DEVELOPMENT OF A BEAM INDUCED HEAT-FLOW MONITOR FOR THE BEAM DUMP OF THE J-PARC RCS

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Abstract

A beam induced heat-flow monitor (BIHM) will be installed in front of the beam dump of the RCS (Rapid Cycling Synchrotron) at J-PARC (Japan Proton Accelerator Research Complex), where a power limitation of the beam dump is 4 kW. The purposes of this monitor are to observe a beam current injected into the beam dump and to generate an alarm signal for the main control system of the RCS. At the BIHM the beams penetrate a carbon plate of 1.5 mm in thickness, where the plate is supported by four rods on the monitor chamber. The heat generated by the interactions between the beam and the carbon plate propagates to the outer edge of the plate, and then to the monitor chamber through the four rods. By measuring the temperature differences between upstream and downstream ends of each rod, the total heat flow can be measured. The beam current can be determined by the measured heat flow with the help of the calculated stopping power of a proton in a carbon material. The design of the BIHM and test results will be presented.

INTRODUCTION

The accelerator series of J-PARC is composed of 181/400 MeV Linac, 3 GeV RCS, and 50 GeV MR (Main Ring) Synchrotron [1]. The Linac accelerates the H^- beams up to 181 MeV at the first stage, and then will be upgraded to the maximum energy of 400 MeV at the second stage. The Linac beams are delivered along the L3BT beam transport line to the 3 GeV RCS. After transform the H^- into proton beams, the RCS accelerates these up to 3 GeV within 20 ms. An operation frequency of the RCS is thus 25 Hz. The extracted beams are for a neutron target of Meterials and Life Science Facility and for the 50 GeV MR.

At the injection point of the RCS, the H^- beams penetrate the electron stripper carbon foil of thickness 200 μg/cm^2 and 290 μg/cm^2 for 181 MeV and 400 MeV, respectively [2]. As a result, electrons bound to a proton are stripped. Therefore, H^-, H^0, and proton beams are generated all at once. However, only the proton beams go into the RCS ring. The ratio of the proton beams to the Linac beams depends on the thickness of the foil. Since the passage of H^- beams degrades the thickness of the foil, the ratio decreased with increasing the integrated beam current through the foil.

The H^- and H^0 beams penetrate again rather thick two carbon foils, 2nd and 3rd stripper foil, thus almost all its electrons are stripped. The generated proton beams are transported along the H^0 dump line to a beam dump. The beam dump named as H^0 dump. The limitation of the beam power to the dump is 4 kW.

To avoid serious thermal damage of the H^0 dump and to control the radioactivity of the dump beam transport line, a solid and maintenance free current monitor is required. We have developed a calorimeter, BIHM (Beam Induced Heat-flow Monitor), for the purpose of the current measurement. In this paper, after some description of the principle of the measurement, we will present the results of preliminary experiments using a heater.

PRINCIPLE OF THE BIHM

The BIHM will install at 200 mm upstream from the entrance of the H^0 dump. The schematic drawing of the monitor is shown in Figure 1. The main components are a circular carbon plate, four plate-support rods, and four pairs of platinum resistance thermometer. The chamber is made of titanium. This monitor measures the heat generated by the interaction between proton beams and the carbon plate.

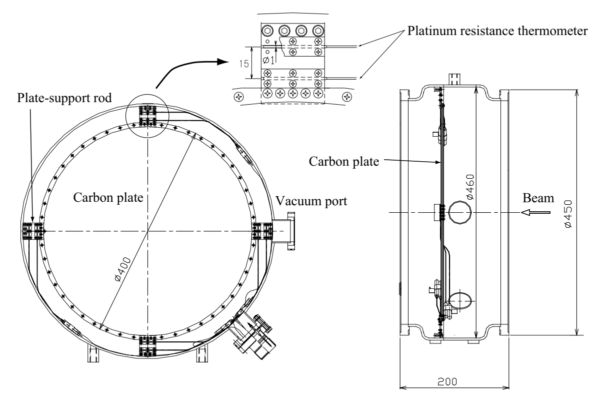

Figure 1: Shematic drawing of the BIHM.

