

# Trapped magnetic field between double stacked $\text{MgB}_2$ bulks magnetized by pulsed field

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**Abstract.** Pulsed field magnetization (PFM) was performed at  $T_s=14$  K for the double stacked  $\text{MgB}_2$  bulks (bulk pair) 55 mm diameter fabricated by a reactive liquid Mg infiltration (Mg-RLI) method, compared with that for the single bulk. The trapped field of  $B_z=0.80$  T was achieved between two bulks and  $B_z$  at the bulk surface was enhanced from 0.42 T to 0.50 T by stacking of the bulks. The trapped field characteristics of the bulk pair can be qualitatively explained by the model analyses.

## 1. Introduction

$\text{MgB}_2$  bulk magnet has attractive natures such as low cost, light-weight, and weak-link-free homogeneous current flow, which are clear contrast with  $\text{REBaCuO}$  ( $\text{RE}=\text{rare earth element}$ ) superconducting bulk magnets. To magnetize the superconducting bulks, a pulsed field magnetization (PFM) is an inexpensive and mobile experimental setup with no need of a superconducting magnet, as a substitute for field-cooled magnetization (FCM). We have investigated the PFM procedure for the  $\text{REBaCuO}$  bulks to enhance the trapped field [1-3]. Considering the obtained experimental results, we proposed a new PFM technique, in which multi-pulses are applied under different temperatures, and realized over 5 T on a  $\text{GdBaCuO}$  bulk, which is a record-high value by PFM to date [3]. For  $\text{MgB}_2$  bulks, the results of the trapped field by FCM have been mainly reported. The higher trapped field was reported to be 2.25 T at 15 K on the single  $\text{MgB}_2$  bulk [4] and 3.14 T at 17.4 K in the double stacked  $\text{MgB}_2$  bulks [5]. We have performed the PFM procedure for the single  $\text{MgB}_2$  bulk fabricated by a reactive liquid Mg infiltration (Mg-RLI) [6] and by a capsule method [7] with 20-50 mm in diameter at 16-30 K, where the trapped field of 0.47 T at 23 K and 0.71 T at 16 K were realized, respectively. To analyze the flux dynamics during PFM, we performed a numerical simulation of PFM for the  $\text{MgB}_2$  bulk [8], which reproduced qualitatively the experimental results. The enhancement of the bulk thickness can achieve the higher trapped field because of the elimination of the demagnetization factor.

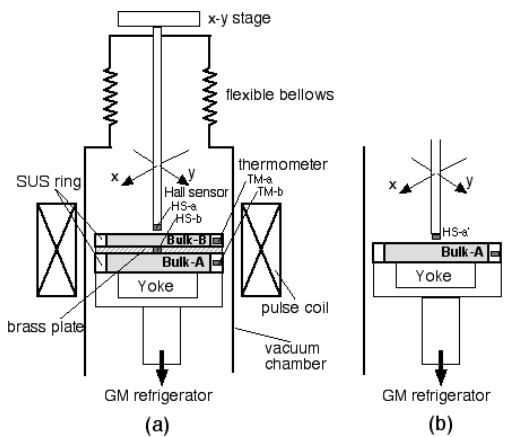
In this study, we investigated the trapped field characteristics by PFM for large  $\text{MgB}_2$  of single bulk and double stacked bulks (bulk pair) fabricated by Mg-RLI method. The magnetic flux intrusion and flux trap during PFM are discussed using a numerical simulation.

## 2. Experimental Procedure

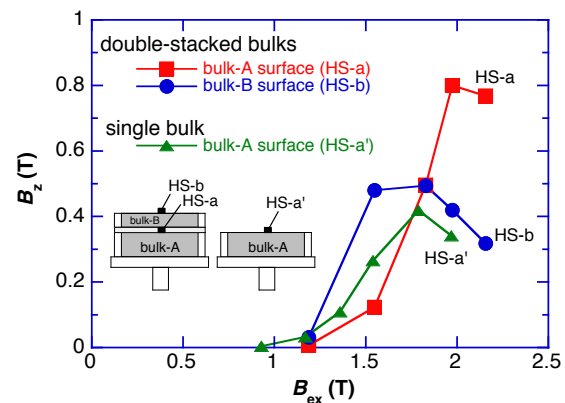
The thick  $\text{MgB}_2$  bulk disk of 55 mm in diameter, which was fabricated by the Mg-RLI technique [9], was sliced and two bulk plates (A and B) were prepared. The thickness of bulk-A and bulk-B was 15.3



