Trapped Field Properties of GdBaCuO Bulk Superconductors of Various Diameters Magnetized by Pulsed Fields using an Identical Split Coil

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***Abstract*—In this paper, the trapped field properties of GdBaCuO disk bulk superconductors of various diameters during pulsed-field magnetization (PFM) using an identical split coil at 65 K have been investigated both experimentally and numerically. The maximum trapped field, B_T^{max}, of the ϕ43 mm bulk was larger than that of the ϕ30 mm bulk. However, B_T^{max} of the ϕ65 mm bulk was smaller than that of the ϕ43 mm bulk and the trapped field profile exhibited a distorted "C-shaped" profile. Using the numerical simulation, these results for the ϕ65 mm bulk can be explained by an inhomogeneous temperature profile and the larger generated heat, *Q*, due to the lower cooling power of the refrigerator compared to the generated heat. The important issues to achieve higher and homogeneous trapped fields are discussed when using split-coil PFM for larger bulks.**

***Index Terms*—Bulk superconductors, numerical simulation, pulsed-field magnetization, split coil, trapped field magnet.**

I. Introduction

Bulk superconductors, acting as trapped field magnets (TFMs), can achieve higher magnetic fields of magnitude over ten times higher than the maximum field of conventional permanent magnets. The pulsed-field magnetization (PFM) is a practical magnetizing technique using a copper coil magnet, which is a clear contrast to field-cooled magnetization (FCM) using a superconducting coil magnet [1]. However, the trapped field, B_T, by PFM is generally much smaller than that by FCM because of a large temperature rise due to the dynamical motion of magnetic flux [2]. To enhance the B_T value, multi-pulse techniques have been shown to be effective [3], [4], in which we have achieved a record-high B_T of 5.2 T at 30 K on a GdBaCuO bulk by using a modified multi-pulse technique combined with a stepwise cooling (MMPSC) using a solenoid coil [5].

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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Based on Bean's critical-state model [6], the trapped field at the center of the disk bulk is proportional to the bulk diameter for an identical critical current density, J_c. The trapped field properties by PFM have been investigated for larger disk bulks 60 mm in diameter at 40 K using a solenoid coil [7], and 60 and 140 mm diameters at 77 K using a vortex coil [8], [9]. However, the B_T value was not necessarily enhanced, compared to that for smaller bulks 30 - 45 mm in diameter [5], [10]. This is because the J_c value of the larger bulks was not necessarily as large as that of the smaller bulks and the J_c distribution was inhomogeneous.

The use of vortex or split coils has also been shown to be effective to enhance the B_T value for smaller bulks during PFM, both experimentally and numerically [11], [12]. It is easier for the magnetic flux to penetrate via flux jumps, which can enhance the trapped field for REBaCuO bulks. We have previously reported the trapped field properties of a 30 mm diameter GdBaCuO bulk magnetized by a split coil, for which B_T = 3.2 T was achieved at 40 K using a single magnetic pulse of 5.0 T [13]. However, there has not yet been a systematic investigation of the trapped field properties by PFM using such a split coil for the disk bulks of various diameters at lower temperatures. The research of the large-sized TFMs and the enhancement of the trapped field using the split coil are valuable for engineering applications such as superconducting rotating machines, which requires large field poles.

In this paper, the trapped field properties of GdBaCuO bulk superconductors 43 and 65 mm in diameter using the split coil at 65 K are investigated experimentally and numerically, and compared with our previous data for the 30 mm diameter GdBaCuO bulk [14]. The possibility of trapped field enhancement for larger disk bulks using the split coil is discussed.

