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# Study on Trapped Field Characteristics of HTS Bulk Annuli With Iron Rings for Ferromagnetic Shimming of a Compact NMR Magnet

SeokBeom Kim, Toshiya Nakano, Riki Takano, and Seung-yong Hahn

***Abstract*—Recently, the performance of high temperature superconducting (HTS) bulks such as critical current density, size, and mechanical strength has been improved rapidly. So, various applications with HTS bulks such as motors, bearings, and flywheels have been investigated by many research groups. A compact nuclear magnetic resonance (NMR) magnet is one of the new applications after the technique to enhance maximum trapped field of the HTS bulk more than 11.74 T, a corresponding $^1$H NMR frequency of 500 MHz, has been developed. This new compact NMR magnet out of HTS bulks is far less expensive than those conventional NMR magnets and expected to be widely used in food and drug industry. In design and manufacture of those compact NMR magnets, spatial field homogeneity of large trapped magnetic field in HTS bulk annuli is essential. This paper presents the magnetic field distribution in single and three assembled HTS bulk annuli, measured by a 3-axis hall sensor, and experimental results of its spatial homogeneity improvement by mounting an iron ring inside or outside of the HTS bulk annuli.**

***Index Terms*—Bulk annuli, compact NMR, HTS bulk.**

## I. Introduction

Nuclear magnetic resonance (NMR) spectroscopy has been paid to attention in food and drug industries as an effective tool for a non-destructive testing of nucleic acids, and its performance, particularly resolution of signal imaging, has been continuously advanced with the enhancement of operating NMR frequency. Though superconducting magnets with active shielding coils contribute to the compact footprint of NMR magnets, still many institutes involving NMR studies struggle with lack of laboratory space as well as high fixed cost to accommodate additional NMR devices. After recent progress of manufacturing high-temperature superconducting bulks [1], the concept of the new type of NMR magnet comprised of stacked high temperature superconducting (HTS) bulk annuli that have more than one-order higher critical current density than that of a superconducting wire was suggested [2].

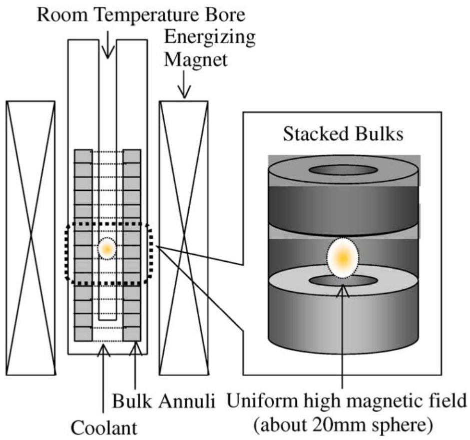

Fig. 1. Conceptual drawing of a compact NMR device using oxide superconducting bulk annuli. After the magnetic field is trapped in the stacked annuli, the external magnet will be removed and may be replaced with stacked iron sheets to reduce a stray field. The target DSV (Diameter Spherical Volume) in this paper is set to 20 mm [2].

Currently, we are undertaking a research of the new type "compact" NMR magnet made out of HTS oxide bulk annuli. It is expected that the new NMR device can achieve not only the compactness (lower footprint) but also cost-efficiency.

Key issues in a success of the compact NMR magnet with HTS annuli include: 1) field impurity that may be easily originated from the passive characteristic of the HTS bulk annulus: 2) homogeneity improvement techniques such as an active or passive shimming, which may be more difficult compared with those conventional NMR magnets because of the magnetic interaction between HTS bulks and shimming devices.

This paper presents an experimental study on the trapped field characteristics in a stack of HTS bulk annuli of which an inner diameter is 20 mm. Also, to further investigate the interaction between the HTS annuli and ferromagnetic pieces as the fundamental study for passive shimming in the compact NMR magnet, an iron ring of different thickness, 1 mm or 2 mm, is inserted into a cold bore of the stacked HTS annuli and the trapped field variation was examined.

