Thermal Design of the 4 T Magnet for an Adiabatic Demagnetization Refrigerator (ADR)

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ABSTRACT

A high temperature superconducting (HTS) solenoid magnet has been fabricated to provide a time-varying magnetic field for an adiabatic demagnetization refrigerator (ADR). The fabricated magnet has an outer diameter of 88 mm, an inner diameter of 24 mm, and a height of 54 mm. The magnet is designed to operate in a ramping mode with a maximum field of 4 T, and to be conduction-cooled by a 4 K Gifford-McMahon (G-M) cryocooler. Since the changing current operation of the superconducting magnet involves inevitable energy dissipation and resulting heating of the HTS tape, copper thermal drains are inserted into every layer of the magnet winding. The AC loss of the designed magnet is estimated to confirm the feasibility of the conduction cooling of the AC magnet. The time-varying AC loss of the HTS magnet is calculated by using the T-A formulation, which is based on calculation of the current vector potential T and the magnetic vector potential A. The detailed design and the fabrication processes are presented in this paper.

INTRODUCTION

An adiabatic demagnetization refrigerator (ADR) produces cooling by using the variation of the magnetic field, known as the magnetocaloric effect [1]. ADR's have been used to achieve sub-kelvin temperatures with high reliability, since the cooler is not accompanied with mechanical vibration [2,3]. With this background, our research group previously proposed an integrated cooler that consists of a sorption precooler and an ADR for stable quantum computing [4]. The superconducting magnet in the ADR needs to operate in an AC mode to vary the magnetic field while the whole refrigeration system remains stationary. The superconductor, however, is intrinsically dissipative when AC current flows through it [5]. This ‘AC loss’ induces a temperature rise of the conductor under poor cooling conditions. Under excessive AC losses, the superconductor may even lose its superconductivity and transforms to the normal state. This phenomenon, ‘quench’, must be prevented for stable AC operation of the magnet.

As a high temperature superconductor (HTS) has sufficient temperature margin due to its high transition temperature, an HTS magnet has been specifically designed for the ADR and fabricated in this study. The design target is to achieve a center field of 4 T with a maximum 0.1 T/s ramp rate. The HTS magnet is to be conduction-cooled by a 4 K Gifford-McMahon (G-M) cooler (RDK 415-D, Sumitomo). Furthermore, the G-M cooler works as a heat sink not only for the AC magnet, but also for the proposed ADR [4]. The target temperature of the heat sink should be maintained lower than the critical temperature of helium (5.2 K) and was decided to be 4.5 K. Since the cooling capacity of the G-M cooler is a function of the cold head temperature and is very limited near 4 K, the AC loss of the magnet needed to be accurately estimated in advance to confirm the feasibility of the conduction cooling. After the specifications of the

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Table 1. Specifications of the designed magnet

Conductor	
Material	GdBCO (SuNAM Inc.)
Geometry	4.2 mm × 0.24 mm × 245 m (width × thickness × length)
Critical current	200 A (@ 77 K, self-field)
Substrate	stainless-steel
Stabilizer	copper (both sides)
Insulation	wrapped Kapton
Magnet	
Geometry	layer wound solenoid (112 layers, 12 turns per layer) I.D. 24 mm // O.D. 88 mm // H. 54 mm
Inductance	45.4 mH
Magnet constant	20.7 mT/A

magnet were determined, a HTS magnet was fabricated as a layer-wound solenoid. In the winding pack of the solenoid magnet, copper strips are inserted to effectively transfer the heat generated by the AC loss of the conductor. The flange of the magnet is also designed to minimize the eddy current loss induced from the alternating field. The detailed design and fabrication processes are presented in the remaining sections of this paper.

