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Trapped Field over 4 Tesla on GdBaCuO Bulk by Pulse Field Method and Magnetizing Mechanism

Hiroyuki Fujishiro[1], Masahiko Kaneyama[1], Tatsuya Tateiwa[1] and Tetsuo Oka[2]

[1] Faculty of Engineering, Iwate University, 4-3-5 Ueda, Morioka 020-8551, Japan
[2] IMRA Material R&D Co. Ltd., 5-50 Hachiken-cho, Kariya 448-0021, Japan

E-mail: fujishiro@iwate-u.ac.jp

Abstract. We report a new pulse field magnetizing (PFM) method using the modified multi pulse technique combined with a stepwise cooling (MMPSC) to obtain the trapped field B_T^P over 4 T on a bulk superconductor. The B_T^P value as high as 4.47 T has been attained on the surface of the GdBaCuO bulk, which is the present highest using PFM. The key points to obtain the higher B_T^P are the introduction of a small amount magnetic flux (B_T^P~1 T) into the bulk with the "*M-shaped*" trapped field distribution at a higher starting temperature T_s~45 K, and the following application of the optimum stronger pulse fields of B_{ex}~6.7 T at a lower T_s~30 K. The reduction in the temperature rise ΔT due to the already existing trapped flux is a very important issue.

1. Introduction

The superconducting bulk magnet using the melt-textured REBaCuO superconducting bulk is one of the exemplary models for practical applications. Recently, the pulse field magnetizing (PFM) has been intensively investigated because of the relatively compact and mobile setup. The trapped field B_T^P by PFM is, however, generally smaller than that attained by the field-cooled magnetizing (FCM) at low temperatures, possibly due to the large temperature rise ΔT caused by the dynamical motion of the magnetic fluxes. The highest B_T^P value ever reported was 3.80 T on the SmBaCuO bulk at 30 K by the iteratively magnetizing pulsed-field method with reducing pulse amplitude (IMRA) [1].

ΔT during PFM results from the sum of the pinning loss Q_p related to the flux trap and the viscous loss Q_v related to the flux movement. After applying the successive pulse fields with the same amplitude, B_T^P increases with increasing number of the magnetic pulse and then saturates to a final value. ΔT decreases and saturates, then the main contribution to ΔT being due to Q_v because of the absence of the increment of B_T^P [2,3]. In order to reduce ΔT and to enhance B_T^P during PFM, the metal ring setting onto the bulk disk is very effective due to the heat transfer from the bulk to the ring [4]. Sander *et al.* attempted a multi pulse technique with stepwise cooling (MPSC) and confirmed the enhancement of B_T^P [5]. The lowering of the starting temperature T_s of the bulk is also effective to enhance B_T^P because of the increase in the pinning force F_p.

Taking these results into consideration, we recently developed a new PFM method using the modified MPSC technique (MMPSC) and the attained B_T^P as high as 4.47 T on the surface of the GdBaCuO bulk superconductor, whch is the present highest using PFM [6]. After a small amount of magnetic flux has been trapped into the bulk center at a higher T_s, the higher pulse field is applied at a lower T_s. The reduction in ΔT due to the already trapped flux and the optimization of higher B_{ex} at the

Table 1. The conditions of MMPSC and SPA processes and the trapped fields for each step.

Run		Pulse No.1	Pulse No. 2	Pulse No. 3	Pulse No. 4
MMPSC1	T_s (B_{ex})	45 K (4.54 T)	48 K (4.60 T)	29 K (6.72 T)	28 K (6.59 T)
	B_T(C)	0.89 T	1.00 T	2.61 T	4.47 T
	B_T(E)	2.49 T	2.20 T	2.27 T	2.42 T
MMPSC2	T_s (B_{ex})	63 K (3.84 T)	63 K (3.97 T)	24 K (6.73 T)	33 K (6.78 T)
	B_T(C)	0.93 T	1.00 T	3.57 T	3.27 T
	B_T(E)	1.82 T	1.64 T	2.16 T	2.31 T
MMPSC3	T_s (B_{ex})	45 K (4.03 T)	45 K (3.96 T)	24 K (6.65 T)	29 K (6.72 T)
	B_T(C)	0.15 T	0.11 T	2.79 T	3.01 T
	B_T(E)	0.45 T	0.48 T	1.34 T	2.42 T
SPA1	T_s (B_{ex})	31 K (6.61 T)	32 K (6.73 T)	31 K (6.60 T)	29 K (6.67 T)
	B_T(C)	2.36 T	2.78 T	2.93 T	2.98 T
	B_T(E)	1.74 T	2.39 T	2.42 T	2.42 T

