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Construction of A Wide and Strong Magnetic Field Generator Using melt-processed High T_c Bulk Superconductors Arrayed in One Plane

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The authors have succeeded in constructing a superconducting bulk magnet system capable of generating strong trapped magnetic field by melt-processed RE-Ba-Cu-O bulk superconductors. The trapped field was measured in the open gap between the magnetic poles settled face-to-face after the magnetization processes operated at the lower temperature than 77K by using refrigerators. A novel face-to-face field generator has been composed by a pair of wide magnetic poles with seven bulk magnets arranged in one plane. The size of the bulk magnets and the arranged magnetic pole are 45 and 150 mm in diameter, respectively. The performance of the magnetic field activated by the field cooling mode operated at 5 T generated by conduction-cooled superconducting solenoid has reached 1.4 T and 0.9 T at the midst of the pole surface and at the center of the gap of 34 mm between the magnetic poles, respectively. The intense magnetic fields are investigated to be applied in various industries in Iwate CREATE (Collaboration of Regional Entities for the Advancement of Technological Excellence) project supported by Japanese government.
Key words: bulk superconductor, trapped field magnet, magnetic field generator, refrigerator

1. INTRODUCTION

The melt-processed $REBa_2Cu_3O_y$ (abbreviated as RE123, where RE=Y, Sm, Gd, Dy, Eu) bulk materials with RE_2BaCuO_5 (RE211) precipitates act as quasi permanent magnets when they capture the magnetic field [1, 2]. As was reported by Tomita et al. [3], the maximum trapped field has reached 17.2 T at 29 K for the Y-Ba-Cu-O system activated by the field cooling magnetizing method (FC). It is emphasized that the reinforcing the bulk materials is the most important to prevent the fracture against the magnetic forces. The field trapping ability has been also greatly improved by choosing Sm or Gd in place of Y [4].

The pulsed field magnetization (PFM) technique has been considered to be more compact and convenient way than FC to magnetize them. It was stated by Mizutani et al. [5] that the "IMRA" method, a kind of iterative applications of magnetic fields, is very effective to activate the high field trapping magnets. The performance of PFM has reached the highest value of 4 T.

Since the magnetic flux distribution of bulk magnets shows a conical shape, the spatial volume of strong field is limited in the narrow space just above the bulk surface. Therefore, it is difficult to emit strong magnetic fields in large open spaces. The authors have recently constructed a novel magnetic field generator with wide magnetic poles that consist of seven bulk superconducting permanent magnets in each pole. The FC magnetizing method with use of a 5 T superconducting solenoid magnet was adopted to magnetize the wide poles because it is difficult to generate the sufficient pulsed fields in large area by ordinary solenoid coils made of copper.

In the paper, we report on the construction of various superconducting bulk magnet systems that are composed of RE-Ba-Cu-O (RE=Gd, Sm, Y) bulk superconductors, refrigerators and a vacuum pump system, and describe their performances.

2. EXPERIMATAL

Melt-processed RE-Ba-Cu-O bulk superconductors with the size of 45 mm in diameter and 15-18 mm in thickness were purchased from Nippon Steel Co. and Dowa Mining Co. As shown in Fig. 1, the samples were impregnated by epoxy resin with grass fibers and then reinforced by embedding them in the stainless steel rings with epoxy resin.

Two types of refrigerators, Gifford-McMahon (GM) cycle and Stirling pulse tube cooler, were adopted to cool the bulk samples below 77 K. They were driven by ac 100 V without any cooling water, and their ultimate temperatures are 38 K and 57 K, respectively.

The magnetization technique so-called FC was conducted to activate the arrayed magnets in each magnetic pole.

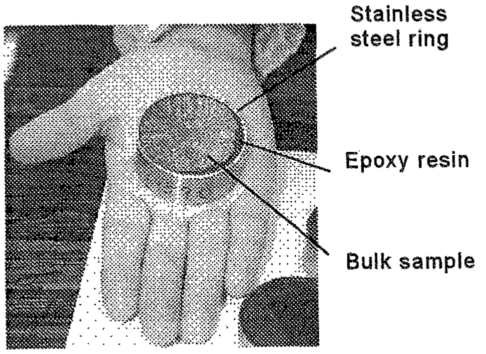

Figure 1. A photograph of the Sm123 melt-processed bulk magnet reinforced by a stainless steel ring with epoxy resin.

