Development of a New Production Target at the J-PARC Hadron Experimental Facility

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We have developed a new production target at the J-PARC Hadron Experimental Facility. The target is made of gold and is indirectly cooled by water through a copper block. Although this cooling structure is the same as that of the current production target, the cooling efficiency is improved by doubling the copper cooling block. We performed an elastic-plastic analysis for thermal-stress evaluation of the new target, using the tensile-test results of bulk gold. For each type of stress, we compared the results of the analysis to the allowable stress. It turns out that the new target is capable of a primary-proton beam power up to 90 kW for a 5.52-s repetition cycle. In this paper, the design and preparation of the new target are presented.

KEYWORDS: production target, hadron beam, pion beam, kaon beam.

1. Introduction

The Hadron Experimental Facility is one of the two experimental facilities at J-PARC main ring (MR). It utilizes a slowly extracted intense primary-proton beam at 30 GeV to produce various secondary particles, such as kaons, pions, and anti-protons [1,2]. The secondary-particle beams are delivered to experimental areas in the hadron experimental hall (HD-hall) and are used for various particle and nuclear physics experiments [2,3]. Figure 1 shows a layout of the HD-hall. A production target, referred to as T1, is located at the primary beam line inside the central shielding, and three charged beam lines and one neutral beam line were constructed until 2018. The first beam injection to the T1 target was carried out in February 2009, following the successful slow extraction from the MR and transportation to the HD-hall in January 2009. The repetition cycle was initially started from 6 s, improved to 5.52 s in 2015, and reduced to 5.2 s in 2018.

The maximum primary beam power to the
current T1 target is estimated to be 50 kW for a 6-s cycle [4]. The current target has been in operation since April, 2015. During these 3 years until 2018, 1.1E+20 protons were accumulated and no serious damage was observed. The beam power was gradually increased and reached to 50 kW, which is the design maximum power. Thus, to further increase the beam power, the new target described in this article was developed.

2. New target design and its expected performance

2.1 Requirements

The production target in the high-power accelerator facility should be equipped with adequate cooling capability as well as corrosion resistance to substances such as nitrogen oxide (NOX) produced by radiations in air. It should also exhibit long-term stability of physical properties for radiation exposure. In addition, to satisfy secondary-beam quality and intensity for the nuclear and particle physics experiments in the HD-hall [2,3],

1. a high density and large mass-number material should be adopted, and
2. the beam size on the target should be as small as possible.

To satisfy these requirements, gold (19.3 g/cm³) was adopted as the target material because its thermal properties are suitable for our application. Initially, we used platinum, which also has a high density (21.4 g/cm³) and corrosion resistance, as a target material [1]. Compared to platinum, gold has a better thermal conductivity (318 W/m/K for gold, and 72 W/m/K for platinum), and the thermal-expansion coefficient is closer to that of copper (14.2 ppm/K for gold, 17.9 ppm/K for copper and 9.4 ppm/K for platinum). The agreement in the thermal-expansion coefficients between the target material and the copper cooling block is important in our target design because a difference would cause a large thermal stress at the bonded interface.

2.2 New target design

The designs of the current target and new
The basic structure of the new target is the same as that of the current target. The target is made of gold and indirectly cooled by water through a copper block. There are two sets of gold ledges; one of them is exposed to the primary beam. In case damage is found to the gold, it can be switched to the other side by a driving unit [4]. The total length of the gold block, 66 mm, is not changed because of the secondary-beam optics requirements [2]. To reduce thermal stress, 0.2-mm-width slits were machined with an 11-mm pitch in the gold block. As shown in Fig. 4, for the new target, the width of the gold block and the depth buried in the copper are changed to 12 mm in width, and to 2 mm in depth, respectively, to reduce the thermal stress at the bonded interface while not reducing the secondary-beam yield. For the water pipes, the design is not changed. The pipes are made of stainless steel with a 15-mm outer diameter and 1-mm thickness. The water return paths are curved in the stainless-steel blocks, which are located in the front and rear of the copper block. To improve the cooling efficiency, the water pipes are located as close as possible to the gold blocks. The gold block, copper block, water pipes and stainless-steel block are all bonded together by a hot-isostatic pressing (HIP) process. After applying the HIP process, the interfaces are examined using ultrasonic testing to evaluate potential bonding defects between the gold and copper blocks. Thermocouples are attached to each piece of the gold, to the copper block and to the cooling pipes for temperature monitoring during beam operation. In the current target, one thermocouple was attached on the top of one gold block. In the new target, to guarantee redundancy on temperature monitoring, two thermocouples are attached on both sides of each gold block. In addition, the horizontal beam injection position is expected to be measured by the temperature balance between the left and right sides of the gold.

