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Trapped field and temperature rise in rectangular-shaped HTSC bulk magnetized by pulse fields

T. Tateiwa [a], Y. Sazuka [a], H. Fujishiro [a,*], H. Hayashi [b], T. Nagafuchi [b], T. Oka [c]

[a] Faculty of Engineering, Iwate University, 4-3-5 Ueda, Morioka 020-8551, Japan
[b] Kyushu Electric Power Co. Inc., 2-1-47 Shiobaru, Fukuoka 815-8520, Japan
[c] Faculty of Engineering, Niigata University, Niigata, Niigata 950-2181, Japan

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Abstract

A rectangular-shaped GdBaCuO bulk ($33 \times 33 \times 20\ mm^3$) has been magnetized by pulse fields with various strengths from $B_{ex} = 3$ T to 7 T at 44 K and 20 K. The time dependences of the local fields and temperatures have been measured at five positions on the bulk surface. The flux movement, flux trapping and the heat generation are closely related for lower applied fields, i.e., the temperature rise is larger at the specified positions, where a large number of magnetic fluxes are trapped. The heat generation is mainly due to the pinning loss in this condition. The maximum trapped field $B_T = 4.0$ T can be realized on the bulk surface by a modified multi-pulse technique with stepwise cooling (MMPSC) method, on which B_T reaches only 2.5 T at 20 K for a single pulse application.

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Keywords: Pulse field magnetization; Rectangular-shaped bulk; Temperature rise; Trapped field; MMPSC method

1. Introduction

REBaCuO superconducting bulks (RE: rare earth element) are used as a conductor with zero resistance for power current leads, as a levitation device using a pinning effect and as a high strength bulk magnet using a strong pinning force [1]. A field-cooled magnetization (FCM) using a superconducting magnet (SM) is a usual technique to magnetize the bulks and makes the trapped field maximize. A pulse field magnetization (PFM) technique has been intensively studied because of the inexpensive and mobile experimental setup with no use of SM. Several approaches have been performed and succeeded to enhance the trapped field by an iteratively magnetizing pulsed-field method with reducing amplitude (IMRA) [2], a multi-pulse technique with stepwise cooling (MPSC) [3] and so on. Disk-shaped REBaCuO bulks are commonly used for a basic study and practical applications [4]. Rectangular-shaped bulks have been also fabricated and used for the specified applications such as a flywheel [5], magnetic bearings [6] and a magnetic separation system [7]. We have developed the bulk magnet system with five-aligned rectangular-shaped REBaCuO bulks, which has been used for the magnetic separation to purify waste water [8]. When the rectangular-shaped bulk is magnetized by PFM using a solenoid-type pulse coil, different behaviors as for the magnetic flux intrusion and the field trapping profile are supposed, compared with those for a disk-shaped bulk. Because the length of the flux intrusion path from the periphery to the bulk center is not identical at each position. However, there are no systematic reports of the trapped field properties for the rectangular-shaped bulks by PFM.

In this paper, we investigate the time dependences of both the local fields $B_L(t)$ and temperatures $T(t)$ at identical

* Corresponding author. Tel./fax: +81 19 621 6363.
E-mail address: fujishiro@iwate-u.ac.jp (H. Fujishiro).

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positions on the surface of the cryocooled rectangular-shaped GdBaCuO bulk after applying pulse fields. The relation between the flux intrusion and the temperature rise is discussed. A two-stage PFM technique, named as a modified multi-pulse technique with stepwise cooling (MMPSC) method [9], is applied in order to enhance the trapped field, in which the highest record of 5.20 T had been realized on the disk-shaped GdBaCuO bulk [10].

