryogenic permalloy. These values are quite acceptable for constructing a hybrid three-layer screen, including two more superconducting shells, and for creating the necessary attenuation of the absolute value of the magnetic field and its variations in the region where the superconducting flux qubit is to be placed.

CONCLUSIONS

1. The attenuation factors for external dc and ac low-frequency magnetic fields of various magnitudes were experimentally measured inside a cylindrical shield with a bottom, made of cryogenic permalloy Cryoperm 10, at room and liquid nitrogen temperatures. The Cryoperm shell will be the part of a hybrid three-layer shield to protect (isolate) the superconducting flux qubit from the electromagnetic environment during quantum measurements in order to build a single microwave photon counter.

2. The maximum attenuation factors deep inside the shield for an external longitudinal field of 0.3–20 Oe are in the range of 600–4000, or 55–70 dB, which is quite sufficient for solving the indicated problem.

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