To improve the total cooling capability for the new target, two sets of target blocks are prepared, and one block is placed on the other one. As a result, the gold ledge of each target block faces to each other, as shown in Fig. 3 and Fig. 4. The proton beam is injected to the center between the top and bottom gold blocks. However, the thermal analysis predicts a 0.1-mm vertical expansion in each gold block by the beam thermal load. Moreover, a manufacturing error of 0.1 mm is expected. Because the collision between the top and bottom blocks would cause a large thermal stress, a 0.3-mm gap is applied between the top and bottom gold blocks to avoid the confliction. Owing to this gap, the total interaction rate of the primary proton in the gold is reduced to be 42%. This rate would be 48% for a no-gap design, which correspond to a decrease of 12.5% for the secondary-beam yield. However, the

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Ultimate strength (MPa)</th>
<th>Yield strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>118</td>
<td>8.6</td>
</tr>
<tr>
<td>200</td>
<td>87</td>
<td>7.8</td>
</tr>
<tr>
<td>400</td>
<td>43</td>
<td>7.6</td>
</tr>
</tbody>
</table>

Fig. 5. Measured stress-strain curves of bulk gold.
primary beam power can be increased more than the gap loss precisely because of the large reduction of thermal stress. As a result, the maximum primary beam power for the new target is increased by a factor of 1.8 compared to that of the current target, as described in the following sections.

2.3 Analysis conditions

In previous works [4], a thermal stress analysis of the current target was performed by an elastic analysis based on the Young’s modulus of gold. The safety factor was evaluated using the stress at the bonded interfaces, which gives the highest stress in the analysis. Meanwhile, stress relaxation with plastic deformation would play an essential role. This is the reason why we have newly measured the stress-strain curves of the bulk gold using tensile tests at 25, 200 and 400 °C. For these tensile tests, JIS-Z2241-13B-type test pieces made of gold were fabricated. The same heat treatments as the actual fabrication process of the target were applied to the test pieces. Figure 5 shows the resulting stress-strain curves. The ultimate and yield strengths are listed in Table I. Given that the bonding strength between the gold and copper is higher than the bulk-gold strength [4], the bulk-gold strength is adopted as the evaluation criteria as a conservative assumption. Using these data, we calculated the thermal stresses for the new target using an elastic-plastic analysis method.

The beam conditions in the evaluation are as follows: (1) the proton kinetic energy is 30 GeV; (2) the primary beam power is 90 kW with a 5.52-s repetition cycle (2 s with the beam on and 3.52 s with the beam off); (3) the beam size on the target is a Gaussian shape with $(\sigma_{\text{horizontal}}, \sigma_{\text{vertical}}) = (2.5 \text{ mm}, 1.0 \text{ mm})$.

The calculations comprise two steps: (1) estimation of the heat density deposited in the target by proton-beam injection using a MARS-15 simulation code [5]; (2) thermal-stress transient analysis by finite-element calculations using ANSYS-12.0.1 [6].

The criteria for the allowable stress are:

- $S_M \times 3$ for thermal stress,
- $10^4$-cycle fatigue strength $\times 1/2$ for low-cycle fatigue, and
- $10^7$-cycle fatigue strength $\times 1/2$ for high-cycle fatigue,

where $S_M$ refers to a design stress, which is adopted as the smaller value between the [ultimate strength $(\sigma_u) \times 0.85/3$] or [yield strength $(\sigma_y) \times 0.85/1.5$] of the bulk gold. The design margins – a factor of 0.85/3 and a factor of 0.85/1.5 – are determined according to the standard for welding pipes prescribed in JIS B-8266 [7]. The low-cycle

![Fig. 6. Results of the thermal analysis for the 90-kW proton beam.](image)
fatigue is caused by the average temperature changes due to a beam-operation cycle typically with a period of several hours. The high-cycle fatigue is caused by short-term temperature changes due to spill-by-spill cycles typically with a period of 5.52 s. Assuming a 15,000-h (625 days, 125 days × 5 years) life of the new target, the numbers of low and high cycles in typical cases correspond to $10^4$ and $10^7$ cycles, respectively. Given that the $10^4$-cycle and $10^7$-cycle fatigue strengths of bulk gold are 0.7 and 0.4 times smaller than its ultimate strength of the bulk gold, respectively, we adopted $\sigma_u/2$ and $\sigma_u/3$ as the low-cycle and high-cycle fatigue strengths, respectively [8,9]. The design margin for fatigue, which is a factor of 1/2, is also determined according to JIS B-8266 [7].

