Magnetization of Bulk Superconductors Using Thermally Actuated Magnetic Waves

Q. Li, Y. Yan, C. Rawlings, and T. Coombs

***Abstract*—A novel technique is proposed to magnetize bulk superconductors, which has the potential to build up strong superconducting magnets. Instead of conventionally using strong magnetic pulses, periodical magnetic waves with strength as low as that of rare-earth magnets are applied. These magnetic waves travel from the periphery to the center of a bulk superconductor and become trapped little by little. In this way, bulk superconductors can gradually be magnetized. To generate these magnetic waves, a thermally actuated magnet was developed, which is constructed by a heating/cooling switch system, a rare-earth bulk magnet, and a Gadolinium (Gd) bulk. The heating/cooling switch system controls the temperature of the Gd bulk, which, along with the rare-earth magnet underneath, can transform thermal signals into magnetic waves. The modeling results of the thermally actuated magnet show that periodical magnetic waves can effectively be generated by applying heating and cooling pulses in turn. A YBCO bulk was tested in liquid nitrogen under the magnetic waves, and a notable accumulation of magnetic flux density was observed.**

***Index Terms*—Bulk superconductor, Gadolinium (Gd), magnetize, rare-earth magnet, thermally actuated magnet.**

I. INTRODUCTION

HIGH-TEMPERATURE superconducting (HTS) bulks, such as YBCO bulks, have the potential to trap extremely high magnetic flux densities that are much higher and more compact than those of the rare-earth magnets of the same size. Therefore, HTS bulks have broadly been applied as strong-field magnets [1]–[4]. According to the Bean model, a strong magnetic field that is twice as high as the critical magnetic field H_C is needed to fully magnetize superconductors, which is called the full penetration field. Hence, for conventional magnetization methods, strong magnetic pulses are generated as the source in order to increase the magnetic flux density trapped by HTS bulks [5]–[7]. The devices used to generate these pulses are usually solenoid coils, which are big in size, high in cost, and high in energy consumption. To avoid this problem, it is desirable to make the magnetic field applied to HTS bulks as small as possible.

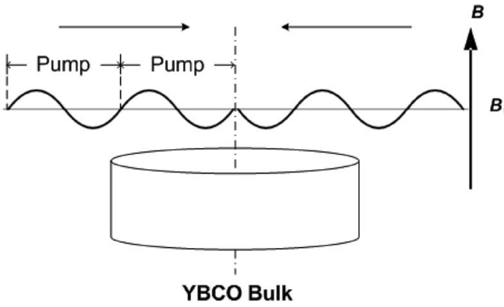

Fig. 1. Periodical magnetic waves, which are generated by the thermally actuated magnet, travel from the periphery to the center of the YBCO bulk.

In this paper, a thermally actuated superconductor magnetization system (TASMS) is proposed for the magnetization of bulk superconductors. Instead of using strong applied pulses, the TASMS uses a rare-earth bulk magnet to magnetize a YBCO bulk. The rare-earth bulk magnet, together with a Gadolinium (Gd) bulk and a heating/cooling switch system, composes a thermally actuated magnet, which is developed to generate periodical magnetic waves. The magnetic waves travel from the periphery to the center of the YBCO bulk and get trapped little by little, as shown in Fig. 1. In this way, the YBCO bulk can gradually be magnetized. Experimental results show that, after a number of magnetic waves, a notable accumulation of magnetic flux density in the YBCO bulk can be achieved, which proves the possibility of magnetizing bulk superconductors using multiple magnetic pumps and has the potential to produce strong superconducting magnets.

First, the details of the thermal actuated magnet are described. Modeling of the thermal actuated magnet was carried out with COMSOL software, and the simulation results are analyzed. Following this, the construction of the TASMS is presented. Finally, the testing of the TASMS has been completed, and the experimental results are summarized.

II. THERMALLY ACTUATED MAGNET

The thermally actuated magnet, which is developed to produce periodical magnetic waves, is constructed with a rare-earth bulk magnet, a Gd bulk, and a heating/cooling switch system. The rare-earth bulk magnet is the source of magnetic waves. By controlling the temperature of the Gd bulk, it is possible to change its magnetic permeability. In this way, the path of magnetic flux, starting from and ending to the rare-earth bulk magnet, can correspondingly be altered, which eventually actuates traveling magnetic waves.

