Proceedings of ITC18, 2008

Measurement of divertor heat flux in helical-axis Heliotron-J device using a thermal probe

Hiroto MATSUURA[1)], Ken NAKANO[1)], Katsuyuki HOSAKA[2)], Kenichi NAGAOKA[3)], Takashi MUTOH[3)], Hiroyuki OKADA[4)], Shinji Kobayashi[4)], Tohru MIZUUCHI[4)], Katsumi KONDO[3)], and Fumimichi SANO[4)]

[1)]*Graduate School of Engineering, Osaka Prefecture University, Osaka 599-8531, Japan*
[2)]*Graduate School of Energy Science, Kyoto University, Uji 611-0011, Japan*
[3)]*National Institute for Fusion Science, Gifu 509-5292, Japan*
[4)]*Institute of Advanced Energy, Kyoto University, Uji 611-0011, Japan*

Direct measurement of divertor heat flux is an important task. But heat flux calibration is often difficult since heat diffusion in sensors is slower process than discharge duration time of present experiments. In this paper, using unsteady heat conduction model, heat flux in Heliotron J edge plasma is firstly measured. Obtained heat flux value, although it is time averaged, does not contradict edge plasma parameters.

Keywords: Thermal probe, divertor, Heliotron-J, Heat flux, Heat conduction

1 Introduction

It is well known that there exist the sheath regions between plasmas and solid components which face to plasmas and that current through these sheath is determined by the sheath potential drop. According to sheath theory, momentum and heat flux through the sheath is also the function of the sheath potential drop. Recently Combined force-Mach- Langmuir probe[1] and thermal probe[2, 3] were proposed to measure these flux and to obtain not only electron parameters but also ion information such as its temperature. Recently, the first result on ion temperature measurement with thermal probe is reported in [4], but importance of energy reflection coefficient on thermal probe measurement is pointed [5].

It is also very important to measure the heat flux itself in divertor plasma. In the design of fusion reactors like International Tokamak Experimental Reactor(ITER), vast heat flux(> 10[MW/m^2]) is expected to flow onto divertor target plate through this sheath boundary. In order to check proposed methods to reduce this heat load such as "detached plasma formation", direct measurement of heat flux is indispensable, since relation between heat flux and plasma parameter is very complicated. Moreover ion temperature contribution could not be ignored as usual text books, since ion temperature is larger than electron temperature in divertor plasma [6] . So development of direct measurement tools for divertor heat flux would be an important task.

In this paper, first results of heat flux measurement for Heliotron J edge plasma are given. In section 2, an experimental setup is described. In section 3, unsteady heat conduction model is applied for thermal probe data in Heliotron J. Some results are shown in Sec.4.

author's e-mail: matsu@me.osakafu-u.ac.jp

2 Experimental Setup

Heliotron J is a medium sized helical axis Heliotron device with a helical winding coil of $L = 1/M = 4$. The details of Heliotron J are described in Refs. [8] and [9]. Last year the Hybrid Directional Probe (HDP) used in Compact Helical System [7] were moved to Heliotron-J device under Collaboration with NIFS. HDP is composed of 1 magnetic probe sensor(Pin 6) and 7 Langmuir probe tips(Pin 1-5, 7-8), 5 tips of which are equipped with type-K thermocouples(TC) and available also as thermal probes. In this paper, data of Pin 3 and 4 are mostly used. These pins are made of oxygen-free-cupper and the diameter and length are 4.5 and 11[mm] respectively.

HDP has a driving system of three parameters (R_p, θ_p, α_p) and positions of its pins and can be changed shot by shot. R_p is the HDP probe head shift along the major radius direction in mm unit. θ_p is the swing angle in degree unit along the poloidal direction, although in this paper data only for $\theta_p = 0$ are used. α_p is the rotation angle in degree unit around the axis of cylindrical HDP head. Due to the mechanical limitation, only half rotation data are available. α_p can be scan $-110 \sim 10$ and difference of initial position of Pin3 and Pin4 is 60.

