Electron Temperature and Density Distributions of Detached Plasma in Divertor Simulation Experiments in GAMMA 10/PDX

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Abstract. Spatial characterization of plasma detachment attributed to molecular activated recombination (MAR) has been done by measuring distributions of electron temperature, electron density, space potential and floating potential of divertor simulation plasma in GAMMA 10/PDX tandem mirror with Langmuir probes. As the hydrogen pressure in the divertor simulation experimental module was increased by supplying additional hydrogen gas, the electron temperature near the target decreased from 30 eV to about 2 eV and the electron density first increased to an order of nearly 10^{17} m^{-3}, and then decreased in contrast to the density measured at the upstream of the target which became saturated. The density decrement was higher near the corner of the V-shaped target although temperature distribution was almost flat near the target. In addition, space potential decreased, floating potential increased, and then the potential difference between those became small. The potential difference decreased to almost zero near the target. In a direction crossing a plasma column along the target, electron temperature decreased with increase in the pressure, keeping its distribution almost flat.

INTRODUCTION

In future fusion devices such as ITER and DEMO, plasma discharges with detached divertor are scheduled in order to reduce heat and particle loads onto divertor plates [1,2]. To achieve this successfully, establishing the way to control and sustain detached plasmas is needed. In a viewpoint of balancing competing two regions of low temperature detached divertor plasma with high neutral density and high temperature burning core plasma, better understanding of spatial characteristics of detached plasmas is important. So far, detached plasmas contributed by electron-ion recombination (EIR) or molecular activated recombination (MAR) have been observed in torus devices [1, 3] and linear devices [4, 5]. Rate coefficient of MAR is higher than that of EIR at electron temperature around a few eV [6].

In GAMMA 10/PDX tandem mirror, divertor simulation experiments have been carried out by using end-loss plasma in order to reveal physical characteristics of plasma detachment and detached plasmas have been observed in the case of additional gas supply to divertor simulation plasma (i.e. plasma inside the divertor simulation experimental module (D-module) which is installed in the west end region of GAMMA 10/PDX) [7]. When the plasma was detached, electron density distribution along a magnetic field line measured by Langmuir probes indicated density roll-over [8] which is one of the characteristics of detached plasma [9]. Recently it was confirmed that those detached plasmas especially in the case of additional hydrogen gas supply were mainly caused by MAR [10]. In this study, we aim to characterize spatial distribution of the detached plasma in GAMMA 10/PDX. Additional hydrogen gas was supplied to divertor simulation plasma and distributions of electron temperature (T_e), electron density (n_e), space potential (V_s) and floating potential (V_f) were measured by Langmuir probes.

EXPERIMENTAL SETUPS

GAMMA 10/PDX is a tandem mirror device, which is composed of a central cell, anchor cells, barrier cells, plug cells and end regions. The length of the device is 27 m and the volume of the vacuum vessel is 150 m^3. In the west end region, the D-module is installed.

Figure 1a) shows a schematic view of the D-module. It consists of a stainless-steel cuboid chamber with an inlet hole and a V-shaped target. The size of the chamber is 500 mm x 700 mm x 480 mm and the shape of the inlet hole is circular with the diameter of 160 mm for the top and bottom and its width is cut down to 120mm by a tungsten limiter. The size of each side of the V-shaped target is 300 mm x 350 mm. Tungsten plates with the thickness of 0.2 mm are attached on a target base. The open angle of the V-shaped target was 45 degrees in this study. Thirteen Langmuir probes are installed on the upper target as shown in Fig.1b) and two probes are installed near the inlet of the D-module as shown in Fig.1a). Pipes of additional hydrogen gas supply are installed near the inlet and are connected to a small gas tank via a piezoelectric valve. The amount of the supplied gas can be controlled by changing the plenum pressure (i.e. pressure in the tank), as well as timing and duration concerning the opening of piezoelectric valve. The neutral pressure inside the D-module is measured by an ASDEX gauge which is mounted at the top side of the D-module.