DESIGN

The design target of the magnet is a center field of 4 T with a ramp rate of 0.1 T/s. The magnet is configured to be a layer-wound solenoid to minimize the dead volume and achieve a compact size. The bore diameter is set to 24 mm, which is enough for installing the magnetic material of the ADR. The conductor is selected as SCNk04200 (SuNAM) which has a stainless-steel (SS) substrate layer, a copper stabilizer layer on both sides of the conductor, and a wrapped Kapton insulating layer. The conductor has a width of 4.2 mm, and its total thickness is 0.24 mm.

Table 1 shows the detailed specifications of the designed magnet. The magnet has 112 layers, and each layer is composed of 12 turns of the conductor. The height and the outer diameter of the solenoid winding are 54 mm and 88 mm, respectively. Figure 1 shows the magnetic field distribution of the designed magnet. The field distribution is illustrated for a quarter of the magnet by considering its symmetry. The distribution of magnetic field is calculated by solving the Maxwell equation using a commercial FEM tool [6]. When the current of 200 A is supplied to the magnet, the center field is 4.14 T.

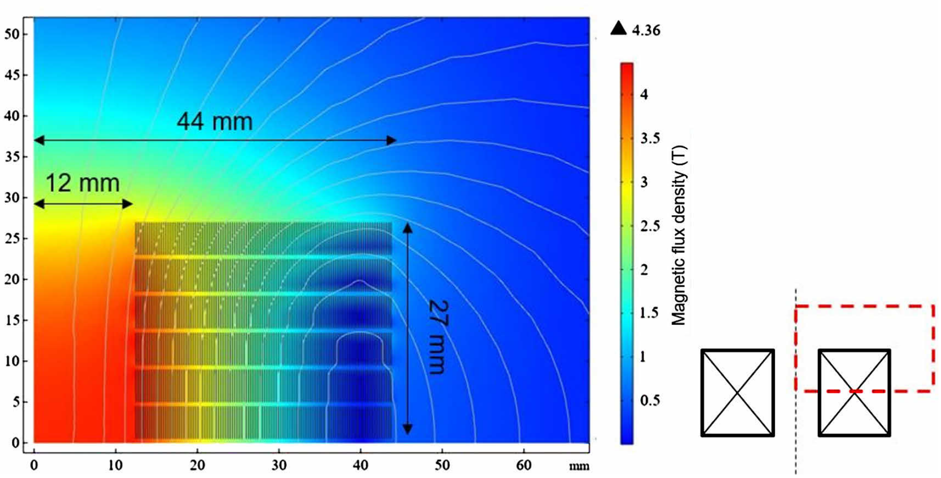

Figure 1. Magnetic field distribution of the designed magnet. This plot shows a quarter of the whole magnet domain. Current of 200 A is supplied to the magnet, and the corresponding center field is 4.14 T.

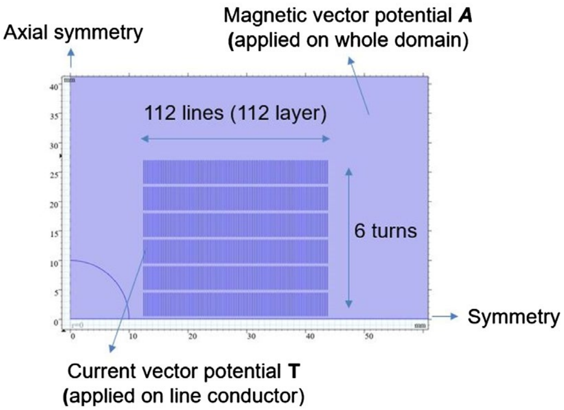

Figure 2. Computation domain of the AC loss estimation

AC LOSS CALCULATION

The designed magnet generates a dissipative heat due to its AC operation. Furthermore, the magnet is to be conduction-cooled by a cryocooler which has limited cooling capacity at cold head temperatures near 4 K. To check if the design targets (maximum field and ramp rate) are feasible or not, the AC loss was calculated and compared to the cooling capacity of the cryocooler. Electric field **E** and current density **J** are required to obtain instantaneous AC loss $\mathbf{E}\cdot\mathbf{J}$. The AC loss and electromagnetic behavior of the designed magnet is estimated by using the T-A formulation. The formulation is based on the calculation of the current vector potential **T** and the magnetic vector potential **A** as defined in following equations, where **B** is the magnetic flux density.