and 10.3 mm, respectively. The superconducting transition temperature  $T_c$  and the trapped field  $B_z$  of the bulk-B magnetized by FCM at 20 K were, respectively, confirmed to be 38 K and 2.0 T. Each bulk was mounted in stainless steel (SUS) ring of 8 mm thickness filled with a stycast 2850GT resin. Figure 1 shows the experimental setups for PFM around the bulk. For the bulk pair as shown in figure 1(a), the bulk-A was set on a soft iron yoke cylinder and tightly anchored onto the cold stage of a Gifford–McMahon cycle helium refrigerator. The bulk-B was also mounted on the bulk-A with the insertion of the brass plate 2 mm in thickness. The initial temperature  $T_{SA}$  of the bulk-A was set to 14 K. A magnetizing solenoid copper coil (94 mm i.d., 153 mm o.d., and 50 mm height), which was dipped in liquid nitrogen, was placed outside the vacuum chamber. A magnetic pulse  $B_{ex}(t)$  with a rise time of 0.012 s and a duration time of 0.15 s was applied to the bulk by flowing the pulsed current. The time evolutions of the local fields  $B_L^C(t)$  and the subsequent trapped fields  $B_z$  between two bulks and at the center of the surface were, respectively, monitored by Hall sensors of HS-a and HS-b (F W Bell, BHT 921 and BHA 921). Two-dimensional trapped field profiles of  $B_z(1\text{ mm})$  were mapped at a distance of  $z=1\text{ mm}$  above the bulk surface. During PFM, the time dependence of temperature  $T(t)$  of each bulk was measured at each SUS ring using Cernox<sup>TM</sup> thermometers of TM-a and TM-b. The similar experiments were performed for the single bulk-A as shown in figure 1(b).



**Figure 1.** Experimental PFM setups for (a) the bulk pair and (b) the single bulk-A.



**Figure 2.** Trapped field  $B_z$  for the bulk pair (HS-a and HS-b) and the single bulk (HS-a'), as a function of the applied pulsed field  $B_{ex}$ .

### 3. Results and discussion

#### 3.1. Experimental results

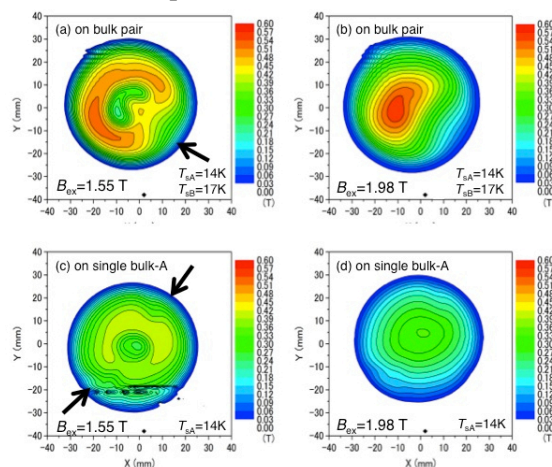
Figure 2 shows the trapped field  $B_z$  for the bulk pair and the single bulk-A, as a function of the applied pulsed field  $B_{ex}$ . For the bulk pair,  $B_z$  at the surface (HS-b) increases, takes a maximum of 0.50 T at  $B_{ex}=1.79\text{ T}$  and then decreases with increasing  $B_{ex}$ .  $B_z$  in the bulk pair (HS-a) also increases with increasing  $B_{ex}$  and takes a maximum of 0.80 T at  $B_{ex}=1.98\text{ T}$ , which is the highest  $B_z$  value by PFM to date. The  $B_z$  vs  $B_{ex}$  curve in the bulk pair shifts the higher  $B_{ex}$  side, compared with that for the surface because the demagnetization factor between the bulks was eliminated and the shielding behavior of the stack is more effective. For the single bulk-A, the maximum  $B_z$  was 0.42 T. The maximum of total trapped flux  $\Phi$  for the bulk pair and single bulk-A was, respectively, 0.88 mWb for  $B_{ex}=1.55\text{ T}$  and 0.69 mWb for  $B_{ex}=1.36\text{ T}$ , which were obtained at  $B_{ex}$  lower than that, at which  $B_z$  took a maximum.

