(ASC 2010 preprint 2MP1A-07/29 submitted to IEEE Transactions on Applied Superconductivity and pre-published by ESNF conforming to IEEE Policy on Electronic Dissemination, Section 8.1.9)

Performances of Trapped Magnetic Field in Superconducting Bulk Magnets Activated by Pulsed Field Magnetization

T. Oka[1], H. Seki[1], J. Ogawa[1], S. Fukui[1], T. Sato[1], and K. Yokoyama[2]

***Abstract*—Melt-textured large grain high temperature superconducting materials have a characteristic feature so as to trap the magnetic fields applied from outside, and act as quasi permanent magnets yielding intense magnetic fields which reach the values of several T in the open space above the sample surface. The performances of the magnets have been precisely investigated when intense pulse magnetic fields generated by feeding the currents up to 9.12 kA to the pulse coil settled around a cylindrical bulk magnet. In the experiment a condenser bank with large capacitances of 40-120 mF has been adapted to apply the magnetic fields up to 8.44 T to the Gd-Ba-Cu-O-based bulk magnet with the size of 30 mm in diameter. The performance of the trapped field has reached 3.28 T on the sample surface. The magnetic fields successively invading into the sample in the process called IMRA method have been investigated with respect to the behaviors of the magnetic flux in the sample.**

***Index Terms*—bulk superconductor, magnetic field generator, refrigerator, trapped field magnet,**

I. INTRODUCTION

High temperature superconductors composed of c-axis oriented melt-processed $REBa_2Cu_3O_y$ (RE=Y, Sm, Gd, Dy, Eu; abbreviated as RE123) materials containing RE_2BaCuO_5 (RE211) fine particles act as quasi-permanent magnets when they trap the applied magnetic field from outside [1, 2]. We call the magnets as "bulk magnets" in this paper. The performances of trapped fields of the superconducting bulk magnets have been greatly improved by fabricating large and homogeneous material, which exhibit what we call single domain distributions in the magnetic field mapping [3, 4].

Thanks to the progress in sample fabrication coupled with mechanical reinforcement techniques, very high trapped fields of the bulk superconductors have been achieved [5, 6]. The development of compact refrigerators has also encouraged us to utilize bulk magnets at as low temperatures as 20-40 K, since J_c and trapped fields are known to be significantly enhanced with lowering temperature [7]. The authors have been emphasizing the importance of adopting refrigerators to keep the superconductivity instead of using cryogen such as liquid nitrogen, since the handling of cryogen requires us complicated skills and does not fit the widespread industries [8].

The trapped field abilities thus referred are generally obtained by the field cooling method (hereafter abbreviated as FC). The pulsed field magnetization (PFM) method is known as an easier and compact way than FC, and is also well known that the flux motion in the sample causes the local heat generation, raises the temperature, lowers the critical current density, and subsequently degrades the trapped field ability [9]. To suppress heat generation, many attempts have been made, including the development of the present multi-PFM technique named iteratively magnetizing pulsed field operation with reducing amplitudes (IMRA) [10], locating yoke pieces around a bulk superconductor [11], and repeating pulses with step-wise cooling [12]. In 2005, a smart process called MMPSC as a kind of PFM processes derived the maximum performance of trapped field of 5.2 T, which was conducted by Fujishiro *et al.* [13, 14]. In the way, the heat generation would have been suppressed by means of applying iterative pulsed fields at two temperature ranges in the course of magnetizing processes.

In the former experiments thus reported, the pulsed magnetic flux densities of up to 6 T have been usually given to the samples. Since it is expected that intense applied fields more than 7 T must be required to obtain the trapped fields of exceeding 5 T, the authors intended to prepare a small-sized pulse coil, a small bulk magnet with a size of 30 mm in diameter, and a condenser bank with large capacitances up to 120 mF to generate such intense magnetic fields. In the study, we aim to evaluate the experimental data of the trapped magnetic fields, and their distributions, and resultant temperature rises after every application of pulsed magnetic fields, and discuss on the behaviors of the magnetic flux in the sample and resultant heat generation during and after the PFM operations.

