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Numerical study on split coil-shaped HTS bulks to improve the field homogeneity for compact NMR relaxometry magnets

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Abstract

We have been developing a new compact NMR magnet using stacked HTS bulks. In this paper, in order to improve the trapped magnetic field homogeneity and to obtain the enlarged sample space of HTS bulk magnet for compact NMR relaxometry, the HTS bulk magnet with 10 mm gap length in the center region of HTS bulk magnet (we call it "split coil-shaped THS bulks") were proposed and studied as the functions of size and shape of HTS bulk using 3D FEM based electromagnetic analysis. The improved field homogeneity was obtained using notch coil shaped HTS bulk configuration and the field compensation by attached the coil instated of the bulks.

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Keywords: NMR relaxometry; HTS bulk magnet; field homogeneity; enlarged sample space; field compensation

1. Introduction

We have been developing the NMR relaxometry device. The strength and homogeneity of the magnetic field required for the NMR relaxometry device are 1.5 T and 150 ppm/cm^3 respectively, these values are much lower than a conventional NMR device. It is possible to generate a magnetic field over 1.5 T at 77.4 K using the stacked HTS bulk annuli [1, 2], but it is still hard to obtain 150 ppm/cm^3 field homogeneity. In this paper, the target field homogeneity of HTS bulk magnet is 150 ppm/cm^3, and the cylinder, the step shaped and the modified models consisted with stacked HTS bulks and coil for field compensation were suggested and studied analytically in order,

- to make it possible to insert a sample tube in the transverse direction

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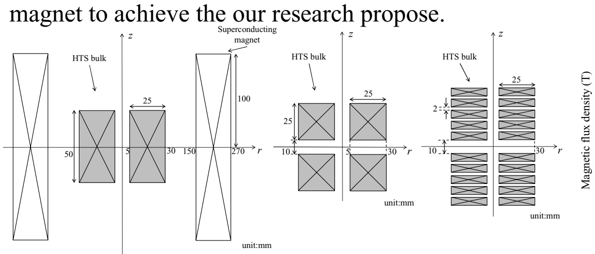
- to decrease the total volume of HTS bulks
- to obtain the enlarged sample space
- to operate in the liquid nitrogen temperature

2. Cylinder and split analytical models

We have a superconducting magnet (SCM) with 100 mm room temperature bore size and 10 T. The magnetic field homogeneity at center region of SCM is 610 ppm/ cm^3, and the almost same SCM was used as energizing magnet in our analysis. Fig.1 (a) shows the scaled the SCM and single cylinder HTS bulk model used as evaluation criteria, and split HTS models with 2 and 10 stacked HTS bulks were shown in Figs.1 (b) and (c). The thickness of split models of 2 and 10 stacked HTS bulks were 25 mm and 5 mm, respectively. In this study, the trapped magnetic fields of HTS bulk magnets were obtained by field cooling method with 1.5 T magnetization field at 77.4 K. In this study, the current flowed in the HTS bulk during the FC process were induced by the Bean's critical state model and n-value model, and the trapped magnetic fields of HTS bulks were calculated by their currents, and the critical current density of 2.01×10^8 A/m^2 was used at 1.5 T and 77.4 K.

Fig.2 shows the calculated magnetic field distribution and the field homogeneity along the *z*-axis of the HTS bulks magnets. The trapped magnetic fields at the center region in the split models were dented, and the strength of magnetic field was smaller (1.4 T) than single cylinder model (1.5 T). The field homogeneity of the split models was decreased by the field leakage in the 10 mm gap region. So, we should optimize the shape of the split HTS bulk magnet to achieve the our research propose.



(a) t = 50 mm × 1 ea (b) t = 25 mm × 2 ea (c) t = 5 mm × 10 ea

Fig. 1. Scaled schematic draw of (a) SCM and single cylinder HTS bulk model, (b) split model with two HTS bulks and (c) split model with 10 stacked HTS bulks.

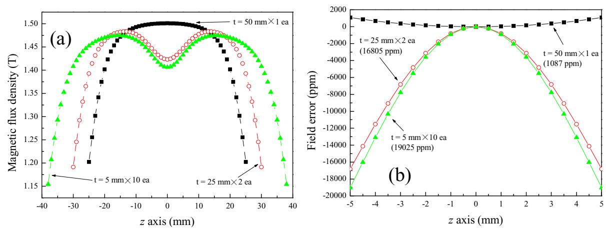
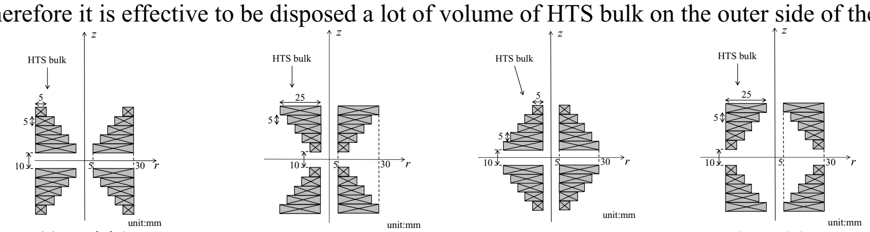


Fig. 2. The calculated (a) magnetic field distributions and (b) the field homogeneity along the z-axis of the cylinder and split shaped HTS bulk magnet models (@ 1.5 T and 77.4 K).

