PRESENT STATUS OF MUON ROTATING TARGET AT J-PARC/MUSE*

Shunsuke Makimura, Shiro Matoba, Naritoshi Kawamura, KEK, Ibaraki, Japan
Satoshi Onizawa, Yukihiro Matsuzawa, NAT, Ibaraki, Japan
Masato Tabe, Seekel, Ibaraki, Japan
Yasuo Kobayashi, Hiroshi Fujimori, Yutaka Ikedo, Akihiro Koda, Kenji Kojima, Yasuhiro Miyake, Jumpei Nakamura, Koichiro Shimomura, Patrick Strasser, Ryosuke Kadono, KEK, Ibaraki, Japan

Abstract

A pulsed muon beam with unprecedented intensity will be generated by a 3-GeV 333-microA (1-MW) proton beam on a muon target made of 20-mm thick isotropic graphite at J-PARC/MUSE (Muon Science Establishment). The energy deposited by the 1-MW proton beam is estimated to be 3.9kW on the muon target. The first muon beam was successfully generated in September of 2008. Gradually upgrading the beam intensity, continuous 300-kW proton beam has been operated by a fixed target method without replacements till June of 2014. However, the lifetime of the fixed target will be less than 1 year by the proton-irradiation damage of the graphite in case of 1-MW proton beam operation. To extend the lifetime, the muon rotating target, in which the radiation damage is distributed to a wider area, had been developped. In the rotating target, the lifetime of bearing will have a dominant influence on the lifetime of the muon target. The disulfide tungsten are introduced as solid lubricant of the bearings. The muon rotating target was installed in September of 2014 and has been stabley utilized up to 500-kW proton beam operation. In this report, the present status of the muon rotating target will be described.

INTRODUCTION

The muon production target is placed on the upstream of the neutron mercury target at J-PARC/MLF/MUSE (Japan Proton Accelerator Research Complex/ Materials and Life Science Experimental Facility/ Muon Science Establishment) [1, 2]. A pulsed muon beam with unprecedented intensity will be generated by a 3-GeV 333-microA proton beam on a muon target made of 20-mm thick isotropic graphite, IG-430 (Toyo Tanso Co. LTD. [3]). The energy deposited by the 1-MW proton beam is estimated to be 3.9kW on the muon target by PHITS [4, 5]. The first muon beam was successfully generated on September 26th, 2008. Gradually upgrading the beam intensity, 300-kW proton beam has been operated continuously since January of 2013 [6]. The current muon target with a fixed target method, hereafter described as “muon fixed target”, has been utilized without replacements since the first muon beam generation till May of 2014. Proton irradiation gives radiation damage to material properties of graphite [7, 8, 9]. In particular, the effect on the dimension of graphite is serious. The lifetime of the muon fixed target is estimated to be 1 year by the simulation under the 1-MW proton irradiation on graphite. Because the muon target is highly activated by proton irradiation, the handling of the used muon target must be performed at a remote handling room, Hot cell [10]. The remote controlled tasks require a lot of time, cost and manpower. Therefore the extension of the lifetime is essential for stable operation of our facility. To extend the lifetime, the developments of the muon rotating target, in which the radiation damage is distributed to a wider area, had been started since 2008 in parallel with the proton beam operation. While the lifetime of graphite becomes long enough, the lifetime of the bearing is supposed to be the critical issue for the muon rotating target. The development of the muon rotating target has already been completed as the results of the analyses, the detailed designs, and durability tests with a heating and rotating mock-up. The muon rotating was installed in September of 2014. Figure 1 shows pictures of the rotating target assembly on the left and the rotating target on the down-right. The schematic cutting section is shown on the up-right. In this article, the muon rotating target will be described.

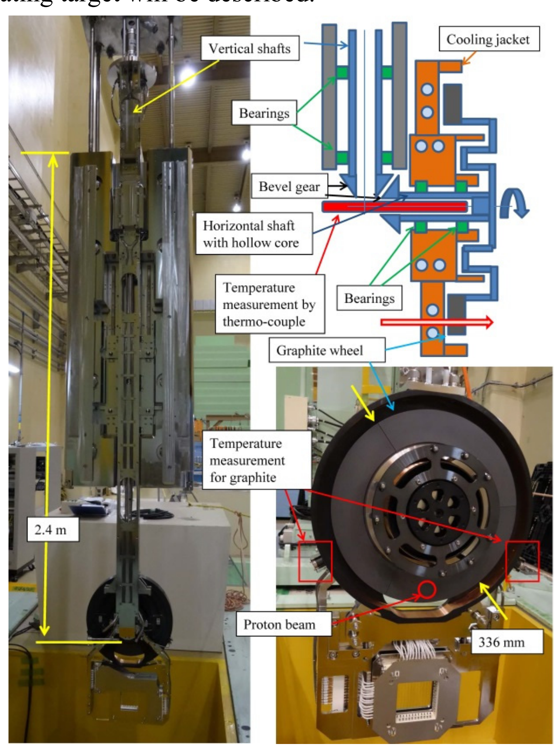

Figure 1: Pictures of the rotating target assembly on the left and the rotating target in the down-right. The schematic cutting section is shown in the up-right.

