Magnetic shielding and relaxation characteristics of superconducting $YBa_2Cu_3O_7$ tubes

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High-T_c superconducting tubes have been developed for magnetic shielding of SQUIDs at 77 K. The characteristics of such tubes show that adequate shielding exists for magnetic fields up to a critical field determined by the current density of the tube. Relaxation phenomena with two different time dependencies are observed when the external magnetic field enters the tubes.

The very high sensitivity of SQUIDs imposes a severe requirement on the magnetic shielding needed to isolate such devices from external magnetic fields. Since SQUIDs can be used in magnetometers and in superconducting electronics, magnetic shielding[1,2] is very important in design considerations. In many situations the magnetic shield consists of a superconducting tube with the SQUID at its center. Because the resistance of the tube is zero, any changing magnetic field will be compensated continuously by induced currents in the tube in order to keep the magnetic flux inside the tube constant. Magnetic fields will also be screened out from inside the material due to the Meissner effect. Such shielding has been effectively applied to a variety of devices based on regular superconductors.[3]

We present here an extension of this shielding principle to high-T_c superconductivity for operation with superconducting devices at 77 K. High-T_c SQUIDs based on either thin films[4] or bulk material[5,6] have been reported with high sensitivity. Data on current persistence and magnetic shielding have been presented[7] for short $YBa_2Cu_3O_7$ tubes; however, because of the short length of their tubes, good shielding was not achieved. We present here detailed measurements of dc and ac magnetic field shielding of long $YBa_2Cu_3O_7$ tubes.

The tubes were made from high-purity powders of $BaCO_3$, CuO, and Y_2O_3; the mixture was wet ball milled for 24 h. The resulting slurry was dried at room temperature, calcined at 930 °C for 45 h, wet ball milled again for 24 h, and then an isostatic pressing technique was used to obtain green ceramic tubes. The tubes were fired at 960 °C for 12 h in air and slowly cooled in the furnace; they were annealed in an oxygen atmosphere for 18 h at 850 °C. Three tubes (tubes 1, 2, and 3) of inner and outer diameters 0.96 and 1.2 cm, respectively, and length 5.5 cm, were studied; they were mounted axially in a long solenoid which provided either dc or ac magnetic field. Except where stated, the characteristics of the tubes were measured using a Hewlett-Packard Model 4288R Fluxgate Magnetometer with a sensitivity of better than 10^{-5} G. The magnetometer probe, with an external volume corresponding to 2 cm long and 0.4 cm diam (the active volume is much smaller since the core consists of two magnetic metal strips 1.5 cm long by 0.2 mm thick and 2 mm wide), was placed in the interior of the tube to measure at 77 K the interior field at different positions.

After zero-field cooling of the tube, the interior magnetic field H_{int} at the center of the tube was monitored as the external magnetic field H_{ext} was slowly increased from zero. The shielding curves of H_{int} as a function of H_{ext} are shown in Fig. 1 for tubes 1 and 3 at 77 K; tube 1 was measured with a Hall probe. As H_{ext} was applied axially a persistent current was induced in the tube to keep the interior flux constant. Such currents increased with H_{ext} until the critical current of the tube was reached. At this point, H_{ext} was the largest magnetic field that could be effectively shielded before flux started to penetrate into the interior of the tube. Further increase in H_{ext} caused H_{int} to change; because there was still a persistent current in the tube, H_{ext} was partially shielded from the interior of the tube. Figure 1 shows that the maxi-

