Pulsed Field Magnetizing Characteristics of Rectangular-Shaped Gd-Ba-Cu-O Bulk using Split- and Solenoid-type Coils

Keita Takahashi, Mark D. Ainslie, *Member*, *IEEE*, Hiroyuki Fujishiro, and Tomoyuki Naito

***Abstract*— We have investigated the trapped field characteristics of a rectangular-shaped Gd-Ba-Cu-O bulk (33 x 33 x 15 mm^3) magnetized by pulsed field magnetization (PFM) using split- and solenoid-type coils. A soft iron yoke was set below the bulk for the solenoid coil and two yokes are inserted in the bores of the split coil. The maximum trapped field, B_{Zmax}, at the center of the bulk surface was 1.73 T at 40 K in the case of the solenoid coil, with a distorted profile. On the other hand, B_{Zmax} was enhanced to 3.05 T at 40 K for the split coil with two yokes, for which a symmetric trapped field profile was observed. The behavior of the magnetic flux motion indicated two conditions for the enhancement of the trapped field: that the magnetic flux intrudes easily into the bulk even for lower applied fields and then saturates with minimal flux creep. We also have investigated the electromagnetic and thermal properties of the bulk during PFM using a numerical simulation, in which the magnetic flux tended to align along the *z*-axis due to the presence of the soft iron yoke. The use of the split coil with two yokes is effective in enhancing the trapped field for the rectangular-shaped bulks.**

***Index Terms*—(RE) BaCuO bulk, pulsed field magnetization, numerical simulation, trapped field, soft iron yoke**

I. Introduction

PULSED FIELD MAGNETIZATION (PFM) of (RE)BaCuO bulks (RE: rare earth element or Y) has been investigated intensively for practical applications as a substitute for field-cooled magnetization (FCM) because PFM is an inexpensive and mobile experimental setup with no need for a superconducting magnet. However, the trapped field, B_Z, by PFM is generally lower than that by FCM, where B_Z values over 17 T have been achieved [1], because of the large temperature rise caused by the dynamical motion of the magnetic flux [2]. To enhance B_Z by PFM, multi-pulse techniques using a solenoid coil are usually effective due to the reduction of temperature rise [3-6]. Using a new multi-pulse technique – the so-called modified multi-pulse technique with stepwise cooling (MMPSC) – we successfully achieved a highest trapped field of B_Z = 5.20 T on a 45 mm Gd-Ba-Cu-O bulk disk at 30 K, which is a record-high value to date [7].

In addition, the use of new types of coils, such as a split coil or a vortex coil was confirmed to enhance B_Z both experimentally and numerically [8, 9]. Its cooling procedure along the *ab*-plane of the bulk is assumed to improve the heat dissipation and reduce the temperature rise during PFM, because the *ab*-plane thermal conductivity, κ_{ab}, is much higher than along the *c*-axis, κ_c [10]. From these reasons, the use of split coil also has a potential to realize a high-trapped field bulk magnet. A ferromagnetic yoke incorporated in the magnetizing apparatus has been also used to directly improve the available magnetic flux. M. D. Ainslie *et al* realized the enhancement of trapped field of B_Z = 3.27 T on the top surface of a 30 mm diameter Gd-Ba-Cu-O bulk at 40 K employing such a split coil with a pair of soft iron yoke [11]. It is also the intention of this study to make a comparison of the magnetic flux dynamics between using solenoid- and split-type coils and to acknowledge the nature of the trapped field enhancement for higher trapped field magnets.

We also reported the PFM results of a rectangular-shaped bulk using a solenoid coil, showing that an inhomogeneous J_c distribution and the shape of the bulk leads to an asymmetric trapped field profile [12]. There has been no research reported in the case of a rectangular-shaped bulk magnetized using a split coil so far. Additionally, a rectangular-shaped bulk would make the difference of the magnetic flux dynamics clearly between a solenoid and split coils.

The experimental measurements have shown progress towards a more effective approach to enhance B_Z using a split-coil with a soft iron yoke [11, 13, 14]. To clarify the multi-physics during the PFM process, numerical simulations are a useful aid because the experimental measurements are restricted. Several studies of numerical simulation have been reported for PFM [2, 15 - 21]. In this study, we experimentally investigate the trapped field characteristics of a rectangular-shaped Gd-Ba-Cu-O bulk magnetized by PFM using solenoid and split coil. We also construct a numerical model to reproduce the experimental assembly and numerically analyze the time dependence of the local field $B_Z(t, r)$ in the bulk. The choice of the magnetizing coils and the effect of a soft iron yoke on the trapped field characteristics are also discussed.

