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Contribution of molecular activated recombination to hydrogen plasma detachment in the divertor plasma simulator NAGDIS-II

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Abstract

We have performed experiments on detached hydrogen plasmas associated with molecular activated recombination (MAR) in a linear divertor plasma simulator. 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 shows that MAR mainly appears as a weak dependence of the Balmer series emission intensities on experimental conditions in detached hydrogen plasmas. The plasma conditions necessary to obtain plasma detachment through MAR or EIR (electron ion recombination including the radiative and three-body recombination) in tokamak divertors are also discussed.

Keywords: Collisional-radiative model; Detached plasma; Divertor plasma; Divertor simulator; Gas-target divertor; Hydrogen; Molecules; Plasma neutral interaction; Recombination

1. Introduction

Recent experiments in diverted tokamaks and divertor simulators have shown that the volumetric plasma recombination in detached divertor regime plays an essential role for the reduction of the particle flux and heat load to the divertor plate [1–3]. In these experiments, continuum and visible line emissions from highly excited levels can be attributed to EIR in detached plasmas. On the other hand, a new recombination process associated with excited hydrogen molecule, so called molecular activated recombination (MAR), was theoretically predicted in divertor plasma conditions [4–7]. This MAR process is described as follows; (1) $H_2(v) + e \Rightarrow H^- + H$ followed by $H^- + A^+ \Rightarrow H + A$ (charge exchange recombination), and (2) $H_2(v) + A^+ \Rightarrow (AH)^+ + H$ followed by $(AH)^+ + e \Rightarrow A + H$ (dissociative recombination), where $A^+(A)$ is a hydrogen or an impurity ion (atom) existing in divertor plasmas. The MAR is expected to lead to an enhancement of the reduction of ion particle flux, and to modify the structure of detached recombining plasmas because the rate coefficient of MAR(K_{MAR}) is much greater than that of EIR (K_{EIR}) at relatively high T_e above 1.0 eV (see Fig. 8). Our recent experimental results in a linear divertor simulator gave the 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 dicussed 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.

In this paper, we will present the comprehensive study on the detached hydrogen plasmas in the linear divertor plasma simulator of Nagoya University, NAGDIS-II [3]. The reduction of the ion particle flux

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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 date (CRAMD) code [7] shows that the influence of MAR is to make the Balmer series spectral emission insensitive to experimental conditions in detached hydrogen plasmas.

2. Experimental setup

Fig. 1 shows a schematic of the NAGDIS-II, which 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. The anode and the vacuum vessel are connected to the ground. Primary gas (hydrogen) was introduced into the discharge region to generate hydrogen plasmas in a steady state by the sophisticated dc discharge system, which is designed to improve the ionization efficiency using a cusp magnetic configuration and a heated LaB_6 disk cathode [10]. A generated hydrogen plasma ($n_e \sim 1 \times 10^{19}$ m^{-3}, radius $\sim$2 cm) flows into the divertor test region.

In the case of an attached plasma, the plasma is terminated by the water-cooled target plate at $X = 2.05$ m, where X means the distance from the anode. Neutral pressure P was measured with capacitance manometers (baratron gauges) at $X = 1.06$ m. The P can be varied from less than 1 mTorr to 30 mTorr by introducing the secondary gas to the vacuum vessel or controlling the pumping speed of two turbo molecular pumps. The changing of P in the divertor test region has little effect on the discharge condition because there is a substantial pressure difference between the discharge and the divertor test regions. Owing to the above reasons, this device makes it possible to do flexible plasma–gas interaction experiments.

Three fast scanning double-probes were located at $X \sim 0.25$, 1.06 and 1.72 m, which are referred to as 'entrance', 'upstream' and 'downstream', respectively. Spectra of the visible light emissions were also observed at the upstream and downstream positions. Heat flux onto the target plate was measured with the calorimetric method.

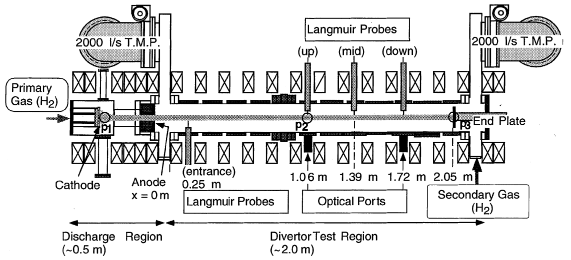

Fig. 1. Schematic of experimental apparatus, NAGDIS-II.