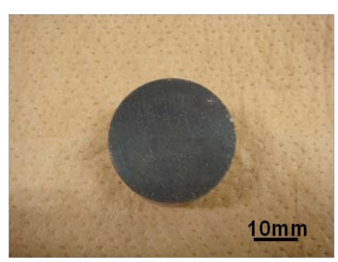


Fig. 1 Gd 123 superconducting bulk magnet with a size of 30 mm in diameter and 10 mm in thickness.

Manuscript received 3 August 2010
T. Oka, H. Yamazaki, H. Seki, J. Ogawa, S. Fukui, and T. Sato are with Niigata University, 8050 Ikarashi-Ninocho, Nishi-ku, Niigata, 950-2181 Japan (corresponding author to provide phone: +81-25-262-7668; fax: +81-25-262-7666; e-mail: okat@eng.niigata-u.ac.jp).
K. Yokoyama is with Ashikaga Institute of Technology, 268-1 Ohmae-cho, Ashikaga, Tochigi, 326-8558, Japan (e-mail: k-yokoyama@ashitech.ac.jp).

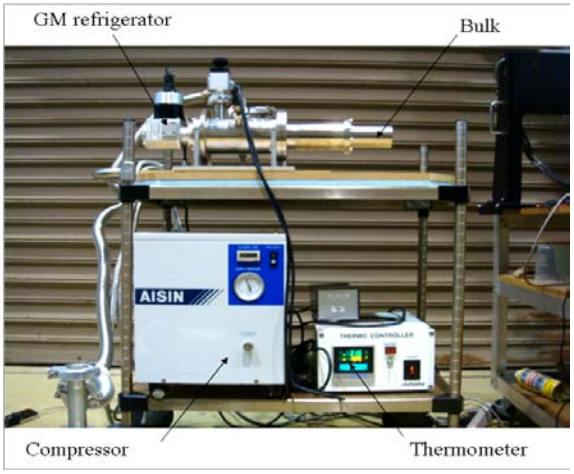


Fig. 2 Strong magnetic field generator equipped with GM refrigerator which cooled to the bulk magnet to 30 K in the vacuum chamber.

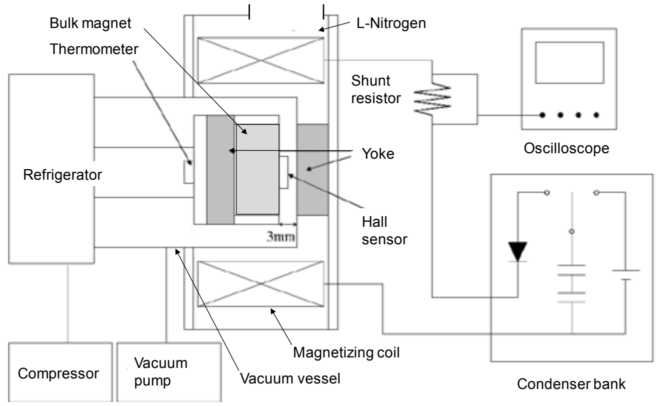


Fig. 3 Schematic illustration of inside structure of bulk magnet system equipped with GM refrigerator and the magnetizing circuit system.

II. EXPERIMENTAL PROCEDURE

A. Experimental equipments

A Gd-Ba-Cu-O bulk magnet (T_c = 90 K) which was manufactured by Nippon Steel Co. was adapted to the experiments, as shown in Fig. 1. The dimensions are 30 mm in diameter and 10 mm in thickness. As the sample size was chosen to be smaller than those of former PFM or FC experiments so as to generate the stronger magnetic fields of more than 7 T [8-10]. The bulk magnet shown in the figure was actually installed to the compact bulk magnet system composed of the GM refrigerator (AISIN SEIKI Co., GR-103), as shown in Fig. 2, and cooled to the nominal temperature of 30 K. An illustrated structure of the total system is shown in Fig. 3, containing the magnetizing electrical circuit composed of a condenser bank, a shunt resister, and a pulse coil which is dipped in the liquid nitrogen vessel to reduce the resistance by cooling it to 77 K [8-10]. It is noted that the iron yokes are couples with the bulk magnet to attract and lead the magnetic flux into the sample during the field application [11]. The coil constant is 0.925 mT/A.