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II. Experiment and Simulation Setup

A. Experimental Setup and Procedure

The rectangular-shaped Gd-Ba-Cu-O bulk superconductor (Nippon Steel) of area 33 x 33 mm2 in the ab-plane and 15

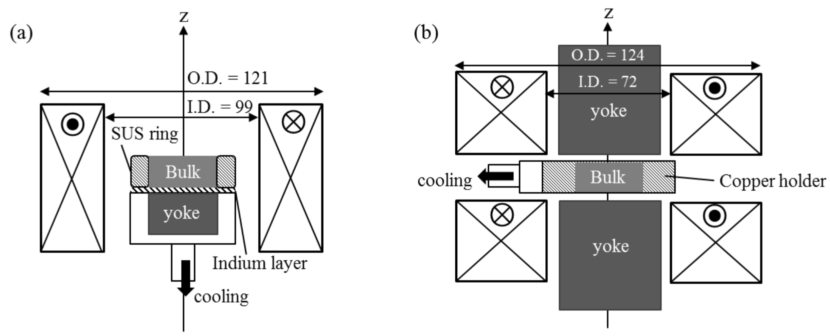

Fig. 1 Experimental setup of two kinds of apparatus for PFM and the magnetizing coil, (a) solenoid-type and (b) split-type.

mm in thickness was mounted on the cold stage of a Gifford-McMahon (GM) cycle helium refrigerator. A schematic view of two kinds of apparatus for PFM is shown in Fig. 1. Two types of magnetizing coils (solenoid and split coil), which were cooled using liquid nitrogen, were placed outside the vacuum chamber. In Fig. 1 (a), the bulk was tightly mounted in a stainless steel (SUS304) frame using Stycast™ 2850GT resin. A soft iron yoke was set below the bulk in the solenoid type apparatus. In Fig. 1 (b), the bulk was mounted in a copper holder and magnetized between the two coils of the split coil, in which two soft iron yokes were inserted. Single magnetic pulses, B_{ex}, of amplitudes ranging from 2.2 to 6.0 T were applied individually to the bulk, which was cooled to either T_s = 65 or 40 K. During PFM, the time dependence of the local field B_Z (t) at the center of the bulk surface was measured by using a Hall sensor with a digital oscilloscope. The temperature, T (t), was also measured by a CERNOX™ thermometer on the side of the sample holder. The trapped field profiles were mapped at 2 mm above the bulk surface by scanning the Hall sensor with a pitch of 1 mm using an *x-y* stage controller.

B. Numerical Simulation

Based on our experimental setup shown in Fig. 1, a three-dimensional (3D) numerical model was constructed using the finite element method (FEM). The physical phenomena during PFM are described by electromagnetic and thermal equations, which were referred to refs. [22, 23]. Commercial software, Photo-Eddy, combined with Photo-Thermo (Photon Ltd, Japan), was adopted for the analysis, which was carried out using a personal computer. The simulation procedure and the parameters used were described elsewhere in detail [24].

The power-*n* model (n = 8) was used to describe the non-linear *E-J* characteristic of the bulk. The Kim model was considered for an approximation that the temperature and magnetic field dependence of J_c (T, B) was described as,

$$J_c(T,B) = \alpha\left\{1-\left(\frac{T}{T_c}\right)^2\right\}^{\frac{3}{2}} \frac{B_0}{|B|+B_0} \qquad (1)$$

where T_c (= 92 K) is the critical temperature of the bulk at B = 0 T, and B_0 (= 1.3 T) is a constant. An interpolation method, the most accurate method to model the experimentally measured J_c (T, B) data was adopted in our recent paper [11]. A homogeneous J_c distribution, with a constant α value of 3.0 x 10^8 A/m^2, was used in this study, which corresponded to J_c (40 K, 0 T) = 2.2 x 10^8 A/m^2. The anisotropic thermal conductivities κ_{ab} = 20 Wm^{-1}K^{-1} in the *ab*-plane and κ_c = 4 Wm^{-1}K^{-1} along the *c*-axis were assumed. The rectangular shaped bulk, with the same dimensions as that used in the experiments, was cooled to T_s = 40 K. Three types of coils (solenoid without yoke, split without yoke and split with yoke) were analyzed. For solving the models in a reasonable time, one-fourth of the superconducting bulk was considered. The magnetic saturation that limits the maximum achievable magnetic flux density in the soft iron yoke was presumed to be 1.6 T as a practical value of a ferromagnetic material.

