Hydrogen Recycling Study with a High Temperature Target in the Divertor Simulation Experiment in GAMMA 10/PDX*)

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Hydrogen recycling with a high-temperature W target has been studied in GAMMA 10/PDX. The V-shaped target with W plates was heated up to 573 K and then exposed to the end-loss plasma. When the target temperature was increased from room temperature to 573 K, the intensities of the H_α and H_β lines almost doubled even though the electron density increased from $\sim 2.3\times10^{16}$ m^{-3} to $\sim 2.6\times10^{16}$ m^{-3}, an increase of $\sim 12\%$. On the contrary, the electron temperature did not change at approximately 30 eV. The vibrational temperature was ~ 3400 K and did not change, thus suggesting that the hydrogen molecules were highly vibrationally excited and that the vibrational level did not change. The intensities of the Q1-branch of the Fulcher-α band almost doubled, thus indicating that the molecular density of hydrogen also doubled. The increase of the Balmer-line intensities with increasing target temperature may be caused by the increase in the excited hydrogen atoms produced by the dissociation of vibrationally excited molecules desorbed from the high-temperature target. This increase in excited hydrogen atoms enhances the overall hydrogen recycling.

Keywords: GAMMA 10/PDX, divertor-simulation experiment, hydrogen recycling, high-temperature target, Fulcher-α band spectroscopy

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1. Introduction

Hydrogen recycling is important for stable plasma operation in fusion reactors and for the improvement of plasma confinement. Global wall saturation, which leads to a loss of density control, has been observed during long duration discharges in the TRIAM-1 M and JT-60U tokamaks [1, 2]. The increase in wall temperature is the key to understanding global wall saturation. Therefore, hydrogen recycling in high-temperature walls or targets should be investigated.

In GAMMA 10/PDX, hydrogen recycling with a high-temperature target has been studied using a divertor-simulation experimental module (D-module) installed in the west end region [3]. The background neutral pressure in the vacuum vessel of GAMMA 10/PDX is low enough ($\sim 10^{-8}$ Torr) to clearly observe the behavior of the recycled neutrals. We observed that the H_α intensity ($I_{H\alpha}$) and the electron density (n_e) in front of the target increases with increasing target temperature, thus indicating that recycling is enhanced owing to the increase in target temperature [3]. The interactions of hydrogen molecules with a high-temperature target are involved with the recycling enhancement mechanism. In the current study, the spectra of the Fulcher-α band were measured to evaluate the electronic ground state of the vibrational temperature (T_{vib}) and rotational temperature (T_{rot}) of the hydrogen molecules ($X^1\Sigma_g^+$). This study also discusses the enhancement of hydrogen recycling due to increased target temperature.

2. Experimental Setup

The tandem mirror GAMMA 10/PDX consists of a central cell, anchor cells, plug-barrier cells, and end regions. The main plasma is produced and maintained by ion-cyclotron range-of-frequency (ICRF) heating at the central cell. The D-module is installed at the west end to simulate a divertor by using end-loss plasma. Figure 1 shows a schematic view of the D-module. The D-module consists of a rectangular box with a 480 mm × 500 mm × 700 mm dimension. An inlet aperture is included in the front panel, and a V-shaped target is installed inside the box. Sheath electric heaters and thermocouples are attached to the backside of the V-shaped target to control the target temperature (T_{target}). The V-shaped target is exposed to the end-loss plasma. Neutral gas pressure in the D-module is measured by an ion gauge installed at the top.

Figure 2 (a) shows the line of sight of the spec-

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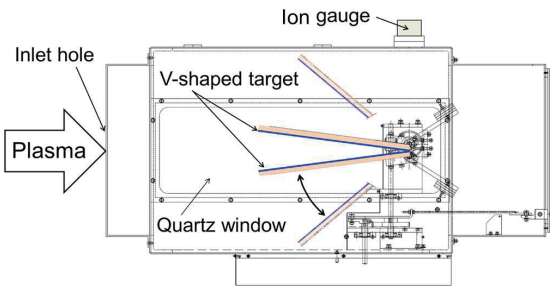

Fig. 1 Schematic view of the D-module.

