

MUON PRODUCTION TARGET AT J-PARC

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Abstract

A pulsed muon beam has been generated by a 3-GeV 333-microA proton beam on a muon target made of graphite at J-PARC, Materials and Life Science Experimental Facility (MLF). The first muon beam was successfully generated in 2008, and 300-kW proton beam has been operated by a fixed target till 2014. To extend the lifetime, a muon rotating target, in which the radiation damage is distributed to a wider area, had been developed. The muon rotating target #1 was installed in 2014 and had operated for five years until 2019. The rotating target #2 has stably operated at 950 kW until now in 2024. Simultaneously, in the COMET experiment to explore the muon-electron conversion process, 8 GeV proton beam with an intensity of 3.2 kW in Phase 1 and 56 kW in Phase 2 will irradiate targets in a superconducting sole-noid magnet. The MLF second target station is a future project where 3 GeV protons will irradiate a tungsten target to produce high-brightness neutrons and muons.

In this presentation, the status and future prospect of the muon target at J-PARC MLF MUSE, the COMET target, and the MLF second target station will be introduced.

INTRODUCTION

Muons, produced by the decay of pions in high-energy proton beams, are becoming increasingly important in nuclear physics and material and life science. The muons were produced by irradiating target material with a 3 GeV, 1 MW proton beam for multi-purpose user experiments at the J-PARC Materials and Life Science Experimental Facility, MLF. The muon production target is located approximately 30 m upstream of the neutron production target at the J-PARC MLF MUSE [1]. The target material is isotropic graphite (IG-430U, Toyo Tanso Co., Ltd. [2]) with a thickness of 20 mm. About 5% of the proton beam is spared for muon production.

In the South Building of the Hadron Experimental Facility, a muon production target has been installed for the COMET experiment to search for the muon-electron conversion process [3]. The advantage of the COMET experiment is that the muon production target is installed in a superconducting capture solenoid magnet, which allows the muon beam to be transported at a larger solid angle than in conventional beamlines. Initially, an engineering operation in phase alpha with an 8 GeV, 300 W proton beam was completed in February 2023 to confirm the validity of the proton beam transport to the south building and the muon beam transport to the detector system without the capture solenoid around the target [4]. The design and construction of Phase 1 with a 3.2 kW proton beam and Phase 2 with a

56 kW proton beam are underway. The target material and thickness are C/C composite (CX761, Toyo Tanso Co., Ltd.), 1.1 mm in Phase alpha, isotropic graphite, 700 mm in Phase 1 and tungsten, 160 mm in Phase 2.

The construction of the MLF second target station is planned to obtain the neutron and muon beam with higher flux rather than higher intensity. The pion beam produced on the common tungsten target, which is shared with the neutron target, is transported by a superconducting solenoid to the secondary beamline at large solid angles.

In modern accelerators, the survivability of the target determines the success or failure of the experiment. In the MLF, it is necessary to provide a structure that disperses the high heat load and irradiation damage on target materials caused by the high-intensity proton beam, as well as a maintenance process, and to extend the life of the target. In the COMET experiment, the intensity of the proton beam is low, but the problems associated with installing the target in a high magnetic field must be solved.

The target is sometimes called a pion production target because it produces pions, which are the parent particles of muons, but in this article, it is referred to as a muon production target.

MUON PRODUCTION TARGET AT MLF

When the beam operation started in 2008, a fixed target was used for the muon target. After the first muon production in September 2008, the proton beam intensity was gradually increased to 300 kW for stable operation [5]. The fixed muon target is made of 20 mm thick, 70 mm diameter isotropic graphite. The beam profile has a Gaussian distribution with a standard deviation of about 3.5 mm. The energy deposited on the muon target by the 1 MW proton beam was estimated to be 3.9 kW using the PHITS simulation code [6]. Due to radiation damage to the graphite, the muon target is expected to fail within one year in the fixed target. The muon target will have to be handled remotely as the radiation dose rate is 5 Sv/h after one year of 1 MW proton beam irradiation on the simulation [7]. If the muon target fails, the MLF has to be shut down for more than three weeks to replace it. It was therefore necessary to extend the lifetime of the muon target in order to continue the MLF experiments in a stable manner.

To extend the lifetime, a method called rotating target was introduced, learning from the Paul Scherrer Institute (PSI) in Switzerland, which had previously developed the target. In the rotating target, the graphite is rotated to spread the damage to the graphite over a wide area. Similarly, the heat is widely dispersed and cooled by thermal radiation. Bearings supporting the rotating body consist of an outer ring, an inner ring and several balls between the

rings. Lubricants are used to reduce friction between the balls and rings. In industrial applications, grease, an organic functional material with properties between those of a solid and a liquid, is used as a lubricant. However, the grease cannot be used for bearings in rotating targets because it releases a lot of gas into the vacuum at high temperature and is affected by the high-radiation environment due to proton beam irradiation. It is therefore necessary to use solid lubricants made of inorganic materials which are less affected by radiation and release less gas. The life of a rotating target bearing is greatly affected by the type and form of solid lubricant, and PSI has used bearings coated with molybdenum disulphide or silver as solid lubricants for inner and outer rings, balls and ball separators. However, when the coatings peel off, the bearings lose their lubricating performance. Therefore, J-PARC adopted a bearing (JTEKT Corporation [8]: WS bearing) in which lumps of tungsten disulphide, an inorganic material, are inserted between the balls. In this case, the amount of lubricant is much greater than in the case of coating, and thus a longer service life can be expected.