## II. Outline of a Compact NMR Magnet

Fig. 1 shows a conceptual drawing with fundamental structures of the proposed compact NMR device. It utilizes a strong magnetic field that is trapped inside the HTS bulk annuli of which critical current density is, at least, one-order higher than

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TABLE I
SPECIFICATION OF BULK ANNULI

| Parameter | Bulk *a,b,c* | Bulk *d,e* | Bulk *f* |
|---|---|---|---|
| Inter diameter of bulks (mm) | 20 | 20 | 20 |
| Outer diameter of bulks (mm) | 60 | 60 | 60 |
| Thickness of bulk (mm) | 15 | 15 | 20 |
| Material of bulk | GdBCO | GdBCO | GdBCO |
| Condition | Used | New | New |

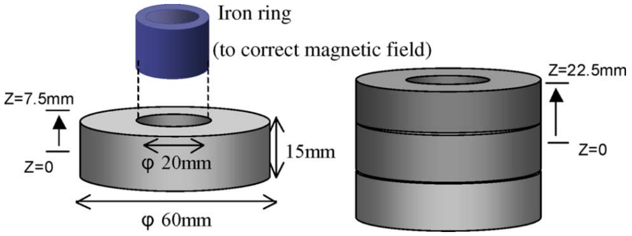

Fig. 2. Schematic to-scale drawing for a single annulus and three stacked annuli, and an iron ring for field homogeneity improvement. The center of stacked annuli or a single annulus was defined as $\mathrm{z} = 0\ \mathrm{mm}$.

that of the LTS wire used for conventional NMR magnets; This high critical current density is an important advantage of the proposed NMR magnet that allows its compactness. An external energizing magnet in Fig. 1 is supposed to produce a homogeneous magnetic field though final field uniform homogeneity for a real NMR application may be achieved by some homogeneity improvement techniques such as an optimized adjusting of relative displacement between each adjacent bulk annuli or active/passive shimmings. The ability of trapping a strong magnetic field is an unique characteristic of the oxide superconducting bulks and, combined with the structure of stacked annuli, the proposed NMR magnet is expected to produce more than 11.74 T which corresponds to the $^1\mathrm{H}$ NMR frequency of 500 MHz.

## III. EXPERIMENTAL DETAILS

In this study, six GdBCO oxide-superconducting bulks shown in Table I were used, of which inner/outer diameter and thickness are 20/60 mm and 15 mm, respectively, except the bulk $f$ having a thickness of 20 mm. Though Bulks $d$, $e$ and $f$ are primary samples that had never been used before in any other experiments, for the purpose of comparison, those used Bulks $a$, $b$ and $c$ having a few cracks were also tested in the present research.The stacked oxide superconducting bulks may be placed in a bath of liquid nitrogen, neon or helium depending on a target operating temperature as well as a required NMR frequency level. A separate room-temperature (RT) bore provides an axial access of a NMR probe; A typical minimum RT bore size is 38 mm though, in the present research, it is 20 mm, an acceptable range in a laboratory research purpose. Once the target field is trapped and the external magnet is discharged, a set of external iron shielding stacks may be installed for the purpose of limiting a stray field less than 5 gauss in ~3 meter radius.

Fig. 2 shows a schematic to-scale drawing for a single annulus and three stacked annuli, and iron ring used to improve the homogeneity of a trapped magnetic field in a bore of the bulk magnet. Two iron rings with different thickness of 1 mm and 2 mm, respectively, were used to improve the trapped field homogeneity. The HTS bulk annuli were magnetized by a field cooling (FC) method, and the axial and radial components of the trapped magnetic field on the surface and in the bore of the stacked annuli were scanned by a 3-axis Hall probe. The 3-axis hall probe with a $50 \times 50\ \mu\mathrm{m}^2$ sensing area was mountedon a computer controlled $x - y$ stage with a spatial resolution of 1 $\mu\mathrm{m}$. The scanning area and its resolution on the top surface of a sample annulus are schematically shown in Fig. 3.

