CHANGE IN DETACHED HELIUM PLASMA'S STRUCTURE ASSOCIATED WITH MOLECULAR ACTIVATED RECOMBINATION

D. Nishijima, N. Ezumi, H. Kojima, N. Ohno and S. Takamura

Department of Energy Engineering and Science, Graduate School of Engineering, Nagoya University, Nagoya 464-8603, Japan

1. Introduction

The importance of molecular activated recombination (MAR) associated with vibrationally excited hydrogen molecules ($H_2(v) + e \rightarrow H^- + H$ followed by $H^- + A^+ \rightarrow H + A$, and $H_2(v) + A^+ \rightarrow AH^+ + H$ followed by $AH^+ + e \rightarrow A + H$, where A^+ (A) is the hydrogen or the impurity ion (atom)) has been theoretically pointed out and discussed [1 - 5]. The MAR is expected to be a dominating volumetric recombination process because the rate coefficient of MAR is much larger than that of electron-ion recombination (EIR), which includes radiative and three-body recombinations, at $T_e > 0.5$ eV as shown in Fig. 1. We have shown the experimental evidence of the MAR in the helium plasma with the hydrogen gas puff in a linear divertor plasma simulator, NAGDIS-II [6]. The detached plasmas were also analyzed with the 2-D fluid B2 code by taking both EIR and MAR effects into account, which indicates the MAR has strong effect on the structure of the detached plasma [7]. However, there is no clear experimental investigations on the structural change of the detached plasmas associated with the MAR effects, comparing to the EIR.

In this paper, we will show the change in the detached helium plasma's structure with the hydrogen gas puff compared to that with the helium gas puff. The plasma density dependence of the reduction rate of the ion flux along the magnetic field in the pure helium plasma and helium plasma/hydrogen gas mixture is also presented.

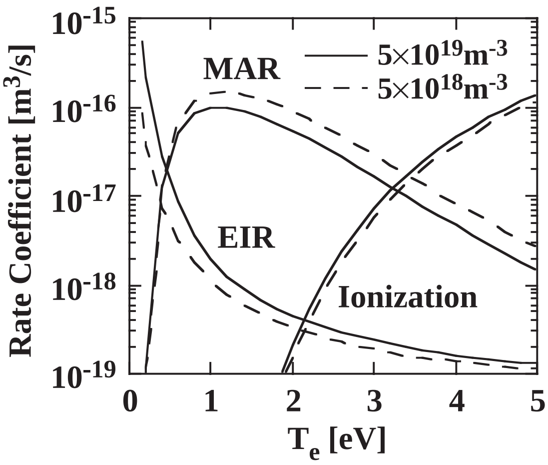

Fig. 1 *Rate coefficients of electron-ion recombination (EIR), K_{EIR}, molecular activated recombination (MAR), K_{MAR}, and electron impact ionization of helium atom for helium plasma with molecular hydrogen as a function of electron temperature.*

2. Experimental Results and Discussion

2.1. *The structural change of the detached plasmas associated with the MAR effects*

The experiments were performed in the linear divertor plasma simulator, NAGDIS-II [8]. We generated the helium plasma at a discharge current I_d ~ 80 A without any secondary gas puff (initial condition), when the neutral helium gas pressure was kept to be around 4 mTorr using the control of the pumping speed. Figure 2 shows the changes in spectra of visible light emissions from 310 nm to 370 nm observed in the downstream (X = 1.72 m) when the helium or the hydrogen gas as the secondary gas was introduced to the initial condition. We should notice that the helium or the hydrogen gas puff into the divertor test region had little effect on the plasma production in the discharge region. With the helium gas puff of 2 mTorr, a continuum and a series of visible line emissions from highly excited levels, up to the principal quantum number $n \sim 16$, due to the EIR were strongly observed compared to the initial condition in the downstream as shown in Fig. 2(b).

On the other hand, in the case of hydrogen gas puff of 2 mTorr there was little change in the emission intensity compared to the initial condition in the downstream as shown in Fig. 2(c). This means the EIR is not enhanced by the hydrogen gas puff, which is different from the case of the helium gas puff.

The horizontal profiles of the ion flux, corresponding to the plasma conditions in Fig. 2, measured in the upstream (X = 1.06 m), midstream (X = 1.39 m) and downstream are shown in Fig. 3. When the helium gas was introduced into the plasma with the initial condition, the horizontal profiles are similar to those in the initial condition both in the upstream and in the midstream. In the downstream, however, the EIR strongly occurs with the helium puff as shown in Fig. 2(b), therefore the ion flux drops. On the other hand, with the hydrogen gas puff the ion flux in the upstream, where T_e is relatively high (around 4 eV obtained with a double probe measurement), already starts to decrease due to the MAR effect compared to that in the case of the pure helium plasmas. Then the ion flux in the helium plasma with the hydrogen gas puff is gradually decreasing from the upstream to the downstream, where the EIR is suppressed as shown in Fig. 2(c). Although the ion fluxes in the downstream are almost same in both cases of the helium and hydrogen gas puff, the gradient of the ion flux along the magnetic field is different from each other. It is found that the decay length of the ion flux with the hydrogen gas puff is longer than that with the helium gas puff.