DEVELOPMENTS OF ROTATING TARGET

Basic Design of Rotating Target

The current muon fixed target will break down by the radiation damage of the graphite in less than 1 year by 1-MW proton beam on the simulation. To extend the lifetime, the developments of the muon rotating target, in which the radiation damage is distributed to a wider area, had been started since 2008 in parallel with the proton beam operation. A horizontal shaft, which is a rotation axis of the rotating target, is parallel to the proton beam line. Because a motor device of the rotating target must be located 2.4 m above the beam line level due to high radiation, the rotating motion is transmitted into the horizontal shaft through a vertical long shaft and a pair of bevel gears. The rotating body is composed of a graphite wheel, a wheel support, and the horizontal shaft supported by two horizontal bearings. The two bearings are attached to a cooling jacket in which water piping is embedded. The outer and inner diameters of the graphite wheel are 336 mm and 230 mm, respectively. The temperature of the graphite wheel was estimated to be 940 Kelvins. The temperature of the hottest bearing was 390 Kelvins. The rotation speed of the rotating target could be determined from the evaluation of the maximum temperature gradients inside the graphite. Consequently, it was determined to be 15 rounds per a minute (abbreviated as rpm afterwards). For the rotating target, the bearings supplied from JTEKT CO., LTD [11] were selected, considering the actual performance in the past accelerators field.

Bearings and Solid Lubricants

When the rotating target method is applied, the lifetime of graphite will be more than 30 years. Then, the lifetime of bearing will have a dominant influence on the lifetime of the muon target. The bearings of the rotating target are located in high vacuum of 10^{-4} Pa, at high temperature of 390 Kelvins, and under high radiation dose of 100 MGy/year. Though disulfide molybdenum or silver is generally used in these conditions, the sintered compact of disulfide tungsten is used for our target. Hereafter, disulfide molybdenum, silver, and disulfide tungsten are abbreviated as MoS_2, Ag, and WS_2 respectively. In case of the MoS_2 or the Ag, it is coated on the components of the bearing, such as balls, an inner ring, an outer ring, and retainers. On the other hand, the sintered compact of WS_2 is inserted as separators of the balls. In case of the WS_2, the quantity of the lubricants is expected to be much larger than the MoS_2 and the Ag. Actually, according to the evaluation formula in JTEKT catalogue, the lifetimes for our bearings in cases of the MoS_2, the Ag, and the WS_2 are 1100 hours, 5800 hours, and 110000 hours, respectively. Actually the proton beam has been operated for 5000 hours in a year. In case of the WS_2, the lifetime of the bearings can be evaluated to 22 years. However, it has not been proven that the WS_2 is used as the solid lubricant under high radiation dose. Therefore, an irradiation test of the WS_2 by an electron beam was performed. In the irradiation test, 80 pieces of the sintered compacts of the WS_2 were irradiated by 2-MV, 1-mA electron beam in Takasaki Advanced Radiation Research Institute, Japan Atomic Energy Agency [12]. The lubricants were disassembled from the bearings and were set in jigs for irradiations. The jigs were placed in a vacuum vessel with pressure of 5 Pa. During the electron irradiation, the temperatures of the jigs were monitored to be from 310 to 340 Kelvins. The radiation damage given to the pieces of theWS_2 can be evaluated from 50 to 100 MGy through the pre-irradiation with CTA dose-meter. The irradiated pieces of the WS_2 were assembled into 8 bearings again. Then the durability tests under the similar conditions to the beam line were performed in JTEKT. Then no irradiation effect was observed in the durability tests. Figure 2 shows the pictures of the disassembled bearing on the up-left, the irradiation jig including only the compacts of the solid lubricant on the up-right, and the electron-irradiation apparatus on the down.