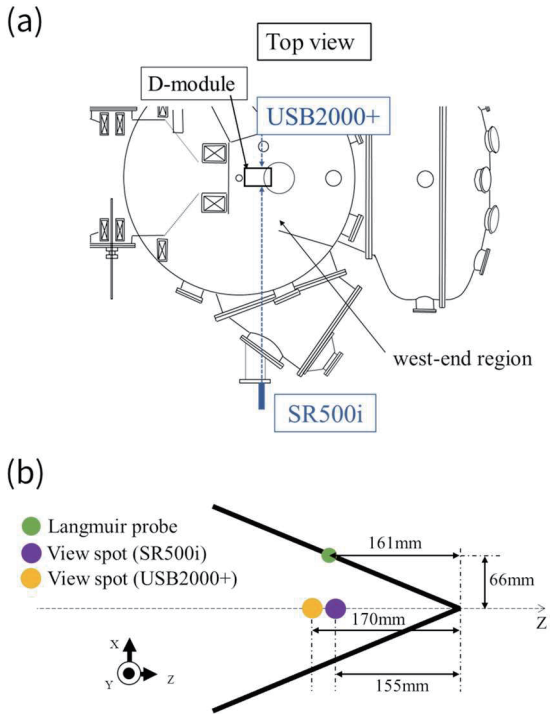

Fig. 2 (a) Top view of the west end region and line of sight of the spectrometers (USB2000+ and SR500i); (b) measurement positions of Langmuir probes and USB2000+ and SR500i.

trometers. Balmer-line intensities were measured with a low-dispersion spectrometer (USB2000+, Ocean Optics). Fulcher-α band spectral intensities were measured using a high-dispersion spectrometer (SR500i, Andor). Figure 2 (b) shows the measurement positions of the spectrometers and Langmuir probes.

3. Results and Discussion

In this study, the main plasma was produced and maintained by ICRF heating at the central cell of GAMMA 10, and the plasma duration was 400 ms. The V-shaped target was exposed to the end-loss plasma, and the temperature of the V-shaped target varied from room temperature ($\sim$ 300 K) to $\sim$570 K shot-by-shot. The pressure in the D-module was 5.8×10^{-7} Torr when the T_{target} was 330 K and 6.2×10^{-7} Torr when at 573 K without plasma. The change

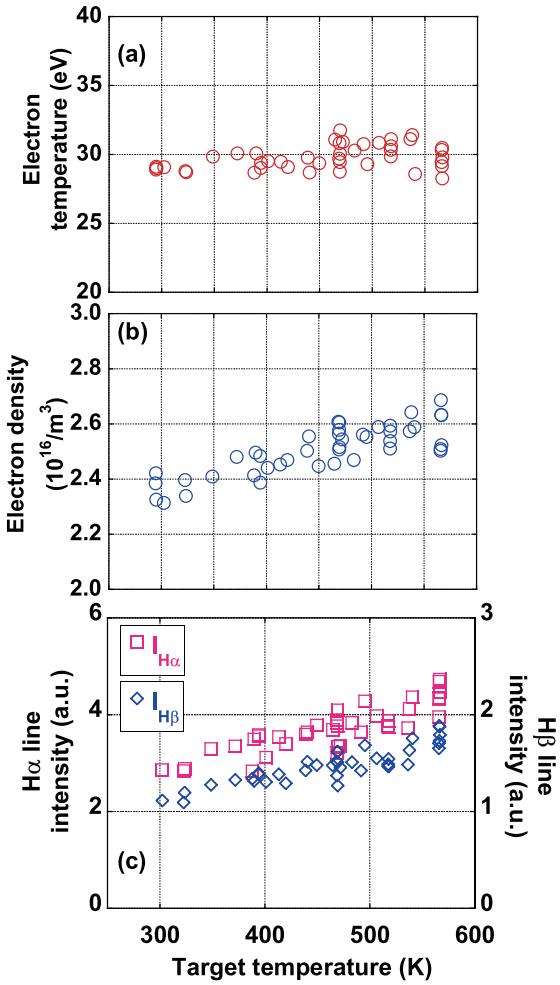

Fig. 3 (a) Electron temperature, (b) electron density, and (c) H_α and H_β intensities measured by spectroscopy (USB2000+) as a function of the target temperature.

in the neutral pressure in the D-module was 6.7%, which is low enough that outgassing can be ignored.