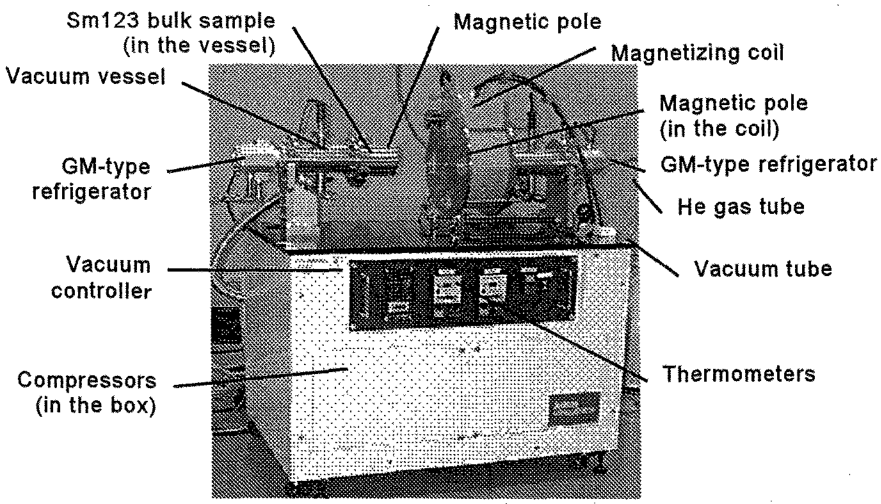

Figure 2. A view of the face-to-face type superconducting bulk magnet system with a pulse coil set on the right-hand side of magnetic poles. The coil is removed after the PFM operation. A strong magnetic field of 3.2 T has been generated between the poles in which Sm123 bulk samples were mounted.

The trapped field distributions were measured by scanning a Hall sensor (F. W. Bell BHA/T921) with respect to an element along the pole axis B_z in the open gaps between the magnetic poles. The sensor was scanned with every pitch of 2 mm and an interval of 0.5 s.

3. RESULTS AND DISCUSSIONS

3.1 Face-to-face type field generator

Figure 2 shows a strong magnetic field generator with face-to-face magnetic poles, which has been previously examined, in comparison with the present study. The magnetic poles were composed of a pair of Sm-Ba-Cu-O bulk magnets which was set on the respective cold stages of the GM refrigerators in the vacuum vessels [6]. The bulk magnets were activated by IMRA method [5] at 38 K. The magnetizing coil set on the right-hand side magnetic pole, as shown in Fig. 2, was removed after the magnetizing operation.

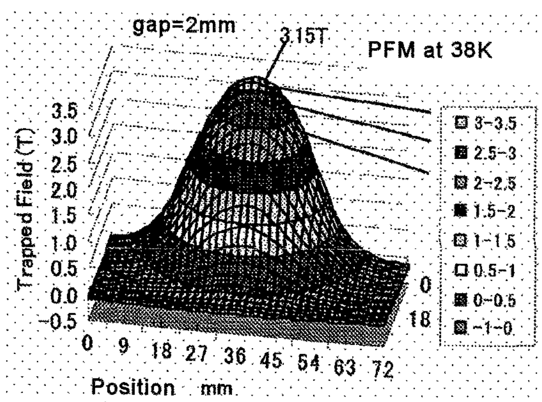

Figure 3 Field distribution of the superconducting bulk magnet system measured in the open space between the face-to-face magnetic poles with a gap 2mm. The axial component was measured by scanning a Hall sensor after the IMRA method. The maximum trapped field has reached 3.15 T at the center of the area.

The trapped field distribution in an open gap of 2 mm is shown in Fig. 3. One can see that the profile shows a clear cone-shape and the maximum magnetic field is located at the center of the poles. The maximum trapped field has reached 3.15 T. The magnetic flux distributions along the pole axis as a function of the gaps are shown in Fig. 4. Each magnetic pole is generating the field of over 2 T on its surface center.

The PFM is the easiest among all possible magnetizing techniques. However, the flux penetration into the bulk magnets is sluggish due to the presence of pinning centers [7]. The flux motion during the penetration process causes local heating, raises the temperature, lowers the J_c value, and subsequently degrades the field trapping ability.

