

Numerical study to obtain the improved field homogeneity of HTS bulk magnet with enlarged inner diameter for compact NMR

S Fukada, S B Kim, T Nakagawa, R Nomura and H Ueda

Graduate School of Natural Science and Technology, Okayama University, 3-1-1, Tsushimanaka, Kita-ku, Okayama 700-8530, Japan

kim@ec.okayama-u.ac.jp

Abstract. The strength and homogeneity of the magnetic field required for NMR relaxometry device are 1.5 T and 150 ppm/cm³ respectively. It is relatively easy to generate the trapped magnetic field over 1.5 T at 77.4 K using the stacked HTS bulks, and 150 ppm/cm³ field homogeneity was obtained using the fabricated field compensation methods on HTS bulks magnet with 20 mm inner diameter. However, it is still hard to obtain 150 ppm/cm³ field homogeneity without field compensation methods. In this paper, in order to improve the trapped magnetic field homogeneity, the HTS bulk magnet with enlarged inner diameter was proposed and studied as the functions of size and shape of HTS bulk. The analytical study based on FEM was carried out to optimize the shape of HTS bulk magnet with enlarged inner diameter.

1. Introduction

Nuclear magnetic resonance (NMR) device is used for analyzing tool of organic compound and has been paid attention in food, medicine and drug industries. The NMR signal resolution is improved by increasing the magnetic field strength, and 1 GHz-class (23.5 T) NMR magnet wound with low temperature superconducting conductors such as NbTi and Nb₃Sn has been already developed. On the other hand, a new type NMR magnet consisted of the stacked HTS bulk annuli (ring-shaped) where magnetic fields were trapped by field cooling method had been suggested and fabricated by Nakamura at RIKEN in Japan [1], [2]. The magnetically charged HTS bulk magnet for NMR device does not need a power supply and additional coolant supply system. Therefore, this is not only economical but also compact [3], [4]. Furthermore, the NMR relaxometry device was produced by Stelar s.r.l., and its field homogeneity is 150 ppm/cm³ [5]. We have been developing a new compact NMR magnet using stacked HTS bulk magnets. The strength and homogeneity of the magnetic field required for NMR relaxometry device are 1.5 T and 150 ppm/cm³ respectively, these values are higher than the permanent magnet NMR and lower than the conventional NMR device. In a previous study, we have already achieved the target values of 1.5 T and 150 ppm/cm³ by using passive and active field compensation methods [6], [7] and remagnetization method [8]. However, it is still hard to obtain 150 ppm/cm³ field homogeneity using the conventional superconducting magnet (SCM) without field compensation methods. The magnetic field distributions and intensities of the HTS bulk depend on the magnetic field of SCM. The field homogeneity of our SCM is more than 600 ppm/cm³, and it is impossible to achieve 150 ppm/cm³ without any shimming methods. In general, the NMR magnet with a large sample space is required to provide the space for shimming coils. In this study, the shape design of HTS bulk magnet was studied



using FEM based analysis to obtain the field homogeneity of 150 ppm/cm³ without field compensation methods and to provide the enlarged inner space.

2. HTS bulk magnet for NMR relaxometry

In this study, GdBa₂CuO_x (GdBCO) HTS bulks and SCM were used. Each annulus HTS bulk have 5 mm thickness, 20 mm inner diameter and 60 mm outer diameter. The SCM (JASTEC.Inc.) which have been used in our laboratory have a 100 mm room temperature bore size and 10 T magnetic field strength. The field homogeneity of SCM is 610 ppm/cm³ in the center region along the ± 5 mm axial direction, and the almost same scale SCM was used in analysis. In this study, the trapped magnetic fields of HTS bulk magnet were obtained by field cooling (FC) method with 1.6 T magnetization field at 77.4 K. The current flowed in the HTS bulk during the FC process were induced by the Bean's critical state model and n -value model. The trapped magnetic fields of HTS bulks were calculated by their currents. In this study, the properties of the enlarged inner diameter (ID) HTS bulk magnet were investigated. Figure 1(a) shows the scaled cross-sectional drawing of the "Basic model" of HTS bulk magnet with various ID when the outer diameter (OD) was fixed at 60 mm. Figure 1(b) shows the "Hollow model", the inside of a center part of HTS bulk magnet having an inner diameter of 20 mm is hollowed out in the radial direction. The height (5 and 10 mm) and diameter of enlarged hollow space were used as parameters when the OD was fixed at 60 mm. Figure 1(c) shows the "Bugle model" with the various height (5 and 10 mm) and diameter of the enlarged hollow space while maintaining the radial thickness of HTS bulk at 20 mm. Therefore, the diameter of the enlarged hollow space in figures 1(b) and 1(c) is defined as ID, and the total volume of HTS bulk of each model was different. So, in this study, the three models were examined with various inner diameter and height of hollow space to investigate the optimal shape that enhances the field homogeneity of HTS bulk magnets.