Figure 3 shows the electron temperature (T_e), n_e, $I_{H\alpha}$, and H_β intensity ($I_{H\beta}$) in front of the target as a function of the T_{target}. The values of $I_{H\alpha}$ and $I_{H\beta}$ almost doubled when the T_{target} increased from room temperature to 573 K. The electron density increased from $\sim 2.3 \times 10^{16}$ m^{-3} to $\sim 2.6 \times 10^{16}$ m^{-3}. The increase in the Balmer-line intensities was larger than that of n_e. On the other hand, T_e was nearly constant ($\sim$ 30 eV), thus indicating that the rate coefficients of electron-impact excitation and ionization were not affected by the change in T_{target}. The mean free path of excitation for $n = 1$ to $n = 3$ is $\sim$ 100 m, which is longer than the dimensions of the plasma. Therefore, the increases in $I_{H\alpha}$ and $I_{H\beta}$ are not caused by electron-impact excitation. The significant increase in the ratio $I_{H\alpha}/n_e$ suggests that the production of excited atoms is due to dissociative excitation. Excited hydrogen atoms are produced by the dissociation of vibrationally excited hydrogen molecules, and the dissociation rate increases with the vibrational level and density of vibrationally excited

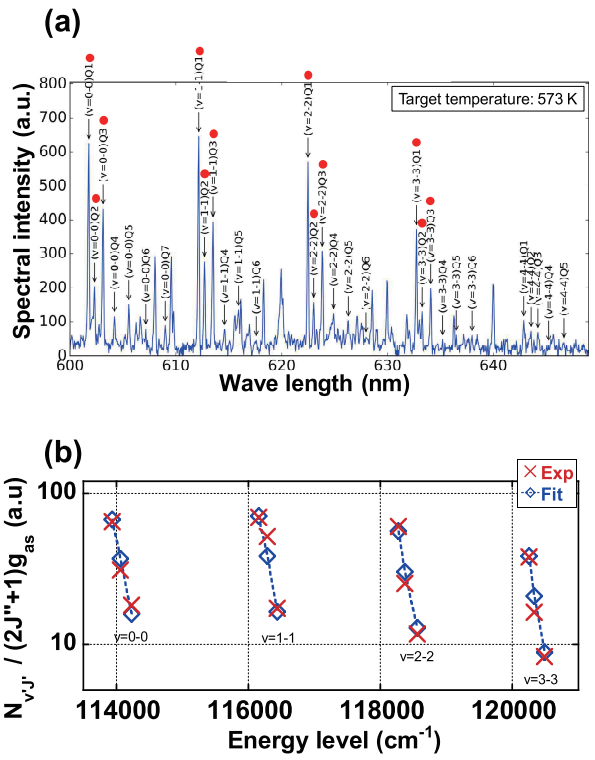

Fig. 4 (a) Fulcher-α band spectrum and (b) relative population densities of $d^3\Pi_u^-$ for various rovibrational states at the target temperature of 573 K.