HDP is installed to port 7.5 cross section of Heliotron J and so called X-point can be studied. Figure 1 shows outer part of port 7.5 section (Toroidal angle is 163[deg.]) and magnetic surface in standard configuration. Horizontal solid line at $Z = 0.271$[m] is the trajectory of HDP head axis for $\theta_p = 0$. When $R_p \sim 135$, the top of HDP head reaches the Last Closed Flux Surface(LCFS). Two symbols (cross and dagger) in this figure are the position of Pin3

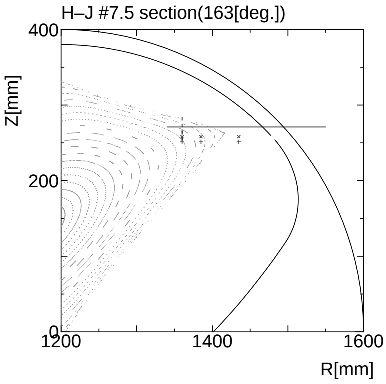

Fig. 1 Probe pins position of the Hybrid Directional Probe (HDP) on port 7.5 cross section. HDP head moves along horizontal solid line at $Z = 0.271$[m] with setting parameter R_p. Probe pins move along vertical dashed line at $R = 1.36$[m] with α_p.

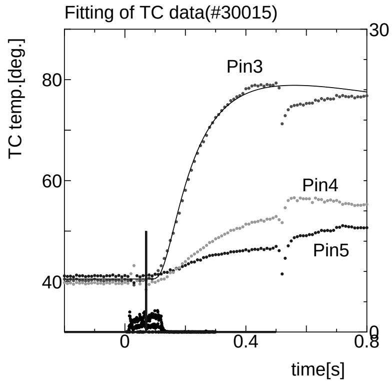

Fig. 2 Example of TC data and fitting result for the HDP. The position of Pins are $R = 1.36$[m](Pin3 and 4), 1.38[m](Pin5), and $Z = 0.25$[m](Pin3 and 5), 0.26[m](Pin4). Solid line fitting Pin3 data is obtained by eq.(1) with $x_{tc} \sim 1.07 \times 10^{-2}$[m] and $q\Delta t \sim 2.9$[J/mm^2].

and Pin4 for $R_p = 210, 185$, and 135. Small vertical dashed line at $R = 1.36$[m] shows the movement of Pin3 and Pin4 with α_p scanning at $R_p = 210$.

3 Heat conduction model

Basic concept of thermal probe is very simple. From the probe tip temperature (T_p) data, heat flux to probe surface Q can be deduced by solving heat conduction problem. For DC discharge plasma, we can use the simple steady relation such that $Q \sim \Delta T_p$. However, heat flux calibration of thermal probes of HDP has not yet completed, mainly since discharge pulse length ($\Delta t \sim 0.1$[s]) is shorter than thermal diffusion time in a probe tip (about 1[s]) and steady state heat conduction model is not available. Figure 2 shows the example of thermocouple data measured at $(R_p, \theta_p, \alpha_p) = (210, 0, 0)$ for NBI plasma. Temperature increases almost after main discharge terminates and reaches maximum value about at $t = 0.5$[s]. After that TC signal show the abnormal jump, which is thought to be due to helical coil current noise.

As the first step, we used a very simple model to analysis heat conduction in probe pins. A probe pin is treated as semi-infinite plane and plasma heat flux is treated as Delta-function type short pulse. Then temperature in a probe pin is the function of time t and distance from the pin surface x and given as

$$\begin{aligned} \Delta T &= T(x,t) - T_\infty \\ &= \frac{q\Delta t}{k}\sqrt{\frac{a}{\pi(t-t_0)}}\exp(-\frac{x^2}{4a(t-t_0)}) \qquad (1) \end{aligned}$$

where k is heat conductivity, a is thermal diffusivity, q is the averaged heat flux density, T_∞ is initial temperature, and t_0 is the time when heat pulse reaches the pin surface, which is indicated as a vertical line at $t = 0.07$[s] in Fig. 2.

