Trapped Field Enhancement of a Thin, High-J_c MgB_2 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_2 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_2 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_2 bulk, pulsed field magnetization, split coil, flux jump, soft iron yoke.**

I. Introduction

MgB_2 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 REBaCuO bulk magnets (RE: rare earth elements and Y) [3]. MgB_2 polycrystalline bulks with high critical current density, J_c, have been fabricated by various methods and activated by field-cooled magnetization (FCM) [4, 5, 6]. A record-high trapped field of B_z = 5.4 T has been attained at 12 K on a single MgB_2 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, 10, 11]. The PFM technique was also applied to MgB_2 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_2 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, 16, 17]. We have also analyzed the electromagnetic and thermal instability of a high-J_c MgB_2 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_2 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_2 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_2 bulks of different geometries, a thin, disk-shaped MgB_2 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_2 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_2 disk was fastened in a copper sample holder around the bulk periphery and was connected to the cold stage of a 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™ thermometer was connected to the sample holder. The split-type coil (72 mm inner diameter (I.D.), 124 mm outer

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diameter (O.D.), 35 mm height, wire cross-section of 1.3 x 3.0 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.

In the case of using the solenoid coil, the same MgB_2 disk was mounted in a stainless steel (SS) ring using epoxy resin (Stycast 2850™) 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 x 3.0 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

Figure 1 presents the trapped field, B_z, on the 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.

Figure 2 shows the applied pulse field dependence of the maximum temperature rise, ΔT_{max}, using each magnetizing coil at 20 K and 14 K. ΔT_{max} increases with increasing B_{ex} at each temperature due to the increase in the viscous loss, Q_v, of the vortex motion, and ΔT_{max} at 14 K is larger and that at 20 K

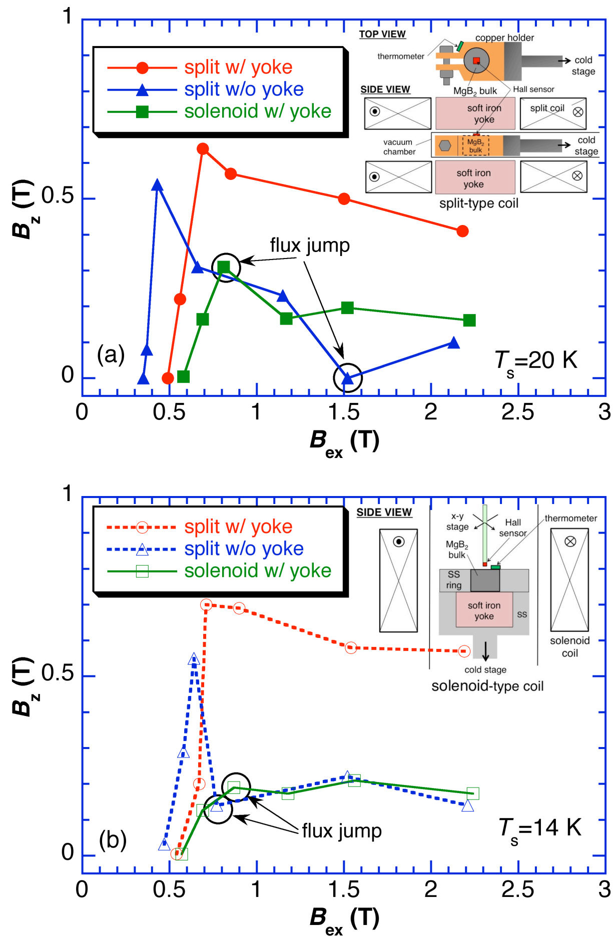

Fig. 1. Applied pulsed field, B_{ex}, dependence of the trapped field, B_z, for each case at (a) $T_s = 20$ K and (b) 14 K using the "split coil with yoke", "split coil without yoke" and "solenoid coil with yoke".