Finally, the rotating target #1 was installed in the proton beamline in 2014 and has been in stable operation for 5 years [9]. The rotating target #2, which was replaced in 2019, has so far achieved stable operation with a beam intensity of 950 kW in 2024. Based on the stable operation record of this bearing at J-PARC, we offered PSI to adopt the bearing with the same lubricant and geometry. Target E, which uses the bearings, was then installed in the beamline. As a result, one year of stable operation was achieved in December 2021. This achievement has given us the prospect of providing muon beams for experiments without loss of beam time [10, 11]. Figure 1 shows the images of the fixed target on the left and the rotating target on the right.

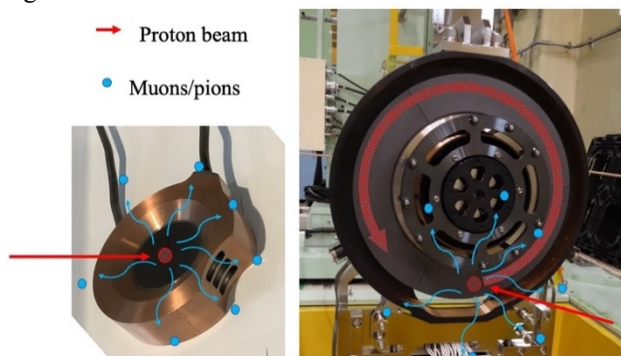


Figure 1: The images of the fixed target on the left and the rotating target on the right.

COMET TARGET IN PHASE 1

In COMET Phase 1, the heat load on the graphite target rod is not high (110 W), but the rod must be kept suspended in the centre of the magnetic field of the magnet and must not interfere with pion transport. Therefore, the target must be suspended by a thin target support made of a low-density material. In addition, since the target is likely to be directly irradiated by the proton beam, it must have high thermal resistance. Although graphite material has high

thermal resistance, it is a brittle material and is not expected to be used as a structural material. Therefore, after confirming the validity of the C/C composite material used as the target in Phase Alpha, it will be used as a target support in Phase 1. The graphite target rod is expected to reach a temperature of about 200°C, which is much lower than the maximum available temperature of the C/C composite material. The temperature rise of the target support is also low enough to allow it to be exposed to the proton beam.

As the target is installed in a superconducting magnet, the superconductors must not be rendered inoperable by heat generation or radiation damage caused by the proton beam. Shields are therefore installed around the target to protect the superconductors. Tungsten, copper, and stainless-steel are candidates for the shielding material. The material will be chosen based on budget and shielding capability. Currently we are planning to use a hybrid shielding material of copper and stainless steel. Figure 2 demonstrates the cutting section of the target surrounded by the shielding in the left and the schematic drawings of the muon production target in the right.

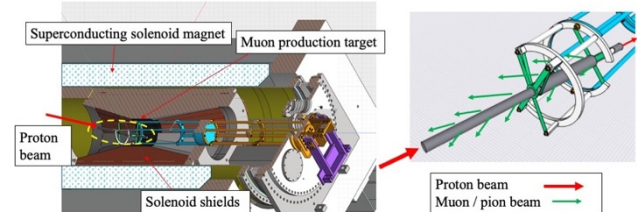


Figure 2: The cutting section of the target surrounded by the shielding in the left and the schematic drawings of the muon production target in the right.

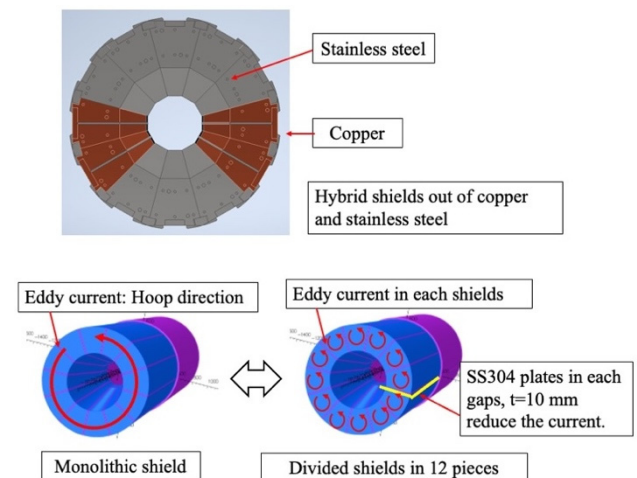


Figure 3: The hybrid shields out of copper and stainless steel are shown at the top. And conceptual diagrams comparing the eddy currents generated in a monolithic shielding and a 12-segmented shielding are shown at bottom left and bottom right.