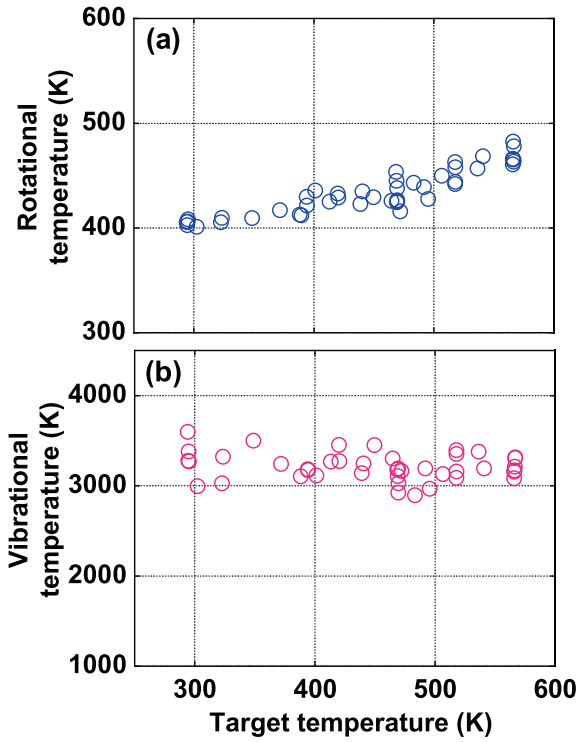

Fig. 5 (a) Vibrational temperature (T_{vib}) and (b) Rotational temperature (T_{rot}) as a function of T_{target}.

molecules [4].

Figure 4 (a) shows a Fulcher-α band spectrum with a T_{target} of 573 K. The exposure time in this measurement was ~ 250 ms to increase the S/N ratio. Figure 4 (b) shows the relative population densities of $d^3\Pi_u^-$ at 12 rovibrational states. The data are well fitted by a Boltzmann–Maxwellian distribution of $d^3\Pi_u^-$ population density, and a corona model is adopted such that T_{vib} and T_{rot} are ~ 3400 and ~ 460 K, respectively. In low-density plasma, such as that in the present experiments (i.e. $\sim 10^{16}$ m^{-3}), the assumption of coronal equilibrium is considered valid [5, 6].

The vibrational temperature was rather high compared with the target temperature, thus indicating that the vibrationally excited level of the molecules is significantly higher than that expected at the thermal equilibrium between the molecules and the target. Vibrationally excited molecules are produced by transitions of B-singlets and C-singlets to the electronic ground state ($X^1\Sigma_g^+$) via $X^1\Sigma_g^+ \rightarrow B^1\Sigma_u^+$, $C^1\Pi_u$ electron-impact excitation [7]. Vibrationally excited hydrogen molecules have been observed to be produced by atom recombination with Cu and W materials [8]. Hot-atom recombination on the material has been proposed to be a mechanism for the production of vibrationally excited hydrogen molecules [9, 10]. In the present experimental conditions (i.e. $n_e = 2.5 \times 10^{16}$ m^{-3}, $T_e = 30$ eV), the mean free path of the electron-impact excitation of $X^1\Sigma_g^+ \rightarrow B^1\Sigma_u^+$, $C^1\Pi_u$ is estimated to be ~ 5 m, which is approximately one order of magnitude longer than the D-module. Hot-atom recombination on the W target may be the dominant source of vibrationally excited molecules, although electron-impact excitation is also involved in the production of vibrationally excited hydrogen molecules.

Figure 5 plots T_{vib} and T_{rot} as a function of T_{target}. The rotational temperature increased with increasing T_{target}, but the temperatures were not equal. The difference between T_{rot} and T_{target} may be attributed to the collisions of molecules desorbed from the target with the room temperature wall and with high-temperature ions (~ 400 eV). On the contrary, T_{vib} did not change when T_{target} increased, thus indicating that the vibrationally excited level of the hydrogen molecule did not change when T_{target} changed. The observation of constant T_{vib} seems to be reasonable because electron-impact excitation and hot-atom recombination do not depend on the T_{target}.

