INVESTIGATION OF HYDROGEN PLASMA DETACHMENT IN THE DIVERTOR PLASMA SIMULATOR NAGDIS-II

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Abstract

We have performed the experiments on the detached hydrogen plasmas in a linear divertor plasma simulator. The reductions of the ion particle flux and heat load to the target plate were clearly observed in hydrogen plasmas with the hydrogen gas puff. Detailed analysis of Balmer series spectra with the Collisional-Radiative Atomic-Molecular Data (CRAMD) code indicates that the molecular activated recombination (MAR) effect mainly determines the variation over the Balmer series emission intensities. The conditions to obtain plasma detachment through MAR or EIR are also discussed associated with the difference in plasma parameters between the diverted tokamaks and the divertor simulator.

1. Introduction

The importance of plasma recombination process in detached plasma is recognized on the point of view of handling of plasma heat and particle flow. In recent experiments in diverted tokamaks and divertor simulators, the observation of emission spectra clearly shows that 3-body and radiative recombination (EIR) is occurred in the detached plasma[1-3]. On the other hand, in theoretical study and modeling, the importance of the molecular activated recombination (MAR) associated with the vibrational excited hydrogen molecule in divertor plasma conditions was pointed out[4-7]. MAR is expected to enhance the reduction of particle flux into the divertor plate, and to modify the spatial structure of detached plasmas because of the rate coefficient of MAR is much larger than that of EIR. Our recent experimental results in the linear divertor simulator gave the clear evidence of MAR, showing the reduction of ion flux in hydrogen/ helium mixture plasmas[8]. In a tokamak, the superposition of MAR and EIR spectra was discussed in Alcator C-Mod experiments[9]. However, no systematic experimental investigation on the hydrogen detached plasmas due to the MAR effects has been done yet. Therefore, it is necessary to understand such a detached plasma regime with MAR effects. In this paper, we will present the comprehensive study on the detached hydrogen plasmas in the linear divertor plasma simulator, NAGDIS-II.

2. Experimental Setup

NAGDIS-II consists of a dc plasma discharge region and a divertor test region equipped with solenoid magnetic coils to generate a magnetic field strength up to 0.25 T. Primary gas (hydrogen) was introduced into the discharge region to generate hydrogen plasmas (electron density $n_e \sim 1 \times 10^{19}$ m^{-3}, radius of plasma column ~ 2 cm) in a steady state by the sophisticated dc discharge system[3, 10].

Detached hydrogen plasmas are produced by increasing neutral pressure P in the divertor test

region with secondary hydrogen gas puff[3].

3. Experimental Results and Discussion

Radial profiles of the ion particle flux measured in the entrance ($x = 0.25$ m), upstream ($x = 1.06$ m) and the downstream ($x = 1.72$ m) are shown in Fig. 1. The n_e at the center of the plasma column is about 1.0×10^{19} m^{-3} at the entrance. At $P \sim 4.0$ mtorr, the ion particle flux along the magnetic field is found to reduce by an order of magnitude from the entrance to the downstream. When P is increased to be 10 mtorr, there is little change of the ion particle flux at the entrance, however, the ion particle flux at the downstream becomes almost one-fiftieth as large as that at the entrance. The change of the ion particle flux is thought to be mainly due to the change of n_e because of the weak dependence of the ion current on the electron temperature T_e. We can see a strong reduction of the ion particle flux by addition of a small amount of hydrogen gas. However, this strong reduction cannot be explained by taking account of the particle loss due to the radial diffusion process alone, because of the radial profile does not change in increasing P. This means that some plasma volumetric recombination process should occur in the present hydrogen plasma condition.

