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Hydrogen recycling study by Balmer lines emissions in linear plasma machine TPE

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Abstract

We have investigated the influence of target materials and temperatures on Balmer series emission in a linear plasma apparatus, Tritium Plasma Experiment (TPE). The intensities of the Balmer series emission in front of the target were higher for heavier mass target and also for lower target temperature, showing rather linear relationship between the emission intensity and hydrogen reflection coefficient. For exothermic hydrogen occluders of Ti and Ta, the intensity ratio of $D\beta/D\alpha$ increased with the target temperature markedly, whereas the intensity ratio stayed rather constant for endothermic hydrogen occluders of Ni, Cu and W. This is a clear demonstration that the target materials and temperatures modify the boundary plasma. In addition the intensity ratio $\mathrm{D}\beta/\mathrm{D}\alpha$ is not simply a function of plasma temperature but has clear target temperature dependence.

Keywords: Hydrogen recycling; Balmer lines; Exothermic hydrogen occluders; Endothermic hydrogen occluders; Plasma–material interaction

1. Introduction

Hydrogen recycling process at a limiter or divertor plate in fusion systems plays an important role not only in boundary plasma physics but also in engineering aspects. Most of the hydrogen recycling studies in tokamaks are relying on Balmer series line emission in the boundary plasma [1–5]. Generally the line emission is assumed to be caused by the electron excitation of ground-state atoms and molecules in the boundary plasma. The hydrogen particles from the wall include lots of different species, i.e., backscattered neutrals and ions, ion-induced desorption atoms, ions and molecules, and reemitted molecules. Nevertheless, in most of the recycling simulations, hydrogen released form the wall has been assumed to be in the ground state. Recent laboratory studies, however, have indicated that target materials and their temperature could change Balmer lines emission due to changes in reflection coefficients, and reemission of excited molecules and atoms [6].

In order to examine how materials and temperature influence the intensity of Balmer lines emissions, we have made detailed measurements of deuterium Balmer series emissions in front of various target materials (Cu, Ti, Ni, Ta and W) in the linear plasma apparatus, Tritium Plasma Experiment (TPE).

2. Experiment

Experiments were performed in the Sandia National Laboratories TPE [7]. The schematic of TPE is shown in Fig. 1. The plasma is generated by the ion source and electrically and magnetically guided through vacuum vessel to the main chamber, in which electron tempera-

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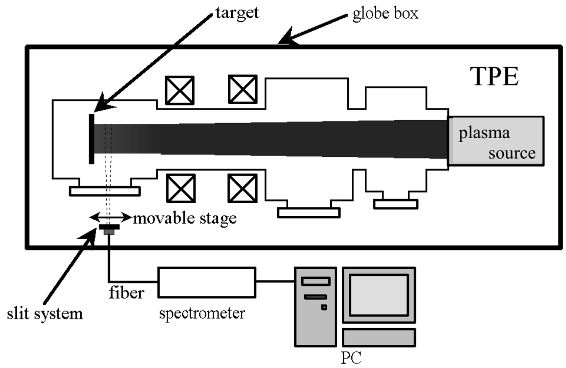

Fig. 1. Experimental setup in TPE.

ture and density are 10–15 eV and approximately 10^{19} ions/m^3, respectively. Negative biasing of the target around 130 V leads to a particle flux of approximately 3.9×10^{21} ions/m^2 s or a current density of 1.3 A. The predominant ion species in TPE is D^+, with about 10% D_2^+ and a smaller component of D_3^+. This means that about 20% of the deuterium ions entering the sample has an energy of 65 eV and a few percent has an energy of 43.3 eV. Therefore, the effect of D_2^+ and D_3^+ is small due to most of the ions having an energy of 130 eV. The metal sample, 50 mm in diameter and 2 mm in thickness, is fixed at a sample holder, of which temperature is controlled by plasma heating and cooling by either water or N_2 gas. Because of the high heat flux, the target temperature was settled after several minutes of irradiation. As the target metals, Ti, Ni, Cu, Ta and W were used. Ti and Ta are exothermic hydrogen occluders that mean the hydrogen absorption process is exothermic, whereas Ni, Cu and W are endothermic ones that mean the hydrogen absorption process is endothermic. Target mass numbers of Ni and Cu are similar, as are Ta and W. In Ti and Ta the target temperature was sometimes suddenly skyrocketed by the heat generation owing to hydride formation.

