Enhancement of total trapped fluxes on $\phi 65$ mm GdBaCuO bulk by multi-pulse techniques

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We have investigated the total trapped flux $\Phi_T(z)$ on the $\phi 65$ mm GdBaCuO superconducting bulk as a function of distance $z$ from the bulk surface magnetized by a successive pulse field application (SPA) with identical magnitude and subsequent iterative pulsed-field magnetization method with reducing the amplitude (IMRA) at various temperatures $T$. The $\Phi_T(z)$ value was enhanced by the IMRA process and reached 5.02 mWb on the bulk surface at $T_s = 40$ K, which was about 1.7 times larger than that at the end of SPA. The $\Phi_T(4 \text{ mm})$ value at 40 K by the SPA+IMRA method was as high as $\Phi_T^C(4 \text{ mm})$ by field cooled magnetization under $B_{z_c} = 3$ T at 48 K. The IMRA method is quite effective to enhance the $\Phi_T$ value for large superconducting bulks.

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1. Introduction

To magnetize the REBaCuO superconducting bulks (RE: rare earth element) as a strong quasi-permanent magnet for practical applications such as a magnetic separation for environmental cleaning [1] and a drug delivery system (DDS) for medical applications [2], a 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 $B_T$ by PFM was, however, pretty smaller than the trapped field $B_T$ attained by FCM below 77 K because of the large temperature rise caused by the dynamical motion of magnetic fluxes in the bulk. Several approaches have been performed and succeeded to enhance $B_T$ around 77 K such as an iteratively magnetizing pulsed-field method with reducing amplitude (IMRA) [3] and a multi-pulse technique with stepwise cooling (MPSC) [4]. We have systematically studied the time and spatial dependences of the temperature $T(t, x)$, the local field $B(t)$ and the trapped field $B_T$ on the surface of cryo-cooled REBaCuO bulks [5]. To enhance $B_T$, we proposed a new PFM technique called a modified MPSC (MMPSC), which consisted of the two-stage temperature procedures [6]. Using the MMPSC method, we have succeeded in establishing a record of high-field trapping of $B_T = 5.20$ T on the $\phi 45$ mm GdBaCuO bulk at 29 K to date [7], on which the maximum $B_T$ of 3.6 T was attained by a single pulse application.

Recently, REBaCuO superconducting bulks with diameter larger than 60 mm are on the commercial market and even a single-grain bulk of 140 mm in diameter can be realized [8]. According to Bean’s critical state model, a trapped field $B_T$ at the bulk center is proportional to the diameter of the bulk disk $d$, and a total trapped flux density $\Phi_T$ is proportional to the cubic of $d$, if the critical current density $j_c$ of the bulk material is identical. Another advantage of the large bulk magnet is that the magnetic field can reach a long distance, which is especially useful for the practical applications such as electric motor, generator and sputtering cathode.

We have investigated the trapped field characteristics on the $\phi 65$ mm GdBaCuO bulk by the successive pulse application (SPA) [9] and the MMPSC method [10]. The maximum trapped field on the $\phi 65$ mm bulk using SPA was as low as $B_T = 1.9$ T at 40 K, but $B_T$ was enhanced to 3.0 T using the MMPSC method, which were fairly smaller than those on the $\phi 45$ mm GdBaCuO bulk [7]. However, the $\Phi_T$ value for the large bulk is expected to enhance by the IMRA method because the $\Phi_T$ value of the $\phi 45$ mm GdBaCuO bulk had been about 30% enhanced by the IMRA method after the termination of the MMPSC method [11].

In this paper, we perform the SPA+IMRA method on the $\phi 65$ mm GdBaCuO bulk under several temperatures $T_s$ and applied

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pulse fields $B_\text{ex}$ and investigate the effect of the enhancement of the $\Phi_T$ value on the multi pulse technique. We compare the $\Phi_T$ value by the SPA+IMRA method with the $\Phi_T^{\text{FC}}$ value obtained by the FCM.

2. Experimental procedure

A 65 mm GdBaCuO superconducting bulk disk of 20 mm in thickness (Nippon Steel) was used in this study. The trapped field $B_T^{\text{FC}}$ by FCM was as high as 1.92 T at 77 K. The bulk was mounted on a soft iron yoke cylinder and tightly anchored onto the cold stage of a Gifford-McMahon (GM) cycle helium refrigerator. The experimental setup around the bulk was described elsewhere [10]. The magnetizing solenoid coil, which generated the pulse field up to $B_\text{ex} = 6.7$ T with a rise time of 12 ms and a duration of 100 ms, was placed outside the vacuum chamber, in which the central axis of the resulting field coincides with that of the bulk. The temperature $T_s$ of the bulk was controlled over the range from 60 K to 40 K. Fig. 1 shows the experimental sequence of the SPA+IMRA process. Three magnetic pulses (Nos. 1–3) with nearly the same amplitude $B_{\text{ex}}(\text{SPA}) = B_1 = B_2 = B_3$ were applied sequentially after recooling to $T_s$. From the No. 4 pulse, the IMRA process started, in which applied pulsed fields $B_{\text{ex}}(\text{IMRA}) = B_n (> B_{n+1})$ were iteratively reduced down to 3.5 T by a 0.3 T step at constant $T_s$.

