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Spatial Profiles of Molecular Assisted Recombination for the Formation of the Detached Plasma

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Abstract

We have observed the spatial profiles of Molecular Assisted Recombination (MAR) with vibrational hydrogen molecules in a detached hydrogen plasma by using a linear plasma simulator, TPD-SheetIV. From the VUV emission (Lyman-bands:$B^1\Sigma_u^+ \rightarrow X^1\Sigma_g^+$) of hydrogen molecules H_2, it is indicated that the production process of vibrationally excited hydrogen molecules $H_2(X^1\Sigma_g^+(v>3\text{–}7))$ is the deexcitation of electronic excited hydrogen molecules $H_2(B^1\Sigma_u^+)$, which are produced by collisions between the H_2 and hot electrons (T_e = 10–15 eV) at the center of the sheet plasma. The densities of H_2^+ and H_3^+ in the central region of plasma reach a peak in the range of low hydrogen pressure (< 2 mTorr) (dissociative recombination). With increasing the hydrogen pressure from 2 to 4 mTorr, the negative hydrogen ions H-, which are produced by the collision of assisted species with cold electrons (T_e = 0.5–0.7eV) at the circumferential region of plasma, recombine with hydrogen positive ion H^+ (mutual neutralization)

Keywords:

molecular assisted recombination, dissociative recombination, mutual neutralization

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 $H_2^+ + e \Rightarrow H + H$ or $H_2^+ + H_2 \Rightarrow H_3^+ + H$ (dissociative recombination) .

However, the role of the MAR in fusion experiments is still under discussion and various conclusions are derived from the analysis of different experiments [7-10]. 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]. 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 [9]. Recently it is reported that in a typical situation of detached plasma, vibrationally excited hydrogen molecules $H_2(v)$ dissociate and assist ionization before they contribute to recombination [10]. It is, thus, required that the experiments which will be essential to an understanding of the role of the MAR come out. In MAR both the dissociative recombination and the mutual neutralization with vibrationally excited hydrogen molecules $H_2(v)$ have not reported clearly in the detached plasma which is observed in diverted tokamaks and divertor simulators.

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In this paper, we present the experimental observation of spatial structure of MAR for hydrogen detached plasma in the linear divertor plasma simulator, TPD-SheetIV (Test Plasma produced by Directed current for Sheet plasma) [11,12]. In order to investigate the dissociative recombination and mutual neutralization in MAR, measurements of the molecular and atomic ion densities (n_{H^+}, $n_{H_2^+}$, $n_{H_3^+}$), the negative ion density of hydrogen atom (n_{H^-}), the electron density (n_e), electron temperature (T_e), 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. The hydrogen sheet plasma was produced by a modified TPD type dc discharge[12]. Ten rectangular magnetic coils formed a uniform magnetic field of 0.04 T in the experimental region. The hydrogen plasma was generated at a hydrogen gas flow of 70 sccm with a discharge current of 50 A. The neutral pressure P_{Div} in the divertor test region was controlled by feeding a secondary gas from 0.1 to 20 mTorr. The change of P_{Div} in the divertor test region had no effect on the plasma production in the discharge region because the pressure difference between the discharge and divertor test regions extends to 3 orders of magnitude. The electron temperature and the electron density were measured by a plane Langmuir probe. The plane Langmuir probe was located 3 cm apart from the target plate. The power on the target plate Q was measured by a calorimeter. A cylindrical probe made of tungsten (Φ 0.4 × 2 cm) was used to measure the spatial profiles of H^- by a probe-assisted laser photodetachment method [13,14]. The maximum Nd-YAG laser energy at the fundamental wavelength (1064 nm) was 100 mJ. The pulse length was about 10 ns and the diameter of the beam was 8 mm. The negative ion density was determined from the photodetached electron current. The spatial profile of the negative ions was measured by moving the cylindrical probe under the laser irradiation. An "omegatron" mass-analyzer, situated behind a small hole (Φ 0.5 mm) of the endplate with the differential pumping system, is used for analyzing ion species [15]. 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 molecular and atomic ion density was determined from the collector current of the mass-analyzer. The vibrationally excited hydrogen molecules $H_2(X^1\Sigma_g^+ (v{>}3\text{–}7))$ result from the deexcitation of electronic excited hydrogen molecules $H_2(B\Sigma_u, C\Pi_u)$ by electron impact [16]. When this process occurs in plasmas, vacuum ultraviolet lights are emited. Thus it is an effective approach to measure the spectra of VUV light emission of $H_2(B\Sigma_u)$ in recombination plasma of MAR. The plasma through a viewing port installed at the sidewall of the divertor test 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 $H_2(B\Sigma_u)$ were detected 3 cm apart from the target plate.

