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Observation of Dissociative Recombination in the Hydrogen Sheet Plasma

ONO Masataka, TONEGAWA Akira, KUMITA Kentaro, YAZAWA Hiroyuki,
SHIBUYA Takehisa[1] and KAWAMURA Kazutaka[1]

Department of Physics, School of Science, Tokai University, Hiratsuka 259-1292, Japan

[1] *Department of Electro-Photo Optics, School of Engineering, Tokai University, Hiratsuka 259-1292, Japan*

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Abstract

The experimental observation of dissociative recombination in MAR for hydrogen detached plasma have been studied in the linear divertor plasma simulator, TPD-SheetIV (Test Plasma produced by Directed current for Sheet plasma). Measurements of the relative concentrations of the molecular and atomic ions ($n_{H}{}^{+}, n_{H2}{}^{+}, n_{H3}{}^{+}$), and the heat load to the target plate (Q) were carried out in hydrogen detached plasma with hydrogen gas puff at various discharge current. An "omegatron" mass-analyzer, situated behind a small hole of the endplate with the differential pumping system, is used for analyzing ion species. It is shown from these results that the dominant molecular process is dissociative recombination process via $H_2{}^+$, $H_3{}^+$ in the plasma over the range of low discharge current and low hydrogen pressure.

Keywords:

dissociative recombination, molecular assisted recombination, sheet plasma, mass-analyzer

1. Introduction

The knowledge of atomic and molecular processes in detached divertor regions has become more important, as a dynamic gas target regime is considered to be one of the most favourable conditions for divertor plasmas of fusion reactor to control the heat load on the divertor targets [1,2]. In the detached divertor conditions with lower plasma temperature, vibrationally excited hydrogen molecules $H_2(v)$ persist in dissociation and ionization processes of the plasma volume recombination. Thus, the plasma volume recombination associated with vibrationally excited hydrogen molecules $H_2(v)$, that is, Molecular Assisted Recombination (MAR) is effective in the divertor plasma to enhance the reduction of ion particle flux [2-5]. The rate coefficient for MAR is much greater than that one for the radiative and three-body recombination, that is, Electron-Ion Recombination (EIR) at relatively high electron temperatures above 1.0 eV [6]. The vibrationally excited molecules $H_2(v)$ contribute to plasma volume recombination due to the following chains of reactions: (1) $H_2(v) + e \rightarrow H^- + H$ (dissociated attachment) followed by $H^- + H^+ \rightarrow H + H$ (mutual neutralization), and (2) $H_2(v) + H^+ \rightarrow H_2{}^+ + H$ (ion conversion) followed by $H_2{}^+ + e \rightarrow H + H$ (dissociative recombination) or $H_2{}^+ + H_2 \rightarrow H_3{}^+ + H$.

However, the role of the MAR in fusion experiments is still under discussion and various conclusions are derived from the analysis of different experiments [7-12]. One of the experimental results of the spectroscopy in the linear plasma simulator has provided the evidence of dissociative recombination in MAR, showing the reduction of the ion flux in a plasma with a hydrogen/helium mixture [7]. Author presented the observation of the mutual neutralization in MAR via negative ions formation of hydrogen atom for hydrogen detached plasma [8,9]. On the other hand, it has been pointed out that even the contribution of recombination is not critical for the reduction of the ion flux [10]. Recently it is reported that in a typical situation of detached plasma, vibrationally excited hydrogen molecules $H_2(v)$ dissociate (MAD) and assist ionization (MID) before they contribute to recombination [11]. For detached plasma conditions, i.e. high density and low temperature plasma, it turned out that the MAD dominates always over the MAR. It is, thus, required that the experiments which will be essential to an understanding of the role of the MAR come out. In MAR the dissociative recombination with vibrationally excited hydrogen molecules $H_2(v)$ have not reported clearly in the detached plasma which is observed in diverted tokamaks and divertor

Corresponding author's e-mail: tone@keyaki.cc.u-tokai.ac.jp

simulators.

In this paper, we have been studied the experimental observation of the dissociative recombination in MAR for hydrogen detached plasma in the linear divertor plasma simulator, TPD-SheetIV (Test Plasma produced by Directed current for Sheet plasma) [12,13]. Measurements of the relative concentrations of the molecular and atomic ions ($n_{H}{}^{+}, n_{H2}{}^{+}, n_{H3}{}^{+}$), and the heat load to the target plate (Q) were carried out in hydrogen detached plasma with hydrogen gas puff. It is also intended to show that the observed emission intensity (the Lyman-bands $B^1\Sigma_g{}^+ \rightarrow X^1\Sigma_g{}^+$) of VUV (vacuum ultraviolet) wavelength region from electronic excited hydrogen molecules $H_2(B^1\Sigma_u{}^+)$ by electron impact could be explained by MAR.

