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Development of five aligned superconducting bulk magnets by pulse field magnetizing

A. Fujiwara [a], T. Tateiwa [a], H. Fujishiro [a,*], H. Hayashi [b], T. Nagafuchi [b], T. Oka [c]

[a] Faculty of Engineering, Iwate University, 4-3-5 Ueda, Morioka 020-8551, Japan
[b] Kyushu Electric Power Co. Inc., 2-1-47 Shioharu, Fukuoka 815-8520, Japan
[c] IMRA Material R&D Co. Ltd., 5-50 Hachiken-cho, Kariya 448-0021, Japan

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Abstract

A new high-T_c bulk magnet system, which consists of five aligned superconducting bulks, has been developed for the magnetic separation to purify waste water. Five GdBaCuO bulk blocks are cryo-cooled down to 40 K from the side face (along *ab*-plane) and are magnetized in turn by the pulse field magnetizing using a split-type pulse coil with the applied field of $B_{\mathrm{ex}} = 5.0$–5.5 T. The trapped field $B_{\mathrm{T}}^{P} \sim 2.0$ T can be attained on the bulk surface and the $B_{\mathrm{T}}^{6\,\mathrm{mm}}$, 6 mm distant above the bulk surface in the open space, is 1.0–1.2 T for each bulk. The results for the temperature rise and trapped field are compared with those for the same bulk cooled down along the *c*-axis and magnetized using a solenoid-type pulse coil.

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Keywords: Superconducting bulk magnets; Multi-bulk; Pulse field magnetizing; Trapped field

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1. Introduction

For the practical application of high-T_c superconducting bulks, a high-strength bulk magnet in a magnetic separation system for waste water etc., is one of the typical models [1]. On magnetizing the bulks, a field cooled magnetizing (FCM) is usually used to obtain the maximum ability of the trapped field. However, the superconducting magnet with a large bore must be used to magnetize the bulk by FCM. Recently, a pulse field magnetizing (PFM) has been investigated and developed because of a compact and inexpensive experimental setup. The trapped field B_{T}^{P} by PFM is, however, generally smaller than that attained by FCM in terms of the large temperature rise ΔT due to the dynamical flux motion. Several approaches have been performed in order to reduce ΔT and to enhance B_{T}^{P} [2–5]. Recently, we have attained the trapped field of $B_{\mathrm{T}}^{P} = 4.47$ T by the modified multi pulse technique combined with stepwise cooling (MMPSC), which is the present highest value by PFM [6].

In order to realize a superconducting bulk magnet, the bulk is usually cooled down below the superconducting transition temperature (T_c) along the *c*-axis on the cold stage of the helium refrigerator, and is magnetized along the *c*-axis using a solenoid-type pulse coil. In this setup, only one bulk can be utilized for one refrigerator and only the upper surface of the bulk can be utilized as a magnetic pole in open space. Oka et al. constructed a multi-bulk magnet system consisting of seven bulks and attained 0.9 T at the center of the pole surface in open space by FCM [7]. In this setup, however, it is difficult to magnetize the multi-bulks by PFM at a time because of the insufficient mechanical strength of the supporting parts and so on. We have developed a prototype of multi-bulk magnet system consisting of two aligned REBaCuO bulk disks cooled down from the side face (along *ab*-plane) and

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[*] Corresponding author. Tel./fax: +81 19 621 6363.
E-mail address: fujishiro@iwate-u.ac.jp (H. Fujishiro).

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attained the trapped field $B_T = 1.97$ T by PFM on the surface of the vacuum sheath [8].

In this paper, we develop the five-aligned superconducting bulk magnet system using rectangular-shaped high-T_c superconducting bulks for the magnetic separation system, which are cooled down along the *ab*-plane and magnetized using a split-type pulse coil. The superiority to the cooling along the *ab*-plane is presented and the possibility of the extension of the number of the bulks is discussed.