A high magnetic field, 5 Tesla, is generated in the superconducting magnet with a bore diameter of 1.3 m. When a quench occurs and the magnetic field drops sharply, eddy currents are generated in the shielding material to prevent the magnetic field change, resulting in a Lorentz force. For instance, the force of 140 kN is generated in the copper

shielding when the magnetic field is $1/e$ for 60 s. Therefore, in this case, measures such as dividing the copper into sections and inserting stainless steel spacers between them are required. The hybrid shields out of copper and stainless steel are shown at the top of figure 3. And conceptual diagrams comparing the eddy currents generated in a monolithic shielding and a 12-segmented shielding are shown at bottom left and bottom right in figure 3. A stainless-steel plate is inserted in the gap between the shields.

The superconducting magnet is cooled with liquid helium (LHe). If the LHe lines were to rupture unexpectedly due to a catastrophic failure, there could be a rapid increase in pressure due to vaporised helium, which would escape into the vacuum area. The beam windows - relatively weak vacuum components - should be robust enough to withstand such a high and rapidly increasing pressure until the rupture discs work. At the same time, for high proton/muon transport efficiency, the material density must be low and the thickness as thin as possible, while minimising beam loss. It is known that the proof pressure of the spherical window is higher than that of the plate-shaped window. At present, we are producing a spherical beam window of Ti-6Al-4V by additive manufacturing with a diameter of 260 mm and a thickness of 0.5 mm, which, according to analysis, is expected to have a proof pressure of more than 0.9 MPa. After electron beam additive manufacturing, hot isostatic pressing (HIP) to eliminate internal pores left over from the manufacturing process and subsequent polishing were successfully completed. Finally, the manufactured beam windows were installed in the beamline at COMET Phase alpha [12]. The top left of Fig. 4 shows a conceptual diagram of an LHe leakage incident, the bottom left shows a conceptual diagram of a spherical window and the right shows a picture of a fabricated beam window.

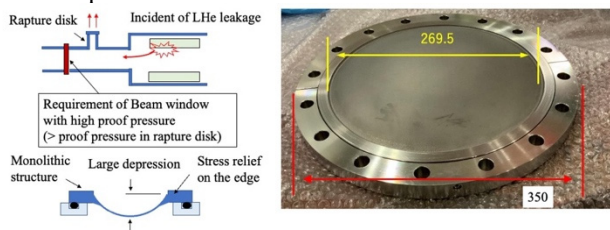


Figure 4: A conceptual diagram of an LHe leakage incident in the top left, A conceptual diagram of a spherical window in the down left, and A picture of a fabricated beam window in the right.

MUON PRODUCTION TARGET IN FUTURE - COMET TARGET IN PHASE 2 AND MLF SECOND TARGET STATION -

The density of the target material should be higher, because a smaller spatial volume of muon/neutron production on the target is beneficial for more efficient transport to downstream experiments. Therefore, we plan to use tungsten as the target material in COMET Phase 2. At low proton beam intensity, it is still possible to use a radiation-cooled tungsten target, but at 56 kW, a water-cooled tungsten target will be used. The water-cooled tungsten target allows much higher beam power to be maintained in the

target, but the use of water cooling presents a further challenge in preventing corrosion of the tungsten. In this case it is necessary to develop cladding materials. Tantalum cladding has been widely used for the water-cooled tungsten target [13, 14], but the decay heat in tantalum due to beam irradiation poses a challenge [15], and it is necessary to develop an alternative cladding material to tantalum.

The MLF second target station is also under consideration. At this stage, the design of the facility is still under consideration, and the following targets are envisaged for the neutron and muon targets: a helium-air cooled tungsten rotating target such as the European Spallation Source [16], a water-cooled tungsten rotating target to be considered as the second target station at the Oak Ridge National Laboratory [17], and a water-cooled tungsten fixed target such as the Rutherford Appleton Laboratory [18]. In the current MLF, the muon target is installed independently, in a tandem configuration, 30 m in front of the neutron target, and 5% of the beam is available on the muon target. In contrast, in the MLF second target station, the muon beam produced by the tungsten target, which is shared with the neutron target, is transported to the secondary beamline at a large solid angle by a superconducting magnet. This will allow 50 to 100 times more muon beams to be transported than in the current muon target.

In both the COMET Phase 2 target and the MLF second target station, recrystallization embrittlement and irradiation embrittlement of tungsten are major issues, and we are developing new novel tungsten materials to address the embrittlement.

CONCLUSION

The muons have successfully been produced by irradiating target material with a 3 GeV, 1 MW proton beam for multi-purpose user experiments at J-PARC, MLF. To extend the lifetime, a method called rotating target was introduced. J-PARC adopted a bearing with lumps of tungsten disulphide as solid lubricant. The rotating target, which was replaced in 2019, has so far achieved stable operation with a beam intensity of 950 kW until 2024.

In the COMET experiment, the proton beam intensity is low, but the problems associated with the target being installed in a high magnetic field need to be solved. The design of the target support, the shield around the muon production target and the beam windows is underway.

The construction of the MLF second target station is planned to obtain the neutron and muon beam with higher flux rather than higher intensity. The pion beam produced on the tungsten target, which is shared with the neutron target, is transported to the secondary beamline by a superconducting solenoid at large solid angle. The cooling method will be investigated according to the requirements of the experiment.

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