Flux Dynamics and Thermal Behavior of a GdBaCuO Bulk Magnetized by Single- and Double-Pulse Techniques using a Split-Type Coil

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***Abstract*—We have investigated the trapped field properties of a GdBaCuO disk bulk during single- and double- pulsed field magnetization (PFM) using a split-type coil for various pulse sequences for the first time. It is well known that the multi-PFM technique using a solenoid-type coil and the single-PFM technique using a split-type coil are effective to enhance the trapped field due to a lower temperature rise. However, it was found, in this work, that the trapped field by double-PFM using the split-type coil was not enhanced in spite of lower temperature rise. We analyzed the magnetizing process using two parameters, the "magnetic flux penetration ratio", R_{in}, and the "magnetic flux residual ratio", R_{out}, for various pulse sequences for the split-type and solenoid-type coils. The R_{in} value was decreased by the double-PFM for both coils, and the R_{out} value was improved only by the double-PFM using the solenoid-type coil. As a result, the trapped field for single-PFM using the split-type coil, which has a higher R_{in}, reduced after the double-PFM due to a decrease of R_{in} and no enhancement of R_{out}. These results are in clear contrast to those using the solenoid-type coil.**

***Index Terms*—Bulk high-temperature superconductors, multi-pulse application, pulsed field magnetization, REBaCuO bulk, split-type coil, trapped field magnets**

I. Introduction

REBaCuO (RE: rare earth element or Y) superconducting bulks have been used as a trapped field magnet (TFM) that can provide a magnetic field of several Tesla for engineering applications such as rotating machines [1], magnetic separation [2], and a magnetic drug delivery system [3]. The pulsed field magnetization (PFM) technique is a magnetizing method for superconducting bulks with a compact, mobile and inexpensive setup, compared to field-cooled magnetization (FCM). However, the trapped field by PFM is generally much lower than that by FCM because of a large temperature rise associated with the rapid and dynamical motion of magnetic flux [4]. The PFM technique consists of an ascending (flux penetration) phase on the order of milliseconds and then a descending (flux flow) phase. To enhance the trapped field by PFM, a large amount of flux penetration and a small amount of flux flow should be achieved. There have been several approaches to enhance the trapped field by PFM using the solenoid-type coil. Multi-pulsed field magnetization techniques, which involve iteratively applying pulsed fields, are effective, such as the successive pulse application (SPA) [5] and the multi-pulse technique with step-wise cooling (MPSC) [6]. The multi-PFM technique achieves a reduction in flux flow from lowering the flux pinning and viscous losses due to the already trapped magnetic flux after the 1st magnetic pulse [7]. Using a modified MPSC (MMPSC) technique, a record-high trapped field of 5.20 T was achieved using a solenoid-type coil with a 45 mm GdBaCuO disk bulk at 30 K [8]. Similarly, there have been reports to enhance the trapped field by PFM using a split-type coil with an iron yoke [9], in which the flux intrudes by a flux jump with reduced flux flow. The cooling of the bulk for the split-type coil is faster than that for the solenoid-type coil because the bulk is cooled from the periphery along the *ab*-plane, which has higher thermal conductivity than the *c*-axis [9]. However, multi-pulse effects using the split-type coil have not yet been reported.

In this study, we investigated the trapped field properties of a GdBaCuO disk bulk during single- and double-PFM using the split-type coil for various sequences. To understand the double-pulse effect, we compared the trapped field properties to those using the solenoid-type coil.

II. Experimental Setup

A GdBaCuO superconducting disk bulk of 41 mm in diameter and 12 mm in thickness was grown using the top-seeded melt-growth (TSMG) process at the University of Cambridge [10]. Fig. 1 shows the schematic view of the experimental setup for the PFM. The split-type coil (72 mm in inner diameter (I.D.), 124 mm in outer diameter (O.D.), and 35 mm in height (H)) and the solenoid-type coil (99 mm I.D., 121 mm O.D. and 50 mm H) are used as magnetizing coils. The bulk was fastened in a brass sample holder using a thin indium sheet and was cooled from the periphery along the *ab*-plane. A pair of permendur yokes (60 mm diameter and 65 mm H) was inserted in the bores of the split-type coil [9]. For the solenoid-type coil, the same bulk was mounted in a stainless steel ring 17.5 mm in width and cooled from the bottom surface along

This research is partially supported from JSPS KAKENHI Grant No. 15K04646. M. D. Ainslie would like to acknowledge financial support from an Engineering and Physical Sciences Research Council (EPSRC) Early Career Fellowship EP/P020313/1. All data are provided in full in the results section of this paper.