II. Experimental and Numerical Framework

A. Experimental PFM procedure

GdBaCuO disk bulks of various diameters (ϕ43 mm × *H*18 mm, and ϕ65 mm × *H*20 mm; Nippon Steel & Sumitomo Metal) were magnetized using a split coil (72 mm in inner diameter (I.D.), 124 mm in outer diameter (O.D.) and 37 mm in height (H)), in which a set of permendur yokes (60 mm in diameter and 65 mm in height) was inserted. Each disk bulk was fastened in brass sample holders of different sizes using a thin indium sheet and was thermally connected to the cold stage of GM-cycle He refrigerator (5 W at 20 K), as shown in Fig. 1, in which the bulk was cooled from the periphery along the *ab*-plane of the bulk. The detailed experimental setup for PFM is described in [14]. The 65 mm bulk was also magnetized using a solenoid coil (95 mm in I.D., 121 mm in O.D. and 50 mm in H) for comparison. The results are then compared to our previous PFM results using the same split coil for a GdBaCuO disk bulk (ϕ30 mm × H14 mm) fabricated by the University of Cambridge [14]. A single magnetic pulse, B_{ex}, with a rise time of 18 ms was applied, ranging from 2.7 to 6.0 T at T_s = 65 K. The results at 65 K can clearly compare with the numerical ones. The time evolution of the magnetic field, $B_T(t)$, and the final trapped field, B_T, were measured at the center of bulk surface by a Hall sensor (F. W. Bell, BHT921) (adhered to the surface), and a two-dimensional (2D) trapped field profile was measured at a distance of 3 mm above the bulk surface, stepwise with a pitch of 1 mm, by scanning an axial-type Hall sensor (F. W. Bell, BHA921). The time evolution of the temperature, $T(t)$, was also measured using the Cernox™ thermometer connected to the sample holder as shown in Fig. 1. A heater was used to control the operating temperature using a Pt-Co thermometer.

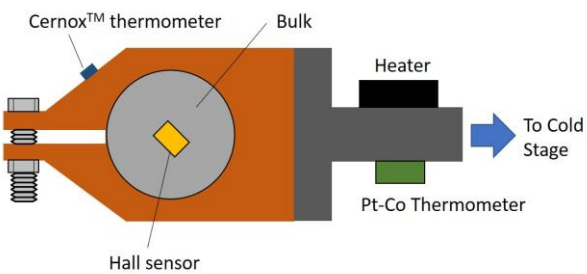

Fig. 1. A schematic view of the disk bulk and brass sample holder, which is thermally connected to the cold stage of the refrigerator.

B. Numerical simulation framework

Based on our experimental setup [14], a three dimensional (3D) numerical model was constructed using the finite element method (FEM). The commercial software package, Photo-Eddy, combined with Photo-Thermo (Photon Ltd, Japan), was used for the analysis. The following magnetic field dependence of $J_c(B)$, proposed by Jirsa, was used in the simulation [15],

$$J_c(B) = J_{c1}\exp\left(-\frac{B}{B_L}\right) + J_{c2}\frac{B}{B_{max}}\exp\left[\frac{1}{k}\left(1-\left(\frac{B}{B_{max}}\right)^k\right)\right]. \quad (1)$$

The experimental $J_c(B, T)$ data [16] were fit up to 10 T between 65, 70, 75 and 80 K using eq. (1) and the parameters (J_{c1}, B_L, J_{c2}, B_{max} and k) were determined at each temperature. For example, each parameter value at 65 K was J_{c1} = 1.17 × 10^9 A/m^2, B_L = 0.57 T, J_{c2} = 7.56 × 10^8 A/m^2, B_{max} = 3.0 T and k = 1.3. The $J_c(B, T)$ profiles at intermediate magnetic fields and temperatures are interpolated based on each parameter [17].