The plasma which goes out from mirror confinement regions (i.e. end-loss plasma) flows into the D-module. The V-shaped target is exposed to the end-loss plasma.

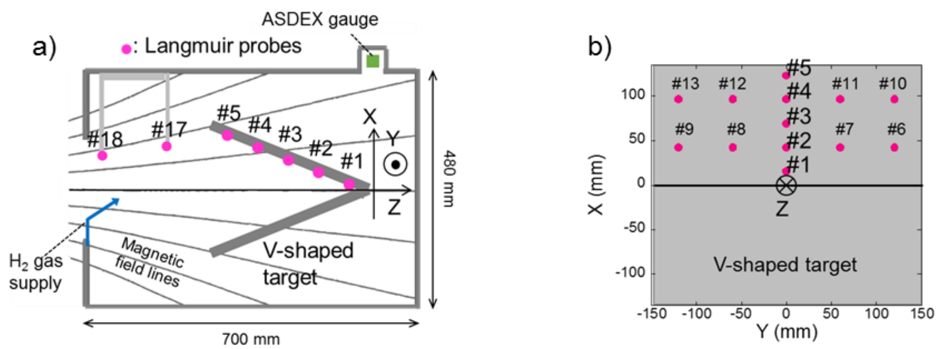

FIGURE 1. a) Schematic view of the D-module and b) array of Langmuir probes on the upper side of the V-shaped target. Probes are numbered as shown.

EXPERIMENTAL RESULTS AND DISCUSSIONS

In this experiment, plasma was sustained for 400 ms. The additional hydrogen gas supply into the D-module started about 450 ms before the plasma generation and continued for 750 ms, where the plenum pressure was varied shot by shot. Figure 2a) shows the time evolutions of hydrogen pressure (P_n) in the D-module measured by ASDEX gauge with respect to each plenum pressure. The plasma generation was started from t = 50 ms. As an example, Fig. 2b) shows the time evolutions of P_n, electron line density in the upstream cell of the west end region (west plug cell) and electron temperature and density measured by probe #1 installed near the corner of the V-shaped target in the D-module (see Fig. 1a)) in the case of 800 Pa of plenum pressure. From t = 300 ms, additional heating was applied in another upstream region. In each discharge, about 100 ms period from t = 180 ms to 280 ms (hatched area in Fig. 2a) and b)) in which the hydrogen pressure in the D-module and plasma parameters such as electron temperature and density were temporally almost constant was used for data analysis. In the case without additional gas supply, particle flux of the divertor simulation plasma estimated by using ion saturation current measured by probe #1 was ~3 x 10^{21} m^{-2} s^{-1}. Though there was no direct measurement of heat flux in the discharges, typical value of the heat flux measured by a calorimeter at the corner of the V-shaped target for similar discharge is ~0.1 MW m^{-2} [7].

Figure 2c) shows T_e and n_e of the divertor simulation plasma measured by the probe #1 as a function of the hydrogen pressure in the D-module. The pressure of almost 0 Pa means the additional hydrogen gas was not supplied. With increase in the pressure P_n, T_e decreased from 30 eV to about 2 eV. The electron density first increased from an order of 10^{16} m^{-3} to nearly 10^{17} m^{-3} and then decreased with increase in P_n, indicating that the plasma was detached. The increment in n_e and decrement in T_e mainly resulted from the ionization of hydrogen neutrals. In the density decrement phase, the density was of the order of 10^{16}-10^{17} m^{-3} and the temperature was in the range around 2 eV. In this n_e and T_e range, considering rate coefficients, EIR is hard to occur but MAR is likely to do. In addition, the hydrogen neutral pressure was high (i.e. there were plenty of hydrogen molecules inside the D-module) when the plasma was detached. Furthermore, line intensity ratio of H_α to H_β of hydrogen atom obtained by spectroscopic measurement increased with increasing the pressure [11]. These trend and values of temperature and density indicate that the detachment was caused by MAR [10].

