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Spectroscopic study of hydrogen particle behavior in attached and detached divertor plasmas of JT-60U

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Abstract

Hydrogen particle behavior, especially H_2 molecule behavior, has been studied spectroscopically in attached and detached divertor plasmas of JT-60U. The decay lengths of the H_2 Fulcher line intensity in attached and detached divertor plasmas were roughly 1 cm and 4 cm, respectively. The fall in intensity of the H_2 Fulcher lines with distance from the divertor plates was reproduced by calculation using a neutral transport and a collisional radiative model code. Molecular assisted recombination was estimated to be as important as H^+–e recombination in a detached divertor plasma.

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1. Introduction

In fusion plasma research, understanding of hydrogen particle (H_2, H and H^+) behavior in the divertor plasma is important to establish the capability of the divertor to control heat and particle loads [1]. In attached divertor plasmas, the H^+ ions recombine at the divertor plates, and the H_2 molecules and H atoms released from the divertor plates are ionized a short distance away. In detached divertor plasmas, which are attractive for mitigating the severe problem of concentrated power loading of the divertor plates, volume recombination of the H^+ ions is considered important in reducing the ion flux to the divertor plates. The H_2 molecules play an important role as a source of cold H^+ ions, but they may also play a role as a sink of the H^+ ions streaming toward the divertor plates by molecular assisted recombination (MAR) [2]. Recently, spectroscopic observation of the H_2 molecules in divertor plasmas and its analysis using a collisional radiative model have been performed to study the H_2 molecule behavior in ASDEX [3,4].

This paper presents a spectroscopic study of hydrogen particle behavior, particularly H_2 molecule behavior, in attached and detached divertor plasmas of JT-60U. Spatial intensity profiles of the H_2 molecule Fulcher lines have been measured; these profiles have been analyzed using a neutral transport and a collisional

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radiative model code. Contribution of MAR is estimated.

2. Experimental

The diagnostics for the present study are shown in Fig. 1. Using a visible spectrometer with 60-ch optical fiber arrays, H I Balmer-series lines and H_2 Fulcher lines ($d^3\Pi_u \rightarrow a^3\Sigma_g^+$) were observed. The spectrometer was a Czerny-Turner spectrometer with an image-intensified CCD camera. The spectral resolution and the spatial resolution were 0.29 nm and 1 cm, respectively. The spectral range covered in a discharge was 37 nm, and the Balmer-series and Fulcher lines were separately observed identical discharges. Electron temperature, electron density and ion flux at the divertor plates were measured with Langmuir probes. In the present study, we will investigate outer divertor plasmas, for which the viewing chords of the spectrometers were parallel to the outer divertor plates.

Fig. 2 shows time evolution of several plasma parameters in the L-mode discharge (plasma current: 1.5 MA, toroidal magnetic field: 3.5 T, NBI heating power: 4 MW) to be investigated. By a feedback technique using H_2 gas puffing, the electron density was raised and then maintained at 52% of the Greenwald density limit. After onset of an X-point MARFE at 7.9 s, the gas-puffing rate decreased. The ion fluxes to the inner and the outer divertor plates rolled over around 6.3 and 7.2 s, respectively. They decreased drastically, when the MARFE appeared. Therefore, partial detachment started gradually before the MARFE onset, and the detachment became pronounced after the MARFE onset. The H_ε line intensities were integrated over the outer divertor plasma (between the outer divertor plates and the X point) and the inner divertor plasma. The H_ε line intensities increased continuously with electron density, but at the MARFE onset the intensity in the outer divertor rose rapidly. Before the MARFE onset, the H_ε emission profile had peaks around the inner and the outer strike points. When the MARFE appeared, the emission profile had a peak around the X point, in addition to the peaks around the two strike points.

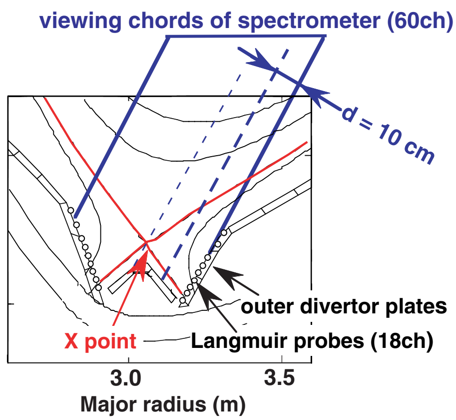

Fig. 1. Divertor diagnostics for the present study.

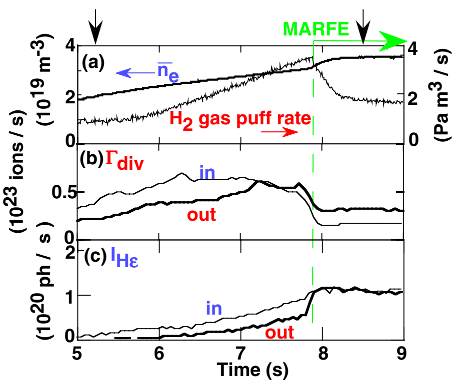

Fig. 2. Time evolution of plasma parameters in an L-mode discharge. (a) Line-averaged electron density in the main plasma and H_2 gas puff rate, (b) ion fluxes to the inner and the outer divertor plates, and (c) intensities of $H\varepsilon$ (λ = 397.0 nm) line emission from the inner and the outer divertor plasma.