3. Experimental results

Fig. 2 shows the dependence of the heat load to the target plate on the hydrogen gas pressure P. The discharge current I_d was 100 A. With an increase in P, the heat load is found to drop rapidly, and at $P \sim 7.0$ mTorr, to be an order of magnitude smaller than that of the initial value at $P \sim 1.3$ mTorr (without gas puff). 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. 3. The plasma density 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 10 mTorr, there is little change of the ion particle flux in the entrance, however, the ion particle flux in the downstream becomes almost 1/50 as large as that in the entrance. The change of the ion particle flux is thought to be mainly due to the change of plasma density because of the weak dependence of the ion current on the electron temperature. We can see a strong reduction of the ion particle flux by the addition of a small amount of hydrogen gas. However, the strong reduction of the ion particle flux cannot explained by taking account of the particle loss due to the radial diffusion process alone. This means that some plasma volumetric recombination process should occur in the present hydrogen plasma condition.

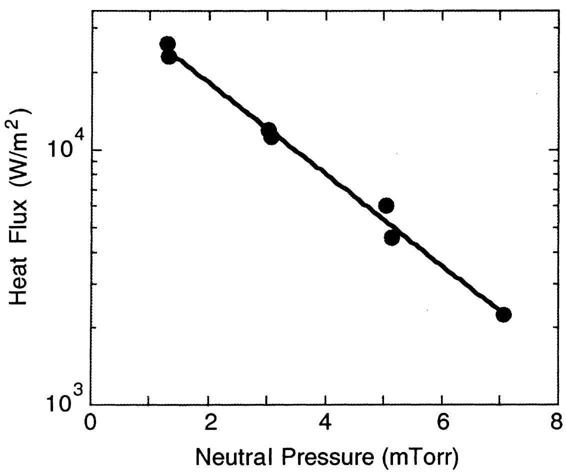

Fig. 2. Averaged heat load to the target plate as a function of the neutral pressure P in the divertor test region.

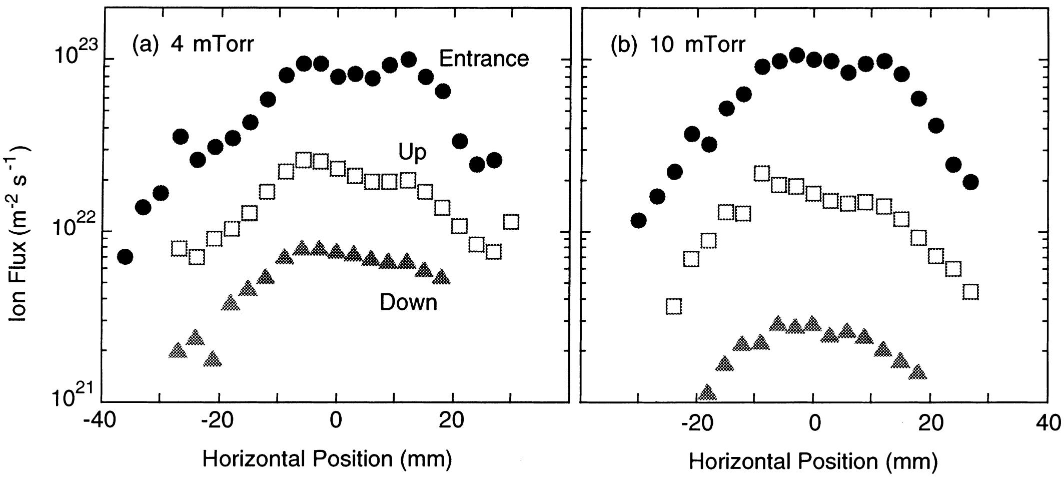

Fig. 3. Horizontal profiles of the ion particle flux measured at the neutral pressure of (a) 4 mTorr and (b) 10 mTorr. Circles, squares and triangles are obtained at the entrance ($X = 0.25$ m), at the upstream ($X = 1.06$ m) and at the downstream ($X = 1.72$ m), respectively.

