Numerical Study to Design the New Type Compact NMR Magnet Using HTS Bulk Annuli with High Magnetic Field Performances

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Abstract — In design and manufacture of a new type compact NMR (nuclear magnetic resonance) magnet which consists of a stack of high temperature superconducting (HTS) bulk annuli, spatial homogeneity and temporal stability of trapped magnetic fields are key issues. This paper presents a study on the effects of magnetization field strength and gap length between stacked HTS bulks for the compact HTS bulk NMR applications. Four-stacked HTS bulk magnet with ID 20 mm and OD 60 mm was prepared to investigate the optimized configuration. The thickness of each HTS bulk is 5 mm, and the gap lengths from 0 mm to 15 mm were used as parameters in analysis and experiment, respectively. The optimized axial gap length was found out by analytical results, and the better magnetic field homogeneity and temporal decay property of trapped magnetic field were obtained by lower magnetization filed.

I. INTRODUCTION

Recently, the performance of high temperature superconducting (HTS) bulks in terms of mechanical strength, size and critical current density are greatly enhanced, thus their trapped magnetic field capability [1] expanded from the conventional HTS bulk applications. The new type compact NMR magnet consisted of a stack of ring-shaped HTS bulks where a magnetic fields are trapped by field cooling method was suggested [2]-[3]. Since this magnetically charged HTS bulk magnet for NMR device don't need a power supply and additional coolant supply system, so it is expected that the new NMR device can achieve not only the compactness but also cost-efficiency. We have been developing a new prototype compact NMR magnet with stacked HTS bulk annuli and fundamental studies for the optimized configuration were carried out experimentally and analytically [4]-[5].

In this study, we prepared the four-stack HTS bulk magnet with each HTS bulk thickness 5 mm. The numerical analysis based on 3-D finite element method (FEM) which superconducting properties were considered was carried out firstly in order to obtain an optimized axial gap length, then, the characteristics of spatial homogeneity according to strength of magnetization field was investigated numerically.

II. OUTLINE OF A NEW TYPE COMPACT NMR DEVICE

Fig. 1 shows a schematic drawing of the proposed compact NMR device using HTS bulk annuli. An external energizing magnet, most likely superconducting magnet, in Fig.1 is supposed to produce a homogeneous high magnetic field, and the stacked HTS bulk annuli will be magnetized by this superconducting magnet. Then, the HTS bulk magnet on which the magnetic field was trapped can be used with cryogenic container as portable compact NMR magnet without superconducting magnet and any power sources. The large critical current density of each HTS bulk is an important advantage of the proposed NMR magnet, especially for its compactness. The stacked HTS bulk magnet to be placed in a bath of liquid nitrogen or solid nitrogen to reach a target operating temperature required for a specific NMR frequency level. In this research, 200 MHz (4.7 T) and 500 MHz (11.7 T) will be obtained by liquid nitrogen (77.5 K) and solid nitrogen (30 K), respectively. A separate room-temperature bore provides an axial access of an NMR probe.

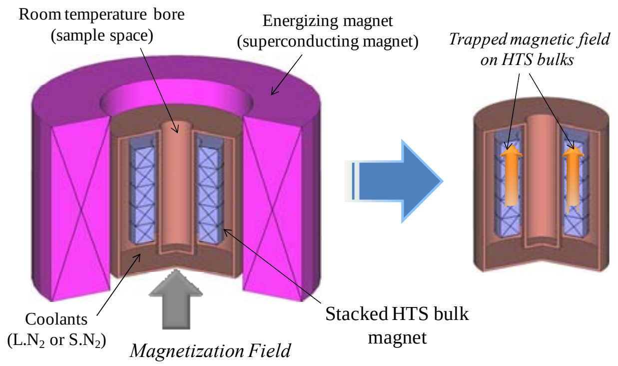

Fig. 1. Conceptual drawing of a portable compact NMR magnet using stacked HTS bulk annuli.

III. CALCULATION METHOD

To investigate the characteristics of trapped magnetic field on HTS bulk magnet, the supercurrent distributions in a field cooled HTS bulk annuli must be determined. Thus, in this study, 3-D FEM based on the magnetic vector potential method has been adopted. Equations (1) and (2) can complete a governing equation based on magnetic vector potential, $\boldsymbol{A}$, where μ and σ are magnetic permeability and electrical conductivity, respectively.

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \boldsymbol{A} \right) = -\sigma \left(\frac{\partial \boldsymbol{A}}{\partial t} + \nabla \phi \right) \tag{1}$$

$$\nabla \cdot \sigma \left(\frac{\partial \boldsymbol{A}}{\partial t} + \nabla \phi \right) = 0 \tag{2}$$

Magnetic field and electrical field can be obtained from (3) and (4), respectively.

$$\boldsymbol{B} = \nabla \times \boldsymbol{A} \tag{3}$$

$$\boldsymbol{E} = -\nabla\phi - \frac{\partial \boldsymbol{A}}{\partial t} \quad (4)$$

In order to consider the non-linear electromagnetic behavior of HTS bulks, a critical state model was adopted as (5) and (6), where J and J_c are current density and critical current density of HTS bulks, respectively.

$$\boldsymbol{J} = \boldsymbol{J}_c\left(|\boldsymbol{B}|\right)\frac{\boldsymbol{E}}{|\boldsymbol{E}|} \qquad if\ |\boldsymbol{E}| \neq 0 \quad (5)$$

$$\frac{\partial \boldsymbol{J}}{\partial t} = 0 \qquad if\ |\boldsymbol{E}| = 0 \quad (6)$$

And the *B-J* characteristics of the HTS bulks were used as shown in Fig. 2.