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the *c*-axis of the bulk, where a soft iron yoke (60 mm in diameter and 20 mm in H) is installed underneath the bulk [4].

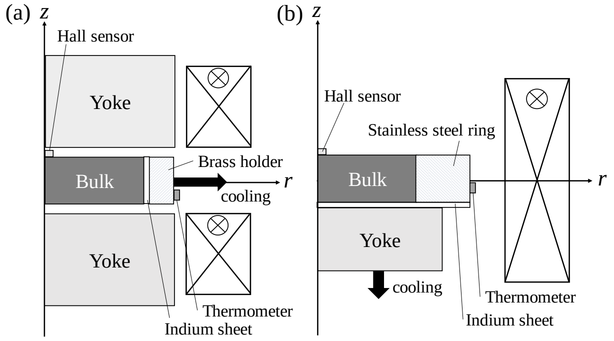

Fig. 1. Schematic view of the experimental setup for the PFM experiments using (a) the split-type coil and (b) the solenoid-type coil.

Fig. 2 shows the time sequences of the operating temperature settings used in this study. For the single-pulse application, shown in Figs. 2(a) and 2(b), the bulk was cooled to T_{s1} = 65 or 25 K, and a single-magnetic pulse with a rise time of 18 ms (split-type coil) or 13 ms (solenoid-type coil), B_{ex1}, ranging from 3 to 6 T was applied to the bulk. For the double-pulse application, shown Figs. 2(c) and 2(d), the 1st pulse of B_{ex1} = 3 T was applied at T_{s1} = 65 K for all cases. In the 2nd stage, the bulk was cooled to T_{s2} = 65 or 25 K and the 2nd pulse, B_{ex2}, ranging from 3 to 6 T was applied to the bulk. The magnetic pulse and temperature sequences for each magnetizing coil are named as follows.

1. Single pulse using split-type coil: S-sp(T_{s1})
2. Double pulse using split-type coil: D-sp(T_{s1}, T_{s2})
3. Single pulse using solenoid-type coil: S-sol(T_{s1})
4. Double pulse using solenoid-type coil: D-sol(T_{s1}, T_{s2})

During the PFM process, the time evolution of the magnetic field, $B(t)$, at the center of the bulk surface was measured using a Hall sensor (F. W. Bell, BHT921). $B(t)$ at 300 ms is defined as the trapped field, B_t. The time evolution of the temperature, $T(t)$, was measured by a CERNOX^{TM} thermometer on the side surface of the brass holder for the split-type coil and on the side surface of stainless steel ring for the solenoid-type coil.

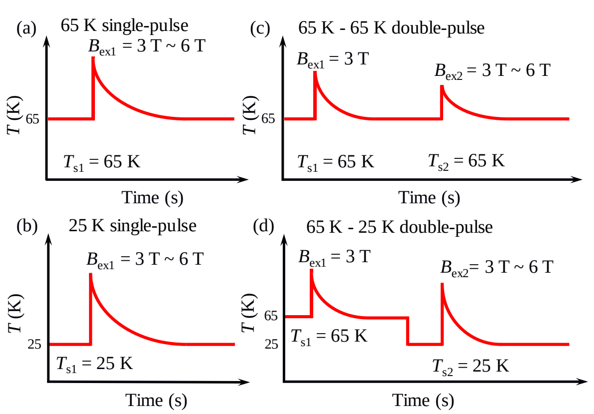

Fig. 2. Time sequences of the operating temperature settings used in this study for (a) 65 K single pulse, (b) 25 K single pulse, (c) 65 K - 65 K double pulse and (d) 65 K - 25 K double pulse.

