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Importance of initial "M-shaped" trapped field profile in a two-stage pulse field magnetization (MMPSC) method

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Abstract

The influence of a shape of a trapped field distribution at a first stage on the final trapped field B_T at a second stage has been investigated in the two-stage pulse field magnetization technique named as a modified multi-pulse technique with stepwise cooling (MMPSC). The final trapped field B_T strongly depends on the shape and the strength of the trapped field at the first stage. The "M-shaped" profile with a moderate number of magnetic fluxes at the first stage maximizes the final B_T. The optimization of the applied field $B2$ and the lowering of the operating temperature $T2$ at the second stage are also effective to enhance B_T. The flux intrusion and the flux trap are effectively promoted at low temperatures by the existence of already trapped fluxes during the first stage.

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Keywords: Pulse field magnetization; MMPSC method; Trapped field profile; Bulk superconductor

1. Introduction

Highly *c*-axis oriented REBaCuO superconducting bulks (RE: rare earth element) can trap a magnetic field as high as 17 T at 29 K by field-cooled magnetization (FCM) because of the improvements in their pinning properties and the mechanical reinforcement [1]. A cryocooled superconducting bulk magnet, which can generate over 5 T in open space, has been developed by FCM for the applications to the sputtering cathode [2]. A pulse field magnetization (PFM) is another technique to magnetize the bulk and has been intensively investigated because of the relatively compact, inexpensive and mobile setup [3]. In PFM, however, a large temperature rise occurs in the bulk due to the dynamical motion of magnetic fluxes and then the trapped field component B_T parallel to the *c*-axis of the bulk is fairly smaller than that by FCM due to the decrease in a critical current density J_c at elevated temperatures. The highest B_T value ever reported had been 3.80 T on the SmBaCuO bulk (35 mm in diameter) at 30 K [4]. We have systematically studied the temperature rise ΔT and the trapped field B_T on REBaCuO bulks during PFM [5–7] and have suggested that both the reduction in ΔT and the lowering of the operating temperature T_s are indispensable issues to enhance B_T [8].

Based on the obtained results, we proposed a new PFM technique, named as a modified multi-pulse technique combined with a stepwise cooling (MMPSC) method [9] and have succeeded a highest field trapping of $B_T = 5.20$ T on the GdBaCuO bulk (45 mm in diameter) [10]. In this technique, a small number of magnetic fluxes should be trapped in the bulk at $T1$ after applying pulse field $B1$ at a first stage. After the bulk is cooled down to the lower temperature $T2$, a higher and optimum pulse field $B2$ ($>B1$) should be applied at a second stage. The so-called "M-shaped"

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trapped field profile at the first stage, in which the trapped field at the bulk center is lower than that at the bulk periphery, is also necessary in order to enhance the B_T value [11]. If a "cone-shaped" profile is realized at the first stage, a sizable enhancement of B_T cannot be realized by the succeeding pulse [11]. In the previous studies, however, we measured the time evolution of local fields $B_L(t)$ and the trapped fields B_T at only three points (center, middle and periphery of the bulk disk) using Hall sensors adhered on the bulk surface [10]. In order to enhance the B_T value still more using the MMPSC method, the role of the "M-shaped" profile at the first stage must be clarified.

In this paper, we measure the two-dimensional trapped field profile 0.5 mm above the bulk surface at both first and second stages in the MMPSC method. The influence of the shape of the trapped field distribution at the first stage on the final B_T value at the second stage is discussed.

2. Experimental procedure

The GdBaCuO bulk disk (Nippon Steel Corporation) used in this study was 45 mm in diameter and 18 mm in thickness, which was different with that attained $B_T = 5.20$ T [10]. 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 experimental apparatus for PFM is described elsewhere [6]. The temperature of the bulk was controlled over the range from 30 K to 70 K. The magnetizing solenoid coil, which generated the pulse field up to $B_{ex} = 6.29$ T with a rise time of ~12 ms, was placed outside the vacuum chamber that the central axis of the resulting field coincides with that of the bulk. Fig. 1 shows the experimental sequence of the MMPSC technique. Four magnetic pulses were applied at different initial temperatures $T1$ and $T2$ on the bulk surface. At the first stage, a pulse field $B1$ was applied twice at $T1$ (=70 K or 60 K) in order to trap a small number of magnetic fluxes in the bulk. Hereafter, we refer to these two pulses as No. 1 and No. 2. At the second stage, the bulk was cooled down to $T2$ (=40 K or 30 K) and a higher pulse field $B2$ was applied twice (No. 3 and No. 4 pulses). At each stage, the trapped field component B_T parallel to the c-axis of the bulk was measured 0.5 mm above the bulk surface by scanning a Hall sensor (F W Bell, BHA 921) inside the vacuum chamber using a scanning device, which has an x–y stage controller with a flexible bellows. The total trapped flux Φ_T was calculated from the trapped field distribution by integrating B_T over the area where its value was positive.