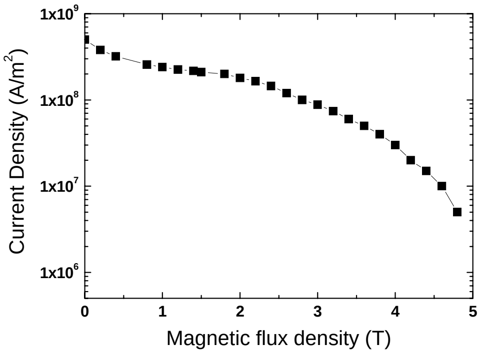

Fig. 2. *B-J* profiles of HTS bulks used in analysis.

IV. RESULTS

Fig. 3 shows the schematic to-scaled analytical model of the four-stacked HTS bulk magnet and superconducting magnet for magnetization, and stacked HTS bulk annuli with various axial gap length. The measured and calculated magnetic field profiles along the z-axis of a single and the four-stacked HTS bulk magnet are shown in Fig. 4 when applied magnetic field was 1 T at 77 K. From Fig.4, the analytical results and experimental ones show good agreement within 3% difference between two, and we know that the trapped field strength and homogeneity were improved by the stacking configuration.

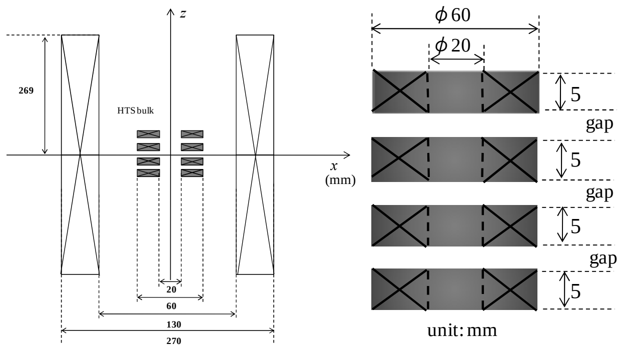

Fig. 3. To-scaled schematic analytical models of the four-stacked HTS bulk magnet and superconducting magnet (left), and stacked HTS bulk annuli with axial gap (right).

The calculated magnetic field profiles along the z-axis of the four-stacked HTS bulk magnet as a function of gap length was shown in Fig.5 when applied magnetic field was

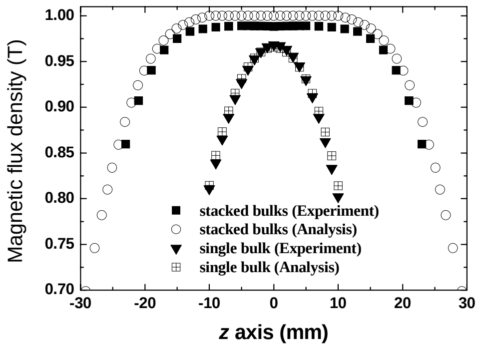

Fig. 4. Measured and Calculated magnetic field profiles along the z-axis of the single and the four-stacked HTS bulk annuli.

1 T at 77 K. The maximum strength of the trapped magnetic field was decreased due to increasing of the gap length, however the spatial homogeneity near the center in axial direction was obviously improved according to increasing of the gap length because the overall height of HTS bulk magnet has been enlarged. But, the trapped magnetic field strength at the center became weaker when the air gap farther increased to 15 mm. The detail magnetic field and supercurrent distributions of the stacked HTS bulk magnet according to the various gap lengths and the strength of applied magnetic field will be presented.

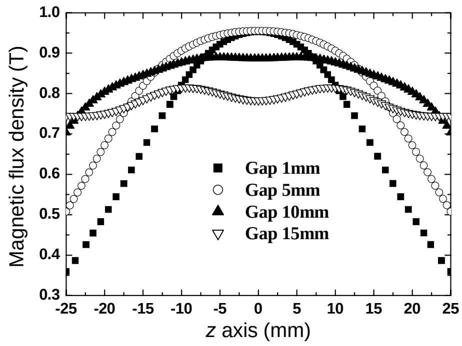

Fig. 5. Calculated magnetic field profiles along the z-axis of the four-stacked HTS bulk magnet as a function of gap length (0, 5, 10 and 15 mm) when applied magnetic field was 1 T at 77 K.

V. REFERENCES

[1] M. Tomita and M. Murakami, “High-temperature superconductor bulk magnets that can trap magnetic fields of over 17 tesla at 29 K”, *Nature*, vol. 421, pp.517-518, 2003.

[2] T. Nakamura, Y. Itoh, M. Yoshikawa, T. Oka and J. Uzawa, “Development of a superconducting magnet for nuclear magnetic resonance using bulk High-Temperature superconducting materials”, Concepts in Magnetic Resonance, Part B, p.65, 2006.

[3] Y. Iwasa, “HTS and NMR/MRI magnets: Unique features, opportunities, and challenges,” *Physica C*, vol.445-448, pp.1088-1094, 2006.

[4] S.B. Kim, , Nakano, R. Takano, and S.Y. Hahn, “Study on trapped field characteristics of HTS bulk annuli with iron rings for ferromagnetic shimming of a compact NMR magnet”, *IEEE Trans.Appli. Supercon*, vol. 19, no. 3, pp.2273-2276, 2009.

[5] S.B. Kim, R. Takano, T, Nakano, M. Imai and S.Y. Hahn, “Characteristics of the magnetic field distribution on compact NMR magnets using cryocooled HTS bulks”, *Physica C*, vol. 469, pp.1811-1814, 2009.