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Trapped field enhancement of five-aligned superconducting bulk magnetized by pulse field for magnetic separation

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ABSTRACT

Five-aligned superconducting bulk magnet system has been improved and the trapped field characteristics have been investigated by the pulse field magnetization (PFM). The trapped field $B_T(z = 0\ \mathrm{mm})$ is enhanced to 2.7 T at the bulk surface because of the lowering temperature T_s and the enhancement of the applied field B_{ex}, compared with those for the proto-type system [Physica C 445–448 (2006) 399]. The operating fields, $B_T(2\ \mathrm{mm})$ at the vacuum sheath surface and $B_T(9\ \mathrm{mm})$ at the surface of the rotating membrane in water-treatment system, are also enhanced because of some structural improvement, and the multi-bulk magnet system available for the magnetic separation is realized.

1. Introduction

The practical applications using a high-T_c superconducting (HTSC) bulk have been proposed and intensively developed. The superconducting bulk magnet using a strong pinning force is one of the promising applications, on which the trapped field B_T is as high as a few Tesla and is about one order of magnitude higher than that of strong Nd–Fe–B permanent magnet. Although, a field cooling magnetizing method (FCM) using a solenoid-type superconducting magnet (SM) is suitable to magnetize HTSC bulks, it is impossible to magnetize the multi-HTSC bulks in a line using it. Saho et al. of Hitachi Ltd., Japan, developed a water-treatment system consisting of a membrane separator using seven-aligned bulks, which were magnetized by the modified FCM; the bulks were cooled below superconducting transition temperature T_c, and during cooling, the bulks were inserted into and withdrawn from the split-type SM repeatedly [1]. This system was used to remove phytoplankton multiplying in highly eutrophic lakes and dams [2]. However, since the magnetizing system for the modified FCM is large, heavy and expensive, the magnetizing process must be operated at a specified institute or laboratory. On the other hand, a pulse field magnetization (PFM) method, which has been intensively investigated and developed, is a compact, inexpensive and mobile experimental setup to magnetize HTSC bulks. We have developed a new HTSC bulk magnet system to purify waste-water using PFM [3]. The system consists of five-aligned GdBaCuO bulks cryocooled to 50 K from the side face and the bulks were magnetized in turn by PFM using a split-type copper coil. The highest trapped field was $B_T = 2.0$ T on the bulk surface and the field $B_T(6\ \mathrm{mm})$, 6 mm distant above the bulk surface at the vacuum sheath surface, was 1.0–1.2 T for each bulk. However, the operating field $B_T(\mathrm{OP})$ on a membrane separator at $d = 18$ mm from the bulk surface, was as low as 0.3 T, which was not strong enough for the practical separation. In this paper, we report the enhancements both of B_T and $B_T(\mathrm{OP})$ of five-aligned superconducting bulk magnet system by several improvements.

2. Experimental procedures

The schematic views of the five-aligned superconducting bulk magnet and the structure of membrane–magnetic separator for water treatment are shown in Fig. 1. Table 1 shows the typical dimensions, the characteristic values and the results of the present bulk magnet system, compared with those of the proto-type system [3]. In this study, several improvements were performed in the system to enhance the B_T and $B_T(\mathrm{OP})$. c-axis oriented five rectangular-shaped GdBaCuO bulks (bulk #1–bulk #5; $34 \times 34 \times 15\ \mathrm{mm}^3$,