III. Results

Fig. 3(a) shows the applied pulsed field (B_{ex}) dependence of the trapped field, B_t, at the center of the bulk surface using the split-type coil for various sequences. Here, the applied field, at which the B_t value begins to increase, is defined as the rise field, B_r. The B_t value for S-sp(65 K) increases from B_r = 3.06 T by the flux jump and the highest B_t value of 2.79 T was achieved at B_{ex} = 3.76 T. The B_t value for S-sp(25 K) increased from B_r = 4.17 T and a highest B_t of 3.96 T was achieved at B_{ex1} = 5.43 T. These rapid increases in B_t above B_r result from flux jumps [11], [12] (or so-called giant flux leaps (GFLs) in other works [13]), which are a characteristic behavior when using the split-type coil. The rise field, B_r, increased and the trapped field, B_t, was usually enhanced when lowering the operating temperature during single-PFM [14]. These results were also obtained for the 2nd pulse application of the D-sp(65 K, 65 K) and D-sp(65 K, 25 K). It should be noted that the rise field, B_r, of the 2nd pulse application increased, but the maximum B_t value was not enhanced, compared to that of single-pulse application.

On the other hand, for the solenoid-type coil, as shown in Fig. 3(b), the B_t value for S-sol(65 K) increases monotonically with increasing B_{ex}. When B_{ex} is 4.0 T, the B_t value for D-sol(65 K, 65 K) is higher than that for S-sol(65 K), which indicates that the flux jump also occurs for the double-PFM. These results are similar to that for S-sol(25 K) and D-sol(65 K, 25 K). These results support the previous reports, in which the multi-PFM using the solenoid-type coil enhances the trapped field [8], [15].

Fig. 4(a) shows the maximum temperature rise, ΔT_{max}, during PFM, as a function of the applied pulsed field (B_{ex}), for each sequence using the split-type coil. ΔT_{max} increased with increasing B_{ex} for all cases. The ΔT_{max} value of the double-PFM is lower than that of the single-PFM, which results from lowering the flux pinning and viscous losses due to the already trapped magnetic flux after the 1st magnetic pulse application [7], [15]. The ΔT_{max} value using the solenoid-type coil, shown in Fig. 4(b), is larger than that using the split-type coil, because the bulk is cooled via the *c*-axis (solenoid-type coil) of lower thermal conductivity, rather than the *ab*-plane (split-type coil) [9].

Figs. 5(a) and 5(b) show the time evolutions of the applied field, $B_{ex}(t)$, and trapped field, $B(t)$, at the center of the bulk surface for S-sp(25 K) for B_{ex1} = 4.17 T and S-sol(25 K) for B_{ex1} = 4.14 T, respectively. In Fig. 5(a), the magnetic flux doesn't intrude into the center of the bulk for the split-type coil. In Fig. 5(b), for the solenoid-type coil, $B(t)$ takes a peak value of B_{in} = 2.13 T, which is defined as the maximum penetration field, and then decreases to a final small B_t value due to a large flux flow.

Figs. 5(c) and 5(d) show similar plots for S-sp(25 K) for B_{ex1} = 4.89 T and D-sp(65 K, 25 K) for B_{ex2} = 4.99 T, respectively. In Fig. 5(c), with increasing B_{ex1}, compared to Fig. 5(a), the magnetic flux intruded rapidly via a flux jump and the $B(t)$ reached B_{in} = 4.67 T. After that, $B(t)$ gradually decreased to B_t = 3.40 T, where the flux flow, defined as ΔB (= B_{in} - B_t), was

1.27 T. For D-sp(65 K, 25 K), shown in Fig. 5(d), after the 1st pulse of B_{ex1} = 3 T was applied at 65 K, the magnetic flux also intruded the bulk center suddenly via a flux jump and then flow out of the bulk to the final value, B_t. The B_{in} and B_t values were slightly smaller than those for S-sp(25 K) as shown in Fig. 5(c) at a nearly identical applied field. The final B_t reduction mainly results from the decrease in B_{in} for the double-PFM.

