Development of a Muon Rotating Target for J-PARC/MUSE

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Abstract

At the J-PARC muon science facility (J-PARC/MUSE), a graphite target with a thickness of 20 mm has been used in vacuum to obtain an intense pulsed muon beam from the RCS 3-GeV proton beam \cite{1}, \cite{2}. In the current design, the target frame is constructed using copper with a stainless steel tube embedded for water cooling. The energy deposited by the proton beam at 1 MW is evaluated to be 3.3 kW on the graphite target and 600 W on the copper frame by a Monte-Carlo simulation code, PHITS \cite{3}. Graphite materials are known to lose their crystal structure and can be shrunk under intense proton beam irradiation. Consequently, the lifetime of the muon target is essentially determined by the radiation damage in graphite, and is evaluated to be half a year \cite{4}. Hence, we are planning to distribute the radiation damage by rotating a graphite wheel. Although the lifetime of graphite in this case will be more than 10 years, the design of the bearing must be carefully considered. Because the bearing in J-PARC/MUSE is utilized in vacuum, under high radiation, and at high temperature, an inorganic and solid lubricant must be applied to the bearing. Simultaneously, the temperature of the bearing must also be decreased to extend the lifetime. In 2009, a mock-up of the Muon Rotating Target, which could heat up and rotate a graphite wheel, was fabricated. Then several tests were started to select the lubricant and to determine the structure of the Muon Rotating Target, the control system and so on. In this report, the present status of the Muon Rotating Target for J-PARC/MUSE, especially the development of a rotation system in vacuum, is described.

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1. Introduction

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The most intense pulsed muon beam will be generated in vacuum by a 3-GeV 333-µA proton beam on a muon target made of 20-mm thick isotropic graphite (IG-430) at J-PARC/MUSE (Japan Proton Accelerator Research Complex /Muon Science Establishment). The first muon beam was successfully produced on September 26th, 2008, and the most intense pulsed muon beam has continuously been produced with a proton beam of 120 kW since November of 2009. The heat deposited by a 1-MW proton beam is estimated to be 4 kW on the muon target by PHITS. At present, the fixed edge-cooling method has been adopted for cooling the muon target. However, it is predicted that the graphite target will break down in six months due to radiation damage. In the primary proton beam line in the vicinity of the muon target (M2 tunnel), some of the components will be so highly irradiated that hand-on maintenance cannot be performed. In case of the muon target, the radiation dose is predicted to be 5 Sv/hour after a 1-MW proton beam irradiation for half a year. Therefore, the maintenance of the components must be performed from the maintenance area located 2.4 m above the beam line level. In addition, a 2-m high plug shield is necessary between the primary proton beam and the maintenance area for radiation shielding. Because of the high radiation, the boundary of the vacuum, the motion drive, the feedthroughs for the signal cables, the thermo-couples, the water pipes, and so on, must be positioned at the maintenance area. Figure 1 shows pictures of the muon target with the fixed edge-cooling method on the left, and the muon target attached to the plug shield on the right. When the muon target should be replaced, the muon target with the plug shield is transported in a shielding vessel to a remote handling room and replaced by several remote-handling devices. The replacement of the muon target requires a lot of time and cost [5]. To extend the lifetime of the muon target, we are planning to adopt the rotating target method, which can distribute the radiation damage of graphite to a wider area. Though the lifetime of graphite becomes long enough, the lifetime of the bearing is supposed to be the critical issue for the rotating target method. In section 2, the basic design of the rotating muon target is described. To measure and compare lifetimes for the candidates of the bearings, a mock-up was fabricated, and heating and rotating tests have been performed. In section 3, the structure of the fabricated rotating target is introduced in detail, and the present status of the tests is described. The summary and future plans are mentioned in section 4.

Fig. 1. Pictures of the muon target with the fixed edge-cooling method on the left, and the muon target attached to the plug shield on the right.
2. Basic design

The rotation axis of the rotating target is parallel to the proton beam line. Because the motor device must be located 2.4 m above the beam line level, the rotating motion is transmitted into a horizontal shaft through a 2.4-m long vertical shaft and a pair of bevel gears. In the proton beam line, the rotating target will be set in a vacuum chamber that has already been installed. Because the target is installed through the rectangular aperture of the chamber, the size of the aperture gives a limitation to the size of the rotating target. The rotating body is composed of a graphite wheel, a support and a horizontal shaft supported by two bearings. The two bearings are attached to a cooling jacket with a cooling pipe. The vertical shaft is also supported by two bearings attached to a stainless rod, which penetrates through the plug shield. In the present design, the outer and inner diameters of the graphite wheel are 336 mm and 230 mm, respectively. In addition, the graphite wheel is divided into three units to relieve the thermal stress. Since the heated rotating body is supported by bearings, almost all of the heat is removed through thermal emission. In a numerical simulation, 4-kW heat is supposed to be removed only through thermal emission from the graphite wheel, while in reality thermal emissions from the support and the shaft are also expected. It is assumed that the emissivity of both the graphite and the inner surface of the chamber with a black coating are 0.8, and the temperature of the chamber is 100 °C. Then the temperature of the graphite wheel is estimated to be 670 °C. When the graphite is rotated at a speed of 5 rpm, the maximum temperature gradient is estimated to be less than 30 °C. With the rotating method, the lifetime of the graphite is prolonged and is estimated to be longer than 30 years.