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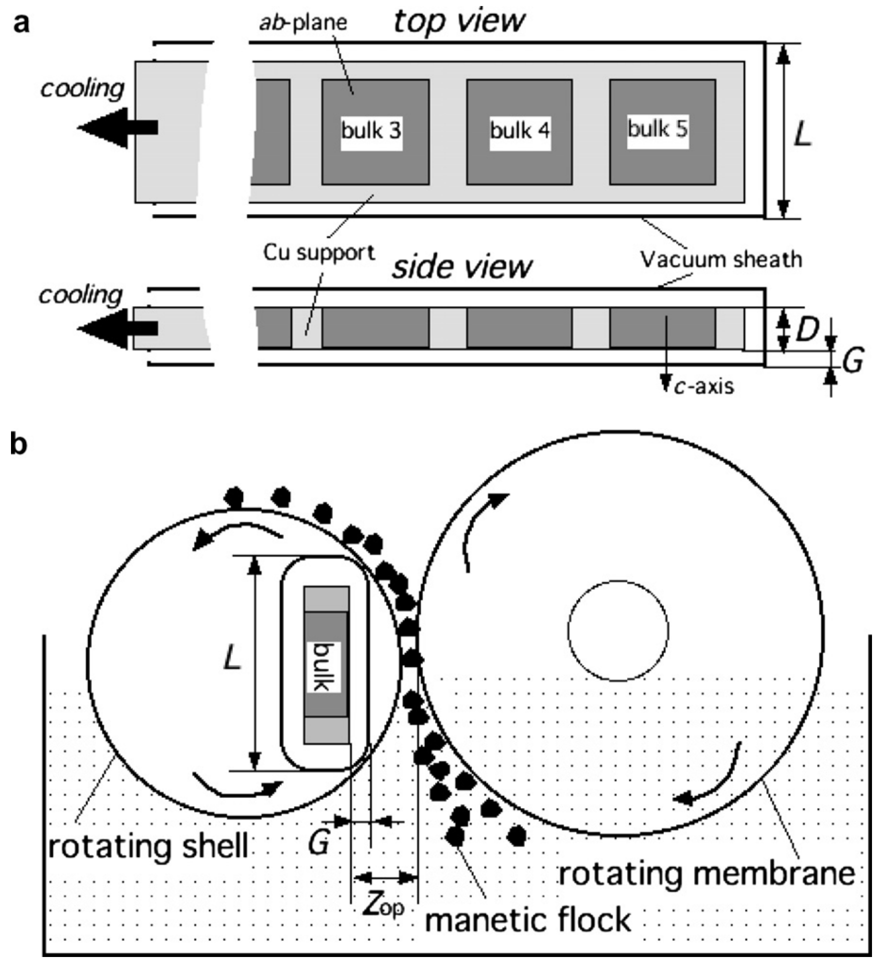

Fig. 1. (a) The top and side views of the five-aligned superconducting bulk magnet. (b) The structure of membrane separator for water treatment. Magnetic flocks deposited on the membrane are removed by the magnetic force generated using HTSC bulks.

Table 1
The typical dimensions, the characteristic values and the trapped fields of the present system, compared with those of the proto-type [3]

	Improved-type (this work)	Proto-type (Ref. [3])
T_s (K)	30	50
Maximum applied field B_{ex} (T)	6.0	5.5
Thickness of bulk D (mm)	15	20
G (mm)	1	4
T (mm)	1.0	1.5
L (mm)	49	70
Z_{op} (mm)	9	18
B_T^{OP} (T)	0.7	0.3
B_{Tmax} (T)	2.6	1.6

Nippon Steel Co., Ltd.) were tightly fastened with the copper holder from the side face (along the *ab*-plane) and the holder was attached to the cold stage of a double stage Gifford McMahon (GM) cycle helium refrigerator. The temperature of the #1 bulk was controlled as low as $T_s = 30$ K. The vacuum gap G between the bulk surface and the inner surface of the vacuum sheath, and the thickness T of the vacuum sheath made of stainless steel were reduced to 1.0 mm and 1.0 mm, respectively. As a result, the distance between the bulk surface and the outer surface of the vacuum sheath became as short as $z = G + T = 2$ mm. The operating distance Z_{op}, which was the distance from the bulk surface to the surface of the membrane filter, was reduced to 9.0 mm because of the reduction of the vacuum sheath width L, G and T. The maximum applied field B_{ex} was enhanced to 6.0 T because of the reduction of the gap of the split-type pulse coil by the reduction of the bulk thickness D. The trapped magnetic field B_T were monitored at the center of the bulk of #1 and #3 using the Hall sensor (F.W.Bell, Model BHT921). The pulse field of $B_{ex} = 3.0$–6.0 T with a rise time of 12 ms was applied to the zero-field cooled bulk. After the completion of magnetizing a bulk, the split-type magnetizing coil was moved in parallel and another bulk was magnetized in turn in the same manner. The successive pulse applications with identical strength (SPA) were performed to enhance B_T. The magnetic field $B_T(z)$ along the z direction away from the sheath surface ($z = 2$ mm) was measured using an axial-type Hall sensor.