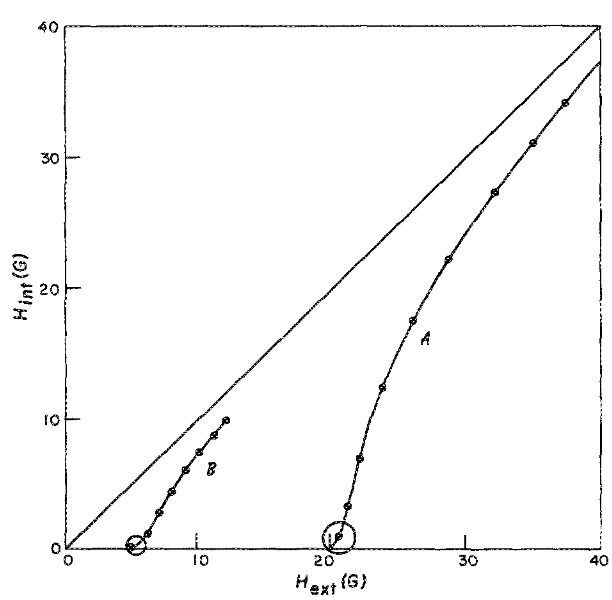

FIG. 1. Magnetic shielding curves of H_{int} vs H_{ext} for tube 1(A) and tube 3(B). The straight line shows the behavior in the normal state. Nonlogarithmic relaxation was found in the circled regions.

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mum dc magnetic field that could be shielded by tubes 1 and 3 as 19 and 4.3 G, respectively; for tube 2 it was 9.5 G. From these values and the geometry of the tube, and based on the Bean model,[8] the estimated average critical superconducting current densities at 77 K are 150, 63, and 30 A/cm^2 for tubes 1, 2, and 3, respectively. Evidently, higher current densities would result in larger shielded fields. After flux had started to penetrate the tube the system exhibited nonequilibrium behavior, to be discussed later.

The ac behavior was also investigated. After zero-field cooling of the tube, the response to an ac magnetic field at 100 Hz was measured as before. The results show that the maximum ac field shielded by tube 3 was 8.8 G peak to peak (the dc value was 4.3 G). This result indicates that the shielding properties of high-T_c tubes at low frequency are similar to those for dc magnetic fields.

To determine the shielding characteristics along the axis of the tube, H_{int} was measured at different positions inside tube 2 as H_{ext} was changed. The results are shown in Fig. 2, the inset indicating the arrangement for the $z = 0$ position; as the probe is moved in, z increases up to 16.7 mm, which is the center of the tube; this shows that the shielding is better nearer the center. To indicate the field where shielding starts to become ineffective for a given position, arrows in the figure point to the critical field values. At such field values, H_{int} starts becoming unstable. The value of this critical field decreases by moving from the center to the edge of the tube. This occurs because the external magnetic field is distorted near the top and bottom edges of the tube, thus requiring a higher induced current density at these positions; as H_{ext} is increased the critical field is reached first at those positions.

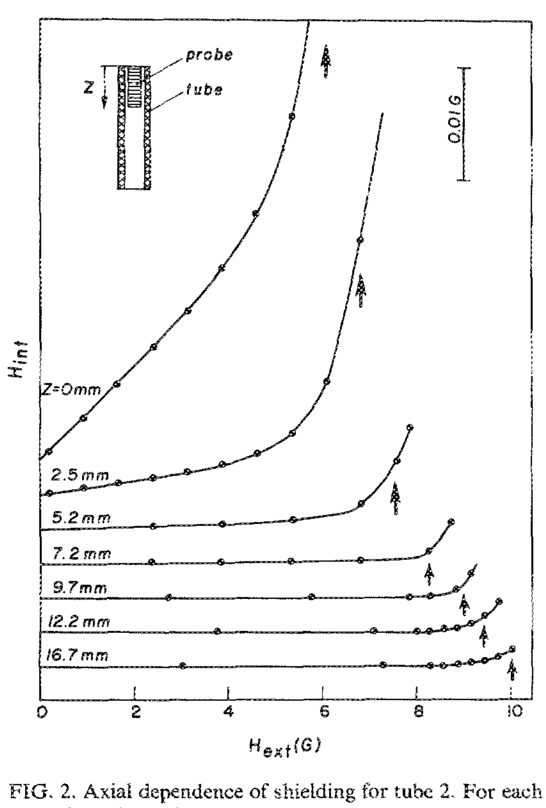

FIG. 2. Axial dependence of shielding for tube 2. For each position z the zero of H_{int} is displaced for clarity.