III. Experimental Results

Figure 2 presents the trapped field, B_Z, at the center of the bulk surface, as a function of the applied field B_{ex} for both the solenoid- and split- coils. Cooling the bulk sample to a lower temperature (from 65 K to 40 K) resulted in a higher trapped field due to an increase in the J_c of the bulk. For the solenoid coil, B_Z at 40 K started to increase at B_{ex} = 4.0 T, became a maximum trapped field B_{Zmax} = 1.73 T at B_{ex}^* = 5.48 T and then decreased with further increasing B_{ex}. Hereafter, we abbreviate the optimum applied field to obtain the maximum trapped field as B_{ex}^*. This is a typical result consistent with a prediction by the critical state model (CSM), the ratio of required applied field to obtain the maximum trapped field B_{ex} / B_{Zmax} to be over two. On the other hand, in the case of the split coil, the magnetic flux started to be trapped at the center for B_{ex} as low as 3.5 T at 40 K and B_{Zmax} drastically increased with slightly increasing B_{ex}. The B_{Zmax} was 3.05 T at 40 K, which was higher than that obtained by using the solenoid coil at relatively low B_{ex}^* = 4.01 T. The measured B_Z here still includes the influence of the presence of the yokes and is slightly reduced (around 0.2 T) when the yokes are removed, as described in [25]. However, the use of the split coil has potential to obtain the trapped field equivalent to the applied field similar to the FCM technique.

Figure 3 shows the temperature rise, ΔT, measured on the side of the sample holder, as a function of the applied field, B_{ex}, for both the solenoid- and split- coils. ΔT increased monotonically with increasing B_{ex} in contrast to the trapped field. ΔT for the split coil was two times higher than that obtained by using the solenoid coil. In this case, the thermal

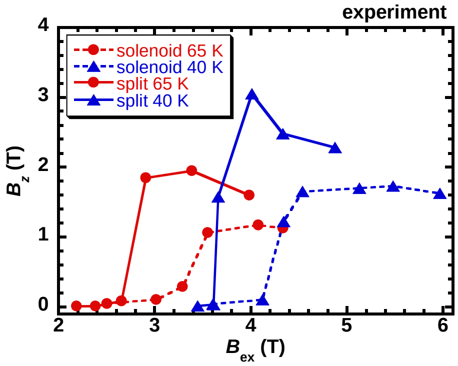

Fig. 2 Experimental results of the trapped field B_Z at the center of the bulk as a function of the applied field B_{ex} using the solenoid- and split- coils at 65 K and 40 K.

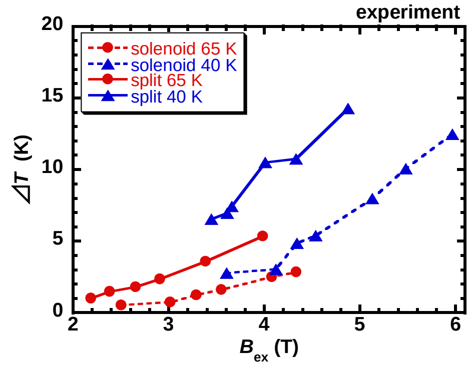

Fig. 3 Temperature rise ΔT measured on the side of the sample holder as a function of the applied field B_{ex} for the solenoid- and split- coils.

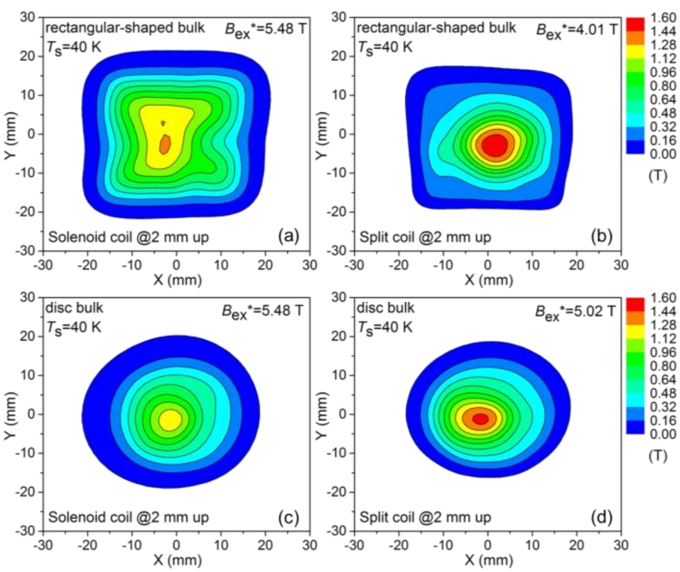

Fig. 4 Experimental results of the trapped field profiles measured at 2 mm above when full magnetization for the rectangular-shaped bulk, using (a) the solenoid- and (b) split- coils and for the disc bulk using (c) the solenoid- and (d) split- coils reported by M. D. Ainslie *et al* [11] at 40 K.