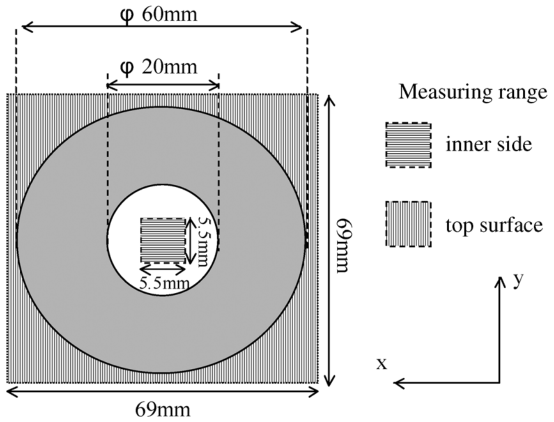

Fig. 3. A schematic view of a scanning area and its resolution on the top surface of a sample bulk annulus.

## IV. RESULTS AND DISCUSSION

In this study, fundamental characteristics of passively shimming a trapped magnetic field was investigated experimentally using iron rings mounted at the inner wall of the stacked annuli bore. The effects of the iron ring are discussed with comparison between the result of a single bulk annulus and that of three stacked bulk annuli. Also, the comparison between trapped fields of cracked and non-cracked samples is discussed with some experimental results. All the tests were done in a bath of liquid nitrogen, i.e., at ~77 K.

### A. Single Bulk Annulus

The measured axial magnetic field distributions, $B_z$, at the upper surface and in the bore of bulk $b$ with/without iron rings are shown in Fig. 4, when the applied magnetic field was 1.0 T. From Fig. 4(a), it is obvious that the bulk b has at least four weak links or more so that the overall field homogeneity is not uniform both at its upper surface and in its inner bore. Even after the iron ring with 1 mm thickness was inserted, its impact on the inner-bore field homogeneity improvement was not significant as shown in Fig. 4(b). However, the homogeneity of the inner-bore magnetic field distribution becomes better when the 2 mm thickness iron ring was mounted and the strength of the magnetic field decreases; the field lines in Fig. 4(c) became more circular than those of (a) and (b). Fig. 5 shows the measured axial field profiles along the radial line indicated as dotted lines in Fig. 4 $(\mathrm{z} = 7.5\ \mathrm{mm})$ which was defined as "x-axis". The best spatial uniformity of magnetic field was obtained with the 2 mm thickness iron ring as expected. However, the trapped