For the carbon plate, we use the commercial carbon foil, which is PARMA-FOIL [3] made by ToyoTanso Co., stacking up to 1.5 mm in thickness. Its thermal conductivity for radial heat propagation is 200 W/(m °C) for 25 °C. The density is 1 g/cm^3 and the emissivity is 0.2 to 0.6 for the wavelength of 20 to 5 μm.

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The dumped beams penetrate the carbon plate and go into the H^0 dump. The typical RMS (root mean square) beam spot size is 3.7 mm×10.0 mm. The generated heat can be estimated to be the product of stopping power of proton beams in the carbon substrate and the mass per unit area of the plate. The estimated heat is 14.3 and 4.1 W for 181 and 400 MeV beam, respectively, when the beam power of 4 kW is considered. Thanks to a low stopping power, which is relative to the atomic number, and low density of the plate, a low heat concentration is achieved. Two dimensional calculations suggest that the low heat concentration and the high thermal conductivity restrict the beam spot temperature to that lower than 250 °C.

The heat propagates to the outer edge of the plate and then to the monitor chamber through four plate-support rods made of Ti-6Al4V alloy. The dimension of the rod is L20×W30×D2 mm. Four pairs of platinum resistance thermometer (class A Pt100) are embedded in each rod at intervals of l =15 mm.

When the heat flow Q propagates through the rod, a temperature difference between the pair of thermometer is

$$\Delta T = Ql/\lambda s, \tag{1}$$

where λ is the thermal conductivity of the Ti-6Al4V alloy, 7.5 W/(m°C), and s is area of the cross section of the rod, 30×2 mm^2. Hence, the temperature difference of each pair of thermometer is a measure of the heat. The low conductivity λ of the alloy makes the ΔT signal high.

The principle of the BIHM can be simply expressed by the equivalent circuit as shown in Fig. 2 in analogy to the electric circuit. The carbon plate behaves as a thermal reservoir C like as a capacitance and the four rods behave as a thermal resistance R like as a resistor. The C and R can be calculated as,

$$C = cm = 133J/°C, \tag{2}$$

$$R = l/4\lambda s = 8.3°C/W, \tag{3}$$

where the c and m means specific heat and mass of the carbon plate, respectively. The heat flow Q and temperature difference ΔT can be regarded as current and voltage, respectively. The balance equation of the heat flow can be expressed as follow [4],

$$Q = C(d\Delta T/dt) + \Delta T/R. \tag{4}$$

Therefore the responce time τ is estimeted to be RC = 18 min.

This discussion is rather simple though, it helps to understand the principle of the measurement. Actually, the heat is also escaped by thermal radiation from the surfaces of the carbon plate due to its high emmissivity. Futhermore, the conductivity and specific heat depend on the temperature. To obtain the response time and the relation between the ΔT signals and heat loads, experimental investigations are required.

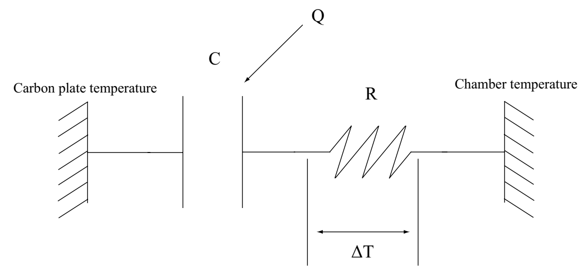

Figure 2: Equivalent circuit of the BIHM.

EXPERIMENTAL SETUP

To obtain the basic characteristics of this monitor, the preliminary experiments were carried out. During the experiments, inside the monitor chamber was kept in vacuum to cut heat convection to the air. The pressure was about 2.0×10^{-2} Pa.