TABLE 1. MAGNITIZAING PROCEDURE BY IMRA METHOD

Sequential pulse No.	Magnetizing voltage (V)	Applied magnetic field B_{ex} (T)
# 1	500	3.98
# 2	550	4.29
# 3	800	6.36
# 4	700	5.58
# 5	650	5.21
# 6	600	4.98
# 7	550	4.35
# 8	500	3.89
# 9	400	3.17
# 10	300	2.24

C = 40 mF

B. Iterative PFM procedures

The PFM processes are conducted after a kind of the IMRA methods. The sequential profiles are referred elsewhere [8-10]. As shown in Table 1, a certain profile composed of successive ten pulses was determined to choose as a typical one. At first, an experiment was planned to be operated sequentially by applying magnetic fields B_{ex} in order with use of a 40 mF condenser bank. The trapped field distributions were estimated ten times after each pulse application by a Hall sensor (F. W. Bell, BHA921) scanning just above the vacuum chamber (z = 0.6 mm) with a 2 mm pitch and an interval of 1 s. The distance between the Hall sensor and the bulk magnet surface was designed to be 3 mm.

C. Iterative PFM with varying capacitances

The second experiment was conducted with varying the capacitances of the condenser bank from 40 mF to 120 mF to estimate the field trapping performances in the region more intense magnetic field than 7 T. Five magnetic pulses B_{ex} (#1 - #5) which correspond to the first half of ten pulses shown in Table 1 were applied in order by feeding the currents up to 9.12 kA. As every capacitance is different in each experimental process, the applied magnetic fields do not coincide with those in the table. The rise times of pulse fields, which are dominated by capacitances, were measured typically to be 5.3 ms and 6.6 ms when the capacitances were adjusted to 40 mF and 80 mF, respectively. The temperatures were measured just on the cold stage behind the bulk sample and iron yoke in the vessel. A Hall sensor (F. W. Bell, BHT921) has measured the magnetic flux densities at the surface centre of the bulk magnet during and after the pulse applications.

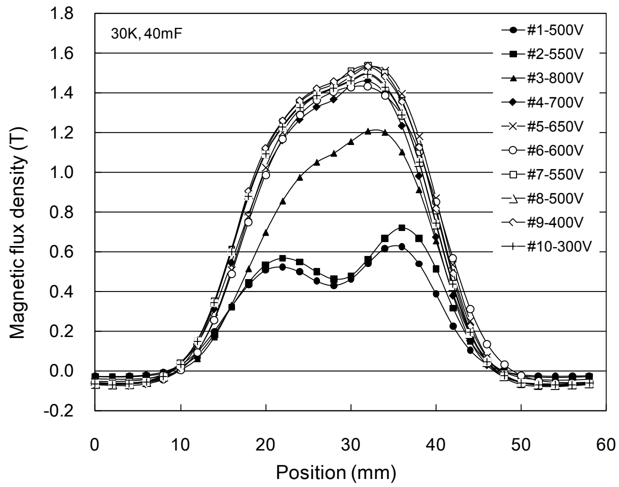


Fig. 4 Distributions of the trapped magnetic flux density magnetized in the process of IMRA method.