As a result of analysis, the calculated field distributions along z -axis and r -axis are shown in figure 2. In figure 2, ID of Basic model is 20 mm, ID of Hollow and Bugle models is 30 mm and the height of hollow space is 5 mm. From figure 2, the magnetic field strengths of the Hollow model and the Bulge model were lower than the Basic model. This result is due to the difference of volume of the HTS bulk in the radial direction of the measurement space. Figure 3 shows the calculated field homogeneity at the center region along ± 5 mm in the z -axis and r -axis directions of the three models as shown in figure 1. From figure 3, the magnetic field homogeneity of the Basic model and the Hollow model was deteriorated because the presence area of the magnetic flux was enlarged by expanding inner diameter. In addition, the field homogeneity of r -axis is usually superior to z -axis, as shown in figure 3, so we mainly discuss the field distribution and homogeneity of z -axis. Figure 4 shows the calculated field homogeneity along ± 5 mm in the z -axis direction of Hollow and Bulge models as a function of ID value. From figure 4, the Bulge model has better uniformity than the Hollow model because the part protruding outermost of the Bulge model plays the role of a notch coil as shown in figure 5. Figure 5 shows the calculated current density distributions in the r - z plane of the Hollow and Bulge model magnets. From figure 5, supercurrent of the Bulge model locally flows to bulging part. Therefore, degradation of uniformity due to the expansion of inner diameter was suppressed in the Bulge model. From the above results, the Bulge model should be suggested to enlarge the ID of HTS bulk magnet with high field homogeneity.

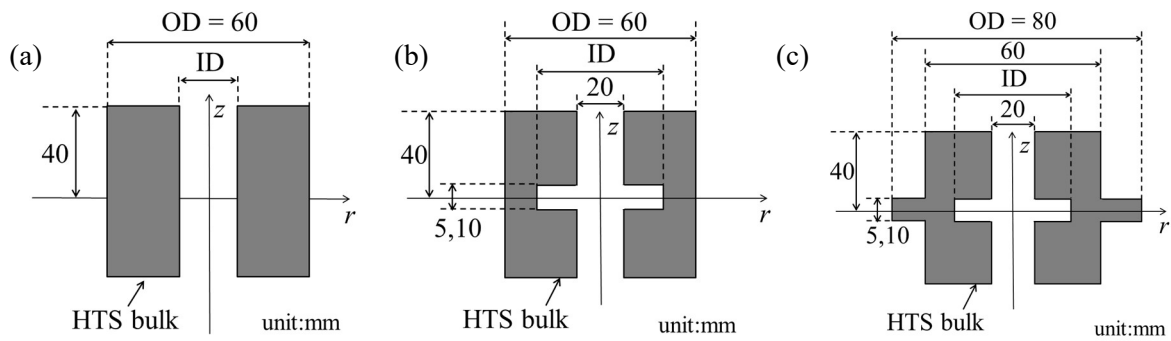


Figure 1. Scaled cross-sectional drawing of the (a) Basic model, (b) Hollow model and (c) Bulge model.

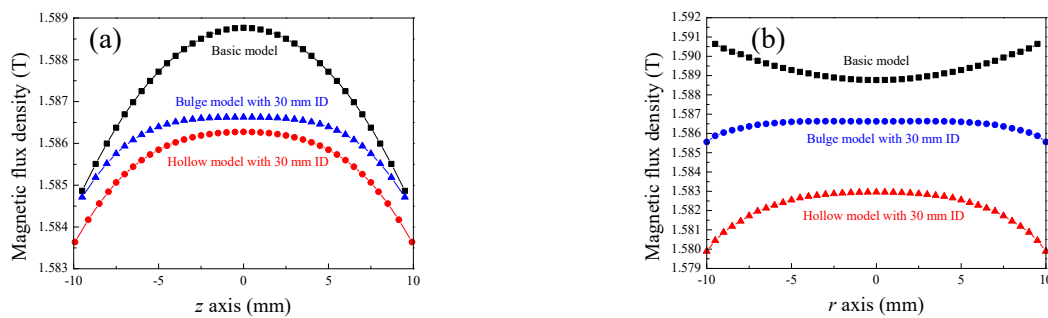


Figure 2. Calculated field distributions on the (a) z -axis and (b) r -axis when the height of enlarged hollow space in Hollow and Bulge models is 10 mm.

