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An edge-cooled graphite target for J-PARC Muon Science Facility

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Abstract

At the Muon Science Facility J-PARC, we are investigating whether we can adopt an edge-cooled non-rotating graphite target because of its ease of handling and maintenance, although one promising candidate of the production target for 1 MW proton beam is a rotating graphite target which has been developed at PSI.

In this paper, we report a promising design of the KEK model of the edge-cooled non-rotating graphite target for 1 MW operation at J-PARC Muon Science Facility, based upon a new idea inserting a Ti buffer layer at the interface between graphite and copper frame, together with the successful fabrication of the proto-type target according to the dedicated design of our request.

1. Design of the building and the NM tunnel

The building of the Materials and Life Science Facility consists of the proton beamline tunnel (so-called NM tunnel), and two wings for the experimental halls. The tunnel structure is for the purpose of keeping radioactive materials inside the tunnel, considering the safety of operations during maintenance work on the neutron target or muon target. The height of the building is 31 m for the tunnel and 21 m for the experimental halls. The width of the tunnel is 13.5 m, and the east and west wings are 24.5 m and 32 m wide, respectively. The proton beam height is 1.6 m from the floor level. The Muon Science Facility is 30 m long along the proton beamline, upstream of the neutron facility. Fig. 1 (top) shows a schematic drawing of the first floor of the Materials and Life Science building.

The proton beamline in the Materials and Life Science building consists of the M1 line and M2 line regions. The M1 line is upstream of the muon target, where no significant beam loss is expected. On the other hand, the M2 line is in the vicinity of the muon target where severe beam loss is deposited on the surrounding beamline components. Fig. 1 (bottom) shows a cutaway view along the primary beamline showing a schematic of the NM tunnel structure of the Materials and Life Science building. Since a certain fraction of the primary 3 GeV proton beam is scattered preferentially downstream toward the neutron target, two sets of scrapers will be installed to prevent severe damage to the beamline components such as quadrupole magnets, beam ducts etc. Even if some beam loss is focused on the scrapers, all the components such as the quadrupole magnets, target chamber, scraper chamber, pillow-seal,

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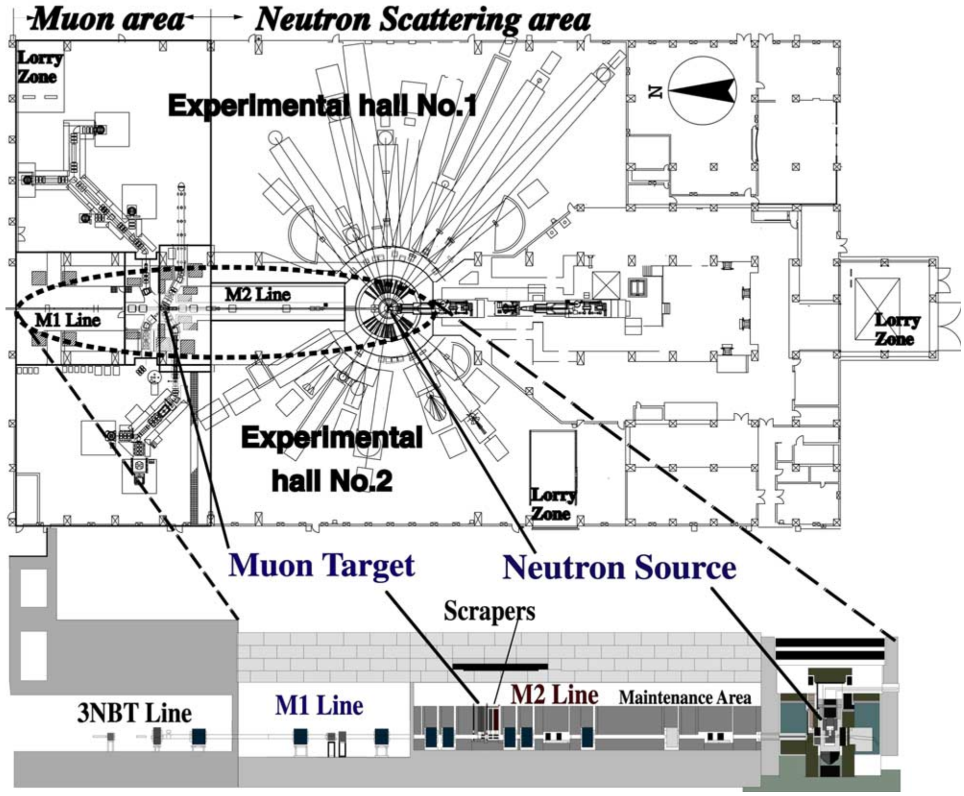