2. Experimental apparatus and method

The experiment was performed in the linear divertor plasma simulator TPD-SheetIV as shown in Fig. 1. Ten rectangular magnetic coils formed a uniform magnetic field of 1.0 kG in the experimental region. The hydrogen plasma was generated at a hydrogen gas flow of 70 sccm, with a discharge current of 30 – 100 A. The neutral pressure P_{Div} in the divertor test region was controlled between 0.1 and 20 mtorr with a secondary gas feed. Electron temperature and electron density were measured by a planar Langmuir probe located 3 cm in front of the target. The heat load on the target plate Q was measured by a calorimeter. At a discharge current of 100 A, the value of Q reaches about 1 MW/m^2.

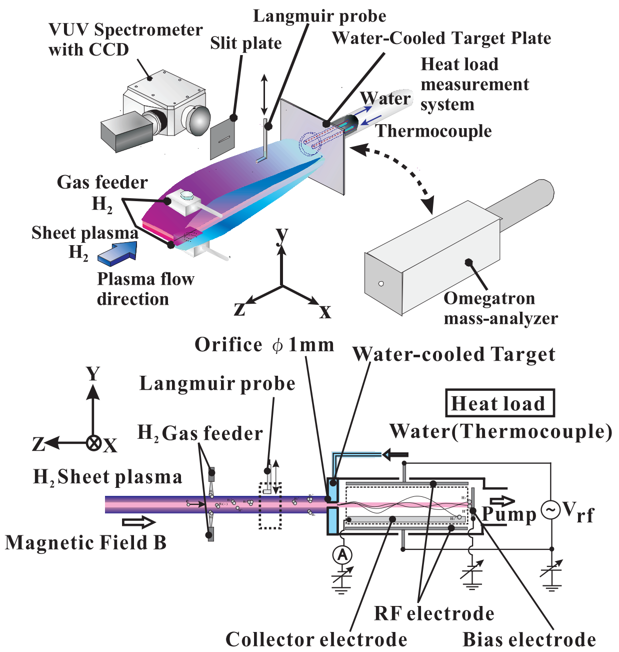

Fig. 1 Schematic diagram of the magnetized plasma simulator (sheet plasma device) TPD-SheetIV and detection system.

An "omegatron" mass-analyzer, situated behind a small hole (Φ 1.0 mm) of the endplate with the differential pumping system, is used for analyzing ion species [14]. This analyzer yields signals due to the cyclotron resonances of ion species. The peaks appear in a collector current of the analyzer when a frequency of applied radio frequency (RF) electric field is equal to the ion cyclotron frequencies. The relative concentrations of the molecular and atomic ions ($n_{H}{}^{+}, n_{H2}{}^{+}, n_{H3}{}^{+}$) were determined from the collector current of the mass-analyzer.

The Lyman Rydberg series lines of neutral hydrogen were measured at an axial distance of 3 cm in front of the target with a CCD camera-equipped VUV spectrometer coupled with a differential pumping system to a side port on the target vacuum chamber. The brightness of the high-n Lyman series lines, such as L_γ, are directly related to the recombination rate of EIR. Therefore the ratio of L_γ (4-1) to L_α (2-1) line intensities can be used as an indicator of EIR. The vibrationally excited hydrogen molecules $H_2(X^1\Sigma_g{}^+(v'' > 4))$ result from the deexcitation of electronic excited hydrogen molecules $H_2(B^1\Sigma_u, C^1\Pi_u)$ by electron impact [15]. When this process occurs in plasmas, vacuum ultraviolet lights are emitted. Thus it is an effective approach to measure the spectra of VUV light emission of $H_2(B^1\Sigma_u, C^1\Pi_u)$ in production of the highly vibrationally excited molecules. The plasma through a viewing port installed at the sidewall of the experimental region is observed by the VUV spectrometer with the differential pumping system and a CCD camera. The spectra of VUV light emission from electronic excited hydrogen molecules $H_2(B^1\Sigma_u, C^1\Pi_u)$ were detected 3 cm apart from the target plate.

