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Development of a small-size superconducting bulk magnet system especially designed for a pulsed-field magnetization

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Abstract

We developed a small superconducting bulk magnet system that was especially designed for a pulsed-field magnetization. The industrial applications of bulk magnets demand the miniaturization of the magnet apparatus as well as the enhancement of the magnetic field. A Gifford-McMahon cycle helium refrigerator with the ultimate temperature of 13 K at the 2nd stage was adopted, and a $GdBa_2Cu_3O_{7-x}$ bulk material of 60 mm diameter and 20 mm thickness reinforced by a stainless steel ring was located on a cold stage. The total length of the magnetic pole was 570 mm including the refrigerator, therefore, the system could easily be managed. A cooling test and a magnetizing test were carried out using a Hall sensor and thermocouples adhered on the top surface of the material. In the cooling test, the value of 22.5 K at the cold stage was achieved in 3 h. In the magnetizing test, five successive pulsed-fields of the same strength were applied while changing the applied field, and the time responses of the trapped flux density and temperature were measured at each stage. When a magnetic field of 6.97 T was applied, the trapped field reached 2.04 T, which is the highest ever reported for a pulsed-field magnetization of ϕ60 mm class bulk material.

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Keywords: superconducting bulk magnet; pulsed-field magnetization; trapped flux density, temperature measurement

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1. Introduction

The trapped magnetic field of a high-T_c RE-$Ba_2Cu_3O_{7-x}$ (RE123, RE = Y, Sm, Gd, etc.) bulk superconductor has increased with the improvement of its superconducting characteristics [1], the enlargement of its size [2], and the progress of the magnetizing technique [3-6]. A superconducting bulk magnet, in which a bulk superconductor is magnetized and used as a permanent magnet, is attracting much attention as an application of bulk materials. A bulk magnet can generate strong magnetic fields exceeding 2 T, which is the limit of ordinary iron-cored electromagnets, in a compact device with a low running cost; thus, various industrial applications, including magnetic separation, motor/generator, drug delivery systems (DDSs), and magnetron spattering, are being considered [7-11]. To increase the industrial applications of bulk magnets in the future, the ease of handling of the apparatus and the enlargement of the magnetic field are important.

In this paper, we propose a small-size superconducting bulk magnet system especially designed for a pulsed-field magnetization (PFM). By limiting the magnetizing methods to PFM, the following advantages are obtained: (1) A small-size and cheap magnetizing apparatus composed of a condenser bank and a conventional copper coil; (2) A small-size magnetic pole. In a field cooling method (FC), using a superconducting magnet (SCM), it is necessary to design a magnetic pole so that the bulk material is located at the center of the magnetic field of SCM and the magnetic field does not influence the refrigerator. Therefore, the distance between the bulk material and the refrigerator is extended, and the magnetic pole increases in size.

We adopt a two-stage-type 13 K refrigerator to achieve the downsizing of the apparatus and the enhancement of the magnetic field at the same time. Although the size of the refrigerator increases in comparison with that of a single-stage-type refrigerator, it is possible to enlarge the magnetic field by cooling down the bulk material to low temperature and improving the critical current density. However, as is well known, the heat generation increases immediately after the application of the magnetic field at low temperature, and, thus, the trapped magnetic field decreases [12]. Moreover, it is difficult with a large-size, high-performance bulk material to trap a high magnetic field [13]. In this paper, the cooling and the magnetizing characteristics are investigated using a Gd123 superconducting bulk material of 60 mm diameter to enhance the magnetic field generated by the prepared bulk magnet system.

2. Construction of the bulk magnet system

Fig. 1 is a schematic and photograph of the proposed superconducting bulk magnet system; the major specifications are listed in Table 1. The two-stage-type Gifford-McMahon cycle helium refrigerator is adopted to achieve cooling down to less than 20 K. This refrigerator is driven by an indoor and air-cooled compressor, and the power consumption is 1.6 kW in 3-phase 200 V (50 Hz) power. The cooling capacity is 5 W at 20 K in the 2nd stage and 19 W at 80 K in the 1st stage. The cooling time from room temperature to 20 K is 45 minutes. A bulk material is attached on a cold stage connected to the 2nd stage of the refrigerator with a copper rod. A superinsulation (SI) is wound between the rod and the 1st stage to prevent radiation. They are covered with a vacuum vessel, and the gap between the vessel and the bulk surface is 3 mm. The total length from the top of the vacuum vessel to the end of the refrigerator is 570 mm, the maximum diameter is 159 mm, and the diameter in the magnetic pole is 87 mm.