Fig. 1. The top figure shows a schematic drawing of the first floor of the Materials and Life Science building. The bottom figure shows a cutaway view along the primary beamline showing a schematic of the NM tunnel structure of the Materials and Life Science building.

vacuum ducts etc. (which will be used in the primary proton beamline and in the extraction secondary beamlines in the vicinity of the muon target) will suffer not only from tremendously high radiation, but also from corrosion induced by NO_x in irradiated air. Therefore, in the M2 beamline, all of the maintenance work including power and water connections is intended to be done over the top from the maintenance area, which is at a level of 4 m from the floor, according to successful experience at PSI which has been dealing with a 1 MW-class proton beam [1].

2. Muon Science Facility

In the timing of Phase 1, we are planning to install one muon target associated with its scrapers, primary beam optics, shield blocks and a superconducting decay/surface channel with a modest-acceptance (about 40 msr) pion injector. In the superconducting decay/surface channel, the estimated intensity of surface muons (μ^+) is 3×10^7/s with a beam size of 25 mm in diameter. The intensity of decay muons (μ^+/μ^-) is 10^6/s for 60 MeV/c and up to 10^7/s for 120 MeV/c with a beam size of 50 mm in diameter. These intensities correspond to much more than ten times those at RIKEN/RAL Muon facility at ISIS [2]. A magnetic kicker system installed in the extraction part of the channel will allow single-pulse experiments, since the 3 GeV proton beam has a time structure with two bunches (One bunch has a temporal width of 80–100 ns.). In addition to the Phase 1, we are planning to install surface muon channels and an ultra-slow muon channel, and if possibly, a high-momentum decay muon channel and a second production target in a more upstream location, when a full budget for Phase 2 is funded.

3. Tandem target configuration

The Materials and Life Science Facility is an integrated experimental facility for neutron science and muon science utilizing the 3 GeV, 1 MW, 25 Hz proton beam. First of all, we had to make an important decision whether we should adopt either a tandem-type target like PSI or RAL, or adopt a dedicated facility with our own beam dump like KEK-MSL. Finally, in order to save on total budget of the project by the common use of utilities and to get rid of the severe beam dump construction associated with high-concentration tritiated water handling facility, and also from the viewpoint of beam sharing with the neutron facility, we decided to extend the muon facility with the tandem target configuration.

The next important issue was what thickness of graphite target can be installed in the proton beamline located upstream of the neutron source, causing a beam loss to some extent. After a long discussion and negotiation with the neutron science group, we reached an agreement that a total beam loss induced by the muon production targets should be no more than 10%. Consequently, we are proposing to install 10 mm and 20 mm thick graphite targets, corresponding to a beam loss of 3.5% and 6.5%, respectively, for pion and muon production on the way toward the neutron target, rather than constructing a separate building with our own proton (1 MW) beam dump.

4. Design of the muon target

Detailed calculations on heat, radiation and duct-streaming in the vicinity of the muon target were performed using NMTC/JAM [3] and MCNP [4] Monte–Carlo codes. For the case of a 20 mm thick graphite target, as much as 3.3 kW heat is deposited into an area 25 mm in diameter due to irradiation by the 3 GeV, 1 MW proton beam [5].

One possible candidate for the production target in the 1 MW proton beam is a rotating graphite target, which was developed at PSI and has been working well for more than ten years (60 mm thick, 6 mm wide, 450 mm in diameter) [6]. At present we are investigating whether we can adopt an edge-cooled non-rotating graphite target, because of its ease of handling and maintenance, and also because our proton beam size (focused to 25 mm in diameter) from the rapid cycling synchrotron (RCS) ring is much larger than that (a few mm) from the cyclotron ring at PSI.