3. Results and discussion

Fig. 2a and b show the trapped fields $B_T(z)$ at the bulk surface ($z = 0$ mm) and at the vacuum sheath surface ($z = 2$ mm) as a function of the applied field B_{ex} for the #1 and the #3 bulk, respectively. The right-hand side ordinate shows the B_{ex} dependence of the total trapped fluxes Φ_T integrated 0.5 mm above the sheath surface. For the #1 bulk, the B_T values are pretty low, slightly increases with increasing B_{ex} up to 5 T and show high values at $B_{ex} = 5.8$ T. For lower B_{ex} region ($B_{ex} < 5$ T), however, Φ_T shows a finite value and slightly increases with increasing B_{ex}, even if the $B_T(z = 0$ mm) value is nearly zero at the bulk center. This result suggests that the magnetic fluxes are mainly trapped at the bulk periphery. On the

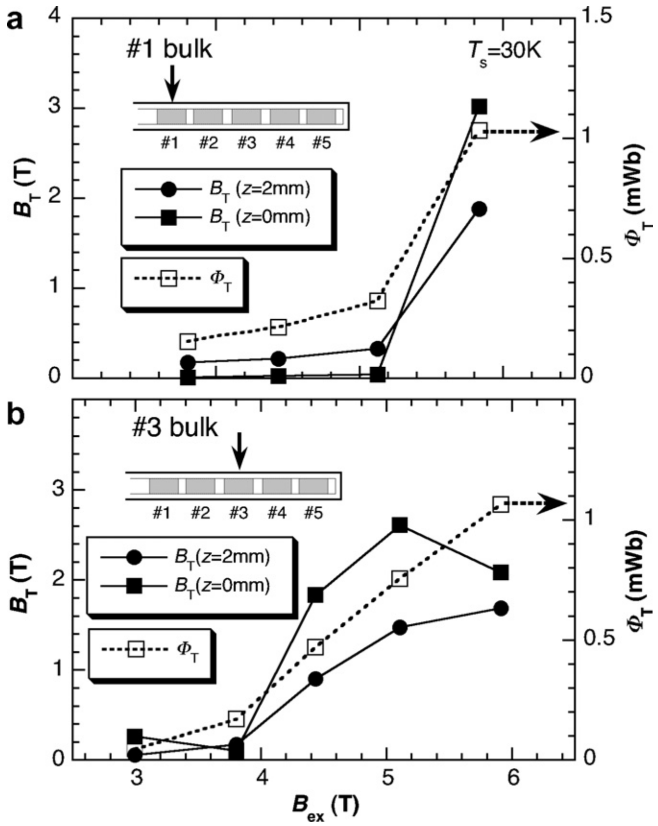

Fig. 2. The trapped fields $B_T(z)$ at the bulk surface ($z = 0$ mm) and at the vacuum sheath surface ($z = 2$ mm) as a function of the applied field B_{ex} for (a) the #1 and (b) the #3 bulk, respectively. The right ordinate shows the B_{ex} dependence of the total trapped fluxes Φ_T integrated 0.5 mm above the sheath surface.

