Observation of charge exchange recombination with the negative ions in detached plasma

Akira Tonegawa, Isao Shirota, Kenichi Yoshida, Masataka Ono, Kazutaka Kawamura*, Tsuguhiro Watanabe** Nobuyoshi Ohyabu**, and Kazuo Takayama*

Department of Physics, School of Science, Tokai University
1117 Kitakaname, Hiratsuka, Kanagawa, 259-1292 Japan.
**Research Institute of Science and Technology, Tokai University*
1117 Kitakaname, Hiratsuka, Kanagawa, 259-1292 Japan.
***National Institute for Fusion Science, Toki, Gifu, 509-5292 Japan.*

Charge exchange recombination (mutual neutralization) in collisions between negative ions and positive ions in molecular activated recombination (MAR) has been observed in a divertor plasma simulators TPDSHEET-IV device. A small amount of secondary hydrogen gas puffing into a hydrogen/helium mixture plasma increased rapidly the density of negative ions of hydrogen atom in the circumference of the plasma, while the conventional radiative and three-body recombination processes were disappeared.

I . Introduction

Recent experiments on diverted tokamaks and divertor simulators have focused on the study of molecular and atomic processes under the detached divertor regimes. Until quite recently, research primarily dealt with plasma momentum/pressure loss which is based on such plasma-neutral interactions as the radiative and three-body recombination, that is, Electron-Ion Recombination (EIR). However, it is difficult from the view of only EIR to explain the loss in plasma particle flux at the plates that occurs as well [1]. In fusion experiments with detached plasma, plasma recombines before it reaches the targets and the recombination is the only process allowing to reduce plasma flux at the wall in fusion experiments without strong impurity radiation loss of EIR [2,3].

The importance of another recombination process associated with molecular reactions, such as the molecular activated recombination (MAR) involving a vibrationally excited hydrogen molecule, has been emphasized in theoretical investigation and modeling[4-6] . In fusion related experiments there are two main paths for MAR: (1)$H_2(v) + e \Rightarrow H^- + H$ followed by $H^- + A^+ \Rightarrow H + A$ (charge exchange recombination: mutual neutralization in collisions between negative ions and positive ions), 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 plasma. However, the role of the MAR in fusion experiments is still under discussions and different conclusions are derived from the analysis of different experiments [2,3,7]. One of the experimental result of the spectroscopy in linear divertor simulator has given the evidence of dissociative recombination in MAR, showing the reduction of ion flux in hydrogen/helium mixture plasma. Another experiments, on the other hand, gave the ambiguous results because it does not define which process is most predominant recombination, the charge exchange recombination or the dissociative recombination. It is, thus, expected that the experiments which will be essential to an understanding of the role of the negative ions come out. In MAR negative ions of hydrogen atom have not reported so far, to the best of our knowledge, in the detached plasma which is observed in diverted tokamaks and divertor simulators.

In this paper, we present the first experimental evidence of the charge exchange recombination in MAR via negative ions formation of hydrogen atom on hydrogen or detached plasma in the linear divertor plasma simulator, TPDSHEET–IV (Test Plasma produced by Directed current for SHEET plasma) [8]. Measurements of the negative ion density of hydrogen atom, the electron density), electron temperature, and the heat load to the target plate were carried out in hydrogen detached plasma with hydrogen gas puff. It is also intended to show that the observed hydrogen Balmer spectra could be explained by the terms of both MAR and EIR.

2. Experimental apparatus

The experiment was performed in the linear divertor plasma simulator TPDSHEET–IV. The TPDSHEET–IV was divided into two regions: the sheet plasma source region and the experimental region for divertor simulator. Hydrogen/Helium mixed sheet plasma was produced by the modified TP-D type dc discharge. The anode slit was 2 mm thick and 40 mm wide. The strength of the uniform magnetic field in the experimental region formed by ten rectangular magnetic coils was of 0.7 kG. The sheet plasma was terminated by the electrically floated and water-cooled target plate, which was made of stainless steel at the axial position of z = 0.7 m from the discharge anode electrode. The hydrogen plasma were generated with the hydrogen gas flow of 70 sccm at the discharge current of 50 A. The neutral pressure P_{Div} in the divertor test region was able to be controlled from 0.1 to 20 mtorr by feeding a secondary gas. The change of P_{Div} in the divertor test region had no effect on the plasma production in the discharge region due to 3 orders of magnitude pressure difference between the discharge and the divertor test regions. The electron temperature and the electron density were measured by the Langmuir probe. The value of W was measured with the calorimetric method. A cylindrical probe made of tungsten (0.4 x 2 cm) was used to measure the spatial profiles of H^- by a probe-assisted laser photodetachment method [9-11]. The maximum power of fundamental (1064 nm) radiation of the laser was 120 mJ. The laser width was about 10 ns and the diameter of a laser beam was 3 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 with the Laser beam. The Balmer spectra of visible light emission from hydrogen or helium atoms were detected at the axial position of 3 cm apart from the target plate. Analysis of the Balmer series line intensities show that the upper levels of these transitions are populated primarily by radiation recombination. Thus the brightness of the Balmer series, such as the 5-2 is directly related to the recombination rate of EIR. Therefore the ratio of the 5-2 to 3-2 line intensities can be used as EIR indicator.