A. Gd Bulk

Gd, the magnetic permeability of which can be altered corresponding with the change of temperature, has a zero-field

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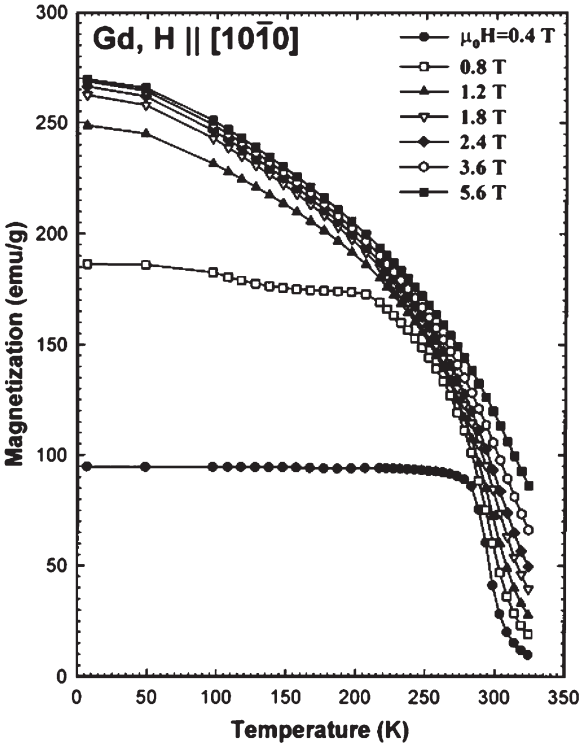

Fig. 2. Magnetization of a single Gd crystal as a function of temperature at selected dc fields with the external magnetic field parallel to the [1010] direction [8].

Curie temperature of 294 K [8]. It is a soft ferromagnet below the Curie temperature, above which its magnetic permeability rapidly decreases under increasing temperature. Fig. 2 shows the magnetization of a single Gd crystal as a function of temperature at selected dc fields, with the external magnetic field parallel to the [1010] direction [8]. Under a field of 0.4 T, which is the strength of the applied external field being used in this paper, the characteristics of Gd previously described can obviously be observed.

B. Thermal Control

Fig. 3 shows a model using heating/cooling on the edge of the Gd bulk to generate the desired traveling magnetic waves. Assuming that the temperature of the side surface sinusoidally changes and both flat surfaces on the top and bottom are ideally insulated, the temperature on the side surface can be described as

$$T_{\text{edge}} = T_\infty + T_0\cos(\omega t). \tag{1}$$

The temperature diffusion equation is

$$\alpha\nabla^2 T = \frac{\partial T}{\partial t} \tag{2}$$

where $\alpha = \lambda/\rho c$ is the thermal diffusivity, and it depends on the conductivity λ, the density ρ, and the heat capacity c. Sensible nondimensional groups for this problem are

$$\overline{T} = \frac{T - T_\infty}{T_0} \quad \bar{t} = \frac{\alpha}{a^2}t \quad \overline{\omega} = \frac{a^2}{\alpha}\omega. \tag{3}$$

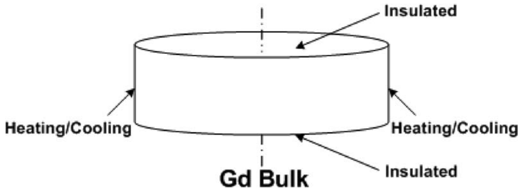

Fig. 3. Apply heating/cooling effect on the edge of the Gd bulk, and keep the top and bottom surfaces insulated.