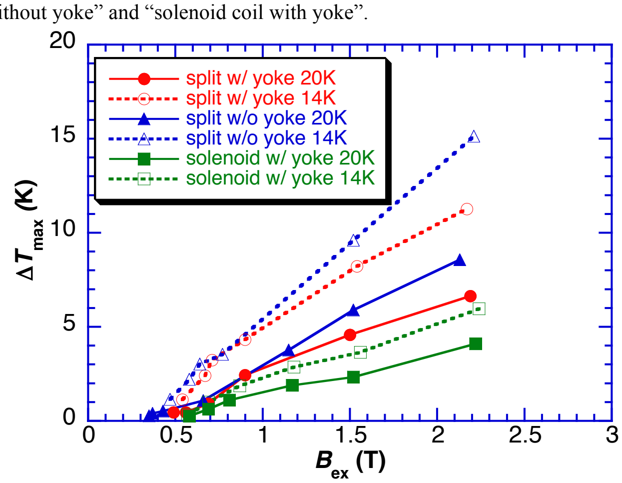

Fig. 2. The maximum temperature rise, ΔT_{max}, as a function of applied field, B_{ex}, for the "split coil with yoke", "split coil without yoke" and "solenoid coil with yoke".

due to the small specific heat and the large pinning loss, Q_p. ΔT_{max} is smallest for the "solenoid coil with yoke", the "split coil with yoke" and the "split coil without yoke," in this order.

Figure 3 shows the total trapped flux, $\Phi_z(z=2\text{ mm})$, estimated 2 mm above the bulk surface, as a function of B_{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 Φ_z–B_{ex} curves take a maximum around the B_{ex} value at which B_z takes a maximum. A large Φ_z is necessary for practical applications such as rotating machines.

Figure 4 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 "split coil with yoke" at $T_s = 14$ K for $B_{ex} = 0.71$ T and 2.17 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 $B_{ex}(t)$, 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 $B_{ex} = 0.71$ T, the local field, $B_z(t)$, takes a maximum and then becomes flat with increasing time and $B_z = 0.71$ T was achieved. For $B_{ex} = 2.17$ T, B_z decreases and a flux jump was not observed up to $B_{ex} = 2.25$ 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 figures 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 $B_{ex} = 0.77$ T, a flux jump can be seen at $t = 60$ ms and the B_z value reduced. As a result, the trapped 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.

Figure 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

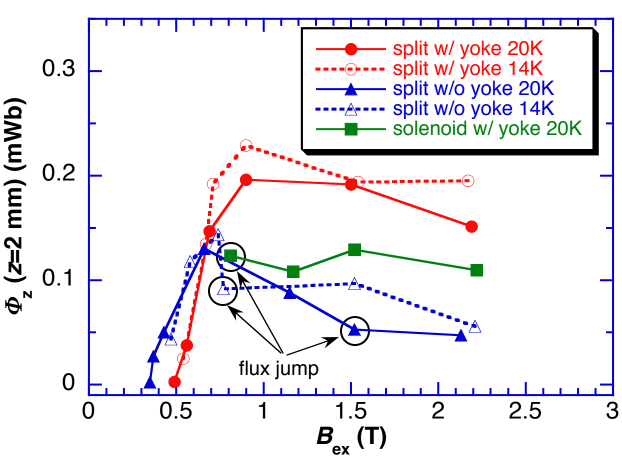

Fig. 3. The total trapped flux, $\Phi_z(z=2\text{ mm})$, estimated 2 mm above the bulk surface, as a function of applied field, B_{ex}, for the "split coil with yoke", "split coil without yoke" and "solenoid coil with yoke".