The curvature below the arrows is due to the gradual shortening of the effective shielding region, in agreement with the computer simulations of Ref. 7.

Figure 3 shows the shielding characteristics at various positions inside the tube for three different H_{ext} values. The straight lines demonstrate an exponential decrease of H_{int} as the probe is moved toward the center; H_{int} is reduced by one order of magnitude for a position change of 3.7 mm. The calculated[9] interior fields for a perfect semi-infinite superconducting tube of inner radius a are of the form

$$H_{\parallel} \propto \exp(-3.83\, z/a) \tag{1}$$

and

$$H_{\perp} \propto \exp(-1.84\, z/a), \tag{2}$$

where $H_{\parallel}$ and $H_{\perp}$ represent the axial and transverse interior magnetic fields, respectively. From our experiment, a prefactor of 3.0 in Eq. (1), which is between the calculated values for the axial and transverse conditions, is found. This is due to the relatively large volume of the probe and the fact that it was not well aligned axially.

The results presented here show that for low magnetic-field shielding, high-T_c superconducting tubes behave just as the conventional ones. We measured magnetic field attenuation by a factor greater than 10^6, the limiting factor being the sensitivity of the probe. Moreover, the application of Eq. (1) with prefactor 3 to our case leads to a change of H_{int} smaller than that of H_{ext} by about nine orders of magnitude. With such characteristics, the high T_c shield is adequate for SQUID operation at 77 K and for other superconducting electronics applications.

When the critical magnetic field is exceeded, the shielding characteristics of the tube begin to break down and flux starts to enter the tube. Once flux penetrates the sample, a metastable mixed state is formed leading to time changes of the magnetization. The relaxation in this critical state is very interesting and it has been studied using a variety of techniques[7,10-12] showing logarithmic time decay. It can be explained by a flux creep theory, in which thermally activated

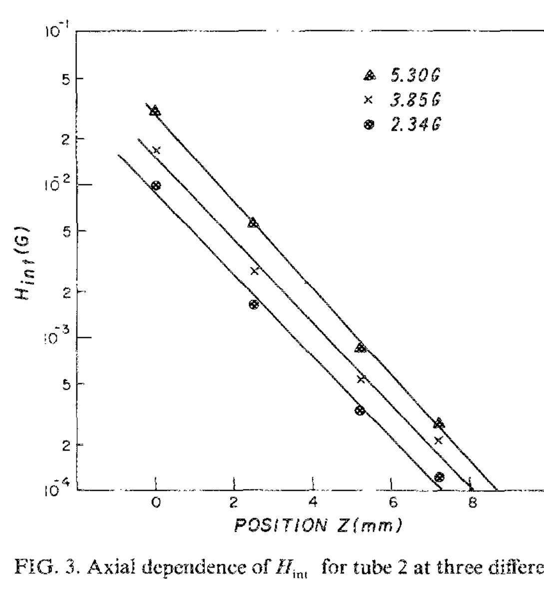

FIG. 3. Axial dependence of H_{int} for tube 2 at three different H_{ext} values.

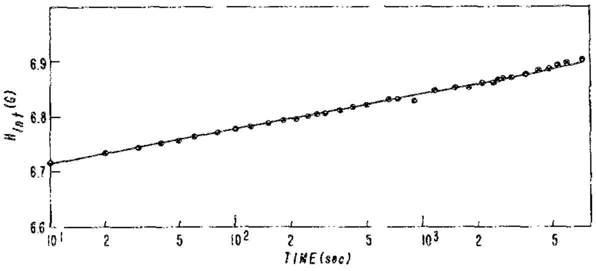

FIG. 4. Time dependence of H_{int} for tube 3 well above the critical field; the straight line is used as a guide.