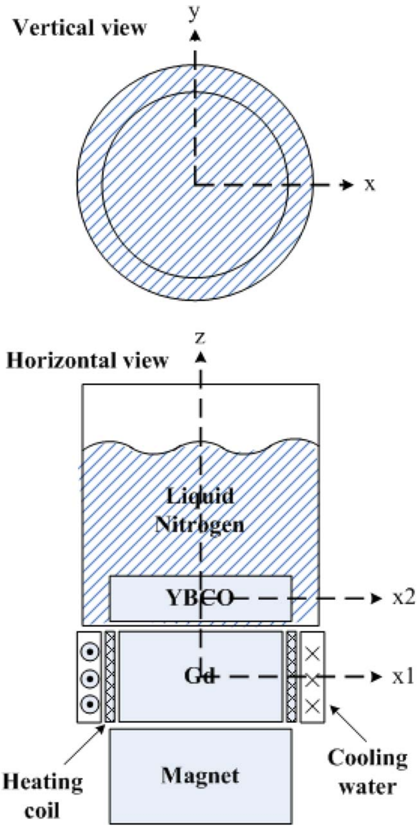

Fig. 4. Vertical and horizontal views of the configuration of the TASMS, with $x1$-axis along the radius of the Gd bulk and $x2$-axis along the YBCO bulk.

Assuming a harmonic solution of $\overline{T} = \psi(x)e^{j\overline{\omega}\overline{t}}$, the diffusion equation for the problem becomes

$$\overline{\nabla}^2\psi - j\overline{\omega}\psi = 0 \tag{4}$$

which is solved for the edge heating model, and the solution for a bulk with diameter of r can be presented as

$$\overline{T}(\overline{x},\overline{t}) = \Re\left[\frac{\cosh(\sqrt{\overline{\omega}}e^{j\pi/4}\overline{x}^2/2r)}{\cosh(1/2\sqrt{\overline{\omega}}e^{j\pi/4})}e^{j\overline{\omega}\overline{t}}\right]. \tag{5}$$

The heating/cooling system developed is composed of a dc heating coil and a cooling water pipe, which are controlled by a dc voltage power supply and a water pump, respectively. Heating and cooling is carried out in turn to maintain the temperature of the Gd bulk around the Curie temperature.

III. NUMERICAL ANALYSIS OF TASMS

The configuration of the TASMS, which is axis symmetric along the z-axis, is presented in Fig. 4. Both the x- and

TABLE I
DETAILS OF THERMAL SIMULATION IN COMSOL

Property	Information
Heating	50 kW/m^2
Cooling	Ice water, 273 K
Gd bulk	Diameter = 22 mm, Thickness = 13 mm
YBCO bulk	Diameter = 22 mm, Thickness = 4 mm
Magnet bulk	Diameter = 26 mm, Thickness = 18 mm SmCo, Central magnetic flux density: 0.92 T
Method	Finite Element Method (FEM)
Simulation Software	COMSOL Multiphysics V3.4

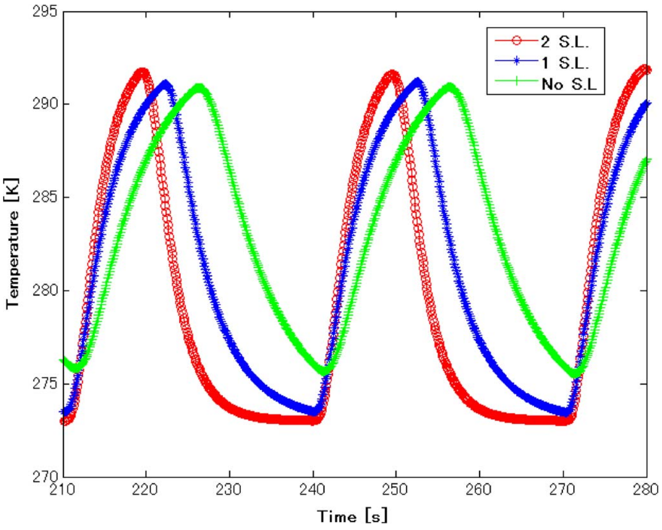

Fig. 5. Temperature as a function of time at the center of the Gd bulk with two, one, or no superconductive layers, respectively.