2. Experimental

The rectangular-shaped GdBaCuO bulk (Nippon Steel Corporation) was used with $33 \times 33\ mm^2$ in the *ab*-plane and 18 mm in thickness along the *c*-axis, which was cut from a disk-shaped bulk 45 mm in diameter. The bulk was mounted on soft iron yoke cylinder 40 mm in diameter and 20 mm in thickness and tightly anchored onto the cold stage of a Gifford–McMahon (GM) cycle refrigerator. The bulk was evacuated using an oil diffusion pump and the magnetizing solenoid coil was placed outside the vacuum chamber. The time dependences of the local magnetic fields $B_L(t)$ and temperatures $T(t)$ were measured at five positions on the bulk surface during PFM as shown in Fig. 1. Two sets of the measuring configurations were performed to measure the $B_L(t)$ and $T(t)$. The doted lines showed the growth sector boundaries (GSBs) and a point of intersection of GSRs slightly shifted from the bulk center. In Fig. 1a, four Hall sensors (F W Bell, BHT 921) and a thermocouple (type T, 76 μm in diameter) were symmetrically adhered at P1–P4 and at the bulk center (P0), respectively. Hereafter, we abbreviate this configuration as set A. The each distance between P0 and P1–P4 was 9 mm. In the set B, a Hall sensor and four thermocouples were set at P0 and P1–P4, respectively, as shown in Fig. 1b. The initial temperature T_s of the bulk surface was fixed at 44 K and 20 K and a single pulse field B_{ex} from 3 T to 7 T with a rise time of ~12 ms was applied to the bulk. In order to enhance the B_T value, the MMPSC method was applied. In the method, a pulse field $B_{ex}(1) = 4.94$ T was applied twice (No. 1 and No. 2 pulses) at $T_s(1) = 44$ K at the first stage in order to trap a small number of magnetic fluxes in the bulk. At the second stage, the bulk was cooled down to $T_s(2) = 20$ K and a higher pulse field $B_{ex}(2) = 6.87$ T was applied twice (No. 3 and No. 4), after recovering to $T_s(2)$.

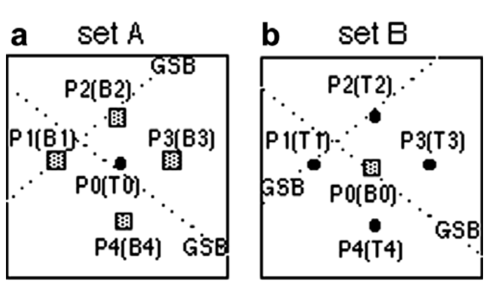

Fig. 1. Two sets of the measuring configurations of the local magnetic fields $B_L(t)$ and temperatures $T(t)$ on the bulk surface (set A and set B).

3. Results and discussion

Fig. 2a shows the trapped field B_T at P0 in the set B configuration as a function of the applied field B_{ex}. B_T at $T_s = 44$ K sharply increases for B_{ex} higher than 3 T, takes a maximum and then decreases with increasing B_{ex}. The $B_T - B_{ex}$ curve at $T_s = 20$ K is a similar behavior with a slight shift to the higher B_{ex}. The maximum B_T was 2.1 T for $B_{ex} = 5.49$ T at $T_s = 44$ K and 2.4 T for $B_{ex} = 6.20$ T at $T_s = 20$ K. These results come from the increase in the pinning force F_p with decreasing T_s. Fig. 2b shows the maximum temperature rise ΔT_{max} at P0 in the set A configuration as a function of B_{ex}. ΔT_{max} increases with increasing B_{ex} and the ΔT_{max} values at $T_s = 20$ K are larger than those at $T_s = 44$ K.

Fig. 3a and b shows the time evolutions of the local fields $B_L(t)$ and the temperatures $T(t)$ at P1–P4 after applying pulse field of $B_{ex} = 3.97$ T at 44 K. The strength of $B_{ex} = 3.97$ T is relatively low because only a small number of the magnetic fluxes intrude into the bulk center as shown in Fig. 2a. In Fig. 3a, $B_L(t)$ at P4 rises up with a sharp peak which is nearly equal to the B_{ex} value. The peak height of $B_L(t)$ at P1–P3 is at most 1–1.5 T. These results suggest that the magnetic flux starts to intrude from P4 more preferentially. The trapped field B_T ($=B_L(t = 200$ ms$)$) at P4 is as small as 1 T which is larger than that at P1–P3. In Fig. 3b, $T(t)$ at P4 also shows a sharp peak at around $t \sim 2$ s and then decreases.

