DESIGN AND MANUFACTURE OF A SUPERCONDUCTING SOLENOID FOR D-LINE OF J-PARC MUON FACILITY

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Abstract

A superconducting solenoid for J-PARC muon facility was newly designed and manufactured. High Energy Accelerator Research Organization (KEK) has been operating the J-PARC Muon Science Establishment (MUSE) since 2008. Among its four muon beam lines, the decay muon line (D-Line) has been extracting and providing positive and negative muon beam with a momentum range from several to 120 MeV/c (decay muon) as well as high intensity 30 MeV/c positive muon beam (surface muon) for a variety of science programs, utilizing a superconducting solenoid. The D-Line as well as the other J-PARC facility suffered severe damages from the earthquake on March 11, 2011. It necessitated rebuilding of the damaged superconducting solenoid. New design parameter of the solenoid is as follows: length of solenoid: 6 m, diameter of warm bore: 0.2 m, magnetic field of bore center: 3.5 T, rated current: 415 A, superconducting wire: NbTi/Cu, quench protection: quench back heaters. The six-meter-long solenoid consists of twelve pieces of 0.5-meter-long superconducting coils. The entire solenoid is forced-indirectly cooled by supercritical helium flow. This report describes the design and manufacturing process of the newly built superconducting solenoid for D-Line of J-PARC muon facility.

INTRODUCTION

A newly built superconducting solenoid was introduced to Decay Muon Line (D-line) of J-PARC Muon Facility. It generates a magnetic field in relatively large region (warm bore diameter 0.2m), while keeping the same outer dimensions and connection interfaces to the existing refrigerator and the power supply of the previous machine [1][2][3]. In addition, the superconducting solenoid provides stable operation utilizing conductive-cooling technologies as superconducting devices.

This paper describes design and manufacture of the superconducting solenoid, and results of magnetic field measurement at room temperature.

SYSTEM CONFIGURATION

General Layout

Major specifications of the superconducting solenoid are shown in Table1. The solenoid consists of twelve pieces of 0.5 meter-long superconducting coils, which are series-connected mechanically and electronically. It is contained in a cylindrical vacuum vessel combined with an iron return yoke. All coils are forced-indirectly cooled by cooling pipes with supercritical helium flow supplied from the helium refrigerator and generate the magnetic field. Thermal shields and current leads are also forced-indirectly cooled with gas helium flow.

Table 1: The Solenoid Specifications

Magnetic Field	3.5 T
Diameter of Warm Bore	0.2 m
Length of Solenoid	6 m
Coil Shape	Solenoid
Wire of Coil	NbTi/Cu
Number of Coils	12
Total Weight	4.7 t

Magnetic Field

Figure1 shows a schematic diagram of coils and iron yoke arrangement and magnetic field profile at the center axis of the warm bore. The entire solenoid generates 3.5 T along six-meter-long bore to confine and transport pions. Pions decay into muons during transportation in the solenoid due to their lifetime. Those muons are supplied to the downstream of the beam line. Since these coils are discrete, the magnetic field generated by the superconducting solenoid has the ripple of +/- 3% maximum. However, this value is small enough not to affect a purpose of use of this device.

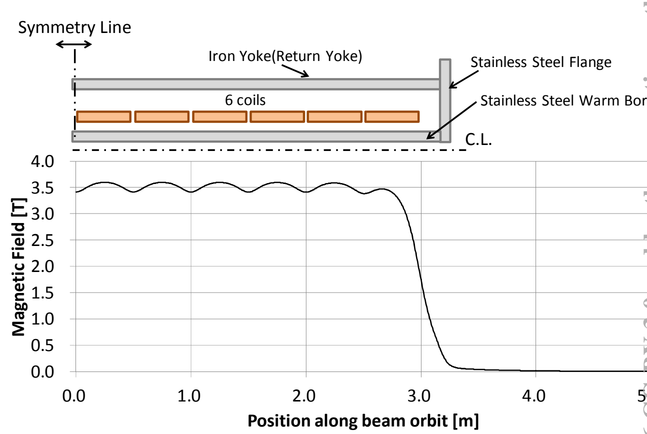

Figure 1: Schematic diagram of the solenoid design and the magnetic field calculation result.

