Crossed-Field Demagnetization of a EuBa₂Cu₃O₇ Coated Conductor with BaHfO₃ Nanorods

M Suyama¹, S Pyon¹, Y Iijima² and T Tamegai¹

¹ Department of Applied Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
² Fujikura Ltd., 1-5-1 Kiba, Koto-ku, Tokyo 135-8512, Japan

E-mail: m-suyama@g.ecc.u-tokyo.ac.jp

Abstract. Superconductors can trap large magnetic fields. However, magnetic fields perpendicular to the trapped field reduces the trapped field effective, which is known as crossed-field demagnetization. Crossed-field demagnetization becomes a problem for the application of stacked magnet. We investigated the crossed-field demagnetization of a EuBa₂Cu₃O₇ coated conductor with BaHfO₃ nonorods which has large critical current density. When an AC transverse field is applied after the magnetization of the coated conductor, the decay of trapped field was significantly accelerated. However, for the AC field smaller than the full penetration field parallel to the ab-plane, the decay becomes slow enough. All these results suggests that we can apply the stacked magnet for rotating machines if the alternating transverse magnetic field is reduced below the penetration field.

1. Introduction

High temperature superconductors (RE)Ba₂Cu₃O₇ (REBCO) have high critical current density (Jc) in high magnetic fields, and they can trap a high field and are expected to be a high-field magnet. To date, various kinds of bulk superconductors [1, 2] and stacked magnets using coated conductors (CCs) [3-8] were fabricated and high magnetic field have been successfully trapped. The highest trapped field of 17.7 T has been achieved so far [5]. These magnets are expected to be used in various applications including rotating machines like motors, and they are exposed to AC transverse fields. When we apply an AC transverse field to a superconductor in the critical state, current profile in the superconductor is redistributed due to the shielding current for the AC field. Such a temporal evolution of current distribution causes flux lines to walk out of the superconductor, and the magnetic field trapped in the superconductor decays significantly. This is known as crossed-field demagnetization or vortex shaking, as explained in detail in Ref. [9]. Several experiments of crossed-field demagnetization have been conducted for a bulk [10] and stacked magnets [11-15], and a slower decay of trapped fields is reported in stacked magnets than that of bulk superconductors. Therefore, stacked magnets have an advantage in the application for rotating machines.

In the present study, we aimed to confirm the crossed-field demagnetization of EuBCO CCs with BaHfO₃ (BHO) nonorods, which we used for the fabrication of a stacked magnet. Since CCs in a stacked magnet have mutual inductance to each other, the crossed-field demagnetization of a stacked magnet is complex [16]. In order to simplify the problem, we measured the crossed-field demagnetization of a single CC piece. With a practical application of the stacked magnet in mind, we monitored the decay of...
trapped field in a CC for 2,000 s, which is long enough for this kind measurement, and we estimated the decay at longer time scale by extrapolation. According to the measurement and the extrapolation, we confirmed that the crossed-field demagnetization is weak for small AC transverse field.

2. Experimental Methods

In the present study, we used EuBCO CCs with BHO nanorods as artificial pinning center fabricated by Fujikura Ltd. This CC include 2.5 µm EuBCO-BHO layer, 50 µm Hastelloy substrate, and 2 µm Ag layer for protection and thermal stability. $J_c - H$ characteristics for a small piece of the EuBCO-BHO CC at various temperature are shown in figure 1. The $J_c$ value is large enough at 77 K, and a large magnetic field can be trapped even at this temperature. For simplicity, the crossed-field demagnetization of one CC was measured. A piece of CC with dimensions of $12 \times 12$ mm$^2$ and the Cu plate were sandwiched by the Cu lid and Cu casing as shown in figure 2(a). A Hall probe (HG-0711, Asahi Kasei Microdevices) was arranged at the center of the Cu plate as shown in figure 2(b) to measure the magnetic field trapped in the CC. The sample holder was fixed at the end of a probe rod which can be rotated about the horizontal axis as shown in figure 2(c). The rotation of the probe end is controlled by a motor at the other end of the probe rod. The sample was cooled by liquid nitrogen to stabilize the temperature at 77 K, and the Cu coil for the external field was also cooled by liquid nitrogen because the coil can generate higher magnetic field at lower temperatures. Figure 3 (a) shows the overview of the experimental setup.

