Measurements of the Plasma Parameters in the D-Module of GAMMA 10/PDX during Impurity Gas Kr Injection*)

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This paper investigates the impact of Krypton (Kr) seeding on plasma parameters in the D-module of GAMMA 10/PDX experimentally based on the calorimeter, Langmuir probe and high-speed camera measurements. The heat flux distribution along the V-shaped target plate reduces with the increasing Kr injection. The time behavior of ion flux shows that it decreases with the increase of Kr seeding. The electron temperature (T_e) reduces significantly due to Kr seeding into the D-module. The electron density shows a so-called roll-over phenomenon during Kr seeding. The heat and ion fluxes reduce with the increasing Kr seeding into the D-module. Two-dimensional images captured by the high-speed camera also show that the emission intensity significantly reduces inside the V-shaped target at the higher Kr injection. These outcomes represent the impact of Kr seeding for generating the detached plasma.

Keywords: GAMMA 10/PDX, D-module, Kr injection, heat and ion fluxes, plasma detachment

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1. Introduction

The reduction of enormous heat-load onto the divertor plates becomes an inevitable research issue to clarify the physical mechanism of plasma detachment. The plasma detachment state is considered to be the most efficient and promising way to solve the enormous heat-load handling issue of the future nuclear fusion machines such as ITER and DEMO [1–4]. The plasma detachment state can be achieved through many molecular and atomic processes such as impurity radiation, electron impact ionization, excitation, volumetric recombination, charge-exchange [4,5]. The physics of divertor plasma detachment is not yet eclearly understood so far. Hence, it is necessary to explore the detailed physical processes corresponding to the plasma detachment. Because of this, the divertor research has been effectively performed in the world experimentally and by computer simulations [2–8]. The recycling has an impact reducing the plasma energy. However, the recycling flux may not be able to achieve the plasma detachment state. The neutral puffing (hydrogen and/or impurity) into the divertor region has been considered to be the most efficient way to form and sustain the detachment state. The radiation cooling effects of the radiator gas have the potential to reduce the electron energy significantly. Thus, the study of impurity seeding into the divertor region becomes an urgent research subject. The engineering structure of the tokamak fusion devices is complex and consequently, it is to difficult to measure plasma parameters precisely near the divertor target plates. On the other hand, the linear plasma devices have a simple magnetic field configuration comparing to the tokamak devices and flexibility for detailed measurements. The linear plasma fusion devices contribute significantly to clarify the physical mechanism of plasma detachment. The divertor simulation research has been effectively performed by using the linear devices such as GAMMA 10/PDX, NAGDIS-II, Pilot-PSI, and MAGNUM-PSI [5].

The GAMMA 10/PDX is one of the most effective linear plasma confinement devices, which significantly contributes to understand the divertor plasma physics [9–12]. The typical Ion Cyclotron Range of Frequency (ICRF) heated plasma parameters in the central-cell of the device are: $T_{i\|}\sim 500\,\mathrm{eV}$, $T_{i\perp}\sim 10\,\mathrm{keV}$, $n_e \sim 2 \times 10^{18}\,\mathrm{m}^{-3}$ and $T_e\sim 50\,\mathrm{eV}$ [9–11]. A divertor module (so-called D-module) has been recently placed at the west end-cell of the GAMMA 10/PDX to investigate the impact of neutral gas seeding on the plasma detachment [10–12].

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Kr gas has been seeded into the divertor region of a few tokamak devices to investigate the radiation cooling effects of Kr [3]. However, the detailed physical mechanism has not been clarified yet. The simple geometry of the GAMMA 10/PDX can help us to clarify the impact of Kr injection on the reduction of the heat and ion fluxes. Therefore, Kr gas has been newly seeded into the D-module of GAMMA 10/PDX. The aim of the paper is to investigate the effects of Kr seeding into the D-module of GAMMA 10/PDX experimentally based on the calorimeter and Langmuir probe measurements.

2. Experimental Apparatus

The schematic view of the west plug/barrier-cell to end-cell of the GAMMA 10/PDX is shown in Fig. 1 (a). A module (D-module) has been installed at the west end-cell as shown in Fig. 1 (a). The module is moved up and down to perform both the mirror experiments as well as divertor simulation experiments. Figure 1 (b) represents the schematic view of the D-module and V-shaped target. As shown in the figure, a tungsten V-shape target plate has been designed inside the module. The angle of the target plate can be changed according to the experimental purpose. In the experiment, the angle of the two plates was adjusted at 45 degrees. Calorimeters and Langmuir probes are installed on the V-shape target to measure the plasma parameters during plasma-neutral interactions. The distribution of the heat flux, electron density, electron temperature and particle flux along the V-shape target plate is investigated based on the calorimeters and probes data. Kr gas was injected into the D-module through the gas line #3 (both front and back side of the lower target plate). Kr gas was injected into the D-module 0.8 s earlier than that of discharge because of low conductance of the gas line. Kr gas injection was carried out under the plenum pressure of 100 mbar to 500 mbar. It is speculated that the real gas pressure in the module is about 0.1 to few Pa. In the future, neutral pressure in the module will be evaluated by the ASDEX-gauge [11]. In this paper, Kr gas plenum pressure indicates the pressure of the gas reservoir tank.