Fig. 4 shows the spectrum of visible light emission in the range 355–445 nm observed in the upstream for the neutral pressure P of 4 mTorr. It is found that no prominent continuum and series of visible line emissions from highly excited levels due to the conventional EIR [3,8] were observed in both upstream and downstream at any gas pressure. It indicates that the EIR is not responsible for the reduction of the ion particle flux. Fig. 5 shows the intensities of the hydrogen Balmer series for $n = 3$–9 (a,b) and intensities normalized by the intensity at 656.3 nm ($n = 3$) (c,d) observed in the upstream and downstream locations. The intensity decreases with increasing neutral pressure P, which corresponds to a decrease in the ion particle flux as shown in Fig. 3. On the other hand, it is found from Fig. 5(c) and (d) that the distribution of normalized intensities does not change against the neutral pressure, and is almost the same in the upstream and downstream, although the ion particle flux (plasma density) is quite different. This experimental result cannot be explained by the EIR and the electron impact excitation from the ground state as will be discussed later. These experimental results suggest that the plasma volumetric recombination process comes from the effect of MAR.

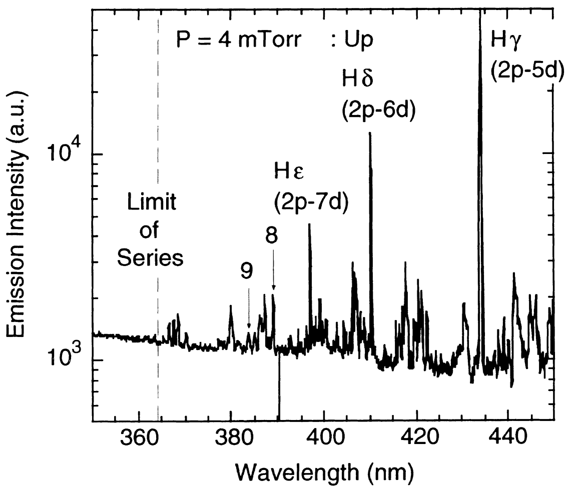

Fig. 4. Visible light emission spectra from the hydrogen plasma with hydrogen gas puff at $P \sim 4.0$ mTorr observed in the upstream.

4. Discussion

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. Fig. 6(a) shows the calculated results with the CRAMD code 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}, which corresponds to the experimental condition in Fig. 3(a). Open triangles, closed triangles, and open squares show the contributions of MAR, the electron impact excitation, and EIR, respectively. All emission intensities are found to come from the contribution of MAR due to the high concentration of hydrogen molecules. Electron impact excitation and EIR have little effect on the emission intensities. Fig. 6(b) shows the calculated intensities normalized by the intensity at 656.3 nm ($n = 3$) as parameters of the electron temperature and density. The variation of the emission intensities through $n = 3$–9 has

