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# Magnetic properties of Ag-added Gd–Ba–Cu–O superconductors

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**Abstract**

In order to obtain helpful guidelines for designing high-$T_c$ bulk superconductor magnet systems, the gap, temperature and time dependence of the trapped field for Y–Ba–Cu–O and Gd–Ba–Cu–O/Ag bulk superconductors were measured. For the gap dependence, we compared the experimental results and the analytical solution on the condition that $J_c$ is constant for the disk-shaped bulk superconductor, and we found that the analytical solution corresponds well with the experimental results. The peak value of the trapped field reached 4.6 T at 63 K for the Gd–Ba–Cu–O bulk superconductor, and the flux creep rate at 63 K was slower than that at 70 and 77 K. This indicates that cooling down to at least 63 K creates superior conditions for the bulk magnet in respect of the increasing trapped field and its stability.


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*Keywords:* Trapped field; HTSC; Y–Ba–Cu–O; Gd–Ba–Cu–O

## 1. Introduction

A melt-processed RE–Ba–Cu–O (RE: Y and rare earth elements) bulk superconductor magnet has become a realistic option for magnet systems through its improvement of the performance of bulk superconductors, e.g. RE–Ba–Cu–O/Ag (RE = Gd, Sm, and Nd) [1–3]. One approach for making use of this advantage is to study the trapped magnetic field of the bulk superconductor [4].

In this paper, in order to obtain helpful guidelines for designing magnet systems with high-$T_c$ bulk superconductors, we measured the gap, temperature and time dependence of the trapped fields for Gd–Ba–Cu–O and Y–Ba–Cu–O bulk superconductors. We also compared the experimental results and the approximate solution for the gap dependence of the trapped field.

## 2. Experimental

A large single-grained RE–Ba–Cu–O (RE: Y, Gd) bulk superconductor was produced by the top-seeded melt-growth technique [5]. The Y–Ba–Cu–O precursor ($YBa_2Cu_3O_x$:$Y_2BaCuO_5$ = 3:1 in

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Table 1
The average of flux creep rate

| Temperature (K) | 77 | 70 | 63 |
|---|---|---|---|
| $R \times 10^{-3}$ | 13.8 | 5.7 | 1.5 |

molar ratio with 0.5 wt.% Pt) was prepared, then heated to 1150 °C, and cooled to 1040 °C. The seed crystal of (Sm,Nd)–Ba–Cu–O was placed on the top of the precursor, and then gradually cooled to 950 °C for crystal growth in air.

On the other hand, the Gd–Ba–Cu–O precursors ($GdBa_2Cu_3O_x$:$Gd_2BaCuO_5 = 3{:}1$ in molar ratio with 0.5 wt.% Pt and 10 wt.% $Ag_2O$) were prepared, then heated to 1170 °C, and cooled to 1040 °C. The seed crystals of (Sm,Nd)–Ba–Cu–O were placed on the top of the precursors, respectively, and then gradually cooled to 950 °C for crystal growth in air. The Y–Ba–Cu–O and Gd–Ba–Cu–O specimens were cut into the shapes shown in Table 1, and then the Y–Ba–Cu–O specimen and the Gd–Ba–Cu–O specimens were annealed for 100 h at 450 and 400 °C, respectively, in flowing oxygen gas. The trapped field distributions were measured by scanning a Hall sensor at a height of 1.2 mm above each specimen surface after the specimens were field-cooled to liquid nitrogen temperature, at 77 K.