Figs. 5(e) and 5(f) show similar plots for S-sol(25 K) for B_{ex1} = 5.56 T and D-sol(65 K, 25 K) for B_{ex2} = 5.57 T. When B_{ex1} is increased, as shown in Fig. 5(e), the B_{in} and B_t values increase, compared to those in Fig. 5(b). For D-sol(65 K, 25 K) in Fig. 5(f), after the 1st pulse of B_{ex1} = 3 T was applied at 65 K, the B_{in} value was smaller than that for S-sol(25 K). This result is consistent with that obtained using the split-type coil. The B_t value for D-sol(65 K, 25 K) was also higher than that for S-sol(25 K). This is in contrast with the double-pulse effect using the split-type coil. The enhancement of the final B_t mainly results from the decrease in the flux flow (ΔB) for the double-PFM.

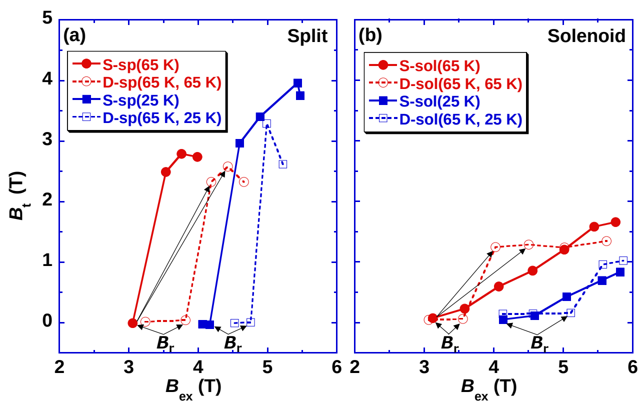

Fig. 3. Applied pulsed field (B_{ex}) dependence of the trapped field, B_t, at the center of the bulk surface using (a) the split-type coil and (b) the solenoid-type coil for various sequences. The applied field, at which the B_t value begins to increase, is defined as the rise field, B_r.

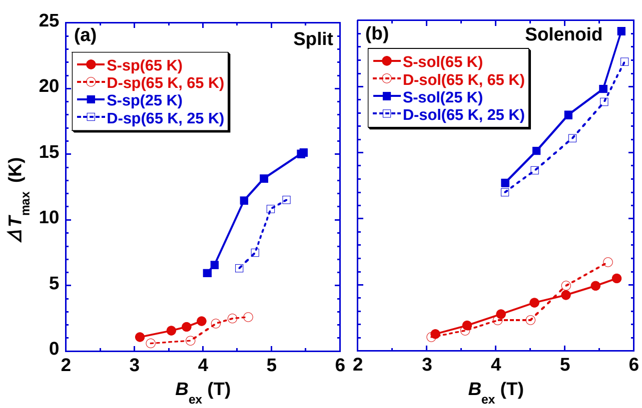

Fig. 4. Maximum temperature rise, ΔT_{max}, during PFM, as a function of applied pulsed field (B_{ex}), for each sequence using (a) the split-type coil and (b) the solenoid-type coil.