lower T_s are key points to enhance B_T^P. The higher B_T^P than 4 T, however, could not be exactly predicted only from B_{ex} and T_s just before applying the field. Another parameters such as the microscopic B_T^P distribution may critically govern the B_T^P value by PFM. In this paper, we survey the MMPSC method under several conditions and discuss what are the important factors to enhance B_T^P.

2. Experimental

A highly *c*-axis oriented GdBaCuO bulk disk (45 mm in diameter and 15 mm in thickness, Nippon Steel Co., Ltd.) was used. The inset of figure 1 shows the experimental setup around the bulk. The bulk was magnetized under the condition sandwiched by two soft-iron yokes; the bulk was tightly stacked on the soft-iron disk on the cold stage of the helium refrigerator and was magnetized using a pulse coil dipped in liquid N_2 with a soft-iron cylinder. Two Hall sensors (F.W. Bell, model BHA 921) were adhered to the position C (bulk center) and E (7 mm distant from the bulk edge) and the time evolutions of the local field $B_L(C)(t)$ and $B_L(E)(t)$ were monitored using a digital oscilloscope. The applied field $\mu_0 H_a(t)$, of which the maximum strength was defined as B_{ex}, was monitored by the current $I(t)$ flowing through the shunt resistor. The temperature $T(t)$ was monitored at the position T.

We have performed three MMPSC runs. Table 1 summarizes the conditions [T_s and B_{ex}] and the trapped fields [B_T(C) and B_T(E)] for each run. For the MMPSC1 run, the pulse field of B_{ex}~4.5 T was applied twice (pulse No. 1 and No. 2) at T_s~45 K. Then the bulk was cooled down to T_s~29 K and the higher B_{ex}~6.6 T was applied twice (pulse No. 3 and No. 4). The highest B_T^P=B_T(C)=4.47 T was attained for the pulse No. 4 [6]. The MMPSC2 run was performed at T_s~63 K for the pulses No. 1 and No. 2 with B_{ex}~3.9 T, in which B_T(C)~1 T could be attained similar to the MMPSC1 run. This process enabled us to clarify the effect of the higher T_s. The MMPSC3 run was performed at T_s~45 K for the pulses No. 1 and No. 2 with lower B_{ex}~4.0 T in order to clarify the effect of the B_T(C) value before applying the No. 3 pulse. For comparison, the results for four successive magnetic pulse applications with the same strength (SPA) are also shown for B_{ex}~6.6 T at T_s~30 K (SPA1).

3. Results and Discussion

Figure 1 pictures B_T(C) at the bulk center as a function of the maximum temperature T_{max} after applying the each pulse field for each run. The trapped field B_T^{FC} by FCM is also presented, which corresponds to the possible maximum of the trapped field in this bulk [3]. Figure 2 shows the time dependences of the applied field $\mu_0 H_a(t)$ and the local fields [$B_L(C)(t)$, $B_L(E)(t)$] after applying the pulse No. 3 (or No. 4) for each run. For the MMPSC1, the bulk temperature rises from T_s=45 K to T_{max}=61 K for the pulse No. 1, but T_{max} decreased to 52 K for the pulse No. 2 due to the absence of the additional flux trap. For the pulse No. 3, B_T(C) increases to 2.61 T and the temperature rises from T_s=29 K to T_{max}=54 K (ΔT=25 K). In figure 2(a), $B_L(C)(t)$ and $B_L(E)(t)$ rise up, take a maximum (~5.2 T) and then slowly decrease to 2.0~2.5 T. For the pulse No. 4, as shown in figure 2(b), the maximum

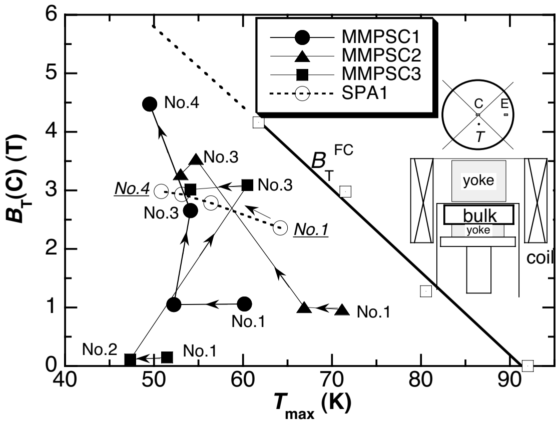

Figure 1. Trapped field B_T(C) at the bulk centre as a function of the maximum temperature T_{max} after applying the pulse field for each run.