The lifetime of the bearing generally depends on the load, the temperature, the pressure, and the lubricant. The bearings of the rotating target are located in high vacuum (10^{-4} Pa) and at high temperature. The bearing, which supports the horizontal shaft and is located the closest to the graphite target, has an intense radial load and the highest temperature. The bearing is supposed to determine the lifetime of the rotating target. Furthermore, the bearing is under intense radiations of 10-MGy/year. Consequently an inorganic solid lubricant must be used. At present, the candidates as solid lubricants are molybdenum disulfide, tungsten disulfide, and arc ion plated silver. By taking advantage of the solid lubricant, the lifetime is aimed to be 50000 hours, which corresponds to 10 years assuming a 5000-hours proton beam operation in a year. For the rotating target, the bearings supplied from JTEKT CO., LTD are selected [6]. The bearing inner and outer diameters are 17 mm and 40 mm, respectively, with a thickness of 12 mm. The outer ring, the inner ring, and the balls are made of SS440C stainless steel. The bearings with three kinds of solid lubricants have the following characteristics [7]. (1) Molybdenum disulfide (MoS2) is generally used in vacuum, at high temperature, and under radiations. Furthermore, because MoS2 covers the bearing retainer, MoS2 runs out after a relatively short period of time. Under the conditions of the rotating target, the lifetime of the MoS2 bearing is one million revolutions, which corresponds to about 3300 hours at a speed of 5 rpm. (2) Tungsten disulfide (WS2) is generally used in vacuum and at high temperature as well. However, there are not many accounts of utilization under intense radiations. WS2 is inserted in between the balls as separators. Therefore, it should be experimentally confirmed if bearings with separators could be used for supporting a vertical shaft. The lifetime of the WS2 bearing is 100 millions revolutions, which corresponds to 330000 hours, long enough. The WS2 bearings can be used at a maximum speed of 210 rpm. Though it is slower than with MoS2 and arc ion plated silver, it is fast enough for the rotating target, which will be rotated at a speed of 5 rpm in the beam line. (3) Arc ion plated silver (AIP-Ag) is used in higher vacuum and at temperatures higher than with MoS2. AIP-Ag has been used under intense radiations as well. However AIP-Ag is easily oxidized and the oxide layer produces increased friction. Therefore bearings with AIP-Ag must be continuously stored in vacuum. The lifetime is estimated to be 5 million revolutions corresponding to 17000 hours. Table 1 shows the characteristics of each solid lubricant such as type, maximum allowable temperature (Temp.), available pressure (Pressure), utilization under radiation (Radiation), maximum allowable speed, storage condition (Storage), and estimated lifetime in case of the rotating target (Lifetime).

| Type       | Temp. (°C) | Pressure (Pa) | Radiation | Speed (rpm) | Storage | Lifetime (hour) |
|------------|------------|---------------|-----------|-------------|---------|-----------------|
| MoS2 retainer | <300      | 10^2 to 10^5  | general   | <500        | air     | 3300            |
The bearing temperature ought to be kept as low as possible in order to prolong its lifetime. To decrease the temperature of the bearings, a long path of thermal conduction from the graphite wheel to the shaft is adopted. Three units of graphite with a pair of reinforced rings are supported by nine narrow rods. These are attached to an outer wheel, which is integrated onto the shaft through two inner wheels and several rods. The components used at high temperature are made of Nickel-Chromium alloy. Meanwhile, the components used at low temperature are made of SS304 stainless steel. The components are applied with a black coating to decrease the temperature through thermal emission. Figure 2 shows a picture of the rotating target, in which the divided graphite target is attached to the wheels and rods. Figure 3 illustrates the mock-up, which will be described in Section 3. In the drawing, the structure of the rotating target, including the rotating body, the vertical shaft, the horizontal shaft and the bearings, is shown.

Fig. 2. Picture of the rotating target showing the divided graphite target attached to the wheels and rods.

Fig. 3. Schematic view of the mock-up. The structure of the rotating target, including the rotating body, the vertical shaft, the horizontal shaft and the bearings, is shown.

3. Heating and rotating tests by the mock-up
Though only a basic design has been performed so far, the validity of the present design and the actual lifetimes of the bearings with each respective lubricant should be confirmed experimentally. In 2009, a mock-up, in which heating and rotating tests can be performed, was fabricated to obtain the durability of the rotating target, and to measure the lifetimes of the bearings. While a 2.4-m long vertical shaft will be used in the proton beam line, at the moment only a 0.4-m long vertical shaft is being used considering handling issues in the tests.