Fig. 4a and b shows the time evolutions of $B_L(t)$ and $T(t)$ at P1–P4 after applying pulse field of $B_{ex} = 4.80$ T at 44 K. Contrary to the results in Fig. 3a, $B_L(t)$ at P1, P2 and P4 shows a sharp peak, which suggests that the magnetic fluxes preferentially intrude into the bulk from these positions for higher B_{ex} application. On the other hand, $B_L(t)$ at P3 rises up to at most 2.5 T. The B_T value at P2 and P3, which is 1.5–1.8 T at $t = 200$ ms, is larger than that at P1 and P4 ($B_T = 1$ T). In Fig. 4b, the temperature rise at P2 and P3 is 2–5 K larger than that at P1 and P4 and

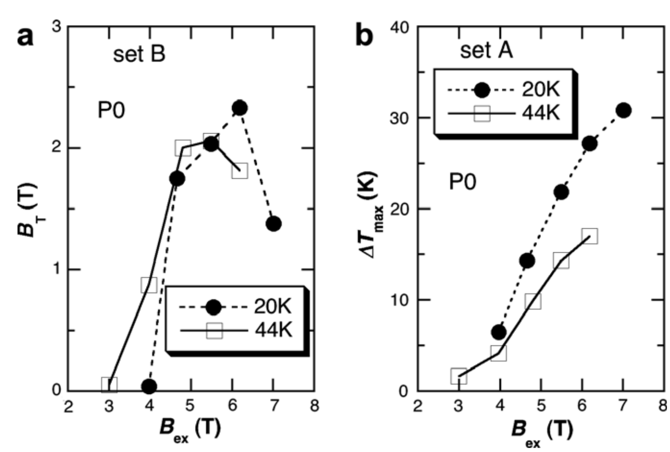

Fig. 2. (a) The trapped field B_T (set B) and (b) the maximum temperature rise ΔT_{max} (set A) at the bulk center (P0) as a function of the applied pulse field B_{ex} at $T_s = 20$ K and 44 K.

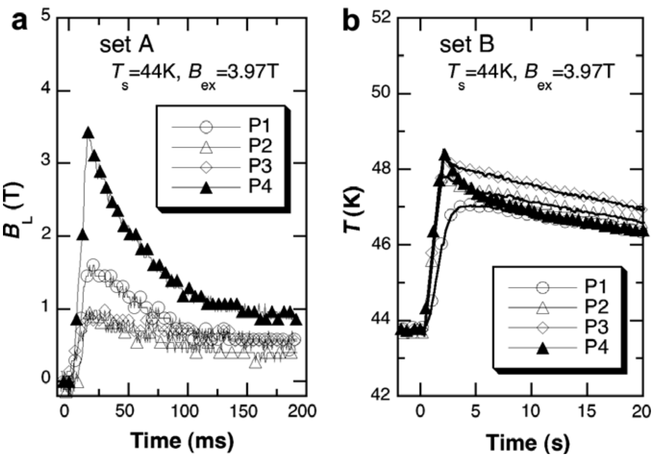

Fig. 3. The time evolutions of (a) the local fields $B_L(t)$ and (b) the temperatures $T(t)$ at P1–P4 after applying pulse field of $B_{ex} = 3.97$ T at $T_s = 44$ K.