3. Step models

To improve the field homogeneity of the split HTS bulks, the various step shaped models were analysed as shown in Fig.3. Fig.4 shows the calculated magnetic field distributions and the field homogeneity along the *z*-axis of the four step HTS bulk magnet models. The total volume of HTS bulk, the magnetic field at center position in axial direction and the field homogeneity of each model were shown in Table 1. The model which has the widest sample space was a model 4, but the strength of magnetic field of models 2 and 4 were attenuated considerably because the volume of HTS bulk at central position in radial direction were too small. However, the total volume of HTS bulk in model 4 was larger than model 2, so the field homogeneity and strength of magnetic field at center region were higher than that of model 2. The highest field homogeneity of 13150 ppm/cm^3 was obtained in model 1, and the worst model was 2. In this analysis, the superconducting currents in the HTS bulk were calculated as the eddy current model, and the currents flowing in the outer side of HTS bulk contribute to the field homogeneity in the sample space. Therefore it is effective to be disposed a lot of volume of HTS bulk on the outer side of the magnet.



(a) model 1 (b) model 2 (c) model 3 (d) model 4

Fig. 3. Scaled schematic draws of the analytical models with various step-shaped HTS bulk magnets.

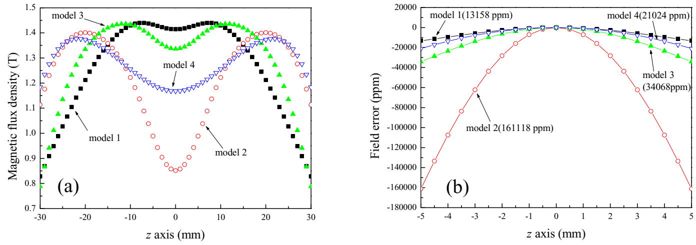


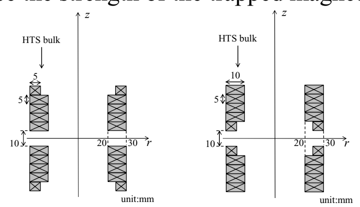
Fig. 4. The calculated (a) magnetic field distributions and (b) the field homogeneity along the *z*-axis of the four HTS bulk magnet models (@ 1.5 T and 77.4K).

Table 1. The value of volume, magnetic flux density at z = 0, and homogeneity of each model along the z-axis of the HTS bulk magnets (@ 1.5 T and 77.4 K).

	t = 50 mm × 1 ea	t = 25 mm×2 ea	t = 5 mm×10 ea	model 1	model 2	model 3	model 4
Volume (cm^3)	137	137	137	98	67	67	98
Magnetic flux density at z = 0 (T)	1.50	1.42	1.40	1.41	0.85	1.33	1.16
Homogeneity (ppm/cm^3)	1087	16805	19025	13158	161118	34068	21024

4. Modified models

The modified analytical models with almost same volume of models 2 and 3 were proposed as the modified models 1 and 2. In the modified models 1 and 2, the notch coil shaped bulks are added to the cylinder HTS bulk magnet as shown in Fig.5. Fig.6 shows the calculated magnetic field distributions and the field homogeneity along the *z*-axis of the model 3 and modified models. The calculated strength of trapped magnetic fields of modified models 1 and 2 were lower than that of model 3, because there are not many bulks near central gap regions. However, the improved field homogeneity was obtained in both modified models 1 and 2, and the field homogeneity of modified model 1 was 2430 ppm/cm^3. It was confirmed that the field homogeneity was improved since the superconducting currents concentrated in outer side of HTS bulk. And the notch coil shaped HTS bulks located at both top and bottom were played a role as a notch coil. Inner diameter was altered from 20 mm to 40 mm, and cylinder and notch coil model was combined, and the field homogeneity improved. It is necessary to optimize the volume of notch part. But, it need to use a HTS bulk with high J_c-B characteristics than that is currently in used, since the strength of the trapped magnetic field was lower than the target value of 1.5 T.



(a) modified model 1 (b) modified model 2

Fig. 5. Scaled schematic draw of the modified analytical models with almost same volumes of models 2 and 3.