The experimental apparatus is in a glove box because of using tritium. The Balmer series emission of deuterium was simultaneously recorded through a light collecting system with an entrance slit and photo multichannel analyzer, PMA11 (Hamamatsu Photonics) in the wavelength region 250–900 nm with a wave-length resolution of less than 2 nm. The light collecting system was remotely controlled to move parallel to the plasma column from the target position to 100 mm deep in the plasma. The width of the entrance slit was set to be 0.5 mm so that the space resolution of the light collection system was about 2.0 mm parallel to the plasma column. Light accumulation time was selected to be 1–1.5 s in order to avoid plasma instability and to optimize S/N ratio.

3. Results

Fig. 2 is a typical spectra for the W target, where are seen the Balmer series line emission ($D\alpha, D\beta, D\gamma, D\delta$), D_2 band emission and various line emissions due to impurities observed irrespective of the target materials. Fig. 3 shows changes of $D\alpha$ line intensity with the distance from the target at around 600–700 K. In the vicinity of the target, the $D\alpha$ intensity increases linearly with the distance, and saturates far from the target. The linear increase is simply due to the geometry of the light collecting system, i.e., suppose the emission intensity is the same everywhere in the plasma column, the intensity change simply reflects the measured volume of the plasma column. Thus the intensity is just a half at the target position (at 59 mm) compared with that intensity at the position of over 70 mm.

The $D\alpha$ intensities were clearly different with the target materials, and the heavier the target mass, the higher the intensity. This was also true for $D\beta$ and $D\gamma$. However, the ratios of $D\beta/D\alpha$ and $D\gamma/D\alpha$ showed different dependence on the distance as shown in Fig. 4, where is shown the dependence of the intensity ratios of $D\beta/D\alpha$ on the distance form the target. The ratio

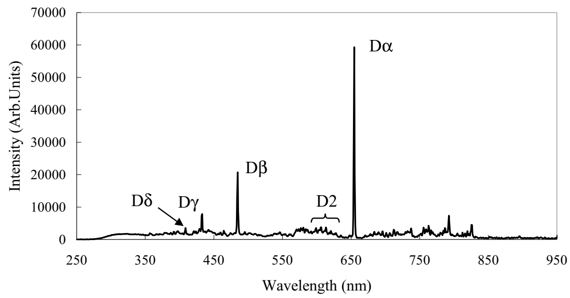

Fig. 2. Emission spectra from deuterium plasma for W target. The Balmer series emission ($D\alpha, D\beta, D\gamma, D\delta$), D_2 band spectrum and the spectrum from the impurities were observed.

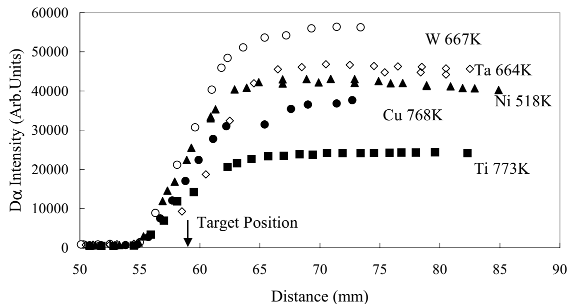

Fig. 3. Change of $D\alpha$ intensity with the distance from the target at around 600–700 K. $D\beta$ and $D\gamma$ intensities showed the same tendency.

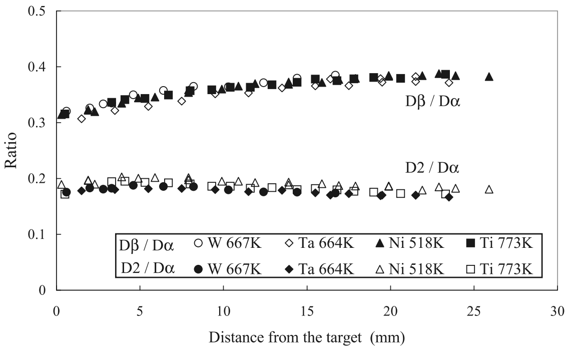

Fig. 4. Change of $D\beta/D\alpha$ intensity ratio and Change of $D_2/D\alpha$ (as for the intensity of D_2 band, intensities from deuterium molecular emission of 569.9, 580.4 and 586.3 nm are summed up) with the distance from the target. $D\gamma/D\alpha$ showed the same tendency as $D\beta/D\alpha$.