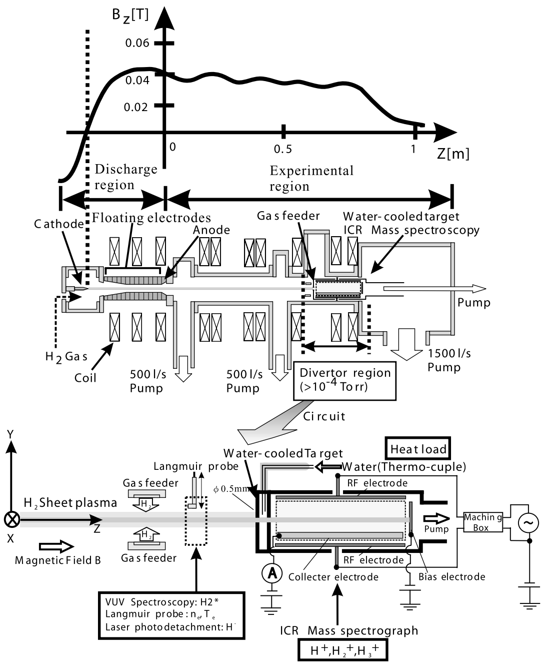

Fig. 1 Schematic diagram of the magnetized plasma simulator (sheet plasma device) TPD-Sheet-IV and detection system. The profile of the axial magnetic field B_z is shown in the upper part.

3. Experimental results and discussion

Figure 2 shows the dependence of the intensity of VUV emission spectrum at the Lyman-band system ($B^1\Sigma_u^+ \rightarrow X^1\Sigma_g^+$), the electron density n_{ec}, the electron temperature T_{ec} and the molecular and atomic ion density at the center of sheet plasma on hydrogen gas pressure P_{Div}, together with the dependence of Q to the target plate on P_{Div}. The VUV emission intense line spectrum is observed at the Lyman-band system ($B^1\Sigma_u^+ \rightarrow X^1\Sigma_g^+$) in hydrogen molecular bands. The Lyman-band at 127.5 nm (0,3), 133.4 nm (0,4), 139.4 nm (0,5), 145.6 nm (0,6), 151.7 nm (0,7) are identified [16]. The densities of the molecular and atomic ions n_{H^+}, $n_{H_2^+}$, and $n_{H_3^+}$ were determined from the collector current (H^+, H_2^+, H_3^+) of the "omegatron" mass-analyzer, respectively. With increasing in P_{Div}, the value of Q is found to decrease rapidly, until less than 30% of the initial value at P_{Div} ~ 3 mTorr, while the radiative and three-body recombination processes disappeared. The value of n_{ec} increases slightly from 4×10^{18} to 5×10^{18} m^{-3} and T_{ec} decreases rapidly from 15 to 10 eV due to ionization until P_{Div} ~ 2 mTorr. At the same time, the densities of hydrogen molecular ions (H_2^+, H_3^+) reach a peak although the

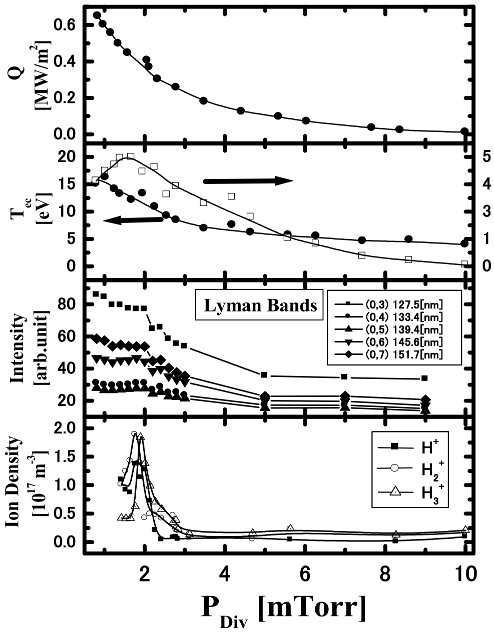

Fig. 2 Averaged heat load to the target plate Q, the intensity of VUV emission spectrum, the electron density n_{ec}, the electron temperature T_{ec} and the molecular and atomic ion density at the center of sheet plasma on hydrogen gas pressure P_{Div} in the divertor test region. The VUV emission intense line spectrum is observed at the Lyman-bands ($B^1\Sigma_u^+ \rightarrow X^1\Sigma_g^+$) at 127.5nm (0,3), 133.4 nm (0,4), 139.4 nm (0,5), 145.6 nm (0,6), 151.7 nm (0,7) in hydrogen molecular bands.

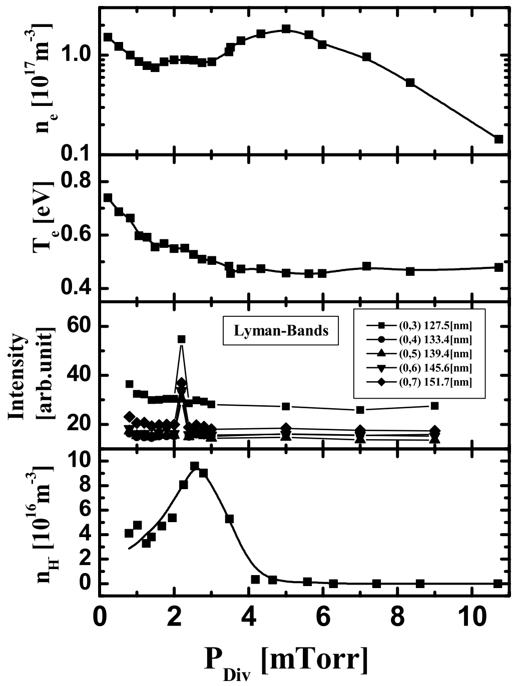

Fig. 3 The characteristics of the electron density n_e, the electron temperature T_e, the VUV emission spectrum at the Lyman-band system ($B^1\Sigma_u^+ \rightarrow X^1\Sigma_g^+$) in hydrogen molecular bands and the negative ions density n_{H^-} on hydrogen gas pressure P_{Div} at the circumferential region of sheet plasma (y = 12 mm).

