Plasma Detachment with Molecular Processes in Divertor Plasmas

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Abstract. Molecular processes in detached recombining plasmas are briefly reviewed. Several reactions with vibrationally excited hydrogen molecule related to recombination processes are described. Experimental evidence of molecular activated recombination observed in a linear divertor plasma simulator is also shown.

1 Introduction

Divertor has important functions in magnetically confined fusion devices such as control of heat and particle, removal of helium ash and so on. In next generation fusion devices intended to have a long pulse or steady state operation, heat flux onto divertor plate is expected to be quite high. Reduction of huge heat flux to the divertor plate is one of the most urgent issues in fusion research.

Plasma detachment with volumetric plasma recombination is considered to be the most promising method to reduce the heat and particle flux onto the divertor plate. Collisional radiative recombination process including radiative and three-body recombination has been clearly observed in detached plasmas of diverted tokamaks and a linear divertor plasma simulator.

On the other hand, new recombination processes associated with vibrationally excited hydrogen molecule, so called molecular activated recombination (MAR) were theoretically predicted by several authors. In this paper, MAR processes are briefly reviewed and its experimental evidence obtained in the NAGDIS-II (NAGoya DIverstor Simulator) device is also reported.

2 Molecular Activated Recombination

Reaction chains in MAR can be described as follows[1];

(a): \( H_2(v) + e \rightarrow H + H \) followed by \( H^+ + A^+ \rightarrow H + A \),
(b): \( H_2(v) + A^+ \rightarrow (AH)^+ + H \) followed by \( (AH)^+ + e \rightarrow A + H \),

where \( H_2(v) \) represents vibrationally excited hydrogen molecule and \( A^+ \) is plasma ion. MAR is expected to lead to an enhancement of the reduction of ion particle flux to the target, and to modify the structure of detached recombining plasmas because the rate coefficient of MAR is much greater than that of radiative and three-body recombinations (EIR) at relatively high electron temperature \( T_e \) above 0.5eV as shown in Fig. 1.

3. Experimental Setup

Figure 2 shows the schematics 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 0.25T.

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 \( P \) 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.
Three fast scanning double-probes were located at \( X = 0.25, 1.06 \) 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.

4 Experimental Results and Discussion

4.1 Helium Plasma with Hydrogen or Helium Gas Puff[2]

Figure 3 shows the change in spectrum of visible light emission from 310nm to 370nm observed in the downstream with hydrogen or helium gas puff. For a pure helium plasma, continuum and a series of visible line emissions from highly excited levels due to the conventional EIR were observed as shown in Fig. 3(c) and (d). Detailed analysis of the population distribution among the highly excited levels shows that \( T_e \) is about 0.4 eV by using the Boltzmann relation, because the distribution follows the Saha-Boltzmann distribution, that is, those excited states above a critical quantum number are in local thermodynamic equilibrium (LTE) with free electrons in the plasma. Analysis of the photon energy dependence of the continuum emission intensities also provides the same \( T_e \).

When a hydrogen gas was introduced into the helium plasma, the spectrum is found to be changed dramatically in Fig. 3(b) when the partial pressure of hydrogen gas exceeds a critical level \( \sim 1.4 \) mtorr. There are neither continuum nor series of visible line emissions, that is, EIR does not occur at all in this plasma condition. Radial profiles of the ion flux measured both in the upstream and the downstream are illustrated in the insets of Fig. 3(a)-(d). The reduction of the ion flux along the magnetic field due to the EIR is found in the insets of Fig. 3(c) and (d). The reduction rates of the ion flux from the upstream to the downstream in Fig. 3(c) and (d) are almost the same, because of a very small helium pressure difference. On the other hand, in the inset of Fig. 3(b), we can see a strong reduction of the ion flux by the injection of a small amount of hydrogen gas. Moreover, the ion flux in the upstream has already decreased compared to that in the case of the pure helium detached plasma. This means that some plasma
volumetric recombination process already starts to occur in the upstream, where $T_e$ is relatively high. From these experimental results, we can conclude that there are the plasma volumetric recombination process coming from the effect of the molecular hydrogen (MAR) in our helium/hydrogen mixture plasma.

The observed helium Balmer series spectra were analyzed with the CRAMD code[1] in detail. The population in excited states and corresponding line intensities are usually determined by the following three different mechanisms; i) EIR, ii) electron impact excitation from the ground state of atoms, and iii) MAR. Precise comparison between the experimental spectra and the relative line intensities obtained with the CRAMD code gives us MAR is the dominant populating mechanism among the above three candidates[2].

4.2 Hydrogen Plasmas with Hydrogen Gas Puff[3]

Radial profiles of the ion particle flux measured in the entrance, upstream and the downstream are shown in Fig. 4, when hydrogen gas was introduced into hydrogen plasmas. The plasma density at the center of the plasma column is about $1.0 \times 10^{19} \text{ m}^{-3}$ at the entrance. At $P \sim 4.0\text{ mtorr}$, 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\text{ mtorr}, there is little change of the ion particle flux in the entrance, however, the ion particle flux in the downstream becomes almost one-fiftieth as large as that in the entrance. We can see a strong reduction of the ion particle flux by the addition of a small amount of hydrogen gas. It is also found that no prominent continuum and series of visible line emissions from highly excited levels due to the conventional EIR were observed in both upstream and downstream at any gas pressure. It indicates
that the EIR does not take responsibility for the reduction of the ion particle flux. These experimental results also 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.

We now consider the detached hydrogen plasma conditions where the EIR or MAR is dominating. The plasma particle loss rate per unit volume due the MAR and the EIR are described as $K_{\text{MAR}}[\text{H}_2]$ and $K_{\text{EIR}}$ respectively, where $[\text{H}_2]$ is hydrogen molecule density and $K$ is rate coefficient. Figure 5 shows the electron temperature dependence of the ratio between the particle loss rate due to the MAR and EIR, that is, $R \sim \frac{K_{\text{MAR}}[\text{H}_2]}{K_{\text{EIR}}}$, 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 0.3eV. Furthermore, to realize the detached hydrogen plasma due to the EIR at relatively high electron temperature about 1eV, much denser plasma ($> 5 \times 10^{19} \text{ m}^{-3}$) with the lower concentration of the hydrogen molecule are found to be required.

5 Conclusion

Our conclusions are as follows;
1. Reduction of the ion particle flux and heat load to the target plate was clearly observed in hydrogen (helium) plasmas with the hydrogen gas puff due to the MAR.
2. Detailed analysis of Balmer and Balmar-like series spectra has been done by using the CRAMD code, which is in a good agreement with the 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 should be required.

References