To determine the inspections of the heating device before the fabrication of the mock-up, more detailed temperature distributions both in the beam line and in the mock-up are estimated through a numerical simulation. In the beam line, the thermal radiation emitted from the graphite wheel is reflected by the chamber surface and absorbed with metal wheels, while in the mock-up the hot graphite is completely covered with heaters. The surface of the heater is colder than the graphite itself because several layered reflectors are used for moderating the electric power, and in addition the heater surface has a lower emissivity. Consequently, the horizontal shaft, which is as hot as the hottest bearing, is supposed to be hotter in the beam line than in the mock-up, if the graphite temperature is the same in both cases. Therefore the graphite in the mock-up must be kept hotter than in the beam line, in order for the shaft in the mock-up to be as hot as in the beam line. In the simulation for the beam line, the graphite temperature is 610 °C and the shaft is 120 °C with the 4-kW heat. Considering a safety factor, the shaft in the mock-up should be heated up to 140 °C, and the graphite to 750 °C.

Fig. 4. Pictures of the mock-up. On the left, the graphite is covered with the heater, and several thermocouples are attached to the rotating body to measure the temperatures directly for calibration. On the right, the bevel gears and the horizontal shaft having a hollow core for the thermocouples are shown.

While in reality the 4-kW heat is deposited on a beam spot size of 25 mm in diameter, in the mock-up a maximum of 6-kW heat can be supplied on the entire target through several Nichrome heaters with stainless-steel sheaths and 5-layered reflectors, in order to heat up and keep the graphite at a temperature of 750 °C. When the rotating target is rotated in the mock-up, the temperatures on the rotating body are indirectly measured through a radiation thermometer. Therefore, the emissivity of each component needs to be calibrated through a direct measurement by thermocouples without rotating the target. Even in the beam line, the temperature of the horizontal shaft will be continuously monitored by inserting thermocouples into a hollow core at the center of the shaft. Table 2
demonstrates the temperature distributions in a simulation for the beam line, a simulation for the mock-up, and an experiment by the mock-up. Figure 4 shows pictures of the mock-up. On the left, the graphite is covered with the heater, and several thermocouples are attached to the rotating body to measure the temperatures directly for calibration. On the right, the bevel gears and the horizontal shaft having a hollow core for the thermocouples are shown.

Table 2: Temperature distributions in a simulation for the beam line (Simulation BL), a simulation for the mock-up (Simulation MU), and an experiment by the mock-up (Experiment MU).

|               | Graphite (°C) | Outer wheel (°C) | Inner wheel (°C) | Shaft (°C) |
|---------------|---------------|------------------|------------------|------------|
| Simulation BL | 610           | 300              | 135              | 120        |
| Simulation MU | 750           | 310              | 160              | 140        |
| Experiment MU | 750           | 340              | 165              | 135        |

The rotation speed can be as slow as 5 rpm in the beam line. However, if the heating and rotating tests are to be performed at that speed, it may take several years for the bearings to break down. Therefore, in the tests, the rotating target can be rotated at a maximum speed of 500 rpm. The resistance of the bearings is carefully monitored through the current of the AC servo-motor for the rotation to acquire the lifetime of the bearings [8]. Figure 5 shows the dependence of the motor current on the rotating speed in case of the bearings with WS₂ solid lubricant. The motor currents at a speed of 30 rpm, 90 rpm, and 180 rpm are shown in the graph. When the motor current is beyond an experimentally determined criterion, the rotating target in the proton beam line will be replaced. The criterion of the motor current will be determined in the tests with the mock-up. So far, it has been confirmed that the rotating target can be heated up to 750 °C and be rotated from 5 rpm to 500 rpm. The durability tests will be completed by the end of 2011.

Fig. 5. Dependence of the motor current on the rotating speed in case of the bearings with WS₂ solid lubricant. The motor currents at the speed of 30 rpm, 90 rpm, and 180 rpm are shown in the graph.
4. Summary and future plans

To prolong the lifetime of the muon target, the rotating method has been adopted. A mock-up, which can perform heating and rotating tests, was fabricated to solve these issues, especially the lifetime of the bearings. The durability tests will be completed by the end of 2011. We have not yet reached a final design for the rotating target, but the research and development is underway.

In addition, the rotating target with a plug shield will be fabricated by March 2011. Then, the rotating tests will be performed with a 2.4-m long vertical shaft. In the new mock-up, several additional bearings supporting the vertical shaft will distribute the larger axial load. The precision of the position of the rotating target against the chamber, which imitates the chamber in the beam line, will also be confirmed. The replacement of the mock-up will be performed in summer 2011. The rotating target will be installed in the beam line after the final design is completed.

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