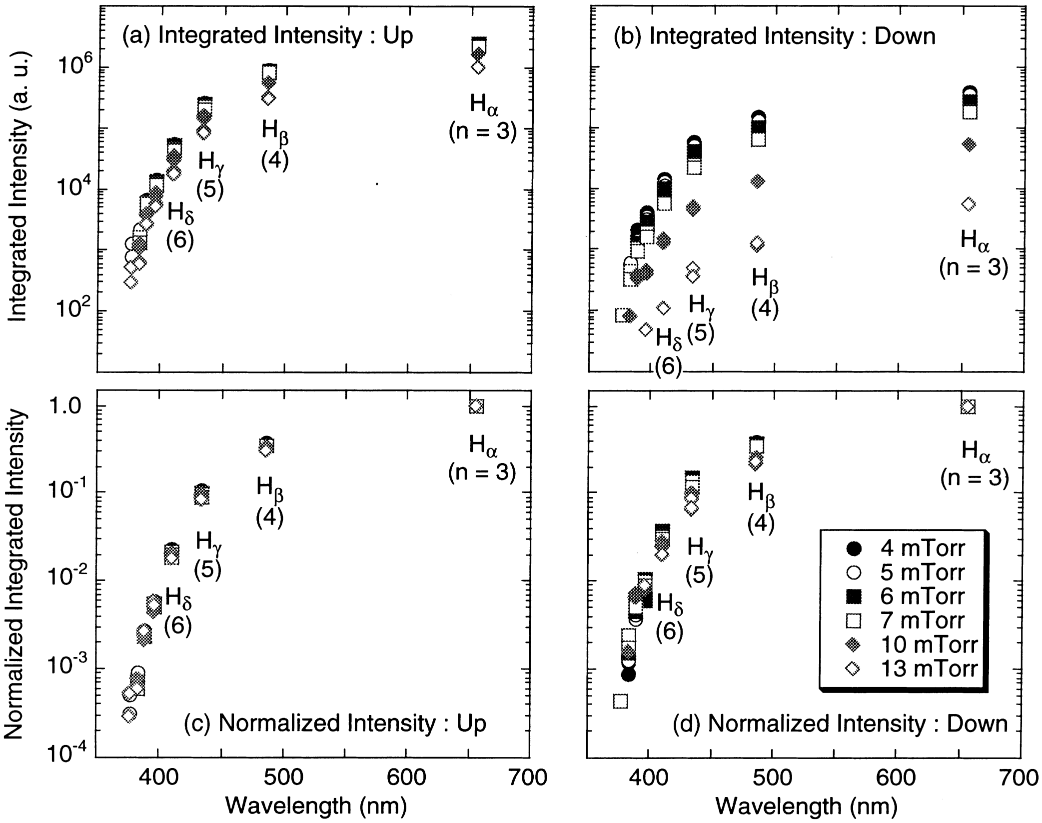

Fig. 5. Dependence of emission intensities of Balmer series as a function of the wavelength in (a) upstream and (b) downstream as a parameter of P, and normalized intensities by the intensity at 656.3 nm ($n = 3$) in (c) upstream and (d) downstream.

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. 5 and also support the hypothesis that the MAR dominates in the hydrogen plasmas of the linear divertor simulator.

We now consider detached hydrogen plasma conditions where one would expect either EIR or MAR to before dominate. The plasma particle loss rate per unit volume due the MAR and the EIR are described as $K_{\mathrm{MAR}} n_{\mathrm{e}} [\mathrm{H_2}]$ and $K_{\mathrm{EIR}} n_{\mathrm{e}}^2$ respectively, where $[\mathrm{H_2}]$ is the hydrogen molecule density. K_{MAR} and K_{EIR} depend on the electron density and temperature. Fig. 7 shows the electron temperature dependence of the ratio between the particle loss rate due to the MAR and EIR, that is, $R \sim K_{\mathrm{MAR}} n_{\mathrm{e}} [\mathrm{H_2}] / K_{\mathrm{EIR}} n_{\mathrm{e}}^2$, as parameters of the plasma density 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, the electron temperature should be cooled down to less than 0.3 eV. Furthermore, to realize the detached hydrogen plasma due to the EIR at a relatively high electron temperature of about 1 eV, much denser plasma ($>5 \times 10^{19}$ m^{-3}) with a lower concentration of the hydrogen molecules such as that seen in Alcator C-MOD divertor plasmas [9] would be required.

Finally, we briefly discuss an influence of energetic electrons (fast electron) on the detached plasma condition. In the dc discharge system like the present device, the existence of very small amount of electron beam components, which can be generated by the primary electrons from the cathode surface entering the divertor test region directly, is thought to be a realistic situation, especially for the hydrogen discharge rather than the helium discharge because of its higher discharge voltage. Fig. 8 shows the rate coefficient for the hydrogen molecule ionization calculated with the CRAMD code, taking into account the electron beam density n_{b} of 0.1% and 0.001% of n_{e} with the beam energy E_{b} of 20 eV and $n_{\mathrm{e}} \sim 10^{18}$ m^{-3}. A small amount of electron beam component gives a strong enhancement of the ionization process at the electron temperature less than about 2 eV. If the electron beam density n_{b} is more than 0.1% of n_{e}, even at the electron temperature less than 0.3 eV, the

