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Trapped field characteristics on φ65 mm GdBaCuO bulk by modified multi-pulse technique with stepwise cooling (MMPSC)

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ABSTRACT

A large GdBaCuO superconducting bulk 65 mm in diameter has been magnetized by a two-stage pulse field magnetization method named as a modified multi-pulse technique with stepwise cooling (MMPSC). The trapped field B_T^P of 3.0 T was achieved at the bulk center at 40 K by optimizing the trapped field profile at the first stage of the MMPSC method, on which the maximum B_T^P was as low as 1.9 T at 40 K for the single pulsed field application. A magnetic gradient along the radius direction larger than that estimated by a Bean's model is realized at the ascending stage of the magnetic pulse field at the second stage, and a large amount of magnetic fluxes staying at the bulk periphery flow to the bulk center at the descending stage.

1. Introduction

Recently, a REBaCuO superconducting bulk of diameter larger than 60 mm is on the commercial market and a single-grain bulk of 140 mm in diameter can also be fabricated [1]. A trapped field B_T and a total trapped flux density Φ_T increase with increasing diameter of the bulk disk, if the critical current density J_c of the bulk material is identical. Thus, a large bulk is useful for the practical applications such as electric motor and generators. To magnetize the superconducting bulk for the quasi-permanent magnet, the pulsed field magnetization (PFM) is suitable, instead of a conventional field cooled magnetization (FCM), because PFM is an inexpensive and mobile experimental setup. The trapped field B_T^P by PFM was, however, pretty smaller than that attained by FCM below 77 K, because of the large temperature rise by the dynamical motion of magnetic fluxes in the bulk [2]. Several approaches have been performed and succeeded to enhance B_T^P around 77 K such as an iteratively magnetizing pulsed field method with reducing amplitude (IMRA) [3], a multi-pulse technique with stepwise cooling (MPSC) [4] and so on. We have systematically studied the time and spatial dependences of the temperature $T(t, x)$, the local field $B_L(t)$ and the trapped field B_T^P on the surface of cryo-cooled REBaCuO bulks of 45 mm in diameter during PFM for various starting temperatures T_s and applied fields B_{ex} [5–8]. We have also investigated the trapped field characteristics on the φ65 mm GdBaCuO bulk by the successive pulse application (SPA) method [9]. Contrary to our expectation, the maximum trapped field on the φ65 mm bulk was as low as $B_T^P = 1.9$ T, which was fairly smaller than that of the φ45 mm GdBaCuO bulk.

To enhance B_T^P, we proposed a new PFM technique called a modified MPSC (MMPSC), which consisted of the two-stage temperature procedures [10]. Using the MMPSC method, we have succeeded a highest field trapping of $B_T^P = 5.20$ T on the φ45 mm GdBaCuO bulk at 29 K, on which the maximum B_T^P of 3.6 T was attained by a single pulse application. The value of $B_T^P = 5.20$ T is a record high B_T^P by PFM to date. The MMPSC has been proved to be a universal and effective method to enhance B_T^P using other bulks [11,12]. In this paper, we apply the MMPSC method to the φ65 mm GdBaCuO bulk and investigate the flux dynamics and the B_T^P enhancement.

2. Experimental procedures

A *c*-axis oriented GdBaCuO bulk superconductor (Nippon Steel Corporation) of 65 mm in diameter and 20 mm in thickness was used. The trapped field B_T^{FC} by the FCM method was 1.9 T at 77 K. The stainless steel (SUS304) ring with 1.0 mm in thickness was fixed onto the bulk disk using Stycast 2850GT. The detailed experimental setup around the bulk and the pulse coil were described elsewhere [9]. The bulk was tightly anchored onto the cold stage of a Gifford–McMahon (GM) cycle helium refrigerator and was