III. RESULTS AND DISCUSSION

A. Experimental results

Fig. 2(a) shows the trapped field, B_T, at 65 K at the center of the surface of the ϕ65 mm bulk, as a function of the applied field, B_{ex}, using the split and solenoid coils. The typical trapped field profiles are also shown in Figs. 2(b) - 2(e). For both coils, B_T increases with increasing B_{ex}, takes a maximum, and then decreases. The maximum trapped field, B_T^{max}, was 1.73 T for the solenoid coil and 1.57 T for the split coil without (w/o) the permendur yoke. However, B_T^{max} was enhanced to 2.24 T by about 29% by inserting the magnetic yoke into the bore of the split coil. For the split coil, a higher B_T^{max} can be achieved for lower B_{ex} than for the solenoid coil. For lower B_{ex}, as shown in Fig. 2(b) for the split coil and Fig. 2(c) for the solenoid coil, the trapped field profiles were homogenous. For higher B_{ex} using the solenoid coil, as shown in Fig. 2(d), the trapped field profile exhibited a conical shape, which suggests that the J_c distribution is homogeneous in the bulk. However, for higher B_{ex}, as shown in Fig. 2(e) for the split coil, the trapped field profile was fairly distorted and exhibited a "C-shaped profile". The similar distorted profile to Fig. 2(e) was also observed for the bulk with yoke. However, it is hypothesized that the distorted profile does not come from an inhomogeneous J_c distribution, but rather that the temperature distribution within the bulk is inhomogeneous during PFM in the case of the split coil at higher B_{ex}, for which a large amount of heat is generated in the bulk due to pinning loss and viscous loss, if the cooling power of the refrigerator is smaller than the generated heat. A large amount of heat generated in the region opposite the cooling side is difficult to be extracted out to the cold stage.

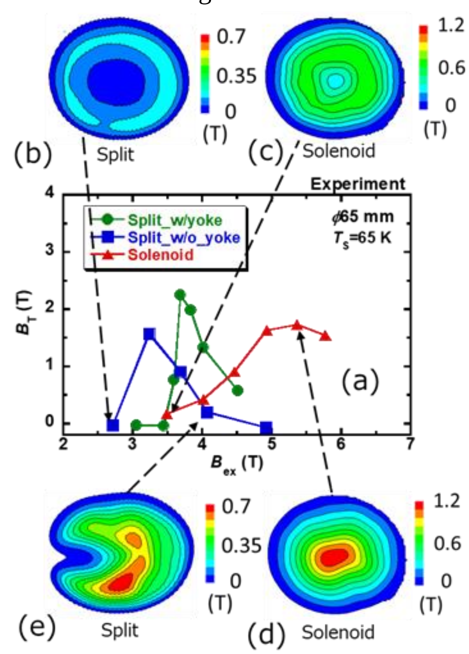

Fig. 2. (a) The trapped field, B_T, at the center of the bulk surface, as a function of the applied field, B_{ex}, at T_s = 65 K for the solenoid and split coils. The typical trapped field profiles are shown in (b) ~ (e) for selected points from (a).

As a result, the temperature rise in that region causes a localized decrease in J_c, and then the trapped flux leaves the bulk easily. On the other hand, for the solenoid coil, the bulk was cooled along *c*-axis through a large area, and the temperature in the *ab*-plane of the bulk is relatively homogeneous. The detail discussion is performed later with the aid of numerical simulations.

Fig. 3 shows the trapped field, B_T, at the center of the bulk surface for the various diameters, as a function of the applied field, B_{ex}, at 65 K using a split coil with the permendur yoke. For all bulks, B_T increases, takes a maximum and then decreases with increasing B_{ex}. The B_T^{max} of the ϕ43 mm bulk was larger than that of the ϕ30 mm bulk. However, B_T^{max} of the ϕ65 mm bulk was lower than that of the ϕ43 mm bulk, and B_T abruptly increased and then decreased, compared to the other bulks. If the $J_c(B, T)$ characteristics of the bulks are assumed to be identical and homogeneous, the magnetic flux starts to penetrate into the bulk center at a higher B_{ex}, and the larger disk bulk should trap a higher magnetic field at the higher B_{ex}. The experimental results for the 65 mm bulk suggest that an inhomogeneous J_c distribution (due to the large heat generation) exists in the bulk and, as a result, the magnetic flux easily penetrates at lower B_{ex} and easily escapes at higher B_{ex}. The maximum B_T^{max} among all the bulks was 2.34 T for the ϕ43 mm bulk. This discrepancy mainly comes from the inhomogeneous J_c distribution in the 65 mm bulk due to the inhomogeneous heat transfer to the sample holder and cold stage.