$$\mathbf{J} = \nabla \times \mathbf{T} \tag{1}$$

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{2}$$

As shown in Figure 2, the magnetic vector potential is computed in the whole domain while the current vector potential is computed in the superconducting layer only. The computational load is minimized by using the geometrical symmetry. From the Maxwell equation, **A** and **T** are computed as the following equations.

$$\nabla \times (\frac{1}{\mu}\nabla \times \mathbf{A}) = \mathbf{J} \tag{3}$$

$$\nabla \times (\rho_{HTS}\nabla \times \mathbf{T}) = -\frac{\partial \mathbf{B}}{\partial \mathrm{t}} \tag{4}$$

The resistivity of the HTS conductor (ρ_{HTS}) is modelled by the E-J relation (Equation 5).

$$\rho_{HTS} = \frac{E_c}{J_c(\boldsymbol{B})}\left|\frac{\mathbf{J}}{J_c(\boldsymbol{B})}\right|^{n-1} \tag{5}$$

In the above equation, the critical electric field, E_c and the index value, n are set to $1 \times 10^{-4} V/m$ and 25, respectively. The critical current density J_c is obtained by interpolating the experimental data at various field and temperature conditions [7]. In the referred study, the critical current density was experimentally obtained by maintaining the conductor temperature at 20 K. The input current has the form of a triangle wave with an amplitude of 200 A and a ramp speed of 5 A/s (0.1 T/s ramp rate). The input current gives the boundary conditions for the current vector potential as shown in Equation 6.

$$I_{input} = \iint_S^{\square} \boldsymbol{J} dS = \iint_S^{\square} \nabla \times \mathbf{T} dS \tag{6}$$

Consequently, the AC loss is obtained by solving Equations 1~6. The detailed approach of using the T-A formulation is presented in several other studies [8, 9].

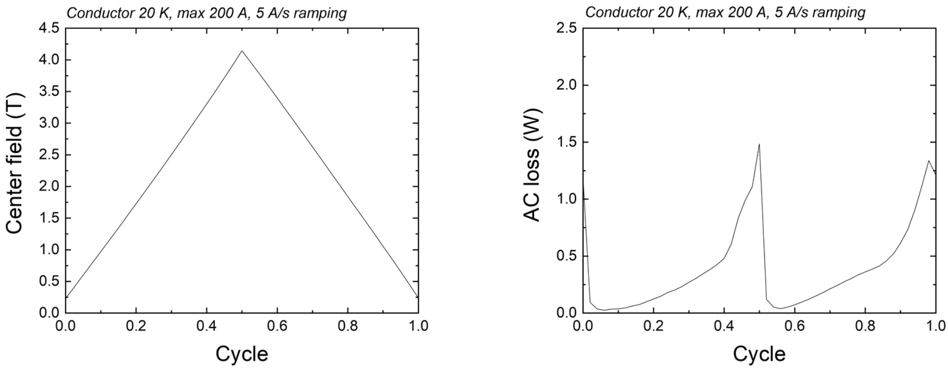

Figure 3. Simulated variation of the magnetic field (left) and variation of the AC loss (right)

Figure 3 shows the intended field variation and the calculated value of the AC loss under the given current ramping conditions. The calculation confirms that the maximum value of the instantaneous AC loss is 1.49 W, and the time-average value is 0.39 W. The G-M cooler for this conduction-cooled magnet has a cooling capacity of 1.8 W at a cold head temperature of 4.5 K. The AC loss estimation, thus, confirms that the cryocooler has enough cooling capacity for coping with the AC loss of the designed magnet without a significant temperature rise.