For fixed x, temperature response to the heat pulse shows a peak at $t = \frac{x^2}{2a}$. If temperature increment becomes maximum ($\Delta T = \Delta T_{max}$) at $t = t_{max}$, TC sensor is expected to locate at $x_{tc} = \sqrt{2a(t_{max} - t_0)}$. From the Pin3 data in Fig. 2, $x_{tc} \sim 1.07 \times 10^{-2}$[m]. And total heat that the probe pin receives ($q\Delta t$) can be estimated by

$$k\Delta T_{max} = q\Delta t\sqrt{\frac{a}{\pi(t_{max}-t_0)}}\exp(-\frac{1}{2}) \qquad (2)$$

If $q\Delta t \sim 2.9$[J/mm^2] is assumed, eq.(1) well reproduces time evolution of Pin3 data in Fig. 2.

It must be noted that x_{tc} is not exactly corresponding to real position of TC connection point. Type-K TC used in HDP has the sheath material around connection point and it works as heat resistance and $t_{max} - t_0$ may become longer than that expected from real TC position.

By using $\Delta t = 0.1$[s], Pin3 is estimated to receive heat flux of about 400[W] in main discharge. On the other hand, ion saturation current measured with the same pin was $\sim$ 100[mA] near LCFS. Although no electron temperature data is obtained by this probe pin, estimated heat flux is the same order as $\gamma T_e I_{is}$, if $T_e = 100$[eV] and heat transmission factor γ of order of 10 are assumed.

According to eq.(1), if TC position can be moved toward probe surface or TC sheath is removed, then x_{tc} would become smaller, TC signal response would be improved, and real time monitoring of heat flux might be possible. To study this improvement more precisely, the second improved model for probe pin heat conduction is now developing.

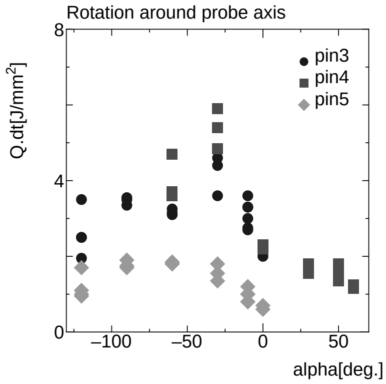

Fig. 3 Heat flux profile around HDP head. Holizontal axis is angle around HDP(α) and vertical axis is the heat received during whole discharge ($q\Delta t$). For rotation angle $\alpha_p = 0$, Pin3 (and Pin5) is at $\alpha = -10$[deg.] and Pin 4 is at $\alpha = 50$[deg.].

4 Heat flux just inside LCFS

Figure 3 shows heat flux profile around the HDP head. Holizontal axis is angle around HDP(α) and vertical axis is the heat received during whole discharge ($q\Delta t$). R_p(= 210) and θ_p(= 0) are fixed and α_p is scanned. Pin3 (and Pin5) covers $\alpha = -120 \sim 0$[deg.] and Pin4 covers $\alpha = -60 \sim 60$[deg.]. As shown in Fig. 1, probe pins reach LCFS at $\alpha = -120$[deg.](mechanical limit) and they go most deeply into main plasma at $\alpha = 0$[deg.]. So if the gradient of plasma parameter(density, temperature, potential etc.) is significant, heat flux would show the maximum at $\alpha = 0$[deg.] and the minimum at $\alpha = -120$[deg.]. But although data is limited and shows scattering, the maximum heat flux is found around $\alpha = -50$[deg.]. Similar profiles have been obtained for ion saturation current. So most probable explanation for these profiles is the existence of plasma flow, which directs toward $\alpha = -50$[deg.] or $\alpha = 130$[deg.]. If this hypothesis is true, angular profile must has periodicity of 180[deg.]. Unfortunately, present heat flux data does not confirm the clear minimum value around $\alpha = 40$[deg.]. Farther measurement will be necessary.