![Figure 1](image1.png)

**Figure 1.** Magnetic field dependences of $J_c$ of EuBCO-BHO CC at various temperatures.

![Figure 2](image2.png)

**Figure 2.** Schematic illustration of (a) a sample and the sample holder and (b) Cu plate to arrange a Hall probe. (c) A photo of the end of the probe rod with a rotating mechanism.

The procedure of the measurement is as follows. First, we applied a positive magnetic field for one second after applying a negative magnetic field for one second to magnetize. Figure 3(b) shows the configuration of the sample holder during magnetization. We applied a negative field to minimize the effect of trapped field in the following trapping and relaxation measurements. The applied field should
be twice larger than the self-field of the CC in the zero-field-cooling process. From the \( I_c \) value of the CC in the self-field at 77 K of 1.7 MA/cm², the self-field is estimated as \( B_{\text{self}} \sim \mu_0 I_c d = 53 \) mT. Hence, we applied a field of 164 mT, which is large enough compared with \( 2B_{\text{self}} \sim 106 \) mT, to magnetize the CC. After the magnetization, we relaxed the CC for 600 s. This process was necessary since a large relaxation is observed for a few minutes after the end of the magnetization, and it masks the effect of crossed-field demagnetization. After 600 s, the decay of trapped field due to conventional flux creep becomes very small, and we can consider the results of measurement as the effect of crossed-field demagnetization. Then we rotated the sample 90 degrees, and the decay of the trapped field of the CC was measured for 2,000 s while applying an AC magnetic field. Figure 3(c) shows the configuration of the sample holder during the measurement. The wave form of the AC fields was determined by a function generator (FG120, Yokogawa), and a sine wave with a frequency of 1 Hz was used. Since the full penetration field \( B^* \) of the transverse field is given by \( \mu_0 I_c d/2 = 26.5 \) mT, we selected the amplitude of AC fields around that value, specifically, 8.2, 16.4, 24.6, 27.9, and 49.2 mT. We measured the relaxation for 2,000 s after the relaxation of 600 s to compare the decay of trapped field due to AC transverse field with that due to simple flux creep.

Figure 3. (a) Overview of the experimental setup in the present study. (b) Schematic configurations of the sample holder and the solenoid coil at magnetization process and (c) demagnetization process of the measurement procedure.

3. Results and Discussion

Figure 4 shows the result of relaxation measurements with and without transverse AC fields with various amplitudes. For crossed-field demagnetization, a number of cycle of an AC field is also important. Since the frequency is 1 Hz in this measurement, we can interpret the horizontal axis as a number of cycle directly. Compared with the relaxation without AC transverse field, the trapped fields decay more significantly due to the AC transverse field. As the amplitude of AC transverse field increases, the decay rate becomes larger. The dashed lines are theoretical asymptotic values of trapped fields for the AC field of each color lower than \( B^* \), which can be written as \( B_{\text{asymptotic}} = 2(B^* - B_{\text{AC}}) \) [9], where \( B_{\text{AC}} \) is the amplitude of AC transverse field. Although we used a sample with 12 mm length in the measurements, \( B_{\text{asymptotic}} \) is independent of the sample length. So, even if we change the sample...
dimensions, we cannot suppress the decrease in the trapped field. For AC fields lower than \( B^* \), the trapped field decreases to these asymptotic values, although it takes more time to reach lower asymptotic value. The decay at \( B_{AC} = 8.2 \) mT continues even below the asymptotic value. This is because the asymptotic values are calculated based on the electromagnetic assumptions. Even though the sample reaches the stable state electromagnetically, it remains in a nonequilibrium state thermodynamically and relaxation continues to decrease the trapped field. For \( B_{AC} > B^* \), the trapped field decreases to almost zero. At \( B_{AC} = 49.2 \) mT, the trapped field is almost fully demagnetized in the time window of 2,000 s. These results indicate that the stacked magnet cannot be used for rotating machines when it is subjected to an AC field larger than \( B^* \).