Figure 3 presents the trapped field profiles on the  $\text{MgB}_2$  bulks for  $B_{ex}=1.55$  and 1.98 T. The profiles for the bulk pair are shown in figures 3(a) and 3(b). For  $B_{ex}=1.55\text{ T}$ , the trapped field profile is concave because of the lower applied field than the optimum one, where the right lower position indicated by the arrow is difficult to trap the magnetic flux, which may reflect the inhomogeneity of critical current density  $J_c$  in the bulk-B. On the other hand, for  $B_{ex}=1.98\text{ T}$  as shown in figure 3(b), the

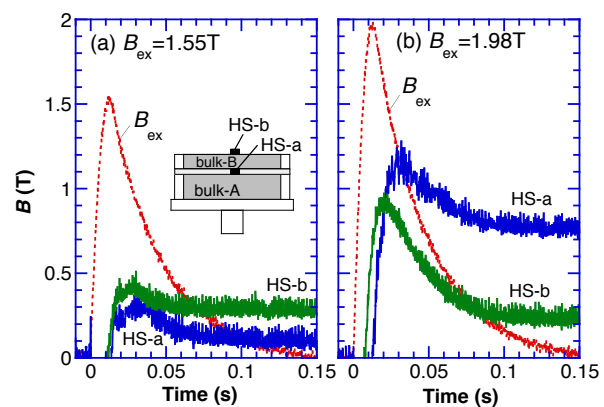
magnetic flux was intruded into the central region of the bulk and the trapped field profiles are nearly the conical one. The profiles on the bulk pair may be influenced by the  $J_c$  distribution in the bulk-A. The profiles for the single bulk-A are shown in figures 3(c) and 3(d). For  $B_{ex}=1.55$  T as shown in figure 3(c), the magnetic flux was intruded into the central region of the bulk with a small inflection around the arrows. The conical  $B_z$  profile can be obtained  $B_{ex}=1.79$  T and, for  $B_{ex}=1.98$  T, the conical profile maintains with the decrease in the maximum value, as shown in figure 3(d). The trapped field profiles of the bulk pair are not necessarily the same as that for each bulk. The complicated flux intrusion and trap can be considered for the stacking, even though  $J_c$  distribution seem to be identical.

Figure 4 shows the time evolution of the applied field  $B_{ex}(t)$  and local fields  $B_L^C(t)$  at the center of the bulk surface for  $B_{ex}=1.55$  and 1.98 T. For each  $B_{ex}$ ,  $B_L^C(t)$  at the bulk surface (HS-b) first starts to increase and takes a maximum, and then decreases to a final value due to the flux flow.  $B_L^C(t)$  in the bulk pair (HS-a) shows the similar time dependence with a time delay because of the strong shielding current in the bulk center. For lower  $B_{ex}=1.55$  T, the final  $B_z$  at HS-a is smaller than that at HS-b. On the other hand, for higher  $B_{ex}=1.98$  T, the magnitude relation of the final  $B_z$  was reversed.

Figure 5 shows the time dependences of the temperatures  $T(t)$  of the bulk pair at TM-a and TM-b for  $B_{ex}=1.98$  T. The temperatures increase abruptly just after the pulse application, and then quickly decrease with increasing time, which are clear contrast with those for the REBaCuO bulk [1]. The sharp temperature changes result from the low specific heat and high thermal conductivity of the MgB<sub>2</sub> bulk. It should be noted that the early temperature profiles are quite different;  $T(t)$  at TM-b shows the spike-like behavior, but  $T(t)$  at TM-a changes moderately. The difference may come from that of the thermal environment for each bulk. Furthermore, the initial temperature of the bulk-B at TM-b was 17 K, which was 3 K higher than that of the lower bulk-A at TM-a. The result suggests that the thermal contact of the bulk-B is not sufficient to the bulk-A and/or the thermal radiation induces from the surface of the bulk-B. The temperature gradient may exist along the thickness direction in the conduction-cooled bulk, even in the single bulk. In the inset, the applied field dependence of the maximum temperature  $T_{max}$  was also shown.  $T_{max}$  monotonically increases with increasing  $B_{ex}$ .