III. Results and Discussions

A. Iterative PFM procedures

Figure 4 shows the trapped field distribution maps which were obtained by applying magnetic fields in the range from 2.24 to 6.36 T with use of 40 mF condenser bank. The trapped fields B_z, along the bulk axis and c-axis, were measured in the open space outside the vacuum chamber after each application of ten magnetic pulse fields, following the IMRA profile shown in Table 1. We obviously recognize the difference between M-shape distributions for the #1 and #2 pulse applications and conical shapes for those later than the #3. Although the invasion of magnetic flux is strongly restricted within the periphery region of the sample at the beginning of the process, they jump into the centre portion and magnetize the whole sample after when the third pulse was applied (B_{ex} = 6.36 T). Meanwhile, we do not observe any substantial changes in the distribution maps for the #6 - #10 pulses. This implies that further field applications never cause any changes to the existing fluxoids which dwells in the sample in spite of applying intense fields more than 5 T. As will be discussed below, however, this hypothesis is inconsistent with the results derived from the experiments with use of a condenser bank equipped by the higher capacitances. The maximum trapped fields have reached 1.54 T when the #7 pulse was fed.

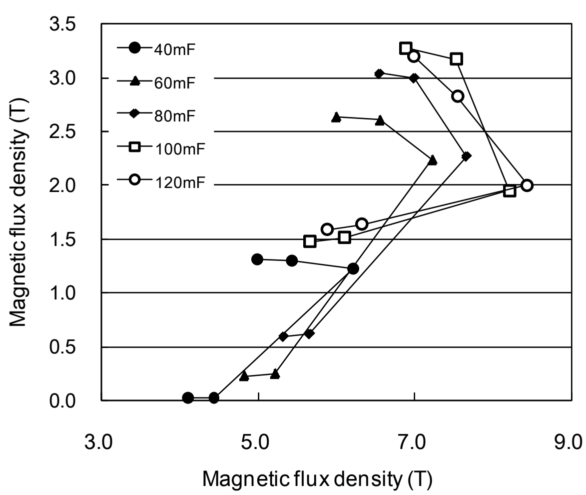
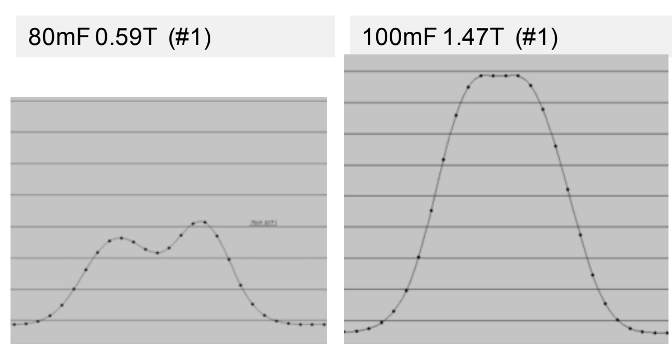


Fig. 5 Evolutions of trapped magnetic flux density on the surface center of the bulk magnet as a function of condenser capacitance when the magnetizing was sequentially operated, 500, 550, 800, 700, and 650V.

B. Iterative PFM with varying capacitances

Further estimations were carried out by applying the pulsed fields of the #1 - #5. The results are shown in Figs. 5 and 6. Figure 5 shows the trapped magnetic fields measured at the centre of the sample surface, which are plotted against the applied fields as a function of the condenser capacitances. The IMRA method was operated in the same manner as the former profile. The first pulse of 500 V which is led from 40 mF condenser bank cannot invade into the sample at all, meanwhile, as for the cases of over 100 mF every first pulse succeeds in arriving at very centre of the sample. Figure 6 shows the differences in the first pulse motions between 80 mF and 100 mF, respectively. The resultant trapped field by 100 mF is more than 2 times larger than that by 80 mF. Although the first pulse is repelled showing “M-shape” in the region less than 5 T, as noted in former section and as reported in ref [14], while the invading fluxoids are allowed to arrive at the centre portion of the magnet when the applied field exceeds 6 T. Although the changes of trapped fields after the strongest field applications are similar in every profile in Fig. 5, we observe significant enhancements in the higher region than 7 T when the applied fields change their direction to reduce.