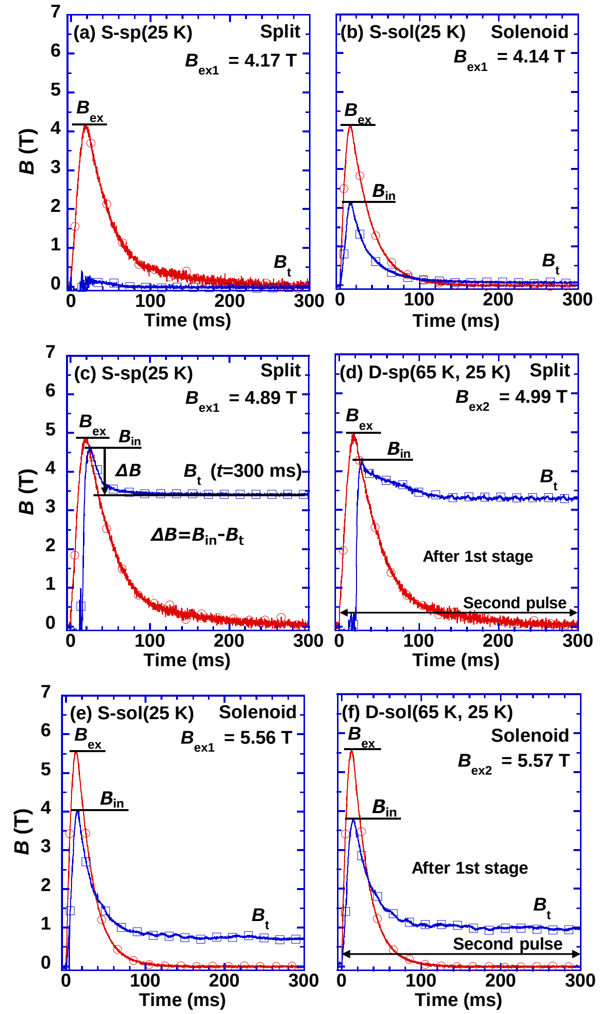

Fig. 5. Time evolution of the applied field, $B_{ex}(t)$, and trapped field, $B_t(t)$ at the center of the bulk surface for (a) S-sp(25 K) for B_{ex1} = 4.17 T, (b) S-sol(25 K) for B_{ex1} = 4.14 T, (c) S-sp(25 K) for B_{ex1} = 4.89 T, (d) D-sp(65 K, 25 K) for B_{ex2} = 4.99 T, (e) S-sol(25 K) for B_{ex1} = 5.56 T and (f) D-sol(65 K, 25 K) for B_{ex2} = 5.57 T.

IV. Discussion

Using the experimental results, we now discuss the double-pulse effect during PFM using the split-type coil, compared with single-PFM and the solenoid-type coil. Fig. 6 shows the applied field (B_{ex}) dependence of the "magnetic flux penetration ratio", R_{in}, using the split-type and solenoid-type coils during single- and double-PFM. Here, R_{in} is defined as B_{in}/B_{ex}. R_{in} = 1.0 corresponds to an ideal flux penetration during FCM using the Bean model [16]. The R_{in} value of S-sp increases rapidly and takes a maximum of higher than 0.9 ~ 0.95 by the assistance of a flux jump. There is a temperature rise due to rapid movement of magnetic flux with flux jump, shown in Fig. 4(a). The R_{in} value for D-sp is nearly equal to or slightly smaller than that for S-sp because of the existence of a trapped flux after the 1st pulse. Using the solenoid-type coil, R_{in} gradually increases with increasing B_{ex} due to the absence of flux jumps and is smaller than that for the split-type coil. Similarly to the split-type coil, R_{in} for D-sol is smaller than that for S-sol. The double-PFM by both magnetizing coils results in a decreased R_{in} value, because it is more difficult for the flux to penetrate the bulk due to the existence of the flux trapped from the 1st pulse [15].

Fig. 7(a) shows the "magnetic flux residual ratio", R_{out}, using the split-type and solenoid-type coils during single- and double-PFM, as a function of B_{in}. Here, R_{out} is defined as B_t/B_{in}, which is the ratio of the trapped field, B_t, to the maximum penetration field, B_{in}. The R_{out} value increases concomitantly with increasing B_{ex} using the split-type coil, and becomes a maximum. And then the R_{out} value decreases with a further increase in B_{ex}, which indicates that the flux flow, ΔB, becomes large due to the large temperature rise [17]. The maximum value of R_{out} is not enhanced by double-PFM using split-type coil. The B_{in} for D-sp(65 K, 25 K) is smaller than that for S-sp(25 K) when the maximum R_{out} is achieved. The temperature rise of ΔT_{max} = 10.8 K (D-sp(65 K, 25 K)) and ΔT_{max} = 15.0 K (S-sp(25 K)) was measured at the maximum R_{out} for each PFM, as shown in Fig. 4(a). These results suggest that R_{out} does not strongly depend on temperature rise. The reduction of the trapped field after the 2nd pulse using the split-type coil can be mainly explained by the reduction of both R_{in} and R_{out}. On the other hand, for the solenoid-type coil, the R_{out} value for D-sol(65 K, 25 K) is larger than that for S-sol(25 K) at B_{in} higher than 3.11 T, which is a different result when using the split-type coil, although the R_{in} value is small. The trapped field enhancement after the 2nd pulse using the solenoid-type coil, as shown in Fig. 3, can be mainly explained by the enhancement of R_{out}.