3. Experimental results and discussion

Figure 2 shows the effect of hydrogen neutral gas pressure, P_{Div}, on the heat to the target plate, Q, the hydrogen Lyman spectrum ratio, L_γ/L_α, and the intensity of VUV emission spectrum (133.4nm) at the Lyman-band (0,4) system ($B^1\Sigma_u{}^+ \rightarrow X^1\Sigma_g{}^+$) at various discharge current I_d. The I_d changes (●) 50, and (△) 70 A. For P_{Div} less than 4.0 mtorr, Q is found to decrease rapidly under 0.1 MW/m^2 with an increase in P_{Div} and a value less than 30 % of the initial value in the attached plasma. The intensity of VUV emission spectrum at the Lyman-band system ($B^1\Sigma_u{}^+ \rightarrow X^1\Sigma_g{}^+$) rapidly decreases with increases in P_{Div}, while the hydrogen Lyman spectrum ratio L_γ/L_α of VUV emission remains nearly constant. With an increase of P_{Div} to ~ 4 mtorr, L_γ/L_α is observed in front of the target plate. The ratio L_γ/L_α rapidly increases above P_{Div} ~ 6 mtorr. At the same time, the intensities of the hydrogen Lyman

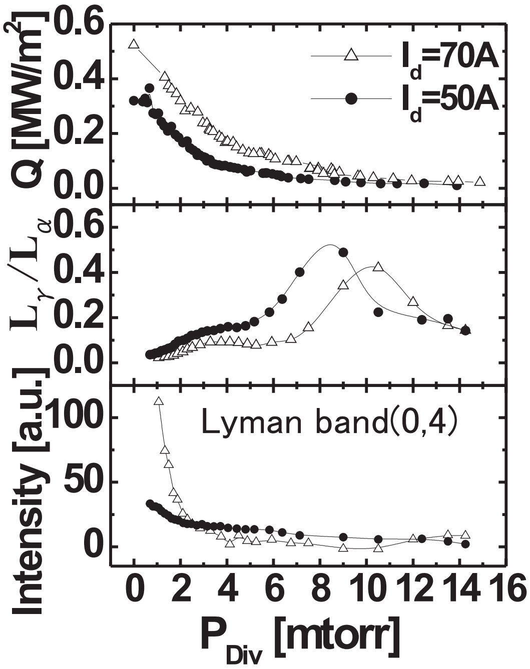

Fig. 2 The effect of hydrogen neutral gas pressure, P_{Div}, on the heat to the target plate, Q, the hydrogen Lyman spectrum ratio, L_γ/L_α, and the intensity of VUV emission spectrum (133.4 nm) at the Lyman-band system ($B^1\Sigma_u{}^+ \rightarrow X^1\Sigma_g{}^+$) at various discharge current I_d. The I_d changes (●) 50, and (△) 70 A.

series from n = 3 to 6 due to the EIR were observed in front of the target (full detachment region), that is, the radiative and three-body recombination processes have appeared.

Figure 3 shows the measured resonance frequency f_{ion} as function of the magnetic field strength B at the discharge current I_d of 50 A and the P_{Div} of 4 mtorr. The value of B changes from 0.5 to 1.0 kG. Mass spectroscopy is performed by applying a radio frequency (rf) field to the parallel plate of the omegatron and measuring the resulting current on the collector plate. Analysis of the ion trajectories in a uniform rf field applied perpendicular to a constant uniform magnetic field shows that the ions execute spiral orbits with a maximum excursion radius. From the typical plasma omegatron experiment, it can be seen that the peaks correspond to $H^+, H_2{}^+, H_3{}^+$. The peak identification is obtained by comparing the observed peak frequencies to the cyclotron frequency $f_c \equiv eB/m$ to obtain the mass charge ratio m/q. The relative ion concentrations of $H^+, H_2{}^+, H_3{}^+ (n_H{}^+, n_{H2}{}^+, n_{H3}{}^+)$ should be roughly equal to the measured ratios of corresponding resonance peak heights.

Figure 4 shows the relative ion concentrations as function of P_{Div} at the discharge current I_d of 50 and 70 A at the magnetic field B of 0.78 kG. For the discharge current of 50 A, $n_H{}^+, n_{H2}{}^+$ and $n_{H3}{}^+$ decrease rapidly until P_{Div} ~ 3 mtorr with increasing in P_{Div}. Above P_{Div} ~ 3 mtorr $n_H{}^+$ gradually increases and obtains the maximum value with increasing P_{Div}. On the other hand, $n_H{}^+$ is larger than that of $n_{H2}{}^+$ and $n_{H3}{}^+$ for the discharge current of 70 A. Therefore, it is shown from these results that the dominant molecular process is dissociative recombination process via $H_2{}^+$, $H_3{}^+$ in the plasma over the range of low plasma density and low hydrogen pressure. For high density and low temperature plasma, the effect of the dissociative recombination process in MAR is smaller than that of molecular assisted dissociation.