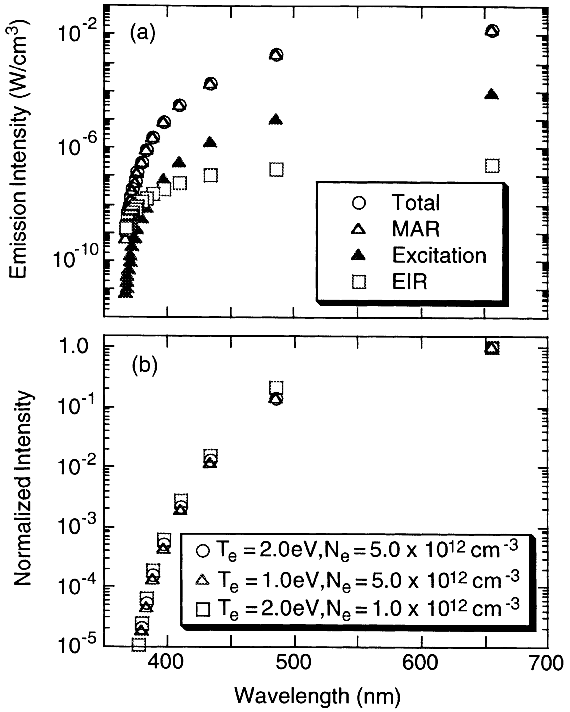

Fig. 6. Calculated emission intensities of hydrogen Balmer series with the CRAMD code from hydrogen plasma at (a) $T_e \sim 2.0$ eV, $n_e \sim 5 \times 10^{18}$ m^{-3} and the neural hydrogen molecule density $\sim 1 \times 10^{20}$ m^{-3} and (b) intensities normalized by the intensity at 656.3 nm ($n = 3$) for various combination of the electron temperature and density.

ionization due to the electron beam component cancel out the plasma particle loss due to the EIR. In order to get a deeper understanding of the detached hydrogen plasma, it is necessary to measure the energy distribution of electrons more precisely.

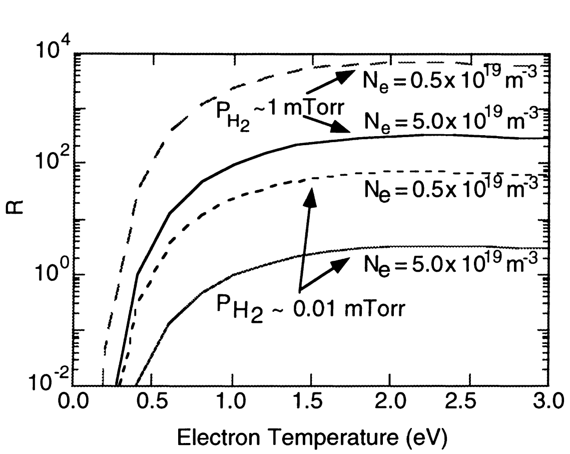

Fig. 7. Electron temperature dependence of the ratio between the particle loss rate due to the MAR and EIR, $R \sim K_{MAR} n_e [H_2] / K_{EIR} n_e^2$, as parameters of n_e and P.

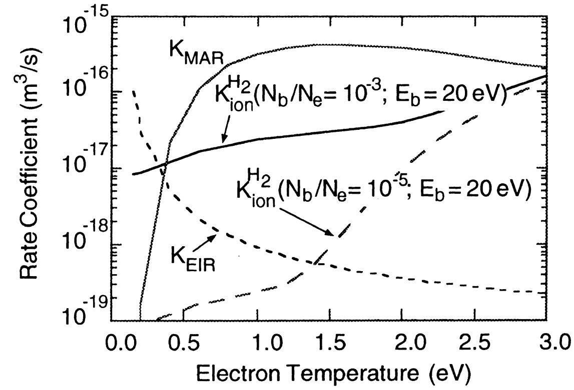

Fig. 8. Rate coefficients of collisional processes as a function of electron temperature; electron–ion recombination (radiative and three-body recombination) K_{EIR}, molecular activated recombination K_{MAR}, and electron impact ionization K_{ion} including the small amount of energetic electron component, where the electron density is assumed to be 1×10^{19} m^{-3}.

5. Conclusion

We have performed the experiments on the detached hydrogen plasmas associated with the molecular activated recombination (MAR) in a linear divertor plasma simulator. Our conclusions are as follows:

1. The reduction 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.
2. Detailed analysis of Balmer series spectra observed in the detached hydrogen plasmas has been done by using the Collisional-Radiative Atomic-Molecular data (CRAMD), which shows that the influence of MAR is to make the Balmer series spectral emission intensities a weak function of plasma conditions. The weak dependence of the Balmer series emission intensities on the plasma density and temperature is found to be consistent with experimental results.
3. 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 is required.

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