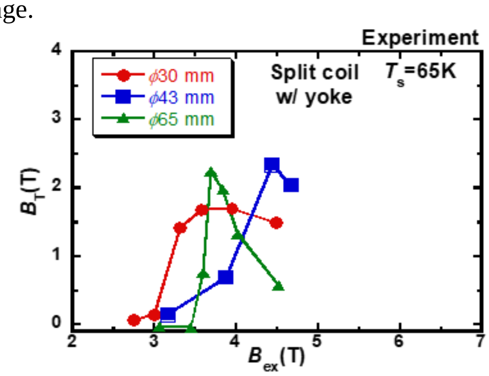

Fig. 3. The trapped field, B_T, at the center of the bulk surface for the bulks of various diameters magnetized by a split coil with yoke at 65 K, as a function of the applied field, B_{ex}.

Fig. 4(a) shows the maximum temperature rise, ΔT_{max}, as a function of the applied field, B_{ex}, for the bulks with various diameters, which was measured on the bulk holder. ΔT_{max} increases with increasing B_{ex} for each bulk and the gradient of $\Delta T_{max}/B_{ex}$ becomes steeper with increasing diameter of the bulk. Fig. 4(b) shows the B_{ex} dependence of the generated heat, Q, for each bulk, which was estimated using following equation [7].

$$Q = \int_{T_s}^{T_s+\Delta T_{max}} C(T) V dT, \qquad (2)$$

where, $C(T)$ is specific heat per unit volume and V is the volume of the GdBaCuO bulk [14]. The Q value in Fig. 4(b) shows a similar B_{ex} dependence to ΔT_{max} shown in Fig. 4(a), which results from the pinning loss due to flux pinning and the viscous loss due to flux movement, but also changes depending on the $J_c(B, T)$ value. The Q values of the ϕ65 mm bulk indicate larger values, compared to those of the other bulks. Since V = 66.3 cm^3 for the ϕ65 mm bulk, 26.1 cm^3 for the ϕ43 mm bulk, and 10.6 cm^3 for the ϕ30 mm bulk, the Q values are nearly proportional to the V value more than B_{ex}= 3.5 T. It should be noted that $J_c(B, T)$ characteristics of the bulks used in the experiment have not been measured/estimated and may be different to each other. The cooling power of the refrigerator used in this study was 5 W (= 5 J/s) at 20 K, which is quite smaller than the generated heat during PFM. The brass holder for each bulk has different size and heat capacity, which also influences the temperature rise and the heat propagation. As a result, the temperature of the bulk increases due to the generated heat exceeding the cooling ability, especially for the larger bulk.

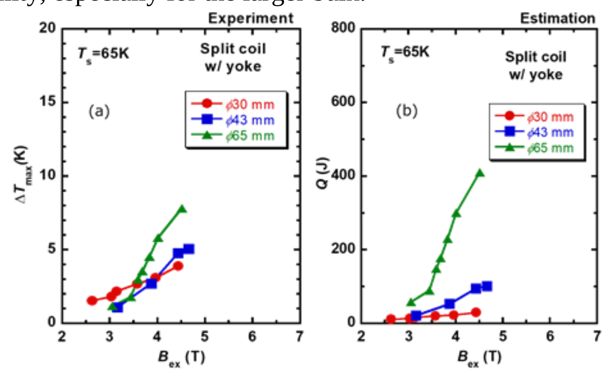

Fig. 4 (a) The maximum temperature rise, ΔT_{max}, of the sample holder of the bulks of various diameters. (b) The generated heat, Q, as a function of the applied field, B_{ex}, which was estimated using eq. (2).