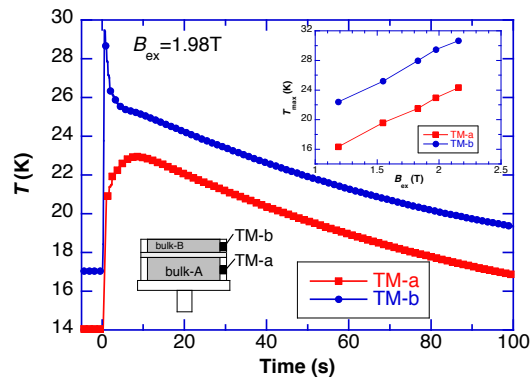
**Figure 3.** Trapped field profiles on the bulk pair ((a) and (b)) and the single bulk-A ((c) and (d)) for  $B_{ex}=1.55$  and 1.98 T.



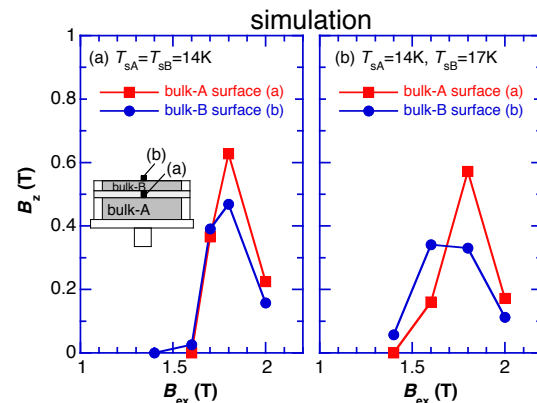
**Figure 4.** Time evolution of the applied field  $B_{ex}(t)$  and local fields  $B_L^C(t)$  at the centre of the bulk surface for  $B_{ex}=1.55$  and 1.98 T.

### 3.2. Results of numerical simulation and discussion

In order to understand the experimental results of the PFM for the bulk pair, we performed the numerical simulation. Physical phenomena during PFM were described using electromagnetic and thermal fields. The power- $n$  model ( $n=50$ ) was supposed to describe the nonlinear  $E$ - $J$  characteristic in the bulk. The temperature and magnetic field dependence of the critical current density  $J_c(T, B)$  was defined. The details of the simulation are described elsewhere [2, 8].



**Figure 5.** Time dependence of the temperatures of the bulk pair at TM-a and TM-b after applying the magnetic pulse of  $B_{\text{ex}}=1.98$  T.



**Figure 6.** Results of the simulation of the trapped field  $B_z$  of the bulk pair at (a)  $T_{\text{SA}}=T_{\text{SB}}=14$  K and (b)  $T_{\text{SA}}=14$  K,  $T_{\text{SB}}=17$  K.

Figure 6(a) shows the results of the simulation of the trapped field  $B_z$  of the bulk pair at  $T_{\text{SA}}=T_{\text{SB}}=14$  K, as a function of  $B_{\text{ex}}$ .  $B_z$  in the bulk pair (HS-a) and on the bulk surface (HS-b) show the similar  $B_{\text{ex}}$  dependences; both of  $B_z$  take a maximum at  $B_{\text{ex}}=1.8$  T and then decrease with increasing  $B_{\text{ex}}$ .  $B_z$  at the position (b) is very slightly higher than that at the position (a) for  $B_{\text{ex}}$  lower than 1.7 T. These results reproduce the experimental ones qualitatively (see Fig. 2). Figure 6(b) shows the similar results of the simulation of the trapped field  $B_z$  at  $T_{\text{SA}}=14$  K and  $T_{\text{SB}}=17$  K, which are the similar condition to the experimental results as shown in figure 5. Both absolute  $B_z$  values at the positions of (a) and (b) decreased, compared with those in figure 6(a) and the  $B_z$  vs  $B_{\text{ex}}$  profile at the position (b) shifts lower  $B_{\text{ex}}$  side. The  $J_c$  value in the bulk-B decreases and the magnetic flux is easy to penetrate in the bulk-B. As a result, the magnetic flux is easy to penetrate also into the bulk-A. The temperature rise increases and the trapped field of both bulks decreases. The relation shown in figure 6(b) is more qualitatively similar than that in figure 6(a) to that obtained by the experimental results in figure 2.

In summary, pulsed field magnetization was performed at  $T_s=14$  K for the double stacked  $\text{MgB}_2$  bulks fabricated by a reactive liquid Mg infiltration (Mg-RLI) method. The trapped field of  $B_z=0.80$  T was achieved between two bulks and  $B_z$  at the bulk surface was enhanced from 0.42 T to 0.50 T by stacking of the bulks. The trapped field characteristics such as the  $B_z$  vs  $B_{\text{ex}}$  relations at the bulk surface and in the bulk pair can be qualitatively explained by the model analyses.

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