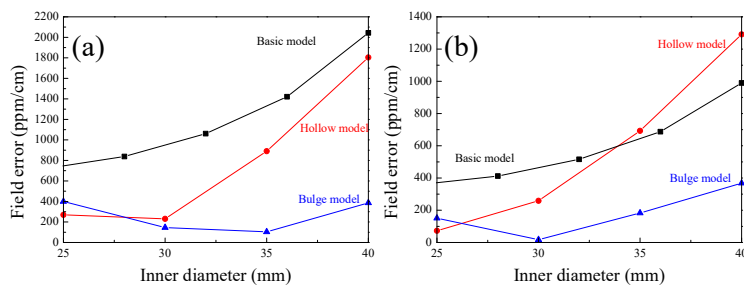


Figure 3. Calculated field homogeneity on the (a) z -axis and (b) r -axis directions as a function of ID value when the height of enlarged hollow space of Hollow and Bugle models is 10 mm.

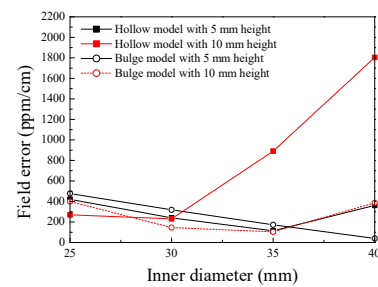


Figure 4. Calculated field homogeneity on the z -axis direction as the functions of ID value and height of enlarged hollow space.

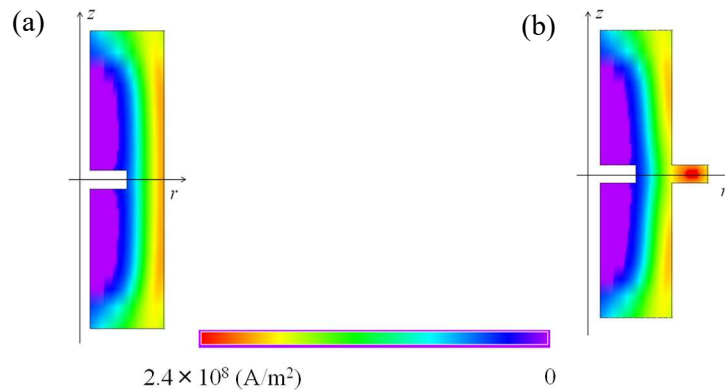


Figure 5. Calculated the current density distributions in the r - z plane of (a) Hollow model and (b) Bulge model.

3. Field distribution and homogeneity of Bulge model

It is clear that the Bulge model is suitable for enlarging the inner diameter and improving the magnetic field homogeneity. Therefore, the possibility of enlarging the inner diameter was investigated as functions of ID and OD values when the heights of the hollow space are 4 and 5 mm.

3.1. The Bulge model with 5 mm and 10 mm height of enlarged hollow space

In order to investigate the influence by the size of the ID of the Bulge model, an analytical model with a fixed OD are prepared firstly. Figure 6 shows the calculated field distributions in z -axis as a function of ID value when the heights of hollow space are 5 mm and 10 mm and the OD of HTS bulk is fixed at 80 mm. Figure 7 shows the calculated field homogeneity along ± 5 mm in the z -axis and r -axis directions as a function of ID value when the heights of hollow space are 5 mm and 10 mm. From figure 6, the magnetic field strength at center part was reduced with increasing ID because the total volume of HTS bulk was decreased with increasing the ID. From figure 7, the magnetic field homogeneity was deteriorated because the presence area of the magnetic flux was enlarged by expanding ID. In the Bulge model with fixed 80 mm OD, there was no ID value to achieve the target magnetic field homogeneity of 150 ppm/cm in the height and the radial directions. Therefore, we examined the Bulge model with various height and diameter of the hollow space while maintaining the radial thickness of HTS bulk at 20 mm. Figure 8 shows the calculated field homogeneity along ± 5 mm in the z -axis and r -axis directions when the heights of hollow space are 5 mm and 10 mm. As shown in figure 8, the target field homogeneities below 150 ppm/cm were obtained when the ID 40 mm, OD 80 mm and 5 mm height of hollow space, and ID 30 mm, OD 70 mm and 10 mm height.