B. Numerical simulation results

In the numerical simulation, the $J_c(B, T)$ characteristics are assumed to be identical and homogeneous for all the bulks. Fig. 5 shows the trapped field, B_T, at the center of the bulk surface without yoke, as a function of the applied field, B_{ex}. In all cases, B_T increased with increasing B_{ex}, took a broad peak and then decreased. It is easier for the magnetic flux to penetrate to the center of the bulk (and be subsequently trapped) for a smaller diameter sample. The B_T^{max} value increases with increasing bulk diameter, which does not reproduce the experimental results shown in Fig. 3. The B_{ex} value to achieve B_T^{max} increases with increasing bulk diameter. These results suggest that it is harder for the magnetic flux penetration into the center of the larger bulk. The sudden increase and steep decrease in B_T for the 65 mm bulk shown in Fig. 3 was not reproduced by the simulation under these initial assumptions.

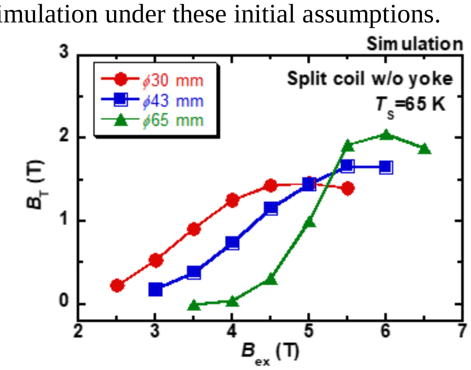

Fig. 5. Numerical simulation results of the trapped field, B_T, at the center of the bulk surface at 65 K using the split coil without yoke, as a function of the applied field, B_{ex}, for the bulks of various diameters.

Fig. 6(a) shows the maximum temperature rise, ΔT_{max}, as a function of the applied field, B_{ex}, for the bulks of various diameters, which was estimated at the same position as the experiment in Fig. 1. ΔT_{max} increases with increasing B_{ex} for each bulk. However, the magnitude of ΔT_{max} is larger than that of experimental results. Furthermore, the gradient of $\Delta T_{max}/B_{ex}$ is nearly identical, which is quite different to the experimental results.

Fig. 6(b) shows the B_{ex} dependence of the generated heat, Q, for each bulk, which was estimated using eq. (2). The results show a similar trend as the experimental results in Fig. 3(b). However, the maximum Q value for the ϕ65 mm bulk is about twice as large as that measured in the experiments. In the actual bulks, there exist regions of lower J_c, through which the magnetic flux penetrates easily, even at lower B_{ex}. As a result, the generated heat becomes small. The "C-shaped" trapped field profile in Fig. 2(e) suggests the possibility of an inhomogeneous temperature distribution in the large bulk due to the insufficient cooling power of the refrigerator. The numerical simulation was performed assuming an inhomogeneous initial temperature distribution in the bulk.

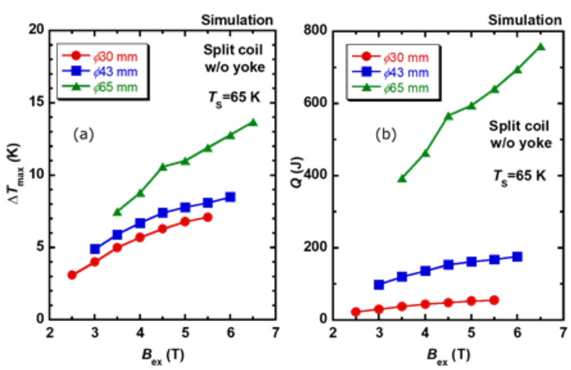

Fig. 6. Numerical simulation results of (a) maximum temperature rise, ΔT_{max}, and (b) generated heat, Q, as a function of the applied field, B_{ex}, for the bulks of various diameters.