TABLE II
DETAILS OF THE CURVES IN FIG. 5

Curve	Information
No S.L.	No superconductive layers attached Heat/Cool = 15 / 15 seconds
1 S.L.	1 superconductive layer attached Heat/Cool = 12 / 18 seconds
2 S.L.	2 superconductive layers attached Heat/Cool = 9 / 21 seconds

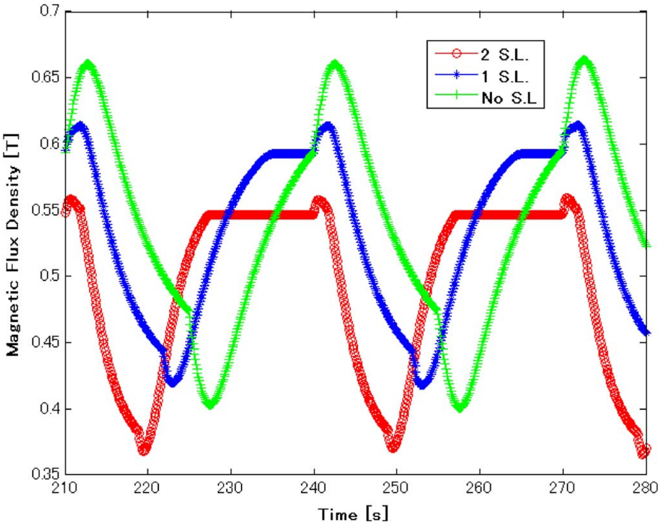

Fig. 6. Magnetic flux density as a function of time at the center of the Gd bulk with two, one, or no superconductive layers, respectively.

y-axis are horizontally allocated, whereas the z-axis is vertically allocated. Specifically, $x1$ scales the Gd bulk, and $x2$ scales the YBCO bulk. The YBCO bulk is placed in a thermal insulating cylinder container filled with liquid nitrogen as coolant, with the thermally actuated magnet set underneath. A heating coil and a water pipe are winded along the periphery of the Gd bulk in turn. To accelerate the transfer of thermal waves, thin sheets of superconductive layer (copper is used in this case) are attached to the top or/and bottom flat surfaces of the Gd bulk, respectively.

Thermal simulations have been carried out in COMSOL. Table I shows all the simulation details, which are consistent with the real experimental conditions. SmCo is selected as the rare earth magnet bulk, which has a more stable M-T curve among the range of experimental temperature. The simulation results, which were collected at the central point of the Gd bulk and are also marked as the original point of the $x1$-axis, are shown in Fig. 5, in which S.L. represents the superconductive layer. All the details corresponding to Fig. 5 are described in Table II.

Apparently, thermal waves transfer faster with the help of superconductive layers. Both heating and cooling become more efficient with more layers adhered to while a much bigger temperature range could also be achieved. Specifically, the Gd bulk with two superconductive layers, compared with that with none, can reach higher/lower temperature values while saving half the time. Based on the preceding results, thermally actuated magnets were constructed in COMSOL with different numbers of superconductive layers. The magnetic simulation results are shown in Fig. 6. These results show how the magnetic flux density changes at the center of the Gd bulk, corresponding to temperature control.

Superconductive layers can boost the transfer of heat, which benefits the temperature control. On the other hand, they increase the space between the rare-earth bulk magnet and the YBCO bulk, which causes a decrease in the magnetic flux density on the YBCO side, as observed from Fig. 6. To balance the pros and cons, experiments were implemented with only one layer of copper sheet. Fig. 7 shows the temperature of the Gd bulk along the radius (which corresponds to the $x1$-axis), as a function of time with heating/cooling applied, while only one layer of copper sheet is attached. Fig. 8 shows the magnetic flux density along the $x1$-axis responding to the thermal waves in Fig. 7. Finally, a series of traveling magnetic waves can be achieved along the $x2$-axis, which is the radius of the YBCO bulk, as presented in Fig. 9, and gradually penetrates the YBCO bulk from periphery, as designed.

