International Journal of Heat and Mass Transfer 103 (2016) 165–172

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Measurement of thermal contact conductance between round-shaped superconducting wires and rectangular slot in copper block for application to cryogenic transfer tube

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ARTICLE INFO

Article history:
Received 1 April 2016
Received in revised form 31 May 2016
Accepted 7 July 2016

Keywords:
Round-shaped superconducting wire,
Thermal contact conductance
Transfer tube
Cryogenics
Thermal joint

ABSTRACT

At J-PARC (Japan Proton Accelerator Research Complex), the COMET (Coherent Muon to Electron Transition) experiment is being prepared. Pion-capture and muon-transport superconducting solenoid magnets will be used to capture pions and transport muons which are produced by pion decays. Since the radiation level is high near the magnets, a cold box and a current lead box, which supply a two-phase forced helium flow and currents to the magnets, will be located apart from the magnets. To connect the cold box and current lead box to the magnets, unique cryogenic transfer tubes that have thermal joints for installing NbTi superconducting lead wires at the insides of the transfer tubes are necessary. The transfer tubes should be able to make the wires thermally stable. In this paper, thermal contact conductance between three round-shaped NbTi/Cu monolith superconducting wires and a rectangular slot in a copper block is measured from 4.5 K to 10 K in six cases and a concept of a thermal joint is proposed for the unique transfer tube of the muon-transport superconducting solenoid magnet. In the thermal joint, the round-shaped superconducting wires make line contacts with the slot covered with one layer of a Kapton tape. The void volume in the slot is filled with Apiezon N grease. An experimental apparatus that uses liquid helium is utilized for measuring the thermal contact conductance in a sample of the thermal joint. The effect of thermal cycles on the thermal contact conductance is observed. The measured thermal contact conductance is used to determine the length of the thermal joint and the size of the gap between the thermal joints.

1. Introduction

At J-PARC, the COMET experiment is being prepared to observe the muon to electron conversion process which is one of charged lepton flavor violations. To control particles, superconducting magnets will be used at high radiation conditions. In a pion-capture superconducting solenoid magnet, a rectangular-shaped NbTi superconducting cable is used as a conductor to make a solenoid magnetic field, which captures pions produced by proton bombardments. In a muon-transport superconducting solenoid magnet, a round-shaped NbTi superconducting wire is used as a conductor and it transports muons generated by pion decays to a stopping target [1]. During 280 days operation (when cool-down and warm-up time is ignored), 0.8 MGy is estimated as a peak dose for the pion-capture magnet. Since the superconducting magnets are cooled down by using a conduction-cooling method with a two-phase forced helium flow, transfer tubes which connect a cold-box to the magnets are necessary. To supply currents to the superconducting magnets, a current lead box with superconducting current leads will be installed. Due to high radiation conditions near the magnets, the cold box and current lead box should be located apart from the magnets to avoid the effect of irradiation on the components of the cold box and current lead box. To supply simultaneously the two-phase forced helium flow and currents to the magnets, unique cryogenic transfer tubes which have thermal joints for installing superconducting lead wires on 4.5 K return pipes are necessary [1]. Fig. 1 shows a schematic diagram that

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.07.025
0017-9310/

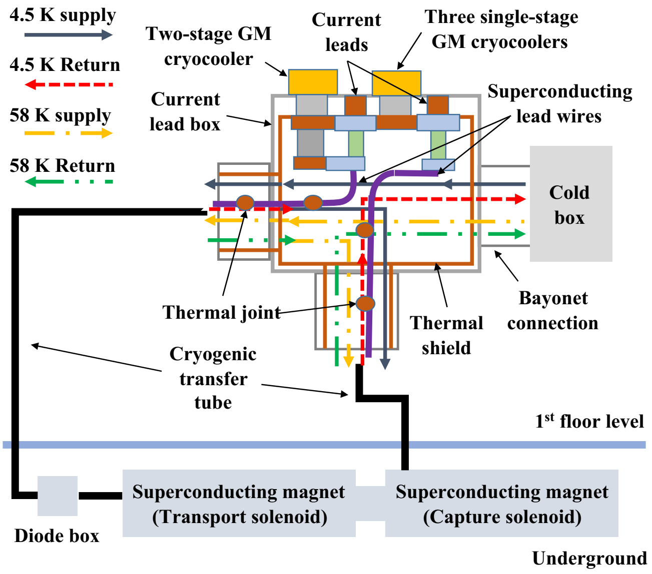

Fig. 1. Schematic diagram of connection between magnets and current lead box.

explains how to connect the magnets to the current lead box and the cold box.

