THERMAL ANALYSIS OF THE INJECTION BEAM DUMP AT J-PARC RCS

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Abstract

The amount of the heat generation in the beam dump for unstripped H^- beam at an injection in a high power beam synchrotron becomes a few thousand watts. In such case, the temperature of the dump materials might reach unacceptable values from the aspect of the mechanical strength decrease. The thermal analysis for the injection beam dump at J-PARC 3GeV synchrotron was performed in order to evaluate the upper limit of the beam power into the dump. The temperature distribution of beam dump was calculated by modelling the detail configuration and enough large region. The upper limit of the beam power into the dump, which keep the concrete temperature below permissible value, was estimated to be about 3 kW. The comparison with the measured temperature shows the thermal resistance between the contacted materials should be considered for more accurate calculation.

INTRODUCTION

Multi-turn H^- charge exchange injection is a popular injection method at many high power beam synchrotrons in the world. Two electrons of H^- beam from the linear accelerator is stripped to the protons, by through a thin stripping foil at the injection point of the synchrotron ring. Unwanted unstripped H^- or partially stripped H^0 beam after the foil is transported to the beam dump. Although the stripping efficiency is usually more than 99 %, the heat quantity into the beam dump by the wasted beam are hundreds of watts due to the high power beam. Moreover, the stripping efficiency would decrease due to foil deterioration, and corresponding heat load into the beam dump become a few thousand watts. Hence, the thermal analysis based on the realistic model for such beam dump is important to estimate the temperature of dump materials and to examine the limit of the heat quantity into the beam dump.

Injection beam dump of the J-PARC 3GeV synchrotron (RCS) is a system, for which the thermal analysis with detail model should be performed. The H^- beam with the energy of 400 MeV is converted to protons by the primary charge stripper foil of hybrid boron doped carbon. The calculated stripping efficiency is 99.7 % with a 333 μ g/cm^2 thick foil [1]. The remaining unstripped H^- is stripped by one secondary foil to protons and transported to the injection beam dump. The partially stripped H^0 is stripped by the other secondary foil and transported to the injection beam dump in the similar fashion. The injection beam dump system is designed to accept 4 kW proton beam with the energy of 400 MeV from a perspective of the radiation shield. In that case, the ratio of the beam loss is 3 % corresponding to the design beam power of the RCS, which is 1 MW at the 3 GeV extraction energy. On the other hand, from a perspective of the material temperature, the acceptable beam power to the injection beam dump is supposed to be lower. One limit would come from the temperature of concrete, which plays a role as radiation shielding and building. The mechanical strength of concrete generally decreases with higher temperature. In J-PARC, a rule is set that the maximum temperature of concrete should not exceed 60 °C. However, the temperature of the concrete is difficult to be measured due to the configuration of the beam dump system. The surface temperature of the beam stopper is directly measured by the thermos couples as the temperature monitor for the dump system. It is necessary to accurately estimate correspondence between the concrete temperature and the measured temperature of the beam stopper surface, and set the threshold level on the measured one. From this motivation the thermal analysis based on the realistic configuration with the enough large modelling region was performed. In this report, we first show the configuration of the RCS injection beam dump system. Then we describe the calculation model and the thermal condition for the calculation. Finally, we present a calculation results and discuss the validity of the calculation through the comparison with the measurement.

RCS INJECTION BEAM DUMP

The injection beam dump consists of the terminal beam pipe, beam stopper and its cooling system, radiation shield of carbon steel, concrete for the radiation shielding and building, and sandy soil. Figure. 1 shows the configuration of the beam dump components. The terminal beam pipe consists of stainless steel with the size of 350 mm in diameter and 4 mm in thickness. The beam stopper consists of carbon steel with the size of 380 mm in height, 380 mm in width, and 300 mm in length. This length is enough long to stop 400 MeV protons, whose stopping length in iron is about 150 mm. The thermocouples are attached to four corners on the upstream surface. The thin thermal radiation shield of 1 mm thick copper plates are placed between the end face of the beam pipe and the upstream face of the beam stopper. The lateral and bottom faces of the beam stopper was covered by the copper plates as thermal conductor and it extends to the upstream. The cooling water pipe of seamless stainless steel is fit to the upstream edge of the cupper plates. The beam stopper with the cooling system was inserted into a hole from the upstream face of the concrete and the steel for shielding. The radiation shield around the beam stopper is composed of layered carbon steels, who measures in total 2.4 m in height, 3 m in width, 2.5 m in length. These steels were constructed

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inside the concrete, whose role is both radiation shielding and the building. The upstream and another lateral faces of the concrete are the wall of the accelerator tunnel. The temperature of the tunnel is controlled to 30 °C. Other faces of the concrete are surrounded by the sandy soil. Thickness of the sandy soil from ground surface to the top face of the concrete is 5.3 m.