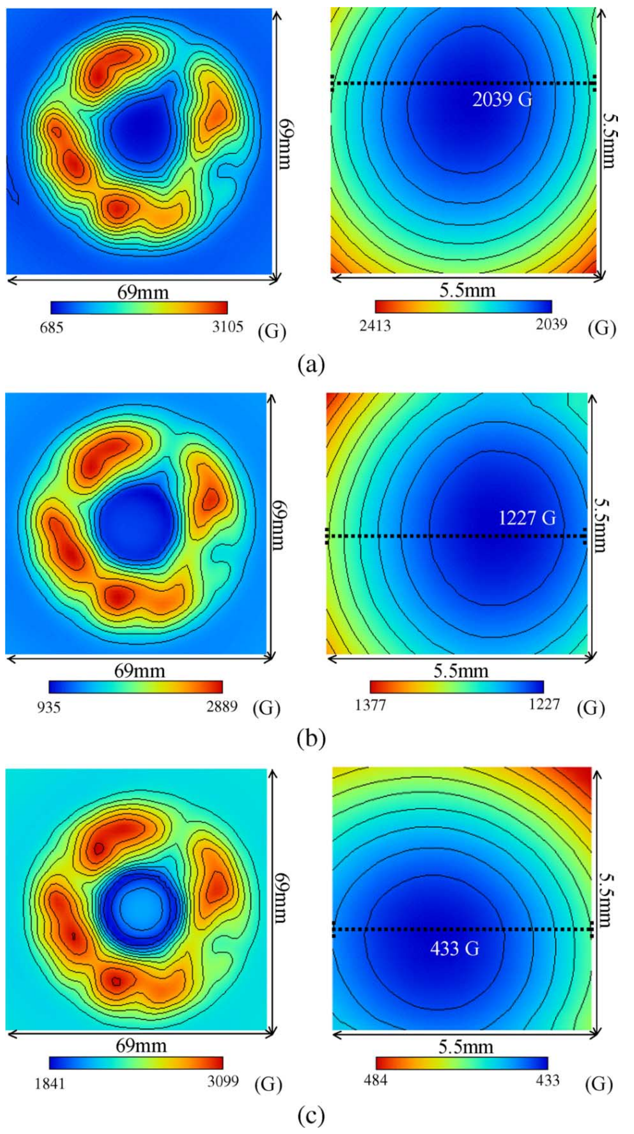

Fig. 4. Magnetic field distributions at the top surface (left, $z = 7.5\ \mathrm{mm}$) and the inner bore (right, $z = 0\ \mathrm{mm}$) of the used bulk annulus (bulk b) with/without iron rings of two different thicknesses, 1 mm and 2 mm respectively, when the applied magnetic field is 1.0 T. (a) Without iron ring, (b) with inserted iron ring (thickness:1 mm), and (c) with inserted iron ring (thickness:2 mm).

field strength was reduced as the length of the iron ring was increased, because more magnetic flux bypassed through the iron rings.

In a real NMR magnet that requires more than a 10 T magnetic field, the iron ring will be saturated and the trapped field reduction may not be significant, while the field homogeneity improvement within a range of $10 \sim 100$ ppm order is still achievable. The present result proves a feasibility of a ferro-magnetic passive shimming for the HTS bulk annuli magnet that is another passive element in a bulk NMR magnet. This passive-passive elements (iron shims vs. HTS bulks) shimming will become a real challenge in the ultimate success of an HTS anulus magnet to achieve an NMR quality homogeneity, $<0.1$ ppm.

Fig. 6 shows the measured magnetic field distributions at the top surface and in the bore of bulk $d$, the new one having no cracks. The critical current density of bulk d is higher and spatially more uniform than those of $a$, $b$, and $c$, too. Fig. 7 shows

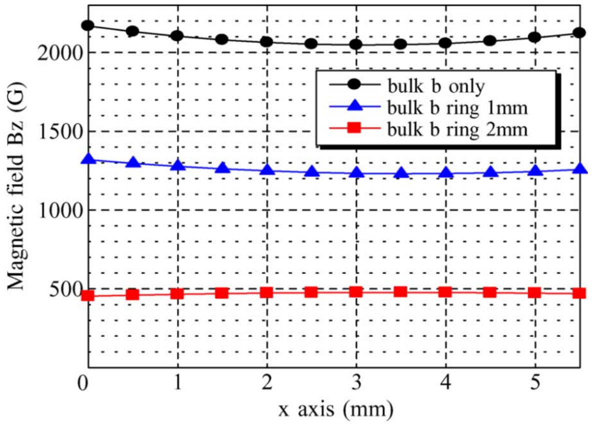

Fig. 5. Measured axial field profiles of bulk $b$ along the radial line indicated as the dotted line in Fig. 4 ($z = 7.5\ \mathrm{mm}$) which was defined as "x-axis" here.

