Formation of uniform magnetic flux distribution for NMR magnets using HTS bulk magnets activated by pulsed-field magnetization

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Abstract

Nuclear magnetic resonance (NMR) magnets generally need an extremely uniform magnetic field in the space where the specimens will be placed. Although high temperature superconducting bulk magnets can obtain an intense magnetic field of more than 3 T, the field distribution is intrinsically characterized to be inhomogeneous, showing steep gradient. Aiming at the practical application of compact and portable NMR magnets, the authors have developed magnet systems capable of generating uniform magnetic fields in a narrow space between face-to-face settled magnetic poles, targeting to obtain a uniform magnetic field between the poles. Here, the authors modified the shape of magnetic field distribution from convex to concave by attaching a ferromagnetic iron plate on one of the pole surfaces, and then settled them face to face with a gap of 70 mm. The uniformity of the magnetic field in the x-y plane was experimentally measured and estimated along various z-axis directions. The best uniformity of 463 ppm at 1.25 T was obtained in the experimental evaluation in the x-y plane of 4 × 4 mm² at z = 0.5 mm from the iron plate surface. The value of uniformity along the z-direction range was extended from 0.8 mm to a depth of 1.1 mm. These results show that the possible space of NMR signal detection or the available sample size can be enlarged.

1. Introduction

As nuclear magnetic resonance (NMR) magnets need extremely high uniform magnetic field spaces, forming homogeneous field distributions using high-temperature bulk magnets (HTS bulk magnets or bulk magnets) was thought to be impossible. HTS bulk magnets essentially exhibit a conical-shaped magnetic field with a steep field gradient [1]. Considerable efforts have been made to achieve a high field trapping of over 16 T in largely grown bulk magnets [2, 3]. The world’s highest trapped flux density in a bulk (RE)BCO superconductor was 17.6 T [4]. Although bulk magnets have substantial potential for NMR magnets, an intense, uniform and stable magnetic field is necessary for the compact NMR devices. Field-cooled hollow-type bulk magnets are promising candidates as strong magnetic field generators for NMR devices [5, 6]. Because hollow-type magnets limit the sample sizes in space, we prepared a uniform magnetic field in the open space of face-to-face magnets.

As the world’s first NMR signal has been detected in a field with a uniformity of 1,500 ppm [5], field uniformity less than 1,500 ppm should be necessary to detect the NMR signals. The authors have attempted to obtain flat magnetic field distribution areas by attaching a ferromagnetic iron plate to one of the pole surfaces [7, 8]. The magnetic field distribution emitted through the iron plate changed from convex to concave through the shielding effect, and the strayed field became inferior to the original field distribution.

In this study, we mainly employed a pair of GM-refrigerators to realize and maintain the superconducting state of HTS bulk magnets instead of any coolant, such as liquid nitrogen. Figure 1 shows an illustrate of the entire system of a bulk magnet system composed of cooling, vacuum, and magnetizing subsystems. After the
evacuation and activation processes, the system enabled the refrigerator to continue driving to maintain the superconducting state. The stability of the trapped field is substantially excellent even in the case of NMR systems when the magnet is cooled to a temperature low enough beneath its critical temperature by cooling it to 40 K after the field trapping at 50 K [9].

The magnetic poles were settled face to face, containing a pair of Sm-Ba-Cu-O HTS bulk magnets. They were cooled to their superconducting state at 30 K using GM refrigerators. When stainless-steel balls were attracted between the poles, they exhibited a shape similar to a bridge. Hence, the maximum field was located at the center of each pole surface [1]. To improve the uniformity of the trapped field, the authors attempted to deform the field distribution using the so-called shimming technique with the use of simple ferromagnetic plates attached to one of the magnetic poles. We refer to the precise measurement results of attempts to obtain uniform magnetic field distributions.

2. Experimental procedure

2.1. Magnetic-pole structures and arrangements

We employed single-pole or face-to-face pole bulk magnet systems, which are kept at around 30 K by a GM cryocooler in a series of experiments. The actual instances of the system configuration are shown elsewhere [7, 8, 10]. Figures 2(a) and (b) show how to create a uniform magnetic field by arranging the original convex- and concave-shaped distributions by attaching a 100 mm-wide iron plate (SS400 in Japanese Industrial Standards). In the figure, the position dependence of the magnetic field uniformity is experimentally estimated as a function of the distance from the iron plate surface on the magnetic pole. They were activated by pulsed-field magnetization (PFM) method by applying a field up to 5 T for 10 times by a copper solenoid. In this paper,
following a single pole containing a hollow bulk magnet magnetized by the field cooling method, the magnetic field distribution between the magnetic poles settled face to face is discussed with respect to the field uniformity, which was activated by PFM [11].

2.2. Evaluation of magnetic field uniformity

Figure 3(a) shows an illustration of the magnetic pole arrangement from the top view of the magnetic pole with an iron plate. To evaluate field uniformity, an iron plate was magnetically attached to a magnetic pole of 86 mm in diameter with a bulk magnet of 65 mm inside diameter. The distance from the bulk magnetic surface to the iron plate was designed to be approximately 6 mm, including a vacuum gap of 1 mm. Figure 3(b) indicates how to analyze the field uniformity data. We obtain the field intensity at 21 points in the $4 \times 4$ mm$^2$ areas of the $x$-$y$ plane by scanning the Hall probe with a pitch of 1 or 0.5 mm. Then the uniformity data were calculated using equation (1) [12]. These data were plotted in a colored map, indicating the data in the respective points in the plane. To restrict the sample area to a small extent, the data of four corner points, indicated by open dots, are removed from the calculation, as shown in (b).

$$ U = \frac{B_{\text{Max}} - B_{\text{Min}}}{B_{\text{Max}}} \times 10^6 [\text{ppm}] $$

3. Results and discussions

3.1. Distribution of the trapped magnetic flux density

Figure 4 shows the magnetic field distribution measured by scanning a Hall sensor independently at the pole surface, exhibiting 1.28 T (S) and 1.48 T (N) and indicating inhomogeneous conical shapes of magnetic field distributions. The slight difference between the field trapping is attributed to the variety of the material. In this paper, the authors refer to the precise measurement results on attempts to obtain uniform magnetic field
distributions by attaching ferromagnetic plates. One of the poles, generating 1.28 T (S), magnetically attached an iron plate on its surface, whose distribution was deformed and showed a concave shape at the centre of the pole surface by shielding the field emission, as shown in figure 5.