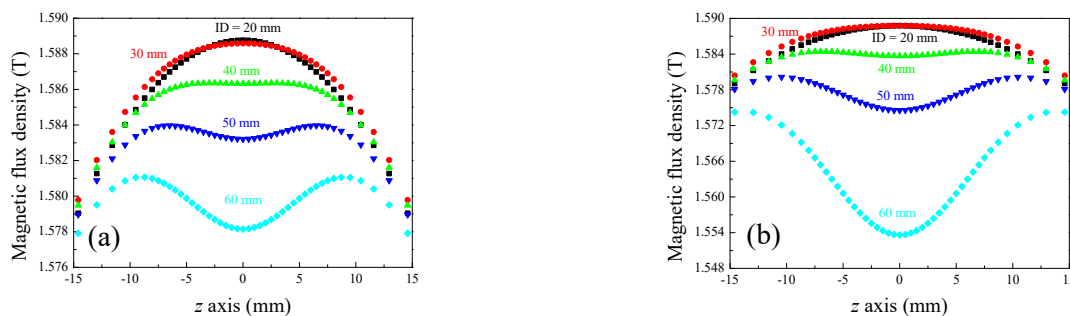


Figure 6. Calculated the field distributions along z -axis direction of Bulge model with fixed 80 mm OD as a function of ID value and the heights of enlarged hollow space are (a) 5 mm and (b) 10 mm.

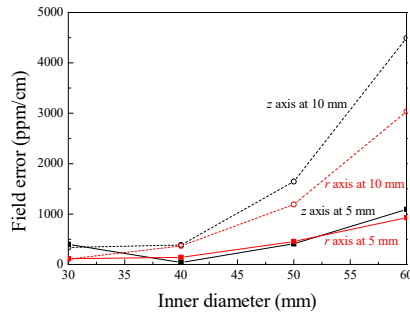


Figure 7. Calculated the field homogeneity on the z -axis and r -axis directions of Bulge model with fixed 80 mm OD as a function of ID value and the heights of enlarged hollow space are 5 mm and 10 mm.

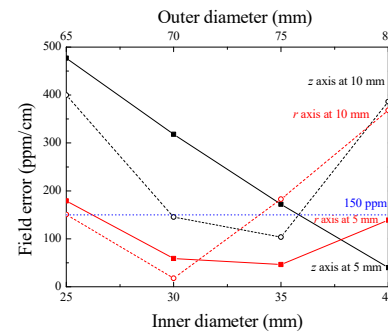


Figure 8. Calculated the field homogeneity on the z -axis and r -axis directions of Bulge model maintaining the radial thickness of HTS bulk at 20 mm as a function of ID value and the heights of enlarged hollow space are 5 mm and 10 mm.

3.2. Reducing of the Number of HTS Bulk

Reducing the number of HTS bulk is directly linked to reducing the cost and size of HTS bulk magnets. So, the analytical study to reduce the number of HTS bulk without decreasing the field homogeneity was carried out using modified HTS bulk magnets used for real applications as shown in figure 9. In previous section, the target field homogeneities below 150 ppm/cm were obtained in the two Bulge models with ID 40 mm, OD 80 mm, 5 mm height and ID 30 mm, OD 70 mm, 10 mm height, respectively. Therefore, we considered how much the number of HTS bulk could be reduced while maintaining the target field homogeneity using two Bulge models. Figure 9(a) shows the model which has 5 mm height of hollow space and HTS bulks were stacked from 11 to 17. Figure 9(b) shows the model which has 10 mm height of hollow space and HTS bulks were stacked from 8 to 16. Figure 10 shows the calculated field homogeneity along ± 5 mm in the z -axis and r -axis directions as a function of the number of bulks when the gap length between HTS bulks except center region were 1 mm and 3 mm. We succeeded to reduce the total number of HTS bulk from 16 up to 10 while keeping the target field homogeneity of 150 ppm/cm.

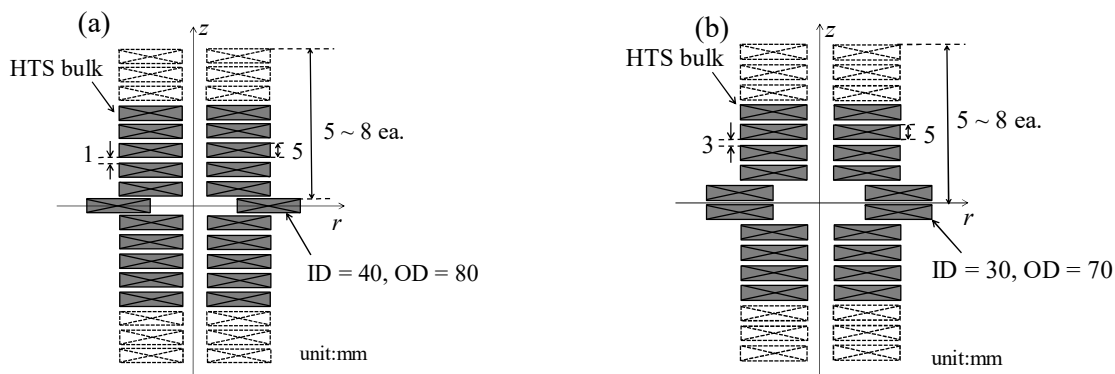


Figure 9. Scaled cross-sectional drawing of Bulge model magnets with different enlarged hollow space to study the reducing the number of HTS.

