**Transient Characteristics of a High-T_c Superconductor Tube
Subjected to Internal and External Magnetic Fields***

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Transient Characteristics of a High- T_c Superconductor Tube Subjected to Internal and External Magnetic Fields

Y. S. Cha and T. R. Askew

Abstract—Transient response of a melt-cast-processed BSCCO-2212 tube at 77 K was studied by using a pulsed current supply. Tests were conducted with a copper coil either inside or outside the superconductor tube.

Experimental results show that the superconductor tube can shield the magnetic field generated by the current in the coil up to a certain limit when the coil is either inside or outside the superconductor tube. Both configurations should work for fault-current limiters. Delayed field penetration (the delay between the penetrated field and the excitation current) was observed in both cases. This delay can be explained by the concept of nonlinear magnetic diffusion, which is valid when the characteristic length of the system is much shorter than the wavelength of the driving field. The rate of magnetic diffusion is increased when (a) the local current density exceeds the critical current density and (b) the local temperature rises as a result of dissipation in the superconductor.

Index Terms—Fault-current limiter, magnetic diffusion, magnetic shielding, pulsed current.

INTRODUCTION

Bulk high-temperature superconductors in the form of hollow cylinders or rings have two potential practical applications. The first is magnetic shielding [1-6]. The magnetic field of the induced current in a cylindrical superconductor tube cancels the applied field so very little field is in the hole of the cylindrical tube, provided that the applied field is below the penetration field of the superconductor tube. The other potential application of high-temperature superconductor tubes is the fault-current limiter (FCL) in the power industry [7-12]. The FCL consists mainly of an iron core inside a superconductor tube and a copper coil wound on the outside of the superconductor tube. When an FCL is used under normal operating conditions, the shielding capability of a superconductor tube keeps the impedance low. Under fault conditions, the large current in the copper coil exceeds the shielding capability of the superconductor tube and there is a jump in impedance because the iron core is no longer shielded from the coil by the superconductor tube.

In principle, the superconductor tube can provide shielding whether the source of the applied magnetic field is outside or inside the tube, because current will be induced in the tube in either case to cancel the applied field. In this paper, we describe the results of measuring induced current and transient characteristics of a melt-cast-processed $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x$ (BSCCO) superconductor tube at 77 K by using a pulsed current supply. Tests were conducted with copper coils placed either outside (externally applied field) or inside (internally applied field) the tube to study the differences in transient characteristics of these two configurations.

EXPERIMENTAL APPARATUS

The pulsed current supply and the test setup are identical to those reported previously [13]. Two test sections were employed and are shown in Fig. 1. In the first test section, shown in Fig. 1a, a copper coil is wound externally on the cylindrical superconductor tube. The copper coil, which has 80 turns and is made of 6.6 x 2.2-mm flat copper wire, is ≈ 145 mm long and has an inside diameter almost identical to the outside diameter of the superconductor tube. The material of the superconductor tube was bulk BSCCO and was made by a melt-cast process. The BSCCO tube was 190 mm long, with a wall thickness of 8.0 mm and an outside diameter of 70 mm. A Hall probe was placed near the center of the tube to measure the axial magnetic field in the hole of the tube. To measure the leakage field, a second Hall probe was placed on the outside of the copper coil, at the same elevation as the Hall probe inside the tube. A Rogowski coil was employed to measure the induced current in the superconductor tube. Response times of both the Hall probe and the Rogowski coil were much shorter than the transient time of the present experiments [13]. The second test section is similar to the first, except that the copper coil is placed inside the superconductor tube, as shown in Fig. 1b. The copper coil inside the tube also has 80 turns, an axial length of 135 mm, and an outside diameter of 52 mm, and is made of 1.80-mm-diameter copper wire (AWG 14). A gap of ≈ 1 mm is present between the superconductor tube and the inside copper coil.

EXPERIMENTAL RESULTS

Figs. 2a and 2b show the measured current and field at relatively low excitation current for the case of the coil outside and inside the tube, respectively. In these figures, N is the number of turns of the driving coil (80 for both cases); I (shunt) is the excitation current in the copper coil, measured by the shunt resistor; I (tube) is the induced current in the superconductor tube, derived from the signal of the Rogowski coil; H_i is the magnetic field strength, measured by the Hall

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Fig. 1. Schematic diagrams of test section: (a) coil outside superconductor tube, (b) coil inside superconductor tube.