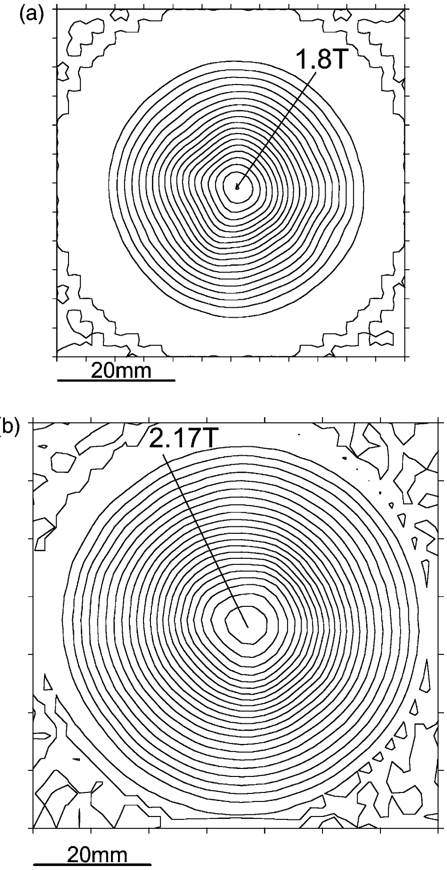


Fig. 1. The trapped field distributions for Gd–Ba–Cu–O bulks 45 mm (a) and 65 mm (b) in diameter.

## 3. Results and discussion

### 3.1. Trapped field distribution

Fig. 1(a) and (b) shows the trapped field distributions for Gd–Ba–Cu–O bulks 45 and 65 mm in diameter, respectively. The trapped fields of both samples were distributed as concentric circles, which means that they had neither cracks nor weak links. The peak value of the trapped field for the 45-mm∅ Gd–Ba–Cu–O superconductor was 1.8 T at a 1.2 mm gap. The 65-mm∅ Gd–Ba–Cu–O's peak value reached 2.17 and 2.6 T at 1.2 and 0.7 mm gaps, respectively.

Fig. 2 shows the axial trapped field ($B_z$) at each gap from the surface of the superconductors to the measuring position on the center axis. Each $B_z$ was measured 30 min after reaching an external field of

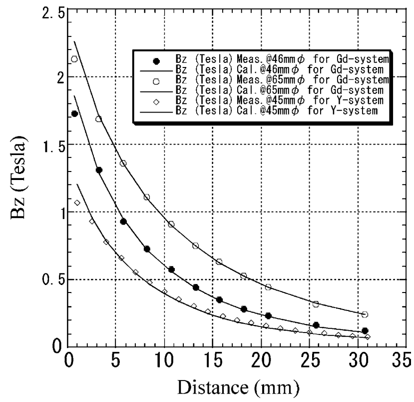


Fig. 2. The axial trapped field ($B_z$) at each gap from the surface of the superconductors to the measuring position on the center axis. The results derived by Eq. (2) are shown by the lines in this figure.

zero. The $B_z$ decreased with increasing distances at various reduction rates that reflected the diameter and thickness of the superconductor. For comparison with the above experimental results and the analytical solution, we used the analytical solution of the trapped field distribution for a disk-shaped superconductor with a constant $J_c$. The $B_z$ at arbitrary coordinates $r$ and $z$, created by a disk with the current density $J$ flow, is given by:

$$B_z(r,z) = \frac{\mu_0 J}{2\pi}\int_0^R \int_z^{D+z} \frac{K(k) + \frac{a_s^2 - r^2 - z_s^2}{(a_s+r)^2+z_s^2}E(k)}{\sqrt{(a_s+r)^2 + z_s^2}}\, \mathrm{d}z_s\, \mathrm{d}a_s, \tag{1}$$

where $k^2 = 4a_s r[(a_s+r)^2 + z_s^2]^{-1}$. $K$ and $E$ are complete elliptic integrals of the first and second kind. $2R$ and $D$ are the diameter and the thickness of the disk-shaped superconductor. In the case of $r = 0$, the trapped field $B_z(z)$ is derived by Eq. (2):

$$B_z(z) = \frac{\mu_0 J}{2}\left((z+D)\ln\frac{R+\sqrt{R^2+(z+D)^2}}{z+D} - z\ln\frac{R+\sqrt{R^2+z^2}}{z}\right). \tag{2}$$

In this study, $J$ was treated as a fitting parameter for the experimental results. The results derived by Eq. (2) are shown by the lines in Fig. 1. This figure indicates a good agreement between the experimental results and Eq. (2). Therefore, Eq. (2) is helpful for estimating the trapped field distribution when designing the magnetic field created by using bulk superconductors as the magnets.