IV. EXPERIMENTAL RESULTS

Based on both thermal and magnetic simulation results, experiments were carried out to test the feasibility of the TASMS,

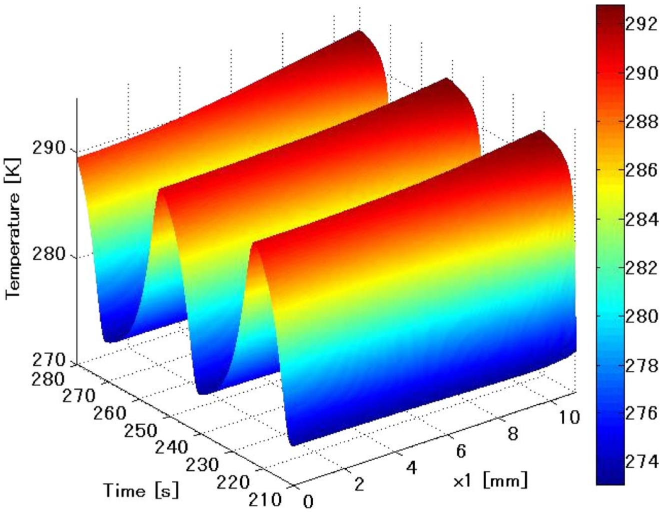

Fig. 7. Temperature as a function of time and position along the $x1$-axis in Fig. 4 from the center to the edge of the Gd bulk.

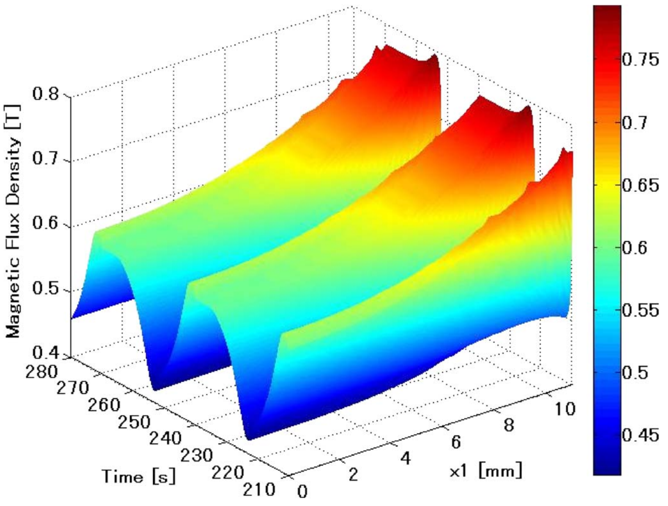

Fig. 8. Magnetic flux density as a function of time and position along the $x1$-axis in Fig. 4 from the center to the edge of the Gd bulk.

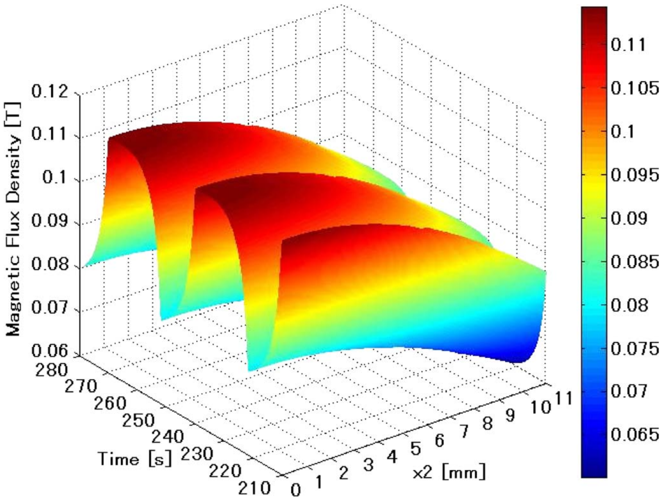

Fig. 9. Magnetic flux density as a function of time and position along the $x2$-axis in Fig. 4 from the center to the edge of the YBCO bulk.

