



27th International Symposium on Superconductivity, ISS 2014

Project Overview of HTS Magnet for Ultra-high-field MRI System

Taizo Tosaka^{a,*}, Hiroshi Miyazaki^a, Sadanori Iwai^a, Yasumi Otani^a, Masahiko Takahashi^a,
Kenji Tasaki^a, Shunji Nomura^a, Tsutomu Kurusu^a, Hiroshi Ueda^{b,d}, So Noguchi^{c,d},
Atsushi Ishiyama^d, Shinichi Urayama^e, Hidenao Fukuyama^e

^aToshiba corporation, 2-4 Tsurumi, Yokohama 230-0045, Japan

^bOsaka University, 10-1 Mihogaoka, Ibaraki, Osaka 565-0047, Japan

^cHokkaido University, Kita 14 Nishi 9, Kita, Sapporo 060-0814, Japan

^dWaseda University, 3-4-1 Ohkubo, Shinjyuku, Tokyo 169-8555, Japan

^eKyoto University, 54 Shogoinkawaharacho, Sakyo, Kyoto 606-8507, Japan

Abstract

A project to develop an ultra-high-field magnetic resonance imaging (MRI) system based on HTS magnets using (RE)Ba₂Cu₃O₇ (REBCO; RE=rear earth) coils is underway. The project is supported by the Japanese Ministry of Economy, Trade and Industry and aims to establish magnet technologies for a whole-body 9.4 T MRI system. REBCO wires have high critical current density in high magnetic fields and high strength against hoop stresses, and therefore, MRI magnets using REBCO coils are expected to have cryogenic systems that are smaller, lighter, and simpler than the conventional ones. A major problem in using REBCO coils for MRI magnets is the huge irregular magnetic field generated by the screening current in REBCO tapes. Thus, the main purpose of this project is to make the influence of this screening current predictable and controllable. Fundamental technologies, including treatment of the screening currents, were studied via experiments and numerical simulations using small coils. Two types of model magnets are planned to be manufactured, and the knowledge gained in the development of the model magnets will be reflected in the magnet design of a whole-body 9.4 T MRI system.

© 2015 Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of the ISS 2014 Program Committee

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

1. Introduction

Ultra-high-field MRI using nuclear magnetic resonance (NMR) signals from, for example, carbon, phosphorous, nitrogen and oxygen instead of the hydrogen used in conventional MRI systems is expected to lead to the development of novel diagnostic equipment. (RE)Ba₂Cu₃O₇ (REBCO; RE=rear earth) wires are promising components for ultra-high-field MRI systems because of their superior superconducting and mechanical properties. These properties of REBCO wires will result in MRI magnets that are smaller and lighter than the conventional ones. Also, the operation and maintenance of the cryogenic system become simpler because there is no need to handle liquid helium. Against this background, an HTS magnet project using REBCO coils for ultra-high-field magnetic resonance imaging (MRI) systems was started [1][2].

* Corresponding author. Tel.: +81-45-510-6695; fax: +81-45-500-1973.

E-mail address: taizo.tosaka@toshiba.co.jp

2. Project schedule

The schedule of the HTS magnet project is shown in Fig. 1. Two types of model magnets are planned to be manufactured and tested: a small-size model magnet and a middle-size model magnet. The target application of our research is 9.4 T MRI magnets for brain imaging and for whole-body imaging, as shown in Fig. 2, and therefore, design studies of whole-body MRI magnets are also being performed in this project.

The small-size magnet has a warm bore of 100 mm in diameter. Its HTS coils are conductively cooled by a cryocooler. The main objective of developing this magnet is to identify problems in producing a homogeneous magnetic field of around 10 T with REBCO coils. The middle-size model magnet is planned to have a wider warm bore of 300 mm or more in diameter to investigate scaling issues as the size is increased toward a whole-body MRI magnet. The central magnetic field of the middle-size magnet is planned to be 7 T, which is limited by the ability to prepare the necessary amount of REBCO wires. About 100 km of REBCO wires are needed even in the middle-size magnet. The cooling system of the middle-size magnet is different from that of the small-size magnet. The HTS coils are thermally connected with circulating gas to conductively cool the coils. An advantage of this cooling system is the small temperature difference between the HTS coils and the cryocooler. The temperature difference is almost independent of the distance between them. This cooling system is planned to be used in target magnets.