The typical emissivity of the surfaces of blank flanges are 0.1 to 0.2, thus the reflectivity on the surfaces is 0.8 to 0.9. This means that the radiated waves from the carbon plate reflected on the flange surfaces and go back to the carbon plate. The reflected waves generate heat on the carbon plate again.

To reduce the reflectivity, the inner surfaces of the blank flanges are coated with fabric tape whose emissivity is typically 0.98 such that the almost all the radiated waves are absorbed in the flanges. This is an imaginary case of the actual situation, where the radiated waves are absorbed into the spaces upstream and downstream of the monitor.

To serve the heat on the carbon plate, we used ceramic heater. The dimension of the heater was 25×25 mm. The heater was set at the center of the plate. The current and voltage of the heater and temperature signals were monitored every second.

EXPERIMENTAL RESULTS AND DISCUSSIONS

We changed the heater setting stepwise at intervals of about 30 min. Fig. 3 shows the sum of each ΔT signals and the changes of heater setting. The response time was 7 min which is quite better than the expected value of 18 min.

During the experiment, the room temperature was kept at 18 °C within ± 2 °C. The signal increase by 0.3 °C at 0.5 hr is due to the sudden drop of the room temperature by 1.5 °C.

We assumed that the mean value measured at the time

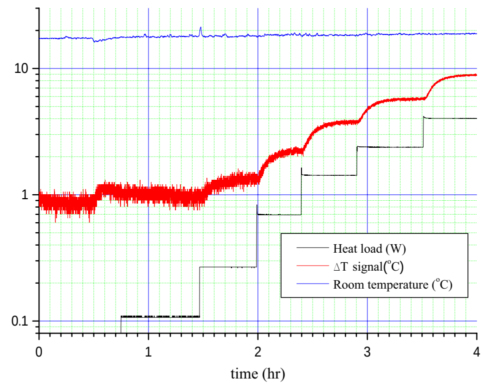

Figure 3: Responce of the sum of the four ΔT signals to the heat loads and room temperature.

over 20 min after changing the heater setting is an equilibrium value. Fig. 4 shows the sum of each equilibrium ΔT signals as a function of the heat load. The solid line is a fitting function. The data shows good linearity to the heat load. The obtained data suggests that the heat flow to the monitor chamber through the plate-support rods was about 5 % of the total heat load. It seems that the rest of it emitted by the thermal radiation.

The signal offset of about 0.9 °C is partly due to the offset of the thermometer itself. The tolerance of the class A Pt100 thermometer is ± 0.15 °C. This can reasonably explain the offset of about 0.4 °C out of the total offset. The rest may be caused by the fluctuation of the room temperature and the thermal radiation from the surroundings like illuminations.

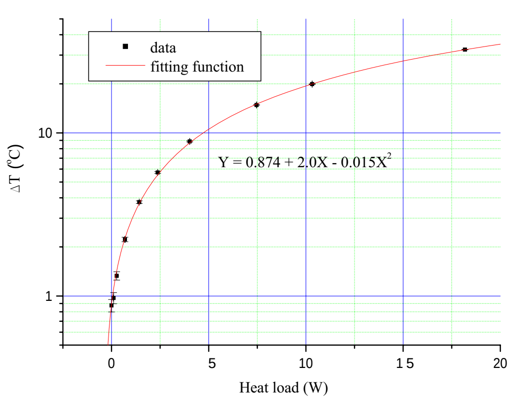

Figure 4: Sum of the equilibrium ΔT signals as a function of the heat load of the heater. The error bars are the standard deviation obtained from the data

SUMMARY

To monitor the dumped beam current of the J-PARC RCS, a calorimeter BIHM has been developed. To check the basic performances of the monitor, the experiments using a heater were carried out. The measured signals show the quite good response time of about 7 min and the good linearity to the heat load, although the only 5 % of the total heat propagated through the four plate-support rods to the monitor chamber.

These experimental results suggest that the monitor has the satisfactory fast response time, however it requires the calibration procedures using actual beams to transform into the beam current. Further theoretical and experimental investigations are needed to obtain reliable monitoring system using this BIHM.

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