REPORT FOR MUON PRODUCTION TARGET WITH PROTON BEAM OPERATION IN J-PARC

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Abstract

The most intense pulsed muon beam will be generated by a 3-GeV 333-μA proton beam on a muon target made of 20-mm thick isotropic graphite (IG-430) in J-PARC/MUSE (Muon Science Establishment). The energy deposited by a 1-MW proton beam is estimated to be 3.9kW on the muon target. The first muon beam in J-PARC/MUSE was successfully generated on September 26th, 2008. The most intense pulsed muon beam has continuously been produced with a proton beam of 120 kW since the run cycle in November of 2009. In December of 2009, 300-kW of beam operation for one hour was successfully performed. Then continuous 200-kW proton beam operation was started in November of 2010. The muon target chamber system has worked properly, and the temperatures of the principle components have been measured and recorded through a control system. Then J-PARC was heavily affected by the Pacific coast of Tohoku Earthquake. At present, we are trying to grasp the whole situation of damage on the muon target system. In this report the status of proton beam operation and the restoration from the earthquake will be described.

PROTON BEAM OPERATION

Basic Evaluation

The muon target is made of a 20-mm thick, disc-shaped, isotropic graphite (IG-430). The energy deposited by a 1-MW proton beam is estimated to be 3.9 kW on the muon target by PHITS [1], [2]. Because the target is located in a vacuum chamber, almost all of the heat must be removed by the cooling water through the stainless steel tube embedded in the copper frame. In order to absorb the thermal stress, a titanium layer is adopted as an intermediate material between the graphite target and the copper frame [3], [4]. Figure 1 shows a picture of the muon target. On the upstream surface of the muon target, there are eight temperature points located just besides the interface between the copper and the titanium, and two more points on the outer side of the copper frame, which are measured by thermo-couples. Temperature points of inlet and outlet of the cooling-water flow are also measured.

Figure 1: Picture of the fabricated muon target.

The inner diameter of the water pipe d is 7.5 mm. While the flow rate of the cooling water is 9 l/min, the mass flow rate m is 0.15 kg/s. The viscosity of water μ is 0.8×10^{-3} Pa·s in 30° centigrade. Then the Reynolds number Re of the cooling water is evaluated as,
$Re=4m/(\pi\mu d)=3.2\times 10^4$.
Thus the water flow can be considered as a turbulent flow. Using a Nusselt number Nu, the thermal transfer coefficient between the cooling water and the surface of

$$h=\frac{Nu\cdot k}{d}=0.023\cdot \mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.3}\,\frac{k}{d}$$

the water-pipe h is introduced from the Dittus-Boelter equation.
Here, the thermal conductivity of water k=0.6 (W/m/K) and a Prandtl number of water Pr=6 are substituted into the equation. Consequently, we can obtain, h=12600 (W/m^2/K).

To compare the simulation with the results in the actual operation, the data through higher beam power is preferable. Therefore the transient response of the muon target through the 300-kW proton irradiation test was evaluated through a FEM method, and was compared with the result of the continuous operation for one hour on 10th of December in 2009. The energy deposition on the muon target is assumed to be 1170 W (3.9-kW beam loss by 1-MW proton beam). The temperature of the cooling water is assumed to be 30° centigrade. The thermal conductivities k (W/m/K), the specific heats C (J/kg/K), and the densities ρ (kg/m^3) of the target materials shown in Table 1 are adopted in the simulation.

Table1: Material properties adopted in the simulation

	graphite	copper	titanium	Stainless steel
k	120	380	17	15
C	1200	380	520	500
ρ	1820	8930	4510	7800

In the simulation, the 1170-W energy deposition begins to take place on a diameter of 20 mm at the centre of the graphite. Here the time is defined as $t=0$. The energy deposition is continuous for 300 seconds. Figure 2 shows the temperature distribution of the muon target at $t=300$ (s). The transient response of the temperature on the measured points will be shown in the next section.

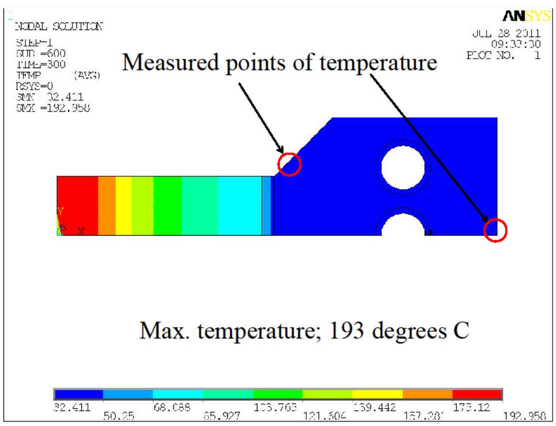

Figure 2: The temperature distribution of the muon target at t=300 (s)

