Design of a half-size 3T REBCO superconducting magnet with active shielding coils for MRI

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Abstract. Research and development for the practical application of a medical-use MRI superconducting magnet that requires without liquid helium started as the New Energy and Industrial Technology Development Organization's (NEDO) supported project in fiscal 2016. This project will test produce a half-size active shield-type 3T REBCO coil and realize high magnetic field homogeneity and stability. To achieve this, issues will be resolved by developing the optimal design method for the coil system, establishing a coil manufacture method, stabilizing the magnetic field, and protecting the coil. We will describe the structure and fabrication conditions of the 3T REBCO coil, calculation results of electromagnetic stress. Cooling system design of this coil is also described.

1. Introduction
Due to demands for high-definition images, high-field and high-stability superconducting magnets are being used more widely today for Magnetic Resonance Imaging (MRI) system, medical imaging diagnostic equipment. The number of 1.5 T or 3 T superconducting magnets used in MRI system is increasing every year, reaching about 6,000 units in Japan as of 2017. However, current superconducting magnets are made of niobium-titanium (NbTi) superconducting wire, which requires cooling with a large amount of liquid helium. With the recent rising price and unstable supply of liquid helium, there is a demand for superconducting magnets that do not use liquid helium for cooling. We have proposed and developed superconducting magnets composed of conduction-cooled high temperature superconducting (HTS) coils [1]. In a project started in fall 2013 for developing a HTS magnet for a medical MRI [2]-[8], we succeeded in the world's first MRI at 3T using a model magnet composed of HTS coils capable of generating a magnetic field of high homogeneity and stability [9]. Still, there are technical issues to solve on practical application of HTS coils for a full-body MRI, such as: design of the coil system that does not deteriorate superconducting properties and can withstand large magnetic forces, winding method in which a large-diameter coil, over one meter, can be wound with an accuracy of 0.1 mm or less, generation method of a magnetic field of high homogeneity and stability for imaging, optimization of the magnet cooling system, and coils protection method. In this project, we are designing and fabricating a half-size active shield-type 3T HTS magnet to examine these issues. Magnetic field homogeneity and stability of this magnet will be measured and adjusted. Then, imaging will be performed in a 200-mm spherical space to check the quality of the magnetic field and to prove that HTS coils can be applied to an MRI magnet. In addition, we will examine a highly stable power supply and a magnetic field control system, which are essential to improving magnetic field stability. Based on the knowledge gained from the R&D, a basic design of a 3T full-body MRI magnet for practical use will be created. In this paper, we report on the design of the half-size active shield-type 3T coil and the cooling system that can reduce the initial cooling time.

2. Design of the Half-size Active Shield-type 3T Coil
We designed an MRI coil considering superconducting properties of wire under the condition of a 2.9 T central magnetic field, 2 ppm or less magnetic field homogeneity in an imaging area of 200 mm sphere, and a 2.5 m x 3.5 m magnetic leakage area at 0.5 mT or less. Figure 1 shows the exterior of the designed half-size active shield-type 3T HTS coil, and Table 1 lists the coil specifications. Two-hundred and twenty pancake coils are used in this 3T HTS coil and the total length of the HTS wire used is about 70 km. The assembled 3T HTS coil, 980 mm in axial length, 560 mm in inner diameter and 1200 mm in outer diameter, consists of a main coil for producing the main magnetic field and a pair of shield coils for reducing magnetic field leakage, as shown in Figure 1. The maximum magnetic field at the rated central magnetic
The radial maximum magnetic field facing perpendicularly to surfaces of the superconducting wire arises at the axial edge of the main coil where the highest load factor on the superconducting wire is observed due to the anisotropy feature of superconductors. To minimize the radial magnetic field, we decreased the number of windings of the main coil in stages. The result is that the radial magnetic field lowered to 2.9 T, decreasing by about 5%. The magnetic homogeneity in the design is 1.7 ppm over 250 mm DSV (Diameter Spherical Volume). Figure 2 shows the magnetic field leakage distribution up to 10 mT. The 5 Gauss line when the coil is excited at 3 T is 2.5 m x 3.4 m from the center of the coil. The maximum axial stress generated in the coil is 30 MPa and the maximum circumferential stress is 55 MPa, both of which are lower than the allowable stress of the superconducting wire of 100 MPa. The current density when the coil is excited at the rated values is 120 A/mm², amounting to about 60% of the maximum load factor at a coil temperature of 20 K.