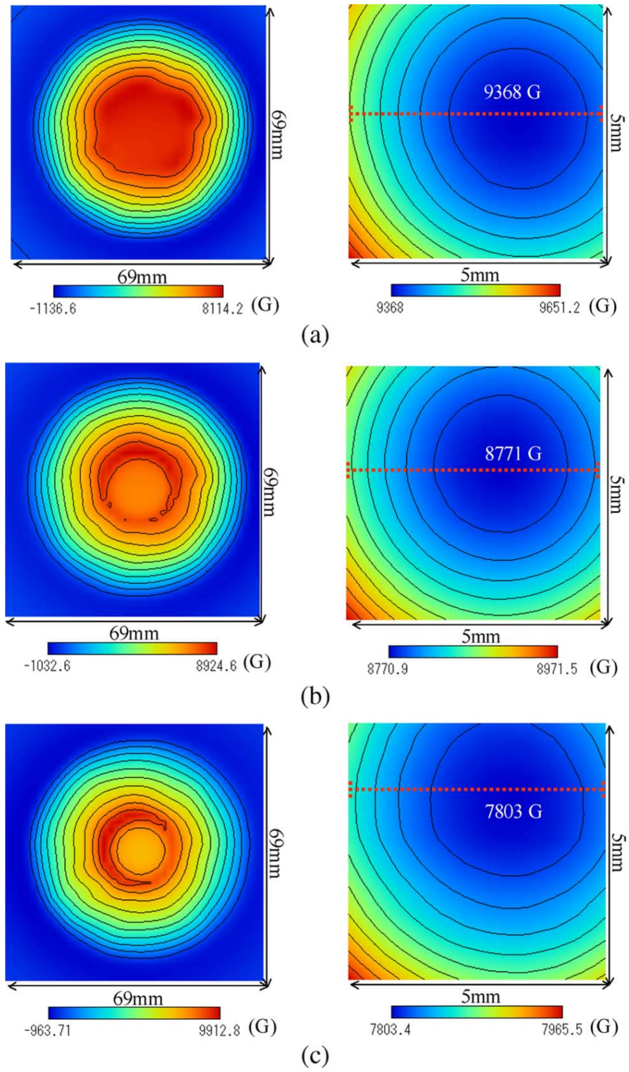

Fig. 6. Magnetic field distributions at the top surface (left, $z = 7.5\ \mathrm{mm}$) and the inner bore (right, $z = 0\ \mathrm{mm}$) of the new bulk annulus (bulk d) with/without iron rings of two different thicknesses, 1 mm and 2 mm respectively, when the applied magnetic field is 1.0 T. (a) Without iron ring, (b) with inserted iron ring (thickness:1 mm), and (c) with inserted iron ring (thickness: 2 mm).

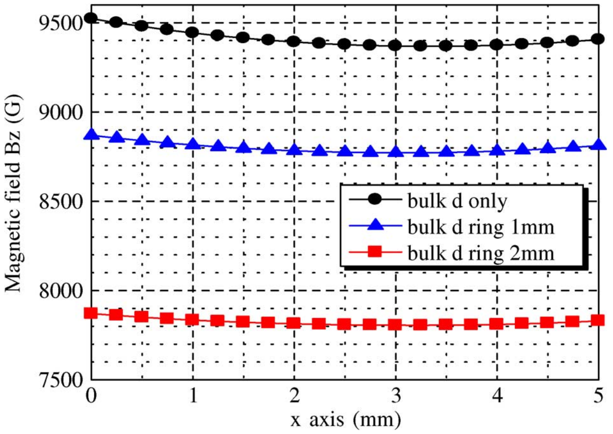

Fig. 7. Measured axial field profiles along the radial line indicated as the dotted line in Fig. 6 ($z = 7.5$ mm) which was defined as "x-axis".

