Trapped field evaluation of ring-shaped GdBCO bulk magnet excited by pulsed field magnetization

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Abstract. Recently, physical and mechanical properties of REBCO bulk are improved, and, accordingly, various practical applications are considered. As one of them, a portable bulk NMR system has been developed, and, then, the improvement of the system for practical use are progressing. In that system, 6 stacked bulks were magnetized by a superconducting magnet for NMR, resulting that the magnetic field of 4.74 T and inhomogeneity of 6.9 ppm were achieved. In this paper, we fabricated the bulk magnet with the room-temperature bore specialized in pulsed-field magnetization. The ring-shaped bulk was activated by pulsed-field magnetization, and, magnetic fields on the bulk surface and in the room-temperature bore of bulk magnet were evaluated. In the bore, the trapped field was approximately 0.79 T and homogeneity was over 150000 ppm.

1. Introduction

Recently, mechanical reinforcing technique as well as material process technique of REBCO bulk are improved remarkably, and, accordingly, a high trapped field in excess of 10 T can be achieved. Therefore, various practical applications in industrial, environmental and medical fields are considered [1]-[4]. As one of the applications, Nakamura, et al. developed a portable NMR system, in which multiple ring-shaped bulks are stacked and they are magnetized by field cooling using a superconducting magnet for NMR. The magnetic field of 4.74 T and homogeneity of 6.9 ppm were achieved, and, moreover, acquiring the cross-sectional images of mouse fetus was succeed [5]. In other studies, several methods were proposed to generate a magnetic field with high uniformity: A trapezoidal-shaped distribution was formed by field cooling with very low applied field [6]. Concave and convex magnetic fields were combined in a face-to-face type bulk magnet [7]. The merits of the above bulk NMR system are space-saving, low-running cost and portability. However, a superconducting magnet was used for excitation in those methods, and, thus, the versatility is reduced because the institution for magnetization is limited.

We discuss to apply to pulsed-field magnetization (PFM) for magnetization of the NMR system to increase the versatility of bulk NMR system greatly because the exciting equipment is not superconducting magnet but common copper coil and condenser bank. However, to our knowledge, a trapped field characteristic in a room-temperature bore when a ring-shaped bulk is activated by PFM has not been investigated. In this study, a ring-shaped GdBCO bulk was excited by PFM. Magnetizing characteristics were investigated by measuring the trapped flux density on the bulk surface, and, moreover, trapped field distribution in the room-temperature bore of the ring-shaped bulk were evaluated.
2. Experimental

We fabricated the bulk magnet with the room-temperature bore of 23 mm in diameter specialized in PFM. Figure 1 shows photographs and schematic of a ring-shaped bulk magnet. A high-performance GdBCO bulk with the dimensions of 60 mm in outer diameter, 28 mm in inner diameter and 20 mm thick (Nippon Steel Corporation), which was reinforced mechanically with a SUS316L steel ring 2 mm thick, was located on the sample stage connected to the second stage of a two-stage GM type refrigerator (RM20, ULVAC). The soft-iron yoke made of pure iron with the dimensions of 64 mm in outer diameter, 28 mm in inner diameter and 20 mm thick was insert between the bulk and the sample stage. The bulk was wrapped with a superinsulation, and, then, the vacuum chamber with a room-temperature bore of 23 mm in diameter and 40 mm in depth was attached.

After the bulk was cooled to 20 K, a single pulsed field was applied with varying the amplitudes from 3.9 to 6.2 T, where the rising time and the fall time of the pulsed field were 10 ms and 100 ms, respectively. During magnetization, the magnetic flux density was monitored using a transverse-type Hall sensor (BHT-921, F.W.BELL) adhered at the center of bulk surface in an interval of 100 μs. After magnetization, the three-dimensional Hall sensor (BH-703, F.W.BELL) was scanned on the chamber surface and in the room-temperature bore with a 2-mm pitch for measuring the distribution of trapped flux density, and, moreover, the homogeneity in the area of 8x8 mm² (r-direction) and -4 to 4 mm (z-direction) was evaluated. In addition, multi pulsed fields of 6.2 T and 5.4 T were applied sequentially without demagnetization.