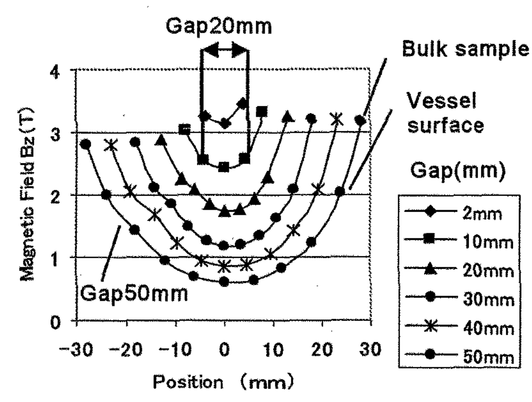

Figure 4. Magnetic field distributions along the magnetic poles axis as a function of the gaps.

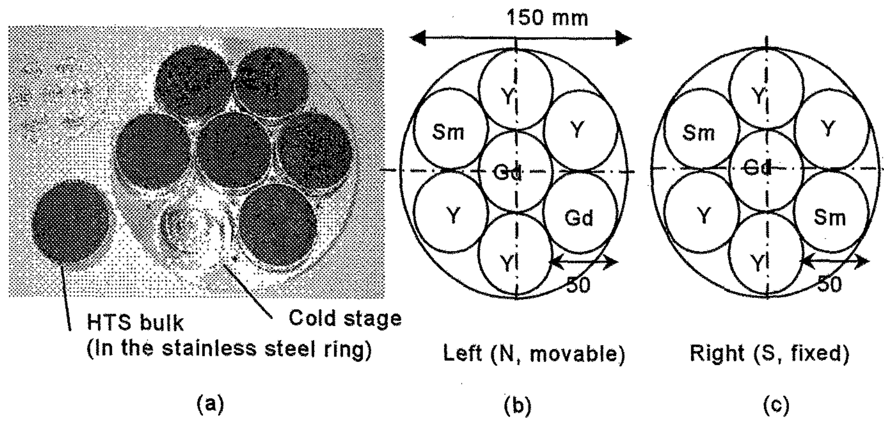

Figure 5. Arrayed seven bulk magnets on the cold stage with a size of 150 mm in diameter (a). Various kinds of RE-Ba-Cu-O bulk magnets were arranged in the same plane. (b) left- hand side N pole, and (c) right- S pole.

3.2 Wide magnetic poles with arrayed bulk magnets

To overcome the drawback that the strong field area is spatially narrow, a novel magnetic field generator with a pair of wide magnetic poles was constructed by using seven RE-Ba-Cu-O bulk superconductors arranged on each plane cold stage of 150 mm in diameter, as is shown in Fig. 5.

Figure 6 shows a construction design of the face-to-face magnetic field generator and Fig. 7 shows a photograph of the whole system. A pair of magnetic poles with a size of 230 mm in diameter containing single domain bulk magnets of 45 mm in diameter was located face-to-face after the FC magnetization process. The magnetic pole on the left-hand side was designed to be adjustable to vary the distance between the bulk magnets. On the other hand, the pole on the right-hand side was firmly fixed to the frame. The cold stage containing bulk magnets was fixed to the stiff flange of vacuum chamber by four FRP plates keeping the thermal insulation, avoiding mechanical damages to the pulse tube of refrigerator due to the magnetic force.

The Stirling cycle pulse tube cryocoolers were adopted to cool the bulk magnets down to 67 K. They need 300 W of ac 100 V power and cool the cold stage to the ultimate temperature in less than 12 hours. The cold stages and cold head of the cooler were connected by a conduction bar made of copper in the vacuum chamber with a long distance of 500 mm, otherwise the voice-coil type motor that drives the refrigerator would be affected by the magnetic field emitted by the superconducting solenoid on its activation process.

3.3 Field cooling (FC) magnetizing procedure

The FC process was operated at 67 K with use of a 5 T superconducting solenoid magnet. Firstly, a magnetic pole was set in the center of the solenoid magnet, and the field was increased to 5 T in the temperature range over 90 K. The refrigerator then started to cool the bulk magnet to 67 K. After decreasing the field to zero, the magnetic pole with the trapped field was put on the frame stand of the field generator and settled face-to-face. The distance between the magnetic poles was adjusted to be 20 mm, when the distance between the bulk magnets was 34 mm.