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cooled down. The bulk was magnetized using a condenser bank and a solenoid-type copper coil dipped in liquid N_2. Two Hall sensors (F.W. Bell, Model BHT 921) were adhered at the positions C (bulk center) and E (20 mm distant from the bulk center) on the growth sector boundary (GSB). The time evolutions of the local fields $B_L(t)$ and the trapped fields $B_T = B_L(t\to\infty)$ at positions C and E were monitored by using a digital oscilloscope. The applied field $\mu_0H_a(t)$, of which the maximum strength was defined as B_{ex}, was monitored by the current $I(t)$ flowing through the shunt resistor. The rising time of the pulsed field was 11 ms and the duration was 80 ms. The temperature $T(t)$ at the center of the bulk surface was measured using fine thermocouple. The experimental sequence of the MMPSC technique is shown in the inset of Fig. 1. At the first stage, the pulsed field $B1$ = 3.26, 3.90, 4.75 or 5.18 T was applied twice (No. 1 and No. 2 pulse) at $T1$ = 60 K to investigate the influence of the B_T profile at the first stage on the final B_T. At the second stage, the bulk was cooled to $T2$ = 40 K and the identical pulsed field of $B2$ = 6.7 T was applied twice (No. 3 and No. 4) for each B_T profile of the first stage.

3. Results and discussion

Fig. 1a shows the time evolution of the applied field $\mu_0H_a(t)$ and the local fields $B_L(t)$ at positions C and E after the No. 1 pulse application ($B1$ = 4.75 T) at $T1$ = 60 K in the first stage. The local field $B_L(E)(t)$ started to rise at t = 3 ms, took a maximum at 15 ms with nearly the same peak height as μ_0H_a, and then decreased. $B_L(C)(t)$ started to rise at 12 ms with a long time delay, at which $\mu_0H_a(t)$ took a maximum of as small as 0.4 T. In this condition, an "*M-shaped*" B_T profile can be realized, which means the lower trapped field at the bulk center than that at the bulk periphery ($B_T(C) < B_T(E)$) [10]. For the No. 2 pulse application (not shown), $B_T(C)$ did not change, but $B_T(E)$ slightly increased from 1.1 T to 1.3 T, which was consistent with the previous results [8]. Fig. 1b shows $\mu_0H_a(t)$, $B_L(C)(t)$ and $B_L(E)(t)$ after the No. 3 pulse application ($B2$ = 6.7 T) at $T2$ = 40 K in the second stage. $B_L(E)(t)$ increased with increasing time and the maximum of $B_L(E)$ was as large as that of μ_0H_a. $B_L(C)(t)$ started to rise at 15 ms, took a maximum of 3.5 T at 20 ms and finally approached to 3.0 T. The $B_T(C)$ = 3.0 T was higher than that obtained by single pulse application [9]. In this way, the trapped fluxes at the first stage enhance the flux intrusion and flux trapping at the second stage.

Fig. 2 shows the estimated cross sections of the B_T profiles on the bulk after the No. 2 pulse application ($B1$) with the various strength at $T1$ = 60 K, and the subsequent No. 3 pulse application of $B2$ = 6.7 T at $T2$ = 40 K. If a B_T profile is supposed to be symmetrical along the circumferential direction, it is roughly estimated using the measured $B_T(C)$, $B_T(E)$ and $B_T = 0$ at the bulk edge (r = 32.5 mm). Let us compare the B_T profiles for the No. 2 pulse at the first stage. For the applied field $B1$ lower than 3.90 T, $B_T(E)$ increases with increasing $B1$, but $B_T(C)$ is nearly zero. For $B1$ = 4.75 T and 5.18 T, a small amount of magnetic fluxes intrude into the bulk center and the difference between $B_T(C)$ and $B_T(E)$ becomes small. After the No. 3 pulse application of $B2$ = 6.7 T at $T2$ = 40 K, the B_T profile strongly depends on the shape of the already trapped B_T profile prepared at the first stage; $B_T(C)$ after the No. 3 pulse increases for the B_T profile of the first stage with increasing $B1$. But $B_T(C)$ was not enhanced for the B_T profile of $B1$ = 5.18 T, where $B_T(C)$ is as high as 1 T and is comparable with $B_T(E)$. The similar profiles for the successive pulse application with identical strength (SPA) were also shown in Fig. 2, where B = 6.7 T was applied twice at 40 K to the zero-field cooled bulk. The B_T profile was cone-shaped, but the $B_T(C)$ value was as low as 1.9 T. In this way, it was found that the optimum "*M-shaped*" profile exists at the first stage to maximize the B_T(C) value for the No. 3 pulse application.