3. Experimental

The bulk material is highly *c*-axis-oriented crystal and consists of 75.0 wt.% $GdBa_2Cu_3O_y$ (Gd123), 24.5 wt.% Gd_2BaCuO_5 (Gd211), and 0.5 wt.% Pt powder (Nippon Steel Corporation). The sample size is 60 mm in diameter and 20 mm in thickness. The sample is embedded in a stainless steel ring (SUS316L) of 2 mm thickness for mechanical reinforcement and the reduction of temperature rise. The trapped field by FC at 77 K is more than 1.9 T, and there is no defect. After the bulk material is set on the cold stage, a Hall sensor (BHT-921; F. W. BELL) is adhered at the center of the top surface with Kapton tape to measure the trapped flux density, B_T. Three Teflon-coated copper-constantan thermocouples of 76 μm diameter are also adhered, as shown in the inset of Fig. 2, with the GE7031 varnish and Kapton tape to monitor the temperature, T: T1 is adhered at the center on the top surface, T2, the outer part of the bulk, and T0, the cold stage. The vacuum vessel is fitted, and it is exhausted to a vacuum less than 10^{-4} Pa by the turbo-molecular pump. A magnetizing copper coil dipped in liquid nitrogen is located outside the vessel, and an exciting pulse current is supplied by a condenser bank of 60 mF. After the bulk material is cooled down to the ultimate temperature, five successive pulsed-fields with the same amplitude are applied while changing the applied field to 4.64, 5.42, 6.19, and 6.97 T, where the rising time of the pulse is 10 ms. The data of B_T and T are recorded at intervals of about 0.2 s at each stage.

4. Results and discussion

While the bulk was cooled down from the room temperature to the ultimate one, the data of T0, T1, and T2 were monitored at intervals of 5 minutes. Fig. 2 shows the results of the cooling test. The values of T0, T1, and T2 reach 22.5, 37.8, and 39.9 K, respectively, in about three hours. The temperature difference between the bulk material and the cold stage was larger than that of previous data, and, hence, it was necessary to decrease the radiation by covering the bulk with SI and improve the heat conduction by placing an indium foil between the bulk and the stage in the next experiment.

Fig. 3 shows the relationship between the applied field, $\mu_0 H$, and the trapped field, B_T, after application of each pulse. The value of B_T roughly increases with $\mu_0 H$. In $\mu_0 H$=4.64 T, B_T=0.2 T is obtained, and the magnetic flux hardly penetrates into the bulk. In $\mu_0 H$=5.42 and 6.19, the B_T value increases slightly with the pulse number. In $\mu_0 H$=6.97, it increases from pulses no.1 to no.2, reaching the maximum of 2.04 T, and then decreases greatly after pulse no.3, where a decrease in B_T is due to the flux creep that generates large heat when a magnetic field that is too strong is applied. The maximum trapped field obtained in this experiment is superior to the data reported in [13]. Although it is difficult to magnetize the large-size, high-performance bulk material by PFM, the goal is to enhance the trapped field in our system, which has a large output in the second stage of the refrigerator.

Fig. 4 shows the time responses of T at T0, T1, and T2 and B_T after application of pulses nos.1 and 2 in $\mu_0 H$=6.97 T. Since the original data include a significant amount of noise, they were removed with a filter. In pulse no.1, T2 exhibits a rapid rise, reaching a value of 60 K, and then decreases slightly. Although it is evident that a rising time of T2 is three orders longer than that of the applied field, a detailed investigation of the cause is in progress. T1 increases rapidly to a value of 50 K and then gradually to 55 K up to 150 s. The value of T0 increases sharply from 23 K to 40 K, followed by a small increase to 45 K, and then decreases monotonously. It is noteworthy that the temperature of the cold stage rises by as much as 20 K. The B_T value remains constant after a slight decline. In pulse no.2, T2 rises linearly to 50 K until 30 s and hardly changes hereafter. The curve for T1 coincides with that of pulse no.1. The T0 value increases faster to 36 K and then remains unchanged. B_T shows a jump at a pulse impression and reaches a value of 2.04 T, which is the highest ever reported for PFM of ϕ60 mm class bulk material.