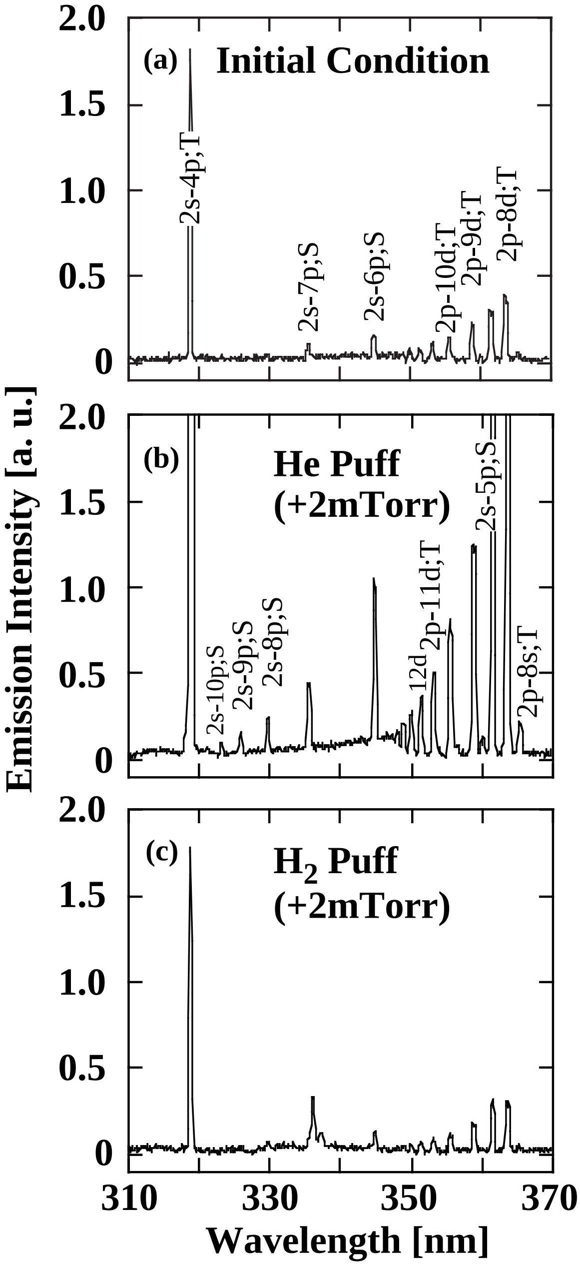

Fig. 2 *Emission spectra in the helium plasma at a discharge current $I_d \sim 80$ A in the downstream : (a) initial condition; (b) with the helium puff; (c) with the hydrogen puff.*

These experimental results are in a qualitative agreement with the simulation results predicted by the 2-D fluid B2 code, which takes both EIR and MAR effects into account [7].

2.2. *Dependence of the ion flux reduction along the magnetic field on the plasma density due to the MAR and EIR*

In order to investigate the dependence of the reduction of the ion flux along the magnetic field on the plasma density in the helium plasma with the helium or hydrogen gas puff, we generated the helium plasma with the neutral helium gas pressure of 4 mTorr using the control of the pumping speed at $I_d \sim 20$ A, 50 A and 80 A. The plasma densities at $I_d \sim 20$ A, 50 A and 80 A in the upstream are around 4.0×10^{18} m^{-3}, 1.8×10^{19} m^{-3} and 3.3×10^{19} m^{-3}, respectively. Figure 4 shows the ratio of Γ_d to Γ_u, where Γ_d and Γ_u are the ion fluxes at the center of the plasma column in the downstream and the upstream, at $I_d \sim 20$ A, 50 A and 80 A in the cases of the helium puff of 2 mTorr and the hydrogen puff of 2 mTorr. It is found from Fig. 4(a) that in the case of the helium gas puff, the low density plasma at $I_d \sim 20$ A has a weak reduction of the ion flux from the upstream to the downstream compared to the high density plasma at $I_d \sim 50$ A and 80 A. This is because in the low density plasma electrons cannot lose their energy due to electron-ion temperature relaxation process followed by the ion-neutral charge exchange process, because the electron-ion temperature relaxation coefficient is proportional to $n_e^2 T_e^{-3/2}$, then T_e remains high and moreover the rate coefficient of the EIR, K_{EIR}, is proportional to $n_e T_e^{-9/2}$, therefore the EIR cannot strongly occur [9].