2. Experimental

Highly *c*-axis oriented five rectangular-shaped GdBaCuO bulks ($34 \times 34 \times 20$ mm^3, Nippon Steel Co., Ltd.) were used, which showed identical trapped field by FCM, $B_T^{FC} = 1.26$–1.30T at 77 K. The bulks were uniformly impregnated by epoxy resin in vacuum. Fig. 1 shows the experimental setup around the bulks. Five bulk blocks (bulk #0–bulk #4) were tightly fastened with the brass-metal holder from the side face (along the *ab*-plane) and the holder was attached to the cold stage of a Gifford McMahon (GM) cycle helium refrigerator. Hereafter, we abbreviate this type of magnet system as an "*ab*-plane cooled type". The initial temperature of the cold stage T_s was fixed at 40 K. The time evolutions of temperature T and trapped magnetic field B_T^P were monitored on the central three bulks (bulk #1, #2 and #3) using the Cernox thermometer and the Hall sensor (F.W. Bell, Model BHA921) adhered on the center of each bulk. The bulk was magnetized using the split-type pulse coil dipped in liquid N$_2$. The pulse field of $B_{ex} = 5.0$ T is applied to the virgin state bulk as the pulse No. 1 and then the pulse fields of $B_{ex} = 5.5$ T were applied as the subsequent pulses (No. 2–No. 5) after recovering to the initial temperature. After the completion of the magnetizing a bulk, the split-type coil was moved parallel and another bulk was magnetized in turn in a same manner. The trapped field $B_T(z)$ along the z direction away from the vacuum sheath surface was measured using an axial-type Hall sensor. We compare the results of the "*ab*-plane cooled type" system with those of the "*c*-axis cooled type" system; the GdBaCuO rectangular bulk is cooled down along the *c*-axis and is magnetized using a solenoid-type pulse coil with a magnetic field $B_{ex} = 4.8$ T or 5.5 T as the pulse No. 1.

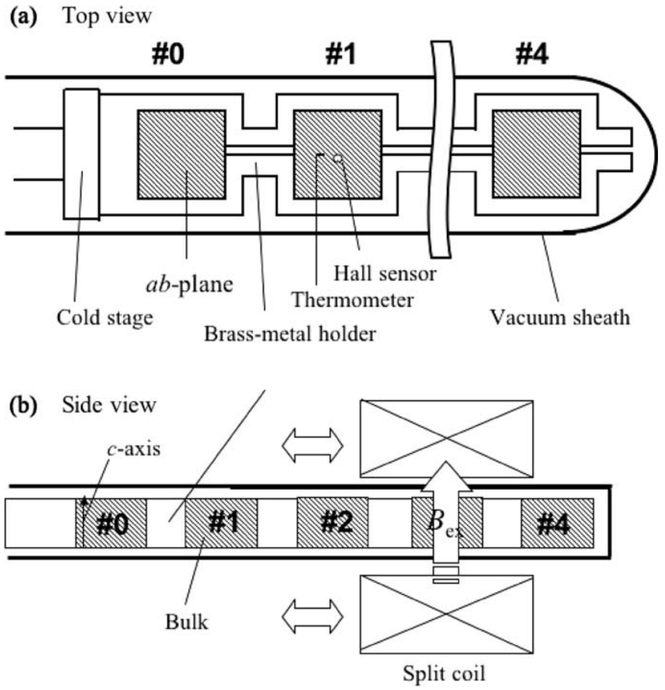

Fig. 1. The experimental setup around the GdBaCuO bulks and split-type pulse coil.