other hand, for the #3 bulk, the magnetic fluxes start to intrude into the bulk center from relatively low B_{ex} value ($B_{ex} > 4$ T) and the B_T value took a maximum at $B_{ex} = 5.2$ T and then decreased. Since the field trapping ability for the #1 and #3 bulk is nearly the same ($B_T = 1.26$–1.30 T at 77 K by FCM), the difference in the B_T vs. B_{ex} curve between #1 and #3 bulk results from the difference

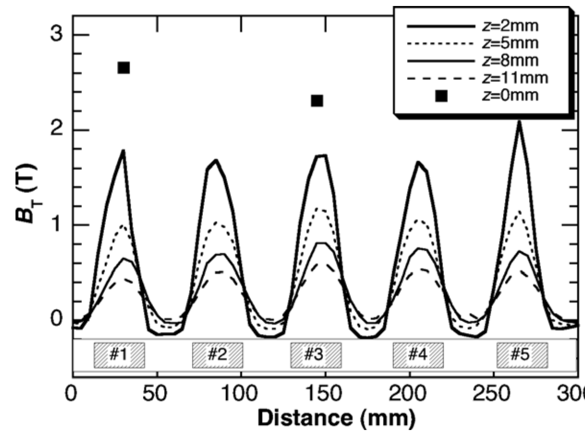

Fig. 4. The line scan profile of the trapped field $B_T(z)$ in open space, along the direction through the bulk center after the magnetization of the five bulks.

in the starting temperature. The temperature of the copper support near the #1 bulk was controlled at 30 K, but we did not measure the temperature at the bulk surface. The temperature would be higher for the bulks far from the cold stage, namely, the temperature of the #3 bulk would be higher than that of the #1 bulk because of the heat intrusion and/or the low cooling power. Then, the appropriate applied field B_{ex} was independently decided for each bulk.

Fig. 3a and b shows the trapped field $B_T(z = 2$ mm) on the vacuum sheath and the total trapped flux Φ_T for each bulk after applying single pulse field B_{ex} and the SPA procedure, respectively. In SPA, the pulse fields with identical strength were applied twice or three times after returning to the initial temperature. In Fig. 3a, the applied field B_{ex} is indicated for each bulk, which was slightly decreased with increasing bulk number as discussed above. The $B_T(z = 2$ mm) value of the #1, #3 and #4 bulks slightly increases by SPA, but that of the #2 and #5 bulks remain constant. However, the Φ_T value is enhanced by SPA for all the bulks. The B_T and Φ_T values are enhanced by the SPA process for a single bulk, but it should be noticed that these values sometimes might be reduced by SPA. Because the generated heat by PFM propagates to the next bulk and the already trapped fluxes might escape due to

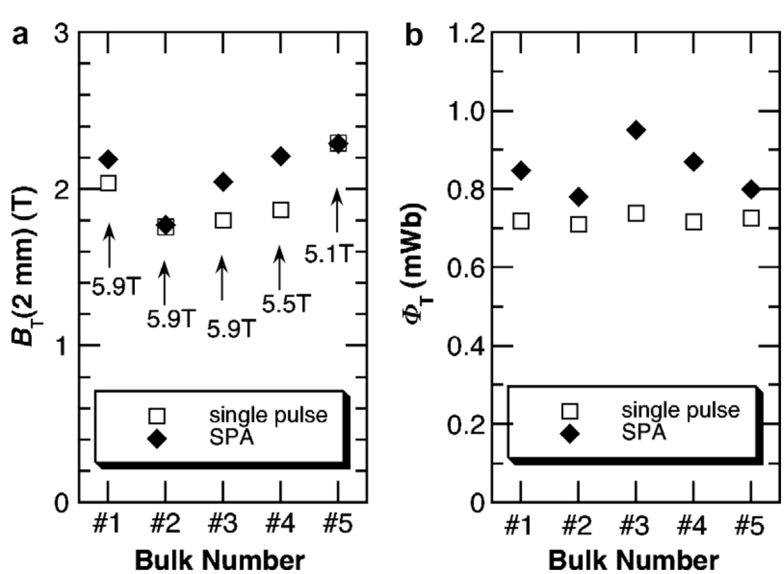

Fig. 3. (a) The trapped field $B_T(z = 2$ mm) and (b) the total trapped flux Φ_T for each bulk after applying single pulse field B_{ex} and the successive pulse application with identical strength (SPA).