![Figure 1. Front perspective view of the half-size active shield-type 3T HTS coil](image1.png)

![Figure 2. Magnetic field leakage distribution of the half-size active shield-type 3T HTS coil](image2.png)

### Table 1. Specifications of the half-size 3T Coil

| Item               | Specification               |
|--------------------|-----------------------------|
| Inner Diameter     | 560 mm                      |
| Outer Diameter     | 1200 mm                     |
| Axial Length       | 980 mm                      |
| Inductance         | 145 H                       |
| Rated Current      | 148 A                       |
| Rated Current Density | 120 A/mm²                  |
| Stored Energy      | 1.58 MJ                     |
| Central Magnetic Field | 2.9 T                     |
| Maximum Magnetic Field | 4.2 T                     |
| Magnetic Field Homogeneity | 1.7 ppm (250 mm DSV) |

### Table 2. Specifications of REBCO superconducting wire

| Dimension            | Conductor width | Conductor thickness |
|----------------------|-----------------|--------------------|
| Structure            | Insulated film (dual) |
| Inner layer          | Polymide tape   |
| Outer layer          | Polyimide tape  |
| Metal circuit board  | Nickel based alloy (Equivalent to Hastelloy RC-276) |
| Electrical characteristics | Critical current |
| current              | 160 A or higher at 77K, self-field |

3. Fabrication of HTS Coils

As R&D of HTS coils, we have investigated methods of solder connection, high-precision coil production and prevention of superconductivity deterioration [2]-[8]. As for a solder connection method, stable connection characteristics were obtained by using a low temperature solder [3]. For high-precision coil production, the target winding accuracy of 0.2 mm or less was achieved [8]. Then, as for prevention of superconductivity deterioration in the winding process, we focused on protection of superconducting thin films, which are vulnerable to the peeling stress. Surfaces of the superconducting wire were covered by fluorine coated insulation films to protect the superconducting surfaces of the wound coil in the step of vacuum impregnation with epoxy resin from the peeling stress. However, while the superconductivity did not deteriorate in coils composed of wire of 50 m or less length, the percentage of non-defective items obtained in a test on pancake coils was about 85% in the case of coils composed of wire of 200 m or more length. We are finding the deteriorated area and investing the causes. Table 2 shows the specifications of the HTS wire used, and Figure 3 shows a cross-section image of the wire. The REBCO superconducting wire consists of hastelloy tape of 4 mm width and 0.075 mm thickness, a REBCO superconducting thin film covering the hastelloy tape through an inner layer.
thin film, and a copper coating of 0.02 mm thickness. Pancake coils need to be wound with an accuracy of 0.1 mm or less due to the parameter of the magnetic homogeneity. The winding precision is monitored using a displacement meter during winding, and the position of the wire is adjusted each time the winding error exceeds 0.1 mm. Figure 4 shows a photograph of trial pancake coils of the main coil and the shield coil. The inner diameter of the main coil is 560 mm, and the outer diameter is 670 mm. The inner diameter of the shield coil is 1145 mm, and the outer diameter is 1200 mm.

4. Cooling System of the Half-size Active Shield-type 3T Magnet
REBCO superconducting coils are cooled by using Gifford-McMahon (GM) cryocoolers to which two cooling agents connected in the second stage through copper cooling plates on each pancake coil. The weight of the coils and their components to be cooled are about 900 kg and the weight of a radiation shield is about 100 kg. We calculated the initial cooling properties by a non-linear primary transient analysis performed based on factors such as the GM cryocooler performance, and the heat capacity, heat conduction and radiation of the cooling agents. The analysis found that it took 21 days to complete cooling when the coils were cooled from the room temperature using one GM cryocooler as shown in Figure 5. Therefore, two GM cryocoolers simultaneously operated at the initial cooling phase, and a thermal switch for controlling thermal short circuits between the first and the second stages was installed on each cryocooler. This switch was turned off after the coils had been cooled to nearly 50 K by the first stage, which has a higher cooling capacity. By this method, the expected initial cooling time was reduced to about seven days as shown in Figure 6. In addition, a solid thermal switch operating by the temperature dependence of thermal conductivity of Carbon Fiber Reinforced Plastics (CFRP) is installed in the cooling system. In the normal operation mode, the magnet is cooled by one GM cryocooler. By installing two GM cryocoolers, because either one operates while the other is being checked and maintained, the cooling process can proceed without interruption. Figure 7 shows the structure of the magnet consisting of the REBCO coils inserted into a cryostat. The height of the magnet is 1800 mm and the diameter of the room-temperature bore for imaging is 480 mm. The shimming system for adjusting magnetic field homogeneity, and a gradient magnetic field coil (G coil) and a radiofrequency coil (RF coil) for generating images are installed in the bore.
5. Summary
The HTS magnet system with a highly stable magnetic field is being developed to create an MRI magnet using high temperature superconductors requires without liquid helium for cooling. The purpose of our project is to fabricate a half-size active shield-type 3T coil to ensure high magnetic field homogeneity and stability the MRI system requires. To achieve this, we are striving to resolve issues such as development of the optimal design method for the coil system, establishment of a coil manufacture method, stabilization of the magnetic field, and protection of coils. Design of the half-size active shield-type 3T coil has been complete and its fabrication has started. We have examined the cooling system and obtained a promising result that the initial cooling time will be reduced to half or less when two GM cryocoolers are installed and the first stage is short-circuited to the second stage by thermal switches.

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Figure 7. Structure of the half-size active shield-type 3T magnet [10]