Fig. 5 shows a comparison of the temperature change of T1 and T2 at five pulses, where the open and solid symbols indicate the data of T1 and T2, respectively. The value of T1 keeps rising monotonously until 150 s in all pulses, although the maximum value decreases gradually with each pulse. The peak value of T2 is substantially reduced. These results are in reasonable agreement with those of previous experiments.

The above experimental data are summarized as follows. The restraint of the temperature rise and fast decrease of T2 originate in cooling through the sample holder shown in Fig. 1. Since the sample holder touches the upper surface of the bulk, which has a 10 mm width, and T2 is located on the rim of the holder with a gap of 2 mm, it is considered to contribute significantly to the cooling. Because T1 is 15 mm away from the rim, on the other hand, the cooling effect with the holder is small. In the results of Figs. 3 and 5, it is evident that the B_T value increases while the maximum value of T2 decreases at pulse no.2, suggesting that the magnetic flux invades from places other than T2. In future studies, a detailed examination will be carried out by increasing the temperature monitoring point and scanning the trapped field distribution to enlarge the trapped field by improving the magnetizing method.

5. Conclusion

We developed a small-size superconducting bulk magnet system while taking ease of handling into consideration. The apparatus could be miniaturized by limiting the magnetizing method to pulsed-field magnetization. In this paper, the produced system was introduced, and cooling and magnetizing tests using Gd123 bulk material of ϕ60×20 mm were carried out. The ultimate temperatures of the cold stage and the bulk material were 22.5 and 38.7 K, respectively, and the cooling time was about three hours. Then, five successive pulsed fields of the same strength were applied with changing the applied field, and the time responses of the trapped flux density and temperatures were measured at each stage. When the magnetic field of 6.97 T was applied, the trapped field reached 2.04 T, which was the highest ever reported. This system was shown to be suitable for PFM of large-size, high-performance bulk material. More detailed investigations are in progress to enlarge the trapped field.

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Table 1 / BLP-25 / ISS2008

Table 1. Specifications of the proposed superconducting bulk magnet system.

Symbol		Spec
Superconductor		$GdBa_2Cu_3O_{7-x}$
Size of bulk material		ϕ60 mm × 20 mm
Magnetization method		Pulsed field
Refrigerator		2-stage-type Gifford-McMahon
Compressor unit		Indoor. Air-cooled
Cooling capacity	1st stage	19 W @ 80 K
	2nd stage	5 W @ 20 K
Ultimate temperature	1st stage	≤ 42 K
	2nd stage	≤ 13 K
Cooling time to ultimate temp.		45 minutes
Power supply		3 Phase AC 200 V, 50 Hz
Operating current		6.0 A
Power consumption		1.6 kW
Total length of magnetic pole		570 mm
Maximum diameter of magnetic pole		159 mm
Diameter of magnetic pole		87 mm

Figure captions

Fig. 1. Schematic and photograph of the proposed bulk magnet system.

Fig. 2. Time responses of the temperature at the center on the top surface (T1), the outer part of the bulk (T2), and the cold stage (T0).

Fig. 3. Trapped flux density in applied fields of 4.64, 5.42, 6.19, and 6.97 T after application of each pulse.

Fig. 4. Time responses of the temperature rises of T0, T1, and T2 and the trapped flux density, B_T, after application of pulses nos.1 and 2 ($\mu_0 H$=6.97 T).

Fig. 5. Comparison of the temperature rises of T1 and T2 at five pulses. Open and solid symbols indicate the data of T1 and T2, respectively.