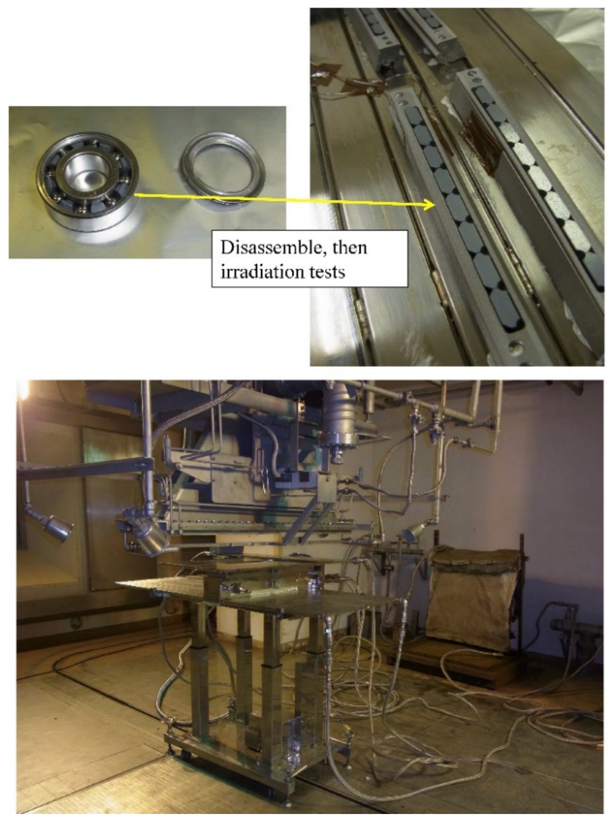

Figure 2: Pictures of the disassembled bearing on the up-left, the irradiation jig including only the compacts of the solid lubricant on the up-right, and the electron-irradiation apparatus on the down.

Heating and Rotating Tests by Mock-up

A mock-up, which could perform the rotating and heating tests, was fabricated to confirm the durability of the rotating target and the lifetimes of the bearings. In the mock-up, the maximum temperature of the bearing, the maximum temperature of the graphite, and the temperature difference inside the wheel support are larger than the ones in the actual beam line to confirm the durability of the rotating target and the lifetimes of the bearings. As the results of simulations for both cases, the specifications of the sheath heater, which covered the whole graphite was decided. In the actual beam line, the temperature of the bearing and the graphite wheel, and the temperature difference inside the wheel support were evaluated to be 390 Kelvins, 940 Kelvins, and 550 Kelvins, respectively. In the mock-up, they were 400 Kelvins, 1020 Kelvins, and 620 Kelvins, respectively. The rotation speed can be as slow as 15 rpm in the beam line. However, if the heating and rotating tests were performed at the speed, it would take one year to confirm whether the lifetime of the bearing is one year. Therefore, in the mock-up, the rotating target could be rotated at a maximum speed of 500 rpm. The resistance of the bearings was carefully monitored through the current of the AC servo-motor for the rotation. From the increment of the motor current, the wear of the bearing can be known. Finally the continuous heating and the rotating test at a speed of 300 rpm for 220 hours was successfully completed. The accumulated number of the revolutions in the tests corresponded to the number at the actual operation speed of 15 rpm for 4400 hours. Thus, the developments, such as the analyses, the detailed designs, and durability tests with a heating and rotating mock-up were completed [13].

INSTALLATION OF ROTATING TARGET AND OPERATON BY THE TARGET

The muon fixed or rotating target is rigidly fabricated into the target rod. The target rod is integrated into the plug shield through four screws, which can be handled remotely. The assembled components are called target assembly. Because the muon target is highly activated by proton irradiation, the used muon target must be controlled by remote handling. The used target assembly will be transported by the shielding vessel, named muon transfer cask, and stored in the tentative storage pod at the Large Apparatus Handling Room, which is located at the floor level of 10 m [10]. Because the muon target must stay in vacuum for corrosion control, storage vessels for the muon target assembly were prepared. The muon fixed target, which had been used for five years, was successfully replaced with a new rotating target in September of 2014. Then, the used muon fixed target was activated up to 400 mSv/hour with 20-cm distance. Simultaneously, there was no crack on the target through observation of remote-controlled digital cameras. Figure 3shows pictures of the muon fixed target, which had been utilized for five years on the up-left, the storage vessels on the up-right, and the replacement by the muon transfer cask on the down. Since then, the proton beam operation by the muon rotating target has been successfully performed without the increment of the rotation-motor current. So far, the 300-kW and 400-kW proton beam operation had been performed for three months. Furthermore, the 500-kW and the 600-kW operation had been performed for 2 weeks and for 1 hour, respectively. During the proton beam operation, the temperatures of the cooling jacket, the horizontal shaft, and the graphite are monitored. Because it is difficult to measure the temperatures of the rotating body directly, the temperature rises of the thermos-couples through thermal radiation are relatively monitored. The temperature of the horizontal shaft is continuously monitored by inserting thermocouples into a hollow core at the center of the shaft. When the thermocouples were calibrated without rotation and a direct thermal contact in the mock-up, the measurement through the thermal radiation is similar to that with the thermal contact. The temperatures of the graphite are also measured by the thermos-couples through thermal radiation. The thermos-couples are isolated by thermal shielding and are irradiated only by the graphite. However the effect of the heat generation by proton beam irradiation must be carefully confirmed with the actual operation. Table 1 demonstrates the comparison of the measurement with the simulation for the typical beam power.