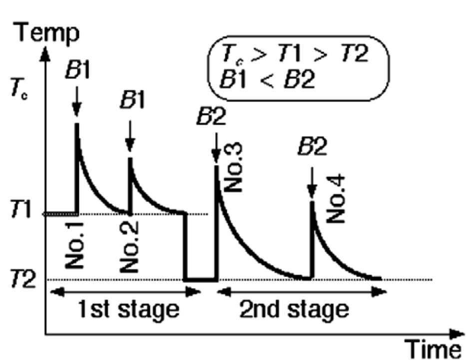

Fig. 1. The experimental sequence of the MMPSC technique. At the first stage, a pulse field $B1$ is applied twice (No. 1 and No. 2) at $T1$. At the second stage, the bulk is cooled down to $T2$ and a higher pulse field $B2$ is applied twice (No. 3 and No. 4).

3. Results and discussion

In order to confirm the field trapping ability of the bulk and determine the conditions in the MMPSC method, a single magnetic pulse was applied and the B_T distribution was measured for various applied fields B_{ex} at temperatures T (=30–70 K). Fig. 2a and b show the vertical section of the B_T profile after applying pulse fields B_{ex} at $T = 70$ K and 40 K, respectively. In the inset of Fig. 2a, an example of the two dimensional B_T profile is shown for $B_{ex} = 2.66$ T. All the vertical sections shown in this study were made along the central line in a same manner. At $T = 70$ K, the trapped field increases with increasing applied field B_{ex}, takes a maximum for $B_{ex} = 4.52$ T and then decreases for higher B_{ex}. The "M-shaped" B_T profile can be observed for $B_{ex} < 3.84$ T, and a symmetric "cone-shaped" profile can be seen for $B_{ex} > 4.52$ T. On the other hand, at $T = 40$ K shown in Fig. 2b, B_T(C) at the bulk center is small, even if the pulse field with the same strength is applied as that at $T = 70$ K. The maximum B_T(C) increases $B_T = 1.8$ T for the highest applied field $B_{ex} = 6.29$ T, but the "cone-shaped" profile cannot be realized because of the strong pinning force F_p at low temperatures.

Fig. 3a–d show the B_T profiles of the cases A–D under various conditions ($T1$, $B1$, $T2$ and $B2$) in the MMPSC

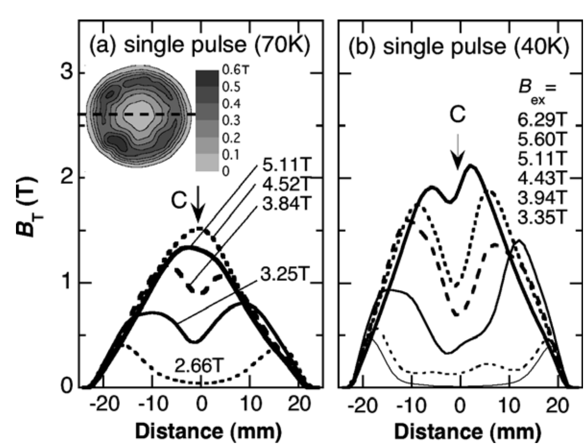

Fig. 2. The vertical section of the B_T profile after applying pulse fields B_{ex} at (a) $T = 70$ K and (b) 40 K. The inset of (a) shows an example of the two dimensional B_T profile for $B_{ex} = 2.66$ T.