3.Experimental Results and Discussion

Figure 1 shows the dependence of W to the target plate, the hydrogen and helium Balmer spectrum ratio closed circle H_γ(2p-5d)/H_α(2p-3d) and open circle He(2p-5d;T)/He(2p-3d;T) of visible light emission, the variations of electron density N_{ec}, the electron temperature T_{ec} at the center of sheet plasma, and the maximum value to the y-direction profile of the negative ion density of hydrogen atom H^-_{max}, on hydrogen gas pressure P_{Div}.

The Langmuir probe was located at 3 cm apart from the target plate. With an increase in

P_{Div}, the value of W is found to decrease rapidly, being an order of magnitude smaller than that of the initial value until P_{Div} ~ 6 mtorr. The value of T_{ec} rapidly decreases from 15 to 4 eV. On the other hand, N_{ec} slightly increases from $3x10^{18}$ to $6x10^{18}$ m^{-3} until P_{Div} ~ 6 mtorr for ionization, while the hydrogen and helium Balmer spectrum ratio H_γ(2p-5d)/H_α(2p-3d)and He(2p-5d;T)/He(2p-3d;T) of visible emission remains to be constant. Above P_{Div} ~ 6 mtorr in which T_{ec} is less than 4 eV, we can observe a sudden drop from $6x10^{18}$ m^{-3} to 10^{17} m^{-3} in N_{ec} rapid increase of the maxim in the photon ratio H_γ(2p-5d)/H_α(2p-3d) and He(2p-5d;T)/He(2p-3d;T). At a small amount of secondary hydrogen gas puffing into a hydrogen plasma H^-_{max} have a maximum characteristics until P_{Div} ~ 6 mtorr and the maximum value of H^-_{max} is $5x10^{16}$ m^{-3} at P_{Div} ~ 2 mtorr. After P_{Div} ~ 8mtorr, H^-_{max} disappears and visible light emission strongly very bright visible light emissions of the hydrogen Balmer spectrum of the spectra of atomic levels with relatively high principal quantum numbers were observed in front of the target plate (full detachment region).

In the detached plasma experiments, plasma recombines before it reaches the targets and such recombination is the only process allowing the reduction of both plasma flux and heat flux at the wall without strong impurity radiation loss of EIR. As a result, it is noted that the detached plasma is achieved by a small amount of secondary hydrogen gas puffing into a hydrogen/helium mixture plasma, although the conventional processes were quenched. Very bright visible light emissions in front of the target plate, moreover, were observed in the detached plasma. A further increase in P_{Div} leads to keep the bright emission region (full detachment region) far apart from the target plate, then it appears a clear dark region between the target plate and the region with the bright visible emissions, resulting the rapid decrease of the photon ratio H_γ(2p-5d)/H_α(2p-3d) and He(2p-5d;T)/He(2p-3d;T). This channel corresponds to the radiation and three-body recombination as EIR.

Figure 2 shows the spatially profiles to the y-direction of the negative ion density of hydrogen atom H with changing the secondary hydrogen gas pressure P_{Div}. The produced sheet plasma has a large gradient of electron temperature with two characteristics in the narrow space of several cm: hot plasma (~15 eV) in the center region and the cold plasma (3-4eV) in the outer region. At P_{Div} ~ 2 mtorr, both T_e and N_e have hill-shape profiles with the half width of N_e of the sheet plasma is about 5 mm. At a small amount of secondary hydrogen gas puffing into a hydrogen/helium mixture plasma, H^- is localized in the outer region (y =10-15 mm) existing cold electrons (Ne = $2x10^{17}$ m^{-3}, Te= 3-4 eV) of the circumference of the plasma. At P_{Div} ~ 5 mtorr, the peak value of H^- is $5x10^{16}$ m^{-3} and the ratio of H^-/Ne in the outer region goes up to over 20%. These experimental results suggest that the plasma recombination process comes from the charge exchange recombination of positive and negative ion of hydrogen atom in outer region of sheet plasma.