For the thermal joints of superconducting lead wires, the most important factor is about thermal contact conductance between superconducting wires and a cold source. The thermal contact conductance is determined by joint methods and there are four kinds of joint methods, soldering, epoxy, grease, and dry joints [2]. In a conduction-cooling case, defective contacts between superconducting lead wires and a cold source generate the temperature increase, which results in the increase of cooling load or decrease of performance. The thermal contact problem happens more frequently in cryogenic systems. Most research is about the measurement of thermal contact conductance between plate-type materials. In our case, a round-shaped superconducting wire is used in the transfer tube for the transport magnet as current leads. It is preferred to use a thermal grease for the thermal joints due to fabrication process and maintenance.

In this paper, thermal contact conductance between three round-shaped NbTi superconducting wires and a rectangular slot in a copper block is measured to apply the thermal joint to the cryogenic transfer tube of the muon-transport superconducting magnet. The surfaces of the slot are covered with one layer of a Kapton tape (1205, 3M) and the void volume between the three round-shaped wires and the slot is filled with Apiezon N grease (M&I Materials). In order to measure the thermal contact conductance between the three round-shaped superconducting wires and the slot from 4.5 K to 10 K, an experimental apparatus that uses liquid helium and has very small heat leaks is utilized. At a sample joint, the thermal contact conductance is measured at six cases and the effects of Apiezon N grease and thermal cycles on the thermal contact conductance are observed. With the measured thermal contact conductance, the dimensions such as the length of the thermal joint and the size of the gap between the thermal joints are determined.

2. Thermal joint for transfer tube of transport superconducting magnet

2.1. Requirements of thermal joint with round-shaped superconducting lead wires

For the transport magnet, currents of 210 A and 165 A are required for main solenoid coils and dipoles, respectively, which means that four current leads are necessary. In the current lead box, four copper and superconducting current leads are cooled down by a two-stage GM-type cryocooler (RDK-408D2, Sumitomo Heavy Industries, Ltd.) and cold ends of the four superconducting current leads are connected with superconducting lead wires. Thermal joints with the superconducting lead wires are installed on a 4.5 K return pipe of the transfer tube from the current lead box to the transport magnet. This is for avoiding the installation of an additional cooling system that preserves the temperature of long superconducting lead wires. The total length of the transfer tube is about 11 m. The thermal joints installed on a 4.5 K return pipe should be thermally and electrically stable during the long operation along the transfer tube because it will be difficult to repair the thermal joints when the magnets operate and residual radioactivity exists. The configuration and mass of the thermal joint should be essentially considered to design the transfer tube because those factors determine the stress and deformation of a 4.5 K return pipe and configurations of spiders installed at the 4.5 K region.

Basically, we want to use a thermal grease in the thermal joints for the convenience of fabrication and modification and for allowing slips on surfaces during cooldown. If a semi-permanent soldering joint or epoxy joint is used, it will be difficult to modify the thermal joint when a problem is generated from the thermal joint. In that case, we need to cut the superconducting lead wires and it induces unnecessary joint resistances. For the thermal joints, we also want to use the round-shaped superconducting wire which is used for the solenoid coils of the transport superconducting magnet. Table 1 shows the specification of the superconducting wire. There are three reasons why the round-shaped superconducting wire is used. First, all of the vertical planes of straight sections in the transfer tube of the transport magnet are not in the same plane. It means that if a rectangular-shaped superconducting wire is used, we need to twist the rectangular-shaped wire to maintain a direction of surface contact in a thermal joint. In the case of the round-shaped wire, we don't need to twist the round-shaped wire. Second, the round-shaped superconducting wire makes a line contact with a surface, so it will be easy to make that slip on a contacted surface when a 4.5 K return pipe and the superconducting wire are deformed at a cryogenic temperature. However, this induces a weak thermal contact condition. Therefore, it is required to exactly measure the thermal contact conductance of the joint in order to check the thermal stability of the joint. The last reason is because of the cost efficiency. We want to use the remaining superconducting wire after winding the round-shaped superconducting wire for the coils of the transport magnet.

2.2. Design of thermal joint

2.2.1. Concept of thermal joint

A body material of the thermal joint is copper because the thermal expansion coefficient of copper is similar with that of stainless steel 304 L or 316 L, which is the material of a 4.5 K return pipe in the transfer tube. There are two sections of bolted joints between a 4.5 K return pipe and the superconducting wires. One section of the

Table 1
Specification of round-shaped superconducting wire.

Items	Values
Conductor	NbTi/Cu monolith wire Cu:NbTi = 6:1
Cable dimensions	ϕ1.57 mm (with insulation)
Cable insulation	Polyimide-imide enamel (AIW)
RRR	150