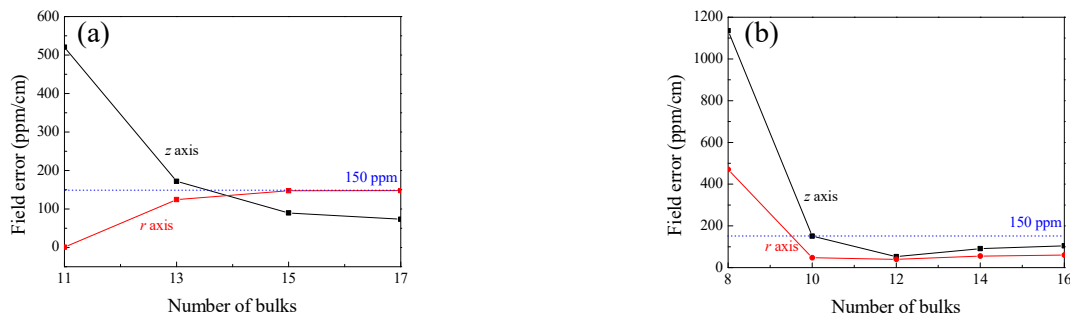


Figure 10. Calculated the field homogeneity of Bulge models in figure 9 as a function of the number of HTS bulks.

4. Conclusions

We have been developing NMR relaxometry magnet using stacked HTS bulk with inner diameter of 20 mm. NMR relaxometry magnet requires the field strength of 1.5 T and field homogeneity of 150 ppm/cm³. It is easy to obtain the field strength. However, it is still hard to obtain 150 ppm/cm³ field homogeneity. In this study, FEM based analysis was carried out to optimize the HTS bulk magnet for NMR relaxometry with enlarged inner diameter. The bulge model was mainly studied analytically because it has better uniformity than the single model and the hollow model. The field homogeneities at sample space were improved with enlarged ID and OD HTS bulks located at centre part in the bulge model. We obtained the high field homogeneity using the proposed 16-stacked bulge model, and succeeded to reduce the number of HTS bulk to 10-stacked while keeping the target field homogeneity of 150 ppm/cm³.

References

- [1] Nakamura T, Itoh Y, Yoshikawa M, Oka T and Uzawa J 2006 Development of a superconducting magnet for nuclear magnetic resonance using bulk High-Temperature superconducting materials *Concepts in Magnetic Resonance Part B* p 65.
- [2] Iwasa Y 2006 HTS and NMR/MRI magnets: Unique features, opportunities, and challenges *Physica C* **445-448** pp 1088-1094.
- [3] Hahn S, Kim Y, Voccio J, Park D K, Gagnon B, Bascuñán J, Tomita M and Iwasa Y 2013 Bulk and Plate Annulus Stacks for Compact NMR Magnets: Trapped Field Characteristics and Active Shimming Performance *IEEE Trans. Appl. Supercond* **23** no. 3, 4300504.
- [4] Ogawa K, Nakamura T, Terada Y, Kose K and Haishi T 2011 Development of a magnetic resonance microscope using a high Tc bulk superconducting magnet *Appl. Phys.* L98 234101.
- [5] <http://www.ffcrelax.com/schoolNMR/school2009/download/pdf/Ferrante/SchoolNMR.pdf>
- [6] Kitamura H, Kim S B, Hayashi N, Ishizuka D and Miyazawa D 2014 The Study to Improve the Field Homogeneity of the HTS Bulk Magnets for NMR Relaxometry Device by Passive Compensation Methods *Physics Procedia* **58** 298-301.
- [7] Kim S B, Ishizuka D, Kitamura H and Miyazawa D 2015 Study on the Shape Optimization of the HTS Bulk Magnets With Active Compensation for Compact NMR Relaxometry Magnets *IEEE Trans. Appl. Supercond* **25** no. 3 4602404.
- [8] Kim S B, Hayashi N, Kitamura H and Eritate I 2014 Study on the Remagnetization Process to Improve the Field Homogeneity of the Stacked HTS Bulk Magnets *IEEE Trans. Appl. Supercond* **24** no. 3 4301405.