2.4 Results

Figure 6 shows the calculation results for the temperature and stress. The maximum temperature of the gold and bonded interface is 374 and 263 °C, respectively. Von-Mises equivalent stress of the gold and bonded interface is 8.1 and 9.0 MPa, respectively. In Table II, the analysis results are listed. The highest stress is located at the bonded interface. However, the margin to the allowable stress in the high-cycle fatigue of the gold is the smallest. In this analysis, the maximum beam power was determined to be 90 kW with 5.52-s cycles, which corresponds to a factor of 1.8 improvement compared to that of the current target.

Given that the heat deposition by the proton beam is divided into the top and bottom gold blocks, the temperature of the gold would be sensitive to a vertical beam position shift. The highest temperature of the gold was obtained at the 2.5-mm vertical shift by the thermal analysis. From the beam operation records, the vertical beam position was stable within ±0.5 mm. Given that the beam extraction is automatically stopped before starting the next cycle by a machine-protection system of J-PARC if the beam position is shifted beyond 0.5 mm, the target should be sound for a single-spill exposure with a 2.5-mm beam shift, as well

<table>
<thead>
<tr>
<th>Location (max. temperature)</th>
<th>Stress classification</th>
<th>Calculated Stress (MPa)</th>
<th>Allowable stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold (374 °C)</td>
<td>Thermal</td>
<td>8.1</td>
<td>13.0</td>
</tr>
<tr>
<td></td>
<td>High-cycle fatigue*</td>
<td>7.9</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>Low-cycle fatigue*</td>
<td>8.2</td>
<td>12.3</td>
</tr>
<tr>
<td>Bonded interface (263 °C)</td>
<td>Thermal</td>
<td>9.0</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td>High-cycle fatigue*</td>
<td>9.0</td>
<td>12.2</td>
</tr>
<tr>
<td></td>
<td>Low-cycle fatigue*</td>
<td>9.2</td>
<td>18.4</td>
</tr>
</tbody>
</table>

(*The stress for the fatigue was calculated from an alternating stress amplitude between the lowest and the highest temperature in the typical cycle, taking the plastic deformation effect with a shake down into account.)

<table>
<thead>
<tr>
<th>Beam condition</th>
<th>Location</th>
<th>Temperature (°C)</th>
<th>Stress calculation result (MPa)</th>
<th>Allowable stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous beam with 0.5 mm shift</td>
<td>Gold</td>
<td>430</td>
<td>8.4</td>
<td>12.9</td>
</tr>
<tr>
<td></td>
<td>Bonded interface</td>
<td>303</td>
<td>9.4</td>
<td>13.1</td>
</tr>
<tr>
<td>Single spill with 2.5 mm shift</td>
<td>Gold</td>
<td>514</td>
<td>9.6</td>
<td>12.7</td>
</tr>
<tr>
<td></td>
<td>Bonded interface</td>
<td>391</td>
<td>10.6</td>
<td>12.9</td>
</tr>
</tbody>
</table>
as for a continuous beam with a 0.5-mm shift. In Table III, the results in both cases for the 90-kW beam are listed; the calculated stresses are lower than the allowable stresses.

The target temperature is dominated by the number of protons per one spill rather than by the average beam power. Thus, for the same average beam power, the temperature of the target becomes lower for the shorter repetition cycle if the beam-extraction period of 2 s is not changed. Through major upgrades of power supplies in MR scheduled in 2021, shorter cycles such as 5 s or even 3.7 s should be archived. In conclusion, the new target is acceptable up to 97 kW of primary beam for a 5-s cycle, and 125 kW of primary beam for a 3.7-s cycle.

3. Preparation status of the new target

The new target is under fabrication. Figure 7 shows a photograph of the new target after the HIP bonding and machining processes. The replacement of the current target with the new one is scheduled in autumn, 2019. Beam operation with the new target is expected to begin in 2020.

4. Summary

For the Hadron Experimental Facility, a new production target was designed by an elastic-plastic analysis based on the tensile-test results of gold. From the analysis, the new target would be exposed up to the 90 kW of primary proton beam for 5.52-s repetition cycle, which is a factor of 1.8 higher in terms of beam intensity than that of the current target. In addition, if the accelerator cycle becomes shorter, an acceptable beam power of 100 kW or higher can be reached, depending on the repetition cycle. The new target is under fabrication, and the installation is scheduled in autumn, 2019.

Acknowledgment

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References