As shown in Fig. 6, the intensities of the Fulcher-α band Q1-branch (I_{Q1}) almost doubled when the T_{target} increased from room temperature (~ 300 K) to ~ 570 K. The intensities of the Q1-branch are proportional to the molecule density when T_e and T_{vib} are constant. Figure 6 shows that the density of hydrogen molecules increased with T_{target} because T_e and T_{vib} were constant (Figs. 3 (a) and 5 (b)). We consider that the molecule density increases with the enhancement of surface recombination due to the increase in T_{target}. The increase in Balmer-line intensities with increasing T_{target} is likely caused by the increase in the number of excited hydrogen atoms produced by the disso-

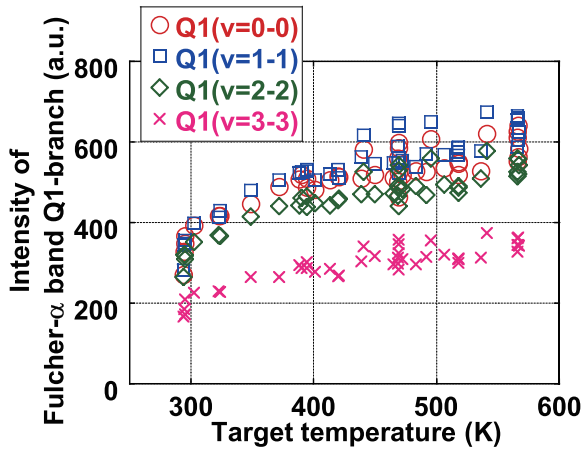

Fig. 6 Intensity of Fulcher-α band Q1-branch as a function of T_{target}.

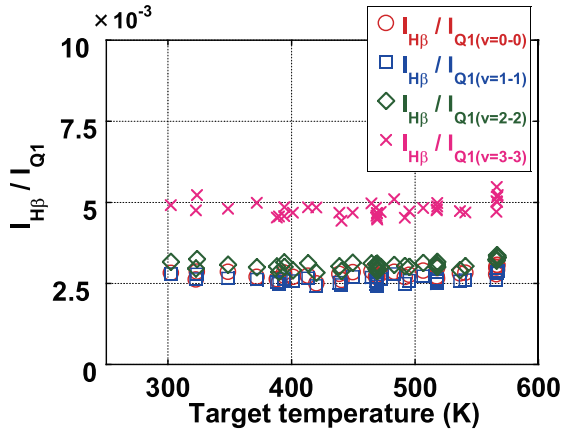

Fig. 7 The ratio of $I_{H\beta}$ to I_{Q1} as a function of the T_{target}.

ciation of vibrationally excited molecules desorbed from the target. The electron density may be increased by the ionization of these excited hydrogen atoms.

Figure 7 shows that the ratios of $I_{H\beta}$ to I_{Q1} are constant with increasing T_{target}. The ratio of $I_{H\beta}/I_{Q1}$ is a good indicator of the density ratio of hydrogen atoms to molecules when T_e and T_{vib} are constant [11]. Given that the ratio of densities of hydrogen atoms and molecules did not change with the T_{target}, the dissociation of molecules that was desorbed from the target was not enhanced in the range $T_{target} < 573$ K. This finding is consistent with the result that T_{vib} remained constant with increasing T_{target}.

4. Summary

The effect of the target temperature on hydrogen recycling was studied using a D-module with a V-shaped W target exposed to the end-loss plasma. When T_{target} was increased from room temperature to 573 K, the intensities of the H_α line, H_β line, and Fulcher-α band Q1-branch doubled even though n_e increased only by ~ 12%, and T_e was constant. The vibrational temperature (T_{vib} = 3400 K) was significantly higher than T_{target} and remained constant, thus suggesting that the hydrogen molecules were highly vibrationally excited, and the vibrational level remained constant. The twofold increase in the Q1-branch intensity indicates that the molecule density doubled owing to the increase in T_{target} because T_e and T_{vib} were both constant. The ratio between the densities of hydrogen atoms and molecules was also unaffected by T_{target}, thus indicating that the rate of dissociation was constant. The significant increase in Balmer-line intensities with T_{target} must be caused by an increase in the number of excited hydrogen atoms produced by the dissociation of vibrationally excited molecules, which leads to an increase in n_e, because the excited hydrogen atoms can be easily ionized by low-energy electrons. This study suggests that vibrationally excited molecules are produced by hot-atom recombination on the target. Therefore, hydrogen recycling is enhanced by the increase in the number of vibrationally excited molecules desorbed from the high-temperature wall.

Acknowledgments

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