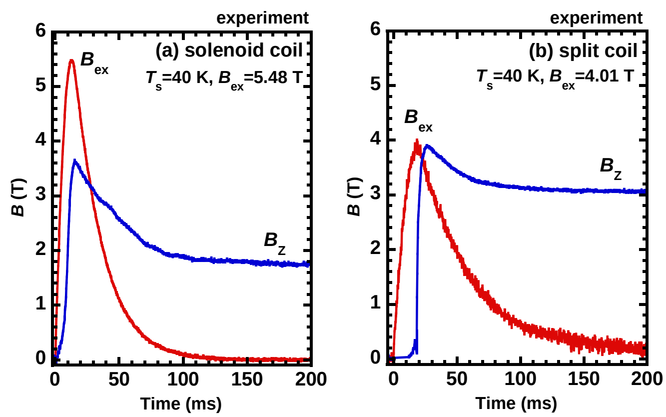

Fig. 5 Time dependence of the local field B_Z (*t*) at the center of the bulk surface for each coil, (a) solenoid coil and (b) split coil, after applying the optimum applied field B_{ex}^*.

properties of the copper sample holder could not be negligible with possible eddy current heating at low temperature. These results suggest that the enhancement of the trapped field characteristics depends on the magnetic flux motion ruling out the influence of heating roughly. We have shown in the numerical simulations in [11] that the magnetizing fixture and presence of the yoke has a minimal effect on the average temperature rise in the bulk.

Figure 4 presents the trapped field profiles of the rectangular shaped bulk using (a) the solenoid- and (b) split- coils measured at 2 mm above the bulk surface after the optimum magnetization at T_s = 40 K. Experimental results of a typical disc bulk using (c) the solenoid- and (d) the split- coils reported by M. D. Ainslie *et al* were also shown as a reference [11]. For all cases (a) ~ (d), the trapped field profiles were saturated with a conical shape when applying optimum applied field B_{ex}^* shown in Fig. 2. In Fig. 4 (a) using the solenoid coil for the rectangular shaped bulk, the trapped field profile was distorted along the growth sector boundary and resulted in lower trapped field at the center of the bulk. The uniformity of the trapped filed profile is correlation with the magnetic flux dynamics [12]. For the solenoid coil, the magnetic flux concentrates on the rim and intrudes into the bulk from the periphery. An asymmetric profile was caused by the local temperature rise due to such an inclination of the magnetic flux. However, (b) using split coil, the trapped field profile is not affected by the influence of the shape of the bulk and compares favorably with the disc bulk (c) and (d). A symmetric trapped field profile can be obtained when the magnetic flux intrudes not from the periphery but from the surfaces for the split coil [9], following the temperature rise on the whole surface of the bulk.

Figure 5(a) and 5 (b) present the time dependence of the local field, B_Z (*t*), at the center of the bulk surface for each magnetizing coil when applying B_{ex}^*. The applied pulsed field, B_{ex} (*t*), was also shown. Using the solenoid coil shown in Fig. 5(a), the magnetic flux started to intrude into the center of the bulk at the same time with increasing of the applied field and B_Z (*t*) gradually increased while the applied field was fluctuating. The maximum value of B_Z (*t*) was lower than B_{ex} by 2 T at *t* = 13 ms and then decreased similarly with increasing time until the end of the magnetizing process. However, by using the split coil shown in Fig. 5(b), the magnetic flux would not intrude at first during the magnetizing process, but then drastically increased after the pulse peak at *t* = 26 ms. B_Z (*t*) took a maximum value close to

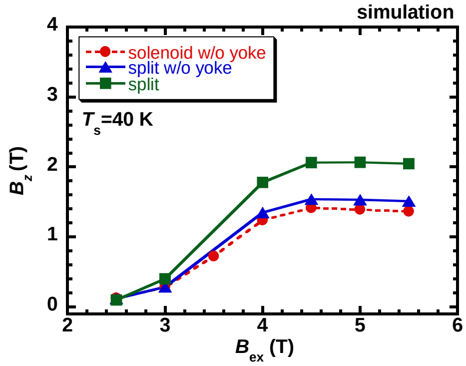

Fig. 6 Analysis results of the trapped field B_Z at the center of the bulk as a function of the applied as function of the applied field B_{ex} for each coil.