intensities of VUV spectra at the Lyman-band system ($B^1\Sigma_u^+ \rightarrow X^1\Sigma_g^+$) of H_2 remain constant. Above P_{Div} ~ 2 mTorr in which T_{ec} is less than ~8 eV, the value of n_{ec} gradually decreases from 5×10^{18} m^{-3} to several 10^{16} m^{-3}. Also, we can observe a decrease of the intensities of VUV spectra ($B^1\Sigma_u^+ \rightarrow X^1\Sigma_g^+$) of H_2 and a sudden drop in hydrogen molecular ions (n_{H^+}, $n_{H_2^+}$, $n_{H_3^+}$). In this range of low hydrogen pressure (< 2 mTorr), vibrationally excited hydrogen molecules $H_2(X^1\Sigma_g^+(v>3\text{-}7))$ result from the deexcitation of electronic excited hydrogen molecules $H_2(B^1\Sigma_u^+)$ by the collision of H_2 with hot electron (T_{ec} = 10–15 eV) in the central region and diffuse to the circumferential region of the sheet plasma. Therefore, it is shown from these results that the dominant molecular process is the dissociative recombination process via H_2^+, H_3^+ in the central region of the sheet plasma over the range of low hydrogen pressure.

Figure 3 shows the dependence of the electron density n_e, the electron temperature T_e, the intensity of VUV emission spectrum at the Lyman-band system ($B^1\Sigma_u^+ \rightarrow X^1\Sigma_g^+$) and the negative ions density n_{H^-} on hydrogen gas pressure P_{Div} at the circumferential region of sheet plasma (y = 12 mm). When P_{Div} increases, the value of n_e is found to constant (~ 1×10^{17} m^{-3}) and T_e decreases gradually from 0.7 to 0.5 eV. On the other hand, the VUV emission spectrum and n_{H^-} have a peak value at the P_{Div} ~ 2 mTorr. The peak value of n_{H^-} is 1×10^{17} m^{-3} and the density ratio of n_{H^-}/n_e reaches to 100%. In this range of hydrogen pressure, vibrationally excited hydrogen molecules $H_2(X^1\Sigma_g^+(v>3\text{–}7))$ are produced by the collision between the H_2 and hot electrons (T_e = 10–15 eV) at the center of the plasma as shown in Fig. 2 and diffuse to the circumferential region of the plasma. Therefore, the negative ions of hydrogen atom are produced by the dissociative electron attachment to vibrationally excited hydrogen molecules $H_2(X^1\Sigma_g^+(v>3\text{–}7))$ at the circumferential region of plasma with cold electron (T_e = 0.5-0.7 eV). After that, these negative ions of hydrogen atom recombine with hydrogen positive ion (mutual neutralization) over the range of low hydrogen pressure at the circumferential region of sheet plasma.

4. Conclusion

Spatial profiles of MAR with vibrational hydrogen molecules $H_2(X^1\Sigma_g^+(v>3\text{–}7))$ have been observed in the linear plasma simulator, TPD-SheetIV, through the probe-assisted laser photodetachement method, Langmuir probe method, the VUV spectrometry and the "omegatron" mass-analysis method. In the range of low hydrogen gas pressure, vibrationally excited hydrogen molecules $H_2(X^1\Sigma_g^+(v>4))$ result from the deexcitation of electronic excited hydrogen molecules $H_2(B^1\Sigma_u^+)$ by the collision of hydrogen molecules with hot electron (T_{ec} = 10–15 eV) in the central region and diffuse to the circumferential region of the sheet plasma. It is shown from the results of the mass-analysis (H^+, H_2^+, H_3^+) that dissociative recombination is taking place in the central region of the sheet plasma over the range of low hydrogen pressure. On the other hand, the negative ions of hydrogen atoms are produced by the dissociative electron attachment to the vibrationally excited hydrogen molecules $H_2(v)$ in the circumferential region of plasma with cold electron (T_e = 0.5–0.7 eV). After that, these negative ions of hydrogen atoms recombine with hydrogen positive ion over the range of low hydrogen pressure, that is, mutual neutralization. These results can be well explained by taking MAR into account in the recombining plasma. Our experimental results could be useful to control the divertor operation and to determine the optimum conditions for a detached plasma production, since the complex phenomena involving the collision with vibrationally excited hydrogen molecules ($H_2(v)$), molecular ions (H_2^+ and H_3^+) and negative ions (H^-) in MAR are elucidated through the present research.

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