4.1. Graphite material

Graphite materials such as pyrolitic and carbon/carbon composite graphite are known to have excellent thermal conductivity and thermal shock resistance in one dimension. But once those graphite materials are irradiated, their crystal structures are easily destroyed and their thermal conductivity are reduced remarkably [7]. Therefore, we decided to adopt a fine-grained isotropic graphite IG-43 rather than the pyrolitic, or carbon/carbon composite graphite, considering a configuration to remove heat effectively and homogeneously at the edge of the muon production target in the environment under high radiation. Thermal conductivity, density, thermal expansion, Young's modulus, and Poisson's ratio of the IG-43 at room temperature without any irradiation, are 139 W/mK, 1.82 g/cm^2 at 300 K, 4.8 ppm/K, 10.8 GPa, and 0.28, respectively. According to the neutron irradiation experiments done at JMTR reactor up to 1.1 to 1.5×10^{21} n/cm^2, mechanical properties such as Young's modulus and the tolerable bending stress and compressive stress increase about 1.2 times their values before irradiation, but the thermal conductivity of the carbon is seriously degraded [8]. It was reported that these result depend upon the temperature during irradiation [7]. We assumed, therefore, that the dependence of the thermal conductivity for the center and outer of the graphite target follows the values at 0.82 dpa (400 °C) and 0.02 dpa (200 °C) of the neutron irradiation performed by Maruyama et al. [7], respectively.

4.2. Frame material

For the frame, in the beginning, we adopted molybdenum which has an almost same thermal expansion 5.1 ppm/C, as carbon. But in the course of the R&D work, we changed the frame material from molybdenum to copper, considering cost and long lifetime radioactivities produced by the neutron irradiation in the case of molybdenum.

4.3. Water tube

For the cooling pipe, we are going to adopt SUS tube rather than copper tube, considering strength against reactive radicals produced by severe radiation. In the first trial, 1/2 in. O.D. SUS tube was brazed with Ni alloy in the groove of the molybdenum frame. It turned out that there exists a certain fraction where brazing material did not flow between the SUS tube and the frame, since it was very difficult to braze whole the edge homogeneously by a torch. Fig. 2 (left) shows a schematic view and a picture of the prototype target with the molybdenum frame. In the second trial, we tried to cast a SUS tube in copper in order to have a better heat contact. But, it turned out that the SUS tube was not stable enough during the casting process. Also, we found a lot of porous structure formed in the copper frame, which can not be used in vacuum. Fig. 2 (right) shows a picture of the prototype target cast in the copper. We also tried to coat copper on the SUS tube to have better heat contact with the copper frame, but it turned out that once it was bent, the shape of the piping was deformed.

On the other hand, the water temperature was found to increase up to 275 °C by ANSYS calculations, in the case of the one turn of SUS tube, resulting in a strong need for at least two turns of tubing to get rid of the film boiling.

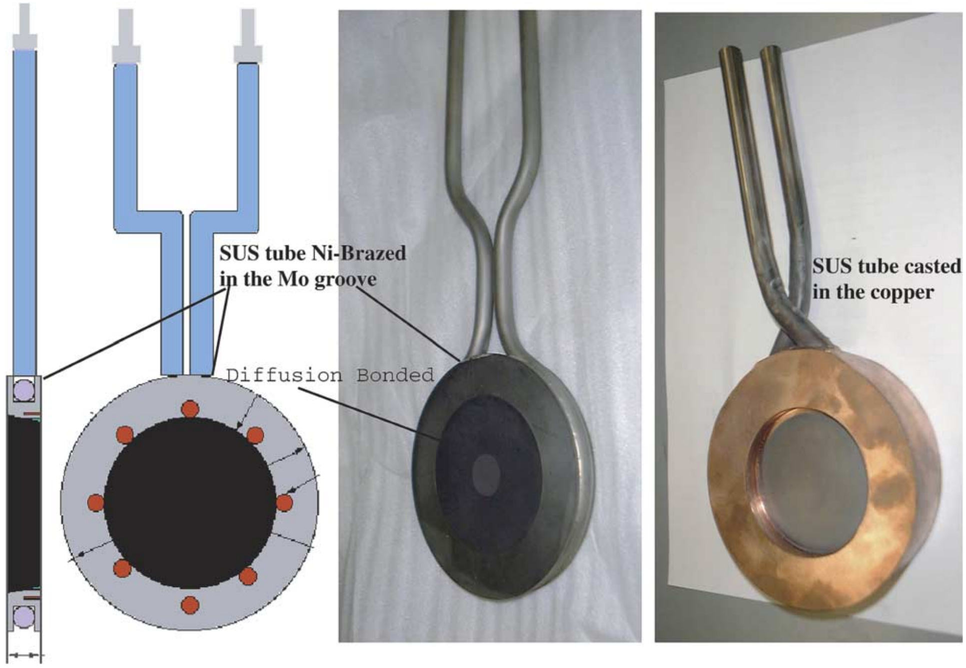

Fig. 2. The left figure shows a schematic diagram and a picture of the prototype target with molybdenum frame. In this trial, 1/2 in. O.D. SUS tube was brazed with Ni alloy in the groove of the molybdenum frame. It turned out that there exists a certain region where brazing material did not flow between the SUS tube and the frame, since it was very difficult to braze whole the edge homogeneously using a torch. The right figure shows a picture of the prototype target cast in the copper. In the casting trial, it was found that the SUS tube can not be stable enough during the casting process, and a lot of porous structure formed in the copper frame.