The capacitance dependence of trapped field is shown in Fig. 7 by rearranging the data derived from Fig. 5. We can clearly see a couple of typical jumps which correspond to the invading flux behaviours from M- to conical shape in the lower field region less than 80 mF and those from conical to conical in the higher region of over 100 mF. Taking a look at 60 mF, for example, the trapped flux density jumps up from 0.2 T to 2.2 T and the changes in the reducing way after this jump are small. In contrast, as for the case of 100 mF, although the trapped field already exhibits a conical shape, it jumps up from 2.0 T to 3.2 T



(a) (b)

Fig. 6 Distribution of trapped magnetic flux density after the first 500V (#1) pulse application with different capacitance (a) 80 and (b) 100 mF

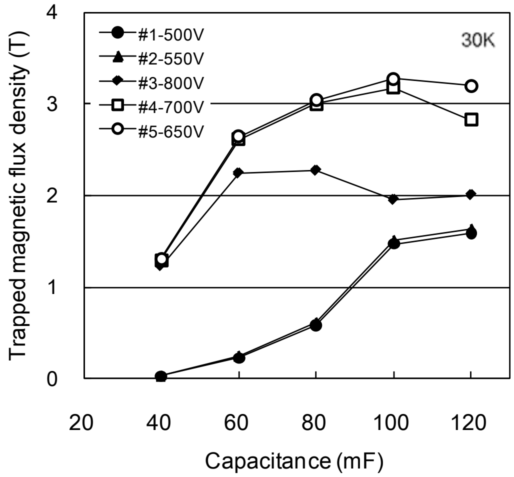


Fig. 7 Capacitance dependence of trapped magnetic flux density as a function of applied pulses

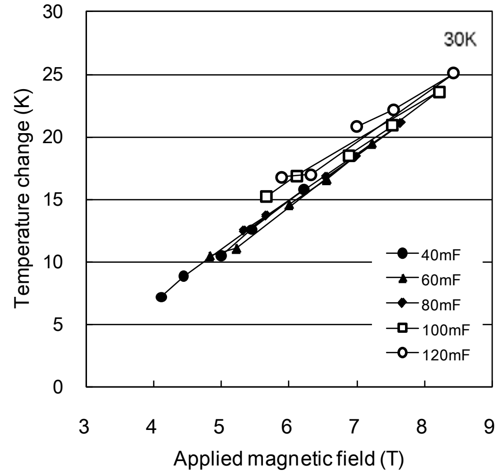


Fig. 8 Temperature changes versus applied magnetic flux density with various capacitance of pulse field generator.

in their reducing way of IMRA method. Thus, one can guess the flux motions must be quite different between before and after exposing to the intense fields of over several T.

Figure 8 shows the temperature changes against the applied magnetic fields in the IMRA method. The heat generation is almost proportional to the applied fields in spite of various conditions and histories of field applications and trappings. It is obvious that the total energy brought by pulsed magnetic field into the sample must perfectly depend on applied whole energy, and the energy must thoroughly change into the heat and attribute to the temperature rises. Existing magnetic flux in the sample before every pulsed field application never takes any roles to suppress the heat generation. This implies that the applied energy is absorbed in the system in every magnetic field application, and then gives the sample substantial heating, resultantly showing us steep summits after curving the existing trapped field distributions. Although it is not clarified why the highest trapped field has been greatly improved in their reducing stage of IMRA method after applying the field of over 8 T, yet, we believe that a certain novel mechanisms must lead us to obtain the further magnetic performances by PFM operation in high field region.

IV. Conclusions

The PFM process was operated in the high field region of over 7 T and the field trapping properties were precisely estimated as a function of condenser capacitance. The invading magnetic flux to the sample shows different behaviours showing significant jumps between the applied field regions lower and higher than 7 T. The temperature rises of every pulse application are shown to be proportional with increasing applied field. This means that the total energy thrown into the HTS bulk sample must change to the heat, and the existing magnetic distribution never suppress the heat generation. The magnetic performances have reached 3.28 T at the surface centre of the bulk magnet when the PFM was operated by the magnetic field less than 8.21 T with use of 100 mF condenser.