probe inside the BSCCO tube; and H_o is the magnetic field strength, measured by the Hall probe on the outside of the superconductor tube. Fig. 2a shows that the field inside the tube (H_i) remains close to zero, which indicates that the externally applied field has not penetrated the tube. This finding is supported by the fact that the induced current I (tube) almost cancels the excitation current NI (shunt). A small field on the outside of the tube ($H_o \approx 0.01$ k-gauss) is the leakage field. This leakage field, which has a finite thickness, originates from one end of the external coil, circulates through a path outside the coil, and returns to the coil at the other end. Fig. 2b shows that the applied field generated by the internal coil has also not penetrated the tube because the field outside the tube (H_o) remains close to zero throughout the test. The field inside the tube is quite large, with a maximum $H_i \approx 0.2$ k-gauss. The field inside the tube (H_i) represents the leakage field, which originates from the center of the coil and circulates around the internal coil, through the gap between the superconductor tube and the internal coil. This leakage field is relatively high because all the fields are concentrated inside the coil, which has a finite (limited) volume. This is different from the case with the coil outside the tube, where the leakage field is circulating through an unbounded space. Another difference between Figs. 2a and 2b is that the current profiles in Fig. 2b are not as symmetric as those in Fig. 2a. Fig. 2a shows that the profile of the induced current in the superconductor tube is almost a mirror image of the excitation current, indicating very good shielding and very little leakage field. This current symmetry with respect to the zero current axis is somewhat distorted in Fig. 2b. For example, the peak excitation current is $\approx 11,700$ A, whereas the peak current in the superconductor tube is only $\approx 10,200$ A. This difference in current is needed to support the relatively large leakage field, which is probably

Fig. 2. Measured current and field at relatively low excitation current for (a) coil outside superconductor tube, and (b) coil inside superconductor tube.

due to the 1-mm gap between the superconductor tube and the internal coil. The leakage field is smaller when the coil is outside the tube because there is almost no gap between the superconductor tube and the external coil. It should be noted that even though the leakage field is relatively large when the coil is inside, it is still capable of shielding the space outside the tube from the internally generated magnetic field at this relatively low excitation current.

Figs. 3a and 3b show the measured current and field at some intermediate excitation current for the case of the coil outside and inside the tube, respectively. The magnetic field inside the tube (H_i) (Fig. 3a) shows that 2.5 ms into the test, when the excitation current reached 33,000 A, the tube is just penetrated by the externally applied magnetic field. The interesting behavior is that when the excitation current NI begins to decrease, the magnetic field inside the tube continues to increase. This behavior has been observed previously for similar experiments [13] and can be explained by the concept of nonlinear magnetic diffusion. The results shown in Fig. 3b do not seem to indicate that the internally generated magnetic field has penetrated the tube because the field outside the tube (H_o) remains close to zero throughout the test, even though the peak excitation current (35,000 A) is approximately the same as that shown in Fig. 3a (34,000 A). The reason for this is that a portion of the excitation current (NI) is used to support the relatively large leakage field inside the tube (H_i), so that the superconductor tube is exposed to an effective excitation current less than NI

Fig. 3. Measured current and field at intermediate excitation current for (a) coil outside superconductor tube, and (b) coil inside superconductor tube.

measured by the shunt resistor. At peak NI of 34,000 A, the externally generated magnetic field barely penetrated the tube (Fig. 3a). At peak NI of 35,000 A, the superconductor is subjected to an effective peak NI of $<34,000$ A, and thus field penetration is not observed in Fig. 3b for the case with coil inside the tube. In other words, the difference is the leakage field in the two cases.

Figs. 4a and 4b show the measured current and field at relatively large excitation current for the case of the coil outside and inside the tube, respectively. With the coil outside the tube (Fig. 4a), the data for H_i clearly indicate that the externally applied field penetrated the tube in 1.0-1.5 ms, and this occurred at NI $\approx 60,000$ A and I (tube) $\approx 55,000$ A. Fig. 4a also shows that there is a delay of ≈ 3 ms between the peak NI and the peak H_i , and during this period, NI begins to decrease while H_i is still increasing. This delay is typical when the coil is outside the tube and is the consequence of magnetic diffusion in the superconductor tube [13]. When the coil is inside the tube, the data for H_o in Fig. 4b indicate that the internally generated magnetic field has penetrated the tube and affected the field outside the tube. This is more clearly shown in Fig. 4c, where only H_o is plotted against time and a more sensitive scale is used. It shows that H_o begins to increase rapidly at 1.0-1.5 ms, indicating that the magnetic field has penetrated the tube. Between 1.0 and 1.5 ms, Fig. 4b shows that NI is $\approx 85,000$ A and I (tube) $\approx 57,000$ A. The induced current in the tube I (tube) at field penetration, is approximately the same (55,000-57,000 A) for tests with the coil inside and outside the tube. This is expected because the same tube was used in both experiments. The excitation

Fig. 4. Measured current and field at relatively high excitation current for (a) coil outside superconductor tube; (b) coil inside superconductor tube; and (c) coil inside superconductor tube, results plotted on more sensitive scale.

