

# Trapped Field Enhancement of a Thin, High- $J_c$ MgB<sub>2</sub> Bulk Without Flux Jumps Using Pulsed Field Magnetization With a Split-Type Coil With a Soft Iron Yoke

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**Abstract**—We have investigated the suppression of flux jumps and the enhancement of trapped field on a thin, high- $J_c$  MgB<sub>2</sub> bulk (30 mm in diameter and 7 mm in thickness) for the pulsed field magnetization (PFM) using a split-type coil with a soft iron yoke, and compared the results to those magnetized using the split-type coil without a yoke and a solenoid-type coil with a yoke. A maximum-trapped field,  $B_z$ , of 0.71 T at 14 K was achieved on the bulk surface without flux jumps by using the split coil with yoke. On the other hand, low  $B_z$  values with flux jumps were observed for the cases using the split-type coil without a soft iron yoke, and the solenoid-type coil with a yoke. These results reproduce previous ones for a thick, high- $J_c$  MgB<sub>2</sub> bulk (22 mm in diameter and 15 mm in thickness), for which the trapped field was enhanced to a record high value of  $B_z = 1.10$  T at 13 K by PFM using the split-type coil with a yoke.

**Index Terms**—MgB<sub>2</sub> bulk, pulsed field magnetization, split coil, flux jump, soft iron yoke.

## I. INTRODUCTION

MgB<sub>2</sub> superconducting polycrystalline bulks as trapped field magnets (TFMs) have been intensively investigated due to their merits of being rare-earth-free, light-weight, presenting a symmetric trapped field distribution and their long coherence length [1], [2], which are in clear contrast with RE-BaCuO bulk magnets (RE: rare earth elements and Y) [3]. MgB<sub>2</sub> polycrystalline bulks with high critical current density,  $J_c$ , have been fabricated by various methods and activated by field-cooled magnetization (FCM) [4]–[6]. A record-high trapped field of

$B_z = 5.4$  T has been attained at 12 K on a single MgB<sub>2</sub> bulk disk 20 mm in diameter [7].

To magnetize superconducting bulks, pulsed-field magnetization (PFM) has been also investigated intensively, usually using a solenoid-type copper coil. However, the trapped field,  $B_z$ , by PFM for REBaCuO bulks is generally lower than that by FCM because of a large temperature rise caused by the dynamic motion of the magnetic flux [8]. Multi-pulse techniques are effective to enhance  $B_z$  due to the reduction of this temperature rise [9]–[11]. The PFM technique was also applied to MgB<sub>2</sub> bulks using a solenoid coil [12], [13].  $B_z$  (PFM) = 0.81 T at 14 K had been the highest value in a high- $J_c$  MgB<sub>2</sub> bulk pair [14], in which flux jumps took place frequently during PFM due to a small specific heat, a large thermal conductivity, and a narrow temperature margin between the operating temperature,  $T_s$ , and the superconducting transition temperature,  $T_c = 39$  K. The use of a split-type coil was effective to enhance the  $B_z$  value for the REBaCuO bulks during PFM both experimentally and numerically [15]–[17]. We have also analyzed the electromagnetic and thermal instability of a high- $J_c$  MgB<sub>2</sub> bulk using conventional parameters, such as the critical thickness,  $d_c$ , and the minimum propagation zone (MPZ) length,  $l_m$  [18]. Recently, we have achieved a trapped field of  $B_z = 1.1$  T on a thick, high- $J_c$  MgB<sub>2</sub> bulk at 13 K without flux jumps using a split-type coil with a soft iron yoke, which is a record high trapped field by PFM for bulk MgB<sub>2</sub> to date [19].

In this study, to confirm the superiority of the use of split coil with soft iron yoke for other high- $J_c$  MgB<sub>2</sub> bulks of different geometries, a thin, disk-shaped MgB<sub>2</sub> bulk was magnetized, and we confirmed an enhancement of  $B_z$  in addition to the avoidance of the flux jumps.