3.4 Trapped field distribution

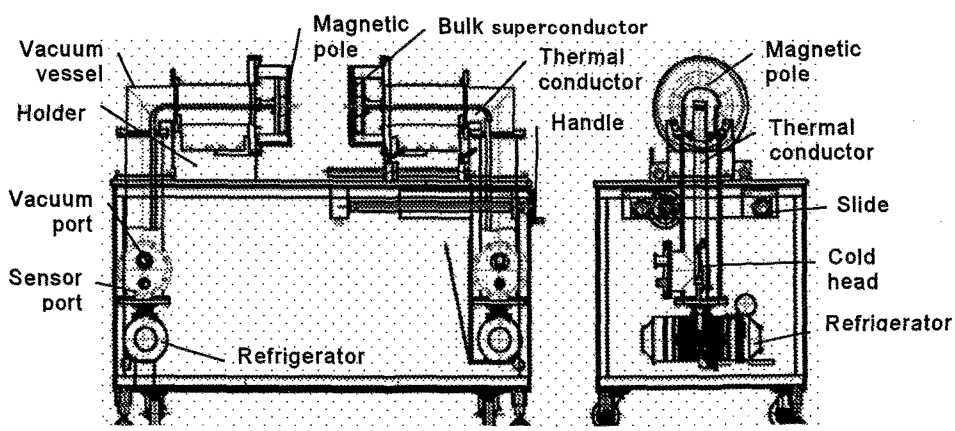

Figure 6. A design of the face-to-face type field generator containing seven bulk magnets in each pole. The Stirling cycle pulse tube cryocoolers were adopted.

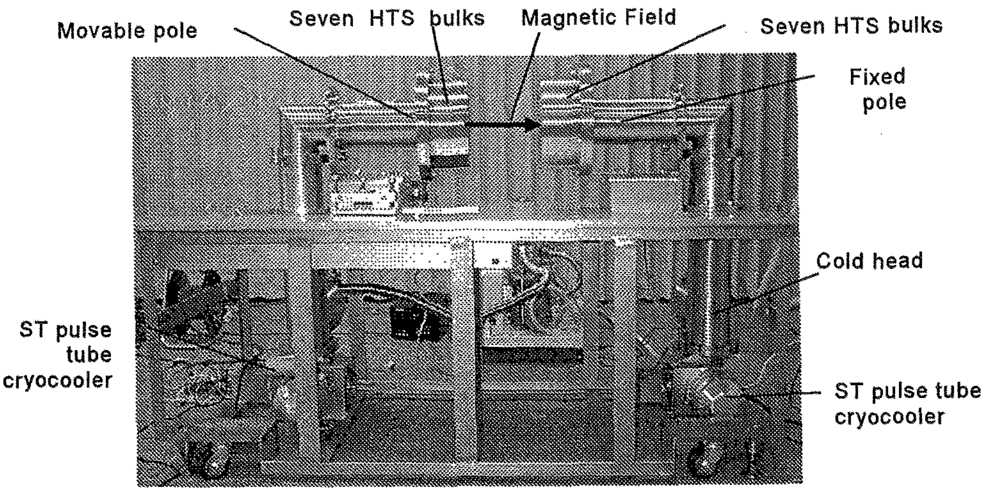

Figure 7. A photograph of the field generator with wide magnetic poles of multiple bulk magnets. The magnetic poles were activated by the field cooling (FC) method operated at 5 T of a conduction-cooled superconducting solenoid magnet.

As shown in Fig. 8, the magnetic flux density of 1.4 T was obtained at the center of the S-pole surface. It is shown that apparent seven peaks of the field distribution honestly reflect the position of the bulk magnets embedded in the magnetic poles even when the distance from the bulk surface to the chamber surface is 6 mm. The performance of Gd and Sm systems are superior to Y system. This indicates that no serious mutual affection on the trapped fields was observed in the present arrangement, because the flux lines loop back through the spaces between the adjacent bulk magnets.