### 3.2. Temperature and time dependence of the trapped field

Fig. 3 shows the temperature dependence of the trapped field for the 45-mm∅ Gd–Ba–Cu–O superconductor. Each value was measured on the surface 30 min after reaching an external field of zero. At 77, 70 and 63 K, the peak trapped fields increased linearly with decreasing temperature, and the slope was 0.19 T/K, which is larger than that of Y–Ba–Cu–O; 0.12 T/K reported in a previous paper [6]. The ratio of the peak trapped field between 63 and 77 K; $B_p(63\ \mathrm{K})/B_p(77\ \mathrm{K})$ for the Gd–Ba–Cu–O and Y–Ba–Cu–O bulk superconductors were both 2.5.

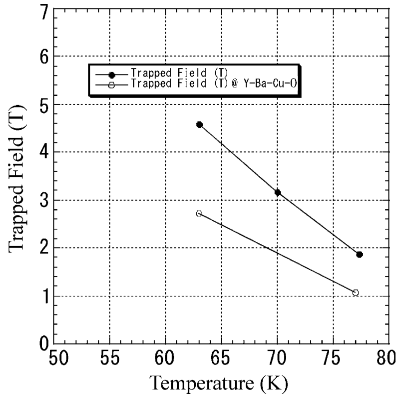


Fig. 3. The temperature dependence of the trapped field for the 45-mm∅ Gd–Ba–Cu–O superconductor.

Fig. 4 shows the time dependence of the trapped field (the flux creep) for the 45-mm∅ Gd–Ba–Cu–O superconductor. Each value was measured on the surface 0 min from when the external field reached zero. Table 1 shows the average of flux creep rate $R$ determined at three different temperatures. $R$ was calculated from the time dependence of flux densities using the following formula:

$$B(t) = B(t_0)(1 - R\ln(t/t_0)). \tag{3}$$

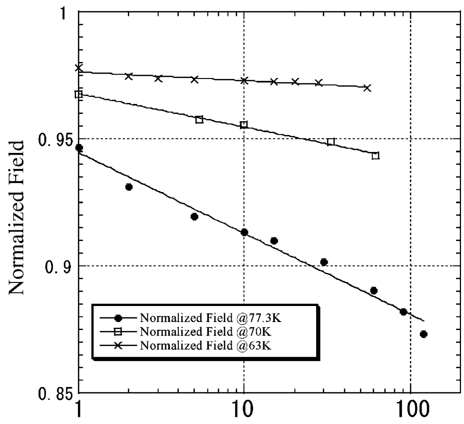


Fig. 4. The time dependence of the trapped field (the flux creep) for the 45-mm∅ Gd–Ba–Cu–O superconductor.

The flux creep rate $R$ decreases rapidly with decreasing temperature. The ratio of $R$ between 63 and 77 K; $R(63\ \mathrm{K})/R(77\ \mathrm{K})$ is 0.11. Thus, the trapped field is more stable at a lower temperature, indicating that cooling down to about 60 K creates superior conditions for the bulk magnet in respect of the increasing trapped field and its stability.

## 4. Conclusion

In order to obtain helpful guidelines for designing high-$T_c$ bulk superconductor magnet systems, the gap, temperature and time dependence of the trapped field for Y–Ba–Cu–O and Gd–Ba–Cu–O/Ag bulk superconductors were measured. For the gap dependence, we compared the experimental results and the analytical solution on the condition that $J_c$ is constant for the disk-shaped bulk superconductor, and we found that the analytical solution corresponds well with the experimental results. The peak value of the trapped field reached 4.6 T at 63 K for the Gd–Ba–Cu–O bulk superconductor, and the flux creep rate at 63 K was slower than that at 70 and 77 K. This indicates that cooling down to at least 63 K creates superior conditions for the bulk magnet in respect of the increasing trapped field and its stability.

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