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R&D Progress of HTS Magnet Project for Ultrahigh-field MRI

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Abstract

An R&D project on high-temperature superconducting (HTS) magnets using rare-earth $Ba_2Cu_3O_7$ (REBCO) wires was started in 2013. The project objective is to investigate the feasibility of adapting REBCO magnets to ultrahigh field (UHF) magnetic resonance imaging (MRI) systems. REBCO wires are promising components for UHF-MRI magnets because of their superior superconducting and mechanical properties, which make them smaller and lighter than conventional ones. Moreover, REBCO magnets can be cooled by the conduction-cooling method, making liquid helium unnecessary. In the past two years, some test coils and model magnets have been fabricated and tested. This year is the final year of the project. The goals of the project are: (1) to generate a 9.4 T magnetic field with a small test coil, (2) to generate a homogeneous magnetic field in a 200 mm diameter spherical volume with a 1.5 T model magnet, and (3) to perform imaging with the 1.5 T model magnet. In this paper, the progress of this R&D is described. The knowledge gained through these R&D results will be reflected in the design of 9.4 T MRI magnets for brain and whole body imaging.

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Keywords: MRI; Magnet; Ultra-high field; REBCO; HTS coil; Screening current

1. Introduction

The nuclear magnetic resonance (NMR) signals from, for example, carbon, phosphorous, nitrogen and oxygen may become easier to detect in high magnetic fields above 7 T. Therefore, novel diagnostic equipment based on ultrahigh-field (UHF) magnetic resonance imaging (MRI) is expected [2]. Rare-earth $Ba_2Cu_3O_7$ (REBCO) wires are promising components for UHF-MRI magnets because REBCO wires have high critical current density in high magnetic fields and high mechanical strength in the longitudinal direction, whose features make REBCO magnets smaller and lighter than low-temperature superconducting (LTS) magnets. In addition, since REBCO magnets can be cooled by using the conduction-cooling method, liquid helium is not required, in contrast to LTS magnets, in which a huge amount of liquid helium is consumed at initial cooling and cooling after quenching. Against this background, an R&D project on REBCO

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magnets for UHF-MRI systems was started in 2013 [2] [3]. In the past two years, some test coils and model magnets have been fabricated and tested to identify the difficulties and problems faced and to establish basic magnet technologies. This paper describes the progress of this R&D project.

2. Project goals

The overall project objective is to investigate the feasibility of adapting REBCO magnets to UHF-MRI systems. The project term is three years, and this year is the final year. The project goals, to be achieved by March 2016, are as follows:

- To demonstrate the generation of a 9.4 T magnetic field with a 10 T test coil
- To demonstrate the generation of a homogeneous magnetic field in a 200 mm diameter spherical volume (DSV) with a 1.5 T model magnet
- To perform imaging with the 1.5 T model magnet

A magnetic field of 9.52 T has already been demonstrated with a 10 T coil, shown in Fig. 1 (a), under conduction-cooling conditions. The 10 T test coil was composed of twenty-two single pancake coils, with an inner diameter of 50 mm, an outer diameter of 129 mm, and a height of 104 mm. Each single pancake coil was wound with a 4 mm-wide and 0.1 mm-thick REBCO wire, and was impregnated with epoxy resin. The 1.5 T model magnet shown in Fig. 1(b) is currently being fabricated. It has three sets of split coils, split coils #1, #2 and #3 shown in Fig. 1(b), which are made of stacked single pancake coils. The number of single pancake coils in split coils #1, #2 and #3 are a pair of six, a pair of ten and a pair of fourteen, respectively.

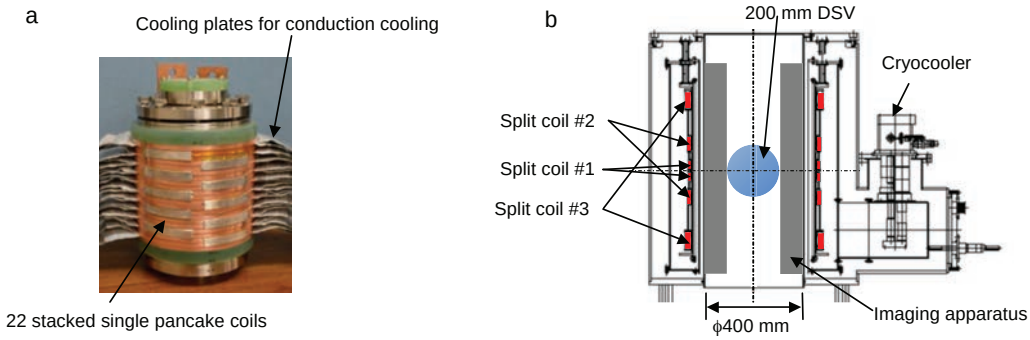

Fig. 1. (a) Photograph of 10 T test coil ; (b) Cross-section of 1.5 T model magnet.