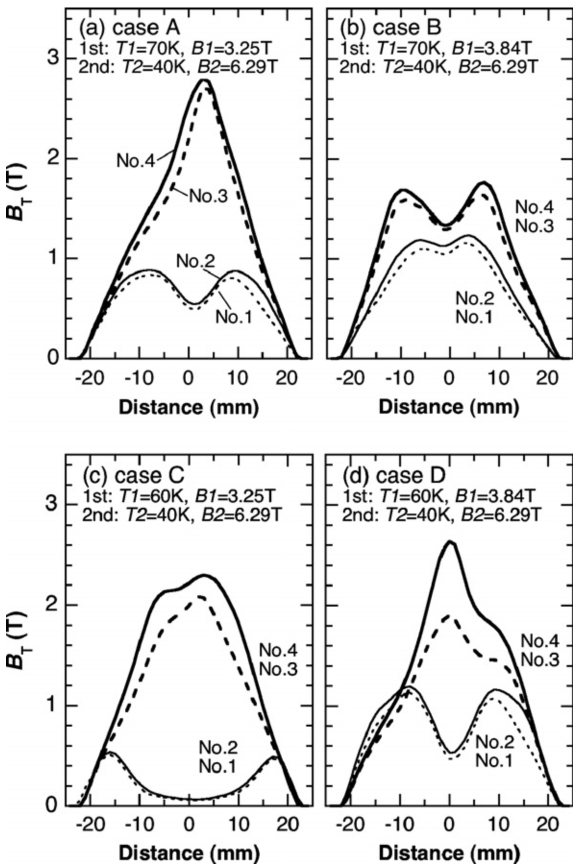

Fig. 3. The B_T profiles in the cases A–D under various conditions ($T1$, $B1$, $T2$ and $B2$) in the MMPSC method.

method. In cases A and B shown in Fig. 3a and b, the influence of the shape of the trapped field distribution at the first stage ($T1 = 70$ K) on that at the second stage ($T2 = 40$ K) is indicated. A small number of magnetic fluxes were trapped on the bulk and the typical "M-shaped" profile was observed at the first stage in the case A ($B1 = 3.25$ T). The B_T profile in the case B($B1 =$ 3.84 T) shows a "trapezoid-shaped" profile rather than the "M-shaped" one due to the higher $B1$. After applying identical higher pulse field $B2 = 6.29$ T for both cases at the second stage ($T2 = 40$ K), the shape of the final B_T profile is quite different; a cone-shaped profile with higher $B_T(C) = 2.8$ T can be observed in the case A, but the "M-shaped" profile is more emphasized and $B_T(C)$ remains the low value of 1.4 T in the case B. A slight increase in the total trapped flux Φ_T in the No. 2 and No. 4 pulse applications, compared with that in the No. 1 and No. 3 pulses, respectively, is due to the decrease in the temperature rise by the identical pulse field applications [7]. In Fig. 3c, where a very small number of the magnetic fluxes are trapped only in the bulk periphery at the first stage ($T1 = 60$ K, $B1 = 3.25$ T), the cone-shaped profile was obtained at the second stage ($T2 = 40$ K, $B2 = 6.29$ T). The maximum $B_T(C) = 2.4$ T value was low, compared with that of the case A, but $B_T(C)$ value and the B_T profile were nearly the same as those obtained by the single pulse application. In the case D, where a slight different "M-shaped" profile from that in Fig. 3a is formed at the first stage ($T1 = 60$ K, $B1 = 3.84$ T), the B_T profile is asymmetric and the $B_T(C)$ is not large at the second stage ($T2 = 40$ K, $B2 = 6.29$ T). In this way, the trapped field profile and the $B_T(C)$ value at the second stage strongly depend on the shape of the trapped field profile and the Φ_T value at the first stage. The optimum "M-shaped" profile exists at the first stage for enhancing the final trapped field in MMPSC.

The influences of the strength of $B2$ and the lowering $T2$ at the second stage were studied under the similar shape of the B_T profile at the first stage. Fig. 4a shows the trapped field distribution after applying No. 3 pulse field with various $B2$ values at $T2 = 40$ K under the identical "M-shaped" profile at the first stage ($T1 = 70$ K, $B1 =$ 3.25 T). For $B2 = 5.95$ T, a nearly symmetrical trapped field distribution with $B_T(C) = 2.8$ T was observed. On the other hand, for $B2 = 5.60$ T and 6.29 T, the B_T profiles are asymmetric and the maximum B_T values are rather small. These results suggest that the optimum strength of $B2$ exists in order to enhance the trapped field and that the optimum $B2$ value changes depending on the shape of the B_T profile at the first stage. Fig. 4b shows the results of the B_T profile, where the temperature $T2$ decreased to 30 K and the $B2 = 6.29$ T was applied under the similar B_T profile at the first stage to that shown in Fig. 4a ($T2 = 40$ K). A symmetrical trapped field distribution was observed and $B_T(C)$ was enhanced over 3 T. An optimum pulse field was probably $B2 = 6.29$ T at $T2 = 30$ K in the bulk which slightly shifts to higher field due to the enhancement of the pinning force by lowering $T2$. The lowering $T2$ is a possible solution to enhance B_T.