3. Results and discussion

Figs. 2(a) and (b) show the time evolutions of temperature $T(t)$ after applying the pulse field of $B_{ex} = 5.0$ T to the "*ab*-plane cooled type" bulk (#1) and of $B_{ex} = 4.8$ T or 5.5 T to the "*c*-axis cooled type" bulk, respectively. In the "*ab*-plane cooled type", $T(t)$ sharply rises up ($\Delta T = 16.7$ K) and then returns to the initial temperature within 10 min. In the "*c*-axis cooled type" bulk for $B_{ex} = 5.5$ T, $T(t)$ also sharply rises up with a larger ΔT (=18.5 K) due to the slightly larger applied field B_{ex}, but rather moderately decreases and returns to the initial temperature in ~20 min. For $B_{ex} = 4.8$ T, $T(t)$ cannot return to the initial temperature within 10 min, although ΔT is smaller than that in the "*ab*-plane cooled type" bulk for $B_{ex} = 5.0$ T. These results mainly come from the difference in the cooling direction for the bulk; the thermal conductivity κ_{ab} in the *ab*-plane is much higher than that along the *c*-axis κ_c and the propagating speed of the generated heat

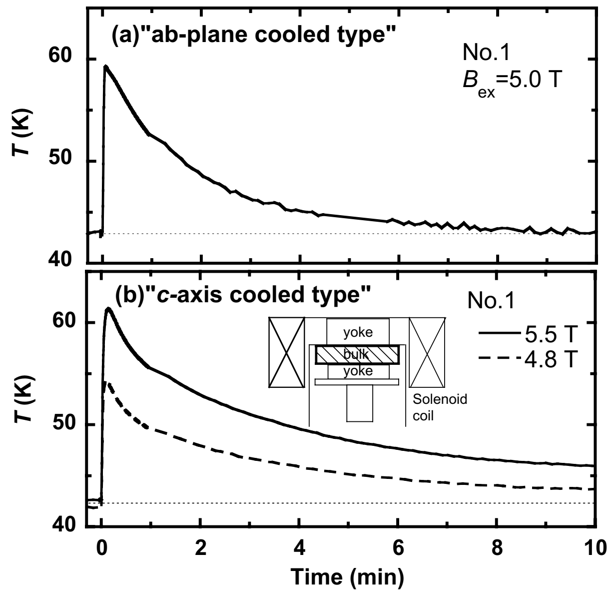

Fig. 2. The time evolution of temperature $T(t)$ after applying the pulse field of (a) $B_{ex} = 5.0$ T for the "*ab*-axis cooled type" bulk and (b) $B_{ex} = 5.5$ T and 4.8 T for the "*c*-axis cooled type" bulk.

is higher in the *ab*-plane [9]. The "*ab*-plane cooled type" has a merit to shorten the cooling time for the heat generation.

Figs. 3(a) and (b) present the pulse number dependence of the maximum temperature rise ΔT and the trapped field B_T^P of the "*ab*-plane cooled type" bulks (#1 and #2). ΔT is the largest for the pulse No. 1 and monotonically decreases and approaches a steady state value with increase number of the magnetic pulse. The largest amount of the fluxes is trapped during the application of pulse No. 1 and B_T^P is gradually enhanced with increasing pulse number. The B_T^P value of the bulk #2 is larger than that of the bulk #1 in spite of the similar B_T^{FC} characters. These results may result from difference in temperature rise; the ΔT of the bulk #2 is smaller than that of the bulk #1. In Fig. 3, ΔT and B_T^P of the "*c*-axis cooled type" bulk are also shown for $B_{ex} = 5.5$ T. For the "*c*-axis cooled type" bulk, the similar pulse number dependence of ΔT and B_T^P can be seen, but the B_T^P is larger than that of the "*ab*-plane cooled type" bulks. These results suggest that the GdBaCuO bulk has a possible potential to trap the B_T^P value up to 2.5 T at 40 K by PFM and that B_T^P can increase by the optimum application of B_{ex}. The detailed investigation for the "*ab*-plane cooled type" bulk is in progress.