The spectrum of visible light emission from 355 nm through 445 nm shows no prominent continuum and series of visible line emissions from highly excited levels due to the conventional EIR in both upstream and downstream at any gas pressure. Figure 2 shows the relative intensities of the hydrogen Balmer series from $n = 3$ to 9 observed in the downstream and normalized intensities by the intensity at 656.3 nm ($n = 3$). The intensity is decreasing as increasing the P, which corresponds to a decrease in the ion particle flux as shown in Fig. 1. On the other hand, it is found from Fig. 2 (b) that the distribution of normalized intensities does not change against P, and is almost same in the upstream and the downstream, although the ion particle flux (plasma density) is quite different. From these experimental results, we can suggest that there are the plasma volumetric recombination process coming from the effect of the molecular hydrogen (MAR) in hydrogen plasma with hydrogen gas puff.

The Balmer series spectra were analyzed with the CRAMD code [7] by adjusting the source of the population of the excited state of hydrogen atoms, corresponding to i) EIR, ii) electron impact excitation from the ground state of atoms, and iii) MAR. All emission intensities are
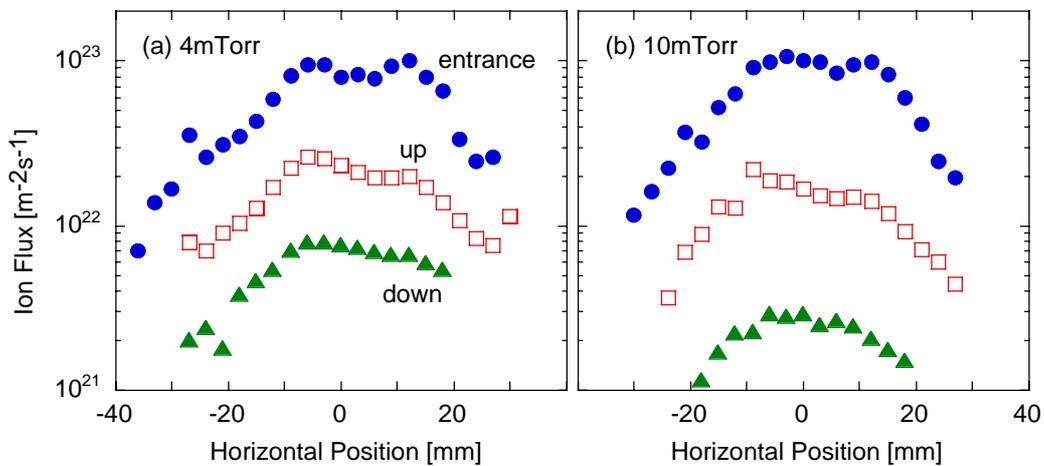

Fig. 1. *Horizontal profiles of the ion particle flux measured at the neutral pressure of (a): 4 mtorr and (b): 10 mTorr. Circles, squares and triangles are obtained at the entrance (X= 0.25 m), at the upstream (X= 0.92 m) and at the downstream (X = 1.58 m), respectively.*

found to come from the contribution of MAR due to the high concentration of hydrogen molecule as shown in Fig. 3. The electron impact excitation and EIR have little effect on the emission intensities. More detailed analysis indicates that the variation of the emission intensities through $n = 3$ to 9 has a very weak dependence on the plasma parameters within our experimental conditions. These calculated results gives a qualitative agreement with experimental data shown in Fig. 2 and also support the fact that the MAR becomes dominating in the experimental environment in the hydrogen plasma of the linear divertor simulator.