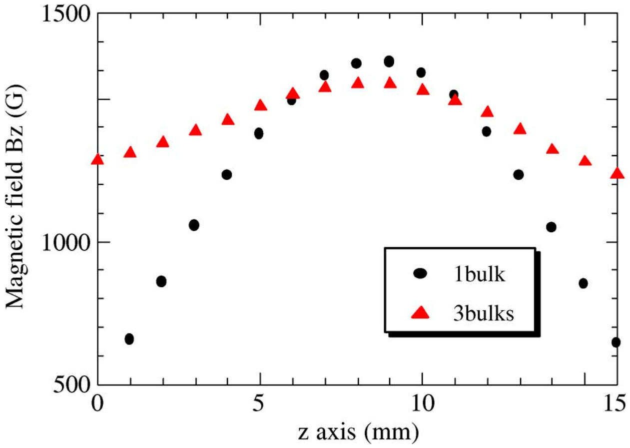

Fig. 8. Measured axial magnetic field profiles along the axis of the stacked annuli from: the single bulk annulus (black circle, bulk $b$) and three stacked bulk annuli (red triangle, bulks $a$, $b$ and $c$) when an applied magnetic field is 1.0 T.

the measured axial field profiles along the radial line indicated as dotted lines in Fig. 6 ($z = 7.5$ mm) which was defined as "x-axis". Although the effect of the iron rings on field homogeneity improvement is still obvious in Figs. 6 and 7, its impact is relatively less than that of the cracked bulk cases in Figs. 4 and 5 because the original trapped field distribution without an iron ring with bulk $d$, $e$, and $f$ was much better than the other a, b, and c.

### *B. Stacked Bulk Annuli*

Here, we experimentally investigated the trapped field characteristics of three stacked bulk annuli. Fig. 8 shows the measured magnetic field profiles along the axis of the stacked annuli (used Bulks $a$, $b$ and $c$) when applied magnetic field was 1.0 T. The total height of the stacked annuli is 45 mm. Although the axial field homogeneity became better than those of a single bulk as shown in Fig. 8, still its field distribution was significantly non-uniform and even the peak field of 3 stacked annuli was a bit smaller than that of a single one because of the presence of cracks in each annulus. However, the field uniformity was improved when the new ones (Bulks $d$, $e$ and $f$) were used as shown in Fig. 9, because not only the field quality from the individual annulus was enhanced but also the total height of the stacked annuli was increased to 50 mm. As a conclusion, it is clear that the better field uniformity of each annulus and the axially longer stack of annuli are preferred in order to obtain a NMR-grade field homogeneity in a real stacked-annulus NMR magnet.

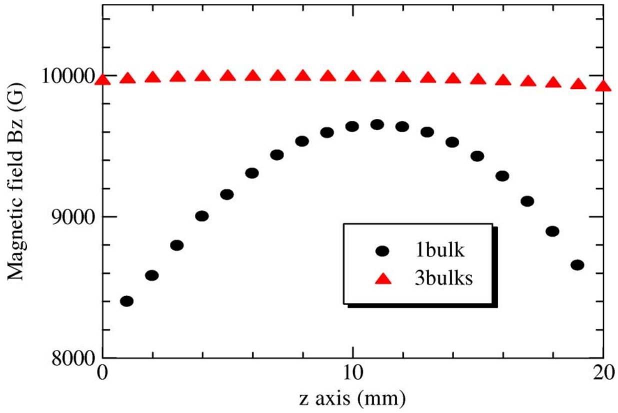

Fig. 9. Measured axial magnetic field profiles along the axis of the stacked annuli from: the single bulk annulus (black circle, bulk $d$) and three stacked bulk annuli (red triangle, bulks $d$, $e$ and $f$) when an applied magnetic field is 1.0 T.

## V. CONCLUSION

The experimental study on trapped field characteristics in a stack of HTS (GdBCO oxide) bulk annuli was performed as the fundamental research to develop the compact NMR device. Axial trapped field distributions were measured in a 3-dimensional space and analyzed with various HTS annulus samples, with or without a crack, under different trapped field conditions. The correction of the magnetic field was examined by inserting an iron ring into the cold bore of the HTS bulk annuli. Although the maximum trapped field was reduced, it was clear that the magnetic interactions between the HTS bulk annuli and the iron ring have improved the quality of the trapped field. The results imply that, in a real compact HTS bulk NMR magnet, the spatial field homogeneity can be enhanced by ferromagnetic shimming, which is one of the most important issue in the successful development of the compact NMR magnet in near future.

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