Two-dimensional trapped field profile $B_T(z)$ was mapped at the distance $z = 0.5$, 4 and 8 mm above the bulk surface, stepwise with a pitch of 1 mm by scanning an axial-type Hall sensor (F.W. Bell, BHA 921) inside the vacuum chamber using an x-y stage controller. The total amount of the total trapped magnetic flux density $\Phi_T = \Phi_T(z)$ was calculated by integrating the $B_T(z)$ value over the region where it was positive. The $B_T^{\text{FC}}(z)$ profiles by FCM were also measured at temperatures from 38 K to 77 K using a cryo-cooled superconducting magnet and $\Phi_T^{\text{FC}}(z)$ was estimated. During FCM, the static magnetic field of 3 T was decreased down to 0 T in 18 min.

3. Results and discussion

Fig. 2a and b, respectively, show the examples of the trapped field profile $B_T(0.5$ mm) for the first (No. 1) and the last (No. 13) pulse application in the SPA+IMRA method ($T_s = 40$ K, $B_1 = 6.6$ T). For the No. 1 pulse, a concave $B_T$ profile with nearly the axial symmetry can be observed and, for the No. 13 pulse, the $B_T$ value entirely increased remaining the concave profile. Hereafter, we show the cross section of the $B_T$ profile along the $y$-axis instead of the two-dimensional $B_T$ profile, for simplicity.

Fig. 3a shows the pulse number dependence of the cross section of the trapped field profile $B_T(0.5$ mm) for the SPA+IMRA method ($T_s = 40$ K, $B_1 = 5.4$ T). Since the applied pulse field $B_1$ is smaller than that in Fig. 3a, only a small...
amount of the magnetic fluxes can intrude and can be trapped at the bulk center. In the IMRA process, the \( B_T \) (0.5 mm) value at the bulk periphery gradually increased and saturated with increasing pulse number. Fig. 4b shows the \( B_T \) (0.5 mm) profiles for the SPA+IMRA method (\( T_s = 60 K \), \( B_1 = 6.6 \) T) at higher \( T_s \). For the No. 1 pulse application, the \( B_T \) (0.5 mm) profile shows nearly the cone-shaped one which results from the weaker pinning force than that at 40 K. The magnetic fluxes were additionally trapped both at the bulk periphery and bulk center in the IMRA process.

Fig. 5 shows the total trapped fluxes \( \Phi_T \) (0.5 mm) vs. the applied pulse field \( B_{ex} \) for each condition in the SPA+IMRA method. In the figure, the numerals represent the pulse number \( n \).

Fig. 6 shows the total trapped fluxes \( \Phi_T(z) \) obtained in this study, as a function of the distance \( z \) from the bulk surface for the SPA+IMRA process at \( T_s = 40 \) K (\( B_1 = 6.6 \) T) and \( T_s = 60 \) K (\( B_1 = 6.6 \) T). \( \Phi_T(z) \) gradually decreased with increasing \( z \); \( \Phi_T(0.5 \text{ mm}) = 5.05 \) mWb and \( \Phi_T(8 \text{ mm}) = 3.19 \) mWb at \( T_s = 40 \) K and at \( B_1 = 6.6 \) T. In the figure, the \( \Phi_T(z) \) values by FCM under...
3 T and at T = 48, 60, 70 and 77 K are also indicated. The Φ_{TFC}(z) value increased with decreasing operating temperature T. It should be noted that the Φ_{TFC}(z) value by the SPA+IMRA method at 40 K is as high as the Φ_{TFC}(4 mm) value by FCM under 3 T at T = 48 K. If the FCM is operated under a static magnetic field higher than 3 T, the Φ_{TFC}(z) values are expected to increase. Since there is a possibility to make the bulk crash due to the hoop stress, we could not perform the FCM for B > 3 T at lower temperature. In Fig. 6, the Φ_{T}(5 mm) value magnetized by the MMPSC+IMRA process at T_s = 30 K for the φ45 mm GdBaCuO bulk is also shown [11], on which B_{T}(z = 0 mm) = 4.33 T and B_{T}(z = 5 mm) = 1.45 T were realized by the MMPSC method. However, the Φ_{T}(z = 5 mm) value was about a half of that for the φ65 mm bulk investigated in this study due to the smaller diameter of the bulk. The multi pulse technique such as the SPA+IMRA method is effective for the enhancement of the Φ_{T} value for the superconducting bulk as large as 65 mm in diameter, even though the B_{T} value at the bulk center is not so high.

In summary, the total trapped flux Φ_{T}(z) on the φ65 mm GdBaCuO superconducting bulk has been investigated as a function of distance z from the bulk surface using a successive pulse field application (SPA) with identical magnitude and subsequent iterative-pulsed-field magnetization method with reducing the amplitude (IMRA) at T_s = 40 and 60 K. The Φ_{T}(0.5 mm) value was enhanced by the IMRA method and reached 5.02 mWb on the bulk surface at T_s = 40 K, which was about 1.7 times larger than that at the end of SPA. The Φ_{T}(4 mm) value by SPA+IMRA process was as high as the Φ_{TFC}(4 mm) value by field cooled magnetization under 3 T at 48 K. The IMRA method is effective for the enhancement of the Φ_{T} value for large superconducting bulks. The Φ_{T} value closely depends on the shape of the trapped field profile at the end of the SPA process, the magnitude of the applied field B_{ex} during both SPA and IMRA processes, diameter of the bulk, the temperature T_s and so on. In this study, the maximum B_{ex} was 6.6 T for the experimental setup reason and we cannot realize the convex shape at 40 K. Within our experimental conditions (T_s ≥ 40 K, B_{ex} ≤ 6.6 T), the maximum Φ_{T} value was realized under the concave trapped field profile. A detailed study is in progress.

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