We now consider the detached hydrogen plasma conditions which is dominating, where the EIR or MAR is dominating. The plasma particle loss rate per unit volume due to the MAR and the EIR are described as $K_{MAR}n_e[H_2]$ and $K_{EIR}n_e^2$ respectively, where $[H_2]$ are hydrogen molecule density. K_{MAR} and K_{EIR} depend on the n_e and T_e. Figure 4 shows the T_e dependence of the ratio between the particle loss rate due to the MAR and EIR, that is, $R \sim K_{MAR}n_e[H_2]/ K_{EIR}n_e^2$, as parameters of the n_e and the hydrogen gas pressure P. In the present experimental conditions ($P > 1$ mTorr), the plasma particle loss due to the MAR is much greater than that due to the EIR. In order to realize the plasma condition where the EIR is dominating, T_e should be cooled down to be less than 0.3 eV. Furthermore, to realize the detached hydrogen plasma due to the EIR at relatively high T_e about 1 eV, much denser plasma ($> 5 \times 10^{19}$ m^{-3}) with the lower concentration of the hydrogen molecule like Alcator C-MOD divertor plasmas are found to be required.
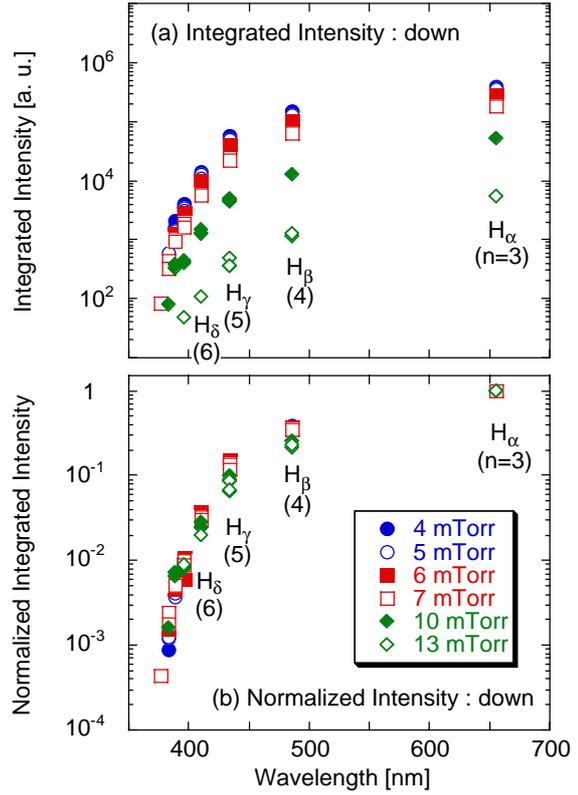

Fig. 2. Dependence of (a): emission intensities of Balmer series as a function of the wavelength as a parameter of P, and (b): normalized intensities by the intensity at 656.3 nm (n = 3) in downstream.
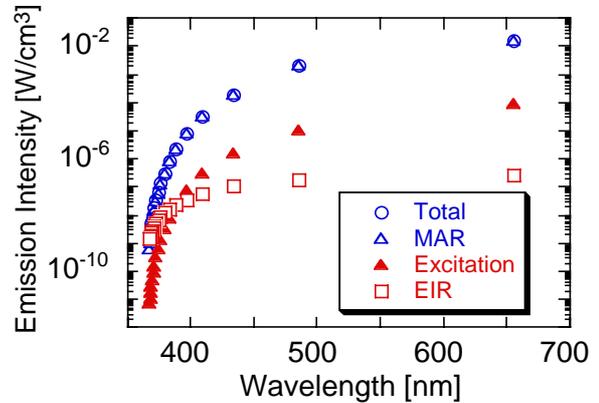

Fig. 3. Calculated emission intensities of hydrogen Balmer series with the CRAMD code from hydrogen plasma at $T_e \sim 2.0$ eV, $n_e \sim 5 \times 10^{18}$ m^{-3} and the neural hydrogen molecule density $\sim 1 \times 10^{20}$ m^{-3}.