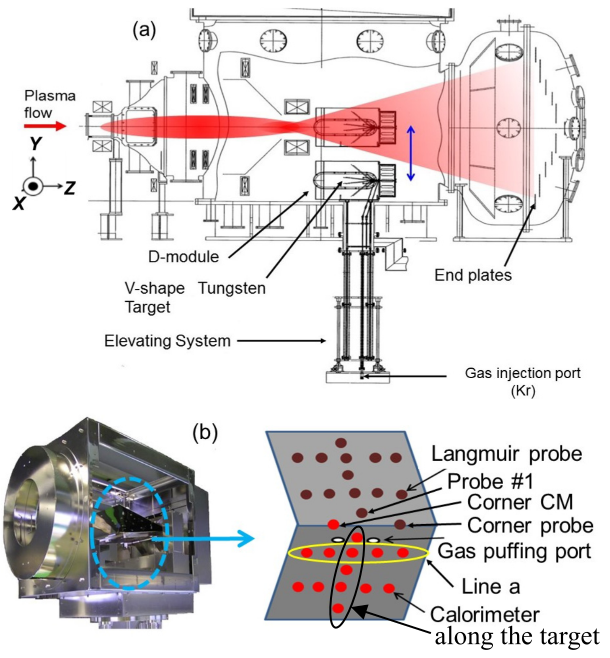

Fig. 1 Schematic view of the (a) GAMMA 10/PDX west plug/barrier-cell to end-cell, (b) D-module.

3. Results and Discussion

The plasma parameters in the central-cell have been investigated by the Thomson scattering and microwave interferometer. The time behavior of the electron line density in the central-cell (NL_{CC}) is shown in Fig. 2 (a). The electron line density slightly increases due to Kr injection into the D-module. It is also shown that the electron line density remains almost constant with the increasing impurity injection, which strongly indicates that the upstream plasma parameters are not significantly affected due to the impurity injection at the end-cell. The electron line density at the west anchor-cell (NL_{WA}) is also investigated. The anchor-cell is close to the central-cell [9, 10]. As shown in Fig. 2 (b), the electron line density at the west anchor-cell also slightly increases during Kr injection. In this case also, the electron line density remains almost stable for Kr injection into the D-module. The time behavior of the diamagnetism at the central-cell is shown in Fig. 2 (a). The diamagnetism (DM_{CC}) is the plasma stored energy and it depends on the perpendicular ion temperature and plasma density. The plasma density slightly increases due to Kr injection. On the other hand, the DMcc slightly reduces during Kr injection. The reason for reducing the DMcc

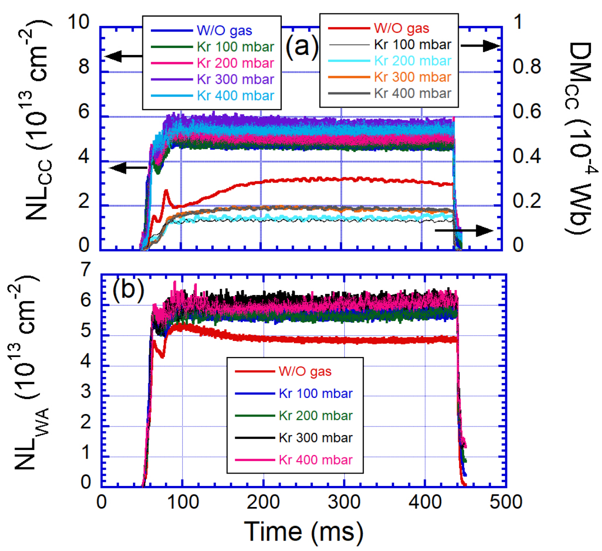

Fig. 2 Time behavior of the (a) electron line density and diamagnetism at the central-cell, (b) electron line density at the west anchor-cell.