FABRICATION

Figure 4 shows a 3-D sketch and a photograph of the constructed magnet bobbin. The bore of the magnet is made of a SS tube with an inner diameter of 24 mm and a thickness of the 0.5 mm. The SS tube is laser-welded with the two slitted SS flanges, and the copper flanges are bolted on the outermost part of the SS flanges. The copper flanges are divided into four pieces to minimize eddy current losses. The induced eddy current loss of the designed bobbin structure is calculated as 0.05 mW under 4 T-0.1 T/s operation. The copper flanges are thermally linked to the 2nd stage of the G-M cooler and work as a heat sink for the winding pack which produces the AC losses.

To supply current to the magnet, an HTS tape with a width of 8 mm is soldered on the copper electrode by using SnPb solder (183°C melting temperature). Then, the first turn of the first layer of the winding conductor is soldered on the round surface of the electrode by using InSn solder (118°C melting temperature). All the soldering joints are made for direct contact of the superconducting layer of the conductor faces to the copper surface to minimize joint resistance. The copper electrode is electrically insulated from the magnet bobbin using G-10 pieces.

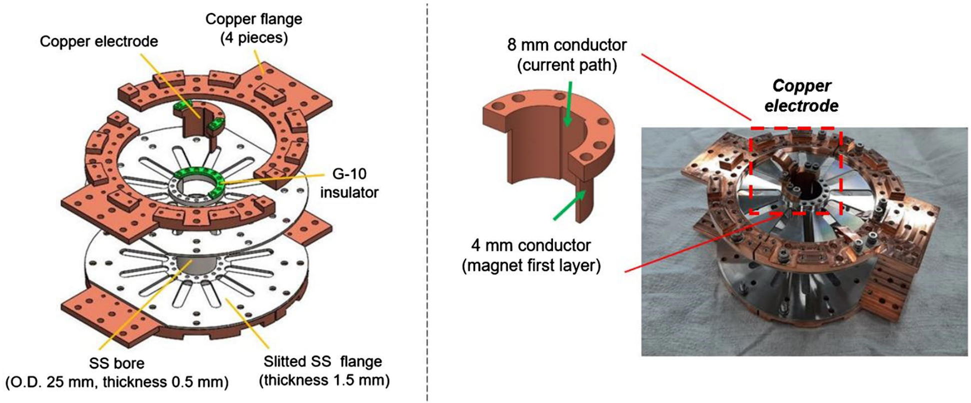

Figure 4. 3-D sketch (left) and photograph (right) of the magnet bobbin structure

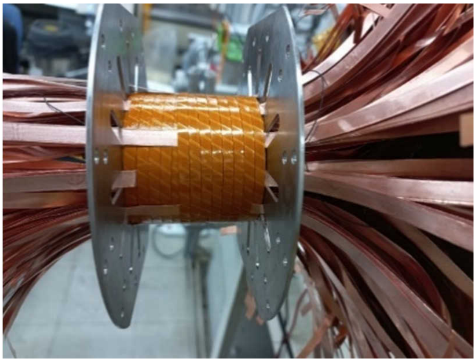

Figure 5. Copper strips inserted inside the winding pack

Table 2. The number of the installed copper strips at each layer

	Copper strip
Cross section area	6 mm × 0.05 mm (width × thickness)
the number of strips	Layer 1-6, 2 pieces Layer 7-22, 3 pieces Layer 23-40, 4 pieces Layer 41-112, 6 pieces

Thin copper strips are inserted into every layer of the magnet as shown in Figure 5. The copper strips provide the thermal path between the wound superconductor and the copper flange. The AC loss heat generated inside the winding pack can be effectively transferred by this thermal path. The copper strips are 6 mm wide, with a thickness of 0.05 mm. By considering the amount of the AC loss at each layer of the winding, the required thermal conductance of the thermal path was determined. The number of the installed copper strips at each layer is summarized in Table 2. To enhance the thermal contact conductance, Apiezon N grease was pasted on the HTS conductor and the copper strips during the winding process. Furthermore, the copper strips were divided into two groups to reduce the number of thermal contact areas between the strips. There are two contact areas in the copper flange with the step difference in height. The contact area 1 is located higher than area 2. As shown in Figure 6, each group of copper strips is attached to the copper flange by compaction. Figure 7 shows a photograph of the fabricated HTS magnet. The fabricated magnet will be thermally connected with the 4 K G-M cooler, and 4 T tests will be conducted.