## II. EXPERIMENTAL PROCEDURE

A Ti-doped MgB<sub>2</sub> superconducting disk was fabricated by a HIP method [6]. The diameter and thickness are 30 mm and 7 mm, respectively, and the relative mass density was as high as 93% of the ideal value. The detailed experimental setup of PFM using the split- and solenoid-coils is shown in the insets of Figs. 1(a) and 1(b) and in ref. [19]. For the split-type coil, the MgB<sub>2</sub> disk was fastened in a copper sample holder around the bulk periphery and was connected to the cold stage of a

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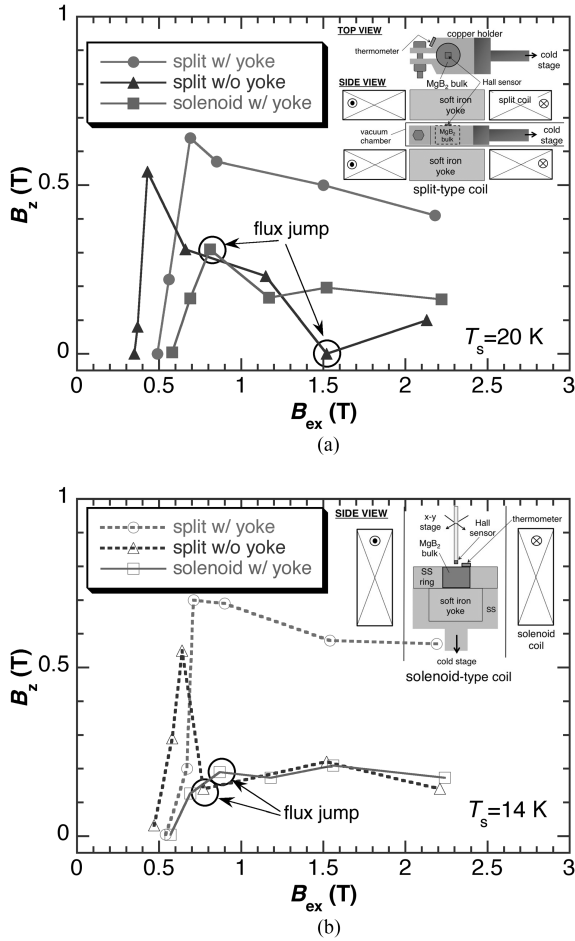


Fig. 1. Applied pulsed field,  $B_{ex}$ , dependence of the trapped field,  $B_z$ , for each case at (a)  $T_s = 20$  K and (b) 14 K using the “split coil with yoke,” “split coil without yoke,” and “solenoid coil with yoke.”

Gifford–McMahon (GM) cycle, helium refrigerator in the vacuum chamber. A Hall sensor (BHT 921; F W Bell) was adhered to the center of the bulk surface, and a Cernox<sup>TM</sup> thermometer was connected to the sample holder. The split-type coil (72 mm inner diameter (I.D.), 124 mm outer diameter (O.D.), 35 mm height, wire cross-section of  $1.3 \times 3.0 \text{ mm}^2$  and 117 turns for each coil), which was submerged in liquid nitrogen, was placed outside the vacuum chamber, in which a pair of soft iron yokes (60 mm in diameter and 65 mm in height) was inserted in the central bores of the coil. This coil setup is named “split coil with yoke (split w/ yoke)”. For comparison, the bulk was magnetized using the split coil without the soft iron yokes, which is named “split coil without yoke (split w/o yoke)”. The initial temperature,  $T_s$ , of the bulk was set to 20 and 14 K, and magnetic pulses,  $B_{ex}(t)$ , with a peak up to 2.15 T, a rise time of 18 ms and a duration of 180 ms were applied via a pulsed current in the coil. During PFM, the time evolution of the temperature,  $T(t)$ , the central field,  $B_z(t)$ , and the subsequent trapped field,  $B_z$ , which was defined as the final value of  $B_z(t)$  at 60 s, were measured at the center of the bulk surface. After the removal of the split coil 15 minutes after the pulse application, two-dimensional trapped field profiles of  $B_z$  were mapped at 2 mm above the bulk surface (on the outer surface of the vacuum chamber) by scanning a Hall sensor (BHA 921; F W Bell) using an  $x$ - $y$  stage controller.