current NI at field penetration is quite different for the two cases because the leakage fields are different for the two cases. With the coil outside the tube, NI = 60,000 A at field penetration; with the coil inside the tube, it is 85,000 A. The NI is larger in the latter case because it must support a larger leakage field due to the presence of the 1-mm gap between the tube and the inside coil. Figs. 4b and 4c show that peak NI occurs before peak H_o . This delay is due to magnetic diffusion from inside to outside of the tube. Fig. 4b also shows that there is a delay between peak NI and peak H_i , which is a measure of the magnetic field generated by the net current of NI and I (tube). When I (tube) can no longer keep up with NI, the two currents become out of phase, which also

drives H_i out of phase with NI and is another indication that the magnetic field has penetrated the tube from within.

DISCUSSION

A. Nonlinear Magnetic Diffusion

High- T_c superconductors usually follow the so-called power law in the flux creep regime, and the resistivity is a function of current. It can be shown that the magnetic diffusion equation becomes nonlinear when the resistivity depends on the current [14]. For cylindrical geometry, the one-dimensional, nonlinear magnetic diffusion equation takes the form

$$[\partial(D_m r \partial B_z / \partial r) / \partial r] / r = \partial B_z / \partial t, \quad (1)$$

where B_z is the magnetic flux density in the axial direction, r is the radial coordinate, t is time, and the magnetic diffusion coefficient D_m is given by

$$D_m = \rho(J) / \mu_0, \quad (2)$$

with the current-dependent resistivity $\rho(J)$ given by the power law. For melt-cast-processed BSCCO-2212 with a wall thickness of several millimeters, the characteristic diffusion time at 77 K and an electric field strength of 1 $\mu\text{V}/\text{cm}$ is several hundred milliseconds [14]. This is much larger (by several milliseconds) than the rise time of the pulsed current in the present experiment. Therefore, magnetic diffusion is important and cannot be neglected. However, a characteristic diffusion time of several hundred milliseconds is too long for the BSCCO-2212 tube to be penetrated in the present experiment, which shows that penetration occurred in a few milliseconds.

Two factors increased the rate of magnetic diffusion and facilitated the field penetration of the tube. First, the speed of magnetic flux propagation (diffusion) strongly depends on the local resistivity ρ in the superconductor. During a transient, the local gradient of magnetic flux density can be greater than that of Bean's model, and the local current density can be greater than the critical current density at a field strength of 1 $\mu\text{V}/\text{cm}$. Local resistivity increases with current density, which speeds up the magnetic diffusion process because the magnetic diffusion coefficient D_m is linearly proportional to ρ . Second, when local ρ increases, so does dissipation (ρJ^2). If heat is not removed quickly enough from the superconductor, the local temperature will rise. When temperature rises, the resistivity increases, further increasing the magnetic diffusion coefficient, and speeding up the magnetic diffusion process. The observation that the penetrated field (H_i in Fig. 4a and H_o in Figs. 4b and 4c) is still rising while the excitation current (NI) is decreasing is the result of magnetic diffusion. A finite time is necessary for magnetic flux density to diffuse from the interior to the boundary of the tube. When the excitation current begins to decrease, the flux density is greater inside the wall of the tube than outside the wall, magnetic diffusion is still in force and causes the penetrated field to increase. This series of events cannot be explained by Bean's critical-state model, which is applicable to steady-state conditions only.

B. Implication for Fault Current Limiters

The present experiments show that the leakage flux is greater when the coil is inside the tube than outside the tube. However, this is likely the result of the 1-mm gap between the superconductor tube and the inside coil. In the test with the coil outside the tube, the coil was wound relatively tightly around the tube. The present experiments also demonstrate that the superconductor tube is equally capable of shielding either the internally or externally generated magnetic field. To further support this conclusion, we have measured the inductance ratio of these two configurations. The inductance of the outside coil alone was 0.22 mH; that of the outside coil with the superconductor inside (at 77 K) was 0.049 mH. The reduction in inductance was a factor of 4.48. The inductance of the inside coil alone was 0.096 mH; that of the inside coil with the superconductor outside (at 77 K) was 0.020 mH. The reduction in inductance was a factor of 4.80. Therefore, both configurations will work for an FCL and the reduction in inductance does not differ by much. However, under fault conditions, an FCL with a coil inside will have an inductance less than that of an FCL with a coil outside because, inherently, the latter has a larger volume than the former. Finally, it should be noted that the present experiments were conducted with an air core only and are different from the superconductor-shielded-core-reactor (SSCR), which usually contains an iron core. A closed iron-core SSCR is mostly a resistive device and is quite different from an air-core SSCR, which behaves more like an inductive device.

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