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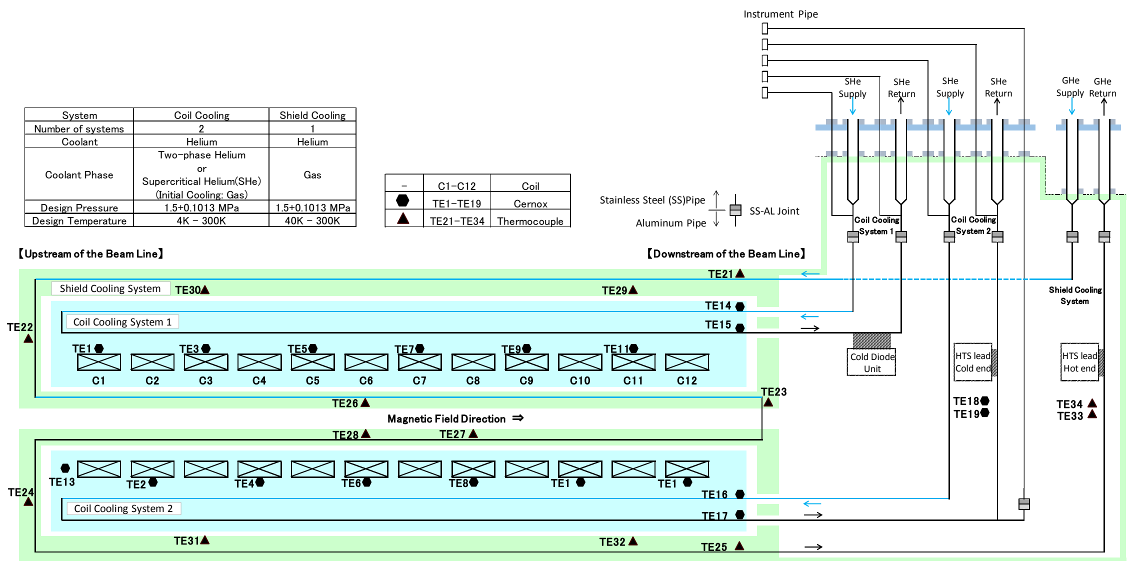

Figure 2: Schematic diagram of the superconducting solenoid cooling system.

MAGNET DESIGN

Coil and Iron Yoke Design

The design parameters of the superconducting solenoid are shown in Table2. The six-meter-long solenoid consists of twelve pieces of superconducting coils connected in series. Each coil was wound with approximately 3400 turns of NbTi/Cu superconducting wire. An aluminum alloy A5056 was adopted for the coil bobbins by the characteristics of mechanical strength and thermal conductivity. The coil dimensions at room temperature were determined to compensate thermal contraction (RT-4K) of the constituent materials.

The iron yoke is a cylinder of outer diameter 0.6m and has 30 mm thickness, which is required for magnetic flux return. As the iron yoke material for this device, low-carbon steel (JIS SS400) is virtually the same as pure iron by comparison of the magnetic field calculation results. Therefore easily procurable JIS SS400 was adopted for the iron yoke.

Cooling Scheme

The cooling system diagram of the superconducting solenoid is shown in Figure 2. The coil bobbins and the thermal shields are equipped with cooling pipes respectively. The superconducting coils are cooled with supercritical helium and the thermal shields are cooled with gas helium, both are supplied from the helium refrigerator. For the material of cooling pipes, an aluminum alloy was adopted to be consistent with the thermal contraction characteristics of coil bobbins and thermal shields. An inner diameter of cooling pipes was determined to be 10 mm from pressure drop calculation. The allowable pressure drop was 100 kPa in normal operation. A thickness of cooling pipes was determined to be 3 mm from the design pressure of the helium refrigerator and the tolerance for pressure increase at coil quench. The design temperature difference between the coolant and the coil bobbins was determined to be 0.25 K maximum. This value is much smaller than 1.3 K as the design temperature margin for the superconducting wire. The heat capacity of the superconducting solenoid estimated from the constituent materials and the weight of the cold mass is approximately 160 MJ. The initial cooling time is determined from the refrigeration power of the refrigerator and the heat capacity of the superconducting solenoid. The initial cooling time was roughly estimated as a week suited for a practical operation.