Fig. 7(b) shows applied field (B_{ex}) dependence of $R_{in} \times R_{out}$ using the split-type and solenoid-type coils during single- and double-PFM. The $R_{in} \times R_{out}$ value is equivalent to the magnetic flux trapping ratio (B_t/B_{ex}), which was rewritten from Figs. 3(a) and 3(b). The higher $R_{in} \times R_{out}$ value approaches an ideal PFM process. The $R_{in} \times R_{out}$ values for D-sp(65 K, 25 K) are smaller than those for S-sp(25 K) in spite of a low temperature rise, because of the decrease of R_{in} and/or R_{out}. On the other hand, for the solenoid-type coil, the $R_{in} \times R_{out}$ value for D-sol(65 K, 25 K) increases for higher B_{ex}, compared to that for S-sol(25 K) because of the enhanced R_{out} value.

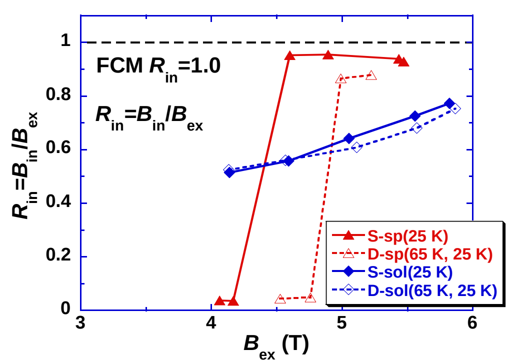

Fig. 6. Applied field (B_{ex}) dependence of the magnetic flux penetration ratio, R_{in}, using the split-type and solenoid-type coils at 25 and 65 K to 25 K during single- and double-PFM.

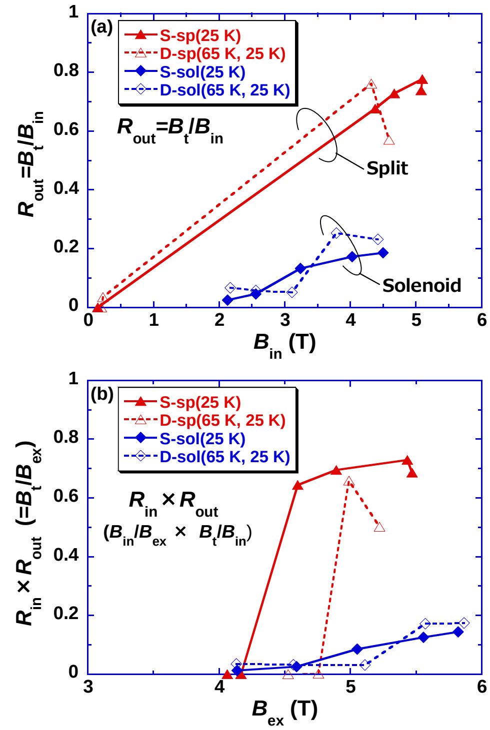

Fig. 7. (a) Magnetic flux residual ratio, R_{out}, for each sequence, as a function of B_{in}. (b) $R_{in} \times R_{out}$ value (= B_t/B_{ex}) for each sequence, as a function of B_{ex}.

V. Conclusion

We have experimentally investigated the trapped field properties of a GdBaCuO disk bulk during single and double pulsed-field magnetization (PFM) using a split-type coil for various sequences for the first time. The important results and conclusion obtained in this study are summarized as follows.

1. The trapped field by double-PFM using the split-type coil was not enhanced in this study, although a lower temperature rise was achieved. These results are in clear contrast with those of the multi-PFM technique using a solenoid-type coil.
2. The magnetizing process was analyzed using the parameters of "magnetic flux penetration ratio", R_{in}, and "magnetic flux residual ratio", R_{out}, for various sequences using the split-type and solenoid-type coils. The double-PFM by both coils resulted in a decreased R_{in} value because of the already trapped flux after the 1st pulse. For the solenoid-type coil, the R_{out} value was enhanced by the double-PFM due to the lower temperature rise. The trapped field during single-PFM using the split-type coil, which exhibits a high R_{in}, was decreased by the double-pulse application due to the decrease of R_{in} and no enhancement of R_{out}.

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