Concurrently with the manufacturing and testing of model magnets, fundamental technologies for designing and manufacturing MRI magnets using REBCO coils are also being studied.

FY2013	FY2014	FY2015	FY2016	FY2017
Study of fundamental technology for HTS magnet			Fundamental technology improvement	
Small-size model magnet development · Warm bore size: $\sim \phi 100$ mm · Central field: ~ 10 T			Middle-size model magnet development · Warm bore size: $\phi 300$ m $\sim \phi 600$ mm · Central field: ~ 7 T	
Design study of whole body MRI magnet				

Fig. 1. The HTS magnet project schedule.

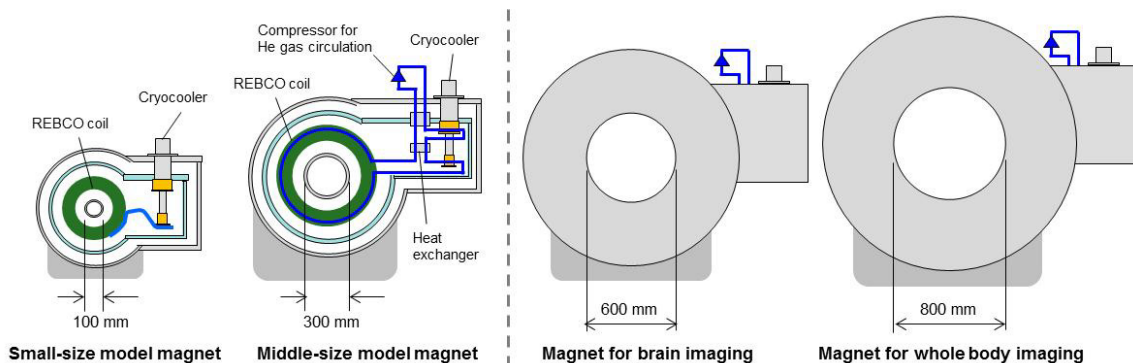


Fig. 2. The model magnets and the target magnets.

3. Research and development of fundamental technologies for MRI magnets

We are currently in the second year of the project, and research and development of fundamental technologies is now underway. Several research and development activities are described below.

Investigations for predicting the irregular magnetic field are being performed using some test coils. The specifications of the planned test coils are listed in Table 1, and some of these coils have already been manufactured and tested [3]-[5]. The major cause of the irregular magnetic fields is the screening currents induced in the REBCO wires [6]. Using multifilamentary REBCO wires is a useful means for suppressing the irregular field caused by the screening

currents [7]. Several multifilamentary wires are used for the Test Coils #B to test the suppression effect of the superconductor width [2]. Cross-sections of the multifilamentary wires are shown in Fig. 3. A copper stabilizer is fabricated after the REBCO film is divided, so that each filament is electrically connected.

The irregular magnetic fields caused by the screening currents are calculated using the three-dimensional (3-D) electromagnetic field simulation program developed in the previous study by the Waseda University group [8][9]. This program is based on the finite element method (FEM) and the fast multipole method (FMM). The irregular magnetic fields are caused not only by the screening currents in the REBCO wires, as described above, but also by dimensional position errors of the REBCO wires. Ways of reducing these irregular magnetic fields are being investigated through design, manufacturing, and testing of test coils and model magnets [10][11].

How to avoid degradation of the coil performance caused by delamination in the REBCO wires has been investigated since 2006 at Toshiba. A suitable method of avoiding degradation by decreasing the radial stress in the impregnated coils has almost been established [12]-[17], and we are going to adapt the method for the coils of the MRI magnets.