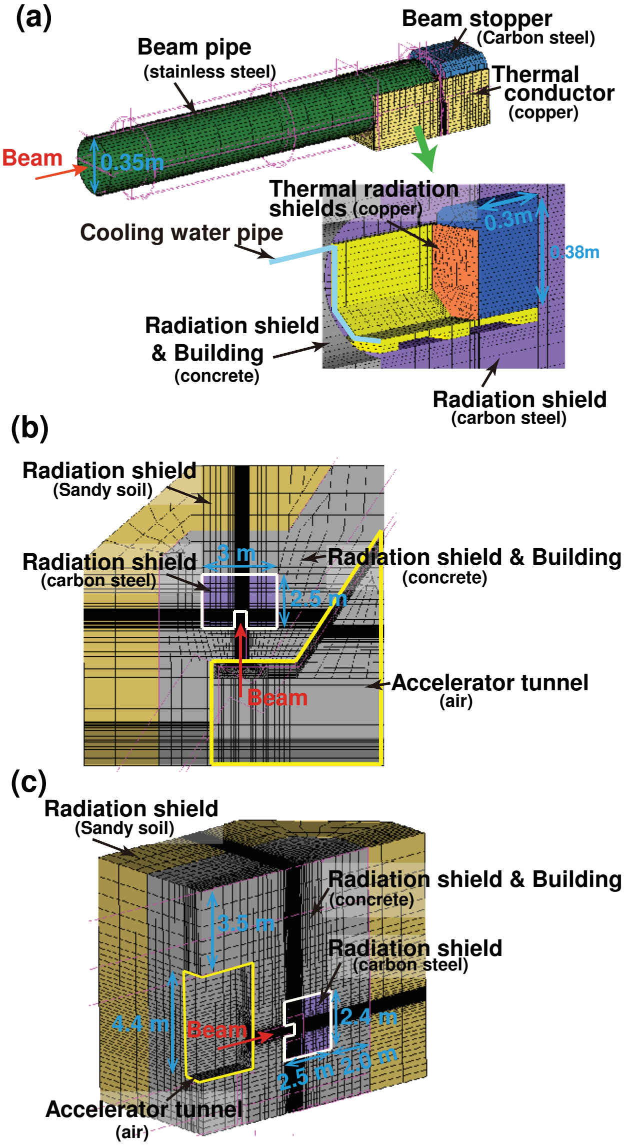

Figure 1: Structure of the beam dump components. Figures are the model for the calculation. (a) The configuration around the beam stopper. (b) Top view of the injection beam dump. (c) Cross-section view of the beam dump.

THERMAL ANALYSIS

Calculation Model

Thermal analysis was performed using the ANSYS code. The calculation model was constructed based on the real structure. The model of the beam pipe, beam stopper, and cooling system is already shown in the diagram (a) of Fig. 1. The whole region of the simulation model is also shown in the diagram (b) and (c) of Fig. 1. Enough large region was modelled for the calculation in order to prevent the temperature of the inner structure from being affected by the boundary condition of the outermost surface. Table 1 summarize the physical properties for each material used in the calculation. For the radiation shielding of steel, the lower thermal conductivity than usual steel was used because of the laminated structure [2]. The thermal conductivity of the sandy soil is also set to the lower value than the general one, which is about 1 W/m K. The reason is to avoid the underestimation of the concrete temperature.

Table 1: Properties of Each Material Used in the Model

Material	Density (g/cm^3)	Specific heat (J/kg K)	Thermal conductivity (W/m K)
Stainless steel	7.9	500	17.1
Carbon steel	7.8	530	52 for the beam stopper 21 for the radiation shield
Copper	8.9	380	403
Concrete	2.2	900	1.6
Sandy soil	1.6	900	0.4

Figure 2 shows the input heat condition. The typical beam shape and the position was modelled for the input heat condition. The energy loss distribution of 400 MeV proton along the beam direction is estimated by the Bethe-Bloch formula. The energy loss in the end face of the beam pipe, the copper thermal radiation shielding plates, and the beam stopper was taken into account.

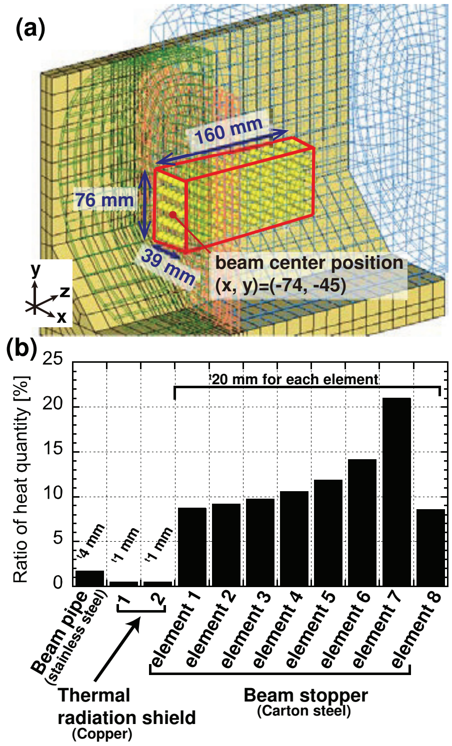

Figure 2: Input heat condition by the 400 MeV proton beam. (a) Size and position of the heat generation in the beam stopper. (b) Distribution of the heat generation ratio in each material.