Fig. 3a and b show the time dependences of the transient magnetic distribution for the ascending ($t \leqslant 11$ ms) and the descending ($t \geqslant 11$ ms) stages of the No. 3 pulse field ($B2$ = 6.7 T) at $T2$ = 40 K as a function of the bulk radius r, respectively, both of which were reconstructed using Fig. 1b. The bold dotted line in Fig. 3a shows the initial B_T profile at t = 0 ms, which was realized at the first stage ($B1$ = 4.75 T, $T1$ = 60 K). The local fields at positions C and E hardly change for $t \leqslant 3$ ms and the magnetic flux distribution shows a

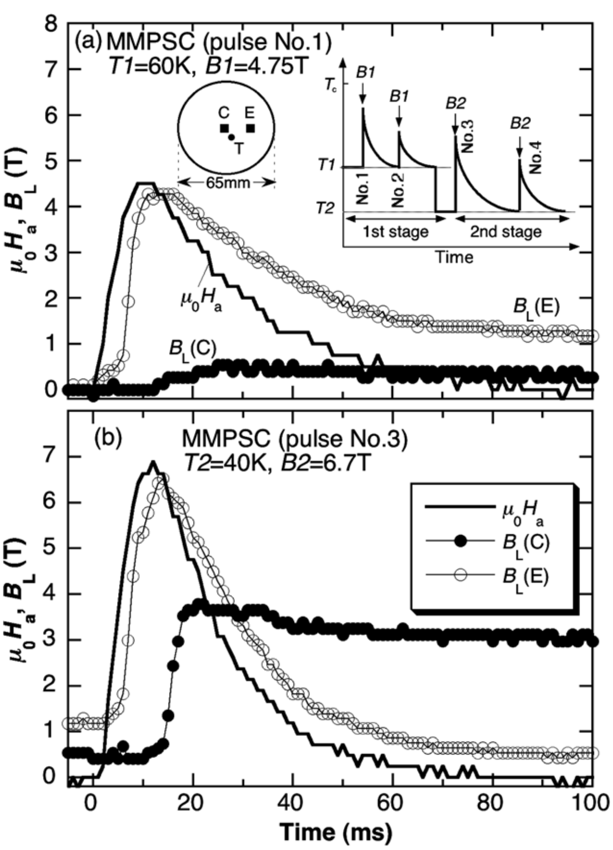

Fig. 1. The time evolution of the applied field $\mu_0H_a(t)$ and the local fields $B_L(t)$ at positions C and E after the (a) No. 1 pulse application ($B1$ = 4.75 T) at $T1$ = 60 K in the first stage and (b) the No. 3 pulse application ($B2$ = 6.7 T) at $T1$ = 40 K in the second stage.

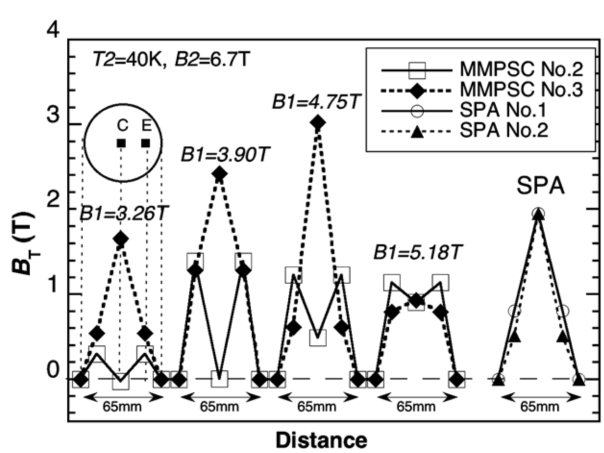

Fig. 2. The estimated cross sections of the B_T profiles after the No. 2 pulse application $B1$ with the various strengths at $T1$ = 60 K, and the subsequent No. 3 pulse application of $B2$ = 6.7 T at $T2$ = 40 K. The similar profiles for the successive pulse application with identical strength (SPA) were also shown.

