Evaluation of Heat Flux from The Plasma Flow by using Calorimeter in The GAMMA 10/PDX end-cell

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Abstract. In this paper, detailed results of the heat flux measurements are presented and the improvement of heat flux evaluation method is also discussed. We measured the heat flux in the case that additional heating with electron cyclotron resonance heating (ECRH).The heat flux reaches about 17 MW/m^2 in the case with ECRH power 380kW. It is found that solving one-dimensional inverse heat conduction problems provides a possibility of improving time response of the heat flux measurement under the condition of changing heat flux in 20Hz.

INTRODUCTION

In the tandem mirror device GAMMA 10/PDX in University of Tsukuba, divertor simulation experiments were conducted for analyzing physical mechanism of detachment plasma [1-3]. The divertor simulation experimental module (D-module), in which a V-shaped target is mounted, was installed in the west end-cell of GAMMA 10/PDX. In the GAMMA 10/PDX, the heat flux measurements have been carried out by using calorimeters. Each calorimeter consists of a substrate which is connected to thermocouple. The heat flux is evaluated from temperature difference (ΔT) between before and after plasma discharge and the plasma duration time [4]. The heat flux was measured at two different locations in GAMMA 10/PDX end-cell. The first one, calorimeters are installed at the lower V-shaped target and its corner. There are 13 calorimeters which installed on the lower V-shaped target. The calorimeters on V-shaped target consist of stainless steel substrate (φ10mm, 0.2mm in thickness) which is connected to thermocouple (K type). The second one, other type of calorimeter is installed near the west end mirror. The calorimeter in this point consist of copper substrate. This calorimeter is measured the heat flux in the case that additional heating experiments. Short and high heat-flux is generated by additional heating with electron cyclotron resonance heating (ECRH). The heat flux of additional heating is evaluated from temperature increment during plasma discharge with ECRH and without ECRH. In the additional heating experiments, the dependence of the heat flux on the ECRH power was observed. In order to measure time dependence of heat flux, we are considering that improvement of time response of heat flux measurement.

EXPERIMENTAL SET UP

GAMMA 10/PDX and D-module

GAMMA 10/PDX is the largest tandem mirror devise in the world. The length of GAMMA 10/PDX is 27m, and vacuum vessel volume is 150m^3. The schematic view of GAMMA 10/PDX is shown in Fig 1. (a) GAMMA 10/PDX consists of a central-cell, two anchor-cells, two plug/barrier-cells and two end-cells. Plasma heating systems are composed of ion cyclotron range of frequencies (ICRF) waves, neutral beam injection (NBI) and electron cyclotron range of frequency (ECRH). The hydrogen plasma generated mainly in the central-cell flows toward the end –cells through other cells as end-loss plasma.

D-module is installed in the west end-sell of GAMMA 10/PDX. In the D-module, a V-shaped tungsten target plate is mounted such as Fig 1. (b) The angle of V-shaped target can be changed between 15 and 80 degrees. On the upper target plate, 13 Langmuir probes are installed to measure electron temperature and density. On the lower target plate, 13 calorimeters are installed to measure the heat flux onto the target plate surface. (Fig. 1 (c)).

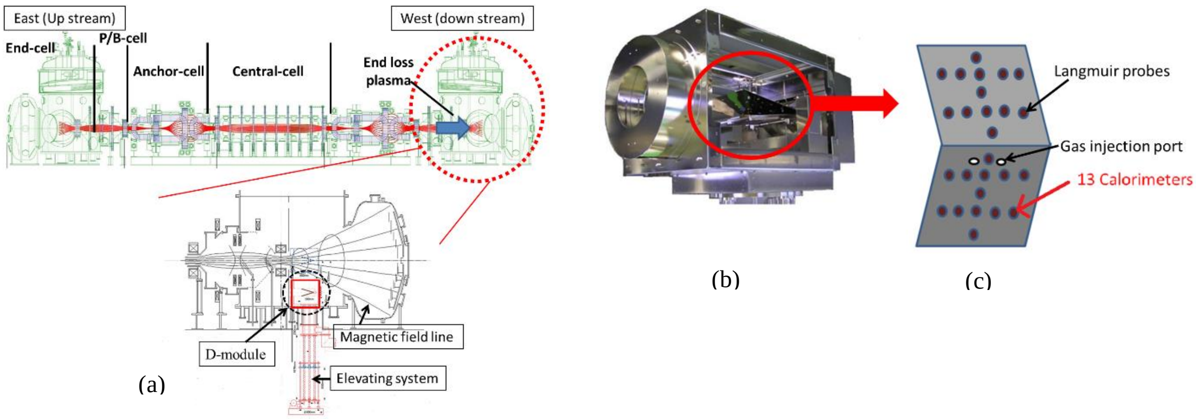

FIGURE 1. (a) GAMMA 10/PDX. (b) The picture of D-module. (c) Target plate.