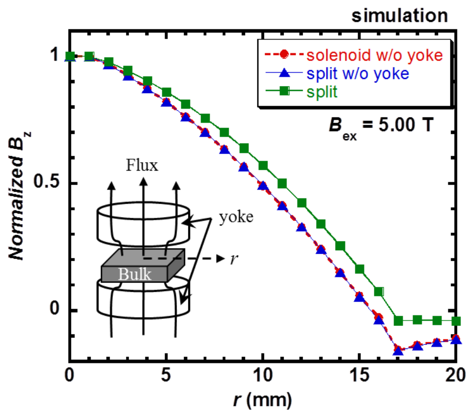

Fig. 7 Analysis results of the trapped field profiles on the bulk surface when full magnetization for each coil.

B_{ex} and the magnetic flux still remained in the bulk even after the whole process of magnetization. This behavior of the magnetic flux motion for the split coil indicated combined conditions in the enhancement of the trapped field: the magnetic flux penetrates fully into the bulk at B_{ex}^* and then saturates with minimal flux creep.

IV. Simulation Results and Discussion

In this section, the results of the simulation for PFM using a split coil without a yoke are also considered. Figure 6 shows the trapped field B_Z at the center of the bulk surface for each coil at 40 K as a function of the applied field B_{ex}. The magnetic flux starts to be trapped at the center at $B_{ex} = 3.00$ T. However, B_Z for the split coil with yoke is higher by 0.5 T at $B_{ex} \geq 4.50$ T. These results suggest the effect of the soft iron yoke might exist in the experimental results shown in Fig. 2. On the other hand, we can notice that the difference in the B_Z-B_{ex} curve for each magnetizing coil is relatively small in the case without the yoke, as observed in [11].

Figure 7 shows the trapped field profiles B_Z on the rectangular-shaped bulk surface normalized by the maximum trapped field B_{Zmax} of the bulk center at t = 300 ms when applying $B_{ex} = 5.00$ T using each magnetizing coil. For the split coil with the yoke, the amount of the magnetic flux along with z-axis direction is kept even in the outer region of the bulk in addition to the higher magnitude of the trapped field as shown in Fig. 6. In other words, the trapped magnetic flux can

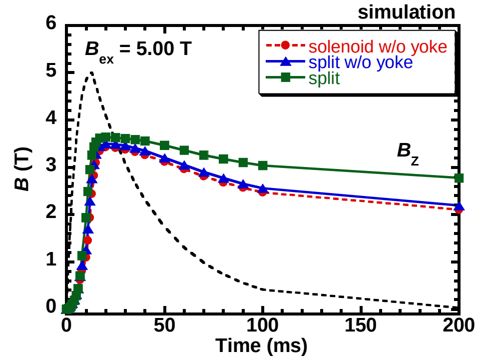

Fig. 8 Time dependence of the local field B_Z (t) at the center of the bulk surface for each coil after applying the pulsed field of $B_{ex} = 5.00$ T.

be oriented towards the z-axis direction on the bulk surface if there is the soft iron yoke. The existence of the soft iron yoke enables to control the direction of the magnetic flux and encourages an additional pinning force in the bulk.

Figure 8 depicts the results of time dependence of the local field B_Z (t) at the center of the bulk surface when applying pulsed field of $B_{ex} = 5.00$ T with each magnetizing coil. The local field B_Z (t) at the center of the bulk surface starts to increase and approaches the maximum value for t = 13 ms. For the split coil, one condition for the enhancement of the trapped field, the penetration of the magnetic flux could not be reproduced as shown in Fig. 5(b). It also suggests that the full penetration of the magnetic flux does not depend on the split coil. The soft iron yoke is effective for reduction of the flux creep in process of demagnetization after the pulse peak. So for now, the proposed reason for the observed enhancement of the trapped field mainly depends on the existence of the soft iron yoke in this simulation.

V. Summary

We have investigated experimentally and numerically the trapped field characteristics of a rectangular-shaped Gd-Ba-Cu-O bulk magnetized by PFM using split- and solenoid- coils. The maximum trapped field B_{Zmax} was enhanced to 3.05 T at 40 K for the split coil with two yokes, for which a symmetric trapped field profile can be seen. For the split coil, the magnetic flux penetrates fully into the bulk at B_{ex}^* and then saturates with minimal flux creep during PFM. Numerical simulation considering electromagnetic and thermal properties of the bulk was performed showing that the soft iron yoke is effective in a reduction of the flux creep by aligning the magnetic flux to z-axis direction. The use of the split coil with two yokes is effective in enhancing the trapped field.

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