Finally, in order to bury the SUS tubes in the copper frame, a hot isostatic pressure (HIP) process was adopted. In this method, we could easily bury more than three turns of the SUS tube in the copper frame, which was sufficient even to prevent nucleate boiling of the cooling water.

4.4. Bonding between graphite and frame

In the beginning, a graphite disk with a taper of 3° was diffusion-bonded to the holder frame by inserting 10 μm of SUS foil. In practice, this bonding method worked well. But the tensile stress calculated at the graphite interface was found by ANSYS analysis to be about 35 MPa, assuming 1 MW operation, which was very close to that of the intrinsic property of IG43, 37 MPa. There existed almost no safety factor for this design. Then in order to prevent from focusing stress on the graphite, we reached a new idea to insert a buffer layer of Ti at the interface between the copper frame and the graphite. The Ti material was selected to have a rather small properties of thermal expansion, Young's modulus, to be 9 ppm/K, and 102 GPa, respectively. Finally, we decided to adopt silver brazing in vacuum to bond between the graphite disk and the Ti layer, and the Ti layer and the copper frame.

4.5. Evaluation for the latest design of the edge-cooled graphite target with the Ti buffer interface

For the latest design of the edge-cooled graphite target with the Ti buffer interface, the calculated maximum temperature induced by the heat deposit of 3.5 kW, is 1462 °C which is much lower than the melting point of the graphite and the vapor pressure at this temperature is in the order of 10^{-9}mbar. The calculated maximum tensile stress is 8 MPa against the 37 MPa property of the IG43 and the maximum compressive stress is 42 MPa against the 90 MPa property of the IG43. In particular, the tensile stress is very much reduced by the insertion of the Ti buffer layer at the interface. Calculations so far done of the heat and stress are clearly showing that we are able to use it with a safety factor of 2, even for the 3 GeV 1 MW proton beam corresponding to heat deposition of 3.3 kW. Fig. 3 shows temperature and stress maps of this model calculated by ANSYS under 1 MW proton beam.

In the next step, mechanical transient response and the thermal transient response should be considered. The ΔT induced by the heat deposition in a 3 GeV, 1 MW proton pulse is estimated to be 6°. In this case, the pressure increment in a pulse is calculated to be small to be only 0.6 MPa. Transient behavior associated with

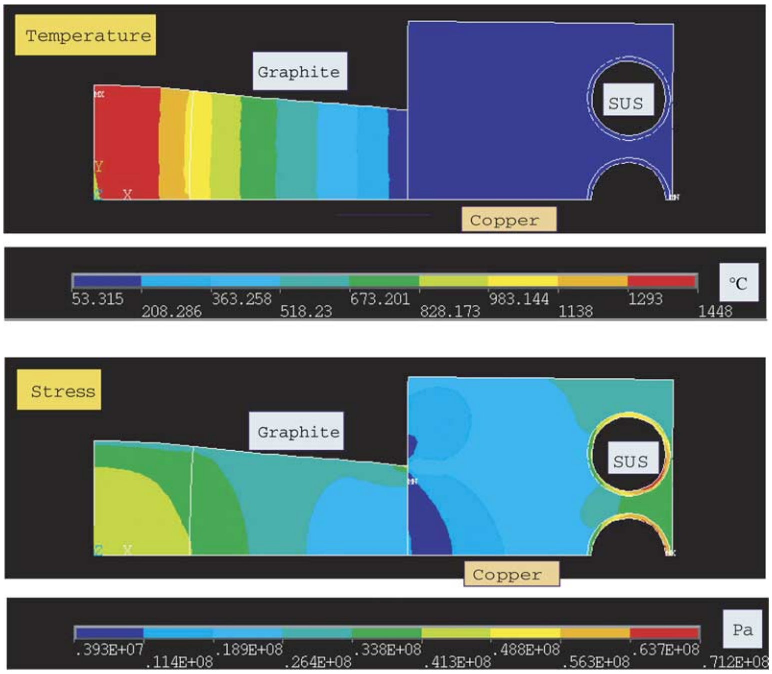

Fig. 3. Temperature and stress maps of the latest edge-cooled model under 1 MW proton beam irradiation as calculated by ANSYS, assuming the dependence of the thermal conductivity on the neutron irradiation and temperature follow Maruyama's data [7]. The maximum temperature is 1462 °C at the center of the graphite target. The calculated maximum tensile stress is 8 MPa compared to the 37 MPa allowable stress of the IG43 at the interface.