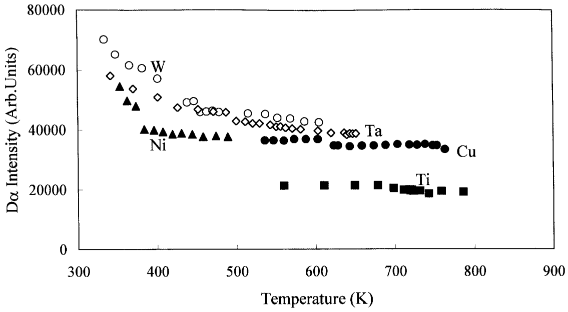

Fig. 5. Dependence of $D\alpha$ intensity at 2.1 mm from the target on target temperature.

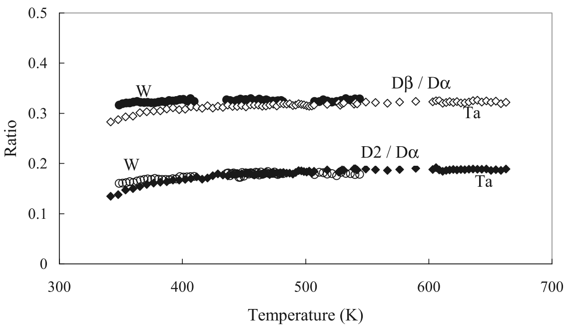

Fig. 6. Dependence of $D\beta/D\alpha$ and $D_2/D\alpha$ intensity ratio on targets temperature for W and Ta.

increased with the distance from the target irrespective of the target materials. The ratio of $D\gamma/D\alpha$ showed the same tendency. Such increases of emission from the higher excited states may correspond to the higher electron temperature at the farther distance from the target.

The increase of higher excited emission is also appreciable in recombination plasmas [8]. Therefore reemitted molecules from the target may be also important. In the original spectra, D_2 molecular band emissions were also appreciable in addition to the Balmer lines emission. Fig. 4 also shows dependence of intensity ratio of the D_2 band (as for the intensity of the D_2 band, intensities from deuterium molecular emission of 569.9, 580.4 and 586.3 nm are integrated) and $D\alpha$ on the distance from the target. Different from the Balmer series emission, the intensity of the D_2 band emission at the plasma column (far from the target) did not change very much with target materials, except those at the vicinity of the target. The $D_2/D\alpha$ ratio increased with the distance from the target until reaching to a broad maximum at about 5 mm from the target, and then decreased for all materials. This means the D_2 band emission at the plasma column is mainly due to deuterium molecules in the vacuum chamber, while reemitted molecules play only limited role at the vicinity of the target. The little deviation of Ni is mainly due to lower temperature (517 K), where $D\alpha$ emission is little higher as seen in Fig. 5. Fig. 5 shows changes of the $D\alpha$ intensity at 2.1 mm from the target with target temperature. The $D\alpha$ intensity clearly decreased with increasing the temperature, and at 600 K, the $D\alpha$ intensities were nearly the half of those at 350 K. Above 600 K the intensities did not change much.

The intensities of $D\beta$ and $D\gamma$ also showed the same tendencies, but the decrease was less significant than that of $D\alpha$. Fig. 6 compares the temperature dependence of the intensity ratio of $D\beta/D\alpha$ and $D_2/D\alpha$ for Ta and W. One can see the $D\beta/D\alpha$ for Ta increases more slowly with increasing temperature than that for W. The difference can be attributed to molecular reemission, i.e., in the exothermic hydrogen occluders most of the deuterium (except the reflected hydrogen) are retained at lower temperatures and reemission increases with temperature, whereas in the endothermic hydrogen occluders the reemission starts much lower temperature. This is more clearly seen in the temperature dependence of $D_2/D\alpha$ ratio in Fig. 6, where the ratios increase with temperature and saturate at higher temperatures for all materials. However the ratio for Ta saturates at higher temperature than that for W, and it is also observed that the ratio for Ti saturates at higher temperature than Ni. Thus the reemission for exothermic hydrogen occluders of Ta and Ti is delayed compared with that in the endothermic hydrogen occluders as demonstrated by the intensity delay in the saturation of $D\beta/D\alpha$ for Ta and Ti.