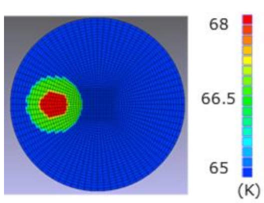

Fig. 7. Initial temperature distribution of the ϕ65 mm bulk, in which regions 1.5 and 3 K higher than the rest of the bulk (= 65 K) were assumed.

Fig. 7 shows the initial temperature distribution for the ϕ65 mm bulk, in which the regions 1.5 and 3 K higher than the rest of the bulk (= 65 K) were assumed on the offside opposite to the cold stage. Fig. 8(a) shows the trapped field, B_T, at the center of the bulk surface, as a function of B_{ex} for the ϕ65 mm bulk in the case of the initial inhomogeneous temperature distribution shown in Fig. 7. The similar relationship for the bulk under the uniform T_s is also shown. The B_T vs B_{ex} curve for the inhomogeneous T_s distribution shifted to the lower B_{ex} side, and B_T^{max} was decreased, compared to the uniform T_s case. The typical trapped field profiles are also shown in Figs. 8(b) - 8(e). In Figs. 8(c) and 8(d), for the inhomogeneous T_s distribution, the "C-shaped" trapped field profile can be reproduced at low and high B_{ex}. On the other hand, for the uniform T_s case, homogeneous trapped field profiles are observed, as shown in Figs. 8(b) and 8(e). These results indicated that the inhomogeneous T_s profile can reproduce the "C-shaped" trapped field profile.

Finally, we should comment on the mechanical reinforcement required to withstand the large repulsion force during the ascending stage of PFM. The repulsion force increases with increasing the diameter of the bulk and with decreasing temperature due to the increase in the J_c value. Sufficient mechanical support is necessary to avoid damage to the refrigerator and/or the PFM apparatus.

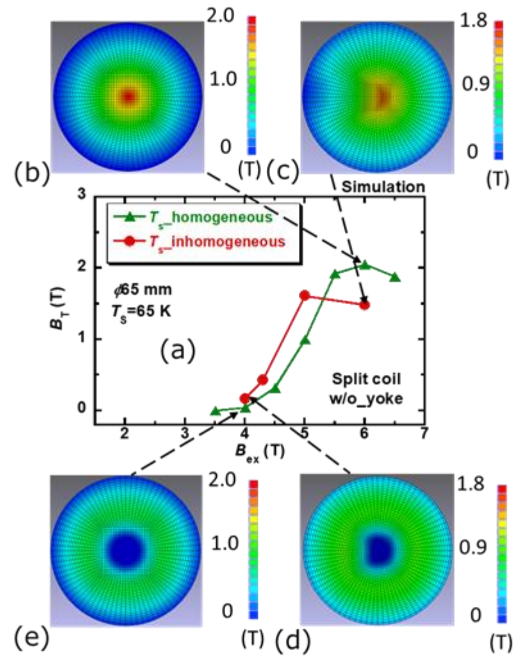

Fig. 8. (a) The trapped field, B_T, at the center of the bulk surface, as a function of the B_{ex} for the ϕ65 mm bulk assuming the initial inhomogeneous temperature distribution shown in Fig. 7 and (b)-(e) typical trapped field profiles.

IV. Conclusion

We have investigated the trapped field properties of GdBaCuO bulks with various diameters at 65 K during PFM using the split coil. The maximum trapped field, B_T^{max}, of the ϕ43 mm bulk was larger than that of the ϕ30 mm bulk. However, B_T^{max} of the ϕ65 mm bulk was smaller than that of the ϕ43 mm bulk and the trapped field profile showed distorted "C-shaped" one. Using the numerical simulation, these results can be explained by the inhomogeneous temperature profile and by the larger generated heat, Q, for the ϕ65 mm bulk due to the lower cooling power of the refrigerator than the generated heat. To achieve the higher and homogeneous trapped field profile for the larger bulk for PFM using the split coil, it is necessary to consider the cooling method and cooling power of the used refrigerator.

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