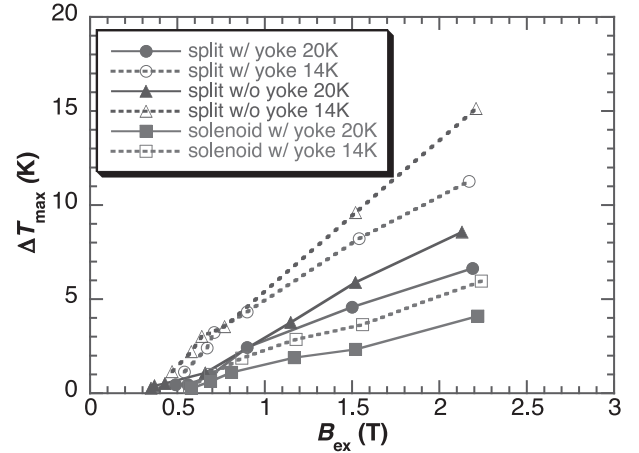


Fig. 2. The maximum temperature rise,  $\Delta T_{max}$ , as a function of applied field,  $B_{ex}$ , for the “split coil with yoke,” “split coil without yoke,” and “solenoid coil with yoke.”

In the case of using the solenoid coil, the same  $\text{MgB}_2$  disk was mounted in a stainless steel (SS) ring using epoxy resin (Stycast 2850<sup>TM</sup>) and was tightly anchored onto the SS holder with a soft iron yoke (40 mm diameter and 20 mm height). This was then connected to the cold stage of a refrigerator using indium foil [6], [11]. The soft iron yoke is fixed to the magnetizing fixture, so cannot be removed after the PFM is carried out. This coil setup is named “solenoid coil with yoke (solenoid w/ yoke)”. The solenoid copper coil (99 mm I.D., 121 mm O.D., 50 mm H, wire cross-section of  $1.3 \times 3.0 \text{ mm}^2$  and 112 turns), which was submerged in liquid nitrogen, was placed outside the vacuum chamber. The initial temperature,  $T_s$ , of the bulk was set to 20 and 14 K. Magnetic pulses,  $B_{ex}$ , up to 2.15 T, with a rise time of 13 ms and duration of 150 ms, were applied via a pulsed current in the coil. The time evolution of the central field,  $B_z(t)$ , and the subsequent trapped field at 60 s,  $B_z$ , at the center of the bulk surface were monitored by a Hall sensor (BHA 921; F W Bell). Two-dimensional trapped field profiles of  $B_z$  were mapped in a vacuum chamber 15 minutes after the pulse application, stepwise with a pitch of 1 mm, by scanning the same Hall sensor using an  $x$ - $y$  stage controller. The time evolution of the temperature,  $T(t)$ , was also measured separately using a thermometer adhered to the bulk surface.

### III. RESULTS AND DISCUSSION

Fig. 1 presents the trapped field,  $B_z$ , on the  $\text{MgB}_2$  disk by PFM at  $T_s = 20$  K and 14 K for the three magnetizing coil cases, as a function of the applied pulsed field,  $B_{ex}$ . For all the used coils,  $B_z$  increases, takes a maximum and then decreases with increasing  $B_{ex}$ . At each temperature, the maximum  $B_z$  can be achieved for the case of “split coil with yoke”;  $B_z = 0.71$  T at 14 K and  $B_z = 0.64$  T at 20 K was achieved on the bulk surface without flux jumps. On the other hand, flux jumps took place for the case using the “split coil without yoke” at higher  $B_{ex}$  values than that which achieved the maximum  $B_z$ , and for the case using the “solenoid coil with yoke” around  $B_{ex}$  that achieved the maximum  $B_z$ .