Finally, we briefly discuss an influence of energetic electrons (fast electrons) on the detached plasma condition. The energetic electrons are often observed in the diverted tokamaks and the divertor simulators. As shown in Fig. 5, a small amount of electron beam component gives a strong enhancement of the ionization process at T_e less than about 2 eV. If the electron beam density n_b is more than 0.1 % of n_e, even at the T_e less than 0.3 eV, the ionization due to the electron beam component cancel out the plasma particle loss due to the EIR. In order to get the
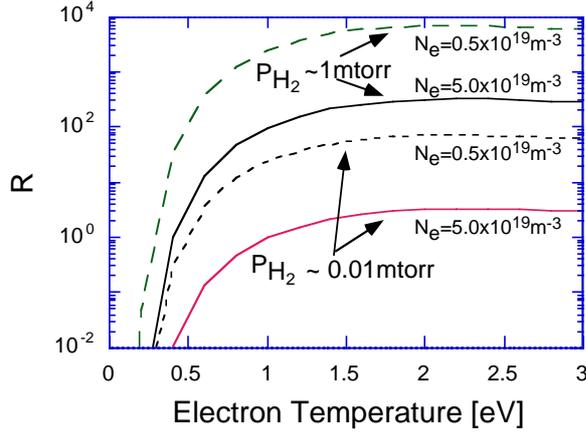
Fig. 4. *Electron temperature dependence of the ratio between the particle loss rate due to the MAR and EIR, $R \sim K_{MAR} n_e [H_2] / K_{EIR} n_e^2$, as parameters of n_e and P.*
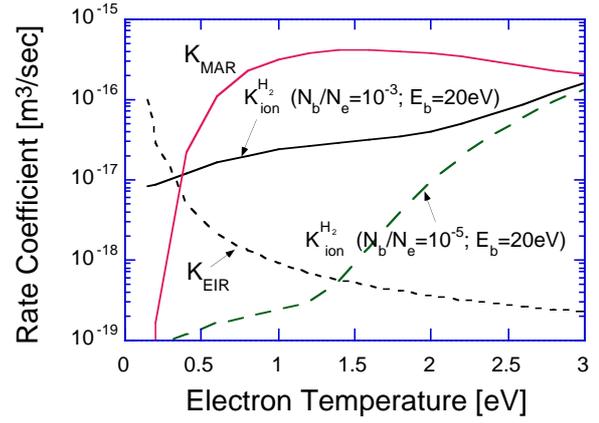
Fig. 5. *Rate coefficients of collisional processes as a function of T_e; electron-ion recombination (radiative and 3-body recombination) K_{EIR} , molecular activated recombination K_{MAR}, and electron impact ionization K_{ion} including the small amount of energetic electron component, where the n_e is assumed to be $1 \times 10^{19}\,m^{-3}$.*

deeper understanding of the detached hydrogen plasma, it is necessary to measure the energy distribution of electrons more precisely.

4. Conclusion

We have performed the experiments on the detached hydrogen plasmas in a linear divertor plasma simulator. The reductions of the ion particle flux and heat load to the target plate were clearly observed in hydrogen plasmas with the hydrogen gas puff due to the MAR. Detailed analysis of Balmer series spectra observed in the detached hydrogen plasmas has been done by using the CRAMD code, which is in a good agreement with the experimental results. In order to realize the detached hydrogen plasma where EIR is dominating in the present divertor simulator, much higher density plasma or effective cooling of the electrons should be required.

References

[1]   D. Lumma *et al*., Phys. Plasma, **4**, 2555 (1997).
[2]   R. Isler *et al*., Phys. Plasma, **4**, 2989 (1997).
[3]   N. Ezumi *et al*., *Proc. of 24th Euro. Phys. Soc. Conf. on Controlled Fusion and Plasma Phys.*, Berchtesgaden, **21A**, Part III, 1225 (1997).
[4]   S. I. Krasheninnikov *et al*., Phys. Plasma, **4**, 1638 (1997).
[5]   S. I. Krasheninnikov *et al*., Phys. Lett. **A 214**, 285 (1996).
[6]   D. E. Post, J. Nucl. Mater. **220-222**, 143 (1995).
[7]   A. Yu. Pigarov *et al*., Phys. Lett. **A 222**, 251 (1996).
[8]   N. Ohno *et al*., *to be published in* Phys. Rev. Lett.
[9]   J. L. Terry *et al*., Phys. Plasma, **5**, 1759 (1998).
[10] S. Narita *et al*., *Proc. of 1996 Int. Conf. on Plasma Phys.*, Nagoya, **2**, 1362 (1996).