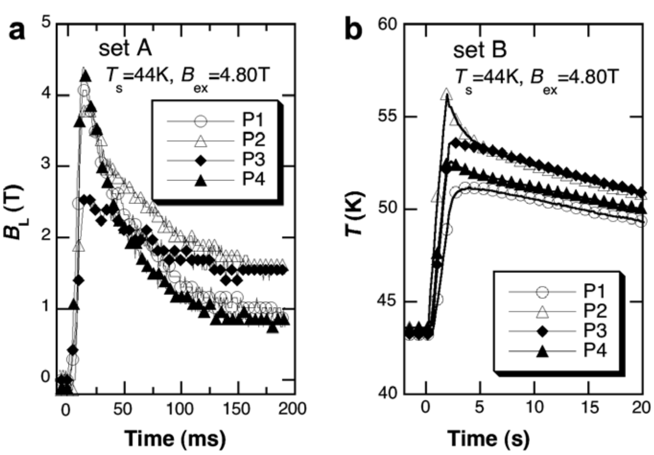

Fig. 4. The time evolutions of (a) the local fields $B_L(t)$ and (b) the temperatures $T(t)$ at P1–P4 after applying pulse field of $B_{ex} = 4.80$ T at 44 K.

$T(t)$ at P2 shows a clear peak. These results shown in Figs. 3 and 4 indicate that the flux intrusion and the flux trap are closely related with the heat generation.

Fig. 5a shows the position dependence of B_T (set A) at $T_s = 44$ K for various applied fields B_{ex}. The position, at which the fluxes are trapped preferentially, changes depending on the strength of B_{ex}. At the positions P3 and P4, B_T increases with increasing B_{ex} up to 5.49 T, but B_T at P1 and P2 decreases for the application of $B_{ex} = 5.49$ T which comes from the escape of fluxes due to the large temperature rise. Fig. 5b shows the position dependence of the maximum temperature rise ΔT_{max} (set B) at $T_s = 44$ K for various applied fields B_{ex}. It should be noted that the position dependence of ΔT_{max} resembles that of B_T. Heat generation Q is the sum of the pinning loss Q_p due to the flux trap and the viscous loss Q_v due to the flux movement [11]. The similarity of the position dependences of B_T and ΔT_{max} suggests that the heat generation is mainly due to Q_p. The similar behaviors also occur at

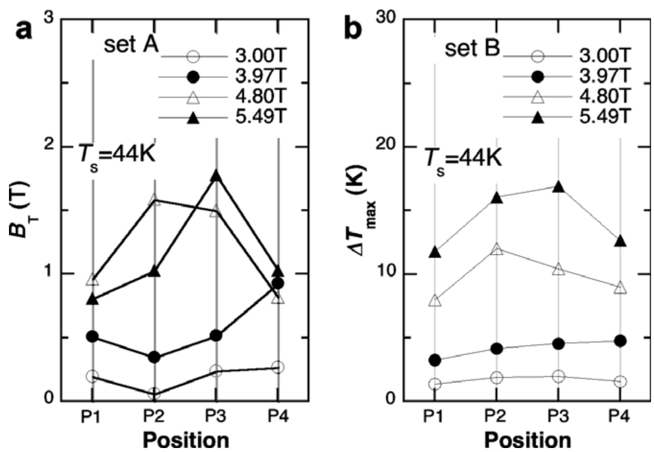

Fig. 5. The position dependence of (a) the trapped field B_T (set A) and (b) the maximum temperature rise ΔT_{max} (set B) at $T_s = 44$ K for various applied fields B_{ex}.

$T_s = 20$ K for $B_{ex} < 5$ T. For higher B_{ex} (>5.5 T at $T_s = 44$ K, >6.1 T at $T_s = 20$ K), Q_v is dominant due to the large temperature rise and decrease in the pinning force F_p [12]. In this way, the measurements of the local field $B_L(t)$ and the temperature $T(t)$ at identical positions give us the valuable information as for the dynamical motion and the trapping of the magnetic fluxes.