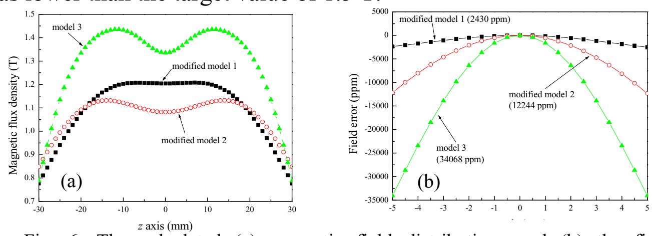
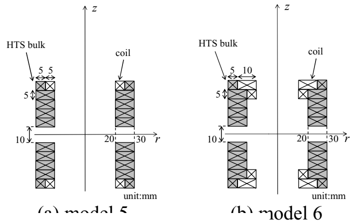


Fig. 6. The calculated (a) magnetic field distributions and (b) the field homogeneity along the *z*-axis of the modified models (1 and 2) and model 3 (@ 1.5 T and 77.4 K).

5. Models with coil

To obtain the target field homogeneity, the hybrid analytical models consisted of the HTS bulk magnet and superconducting coil for the active field compensation were suggested as shown in Fig.7. The current of 100 A was transported in each superconducting coil to generate the magnetic field with same and reverse direction to the applied field by SCM. In the model 5, a one coil with 16 turns winding was added to the HTS bulk magnet, and the two coils with 16 and 32 turns winding were added in model 6. Fig.8 shows the calculated magnetic field homogeneities in the axial and radial directions of the each model, and calculated results were summarized in Table 3. The field homogeneity of model 6 was significantly improved from 2435 ppm/cm to 198 ppm/cm in the axial direction when the current of coil flowed to reverse direction to the magnetic field of SCM. The calculated field homogeneities in the both axes at each model except model 6 (reverse dir) were almost equal, but the spatial symmetry of field distribution in model 6 (reverse dir) was not good and the field homogeneity in the *z*-axis (198 ppm/cm) was better than *r*-axis (957 ppm/cm). Table 2 shows the calculated current density in the coil and HTS bulk at 100 A transported, and we can see that the current density in the HTS bulk was changed by the current density in the coils. In model 6, it was considered that the current density in outer side of HTS bulk was increased by the coil current with reverse direction, and these current density distribution was contributed to the increasing the field homogeneity. Therefore, it was found that the target field homogeneity could obtain by active field compensation using attached the superconducting coil in the HTS bulk model with reduced volume of it.



(a) model 5 (b) model 6

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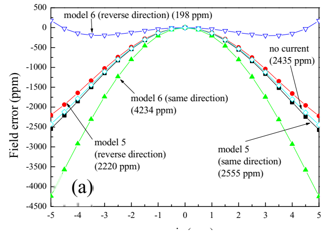
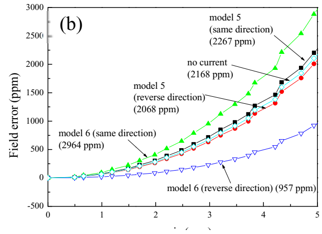




on the @ 1.5

Table 2. The calculated current density distributions in the coils and HTS bulks at the transport current of coil of 100A (@ 1.5 T and 77.4 K).

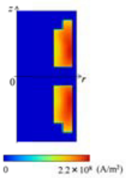
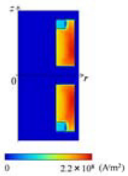
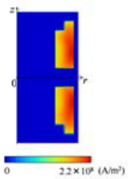
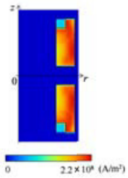
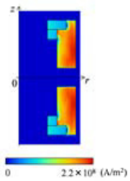
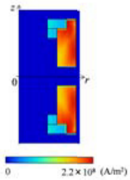
	same direction		reverse direction	
	bulk only	coil and bulk	bulk only	coil and bulk
model 5				
model 6				

Table 3. The total volume of each analytical model, and calculated magnetic field and homogeneities in the external field of 1.5 T at 77.4 K.

	modified model 1	modified model 2	model 5 (same dir)	model 5 (reverse dir)	model 6 (same dir)	model 6 (reverse dir)
Volume (cm^3)	71	71	71	71	71	71
Magnetic flux density at z = 0 (T)	1.20	1.08	1.20	1.20	1.20	1.19
Field homogeneity (ppm/cm in *z*-axis)	2430	12244	2555	2220	4234	198

6. Conclusion

In this paper, we analysed the step models, the notch coil-shaped models, and the models combined with coils and HTS bulks in order to obtain the improved field homogeneity, enlarged sample space and horizontal insertion of the sample for the compact NMR relaxometry device. It was found that the field homogeneity was improved by notch coil-shaped bulks and the hybrid models consisted with coils and HTS bulks when the coil current was transported in reverse direction to the SCM. Therefore, it was found that the target field homogeneity of 150 ppm/cm^3 could obtain by active field compensation method using attached the superconducting coil in the HTS bulk magnets.

References

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