300-kW Proton Beam Operation

First of all, Figure 3 shows the explanation of the parameters used in this section. In the 300-kW proton irradiation test, the beam power of the proton beam was measured to be 303 kW by a current transformer (*CT*) located on the upstream of the muon target. The actual energy deposition on the muon target was estimated from the temperature rise of the cooling water and the water flow. Because the temperature of the inlet flow was not constant, the difference between the temperature rise of the outlet flow and the rise of the inlet flow was adopted as the "*temperature rise of water*". Then the *temperature rise of water* for 9-l/min water flow was 1.8° centigrade. Therefore, the actual energy deposition on the muon target could be estimated to be 1130 W (1170W from the simulation by PHITS). However, it must be also noted that the *temperature rise of water* was too low to allow a precise evaluation of the precise energy deposition. Figure 4 shows the variation of the measured temperature and the simulated temperature. In the simulation the temperature of the water is constant. On the other hand, the actual temperature of the water will have the *temperature rise of water*. Therefore the temperature rise of the copper frame includes the temperature rise of water from the inlet to the outlet. Here we must distinguish "the *temperature rise of water"* with "the temperature rise of water from the inlet to the outlet". The latter temperature rise can be considered as half of the *temperature rise of water*. The temperature rise of the copper frame for comparison must be decided by subtracting the half of the temperature rise of water from the actual temperature rise of copper frame. For an easy comparison, since the initial temperature of the muon target in the simulation is 30 degrees, the data in the graph are given by adding 30 degrees to the temperature rise of the copper frame from the temperature without proton irradiation. The eight measured points of the copper frame just besides the interface between the copper and the titanium, with the normalization above are averaged and it is labelled as "*inner data*". Similarly, the two points on the outer side of the copper frame are also averaged and it is labelled as "*outer data*". They are compared with the temperatures in the simulation, labelled as "*inner simulation*" and "*outer simulation*".

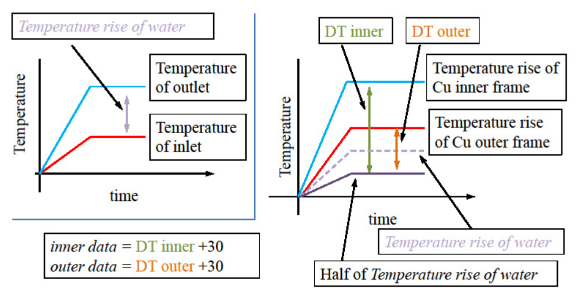

Figure 3: The explanation of the parameters used in this section

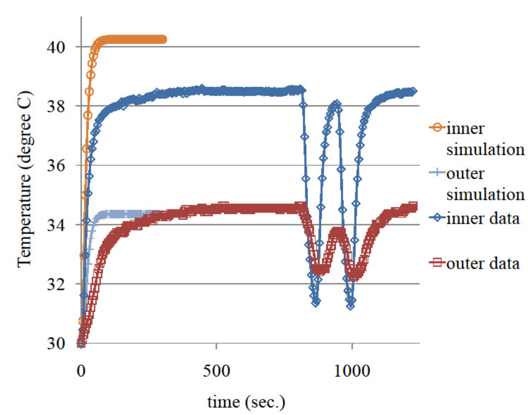

Figure 4: The variation of the measured temperature and the simulated temperature.

In the simulation, the temperatures reach the steady state at 60 seconds after the irradiation begins. Because the target weighing 4kg is fixed to the target support plate and the target rod weighing 40 kg, the heat capacity of the actual target becomes larger. In fact, it took 500 seconds to attain the maximum temperature. The maximum temperature of the *inner data* is 15-% lower than one of the *inner simulation*. The maximum temperature of the *outer data* is almost same as one of the *outer simulation*. The thermal transfer coefficient seems to be consistent to the one in the simulation. The actual thermal conductivity of the copper frame seems to be higher than in the simulation As a result of the 300-kW proton irradiation test, the cooling power of the muon target was found to be higher than in the simulation.

220-kW Continuous Operation and Decrement of Water Flow

To compare the simulation with the actual result, the higher beam power was preferable. However 300-kW proton beam operations were just performed in 3-sets, 5 minutes and 1-set, 1hour. To investigate how valid the method of the evaluation, the operation for a longer period are indispensable. So the 200-kW continuous operation from 21st of January to 19th of February in 2011 was checked. The water flow was always measured by observing the flow meters through an iconoscope camera. In this operation, the water flow decreased gradually from 9 l/min to 6.3 l/min without our intention, though it was a significant problem for us. If the beam loss is assumed to be constant, the decrement of the water flow will give an increment of the *temperature rise of water*. Then the thermal transfer coefficient must be estimated through the inner data and the beam loss as well. Figure 5 shows the variation in 500-seconds intervals of the temperature rise of the water and the temperature of the *inner data* and the *outer data*. In this operation, the flow rate varied from 9 L/min to 6.3 L/min for one month. The temperature rise of the water varied from 1.2 degree C to 2.2 degrees C. The temperature rise in 6.3 L/min must be 1.7 degrees C; however actual temperature was higher than the evaluation. It can be guessed that the target rod and the plug shield are giving some heat to the water. And also, when the flow rate varies from 9 L/min to 6.3 L/min, the thermal transfer coefficient will vary from 12600 W/m/K to 9100 W/m/K. So the temperature rise of *inner data* must be 1.3 times higher than the initial temperature rise. The estimation corresponds to the actual variation. Because the differences between the inner data and the outer data look constant, the beam loss on the muon target is confirmed to be constant.