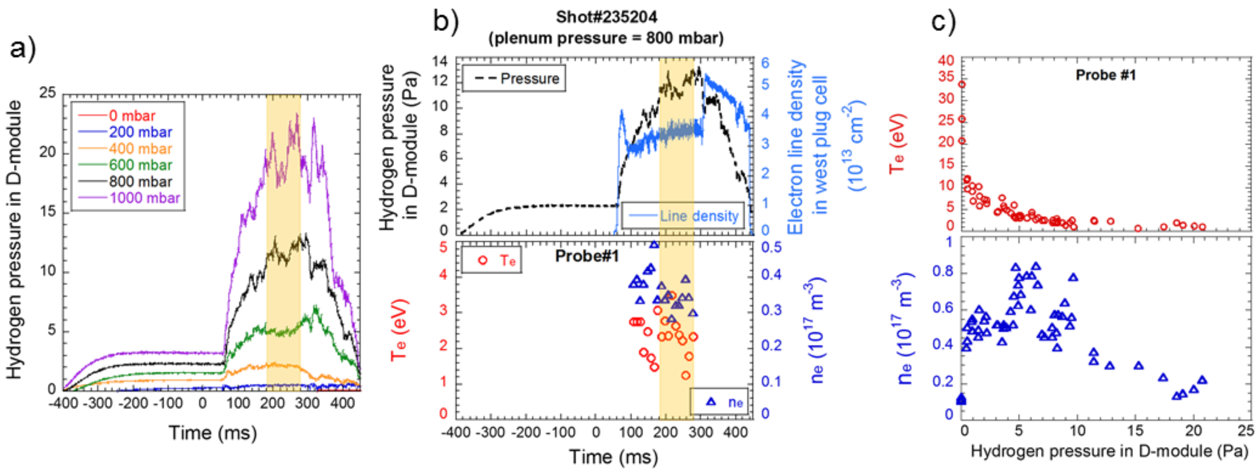

FIGURE 2. a) Time evolutions of hydrogen pressure measured by the ASDEX gauge in the D-module with respect to each initial plenum pressure (i.e. the pressure inside the reserver tank behind the piezo valve) and b) hydrogen pressure and electron line density in the upstream west plug cell (top side) and electron temperature and density measured by Langmuir probe at the corner of the target (bottom side) as a function of time and c) electron temperature (top side) and density (bottom side) of the divertor simulation plasma measured by the corner probe in the hatched period in a) and b) as a function of hydrogen pressure in the D-module.

Next, spatial distributions of T_e and n_e measured by probes #1-5, #17, and #18 (distributions toward Z axis where Z = 0 mm means the position of the corner of the target) are shown in Fig. 3a) and b). Those figures show the case without additional hydrogen gas supply (~0 Pa) and the cases with the hydrogen pressures in the D-module of 0.5 Pa, 5 Pa, and 12 Pa. Electron temperature measured at all of these positions decreased with increase in P_n. Along almost the same magnetic field line (probe #18, #17 and #5), n_e near the target (measured by probe #5) first increased and then decreased in contrast to the upstream n_e (measured by probe #17 and #18) which first increased and then became saturated with increase in P_n. On the other hand, T_e kept its distribution almost flat in front of the target (positions of probes #1-5). As the pressure was increased from 5 Pa to 12 Pa, n_e decreased and the density distribution changed from a flat one to one which had a gradient directed to the upstream. In this phase, the decrement in n_e near the corner of the target (the position of probe #1 and #2) was larger than those of the others (probes #3-5), suggesting that the recombination process was stronger near the corner. It seems that the hydrogen neutral pressure became high near the corner of the target due to a recycling effect of the V-shaped target.

In addition, we show spatial distributions of V_s and V_f measured by the same probes (#1-5, #17 and #18) in Fig. 3c) and d). In most cases, V_s decreased, V_f increased and the potential difference between V_s and V_f (V_s - V_f) became small with increase in P_n. In the cases of additional hydrogen gas injection, the potential difference was larger near the inlet (the position of probe #18) than those near the target (the position of probes #1-5). Near the target, the potential difference decreased to mostly zero. The trend of the potential seems to be similar to that of T_e, indicating that the potential has some dependence on T_e as mentioned in [12].