On the other hand, in the helium plasma/hydrogen gas mixture, the ratio Γ_d / Γ_u in the low density plasma is smaller than that in the high density plasma as shown in Fig. 4(b). One explanation for this result may be the difference of the molecular hydrogen density between the low and high density plasmas. The volumetric particle loss rate due to the MAR, described as $K_{MAR} n_e n_{H2}$, where K_{MAR} and n_{H2} are the rate coefficient of MAR and molecular hydrogen density, depends on the electron and the molecular hydrogen densities. The density of the molecular hydrogen in the high density plasma is thought to become smaller than that in the low density plasma because the attenuation of the molecular hydrogen due to the dissociation and

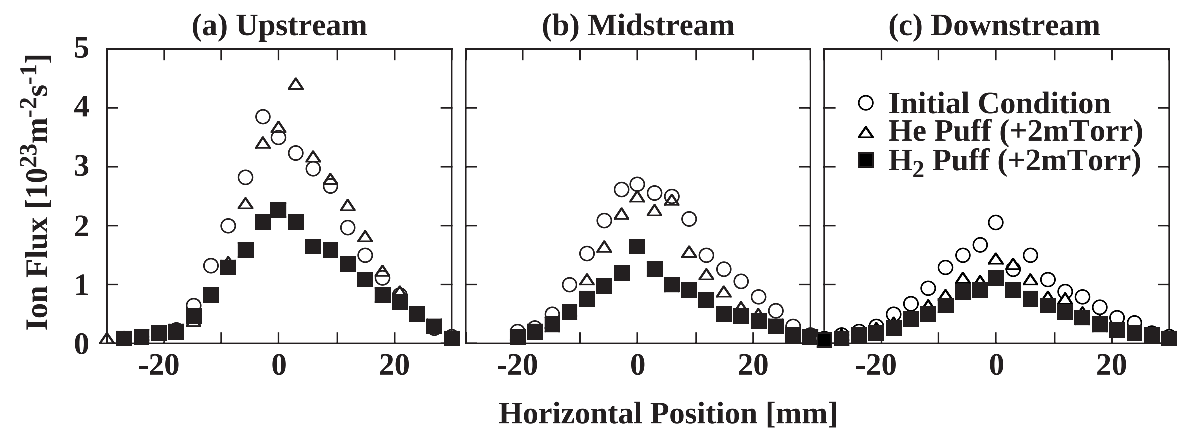

Fig. 3 *Horizontal profiles of the ion flux measured in the upstream, midstream and downstream in the same plasma condition as Fig. 2. Open circles and triangles are obtained at P ~ 4 mTorr without gas puff and at P ~ 6 mTorr with helium gas puff. Closed squares are obtained in the helium plasma with hydrogen gas puff, where the partial pressure of the hydrogen is 2 mTorr.*

molecular ionization processes is likely to occur in the high density plasma. Furthermore, we must also consider the momentum (pressure) balance in the horizontal direction [10], which is expected to attenuate the molecular hydrogen influx at room temperature into the plasma due to the energetic hydrogen atom outflux at a few eV generated by the dissociation of hydrogen molecules [7]. Accordingly, the MAR can be more effective in the low density plasma than in the high density plasma. It should also be noted that the rate coefficient of the MAR has a weak plasma density dependence as shown in Fig. 1.

3. Conclusion

In order to investigate the effect of molecular activated recombination associated with hydrogen molecule on the structure of the detached plasma, we have performed the experiments in the detached helium plasma with the hydrogen gas puff in the linear divertor plasma simulator. We have made a detailed comparison between the hydrogen gas puff and helium gas puff into the helium plasma.

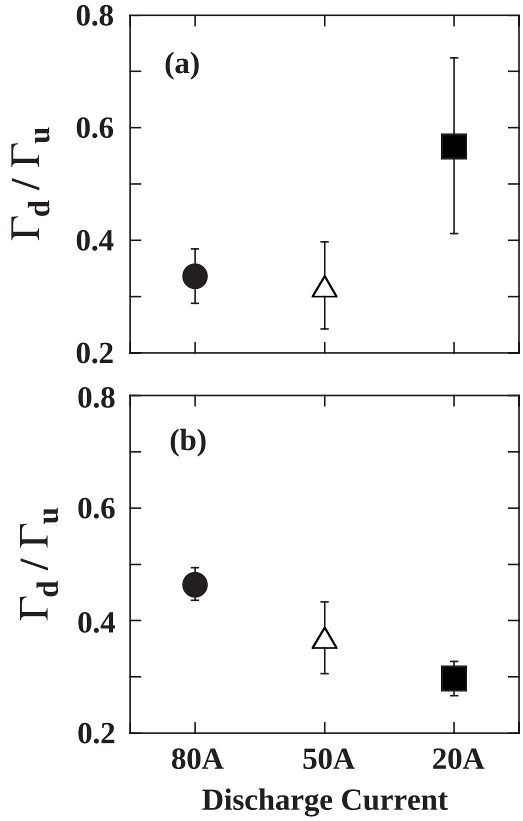

Fig. 4 *Reduction rate of the ion flux, Γ_d / Γ_u at I_d ~ 80 A, 50 A and 20 A: (a) with the helium gas puff; (b) with the hydrogen gas puff. Closed circles, open triangles and closed squares are obtained at I_d ~ 80 A, 50 A and 20 A, respectively.*

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