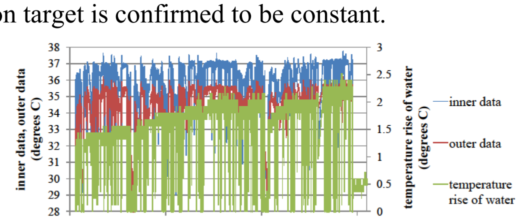

Figure 5: the variation in 500-seconds intervals of the temperature rise of the water and the temperature of the *inner data* and the *outer data*

RESTORATION FROM TOHOKU EARTHQUAKE

J-PARC was heavily affected by the Pacific coast of Tohoku Earthquake on 11th March in 2011. At present, we are trying to grasp the whole situation of damage on the muon target system. On the whole, the muon target system and M2 tunnel, where the primary proton beam components are located, didn't have a severe damage. The high vacuum for the beam line could be already obtained. The control system for the muon target system and the up-down motion system worked well. The precise deformation of the muon target rod will be measured in the remote handling room, *Hot cell* in August and September of 2011. Before the transportation of the muon target to *Hot cell*, the irradiated muon target was checked through taking the pictures and the videos from the port for the pumping station in M1 tunnel, which is 10 m far from the muon target. Figure 6 illustrates the schematic drawing in the observation of the muon target.

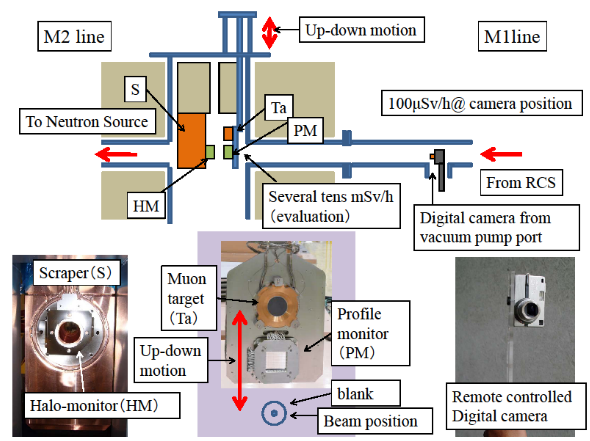

Figure 6: The schematic drawing of the observation for the muon target

The digital camera was inserted into the vacuum duct with a rod. The camera could be controlled by a remote controller to prevent a worker's hand from being irradiated through directly facing to the muon target when pressing the switch of the camera. To operate the proton beam properly, three positions must be obtained on the muon target location: (1) the muon target position for in-beam operation, (2) the profile monitor position for monitoring the beam profile, and (3) the clear position with no components in the proton beam path. Hence, the *Target rod*, which consists of a stainless rod, the muon target and a profile monitor, can be precisely moved along a linear motion guide. When the muon target location was observed from the upstream of the beam line with the up-down motion, the three positions could be distinguished. When the clear position was selected, the halo-monitor, which is set in front of the scraper located on the just down-stream of the muon target, could be observed. Then it was confirmed that these components were located on the approximately precise positions.

Figure 7 shows the taken pictures of the irradiated muon target, the profile monitor, and the halo-monitor.

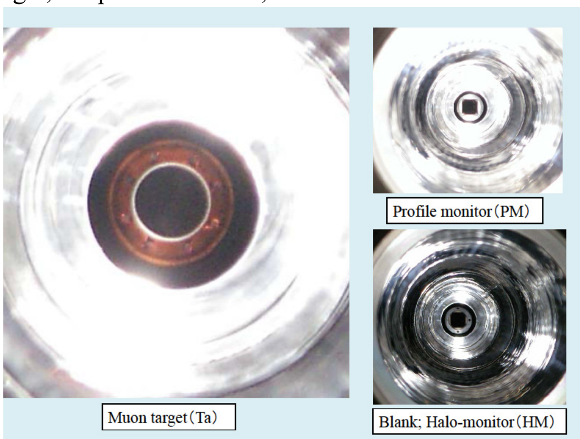

Figure 7: The taken pictures of the irradiated muon target, the profile monitor, and the halo-monitor

SUMMARY

The most intense pulsed muon beam has been generated in J-PARC/MUSE. The 300-kW proton beam operation was performed with the muon target. The 200-kW continuous operation had been successfully performed until the TOHOKU earthquake on 11th March in 2011. At present, we are trying to grasp the whole situation of damage on the muon target system.

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