Fig. 4 shows the line scan profile of the trapped field $B_T^{6\,mm}$, 6 mm distant above the bulk surface in the open space, along the direction through the bulk centers after the magnetization of the five bulks. The measurement was performed after the magnetic fields of pulse No. 1 ($B_{ex} = 5.0$ T) and No. 2 (5.5 T) were applied for each bulk [8]. In this figure, the "front" means the side, on which the Hall sensor was adhered and the "back" means the opposite side. The B_T^P values for the bulks #1, #2 and #3 are also shown. The maximum $B_T^{6\,mm}$ values on the "front" and "back" sides are between 0.9 T and 1.2 T, and the very similar maximum $B_T^{6\,mm}$ values can be seen on both sheath surfaces. The slight difference in the maximum $B_T^{6\,mm}$ value is due to the difference of crystalline property of the bulk on which the seed crystal was attached during the crystal growth. This type of bulk magnet system can be effectively used on both surfaces as magnetic poles in open space, which may be a great merit for a new application.

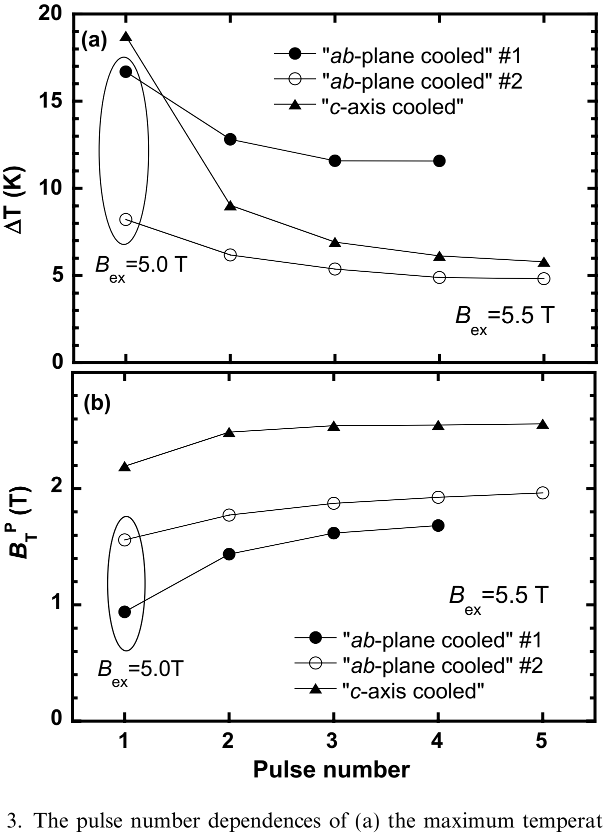

Fig. 3. The pulse number dependences of (a) the maximum temperature rise ΔT and (b) the trapped field B_T^P for the "*ab*-plane cooled type" bulks (#1 and #2). The results for the "*c*-axis cooled type" are also shown.

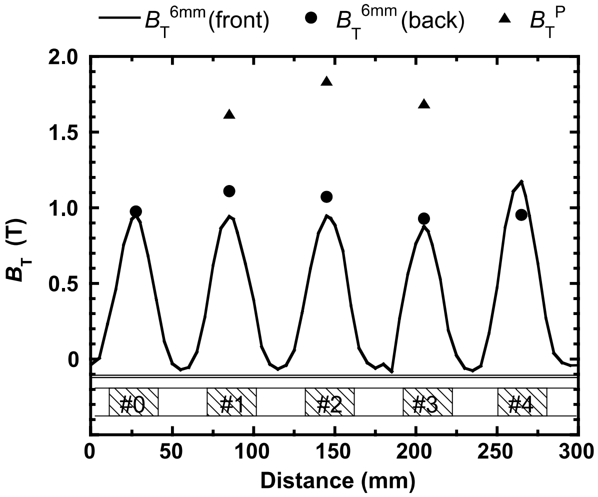

Fig. 4. The line-scan profile of the $B_T^{6\,mm}$ value along the direction through the bulk centers on the sheath surface. The B_T^P values for the bulks #1 to #3 are also shown.