Figure 4 shows the change of heat flux with plasma heating power.(In this case, only ECH was used as the plasma heating device.) Data symbols is the same as Fig. 3 (Pin3: circles, Pin4: squares, Pin5: diamonds). R_p and θ_p are also same as Fig. 3 and α_p is kept to be 0, which means that rotation angle of Pin3 (and Pin5) is $\alpha = -10$[deg.] and that Pin 4 is $\alpha = 50$[deg.]. As increasing plasma heating power, estimated heat flux for each pins also increases. But data scattering is rather large, since keeping line-averaged density nearly constant for different ECH heating power is difficult. For high power ECH, strong gas puffing is necessary to overcome the so-called density clamping. When

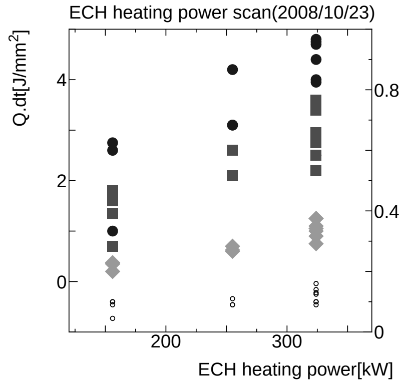

Fig. 4 ECH power scan effect on heat flux. Data symbols is the same as Fig. 3. Small open circles are also plotted for diamag monitor value(right axis with arbitrary unit).

ECH power is reduced, extra gas puffing sometimes terminates main discharge. One example is given in Fig. 5. ECH power of shot number 32435 and 32436 is the same (about 156[kW]). But discharge of #32435 terminates during ECH heating pulse and discharge time is only 40% of #32436, while stored energy is almost the same around $t = 200$[ms].

The $q\Delta t$ data for #32435 in Fig. 4 is also much smaller than #32436. For Pin3, $q\Delta t$ is about 1.0[J/mm^2](#32435) and 2.6[J/mm^2](#32435). If real discharge time, not ECH heating pulse length, is used as Δt, averaged heat flux is nearly equal for these two shots. So, in order to study the relation of heating power and heat flux measured with thermal probe method and present heat conduction model, knowledge on real discharge time would be necessary. On the other hand, although preset method of measuring heat flux can not obtain time variation of it, it could be used as monitoring tool to watch shot reproductivity as likely as ion saturation current. If probe position or bias voltage is kept the same and TC signal (or estimated heat flux) after a shot changes, we can see something wrong has happened in the shot.

5 Summary

Obtained results in this paper are summarized like the following.

- Heat conduction models to calibrate heat flux detected with HDP are constructed.
- Using TC evolution data, averaged heat flux in Heliotron J edge plasma is firstly estimated, which does not contradict with the value calculated from probe current data with most simple sheath theory.
- By rotating HDP around its axis, heat flux angular profile is measured. Obtained profile indicates the existence of some kind of plasma flow.

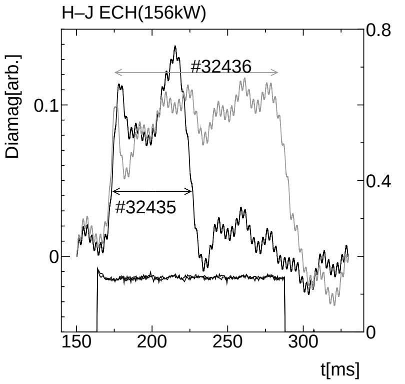

Fig. 5 Diamag monitor signal for two successive shot with the same ECH power and slightly different gas puffing control.

- As increasing plasma heating power, estimated heat flux also seems to increase. But knowledge on real discharge time is necessary to estimate heat flux exactly.

In order to monitor heat flux during main plasma discharge, improvement of TC response is necessary. One method is to reduce heat resistance between TC and probe pins by removing TC sheath material. Another is to move connecting points of TC toward pin surface where plasma irradiation occurs. Design and construction of new thermal probe with considering these improvements are left for the future work.

Acknowledgements

The authors are grateful to the Heliotron J supporting group for their excellent arrangement of experiments. One of Authors (H.M.) acknowledges Prof. Y.Nakamura and Dr. S.Yamamoto of Kyoto University for their advice on Heliotron J magnetic configuration and data acquisition system. This work is partially performed with the support and under the auspices of the NIFS Collaborative Research Program(NIFS08KUHL021).

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