4.Conclusion

We have performed the experiments of the detached hydrogen plasma associated with MAR in a linear divertor plasma simulators TPDSHEET-IV. The reduction over 80 % of heat load to the target plate was clearly observed in hydrogen/helium mixture plasma with the hydrogen gas puff. The negative ion density of hydrogen atom is observed in the outer region with cold electrons of the sheet plasma.

Refereces

[1] S.I.Krasheninnikov, Contribution to Plasma Phys. 36, 293(1996).
[2] S.I.Krasheninnikov et al, Phys. Plasma 4,1638(1997).
[3] J.L.Teery et al, Phys.Plasma 5,1759(1998).

[4] S.I.Krasheninnikov et al, Phys. Lett. A 314,285(1996).
[5] A.Yu.Pigarov et al, Phys. Lett. A 222, 251(1996).
[6] D.E.Post, J.Nucl.Mat. 220-222, 143(1995).
[7] R.F.G.Meulenbroeks et al, Phys.Rev.Lett. 82,2215(1999).
[8] A.Tonegawa et al, J.Advanced Science, 11,232(1999).
[9] M.Bacal et al, Rev.Sci.Inst. 50,719(1979).
[10]M.Bacal, Rev.Sci.Inst. 71,3981(2000).
[11]H.Amemiya et al, Jpn.J.Apppl.Phy. 29,L1712(1990).

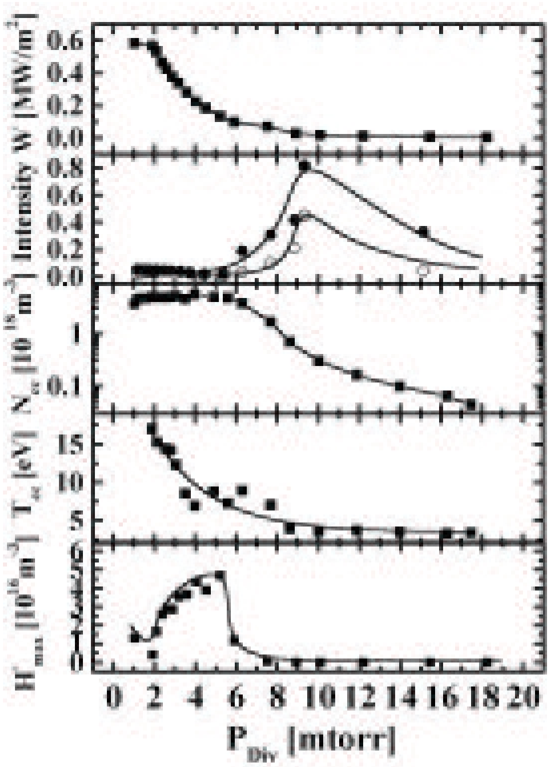

Fig.1 The dependence of W, the hydrogen and helium Balmer spectrum of visible light emission closed circle H_γ(2p-5d)/H_α(2p-3d) and open circle He(2p-5d;T)/ He(2p-3d;T), the variations electron density N_{ec}, the electron temperature T_{ec} at the center of sheet plasma, and the maximum value to the y-direction profile of H^-_{max}, on hydrogen gas pressure.

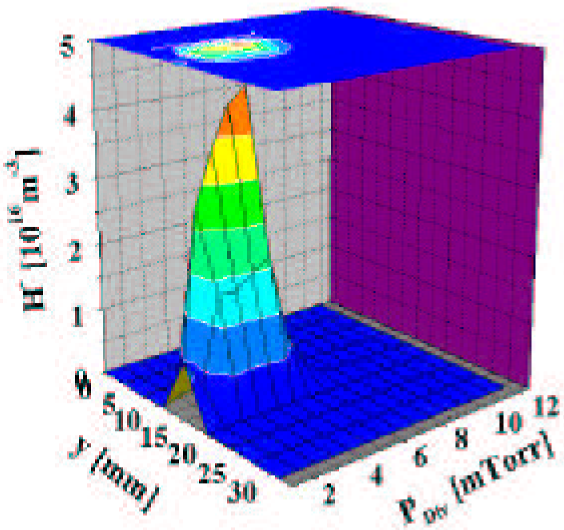

Fig.2 The spatially profiles to the y-direction of the negative ion density of hydrogen atom H with changing the secondary hydrogen gas pressure P_{Div}.