Calorimeter

Calorimeter consists of stainless steel or copper substrate which is connected to thermocouple (Fig.2 (a),(b)). The heat flux is evaluated from temperature difference (ΔT [K]) of the substrate between before and after plasma discharge. ΔT is measured by thermocouple. Input amount of calorific value to the substrate (Q [J]) is

$$Q = mC\Delta T, \tag{1}$$

where m [kg] is the mass of the substrate and C [J/kg K] is the heat capacity. The heat flux is

$$P = Q/tS \ \times 10^{-6}\ [\mathrm{MW/m^2}], \tag{2}$$

where t [s] is the plasma discharge time, S [m^2] is the collection area of plasma. In the case with additional heating by using ECRH, heat flux is measured by using cupper substrate calorimeter (Fig.2 (b)). The heat flux of additional heating is evaluated from temperature increment during plasma discharge using two plasma shots with ECRH and without ECRH, respectively. The heat flux is determined to be

$$P = \frac{\{Q_{with\ ECH} - Q_{w/oECH}\} + \frac{\tau_{applying\ time}}{\tau_{w/oECH}} \times Q_{w/oECH}}{\tau_{applying\ time}}, \tag{3}$$

where $\tau_{applying\ time}$ [s] is applied ECRH time, $\tau_{w/oECH}$ [s] is the plasma discharge time without ECRH shot, $Q_{with\ ECH}$ [J] is input amount of calorific value to substrate with ECRH and $Q_{w/oECH}$ is input amount of calorific value to substrate without ECRH. In order to evaluate the heat flux by using these methods, substrate temperature should be steady-state.

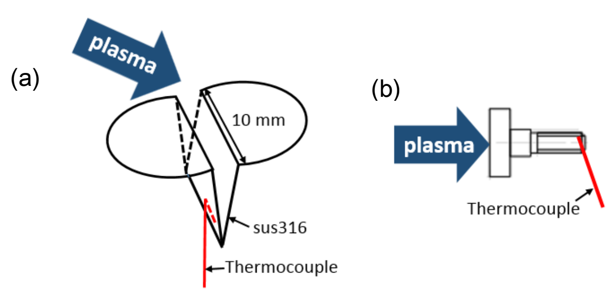

FIGURE 2. (a) The schematic of calorimeter in V-shaped target. (b) The schematic of calorimeter near the target.

EXPERIMENTAL RESULTS

Dependence of Additional Heating Time Length

In order to research heat flux dependence of the additional heating by ECRH time length, we measured temperature difference between plug ECRH heating with 2 pulses, 4 pulses and 6 pulses. Plug ECRH power was 230kW and the additional heating time length of 1 pulse is 5 ms. Figure 3 (a) shows the time behavior of substrate temperature each pulses. Figure 3 (b) shows the dependence of temperature increment of substrate on the length of the heating time. In Fig.3 (b), the temperature differences of substrate increases in proportion to the length of the additional heating by using ECRH. Input amount of the calorific value to the substrate is in proportion to the temperature differences. Therefore, the input amount of calorific value is in proportion to the length of additional heating time. This observation indicate that the heat flux can be evaluated even if the additional heating time length is changed.

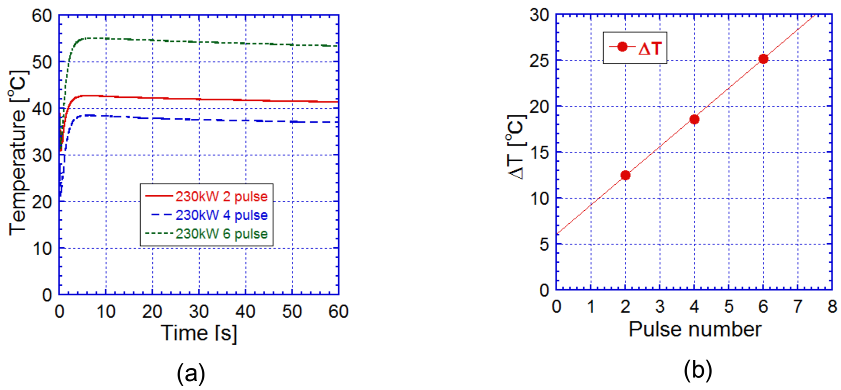

FIGURE 3. (a) Time dependence of substrate temperature. (b) Heating time length dependence of temperature increment.

Evaluation of Heat Flux in the Case with ECRH Additional Heating

Heat flux measurements have been carried out in the case with additional heating experiments by using ECRH. Figure 4 (a) shows the plug-ECRH power dependence of temperature differences obtained in 2015. In Fig.4 (a), in the case with the plug-ECRH power of 0 kW, temperature increments are obtained from only ICRF heated plasma. Figure 4 (b) shows the plug-ECRH power dependence of the heat flux during additional heating. The heat flux reaches about 17 MW/m^2 in the case with ECRH power 380 kW.