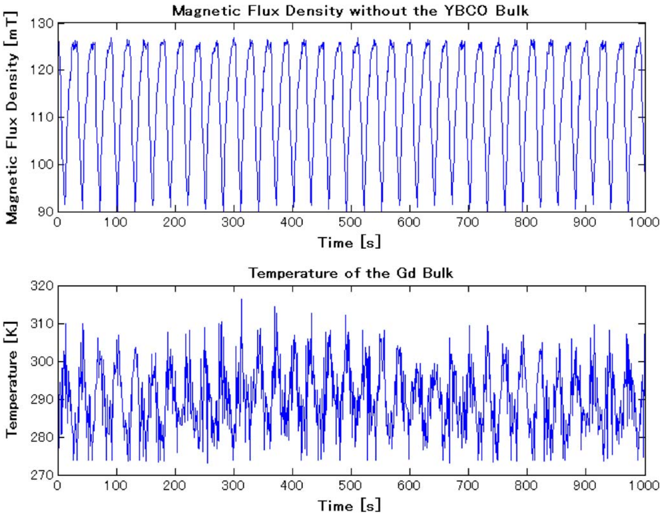

Fig. 10. Magnetic flux density measured without the YBCO bulk, under periodically magnetic waves, actuated by changing the temperature of the Gd bulk.

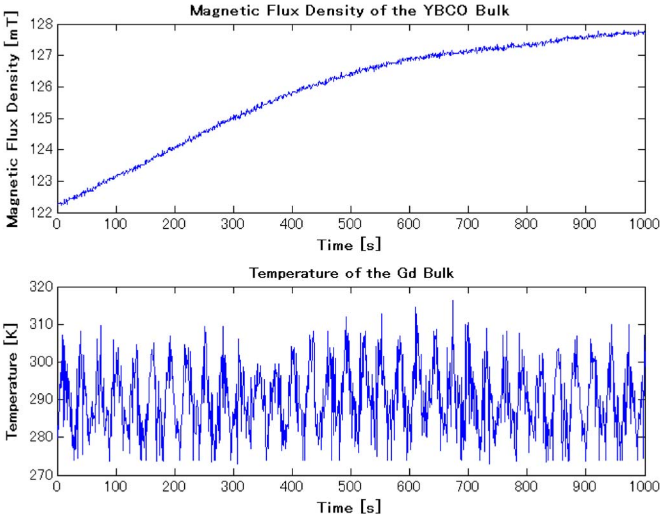

Fig. 11. Accumulation of the magnetic flux density of the YBCO bulk, under periodically magnetic waves, actuated by changing the temperature of the Gd bulk.

of which the purpose is to magnetize the YBCO bulk using a rare-earth magnet. Thermocouples are attached to the Gd bulk to measure the temperature, whereas Hall sensors are attached to the YBCO bulk to measure magnetic flux density. Liquid nitrogen is used as coolant. The heating/cooling effect started to perform while the YBCO bulk was soaked in liquid nitrogen longer than 1 h to turn into superconducting state.

The experiment results show that the temperature of the Gd bulk can effectively be controlled between 275 and 305 K. The thermally actuated magnet can generate magnetic waves changing between 0.09 and 0.126 T, as shown in Fig. 10, in which case the YBCO bulk was removed from the system. Under these waves, the YBCO superconducting bulk can gradually be magnetized, as shown in Fig. 11.

The accumulation of magnetic flux density can be attributed to flux creep, which causes uneven magnetization and demagnetization within each pump (one period of magnetic wave). As shown in Fig. 11, while temperature periodically varies between 275 and 305 K, the flux density of YBCO bulk increases from 122 to 128 mT and even more. This proves that the TASMS is capable of magnetizing superconductors using repeated magnetic waves with the strength of a rare-earth magnet.

V. CONCLUSION

This paper has proposed a novel technique to magnetize superconductors, which is named TASMS. Instead of using strong magnetic pulses, TASMS uses rare-earth magnets to generate periodic magnetic waves for the magnetization of bulk superconductors. For this purpose, a thermally actuated magnet has been developed. With the help of Gadolinium (Gd), the thermally actuated magnet can effectively generate periodic magnetic waves, which alter from 0.09 to 0.12 T. By applying these waves, the YBCO bulk accumulated flux density from 122 mT to more than 128 mT, which proves the feasibility of the TASMS. By this means, the source of applied field is not necessarily to be as strong as the field induced by solenoids but can be constituted by normal rear-earth magnets. Instead of conventional methods, the magnetization can gradually be built up via multiple pumps. In order to enhance the trapped field on the YBCO bulk, high-frequency and wide-range strength-altering magnetic waves are effective. In view of this, more efficient methods to generate magnetic waves are being developed.

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