References

[1] S. Wipf and H. Laquer,"Superconducting Permanent Magnets", *IEEE Trans. on Magnetics* vol. 25, 1989, pp. 1877-1880.

[2] R. Weinstein, In-Gann Chen, J. Liu, and K. Lau, "Permanent magnets composed of high temperature superconductors," *J. Appl. Phys.*, vol. 70, 1991, pp. 6501-6503.

[3] H. Ikuta, A. Mase, Y. Yanagi, M. Yoshikawa, Y. Itoh, T. Oka, and U. Mizutani, "Melt-processed Sm-Ba-Cu-O superconductors trapping strong magnetic field," *Superconductors Sci. Technol.*, vol. 11, 1998, pp. 1345-1347.

[4] G. Krabbes, G. Fuchs, P. Schatzle, S. Gruss, J. Park, and F. Hardinghaus, "Large YBCO-monoliths with peak effect and high trapped fields," presented at the 12th Int. Symp. on Superconductivity (ISS'99), Morioka, Oct. 17-19, 1999. *Advances in Superconductivity XII*, Tokyo: Springer-Verlag, 2000, pp. 437-439.

[5] Y. Ren, R. Weinstein, J. Liu, R. P. Sawh, and S. Foster," ", *Physica C,* vol. 251, 1995, pp. 15- 21.

[6] H. Ikuta, A. Mase, T. Hosokawa, Y. Yanagi, M. Yoshikawa, Y. Itoh, T. Oka, and U. Mizutani, "Very strong magnetic field trapped by melt-processed large Sm-Ba-Cu-O bulk-superconductors," presented at *11th Int. Symp. on Superconductivity (ISS'98),* Fukuoka, Nov. 16-19, 1998. *Advances in Superconductivity XI*, Tokyo: Springer-Verlag, 1999, pp. 657-660.

[7] M. Tomita and M. Murakami, *Nature,* vol. 421, 2003, pp. 517-520.

[8] T. Oka, Y. Itoh, Y. Yanagi, M. Yoshikawa, H. Ikuta, and U. Mizutani, " Construction of a 2-5 T class superconducting magnetic field generator with use of an Sm123 bulk superconductor and its application to high-magnetic field demanding devices," *Physica C*, vol. 335, 2000, pp. 101-106.

[9] Y. Itoh and U. Mizutani, "Pulsed field magnetization of melt-processed Y-Ba-Cu-O superconducting bulk magnet", *Jpn. J. Appl. Phys.* vol. 35, 1996, pp. 2114-2125.

[10] U. Mizutani, T. Oka, Y. Itoh, Y. Yanagi, M. Yoshikawa and H. Ikuta, "Pulsed-field magnetization applied to high-T_c superconductors", *Applied Superconductivity*, vol. 6, 1998, pp. 235-246.

[11] H. Ikuta, H. Ishihara, Y. Yanagi, Y. Itoh and U. Mizutani, "Extracting the utmost from the high performance of Sm–Ba–Cu–O bulk superconductors by pulse field magnetization**",** *Supercond. Sci. Technol*. vol. 15, 2002, pp. 606–612.

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

[13] H. Fujishiro, T. Tateiwa, A. Fujiwara, T. Oka and H. Hayashi, "Higher Trapped Field over 5 Tesla on HTSC Bulk by Modified Pulse Field Magnetization", *Physica C*, vol. 445-448, 2006, pp. 334-338.

[14] H. Fujishiro, T. Hiyama, T. Tateiwa, Y. Yanagi and T. Oka, "Importance of Initial M-Shaped Trapped Field Profile Using a Two-Step Pulsed Field Magnetization (MMPSC) Method", *Physica C*, vol. 463-465, 2007, pp. 394-397.