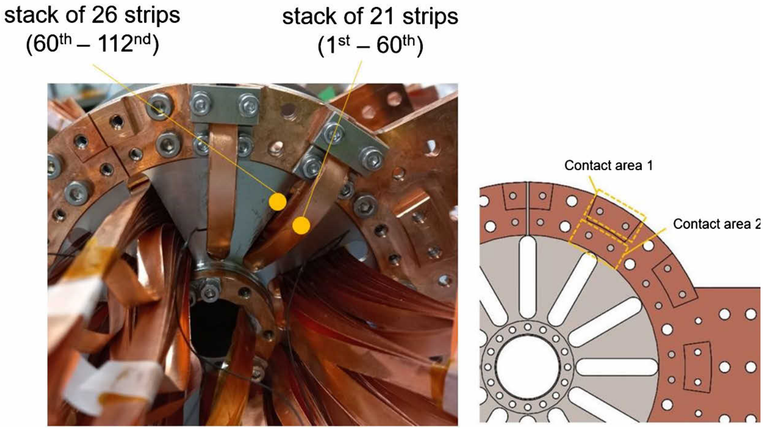

Figure 6. Attachment of the copper strips on the magnet flange. There are two contact areas on the copper flange with a step difference in height. Thermal drains are bent in a radial direction for good thermal contact.

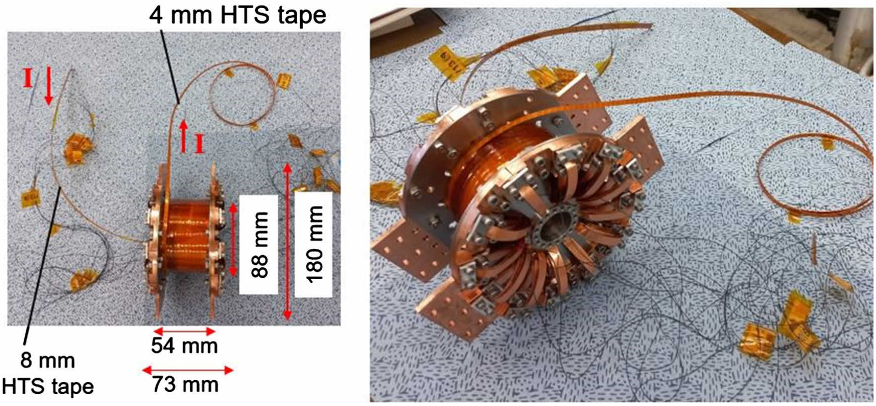

Figure 7. Photograph of the fabricated HTS magnet

SUMMARY

A conduction-cooled HTS magnet has been designed and fabricated to produce a ramping magnetic field for an ADR. The fabricated magnet has an inner diameter of 24 mm, an outer diameter of 88 mm, and a height of 54 mm. A total length of 245 m of HTS conductor was used, and the layer-wound solenoid consists of 112 layers with 12 turns per layer. To effectively dissipate the AC loss from the winding pack to the heat sink, thin copper strips were inserted in every layer of the magnet. The thin strips provide a thermal path between the conductor and the heat sink of the system. The magnet produces a center field of 4.14 T when a current of 200 A is supplied to the magnet. According to our AC loss calculation, the maximum instantaneous AC loss is 1.49 W under a 0.1 T/s ramping condition, and the time-average AC loss is calculated as 0.39 W. Conduction cooling of the magnet is feasible since the cryocooler used for conduction cooling has enough cooling capacity for dissipating the AC loss heat without a significant temperature rise.

ACKNOWLEDGMENT

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