3. Results and discussion

3.1. Magnetic field distribution on the chamber surface

Figure 2 shows the time responses of magnetic flux density on the bulk surface, \( B_z \), for applied fields, \( B_{app} \), of 3.9-6.2 T. The trapped field increased with an applied field from 3.9 T to 5.4 T, and,
after reaching a peak, the $B_z$ value decreased with increasing $B_{app}$ due to large flux flow. The maximum flux density was 0.87 T for $B_{app}=5.4$ T. As compared with a disk-shaped bulk in our previous study, a decrease of magnetic flux was large because the thickness of radius direction was thin.

Figure 3 illustrates the magnetic field distributions of $B_z$ and $B_r$ on the chamber surface at multipulse application. Both $B_z$ and $B_r$ distributions formed concentric shape, indicating that the bulk has the uniform quality in the whole sample without crack. However, there are small distortions in the map. Although it is no problem for strong magnet application, there is a possibility that those have a big influence on uniformity in case of NMR application. The maximum $B_z$ and $B_r$ were more than 0.5 T, while the trapped field at the center part were very small.

Figure 4 shows (a) applied field dependence of magnetic flux density of $B_z$ and $B_r$ at the center of chamber surface and (b) homogeneity at the area of 8x8 mm$^2$ including the center. The $B_z$ and $B_r$ increased monotonically with applied field, and these maximum values were 0.19 T and 0.09 T, respectively. On the other hand, homogeneities of $B_z$ and $B_r$ were almost constant values of about 500000 ppm and 1700000 ppm, respectively. The small heterogeneity of bulk material appears as large inhomogeneity in case of PFM.

![Figure 4](image1.png)

**Figure 4.** Applied field dependence of (a) applied field dependence of magnetic flux density of $B_z$ and $B_r$ at the center of chamber surface and (b) homogeneity at the area of 8x8 mm$^2$ including the center

![Figure 5](image2.png)

**Figure 5.** Magnetic field distributions of $B_z$ and $B_r$ in the room-temperature bore
3.2. Magnetic field distribution in the room-temperature bore

Figure 5 illustrates the magnetic field distributions of $B_z$ and $B_r$ in the room-temperature bore at the multi-pulse application, where $z=0$ indicates the center of bulk magnet as shown in the inset. At $z=0$, there are homogeneous region of $B_z$ in the area of $4 \times 4$ mm$^2$ and the region where $B_r$ is almost zero. At $z=4$, both homogeneities of $B_z$ and $B_r$ were worse.

Figure 6 shows position dependence of magnetic flux density of $B_z$ and $B_r$ as function of applied field, where open symbols and closed symbol denote single-pulse and multi-pulse, respectively. In Figure 6(a), the $B_z$ value of $z=-4$ and -2 was higher than that of $z=0$ for $B_{app}=3.9$ and 4.3 T, implying that magnetic flux was not trapped fully. The $B_z$ increased with applied field, and the maximum value for $B_{app}=6.2$ T was 0.67 T. In a multi-pulse, the $B_z$ was improved to be 0.79 T. In Figure 6(b), the $B_r$ value of $z=0$ was lower than that of other positions for above $B_{app}=5.4$ T, implying that the direction of magnetic flux were aligned in $z$-axis at the center. In Figure 6(c), the variation of homogeneity was big though it was desirable that it was improved near $z=0$. The best value was 150000 ppm in a multi-pulse. However, it is insufficient, and, thus, further improvement was needed. Now, we try to increase the homogeneity by applying more pulsed-fields with changing the amplitude and temperature, and a different improving method is considered using a numerical simulation.

![Figure 6](image)

Figure 6. Position dependence of magnetic flux density of (a) $B_z$ and (b) $B_r$, and (c) homogeneity as function of applied field

4. Conclusions

We fabricated the bulk magnet with the room-temperature bore of 23 mm in diameter specialized in pulsed-field magnetization. A ring-shaped GdBSCO bulk with dimensions of $60 \times 28 \times 20$ mm was excited by PFM with varying the amplitude of applied field, and, the trapped field distributions were measured on the magnetic pole surface and in the room-temperature bore. On the magnetic pole surface, the trapped field distribution was the daunts-shape with the maximum flux density of 0.56 T. The $B_z$ value at the center part was 0.11 T and the homogeneity of the area of 8x8 mm$^2$ including the center was more than 500000 ppm. In the room-temperature bore, the maximum flux density was 0.79 T and the homogeneity was approximately 150000 ppm. The trapped field and homogeneity were not insufficient for practical application, and, thus, those improvement is the subject of further study.

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