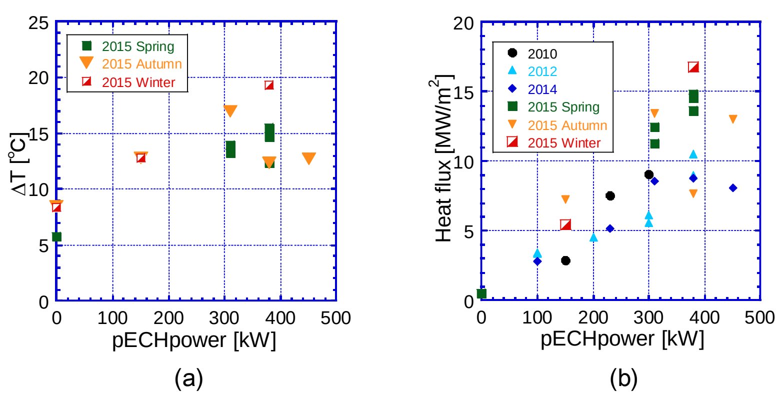

FIGURE 4. (a) Heating power dependence of temperature differences. (b) Heating power dependence of heat flux.

NUMERICAL EXAMINATION OF THE EVALUATION METHOD

In order to the improve time response of heat flux measurement, we are considering to introduce the evaluation method of heat flux by solving one-dimensional inverse heat conduction problems. [5] We can estimate surface temperature and heat flux by solving one-dimensional non-steady heat conduction equation by using Laplace transform. The surface heat flux is

$$\Phi_w = \sum_{j=-1}^{N} D_{j,21} \frac{(\tau - \tau_2^*)^{j/2}}{\Gamma\left(\frac{j}{2}+1\right)} - \sum_{j=-1}^{N} D_{j,12} \frac{(\tau - \tau_1^*)^{\frac{j}{2}}}{\Gamma\left(\frac{j}{2}+1\right)}, \qquad (4)$$

where τ is dimensionless time, $D_{j,12}$, $D_{j,21}$ are expansion coefficient. [5] In order to evaluate heat flux by using Eq. (4), we need two temperature measuring points in the substrate. (Fig.5 (a)) The solution of Eq. (4) diverge to infinity when $\tau = 0$. [5] As an example, we calculate heat flux in three cases (x_1 = 1 mm, x_2 =2 mm, x_1 = 0.75 mm, x_2 = 1.5 mm, x_1 = 0.5 mm, x_2 = 1 mm) and under the same value of input heat flux on the surface $F = F_0 \sin(2\pi \cdot 20 \cdot t)$ [5]. (Fig.5 (b), (c), (d)) Time response becomes better as measuring points become closer to surface, as show in Fig.5 (b) , (c) and (d). However, in the case of Fig. 5(d), the distance of the thermocouple from the surface (x_1) is too short to fabricate the calorimeter tip. Therefore, it is difficult to make the calorimeter that is able to measure the short pulse heat flux such as ECRH additional heating. However, the heat flux which changes smoothly is able to measure by using this method. In divertor simulation experiments, it is expected that the heat flux will change more smoothly than the present experiment. Therefore, there is a possibility to contribute for divertor simulation experiments.

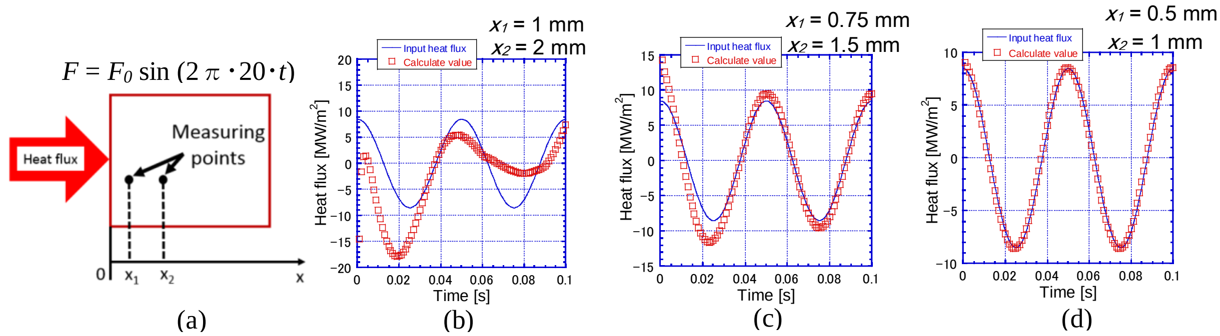

FIGURE 5. (a) The schematic view of calorimeter model. (b) Calculation result in the case with x_1 = 1 mm, x_2 = 2 mm. (c)Calculation result in the case with x_1= 0.75 mm, x_2 = 1.5 mm. (c) Calculation result in the case with x_1= 0.5 mm, x_2= 1 mm.

SUMMARY

We measured the heat flux in the case with additional heating by using ECRH. The heat flux increases in proportion to the length of additional heating, so the heat flux can be measured under the various heat pulse length. Heating power dependence of the heat flux was observed and the heat flux reaches about 17 MW/m^2 in the case with ECRH power 380 kW. It is found that improvement of time response of the heat flux measurement can be expected under the condition of the heat flux that changes in 20Hz by solving one-dimensional inverse heat conduction problems. In the future work, in order to evaluate the time response of the method, we will try to calculate the stepwise heat flux.

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