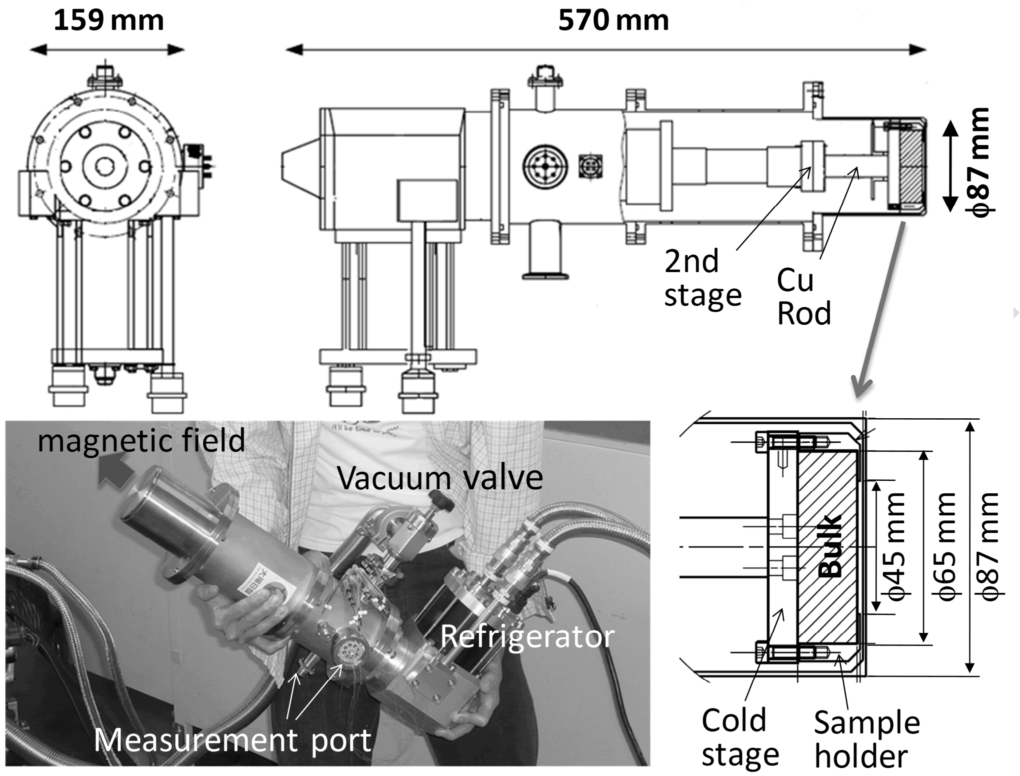
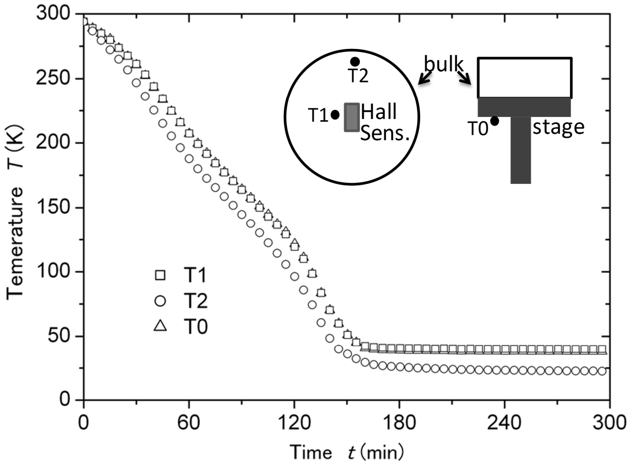

159 mm
570 mm
ϕ87 mm
2nd stage
Cu Rod
magnetic field
Vacuum valve
Refrigerator
Measurement port
Bulk
ϕ45 mm
ϕ65 mm
ϕ87 mm
Cold stage
Sample holder

Fig1



300
250
200
150
100
50
0
Temerature T (K)
0
60
120
180
240
300
Time t (min)
□ T1
○ T2
△ T0
T2
T1
Hall Sens.
bulk
T0
stage