Coil protection is a general problem in HTS magnets [18]. One of the solutions to this problem is to prevent thermal runaway by monitoring the coil temperature. To utilize this coil protection method, it is necessary to precisely predict the V - I characteristics of HTS coils and to develop a reliable cooling structure under conduction-cooled conditions [19]-[23]. On the other hand, a coil without turn-to-turn insulation, a so-called no-insulation coil, has been identified as a promising candidate for coil protection. The study of no-insulation coils is currently underway.

Table 1. Specifications of test coils.

Parameters	Test coil #A	Test coil #B-1,-2,-3	Test coil #C	Test coil #D
Winding type	Pancake	Pancake	Pancake	Pancake
Inner diameter of pancake coil	50 mm	50 mm	100 mm	400 mm
Outer diameter of pancake coil	129 mm	94 mm	126 mm or 127 mm	467 mm or 474 mm
Number of pancake coils	22 (single)	4 (single)	2 (double)+4 (single)	10 (single)
Number of turns	5280	428	883	1960
Wire type	Monofilament	#B-1; Monofilament #B-2; Two-filament type #B-3; Four-filament type	Monofilament	Monofilament

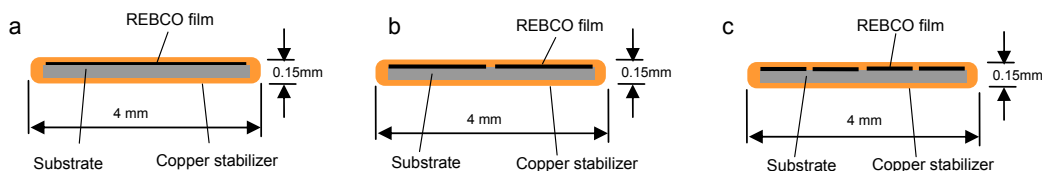


Fig. 3. Cross-sections of a standard wire and multifilamentary wires. (a) Monofilament type (standard wire); (b) two-filament type (REBCO film is divided into two filaments); and (c) four-filament type (REBCO film is divided into four filaments).

4. Experimental results of screening current field with test coil

The main purpose of Test Coil #A is to understand the ability to predict the screening current fields. Excitation tests were performed at several temperatures [7]. The experimental results of the operation at 10 K and the calculation results obtained by the 3-D simulation [24] are shown in Fig. 4(b). The operating current was increased from 0 A to 129 A in 30 minutes, and after holding the current at this level for 30 minutes, it was decreased from 129 A to 0 A in 30 minutes. Hall sensor arrangements corresponding to Fig. 4(b) are described in Fig. 4(c). The screening current fields were converted from the measured value by subtracting the value of the magnetic field at each Hall sensor position calculated using the transport currents. The magnetic fields at the Hall sensor positions were calculated from the coil constant (Tesla/Amps). The coil was operated with small currents at room temperature to obtain the coil constant without the screening current fields. The screening current field at the center position (3A-1) was 0.4 T at an operating current of 129 A, when the magnetic field measured by the Hall sensor was 5.8 T. These results indicate that the influence of the screening current fields is a serious problem for MRI magnets. The screening current fields were calculated using the estimated superconducting properties. For example, the angular dependence of the critical currents was based on published data [25], and the n -index was fixed at the value of 30. The calculation results showed good agreement with the experimental results even though there was a lack of reliable data for the REBCO wires used in the test coil. To

obtain a precise prediction of the screening current field, precise data on the superconducting properties must be obtained. In particular, the longitudinal distribution of the superconducting properties in the REBCO wires will be necessary [26].