the unscheduled beam interruptions such as water-flow trouble is a very important issue in the sense of the safety of operation. For the center of the target, it takes about 70 s to level off at 1462 °C, after the 1 MW proton beam is accepted. Twenty seconds after the water flow is stopped, the temperature of the copper frame and graphite target increase up to 300 and 1470 °C, respectively. Seventy seconds after the water flow is stopped, the temperature of the interfacing brazing part and graphite target increase up to 680 and 1660 °C. One hundred twenty seconds after the water flow is stopped, the copper frame may start to melt down. Therefore, the

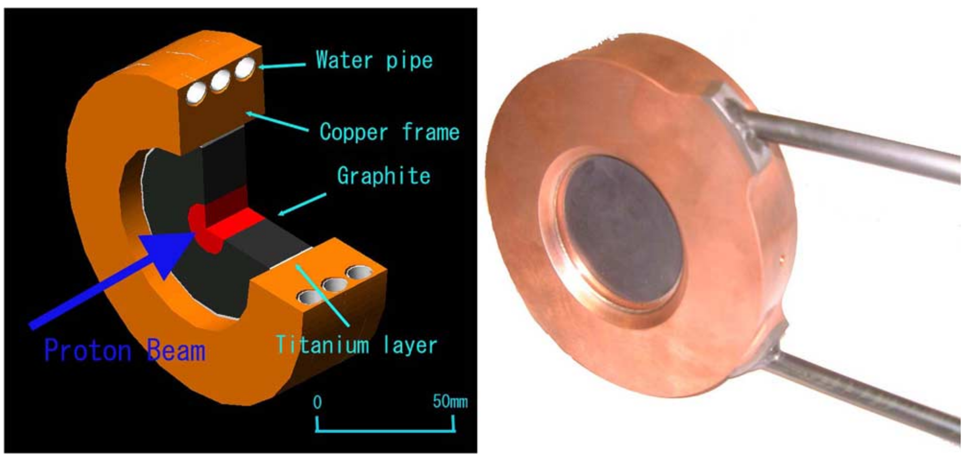

Fig. 4. The left panel shows a schematic drawing of the target assembly. For the graphite material, we adopted an isotropic graphite IG-43 which has a thermal conductivity of 139 W/mK, density 1.82 g/cm^2 at 300 K, thermal expansion 4.8 ppm/C, Young's modulus 10.8 GPa, Poisson's ratio 0.28 at room temperature. Fig. 4 right shows a picture of the edge-cooled graphite target designed for 1 MW operation, the first KEK model.

proton beam should be terminated by a safety interlock no later than 30 s after the water flow stops. When 4 proton pulses will be kicked toward the 50 GeV ring from the RCS, no heat deposition is given to the graphite target for an interval of only 160 ms, which will induce a small temperature decrease for the scheduled beam interruption. A detailed calculation including an optimization of the thickness of the Ti buffer layer is reported elsewhere by Makimura et al. [9].

4.6. Fabrication of a prototype target

In practice, a prototype target was fabricated successfully according to the following design. For the cooling pipe, a SUS tube with 3/8 in. O.D. was adopted. In order to bury the three turns of the SUS tube in the copper frame, the HIP process was adopted. A titanium layer with a thickness of 2 mm was placed as a buffer material to relieve stress. The copper frame, titanium layer and isotropic graphite with a taper of 3° were silver-brazed in vacuum. The prototype target is now under examination under heating tests with electron guns. Fig. 4 shows a picture and a schematic view of the first KEK model, edge-cooled graphite target designed for 1 MW operation.

5. Conclusion

We have been developing a new design of the edge-cooled non-rotating graphite target for the muon and pion production by 1 MW proton beam operation at J-PARC, which seems satisfactory even considering the degradation of the thermal conductivity by the neutron irradiation. A very promising model of the target was designed by inserting a buffer layer of Ti at the interface between the graphite and the copper frame. In practice, a prototype target was fabricated successfully utilizing the HIP process to bury the SUS tubes in the copper frame, and silver brazing in vacuum to bond the copper frame, the Ti buffer layer and the graphite disk.

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