Table 2: Parameters of the Superconducting Solenoid

Superconducting wire	
Type	Monolithic, NbTi/Cu
Cu/NbTi ratio	4.8
Dimensions(insulated)	ϕ1.56 mm
Magnet	
Number of Turns / Coil (design)	3,377
Rated current	415.7 A
Central magnetic field	3.5 T
Peak field at conductor	3.56 T
Total stored magnetic energy	2.2 MJ
High-field inductance	25.5 H
Magnetomotive force	1.4 MA

Quench Protection

Sheet shaped quench-back heater was installed to the outer surface of each coil. The heater is made of stainless steel, whose resistivity is not sensitive to temperature. After a normal zone emerges in one coil, a cold diode turns on, the coil current flows into all heaters. The generated heat causes quench in every coil, and the dissipation of magnetic energy in the entire solenoid. This avoids local heat concentration, then enables to protect the solenoid.

Cryostat Design

To reduce heat load of the cold mass, the aluminum thermal shields were installed to the inside and outside of the solenoid. A multi-layer insulation (MLI) was placed on the coil surface and the thermal shield surface. The total weight of the solenoid and the thermal shield is approximately 1,000 kg. CFRP cold-mass support system was introduced to bear this weight. In its current supply circuit, the high-Tc superconducting leads [4] were introduced between 4K and 60K in order to reduce heat load and to simplify the cooling scheme of current leads in comparison with the previous device. The summary of design heat loads is shown in Table 3. Both 4K system and the shield system, design heat loads were much smaller than the refrigeration power. Therefore, stable operation was expected.

A chimney structure was attached to the downstream end of the solenoid, which serves as the interface to the refrigerator and the power supply. Non-magnetic stainless steel was adopted for the chimney vacuum vessel to avoid asymmetric magnetic field. A warm bore with 0.2 m diameter was installed to the innermost area of the solenoid. A pillow seal flange was placed to the upstream end of the solenoid. A polyimide material was adopted to a part of MLI and instrumentation wires for its radiation resistance.

Table 3: Summary of Design Heat Loads

Source	Heat Load to Shield System [W]	Heat Load to 4K System [W]
Current Leads	43.2	0.5
Thermal Radiation	42.1	4.1
Magnet Supports	25.5	0.6
Instrumentation Wires	10.5	2.1
Transfer Tubes	4.3	3.1
Total	125.6	10.4
Refrigeration Power	200	35

MANUFACTURE OF MAGNET

Figure 3 shows an appearance of the completed superconducting solenoid for D-Line. In this picture, the near side is the upstream and the far side is the downstream of the beam line.

MAGNETIC FIELD MEASUREMENT

The magnetic field measurement along the beam axis was carried out. After the completion of the solenoid, a very small current was supplied to the superconducting coils at room temperature. The value of the current was determined as one ampere. Measurement results and magnetic field calculation results are shown in Figure 4. The measurement had a good agreement with the calculation result in an error of less than +/- 0.5 %.

Figure 3: Completion of the Superconducting Solenoid.

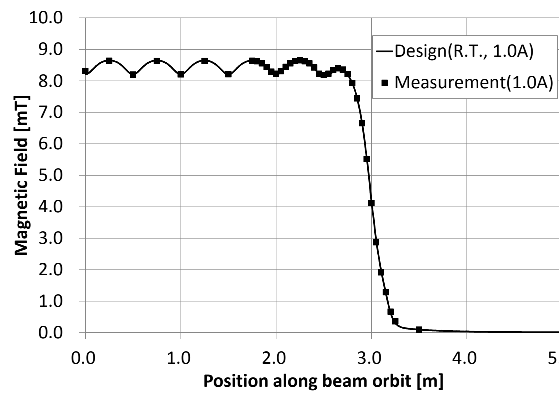

Figure 4: Magnetic field measurement at R.T. in comparison with calculation. This graph indicates the measurement of the beam line downstream region.

CONCLUSION

A new superconducting solenoid for D-Line of J-PARC muon facility was designed and manufactured. It is a replacement for the severely damaged superconducting solenoid from the 3.11 earthquake in Japan. The magnetic field measurement had a good agreement with its design value. This result indicates high accuracy manufacture was carried out.

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