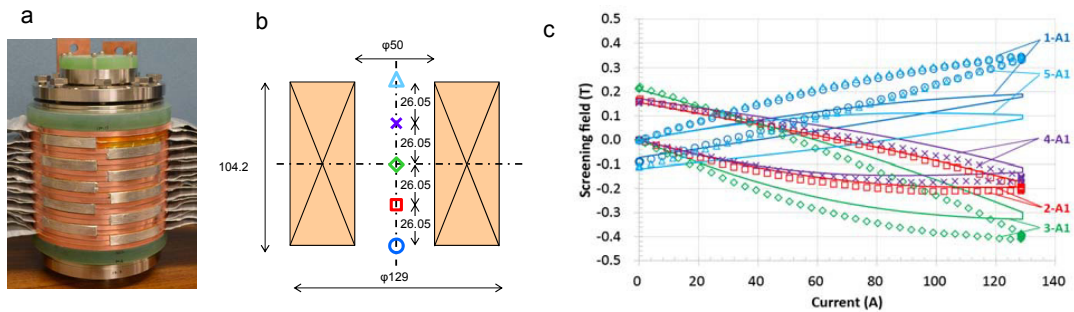


Fig. 4. (a) Outer view of Test Coil #A; (b) arrangement of hall sensors; (c) measurement results (points) and calculation results (lines) of screening current field.

5. Conclusions

An HTS magnet project for ultra-high field MRI has already begun, and research and development of fundamental technologies and design studies of a small-size model magnet and a whole-body 9.4 T magnet are currently underway. How to deal with the screening current field is one of the important issues in this project. Investigation of methods of predicting and suppressing the screening current fields is underway through experiments using several test coils.

Acknowledgements

This work has supported by the Ministry of Economy, Trade and Industry of the Japanese Government.

References

- [1] T. Tosaka, et al, Abstracts of CSSJ conference, 89 (2014) 151
- [2] T. Tosaka, et al, Abstracts of CSSJ conference, 90 (2014) 192
- [3] H. Miyazaki, et al, Abstracts of CSSJ conference, 89 (2014) 152
- [4] H. Miyazaki, et al, Abstracts of CSSJ conference, 90 (2014) 193
- [5] A. Mochida, et al, Abstracts of CSSJ conference, 90 (2014) 195
- [6] H. Ueda, et al, Abstracts of CSSJ conference, 89 (2014) 155
- [7] Y. Imaichi, et al, Abstracts of CSSJ conference, Vol. 90 (2014) 151
- [8] H. Ueda, et al, IEEE Trans. Appl. Supercond., 23 (2013) 4100805
- [9] H. Ueda, et al, IEEE Trans. Appl. Supercond., 24 (2014) 1701505
- [10] A. Ishiyama, et al, Abstracts of CSSJ conference, 89 (2014) 153
- [11] A. Ishiyama, et al, Abstracts of CSSJ conference, 89 (2014) 154
- [12] T. Tosaka, et al, Abstracts of CSSJ conference, 83 (2010) 9
- [13] S. Iwai, et al, TEION KOGAKU, 48 (2013) 187-195
- [14] H. Miyazaki, et al, Abstracts of CSSJ conference, 88 (2013) 100
- [15] S. Iwai, et al, Abstracts of CSSJ conference, 88 (2013) 101
- [16] T. Tosaka, et al, Abstracts of CSSJ conference, 88 (2013) 102
- [17] H. Miyazaki, et al, IEEE Trans. Appl. Supercond., 24 (2014) 4600905
- [18] Y. Iwasa, Case studies in superconducting magnets, second ed., Springer, New York, 2009.
- [19] T. Tosaka, et al, Abstracts of CSSJ conference, 88 (2012) 113
- [20] H. Miyazaki, et al, IEEE Trans. Appl. Supercond., 21 (2011) 2453-2457
- [21] H. Miyazaki, et al, Physica C, 494 (2013) 203-207
- [22] S. Iwai, et al, Physica C, 494 (2013) 287-291
- [23] H. Miyazaki, et al, TEION KOGAKU, 48 (2013) 239-246
- [24] H. Ueda, et al, Abstracts of CSSJ conference, 90 (2014) 194
- [25] V. Selvamanickam, et al, Supercond. Sci. Technol., 25 (2012) 125013
- [26] A. Matsumi, et al, Abstracts of CSSJ conference, Vol. 90 (2014) 151