4. Discussion

As clearly seen in Figs. 3 and 5, the $D\alpha$ intensity increases with the mass of the targets. Since the deute-

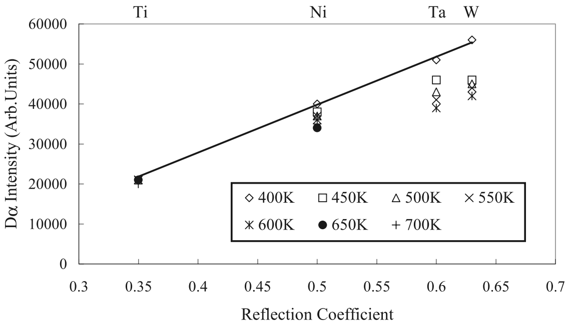

Fig. 7. Dependence of Dα intensity with target materials plotted as a function of reflection coefficients.

rium reflection coefficient increases with an atomic number, the Dα intensities are plotted against the reflection coefficients of the target materials in Fig. 7. Surprisingly, the plot shows a quite good linear relationship. With increasing temperature, the gradient becomes smaller and deviation from the linear relationship becomes large.

This means that the Dα emission in TPE is dominated by reflected atoms and not reemitted molecules. Probably reemitted D_2 molecules from the target are shielded and cannot easily penetrate to the plasma column. With increasing target temperature, contribution of the reemitted molecules should increase, whereas the total Balmer emission was observed to decrease. This is a little strange, because in a general sense hydrogen recycling should increase so as the Balmer lines emission, owing to the increase of the reemitted atoms with increasing temperature. One possible reason may be the increase of excited or ionized atoms in reflected particles with increasing temperature, in other words, the increase of penetration depth to the plasma reduces the emission near the target.

Balmer lines emission is often used for the determination of electron temperature through the Boltzman plot. In this respect, the increase of Dβ/Dα with increase of the target temperature should correspond to the increase of the electron temperature.

At higher temperature, however, such simple estimation may be wrong. One can see clear difference in Dβ/Dα ratios between the exothermic hydrogen occluder (Ta) and the endothermic one (W) in Fig. 6. The difference can be attributed to molecular reemission, i.e., in the endothermic hydrogen occluders, most of the deuterium (except the reflected hydrogen) are retained at lower temperatures, while with increasing temperature the molecular reemission increases. This is more clearly seen in the temperature dependence of D_2/Dα ratio in Fig. 6, where both the ratios for Ta and W increase with the temperature and saturate at higher temperatures but the saturation for Ta is delayed markedly. The ratio for Ti saturates at higher temperature than Ni too.

Thus the reductions of the Dα intensity and the increase of Dβ/Dα ratio with the temperature are attributed to the increase of the reflected energy i.e., increase of the excited atoms and molecules which in turn results in the increase of the plasma temperature. The increase of molecular remission also has some contribution through molecular recombination which would contribute to higher excited emission.

5. Conclusion

In the vicinity of the target, the intensities of the Balmer lines emission were higher for the heavier mass target and also for the lower target temperature. For Ti and Ta targets, the intensity ratios of Dβ/Dα increased with the target temperature markedly, whereas they stayed rather constant for the Ni, Cu and W targets. In the former, most of the implanted hydrogen (except the reflection) are absorbed at lower temperatures, but the molecular reemission (recycling) increases with increasing temperature.

Accordingly, the decrease of the Dα intensity for Ta with increasing temperature was not so significant as that for W and Dβ/Dα for Ta increased more markedly probably due to the molecular recombination. These results clearly demonstrate that the Balmer line emission can be varied with a target character and temperature, i.e., the character of the target materials can change the edge plasma.

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