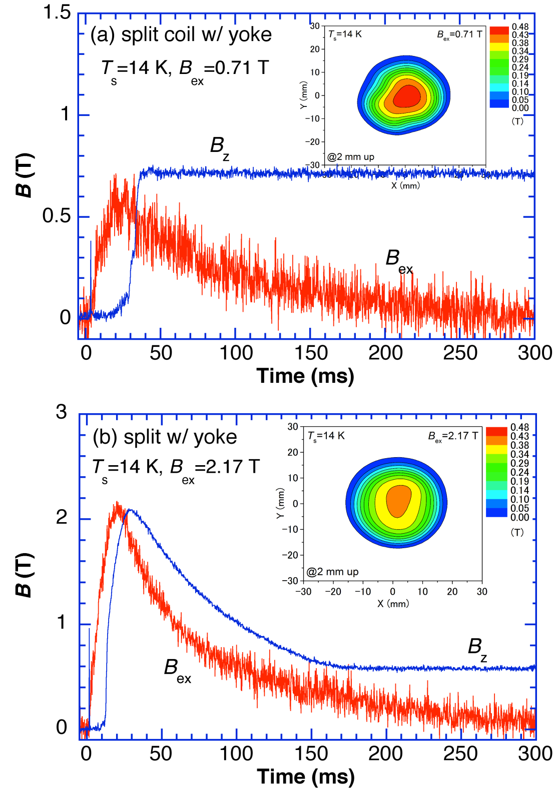

Fig. 4. Time dependence of the local field, $B_z(t)$, at the center of the bulk surface and the applied field, $B_{ex}(t)$, using the "split coil with yoke" at $T_s = 14$ K for (a) $B_{ex} = 0.71$ T and (b) $B_{ex} = 2.17$ T. The insets show the trapped field profiles 2 mm above the bulk surface.

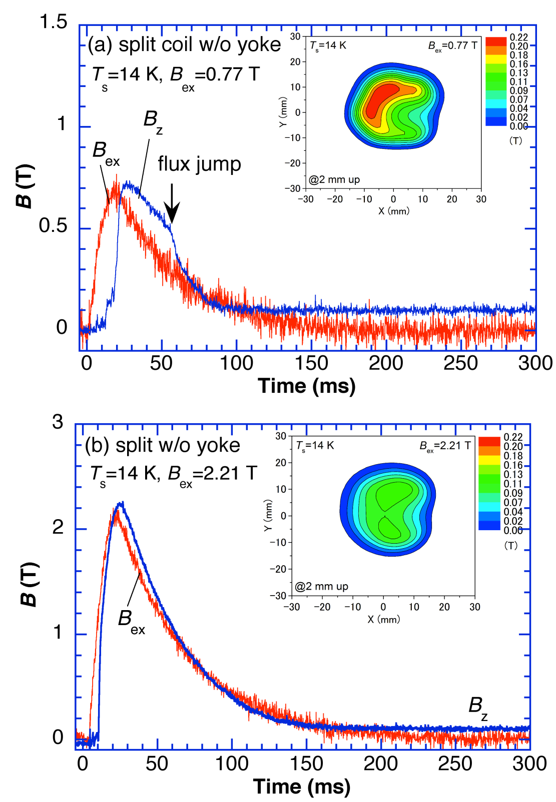

Fig. 5. Time dependence of the local field, $B_z(t)$, at the center of the bulk surface and the applied field, $B_{ex}(t)$, using the "split coil without yoke" at $T_s = 14$ K for (a) $B_{ex} = 0.77$ T and (b) $B_{ex} = 2.21$ T. The insets show the trapped field profiles 2 mm above the bulk surface.

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 figure 6(b), a decrease of B_z with an inhomogeneous B_z profile was observed.