The convection coefficient for the cooling water at the edge of the copper plate was estimated as follows. The Reynolds number was calculated using the given flow velocity of the cooling water, the shape of the water pipe, and the properties of the water at given temperature. Using also the Prandtl number calculated at given temperature, the Nusselt number for the turbulent-flow, which is judged by the Reynolds number, was calculated by the formula

$$\mathrm{Nu} = 0.023\,\mathrm{Re}^{0.8}\mathrm{Pr}^{0.4},$$

where Nu denotes the Nusselt number; Re and Pr denote the Reynolds number and the Prandtl number, respectively. The convection coefficient calculated for free convection was used for the concrete face, which contact with the accelerator tunnel. For the boundary conditions of the outermost surfaces of the concrete and sandy soil, the temperature was fixed to 32 °C and 20 °C, respectively.

Results and Discussion

The calculation was performed in the case of 2000 W beam injection into the beam dump. Temperature distribution of the different input heat can be predicted from this case. Figure 3 shows the calculated temperature distribution of each constitution. Maximum temperature of the concrete is 49 °C. Because the temperature rise from the case without input heat is about 20 °C, the acceptable beam power where the concrete temperature is kept below 60 °C is about 3.1 kW. Maximum temperature of other parts is well below the temperature where the mechanical strength of each material become unacceptably lower, though the stress analysis should be performed for more accuracy.

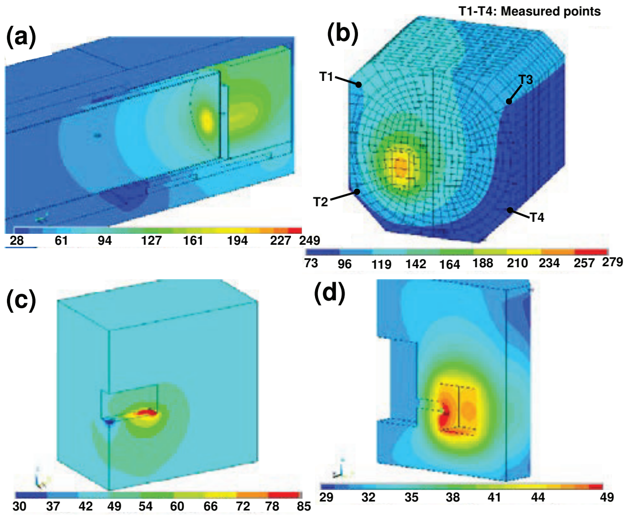

Figure 3: Calculated temperature distribution of beam dump components at 2000 W input power case. (a) The beam pipe, (b) the beam stopper, (c) steel radiation shield, and (d) concrete radiation shield.

Figure 4 shows the comparison of the calculated temperature with the measured one at the four corner of the upstream surface of the beam stopper. Although the actual input power into the beam dump is up to 500 W at the present stage, rough prediction shows the calculated temperature might be under estimated. The reason is thought to be the following. In the realistic structure, materials are not exactly contacted with each other. Hence, the thermal resistances exist between them. Thermal resistance between the beam stopper and thermal conductor around it largely affects the temperature of the beam stopper. In the next step, we will iterate the calculation by treating the thermal resistance around the beam stopper as a parameter in order to make the consistence with the measured temperature.

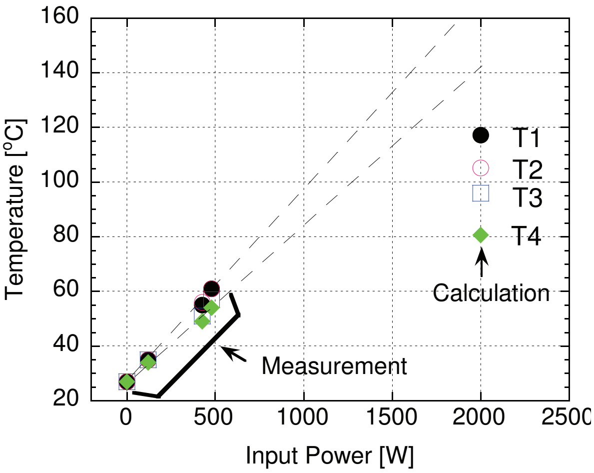

Figure 4: Comparison of the calculation result with the measured one. The dashed line to guide the eye was also shown for the rough prediction of the measured temperature.

SUMMARY

The thermal analysis of the injection beam dump at J-PARC RCS was performed in order to evaluate the upper limit of the beam power injected into the dump. The calculation model was constructed based on the real structure. The calculation result shows that about 3 kW beam is acceptable from the perspective view in which the concrete temperature is kept below the permissible value. Comparison with the measured temperature indicates that the thermal resistance between the material should be taken into consideration for more accurate calculation.

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REFERENCES

[1] P. K. Saha, et al., Nucl. Instrum. Meth. A 776 (2015) 87.
[2] M. Kuramochi, et al., JAERI-Tech, 2003-055 (2003) p.3327.