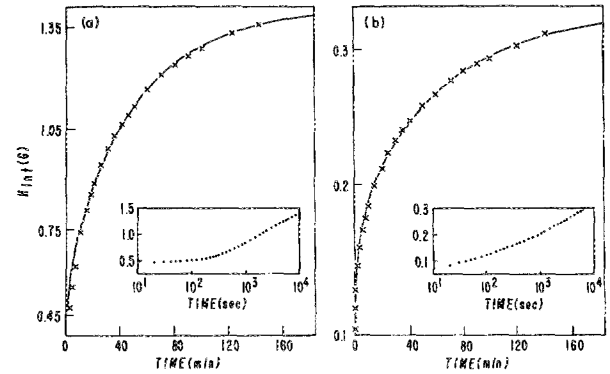

FIG. 5. Time dependence of H_{int} just above critical field. Solid line is a fit to Eq. (3) for (a) tube 1 and (b) tube 3. Insets show the behavior on a logarithmic scale in time.

flux creep sets[12] in, or by a superconducting glassy state theory.[13] We have studied the time dependence of such a flux leak through the material of our tubes.

After zero-field cooling the tube at 77 K, H_{ext} was slowly increased from zero until a field was reached at which flux had penetrated the tube. This point was stabilized for many hours such that changes in H_{int} were small. Then, H_{ext} was suddenly changed by a small amount (ΔH_{ext}) and H_{int} was monitored with time. For cases where H_{int} was relatively large (a few Gauss), the relaxation of ΔH_{int} was logarithmic in time. This is shown in Fig. 4; it was expected on a conventional type-II superconductor model for flux creep.[8,14,15]

At magnetic fields H_{ext}, where the tube barely allows flux to enter, i.e., where H_{int} is about 0.5 G or less, a different type of relaxation behavior is observed. The results can then be fitted to a stretched exponential multiplied by algebraic behavior of the form

$$\Delta H_{int} = \Delta H_0 [1 - \exp(-t/\tau)^{\beta} t^{-\alpha}], \qquad (3)$$

where $0 < \beta < 1$ and $\alpha > 0$, ΔH_0 is the total change of ΔH_{int} at $t = \infty$, and τ is a time constant which defines the time scale. In Fig. 5, data are presented for two different tubes and they are fitted to Eq. (3.) For tube 1 in Fig. 5(a) we get the best fit for $\tau = 100, \beta = 0.33$, and $\alpha = 0.05$, and for tube 3 in Fig. 5(b) the best fit is achieved for $\tau = 130$, $\beta = 0.3$, and $\alpha = 0.1$. Such behavior was found for all the tubes studied.

We want to point out that a stretched exponential multiplied by algebraic behavior is a unique feature[16] of spin glasses. The results presented in Fig. 5 have a shape similar to the one obtained in numerical simulations[17] of the superconducting glassy state. In such a state superconducting clusters are coupled by Josephson tunneling barriers with different phases. The application of a magnetic field leads to frustration and hence to a glassy state. Our data support two regimes for the dynamic processes of flux entry. At relatively low H_{ext}, where there are strong gradients of magnetic field, frustration dominates flux entry; as H_{ext} becomes larger, flux creep caused by thermally activated processes governs the logarithmic relaxation behavior.

We have shown that high-quality $YBa_2Cu_3O_7$ tubes can be used for magnetic shielding at 77 K, the maximum shielded field depending on the current density of the tube. Shielding for our tubes with the given current densities and geometries was excellent up to 20 G for dc magnetic fields and low-frequency ac fields. Above a critical field, flux entry was observed; it has two components. This is very similar to our microwave absorption measurements[18] in bulk ceramic samples; these also had two components. There, we proposed a model where at low fields losses were attributed to Josephson fluxons in the random array of junctions, and at higher fields the losses were due to Abrikosov fluxons in the bulk sample.

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