4. Conclusion

We have been studied the experimental observation of dissociative recombination in MAR for hydrogen detached plasma in the linear divertor plasma simulator, TPD-SheetIV (Test Plasma produced by Directed current for Sheet plasma). Measurements of the relative ion concentrations of $H^+, H_2{}^+, H_3{}^+$ ($n_H{}^+, n_{H2}{}^+, n_{H3}{}^+$) of the molecular and atomic ions, the intensity of VUV emission spectrum at the Lyman-band system ($B^1\Sigma_u{}^+ \rightarrow X^1\Sigma_g{}^+$), and the heat load to the target plate (Q) were carried out in hydrogen detached plasma with hydrogen gas puff. An “omegatron” mass-analyzer, situated behind a small hole of the endplate with the differential pumping system, is used for analyzing ion

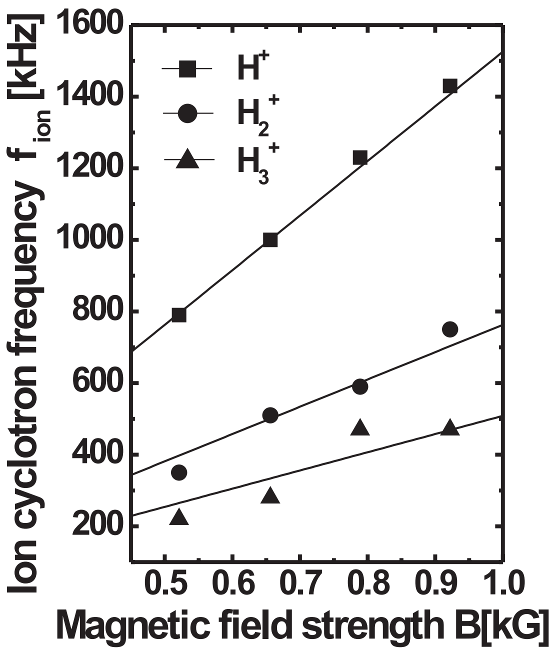

Fig. 3 The measured resonance frequency f_{ion} as function of the magnetic field strength B at the discharge current I_d of 50 A and the P_{Div} of 4 mtorr. The value of B changes from 0.5 to 1.0 kG. From the typical plasma omegatron experiment, it can be seen that the peaks correspond to H^+, $H_2{}^+$, $H_3{}^+$.

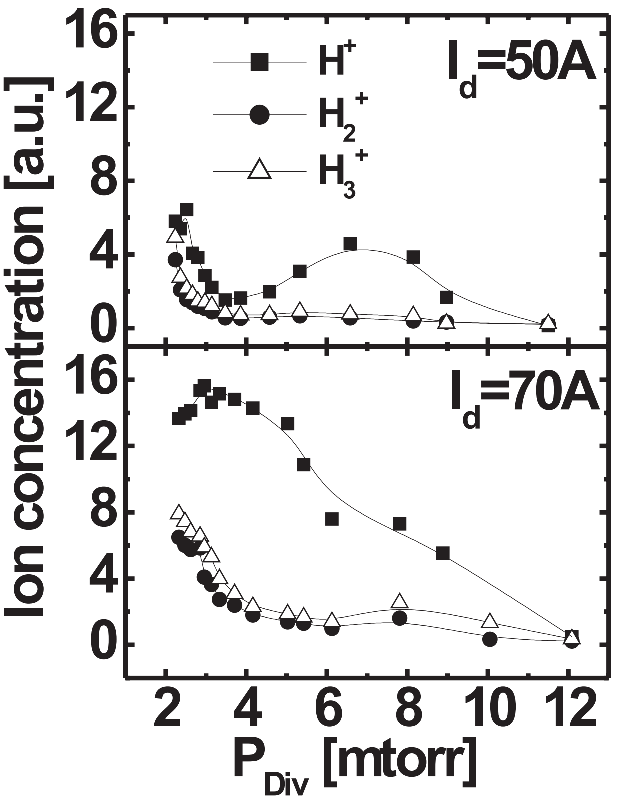

Fig. 4 The relative ion concentrations as function of P_{Div} at the discharge current I_d of 50 and 70 A at the magnetic field B of 0.78 kG.

species. It is shown from these results that the dominant molecular process is dissociative recombination process via H_2^+, H_3^+ in center of the plasma over the range of low discharge current and low hydrogen pressure. For high density and low temperature plasma, the effect of the dissociative recombination process in MAR is smaller than that of molecular assisted dissociation.

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