The technique is well known to those who work on thin film processes using magnetron sputtering because the strong shielding effect of ferromagnetic materials will limit the thickness of the target material plate on sputtering cathodes. As the magnetic flux entering the iron plate will be repelled aside to the edge of the plate, the stray field along the z-axis was degraded to 0.87 T in this case, showing a concave field distribution. The shape of the magnetic field distribution strongly depends on the properties of the ferromagnetic material. Thus, we should consider well the parameters, such as material compositions, dimensions, and anisotropic magnetic properties, to optimize the useful field distribution for NMR magnets. As the concave shape shifts to convex with increasing distance from the pole surface, the presence of a homogeneous field space is expected in the shifting process [12].

3.2. Evaluation of the trapped magnetic flux distribution

Figure 6 shows one of the mapping data obtained at the 20 × 20 mm² area in the x-y plane at z = 0.5 mm above the iron plate surface. The contour map of the magnetic field (a) and uniformity data (b) derived from the respective areas are expressed in the map. The distance between face-to-face poles was set to 30 mm. As reported in [13], the best uniformity of 463 ppm was obtained at 1.25 T over a wide area of less than 1,500 ppm at the center portion of the pole, which is thinly painted by colors in the figure. The area whose uniformity was less than 1,500 ppm was estimated to be 23 mm². Notably, the intensity was enhanced from 0.87 T to 1.25 T because of the addition of a magnetic flux from the counter pole.
Figure 7 shows another distribution map measured at \( z = 1.6 \) mm. The best uniformity of 956 ppm was obtained in the flat concave shape area of 19 mm\(^2\). Although the shape of the contour map does not shift considerably, the regions under 1,500 ppm were observed in every x-y plane in the range of \( z = 0.5 - 1.9 \) mm. The value was found to extend to the z-direction a depth of 1.1 mm. Hence, a uniform space of \( 4 \times 4 \times 1.1 \) mm\(^3\) will be available to detect its NMR signal for the sample with dimensions of \( 4 \times 4 \times 0.5 \) mm\(^3\). The performance was improved compared with that shown in [13].

The measured data of the numerical uniformity are shown in table 1. The finest uniformity of 1,021 ppm was obtained in the average of three measurements, operated to probe the reproducibility. Because all the uniformity data in the table are less than 1,500 ppm, a uniform field distribution may be successfully performed in a narrow space of \( 4 \times 4 \times 0.5 \) mm\(^3\), corresponding to the sample dimensions. This reproducibility of uniformity was confirmed, as shown in table 1. As the performance of uniformity data is sufficient to detect NMR signals, further investigation on the NMR signal detection system is necessary for the world’s first NMR signal.

To make up for the uniform magnetic field distribution on the mountain top of the conical field distribution, it is surely effective to make a flat peak of field distribution. We may employ a couple of methods to let the bulk magnet trap the trapezoid field distribution or to magnetize the ring-shaped bulk magnet by field cooling mode [14]. These are the alternative ways to obtain a flat distribution on the magnetic pole.

### Table 1. Uniformity data (ppm).

| \( z \) (mm) | 1.4  | 1.5  | 1.6  | 1.7  | 1.8  | 1.9  |
|-------------|------|------|------|------|------|------|
| No.1        | 1148 | 1243 | 956  | 1134 | 1249 | 1263 |
| No.2        | 1429 | 1252 | 1053 | 1156 | 1259 | 1352 |
| No.3        | 1431 | 1341 | 1056 | 1161 | 1358 | 1362 |
| Average     | 1336 | 1278 | 1021 | 1157 | 1288 | 1325 |

measured for 3 times.

Figure 7 shows another distribution map measured at \( z = 1.6 \) mm. The best uniformity of 956 ppm was obtained in the flat concave shape area of 19 mm\(^2\). Although the shape of the contour map does not shift considerably, the regions under 1,500 ppm were observed in every x-y plane in the range of \( z = 0.5 - 1.9 \) mm. The value was found to extend to the z-direction a depth of 1.1 mm. Hence, a uniform space of \( 4 \times 4 \times 1.1 \) mm\(^3\) will be available to detect its NMR signal for the sample with dimensions of \( 4 \times 4 \times 0.5 \) mm\(^3\). The performance was improved compared with that shown in [13].

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### 4. Conclusion

We have attempted to obtain uniform magnetic fields in the space between face-to-face settled HTS magnetic poles for possible industrial applications to compact NMR. Attaching an iron plate to one of the face-to-face settled magnetic poles was found to be sufficiently effective in forming a uniform field space. The best uniformity 463 ppm of magnetic field distribution was obtained in the \( 4 \times 4 \times 0.5 \) mm\(^3\) area in the x-y plane at 0.5 mm from the iron plate surface along the z-axis. The area of the uniform magnetic field less than 1,500 ppm was extended to 1.1 mm (\( z = 0.5 - 1.6 \) mm), which was enlarged in comparison with the former range of 0.8 mm along the z-axis.

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