3. R&D progress of technical issues

In this project, some test coils and model magnets have been fabricated and tested to investigate the challenging technical issues faced in realizing a UHF-MRI system. R&D progress of the most important technical issues, that is, generation of a homogeneous and stable magnetic field and coil protection, are described below

3.1. Homogeneous magnetic field

There are some peculiar causes of irregular magnetic fields when using REBCO magnets. These are mainly based on the tape shape of REBCO wires, including that of a filament. In this subsection, the influence of screening current fields and dimensional errors is described. The influence of screening current fields was investigated with the 10 T coil stated above. The measured screening current fields, for example, 0.4 T in the maximum case, with hysteresis behavior were well described by a simulation program developed in previous studies[4] [5]. The influence of the screening current fields of a whole body MRI magnet was calculated to be less than 100 ppm using the same simulation program. Therefore, the irregular magnetic fields due to the screening current seem to be predictable at the level of 100 ppm.

On the other hand, the influence of the dimensional errors was investigated with a 1 T model magnet shown in Fig. 2 [6]. The 1 T model magnet has two pairs of coil units, which consist of a pair of two single pancake coils and a pair of four single pancake coils. The room temperature bore is 200 mm in diameter, and homogeneous region is designed to be

100 mm DSV. The magnetic field homogeneity was evaluated by measuring the magnetic field on the spherical surface with NMR probes. The coefficients of the spherical harmonic expansions were calculated from the measurement results. It was found that the z terms calculated from the measurement results were worse than the designed values. For example, the z2 term of -1.27 ppm in the design was found to be 142 ppm from the experimental results. To investigate the magnetic field inhomogeneity, the positions on the z-axis of all single pancake coils were measured. Then, taking account of those results, the magnetic field distribution in z-axis direction was calculated. As shown in Fig. 2 (c), the calculated irregular magnetic field distribution is in good agreement with the measured one. We are improving the assembly accuracy in the manufacturing process of the 1.5 T model magnet.

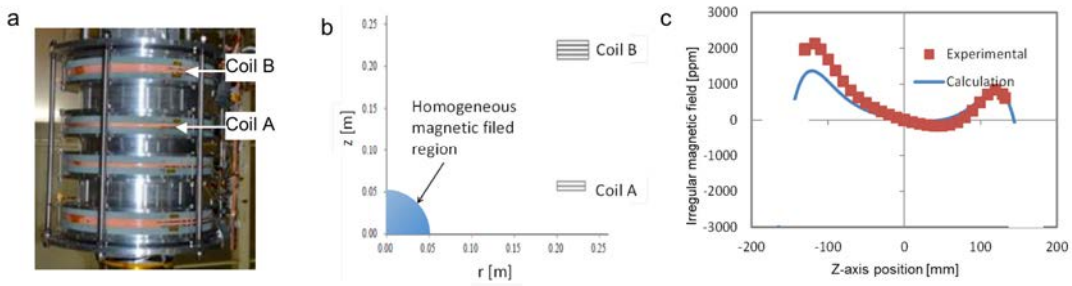

Fig. 2. The influence of dimensional errors on the irregular magnetic field was investigated with the 1 T model magnet: (a) photograph; (b) coil configuration; and (c) irregular magnetic field distribution in z-axis direction.