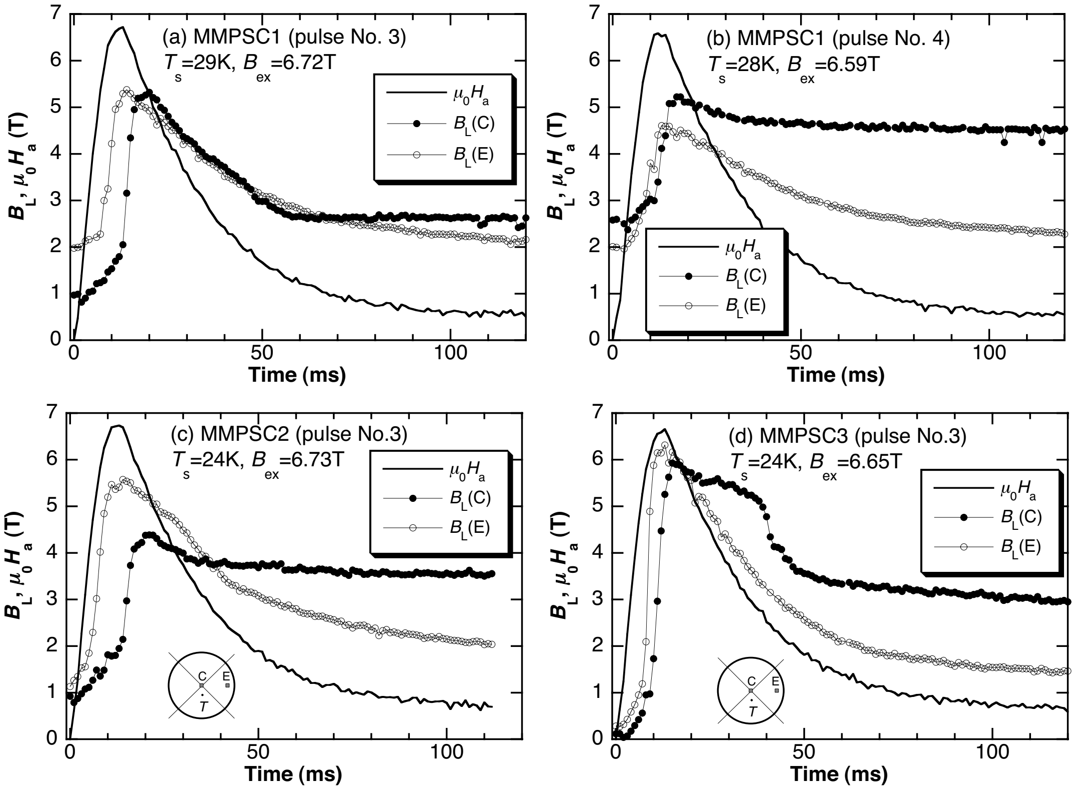

Figure 2. The applied field $\mu_0H_a(t)$ and the local fields ($B_L(C)(t)$, $B_L(E)(t)$) for the (a) pulse No. 3 of MMPSC1, (b) pulse No. 4 of MMPSC1, (c) pulse No. 3 of MMPSC2 and (d) pulse No. 3 of MMPSC3.

B_L(E) decreases to 4.6 T, while the maximum B_L(C) remains at 5.1 T and $B_T^P=B_T$(C) survives at 4.47 T. These results suggest that ΔT is suppressed during the pulse No. 4 and that this small ΔT (~19 K) obstructs the escape of the magnetic fluxes for the pulse No. 4.