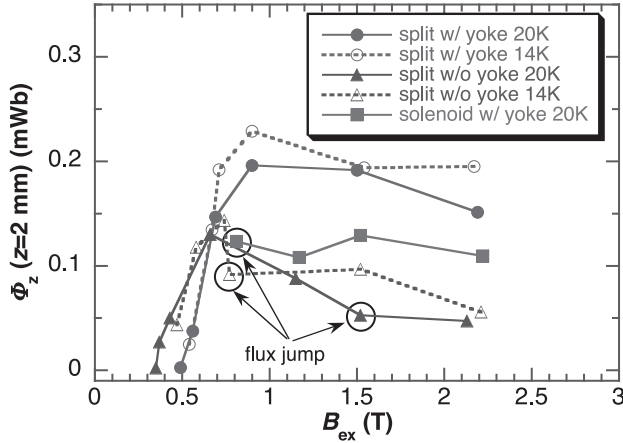


Fig. 3. The total trapped flux,  $\Phi_z(z = 2 \text{ mm})$ , estimated 2 mm above the bulk surface, as a function of applied field,  $B_{\text{ex}}$ , for the “split coil with yoke,” “split coil without yoke,” and “solenoid coil with yoke.”

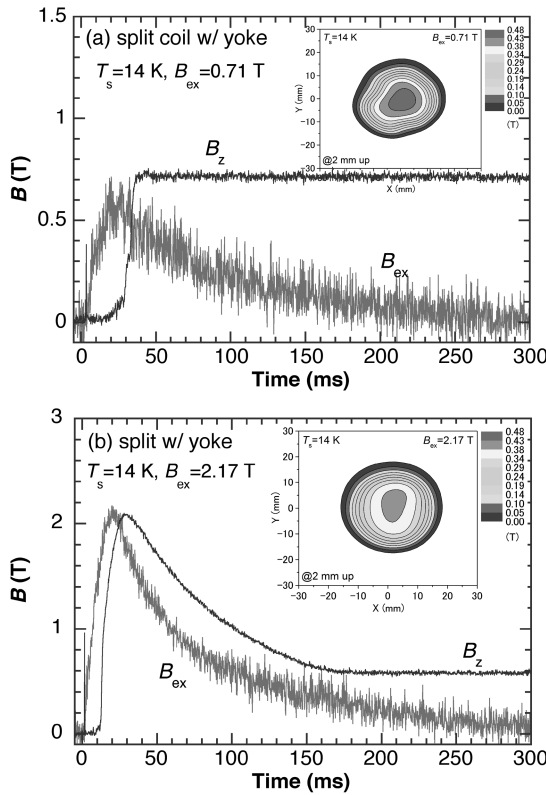


Fig. 4. Time dependence of the local field,  $B_z(t)$ , at the center of the bulk surface and the applied field,  $B_{\text{ex}}(t)$ , using the “split coil with yoke” at  $T_s = 14 \text{ K}$  for (a)  $B_{\text{ex}} = 0.71 \text{ T}$  and (b)  $B_{\text{ex}} = 2.17 \text{ T}$ . The insets show the trapped field profiles 2 mm above the bulk surface.

Fig. 2 shows the applied pulse field dependence of the maximum temperature rise,  $\Delta T_{\text{max}}$ , using each magnetizing coil at 20 K and 14 K.  $\Delta T_{\text{max}}$  increases with increasing  $B_{\text{ex}}$  at each temperature due to the increase in the viscous loss,  $Q_v$ , of the vortex motion, and  $\Delta T_{\text{max}}$  at 14 K is larger and that at 20 K due to the small specific heat and the large pinning loss,  $Q_p$ .  $\Delta T_{\text{max}}$  is smallest for the “solenoid coil with yoke,” the “split coil with yoke” and the “split coil without yoke,” in this order.

