

Development of an MRI system using a high T_c bulk superconducting magnet

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INTRODUCTION

Since the discovery of high temperature superconducting (HTS) material in 1986 [1], the HTS materials have been expected for superconducting magnets for NMR and MRI. However, mainly because of high cost and difficulty in producing long wire, there were very few practical applications to NMR/MRI magnets [2]. In 2007, a new design NMR magnet using a HTS bulk material was reported by Nakamura and his colleagues [3]. This magnet has overcome the above problems for NMR/MRI applications. Moreover, the HTS bulk material has several advantages over superconducting wire in current density, magnet size, and design simplicity. In this study, we performed the first MRI experiments using a bulk superconducting magnet and evaluated its possibility for MRI magnets.

MATERIALS AND METHODS

Annular bulk superconductors (outer diameter = 60 mm, inner diameter = 28 mm, height = 20 mm) made of c-axis oriented single-grain $\text{EuBa}_2\text{Cu}_3\text{O}_y$ crystals were used for the conductor of the magnet as shown in Fig.1 [4]. Six annular superconductors were vertically stacked and stored in a cryostat (outer diameter = 88 mm, room temperature bore diameter = 20 mm) and cooled using a pulse tube refrigerator as shown in Fig.1. The bulk magnet was energized as follows. The temperature of the magnet was kept at 100 K which is above the critical temperature (~ 90 K) of the superconductor, the bulk magnet was inserted into the room temperature bore of a 4.7 T wide-bore conventional superconducting NMR magnet, the bulk material was cooled down to 50 K under the 4.7 T homogeneous (NMR quality) magnetic field with superconducting shimming, and the electrical current of the main magnet was slowly decreased to zero. Magnetic flux generated by the 4.7 T superconducting magnet was trapped by the bulk superconductor and a homogeneous magnetic field was produced in the bore of the bulk magnet.

A three-axis cylindrical gradient coil set was wound on an acrylic pipe (outer diameter = 16.8 mm, inner diameter = 14.8 mm) using 0.3 mm diameter polyurethane coated Cu wire. RF probes for 5 mm and 8 mm NMR sample tubes were made to fit the inner bore of the gradient set. The gradient set and the RF probe were inserted into the bore of the bulk magnet and connected to an MRI console. Magnetic field distribution was measured in the central $\phi 7.0 \text{ mm} \times 12.8 \text{ mm}$ region using a phase shift method. Several phantoms were measured using 3D spin-echo sequences for evaluation of the MRI system.

RESULTS AND DISCUSSION

Figure 2 shows inhomogeneity and histogram of the magnetic field measured in the central $\phi 6.2 \text{ mm} \times 9.1 \text{ mm}$ cylindrical region. Peak to peak and root mean square values of the inhomogeneity were 35 and 3.3 ppm, respectively. Figure 3 shows 2D cross sections selected from a 3D image dataset of a water phantom acquired with a 3D SE sequence (TR/TE = 100ms/10ms, image matrix = 128^3 , voxel size = $(100 \mu\text{m})^3$, NEX = 1). Although signal void caused by a considerable offset of the magnetic field is seen in the images, detailed structure of the phantom is clearly visualized. The inhomogeneity of the magnetic field is mainly determined by that of the bulk superconducting crystals and by their spatial arrangement. The accurate evaluation of the inhomogeneity demonstrated here is helpful for optimization of the spatial arrangement, and the inhomogeneity will be further improved. Available volume for MRI measurements of our system is currently smaller than that of conventional vertical bore superconducting magnets, but the bulk magnet is cryogen free and compact, which is advantageous to conventional superconducting magnets. In conclusion, we have developed the first MRI system that uses the bulk superconducting magnet in the persistent current mode and shown promise of our system.

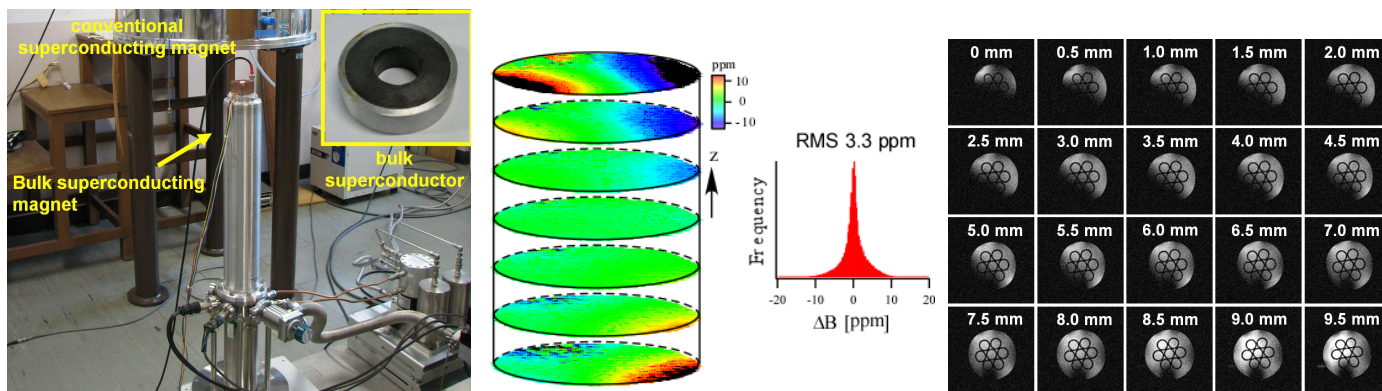


Fig.1(left) Bulk superconducting magnet. The conventional NMR magnet used for energizing the bulk magnet is behind the bulk magnet. Fig.2 (center) Inhomogeneity and histogram of the magnetic field measured in the central $\phi 6.2 \text{ mm} \times 9.1 \text{ mm}$ region. Fig.3 (right) 2D cross sections selected from a 3D image dataset of a water phantom. Numbers in the images are vertical height of the images.

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