In order to estimate the crossed-field demagnetization much longer time scale, we change the horizontal axis into logarithmic scale and replotted in figure 5. In the logarithmic scale, a strong decay like exponential one which goes to zero very fast has convex up curvature until it approaches to nearly zero. However, decays due to AC transverse fields lower than \( B^* \) have convex down curvature beyond \( \sim 1,000 \) s, indicating that a fast decay turns into a slow decay at a finite time scale. The dashed lines are the extrapolations from the end of each measurement. The trapped field decay at \( B_{AC} = 24.6 \) mT becomes zero at \( 6\times10^4 \) s because the amplitude \( B_{AC} \) is very close to \( B^* = 26.5 \) mT. However, at low \( B_{AC} \), trapped fields remain finite even after \( 10^5 \) s. When the trapped field remains for such a long time after it is exposed to AC transverse field, stacked magnet can be used in practical applications. Therefore, in the future, if the AC field that a stacked magnet suffers is reduced to much lower than \( B^* \) of the CC used in the magnet, it can be used for rotating machine.

![Figure 4](image-url)  
**Figure 4.** Time evolutions of trapped fields of CC for 2,000 s while AC transverse fields of 0–49.2 mT were applied. Dashed lines are theoretical asymptotic values of trapped field for the AC field of the same color respectively.

In the future, if the AC field that a stacked magnet suffers is reduced to much lower than \( B^* \) of the CC used in the magnet, it can be used for rotating machine.

![Figure 5](image-url)  
**Figure 5.** Variation of trapped field in logarithmic time scale. Dashed lines are extrapolations from the end of each measurement.
4. Summary
We measured the crossed-field demagnetization of a EuBCO-BHO coated conductor, which has great characteristics to be used in stacked magnets. When an AC transverse field is applied after magnetization, the decay of trapped field is much faster than the conventional relaxation due to flux creep. However, for $B_{AC} \ll B^*$, where $B^*$ is full penetration field of transverse field, the decay after 2,000 s becomes weak like logarithmic decay. From these observations, we conclude that we can use stacked magnets for rotating machines if we can reduce the amplitude of AC transverse field to values much lower than $B^*$. 

References
[1] Tomita M and Murakami M 2003 Nature 421 517
[2] Durrel J H, Dennis A R, Jaroszynski J, Ainslie M D, Palmer K G B, Shi Y-H, Campbell A M, Hull J, Strasik M, Hellstorm E E and Cardwell D A 2014 Supercond. Sci. Technol. 27 082001
[3] Patel A, Hopkins S C and Glowacki B A 2013 Supercond. Sci. Technol. 26 032001
[4] Patel A, Filar K, Nizhankovskii V I, Hopkins S C and Glowacki B A 2013 Appl. Phys. Lett. 102 102601
[5] Patel A, Baskys A, Mitchell-Williams T, McCaul A, Coniglio W, Hänisch J, Lao M and Glowacki B A 2018 Supercond. Sci. Technol. 31 09LT01
[6] Tamegai T, Hirai T, Sun Y and Pyon S 2016 Physica C 530 20
[7] Hashimoto T, Pyon S and Tamegai T 2018 J. Phys.: Conf. Ser. 1054 012050
[8] Hashimoto T, Pyon S, Iijima Y, Sugiura S, Uji S, Terashima T and Tamegai T 2019 J. Phys.: Conf. Ser. 1293 012038
[9] Brandt E H and Mikitik G P 2002 Phys. Rev. Lett. 89 027002
[10] Vanderbemden P, Hong Z, Coombs T A, Ausloos M, Babu N, Cardwell D A and Cambell A M 2007 Supercond. Sci. Technol. 20 S174
[11] Baghdadi M, Ruiz H S and Coombs T A 2014 Appl. Phys. Lett. 104 232602
[12] Baghdadi M, Ruiz H S and Coombs T A 2018 Sci. Rep. 8 1342
[13] Liang F, Qu T, Zhang Z, Sheng J, Yuan W, Iwasa Y and Zhang M 2017 Supercond. Sci. Technol. 30 094006
[14] Baskys A, Patel A and Glowacki B A 2018 Supercond. Sci. Technol. 31 065011
[15] Kapolka M, Pardo E, Grilli F, Baskys A, Climente-Alarcon V, Dadhich A and Glowacki B A 2020 Supercond. Sci. Technol. 33 044019
[16] Dadhich A, Pardo E and Kapolka M 2020 Supercond. Sci. Technol. 33 065003