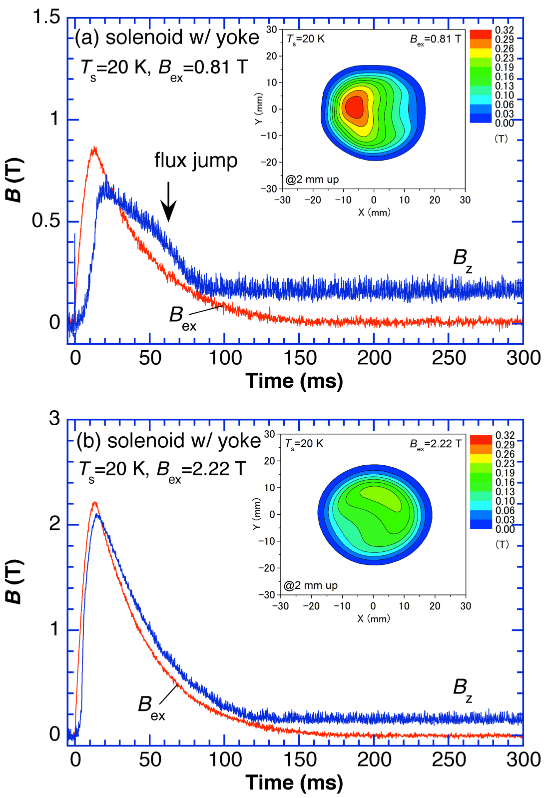

Fig. 6. Time dependence of the local field, $B_z(t)$, at the center of the bulk surface and the applied field, $B_{ex}(t)$, using the "solenoid coil with yoke" at T_s = 20 K for (a) B_{ex} = 0.81 T and (b) B_{ex} = 2.22 T. The insets show the trapped field profiles 2 mm above the bulk surface.

IV. Conclusion

We have performed the pulsed field magnetization (PFM) of a thin, high-J_c MgB_2 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_2 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_2 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.

References

[1] J. Zou, M.D. Ainslie, H. Fujishiro, A.G. Bhagurkar, T. Naito, N. Hari Babu, J-F. Fagnard, P. Vanderbemden and A. Yamamoto, "Numerical modelling and comparison of MgB_2 bulks fabricated by HIP and infiltration growth", *Supercond. Sci. Technol.*, vol. 28, pp. 075009(1)-(9), 2015.

[2] M. Kambara, N. H. Babu, E. S. Sadki, J. R. Cooper, H. Minami, D. A. Cardwell, A. M. Campbell and I. H. Inoue, "High intergranular critical currents in metallic MgB_2 superconductor", *Supercond. Sci. Technol.*, vol. 14, pp. L5-L8, 2001.

[3] M. D. Ainslie, H. Fujishiro, T. Ujiie, J. Zou, A. R. Dennis, Y-H. Shi and D. A. Cardwell, "Modelling and comparison of trapped fields in (RE)BCO bulk superconductors for activation using pulsed field magnetization", *Supercond. Sci. Technol.*, vol. 27, 065008(1)-(9), 2014.

[4] J. H. Durrell, C. E. J. Dancer, A. Dennis, Y. Shi, Z. Xu, A. M. Campbell, N. Hari Babu, R. I. Todd, C. R. M. Grovenor and D. A. Cardwell, "A trapped field of > 3 T in bulk MgB_2 fabricated by uniaxial hot pressing", *Supercond. Sci. Technol.*, vol. 25, pp. 112002(1)-(5), 2012.

[5] A. Yamamoto, A. Ishihara, M. Tomita and K. Kishio, "Permanent magnet with MgB_2 bulk superconductor", *Appl. Phys. Lett.*, vol. 105, pp. 032601(1)-(4), 2014.

[6] T. Naito, T. Yoshida and H. Fujishiro, "Ti-doping effects on magnetic properties of dense MgB_2 bulk superconductors", *Supercond. Sci. Technol.,* vol. 28, pp. 095009(1)-(8), 2015.

[7] G. Fuchs, W. Haber, K. Nenkov, J. Scheiter, O. Perner, A. Handstein, T. Kanai, L. Schultz and B. Holzapfel, "High trapped fields in bulk MgB_2 prepared by hot-pressing of ball-milling precursor powder", *Supercond. Sci. Technol.*, vol. 26, pp. 122002(1)-(5), 2013.