3.2. Stable magnetic field

REBCO magnets have to be operated in driven mode because practical superconducting joints have not yet been developed. Furthermore, important factors in realizing a stable magnetic field include not only the current stability of the power supply, but also how to deal with the magnetic relaxation of the screening current in REBCO wires. The stability of the magnetic field was investigated with the 1 T model magnet, as described above. Fig. 3 (a) shows the behaviors of the magnetic field and the coil temperature after reaching the rated current. The coil temperature increased with time because of Ohmic losses at resistive joints. The magnetic field also gradually increased with time. From these results, it was estimated that the increase in coil temperature influenced the increase in the magnetic field strength. That is to say, the magnetic relaxation of the screening currents was enhanced. Accordingly, we conducted tests in which the coil temperature was controlled by heating it with a cryocooler. The test results with coil temperature control are shown in Fig. 3 (b). It is obvious that the magnetic field variation when the coil temperature was controlled is smaller than that when the coil temperature was not controlled. It was found that coil temperature control is critically important in conduction-cooled REBCO magnets for realizing the stable magnetic field required in MRI magnets.

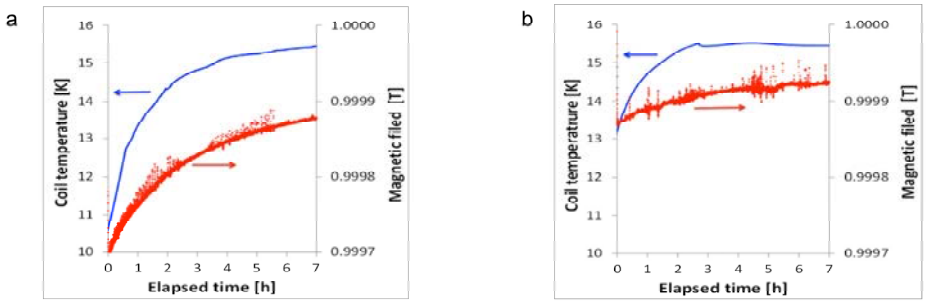

Fig. 3. Magnetic field and coil temperature behaviors after reaching the rated current, observed in the 1 T model magnet: (a) test results without coil temperature control; (b) test results with coil temperature control.

3.3. Coil protection

To prevent thermal runaway in the model magnets, coil protection was designed to be achieved by monitoring the coil temperature. On the other hand, the so-called no-insulation (NI) coil method is being investigated because this method is considered to be a strong candidate for protecting HTS magnet coils. As a first step toward adapting the NI coil method to conduction-cooled HTS magnets, epoxy impregnated NI coils were fabricated and tested. One of the impregnated NI coils is shown in Fig. 4 (a). Current damp test results of the NI coil are shown in Fig. 4 (b). Average electrical contact resistances between adjacent turns were calculated from the time constants (τ) of current decay measured in current damp tests. The results revealed that the electrical contact resistances of the epoxy impregnated NI coil are almost the same as that of a dry NI coil at 77 K [7]. Moreover, it is found that the electrical contact resistance decreases with a decrease in temperature.

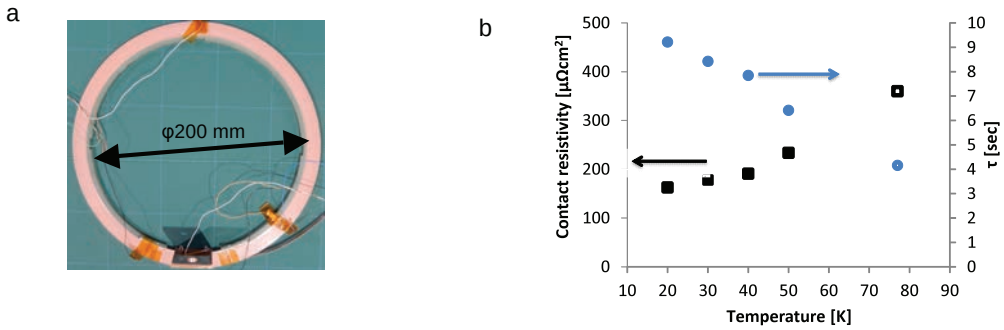

Fig. 4. Impregnated NI coil and its test results. (a) photograph; (b) temperature dependence of time constants and electrical contact resistances.

4. Conclusions

The status of an R&D project on HTS magnets for UHF-MRI has been described. There are challenging technical issues, including the generation of a homogeneous magnetic field and a stable magnetic field, coil protection, and the cryogenic system. In the project, some test coils and model magnets were designed and fabricated for investigating these technical issues. We will demonstrate the generation of a homogeneous magnetic field in a 200 mm DSV with a 1.5 T model magnet by March 2016.

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