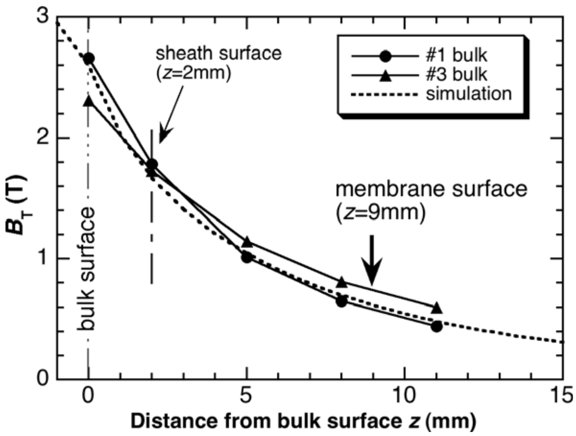

Fig. 5. The trapped field $B_T(z)$ at the center of the #1 and #3 bulks as a function of the distance z. The estimated $B_T(z)$ is also shown, which is calculated using a Biot–Savart's law.

the temperature rise. An inverse magnetic field due to the leak of the applied field might be applied to the next bulk, which results in the decrease of B_T on the next bulk.

Fig. 4 shows the line scan profile of the trapped field $B_T(z)$ in open space, along the direction through the bulk center after the magnetization by SPA of the five bulks. The $B_T(z)$ profile changes periodically and the $B_T(z)$ value decreases with increasing z, i.e., the maximum $B_T(z)$ value is 1.8–2.2 T at $z = 2$ mm, but that at $z = 5$ mm decreases to 1.0–1.2 T.

Fig. 5 shows the trapped field $B_T(z)$ at the center of the #1 and #3 bulks as a function of the distance z from the bulk surface. The $B_T(z)$ value is sharply reduced with increasing z. The estimated $B_T(z)$ line is also shown in figure, which was calculated using a Biot–Savart's law. The calculated $B_T(z)$ profile can reproduce the experimentally obtained data. As shown in Fig. 1b, the operating distance on a rotating membrane separator is $Z_{OP} = 9.0$ mm in the water-treatment system, at which the magnetic field is estimated to be $B_T^{OP} = 0.7$ T. The value is about two times larger than that in the proto-type separator [3]. But the magnetic strength is still weak to attract the magnetic flock sufficiently. The further improvement to enhance the trapped field is in progress.

4. Summary

We have improved the five-aligned superconducting bulk magnet system and investigated the trapped field characteristics by the pulse field magnetization. The trapped field $B_T(z = 0\text{ mm})$ is enhanced to 2.7 T at the bulk surface by lowering the temperature T_s and the enhancement of the applied field B_{ex}, relative to those for the proto-type system. The operating field $B_T(z = 9\text{ mm})$ at the surface of the rotating membrane in water-treatment system was also enhanced to 0.7 T because of some structural improvements.

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References

[1] N. Nishijima, N. Saho, K. Asano, H. Hayashi, K. Tsutsumi, M. Murakami, IEEE Trans. Appl. Supercond. 13 (2003) 1580.
[2] H. Hayashi, N. Nagafuchi, N. Saho, T. Mizumori, K. Asano, Physica C 412–414 (2004) 766.
[3] A. Fujiwara, T. Tateiwa, H. Fujishiro, H. Hayashi, T. Nagafuchi, T. Oka, Physica C 445–448 (2006) 399.