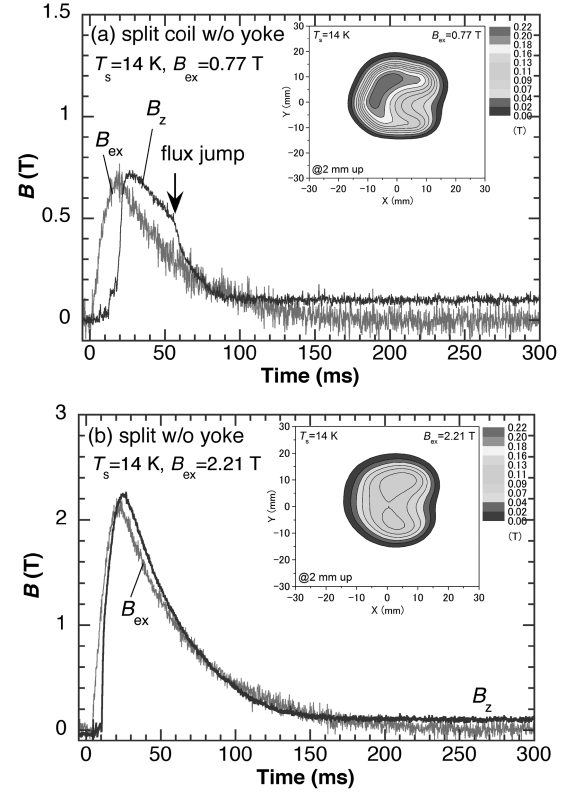


Fig. 5. Time dependence of the local field,  $B_z(t)$ , at the center of the bulk surface and the applied field,  $B_{\text{ex}}(t)$ , using the “split coil without yoke” at  $T_s = 14 \text{ K}$  for (a)  $B_{\text{ex}} = 0.77 \text{ T}$  and (b)  $B_{\text{ex}} = 2.21 \text{ T}$ . The insets show the trapped field profiles 2 mm above the bulk surface.

Fig. 3 shows the total trapped flux,  $\Phi_z(z = 2 \text{ mm})$ , estimated 2 mm above the bulk surface, as a function of  $B_{\text{ex}}$  for each case.  $\Phi_z(z = 2 \text{ mm})$  was calculated by integrating the  $B_z(z = 2 \text{ mm})$  value over the region where it was positive. All the  $\Phi_z - B_{\text{ex}}$  curves take a maximum around the  $B_{\text{ex}}$  value at which  $B_z$  takes a maximum. A large  $\Phi_z$  is necessary for practical applications such as rotating machines.

Fig. 4 shows the time dependence of the local field,  $B_z(t)$ , at the center of the bulk surface and the applied field,  $B_{\text{ex}}(t)$ , using the “split coil with yoke” at  $T_s = 14 \text{ K}$  for  $B_{\text{ex}} = 0.71 \text{ T}$  and  $2.17 \text{ T}$ . The trapped field profiles 2 mm above the bulk surface are shown in each inset. The peak height of  $B_z(t)$  is nearly the same as that of  $B_{\text{ex}}(t)$ , which is a common characteristic for the split coil [19]. However, it should be noticed that the intrusion of the magnetic flux was delayed in the case with the yoke. For  $B_{\text{ex}} = 0.71 \text{ T}$ , the local field,  $B_z(t)$ , takes a maximum and then becomes flat with increasing time and  $B_z = 0.71 \text{ T}$  was achieved. For  $B_{\text{ex}} = 2.17 \text{ T}$ ,  $B_z$  decreases and a flux jump was not observed up to  $B_{\text{ex}} = 2.25 \text{ T}$ . The trapped field profile is close to a conical shape.