In the MMPSC2 run, B_T(C)~1 T was obtained after the pulse No. 2 similar to that for the MMPSC1. For the pulse No. 3, $B_L(E)(t)$ takes a maximum ~5.5 T, but $B_L(C)(t)$ takes a lower maximum of 4.3 T and then approaches to B_T(C)=3.57 T, in contrast to the MMPSC1 run. T_s for the pulse No. 3 is 24 K and is by 5 K lower than that for the MMPSC1. The F_p value increases with decreasing T and the magnetic fluxes cannot fully penetrate into the bulk center for the pulse application of B_{ex}=6.73 T at this low T_s. The minute control of T_s is very important together with that of B_{ex}. For the MMPSC3 run, the smaller trapped field B_T(C)~0.1 T was provided after the pulse No. 2. When the pulse field of

B_{ex}=6.65 T was applied at T_s=24 K as the pulse No. 3, the larger ΔT occurred and T_{max} reached 61 K. In figure 2(d), it should be noticed that a sharp drop in $B_L(C)(t)$ suddenly occurred at the bulk center in the descending stage of PFM due to the large ΔT. The smaller B_T(C) after the pulse No. 2 introduces the large ΔT and promotes the escape of the trapped fluxes. For the SPA1 run, ΔT for the pulse No. 1 is larger than that for the pulse No. 3 of the MMPSC runs. ΔT decreases and B_T(C) increases slightly with increasing number of applied filed. For the virgin state bulk, the pulse field of B_{ex}~6.6 T at T_s~30 K may be too large to enhance the trapped field by the following pulses. The similar sudden drop in $B_L(C)(t)$ as figure 2(d) was also monitored.

Figure 3 shows the one-dimensional B_T profile on the bulk surface through the center for the pulses No. 2, No. 3 and No. 4 of each MMPSC run, in which the measured B_T(C) and B_T(E) values are used and B_T=0 at the bulk edge is assumed. The B_T values between the points C, E, and the bulk edge are linearly interpolated and the B_T profile is assumed to be symmetrical along the circumferential direction. For the MMPSC procedures, it is to be emphasized that the B_T profile for the pulse No. 2 shows "*M-shaped*" one. The B_T barrier in the periphery region (=B_T(E)) is the highest for the MMPSC1 and the lowest for the MMPSC3. For all the MMPSC runs, the "*M-shaped*" profile changes to the "*cone-shaped*" profile for the pulse No. 3 (or No. 4) with B_{ex}~6.6 T at T_s~30 K. However, it should be noticed that the height of the cone (=B_T(C)) depends on the height of the "*M-shaped*" profile; B_T(E) should be higher and B_T(C) should be lower. On the other hand, the B_T profile of SPA1 is "*cone-shaped*" one from the pulse No. 1. In this "*cone-shaped*" profile, it seems that the sizable enhancement of B_T(C) cannot be realized by the succeeding pulse.

In summary, we performed the MMPSC method for the GdBaCuO bulk under several conditions and clarified what are the important factors to enhance B_T^P over 4 T. At the first stage, the "*M-shaped*" trapped field profile should be realized on the bulk; B_T(C) at the bulk center should be as low as ~1 T and the barrier height B_T(E) at the periphery region must be enhanced to 2.5~3 T. At the final stage at lower T_s, the appropriate higher field B_{ex}, should be applied. The optimum B_{ex} and T_s at each stage depend on the bulk used and should be precisely controlled. The reduction in the temperature rise ΔT due to the already existing trapped flux is also an important issue.

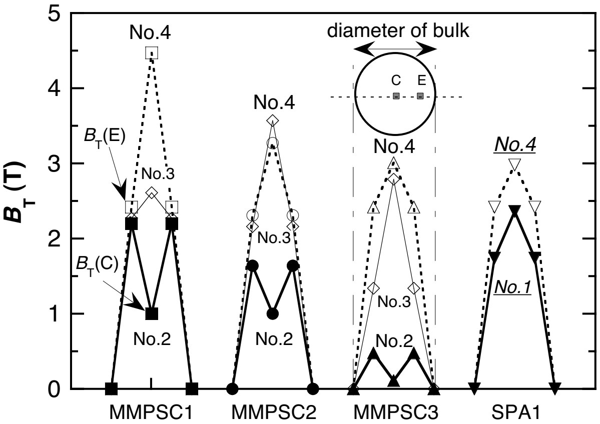

Figure 3. The estimated trapped field distribution for No. 2, No. 3 and No. 4 pulses.

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