Design and Performance Test of Superconducting Transport Solenoid for D-Line at J-PARC Muon Science Facility

Yasuyuki Tanaka¹,¹, Tomoyuki Semba¹, Shotaro Nakajima¹, Yoshiaki Hagiwara¹, Shuichi Kido¹, Yukihiro Murata², Ken-ichi Sasaki², Koichiro Shimomura³, Naritoshi Kawamura³, Patrick Strasser³, Yasuhiro Makida³, Hirokatsu Ohhata³, Noriyuki Kuromasa³, Yasuhiro Miyake³

¹Hitachi, Ltd. Hitachi Works, 3-1-1, Saiwai-cho, Hitachi, Ibaraki, 317-8511, Japan
²Hitachi, Ltd. Research and Development Group, 7-1-1 Omika-cho, Hitachi, Ibaraki, 319-1292, Japan
³High Energy Accelerator Research Organization (KEK), 1-1, Oho, Tsukuba, Ibaraki, 305-0801, Japan

¹yasuyuki.tanaka.xj@hitachi.com

Abstract. A superconducting transport solenoid for Decay Muon Line (D-line) at J-PARC Muon Science Facility was newly designed and manufactured. It was designed to generate a magnetic field in relatively large region (warm bore diameter 0.2 m), while keeping the same outer dimensions, connection interfaces to the existing refrigerator and the power supply of the previous machine [1-3]. Major changes of both solenoids are the reduction of the central magnetic field, the equipment of a warm bore and the adoption of the high Tc current leads. After the installation to the beam line, the initial cooling test, the excitation test and the emergency shutdown test at the rated current were conducted by KEK in order to confirm cryogenic and magnetic performance. These tests were successfully performed with no damage and indicated the solenoid was precisely manufactured and fulfilled the requirements. The solenoid has been under operation since July, 2015. This report describes the design, the manufacturing process, the magnetic field measurement at room temperature and the results of performance tests conducted by KEK.

1. Introduction

The 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 transport solenoid [1-3]. The D-Line as well as the other J-PARC facility suffered severe damages from the earth-quake on March 11, 2011. It necessitated rebuilding of the damaged superconducting transport solenoid. For this reason, a superconducting transport solenoid for the D-Line at J-PARC muon science facility was newly designed and manufactured. It generates a magnetic field in relatively large region (warm bore diameter 0.2 m), while keeping the same outer dimensions, connection interfaces to the existing...
refrigerator and the power supply of the previous machine [1-3]. In addition, the solenoid provides stable operation utilizing conductive-cooling technologies as superconducting devices.

This paper describes the design, the manufacture of the solenoid, the magnetic field measurement at room temperature [4] and the results of performance tests conducted by KEK.

2. System Configuration

2.1. General Layout

Major specifications of the previous machine and the newly built solenoid are shown in Table 1. 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 indirectly cooled by cooling pipes with supercritical or two-phase helium flow supplied from the helium refrigerator. Thermal shields and current leads are also indirectly cooled by cooling pipes with gas helium flow. The major changes of both solenoids are the reduction of the rated current and the magnetic field, the equipment of a warm bore and the adoption of the high Tc current leads.

| Parameter                  | Previous machine [3] | Newly built solenoid |
|----------------------------|-----------------------|----------------------|
| Magnetic Field             | 5.0 T                 | 3.5 T                |
| Diameter of Cold Bore      | 0.12 m                | -                    |
| Diameter of Warm Bore      | -                     | 0.2 m                |
| Length of Solenoid         | 6 m                   | 6 m                  |
| Coil Shape                 | Solenoid              | Solenoid             |
| Wire of Coil               | NbTi/Cu               | NbTi/Cu              |
| Number of Coils            | 12                    | 12                   |
| Type of Current Leads      | Gas cooled            | high Tc              |

2.2. Magnetic Field

Figure 1 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 solenoid has the ripple of +/- 3 % maximum. The gaps are determined to be 20 mm, which is same value of the previous machine. However, according to the result of previous machine, the ripple is small enough to transport the muon beam without beam loss.
3. Magnet Design

3.1. Coil and Iron Yoke Design

The design parameters of the previous machine and newly built solenoid, and the load line of the newly built magnet are shown in Table 2 and Figure 2.

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 because the bobbins are the structural and the heat conductive member of the solenoid. The alloy has both relatively high mechanical strength and thermal conductivity in comparison with other non-magnetic materials. The coil dimensions at room temperature were determined to compensate thermal contraction (RT-4 K) of the constituent materials.

The iron yoke is a cylinder of outer diameter 0.6 m and has 30 mm thickness, which is required for magnetic flux return. The thickness was determined to reduce the leakage magnetic flux by the magnetic field calculation and to withstand a vacuum pressure and the transportation. Easily procurable low carbon steel (JIS SS400) was adopted for the iron yoke.

Approximately 40 km-long superconducting wires divided into 4 lots were used to manufacture the solenoid. The critical currents ($I_c$) of short samples which are collected from both ends of the lots were measured. When load line was calculated, we assume $I_c$ as subtracting 3 sigma from its averaged value and define criteria for a load line ratio of less than approximately 75.0 % to avoid excess training quenches. The rated current is 415.7 A, corresponding to the load line ratio of 72.9 % to the short sample limit at 5.2 K.