On the other hand, for the case using the “split coil without yoke” at 14 K, as shown in Fig. 5(a) and (b), the time delay in  $B_z(t)$  is smaller at the peak, compared to that for the case using the “split coil with yoke” shown in Fig. 4 due to the absence of the soft iron yoke. For  $B_{\text{ex}} = 0.77 \text{ T}$ , a flux jump can be seen at  $t = 60 \text{ ms}$  and the  $B_z$  value reduced. As a result, the trapped



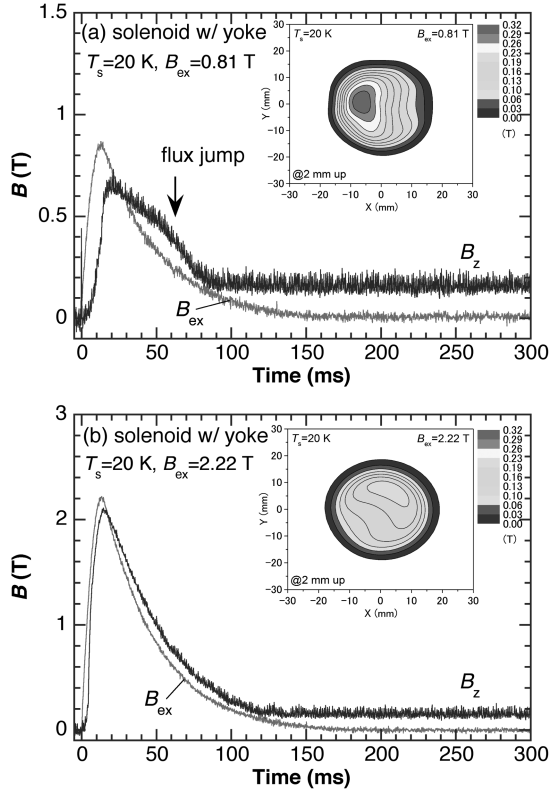


Fig. 6. Time dependence of the local field,  $B_z(t)$ , at the center of the bulk surface and the applied field,  $B_{ex}(t)$ , using the “solenoid coil with yoke” at  $T_s = 20$  K for (a)  $B_{ex} = 0.81$  T and (b)  $B_{ex} = 2.22$  T. The insets show the trapped field profiles 2 mm above the bulk surface.

field profile was inhomogeneous due to the flux escaping the sample. The occurrence of the flux jump using the split coil without yoke is in clear contrast to the previous results for the thick bulk [19], which may come from the difference of the shape of the bulk and/or of the cooling ability.

Fig. 6 shows the time dependence of the local field,  $B_z(t)$ , at the center of the bulk surface and the applied field,  $B_{ex}(t)$ , using the “solenoid coil with yoke” at  $T_s = 20$  K for  $B_{ex} = 0.81$  T and 2.22 T. The peak height of  $B_z(t)$  is smaller than that of  $B_{ex}(t)$  with a very slight time delay around the peak of the magnetic pulse, which is a clear contrast with the case using the split coil. For  $B_{ex} = 0.81$  T, a broad flux jump can be seen at  $t = 70$  ms and the  $B_z$  value reduces and an inhomogeneous trapped field profile was observed. For  $B_{ex} = 2.22$  T, shown in Fig. 6(b), a decrease of  $B_z$  with an inhomogeneous  $B_z$  profile was observed.

#### IV. CONCLUSION

We have performed the pulsed field magnetization (PFM) of a thin, high- $J_c$  MgB<sub>2</sub> disk (30 mm in diameter and 7 mm in thickness) using a split coil with a soft iron yoke, and compared the results to PFM using a split coil without a yoke and a solenoid coil with a yoke. A maximum trapped field,  $B_z$ , of 0.71 T at 14 K was achieved on the disk surface without any flux jumps by using the “split coil with yoke”. On the other hand, low  $B_z$  values with flux jumps were observed for the cases

using the “split coil without yoke” and the “solenoid coil with yoke”. The avoidance of flux jumps was reproduced using the “split coil with yoke,” similarly to previous results for a thick bulk, which is an advantage to magnetize high- $J_c$  MgB<sub>2</sub> bulks. However, the occurrence of the flux jump for the case of the “split coil without yoke” is in contrast with the thick bulk. The cooling conditions, the shape of the MgB<sub>2</sub> bulk and the  $J_c(B, T)$  characteristics also influence the trapped field properties during PFM. In any case, the use of the soft iron yoke with the split coil is likely to enhance the trapped field and avoid flux jumps in such bulks.

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