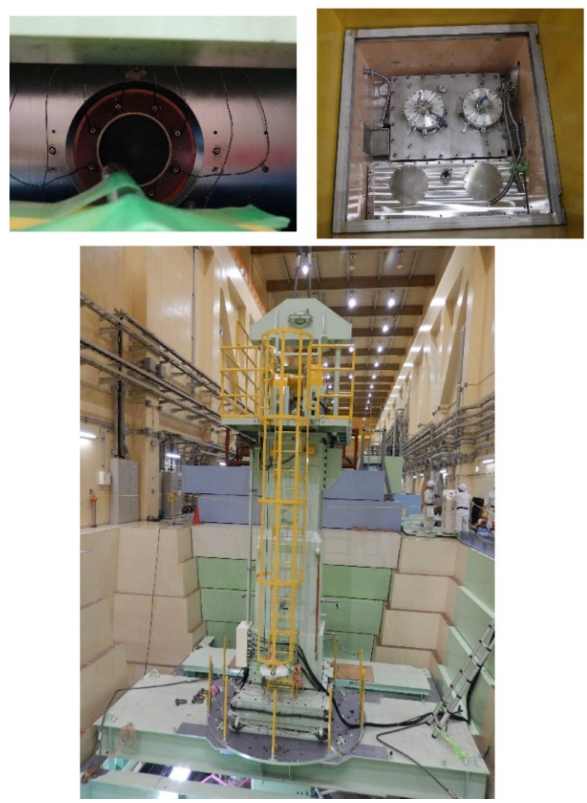

Figure 3: Pictures of the muon fixed target, which had been utilized for five years on the up-left, the storage vessels on the up-right, and the replacement by the muon transfer cask on the down.

Table 1: The Comparison of the Measurement with the Simulation for the Typical Beam Power

	300 kW	**500 kW**	**1 MW**
Shaft Simulation	71 degC	84 degC	115 degC
Shaft Measurement	78 degC	95 degC	-
Graphite Simulation	400 degC	475 degC	620 degC
Grap. (T. Rad.) Measurement	45 degC	60 degC	-

CONCLUSION

The muon fixed target had been utilized without replacements since the first muon beam generation till June of 2014. However, the lifetime of the muon fixed target will be less than 1 year by the 1 MW proton-irradiation damage of graphite. To extend the lifetime, the muon rotating target, in which the radiation damage is distributed to a wider area, had been developed. The muon rotating target was installed in September of 2014. Since then, the proton beam operation by the muon rotating target has been successfully performed without the increment of the rotation-motor current.

ACKNOWLEDGMENT

We would like to thank Hitachi-Zosen CO., LTD [14] for designing the heating and rotating mock-up, Irie-Koken CO., LTD [15] for designing the muon rotating target assembly, JTEKT CO., LTD for selection of the bearings, and Dr. Ohshima and Mr. Hanaya for giving the valuable advices with respect to the electron-irradiation tests in Takasaki Advanced Radiation Research Institute, Japan Atomic Energy Agency.

REFERENCES

[1] http://msl.kek.jp/folder_Eng/index_en.html
[2] S. Makimura et al.: Nucl. Instrum. Methods Phys. Res. A **600** (2009) 146.
[3] http://www.toyotanso.co.jp/index_en.
[4] H. Iwase, K. Niita, T. Nakamura: J. Nucl. Sci. Technol. **39** (2002) 1142.
[5] N. Kawamura et al.: Nucl. Instrum. Methods A **600** (2009) 114.
[6] S. Makimura, et al.: Proceedings of the 8th Annual Meeting of Particle Accelerator Society of Japan, (2011) 1188.
[7] S. Makimura et al.: J. Nucl. Mater. **450** (2014) 110.
[8] H. Matsuo: Graphite **150** (1991) 290.
[9] T. Maruyama et al.: Journal of Nuclear Materials **195**(1992)44.
[10] S. Makimura et al.: Proceedings of the 7th Annual Meeting of Particle Accelerator Society of Japan, (2010) 479.
[11] http://www.jtekt.co.jp/e/index.html
[12] http://www.taka.jaea.go.jp/index_e.html
[13] S. Makimura et al., J. Radioanal. Nucl. Chem., on line first, DOI: 10.1007/s10967-015-3949-0.
[14] http://www.hitachizosen.co.jp/english/index.html
[15] http://www.ikc.co.jp/e_index.html