Table 2. Parameters of Solenoids.

| Parameter                                      | Previous machine [3] | Newly built solenoid |
|------------------------------------------------|-----------------------|----------------------|
| Superconducting wire                          |                       |                      |
| Type                                           | Monolithic, NbTi/Cu   | Monolithic, NbTi/Cu  |
| Cu/NbTi ratio                                  | 3.89                  | 4.8                  |
| Dimensions(insulated)                         | 1.60 mm x 3.21 mm     | φ1.56 mm             |
| Magnet                                         |                       |                      |
| Coil inner / outer diameter                    | 130 mm / 190 mm       | 300 mm / 330 mm      |
| Number of Turns / Coil (design)                | Approx. 3,000         | 3,377                |
| Rated current                                  | 730 A                 | 415.7 A              |
| Central magnetic field / Peak field at conductor| 5.0 T / -             | 3.5 T / 3.56 T       |
| Total stored magnetic energy / High-field inductance | - / -                | 2.2 MJ / 25.5 H     |
| Magnetomotive force / Coil (design)            | 2.2 MA                | 1.4 MA               |

Figure 2. Load Line of the Magnet
3.2. Quench Protection

The electric circuit for the solenoid is shown in Figure 3. A sheet shaped quench-back heater was installed to the outer surface of each coil. The heaters are made of stainless steel, whose resistivity is not sensitive to temperature. After a normal zone emerges in one coil, the current bypassing starts when the current supply is shut down by detection of a quench. The generated heat causes quench in every coil, and the dissipation of magnetic energy in the entire solenoid. This avoids local heat concentration and enables to protect the solenoid.

![Figure 3. Electric Circuit for the Solenoid.](image)

3.3. 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-\(T_c\) superconducting leads [5] were introduced between 4 K and 60 K in order to simplify the cooling scheme and the operation scheme of current leads in comparison with the previous machine. The summary of design heat loads is shown in Table 3. Both 4 K 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. In order to supply lower momentum muons compared to the previous machine, 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.

| 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                        |
4. Manufacture of Solenoid
Figure 4 shows an appearance of the completed solenoid for D-Line. In this picture, the near side is the upstream and the far side is the downstream of the beam line.

![Figure 4](image)

**Figure 4.** Completion of the Solenoid. An aluminum blind plate is temporarily flanged to protect the pillow seal flange face during the transportation (the near side of the figure).

5. Magnetic Field Measurement at Room Temperature
The magnetic field measurement using a Hall sensor along the beam axis was carried out after the completion of the solenoid. Very small current was supplied to the superconducting coils at room temperature. The value of the current was determined as 1 A. The magnetic field calculation results and the measurement are shown in Figure 4. The measurement had a good agreement with the calculation result in an error of less than +/- 0.5%.

![Figure 5](image)

**Figure 5.** Magnetic Field Measurement at R.T. (Downstream) in Comparison with Calculation.

6. Performance Test
In order to confirm cryogenic and magnetic performance, the initial cooling test, the excitation test and the emergency shutdown test at the rated current were conducted by KEK.

6.1. Initial Cooling Test
The entire solenoid was cooled from room temperature over approximately 45 hours. The initial cooling curve is shown in Figure 6. The superconducting coils and thermal shields reached blow 4.5 K and 54 K, respectively. The cooling time shortened in comparison with the previous machine, whose cooling time is approximately 3 days [3].
6.2. Emergency Shutdown Test

The emergency shutdown test at rated current was conducted after the solenoid reached the rated current without a spontaneous quench. The coil temperatures were measured by cernox sensors equipped to the surface of each coil bobbin. We simulated the temperature rise after a spontaneous quench in the adiabatic condition, which is the severe condition of the solenoid operation. The solenoid was designed to withstand the temperature rise, which is estimated as maximum 170 K. The maximum temperature of the coils after the emergency shutdown test was approximately 51 K (Figure 7). It had an agreement with the design limitation of the temperature rise.

All tests were successfully performed with no damage. It is confirmed that the solenoid was precisely manufactured and fulfilled the requirements.

7. Conclusion

A new superconducting transport solenoid for D-Line of J-PARC muon science facility was designed and manufactured. It is a replacement for a severely damaged superconducting solenoid from the 3.11 earthquake in Japan. All tests were successfully performed with no damage. This result indicates that the solenoid was precisely manufactured and fulfilled the requirements. The solenoid was installed to D-Line in July, 2015 and has been under operation.
References

[1] K. Nagamine et al., “Superconducting Solenoid and its Cooling System for Pulsed Muon Channel” IEEE Trans. Mag., vol. MAG-17, no.5, p.1882, Sept. 1981.

[2] K. Nagamine, “Large Superconducting Solenoid and its Cooling System for Muon Channel” Teion Kou-gaku, vol. 20, no.4, p.187, 1985. (In Japanese)

[3] K. Shimomura et al., “Muon Beam Line at J-PARC MUSE -Reuse of a 30-year-old Superconducting Magnet- ” Teion Kougaku, vol. 45, no.4, p.174, 2010. (In Japanese)

[4] T. Semba et al., "Design and Manufacture of a Superconducting Solenoid for D-Line of J-PARC Muon Facility" , in Proc. 7th International Particle Accelerator Conference (IPAC'16), pp. 1177-1179, May 2016

[5] H. Teshima et al., “Recent Progress in Compact, Ro-bust and Superior Field-tolerant QMG Current Leads using RE-Ba-Cu- Bulk Superconductors” IEEE Trans. Appl. Supercond., vol. 26, no.3, 4800204, April. 2016.