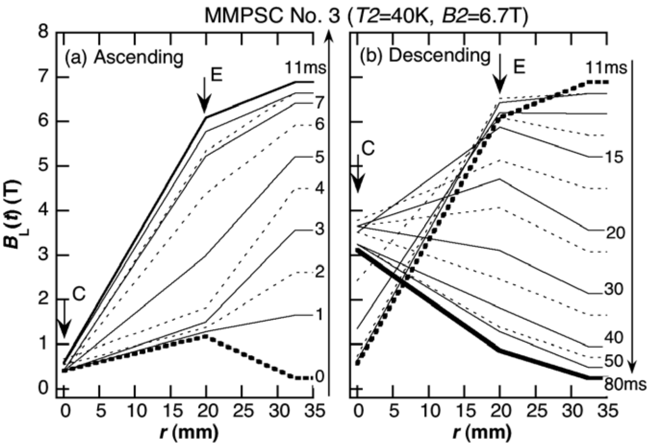

Fig. 3. The time dependences of the magnetic field distribution in the bulk for (a) the ascending ($t \leqslant 11$ ms) and (b) the descending ($t \geqslant 11$ ms) stages of the No. 3 pulse field ($B2 = 6.7$ T) at $T2 = 40$ K, where the optimum "*M-shaped*" profile was realized at the first stage.

kink at position E. This result cannot be explained using a Bean's critical state model, because the magnetic gradient dB/dr, which is proportional to a critical current density J_c, should be constant. This result strongly suggests that the large viscous force F_V exists at the bulk periphery. For $t \geqslant 4$ ms, $B_L(E)(t)$ gradually increases and the flux distribution changes from concave to convex profile with increasing time. For the descending stage shown in Fig. 3b, however, $B_L(C)(t)$ sharply increases and took a maximum at $t = 14$ ms, just after $\mu_0 H_a(t)$ takes a maximum. For $t \geqslant 15$ ms, $B_L(C)(t)$ and $B_L(E)(t)$ gradually decreased and the cone-shaped trapped field distribution with $B_T(C) = 3.0$ T was finally obtained. A magnetic gradient along the radius direction larger than that estimated by a Bean's model is realized at the ascending stage of the magnetic pulse field at the second stage. A large amount of magnetic fluxes staying at the bulk periphery flow to the bulk center at the beginning of the descending stage, because of the decrease of F_V, at which the flux velocity v is nearly zero and F_V is proportional to v. The optimum "*M-shaped*" profile might enhance the magnetic gradient (dB/dr) and the amount of the magnetic flux staying at the bulk periphery.

Fig. 4 shows the similar results for the No. 1 pulse of SPA ($B = 6.7$ T at 40 K), where the magnetic fluxes intrude into the virgin state bulk. A distinct convex trapped field profile can be seen at

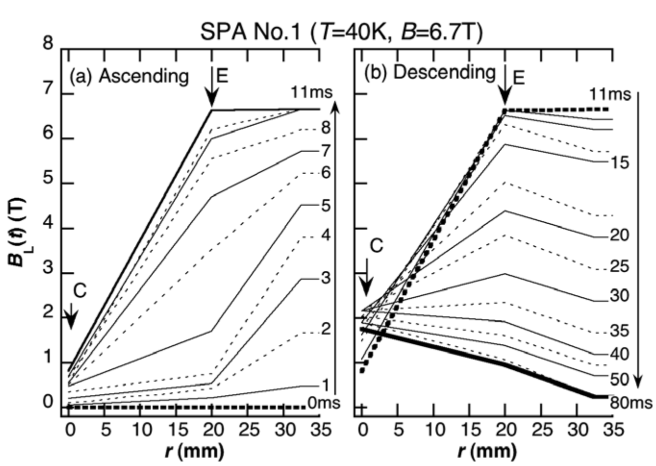

Fig. 4. The time dependences of the magnetic field distribution in the bulk for (a) the ascending ($t \leqslant 11$ ms) and (b) the descending ($t \geqslant 11$ ms) stages of the SPA process ($B = 6.7$ T) at $T = 40$ K.