Fig. 5 presents the trapped field $B_T(z)$ at the center of each bulk as a function of the distance z from the bulk surface. In this figure, $z = 6$ mm means the surface on the vacuum sheath. The$B_T(z)$ value sharply decreases with

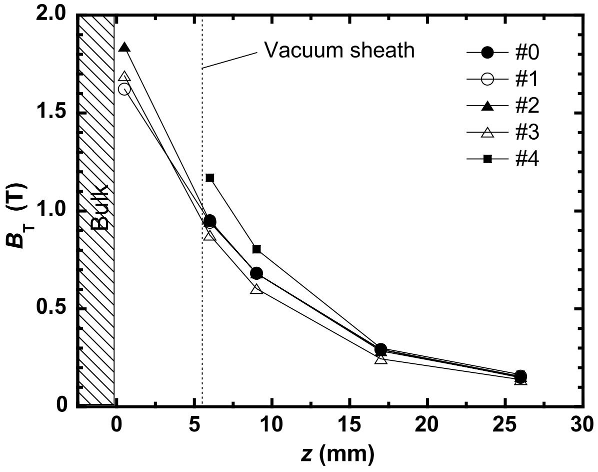

Fig. 5. The trapped field $B_T(z)$ at the center of each bulk as a function of the distance z away from the bulk surface.

increasing z. For example, for the bulk #3, the $B_{\mathrm{T}}(6\,\mathrm{mm})$ value ($= B_{\mathrm{T}}^{6\,\mathrm{mm}}$) is 50% of $B_{\mathrm{T}}(0) = B_{\mathrm{T}}^{P}$, and $B_{\mathrm{T}}(17\,\mathrm{mm})$ is 15% of B_{T}^{P}. These results suggest that, on the application for the magnetic separation, it is necessary to minimize the gap between the bulk and the vacuum sheath in order to effectively take out the magnetic field trapped in the bulk.

4. Summary

We have constructed five-aligned superconducting bulk magnet system magnetized by pulse field magnetizing. The cooling method along the *ab*-plane, which is adopted in this study, has a merit to shorten the cooling time for the heat generation, compared with that along the *c*-axis. The trapped field B_{T}^{P} as high as ~2.0 T is attained on the bulk surface and the trapped field $B_{\mathrm{T}}^{6\,\mathrm{mm}}$ on the vacuum sheath surface is 1.0–1.2 T for each bulk. The optimization of the conditions such as applied field and the bulk stage temperature is necessary in order to enhance the trapped field for the five-aligned bulks, compared with two aligned bulk magnet system.

References

[1] H. Hayashi, K. Tsutsumi, N. Saho, N. Nishizima, K. Asano, Physica C 392–396 (2003) 745.

[2] U. Mizutani, T. Oka, Y. Itoh, Y. Yanagi, M. Yoshikawa, H. Ikuta, Appl. Supercond. 6 (1998) 235.

[3] M. Sander, U. Sutter, R. Koch, M. Kläser, Supercond. Sci. Technol. 13 (2000) 841.

[4] H. Fujishiro, K. Yokoyama, M. Kaneyama, T. Oka, K. Noto, IEEE Trans. Appl. Supercond. 15 (2005) 3762.

[5] H. Fujishiro, M. Kaneyama, K. Yokoyama, T. Oka, K. Noto, Jpn. J. Appl. Phys. 44 (2005) 4919.

[6] H. Fujishiro, M. Kaneyama, T. Tateiwa, T. Oka, Jpn. J. Appl. Phys. 44 (2005) L1221.

[7] T. Oka, K. Yokoyama, K. Noto, IEEE Trans. Appl. Supercond. 14 (2004) 1058.

[8] H. Fujishiro, A. Fujiwara, T. Tateiwa, T. Oka, H. Hayashi, IEEE Trans. Appl. Supercond., in press.

[9] H. Fujishiro, S. Kohayashi, IEEE Trans. Appl. Supercond. 12 (2002) 1124.