Fig. 5a shows the $B_T(C)$ value for the No. 3 pulse ($T2 = 40$ K) as a function of $B2$ after the "M-shaped" trapped field distribution as shown in Fig. 4a is realized

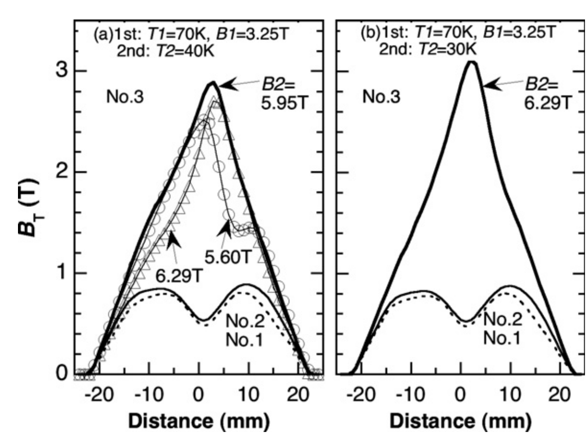

Fig. 4. (a) The B_T profile after applying No. 3 pulse with various $B2$ values at $T2 = 40$ K under the identical trapped field distribution at the first stage ($T1 = 70$ K, $B1 = 3.25$ T). (b) The B_T profile after applying $B2 = 6.29$ T at $T2 = 30$ K under the identical B_T profile at the first stage to that shown in (a).

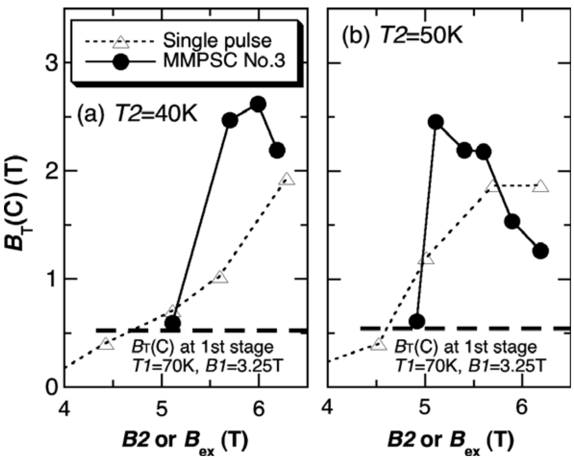

Fig. 5. The B_T(C) value for the No. 3 pulse ((a) $T2 = 40$ K and (b) 50 K) as a function of $B2$ after the "M-shaped" trapped field distribution is realized at the first stage. The B_T(C) values for the single pulse application are also shown.

at the first stage ($T1 = 70$ K, $B1 = 3.25$ T). The B_T(C) values for the single pulse application at $T = 40$ K are also shown. B_T(C) of the single pulse application monotonically increases with increasing applied field B_{ex} up to 6.29 T. In the MMPSC method, B_T(C) is larger than that in a single pulse application. It should be noted that B_T(C) in the MMPSC method also increases with increasing $B2$ and then takes a maximum at $B2 = 6$ T. These results suggest that the magnetic fluxes are easy to intrude and trap in the bulk for the existence of a moderate number of trapped fluxes at the first stage. Fig. 5b shows the similar results at $T2 = 50$ K. B_T(C) in the MMPSC method takes a maximum at 5 T which is larger than that for a single pulse application. The $B2$ value at which B_T(C) takes a maximum at $T2 = 50$ K is lower than that at $T2 = 40$ K due to the decrease in the pinning force F_p.

4. Summary

We have investigated the influence of a shape of a trapped field distribution at a first stage on the final trapped field at a second stage in a modified multi-pulse technique with stepwise cooling (MMPSC). The final trapped field B_T strongly depends on the shape and the strength of the trapped field at the first stage. The optimum "M-shaped" profile with a moderate number of magnetic fluxes at the first stage maximizes the final B_T. The flux intrusion and trap are promoted effectively by the existence of already trapped fluxes in the bulk at low temperature.

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