Fig2

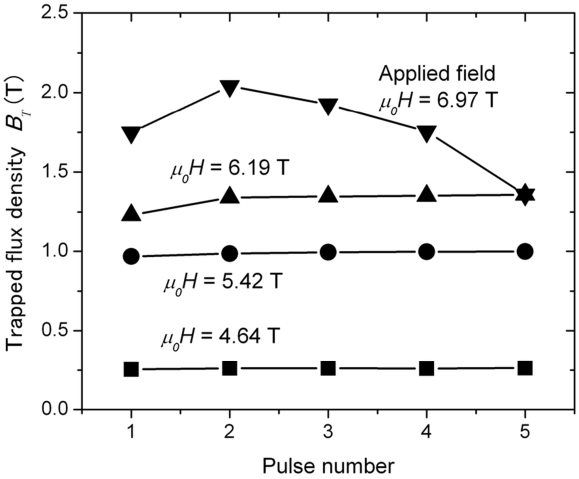

Trapped flux density B_T (T)
Pulse number
Applied field
μ_0H = 6.97 T
μ_0H = 6.19 T
μ_0H = 5.42 T
μ_0H = 4.64 T
0.0
0.5
1.0
1.5
2.0
2.5
1
2
3
4
5

Fig3

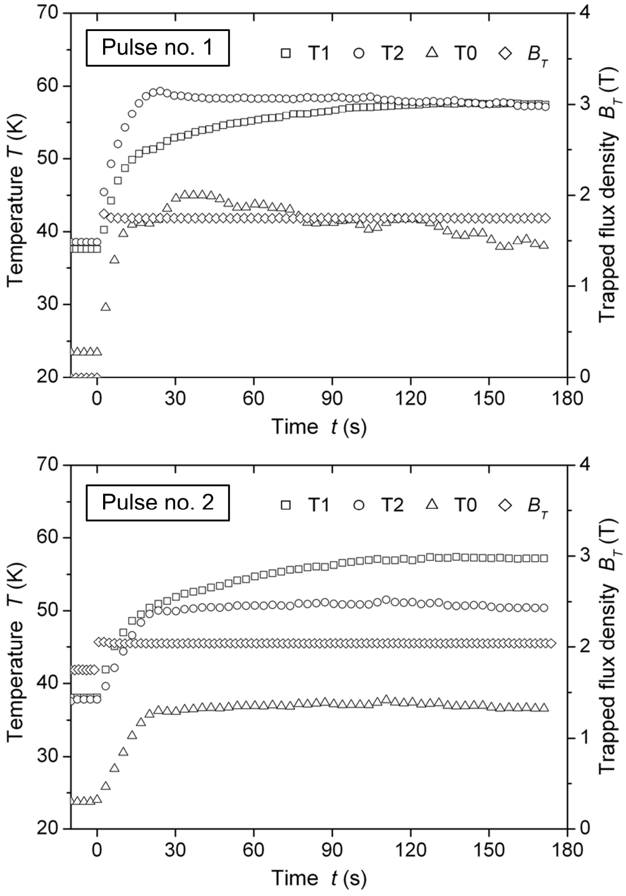
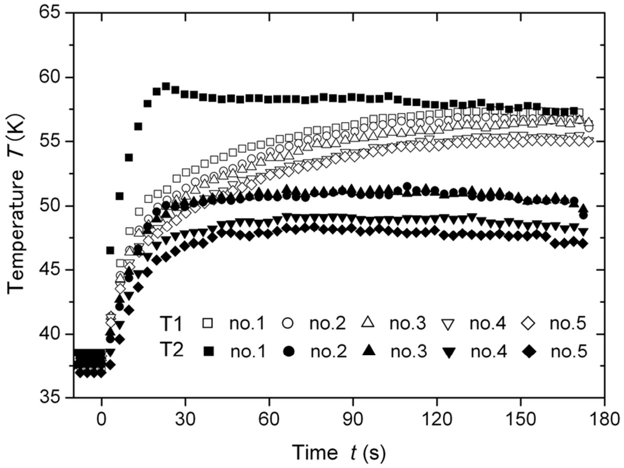

Pulse no. 1
T1
T2
T0
B_T
Temperature T (K)
Trapped flux density B_T (T)
Time t (s)
20
30
40
50
60
70
0
1
2
3
4
0
30
60
90
120
150
180
Pulse no. 2
T1
T2
T0
B_T
Temperature T (K)
Trapped flux density B_T (T)
Time t (s)

Fig4



65
60
55
50
45
40
35
0
30
60
90
120
150
180
Temperature T (K)
Time t (s)
T1 □ no.1 ○ no.2 △ no.3 ▽ no.4 ◇ no.5
T2 ■ no.1 ● no.2 ▲ no.3 ▼ no.4 ◆ no.5

Fig5