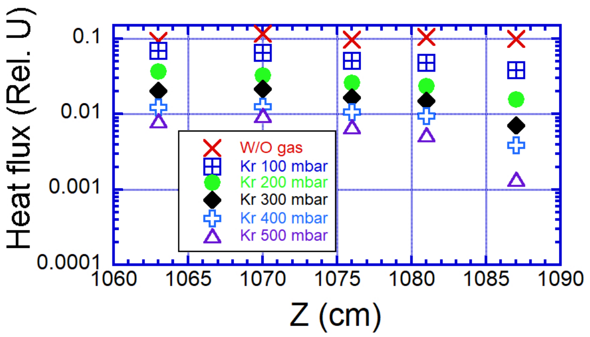

Fig. 3 Dependence of heat flux along the target plate.

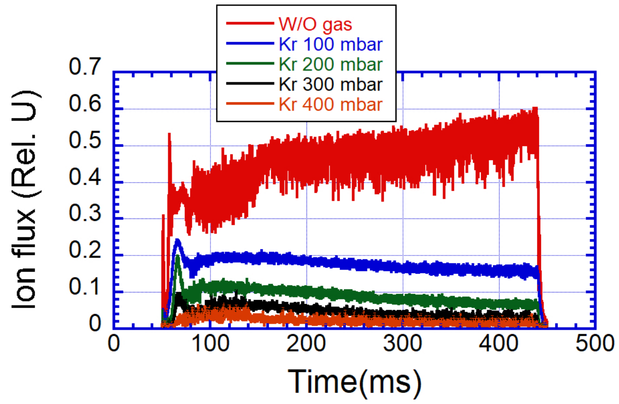

Fig. 4 Time behavior of ion flux measured by the corner probe.

has not yet fully understood. The effect of impurity seeding may reduce the plasma ion temperature. Furthermore, the heating efficiency of the ICRF waves also changes with the increase of plasma density. However, the DM_{CC} was not remarkably affected with the increase of Kr injection. These outcomes clearly represent that the influence of Kr injection on the upstream plasma parameters seems to be small.

The distribution of the heat flux along the V-shape target is shown in Fig. 3 (a). These calorimeters are located on different magnetic field along the Z-axis of GAMMA 10/PDX. The position of these calorimeters is estimated according to the Z-axial distance from the central-cell of GAMMA 10/PDX. More detailed description of the calorimeter arrangements on the V-shape target is explained in the Ref. [13]. The measured heat flux is almost same for the all calorimetric measuring positions in the case without gas injection. However, the distribution profile has been changed during Kr injection. For only Kr 100 mbar injection, the heat flux decreases for all measuring positions along the target plate. Furthermore, the heat flux decreases monotonically with the increasing Kr plenum pressure. For Kr 500 mbar injection, the heat flux decreases significantly. These outcomes represent the impact of Kr injection for reducing the heat flux on the target plate. The heat flux depends on the ion and electron density, temperature and velocity. In GAMMA 10/PDX, the heat flux is dominated by the ion contribution because of high ion temperature. Although the ion temperature has not yet measured in the D-module, a reduction in the heat flux indicates the reduction in the ion temperature. The electron temperature was measured by the Langmuir probe and plotted in Fig. 5 (a). It is shown that the electron temperature reduces drastically during Kr injection. These results indicate that Kr gas injection into the divertor region reduces both the electron and ion temperatures. Bolometric measurement and Ion sensitive probe measurement are very much important to clarify the energy loss processes in GAMMA 10/PDX.

The time behavior of the ion flux measured by the corner probe is shown in Fig. 4. The ion flux slightly increases with time during without gas injection. However, the ion flux reduces gradually with the increasing Kr injection into the D-module. These outcomes also indicate the impact of Kr injection for reducing the ion flux on the target plate. The ion flux on the target plate can be written by the following formula,

$$\Gamma_{\text{target}} = \Gamma_{\text{upstream}} + \Gamma_{\text{source}} - \Gamma_{\text{sink}}. \quad (1)$$

The ion flux depends on the source and sink terms in the divertor regions. Thus, the ion flux can be decreased by the following channels

(i) Decrease in the upstream plasma flux and source terms such as ionization.

(ii) Increase in the sink terms such as momentum loss, recombination, charge-exchange, impurity radiation loss.

As shown in Fig. 2, the upstream plasma parameters did not change significantly due to Kr injection, but the downstream plasma parameters change remarkably. It seems that Kr injection increases significantly the electron power loss channels by increasing the radiation power loss. The ionization effects of Kr particles also play a key role to reduce the electron temperature. The ion-neutral reactions such as charge-exchange also significantly contribute to drop the ion flux on the target plate. The recombination processes (MAR and EIR) become active at the lower electron temperature [5]. Reduction in the ion flux indicates that the energy loss processes significantly boost up with the increasing Kr injection into the D-module.