Figure 3e) and f) shows T_e and n_e distributions across the V-shaped target (Y axis) measured by probes #2 and #6-9. With increase in P_n, T_e decreased at all positions and its distributions were almost flat. The electron density along Y axis near the target first increased and then decreased. In this experiment, its distribution first became peaked profile in the cases of the lower hydrogen pressure (0.2 Pa and 0.5 Pa), and then became almost flat with increase in P_n. However, this changes in density distributions along Y axis is not always the case. Because other experiments show flat distributions even with lower hydrogen pressure. We need more detail experiment and analysis concerning the observed Y axis profiles.

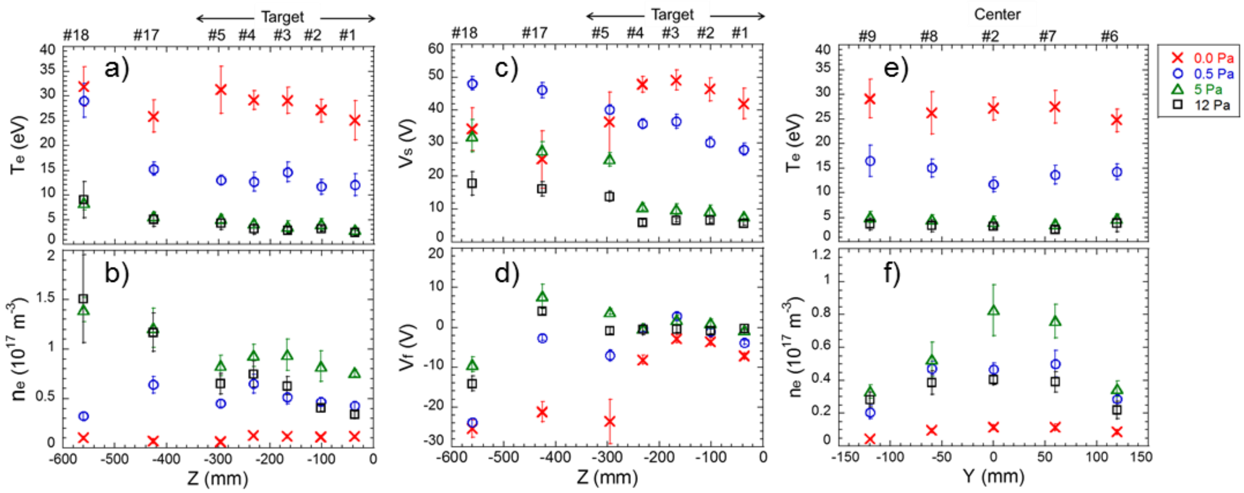

FIGURE 3. Distributions of a) electron temperature, b) electron density, c) space potential and d) floating potential measured by probes #1-5, #17 and #18, and distributions of e) electron temperature and f) electron density measured by probes #2 and #6-9. Those figures show comparison among the case without additional hydrogen gas supply (0.0 Pa) and the cases with the hydrogen pressures in the D-module of 0.5 Pa, 5 Pa, and 12 Pa.

SUMMARY

Electron temperature and density distributions of divertor simulation plasma were measured by Langmuir probes in an additional hydrogen gas supply experiment in GAMMA 10/PDX for spatial characterization of detached plasmas contributed by molecular activated recombination. As the hydrogen pressure was increased, the temperature measured by probes on the V-shaped target decreased from 30 eV to about 2eV and the density first increased and then decreased. It is considered that the plasma density decrease was caused by molecular activated recombination. With increase in the hydrogen pressure, decrement of electron density at the corner of the V-shaped target was larger than the others although the electron temperature distribution was almost flat. The change in distribution suggests that neutral density near the corner became high due to the recycling effect of the V-shaped target. Space potential decreased, floating potential increased, and the potential difference between those became small as the pressure was increased. The trend of changes in the potential difference seems to corresponds qualitatively to the decrement in electron temperature. Along Y axis near the target, electron temperature decreased, keeping its distribution almost flat.

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