[8] M. D. Ainslie and H. Fujishiro, "Modelling of bulk superconductor magnetization", *Supercond. Sci. Technol.*, vol. 28, 053002(1)-(20), 2015.

[9] Y. Yanagi, Y. Itoh, M. Yoshikawa, T. Oka, H. Hosokawa, H. Ishihara, H. Ikuta and U. Mizutani, "Trapped field distribution on Sm-Ba-Cu-O bulk superconductor by pulsed-field magnetization", *Advances in Superconductivity XII*, Springer, Tokyo, pp. 470-473, 2000.

[10] M. Sander, U. Sutter, R. Koch and M. Klaser, "Pulsed magnetization of HTS bulk parts at T < 77 K", *Supercond. Sci. Technol.*, vol. 13, pp. 841-845, 2000.

[11] H. Fujishiro, T. Tateiwa, A. Fujiwara, T. Oka and H. Hayashi, "Higher trapped field over 5 T on HTSC bulk by modified pulsed field magnetizing", *Physica C*, vol. 445-448, pp. 334-338, 2006.

[12] H. Fujishiro, T. Tamura, T. Arayashiki, M. Oyama, T. Sasaki, T. Naito, G. Giunchi and A.F. Albisetti, "Pulsed Field Magnetization of Large MgB_2 Bulk Fabricated by Reactive Liquid Mg Infiltration", *Jpn. J. Appl. Phys.*, vol. 51, pp. 103005(1)-(5), 2012.

[13] H. Fujishiro, T. Ujiie, T. Naito, A. F. Albisetti and G. Giunchi, "Trapped magnetic field between double stacked MgB_2 bulks magnetized by pulsed field", *J. Phys. Cond. Mat.*, vol. 507, pp. 032016(1)-(4), 2014.

[14] H. Fujishiro, T. Naito, M. Oyama, T. Arayashiki, T. Tamura, T. Sasaki and G. Giunchi, "Numerical Simulation of Trapped Field and Temperature Rise in MgB_2 Bulks Magnetized by Pulsed Field", *IEEE Trans. Appl. Supercond.*, vol. 23, pp. 6800804(1)-(4), 2013.

[15] T. Ida, H. Matsuzaki, Y. Akita, M. Izumi, H. Sugimoto, Y. Hondou, Y. Kimura, N. Sakai, S. Nariki, I. Hirabayashi, M. Miki, M. Murakami and M. Kitano, "Magnetization properties for Gd–Ba–Cu–O bulk superconductors with a couple of pulsed-field vortex-type coils", *Physica C*, vol. 412-414, pp. 638-645, 2004.

[16] M. D. Ainslie, H. Fujishiro, H. Mochizuki, K. Takahashi, Y-H. Shi, D. K. Namburi, J. Zou, D. Zhou, A. R. Dennis and D. A. Cardwell, "Enhanced trapped field performance of bulk high-temperature superconductors using split coil, pulsed field magnetization with an iron yoke", *Supercond. Sci. Technol.*, vol. 29, pp. 074003(1)-(16), 2016.

[17] H. Fujishiro, T. Naito and M. Oyama, "Mechanism of magnetic flux trapping on superconducting bulk magnetized by pulsed field using a vortex-type coil", *Supercond. Sci. Technol.*, vol. 24, pp. 075015(1)-(7), 2016.

[18] H. Fujishiro, H. Mochizuki, T. Naito, M. D. Ainslie and G. Giunchi, "Flux jumps in high-J_c MgB_2 bulks during pulsed field magnetization", *Supercond. Sci. Technol.*, vol. 29, pp. 034006(1)-(7), 2016.

[19] H. Fujishiro, H. Mochizuki, M. D. Ainslie and T. Naito, "Trapped field of 1.1 T without flux jumps in an MgB_2 bulk during pulsed field magnetization using a split coil with a soft iron yoke", *Supercond. Sci. Technol.*, vol. 29, pp. 084001(1)-(10), 2016.