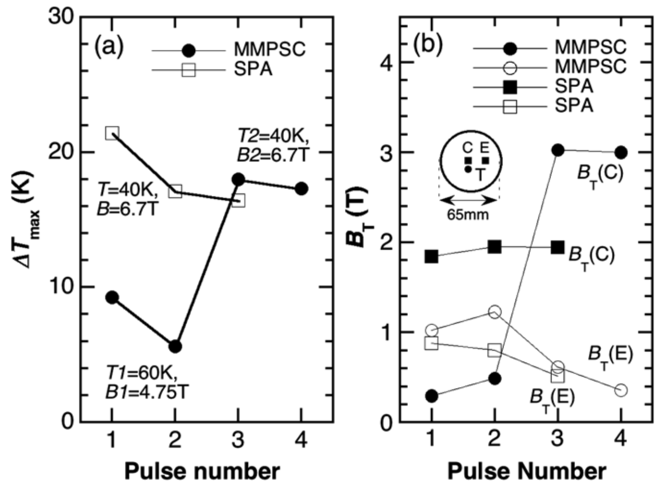

Fig. 5. The pulse number dependence of (a) the maximum temperature rise ΔT_{max} and (b) the trapped fields B_T at positions C and E for the MMPSC method ($B1 = 4.75$ T at 60 K, $B2 = 6.7$ T at 40 K) and the SPA method ($B = 6.7$ T at 40 K).

the end of the ascending stage, compared with the results in Fig. 3a. For the descending stage, the enhancement of $B_L(C)(t)$ was not so large and final $B_T(C)$ was as small as 1.9 T.

Fig. 5a and b show the pulse number dependence of the maximum temperature rise ΔT_{max} and the trapped fields B_T at positions C and E for the MMPSC method ($B1 = 4.75$ T at 60 K, $B2 = 6.7$ T at 40 K) and SPA method ($B = 6.7$ T at 40 K). For the SPA method, ΔT_{max} gradually decreases and $B_T(C)$ gradually increases with increasing pulse number. For the MMPSC method, ΔT_{max} at the second stage is larger than that at the first stage because of the larger pinning loss Q_p and viscous loss Q_v at low temperature. It should be noted that the ΔT_{max} of the No. 3 pulse in MMPSC is 3.5 K lower than that of the No. 1 pulse in SPA. The $B_T(C)$ value after the No. 3 pulse jumps to 3.0 T and then maintains the value for the No. 4 pulse. The reduction in ΔT_{max} is due to the already trapped fluxes at the first stage, which enhances the B_T^P value in the MMPSC process. The $B_T(E)$ value decreases with increasing pulse number for both MMPSC and SPA, which results from the large temperature rise in the bulk periphery.

4. Summary

GdBaCuO bulk (φ65 mm) has been magnetized by a modified multi-pulse technique with stepwise cooling (MMPSC). The trapped field B_T of 3.0 T is realized at the bulk center at 40 K by optimizing the trapped field profile ("*M-shaped*") at the first stage, on which the maximum B_T was 1.9 T at 40 K for the single pulse application. A moderate amount of the magnetic fluxes should be trapped at the first stage to reduce the excess temperature rise for higher pulse field ($B2$) application at lower $T2$ in the second stage. A large magnetic gradient (dB/dr) along the radius direction is also necessary at the ascending stage of the pulse field ($B2$) in the second stage, where a large amount of magnetic fluxes staying at the bulk periphery flow to the bulk center at the descending stage. The optimum "*M-shaped*" profile might enhance the magnetic gradient (dB/dr) and the amount of the magnetic flux staying at the bulk periphery.

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