In order to enhance the B_T value, the MMPSC technique was applied. Fig. 6a and b shows the time dependences of the applied field $\mu_0 H_a(t)$ and the local fields $B_L(t)$ after applying pulse No. 1 ($T_s(1) = 44$ K, $B_{ex}(1) = 4.78$ T) and No. 3 ($T_s(2) = 20$ K, $B_{ex}(2) = 6.72$ T) in the MMPSC method, respectively. B_L(t) was measured at the positions P0, P3 and P5 as shown in the inset of Fig. 6b. For No. 1 pulse at the first stage, $B_T = 2$ T was trapped, and for No. 3 pulse at the second stage, $B_T = 4.0$ T and 2.9 T were trapped at P3 and P0, respectively. The B_T values are higher than those by a single pulse application

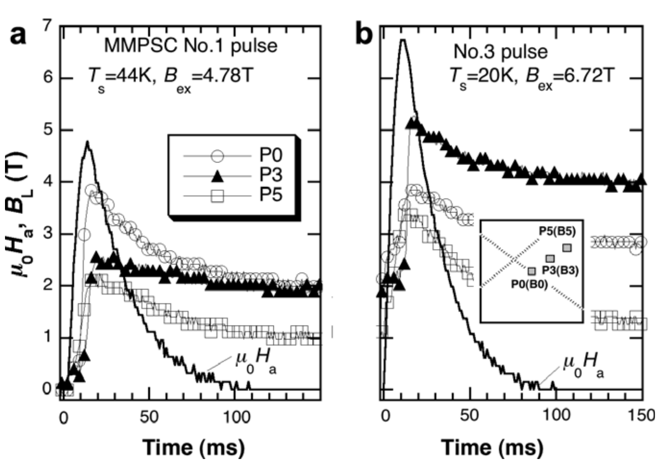

Fig. 6. The time dependences of the applied field $\mu_0 H_a(t)$ and the local fields $B_L(t)$ at P0, P3 and P5 after applying pulse fields of the (a) pulse No. 1 at the first stage and (b) pulse No. 3 at the second stage in the MMPSC method.

shown in Fig. 2a. These results suggest that the rectangular-shaped bulk used in this study has a potential to trap high B_T value and that the MMPSC method is an effective technique to enhance the B_T value.

In summary, a rectangular-shaped large GdBaCuO bulk has been magnetized by pulse fields with various strengths at $T_s = 44$ K and 20 K and the local fields $B_L(t)$ and temperatures $T(t)$ have been measured at identical five positions on the bulk surface. The temperature rise is larger at the specified positions, where a large number of magnetic fluxes are trapped. The heat generation is mainly due to the pinning loss Q_p. The maximum trapped field B_T can reach only 2.5 T at 20 K for a single pulse application, but the B_T value is enhanced up to 4.0 T by a MMPSC method.

References

[1] M. Murakami, N. Sakai, T. Higuchi, S.I. Yoo, Supercond. Sci. Technol. 9 (1996) 1015.
[2] U. Mizutani, T. Oka, Y. Itoh, Y. Yanagi, M. Yoshikawa, H. Ikuta, Appl. Supercond. 6 (1998) 235.
[3] M. Sander, U. Sutter, R. Koch, M. Klaser, Supercond. Sci. Technol. 13 (2000) 841.
[4] S. Nariki, M. Murakami, Supercond. Sci. Technol. 15 (2002) 786.
[5] N. Koshizuka, Physica C 445–448 (2006) 1103.
[6] K. Demachi, I. Masaie, T. Ichihara, M. Kita, Physica C 426–431 (2005) 826.
[7] H. Hayashi, K. Tsutsumi, N. Saho, N. Nishijima, K. Asano, Physica C 392–396 (2003) 745.
[8] A. Fujiwara, T. Tateiwa, H. Fujishiro, H. Hayashi, T. Nagafuchi, T. Oka, Physica C 445–448 (2006) 399.
[9] H. Fujishiro, M. Kaneyama, T. Tateiwa, T. Oka, Jpn. J. Appl. Phys. 44 (2005) L1221.
[10] H. Fujishiro, T. Tateiwa, A. Fujiwara, T. Oka, H. Hayashi, Physica C 445–448 (2006) 334.
[11] H. Fujishiro, K. Yokoyama, M. Kaneyama, T. Oka, K. Noto, Physica C 412–414 (2004) 646.
[12] H. Fujishiro, M. Kaneyama, K. Yokoyama, T. Oka, K. Noto, Supercond. Sci. Technol. 18 (2005) 158.