Figure 9 shows a distribution along the vertical line at the center of the gap. The highest peak corresponds to the Gd-based bulk sample, which shows the maximum value of 0.9 T. The value of the total fluxes has reached 4.3 mWb that corresponds to nearly four times as much as that obtained when a single bulk sample was magnetized by PFM operated at 38 K. The major specifications of the present strong field generators are listed in table 1.

4. CONCLUSIONS

A novel strong field generator with seven bulk magnets set inside the magnetic poles was constructed with face-to-face wide magnetic poles. The maximum trapped field reached 0.9 T and 1.4 T at the center of the gap and at the surface of the magnetic pole, respectively. The total flux reached nearly four times as much as that of face-to-face arranged single bulk magnets. The flux distribution honestly reflects the flux trapping ability of each bulk sample. No mutual degradation due to the effects form other adjacent magnets was observed in the present magnet arrangement.

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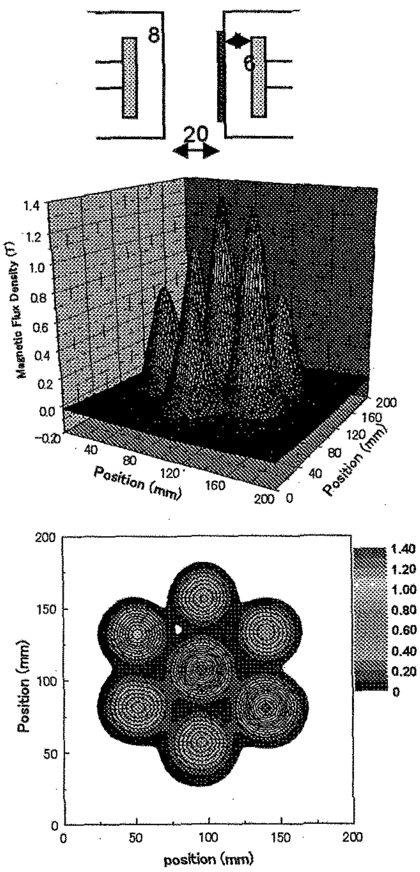

Figure 8. The magnetic field distribution measured on the surface of the right-hand side S-pole (a), and its plan view (b). The gap between the face-to-face poles and bulk samples were 20 and 34 mm, respectively. The maximum data of 1.4 T was obtained at the center of the pole surface.

Table 1

Characteristics of strong magnetic field generators by HTS bulk magnets

	Face-to-face (single bulk)	Wide poles (multi-bulk)
Generating field	3.2 T (gap 2mm)	0.9 T(gap 34mm), 1.4 T(surface)
Superconductors	Sm-Ba-Cu-O	Y, Gd, Sm-Ba-Cu-O
Sizes of HTSs	65 mm (in dia.)x 2 poles	45 mm (dia.)x 7 pieces x 2 poles
Magnetic pole sizes	87 mm (in diameter)	230 mm (in diameter)
Magnetization modes	Pulsed field (at 38K)	Field cooling (5 T at 67K)
Refrigerators	Gifford-McMahon	Stirling Pulse Tube
Ultimate temperature	35 K	65 K
Output of refrigerator	15W (at 77K)	8 W (at 77K)
Dimensions	900x600x1100 mm^3	1250x650x1000 mm^3
Power supply	3 kW (ac100V)	1 kW (ac100V)
Weight	180 kg	220 kg

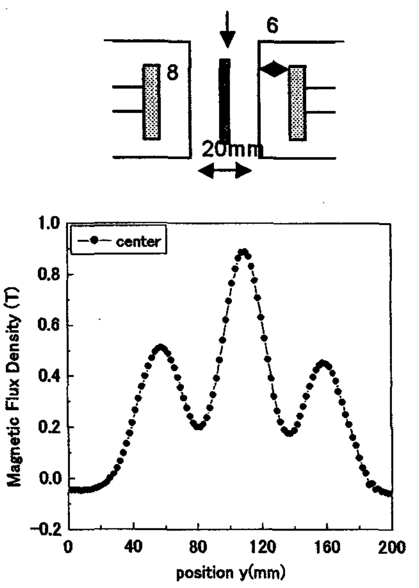

Figure 9. The magnetic field distribution measured along the center of face-to face arranged magnetic poles. The maximum data of 0.9 T was obtained at the center.

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