The dependence of the plasma parameters as a function of the Kr plenum pressure is shown in Fig. 5. As given in Fig. 5 (a), the electron temperature is found to be around 25 eV in the case without any gas injection. On the contrary, the electron temperature reduces drastically when Kr is introduced into the D-module. For Kr injection under the plenum pressure of 100 mbar, the electron temperature drops from about 25 eV to 3 eV. Furthermore, the electron temperature slightly reduces with the increasing Kr injection. The electron temperature reduces to about ∼1.2 eV in the case Kr 500 mbar injection. These outcomes represent the radiation cooling effect of the Kr particles, which

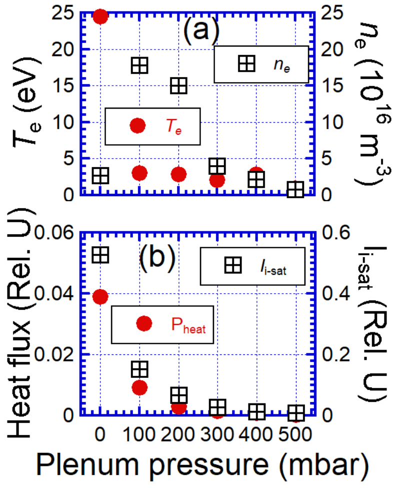

Fig. 5 Dependence of (a) electron density and temperature (measured by probe#1), (b) heat and ion fluxes (corner probe and CM) as a function of the Kr plenum pressure.

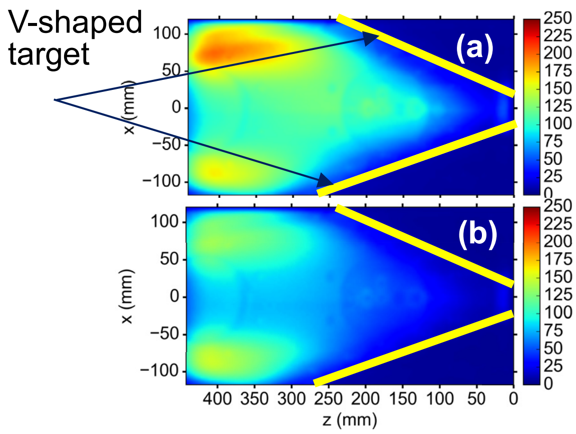

Fig. 6 2D images of visible emission during (a) Kr 100 mbar, (b) Kr 400 mbar injection (without filter, 350 - 380 ms).

reduces the electron temperature remarkably.

A dependence of electron density on the Kr plenum pressure is also plotted in Fig. 5 (a). It is shown that the electron density increases at the lower Kr injection (~100 mbar) and then it reduces with the increasing Kr injection. Kr injection leads to a remarkable reduction in the electron temperature, which stops the ionization of neutral particles. The recombination processes begin to dominate with the reducing electron temperature. Hence, the electron density reduces the at the higher Kr injection. The electron density shows a so-called roll-over phenomenon, which is one of the most important symptoms of the plasma detachment.

The dependence of the heat flux on the Kr plenum pressure is plotted in Fig. 5 (b). It is shown that the heat flux reduces monotonically with the increasing Kr injection. The ion flux also reduces monotonically with the increment of Kr injection as shown in Fig. 5 (b). These outcomes clearly represent the importance of Kr gas as a divertor radiator gas for generating the detached plasma.

The typical 2D images of the visible emission (without any filter) were taken by high-speed camera in front of the V-shape target are shown in Fig. 6. A fast camera has been installed on the horizontal port aimed to capture the visible emission of plasma and neutral particles. It is shown that the emission intensity significantly decreases with the increasing Kr plenum pressure. As shown in Fig. 6 (b), the emission intensity decreases significantly near the corner of the V-shaped target, which strongly represents the formation of a detached plasma by Kr puffing.

4. Summary

In the paper, the impact of Kr injection into the D-module of GAMMA 10/PDX has been investigated experimentally by using the end-loss flux of GAMMA 10/PDX. The plasma parameters in the D-module have been investigated based on the calorimeter and Langmuir probes measurements. It is found that the heat flux and ion flux reduce remarkably due to the Kr injection. The electron temperature also reduces significantly during Kr injection. The electron density shows a so-called roll-over phenomenon for Kr injection. The plasma parameters in the D-module show a strong dependence on the Kr gas plenum pressure. The heat and ion fluxes also decrease with the increasing Kr plenum pressure. These results clearly represent the impact of Kr injection for reducing the plasma energy and generating the plasma detachment state.

The reported phenomenology will be explained numerically by using the multi-fluid code "LINDA" [14–16].

Acknowledgments

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