In the next section, an attached divertor plasma at 5.2 s and a detached divertor plasma at 8.5 s (indicated by arrows above in Fig. 2) will be discussed. In the attached divertor plasma, the electron temperature and density measured with the Langmuir probe near the outer separatrix strike point were 20 eV and $0.7 \times 10^{19}\ m^{-3}$, respectively. In the detached divertor plasma, as described in the next section, the electron temperature and density near the outer divertor plates were estimated from the Balmer line spectrum to be 0.4 eV and $1 \times 10^{20}\ m^{-3}$, respectively.

3. Results and discussion

For the Fulcher line spectra, the Q branches of the v = 0–0, 1–1 and 2–2 bands were identified. Near the outer divertor plates in the attached divertor plasma, the rotational temperatures for the v = 0–0, 1–1, 2–2 transitions were 0.040, 0.057, 0.046 eV, respectively. Fig. 3(a) shows the intensity of the Fulcher v = 1–1 Q3 line, which was one of the most prominent lines, as a function of the distance from the outer divertor plates. It was estimated that spectral contamination of the Q3 line was small, since its line width was explained by the spectral resolution of the spectrometer and the rotational temperature was well determined including the line. In the attached divertor plasma, the decay length of the line intensity was ~1 cm, and this suggests that H_2 molecules were localized near the divertor plates. In the detached divertor plasma with a MARFE, the decay length was ~4 cm, suggesting that H_2 molecules

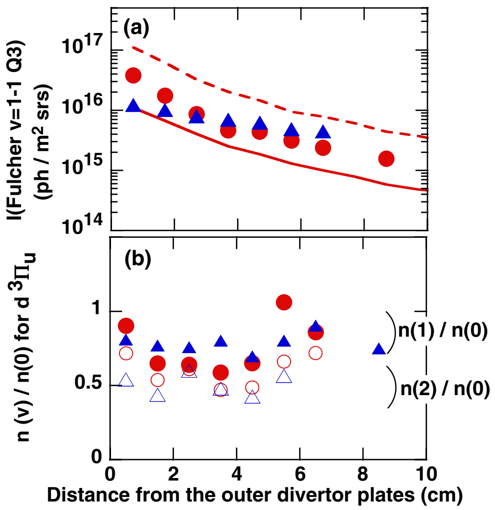

Fig. 3. (a) Intensity of Fulcher $v = 1$–1 Q3 line and (b) vibrational population ratios ($n(1)/n(0)$: closed symbols, $n(2)/n(0)$: open symbols) of the $d^3\Pi_u$ state as functions of the distance from the outer divertor plates. Circles and triangles indicate the attached and the detached divertor plasma conditions, respectively. The lines indicate the intensity calculated for the attached divertor plasma. The continuous and the broken lines are the calculations with and without inclusion of the dissociative attachment from the $n = 3$ state. The distance was measured as d in Fig. 1.

penetrated more deeply. Although higher molecular and electron densities were anticipated for the detached divertor plasma condition than in the attached one, the intensities near the divertor plates in the detached divertor plasma were smaller than that in the attached divertor plasma. This can be explained by the decrease at the low temperature and the high electron density in the Fulcher line emission rate coefficient.

Fig. 3(b) shows the vibrational population ratios of the $d^3\Pi_u$ state (the upper state of the Fulcher transition) determined from the intensity ratios of the Q3 lines. Here, we assumed that the rotational temperatures of the vibrational levels were 0.05 eV since the difference in the rotational temperatures for the $v = 0$–0, 1–1, 2–2 transitions was not large as described above. The vibrational population ratios did not change significantly with distance from the divertor plates, and the vibrational population ratios corresponded to the vibrational temperature of ~1 eV. No clear differences were seen between the attached and the detached cases. Since the MAR rate increases with vibrational excitation of the ground state ($X^1\Sigma_g^+$) [5], it is important to estimate the vibrational population of the ground state. From the vibrational population ratios of the $d^3\Pi_u$ state using a coronal model [6], the vibrational temperature of the ground state was estimated to be ~1 eV. However, the dependence of the vibrational population ratios of the $d^3\Pi_u$ state on the vibrational temperature of the ground state is weak around 1 eV [6]. Considering scattering of the measured vibrational population ratios, uncertainty of the determined vibrational temperature for the ground state was estimated to be about a factor of two. In divertor plasmas, the coronal model is not strictly applicable to calculation of the $d^3\Pi_u$ population. However, it has recently been found that even in such cases the vibrational population ratios can be calculated using the coronal model with reasonable accuracy [7].

For the attached divertor plasma, the Fulcher line intensity was calculated with a three-dimensional neutral transport code (DEGAS2 [8]) and a collisional radiative model code [9]. The background plasma parameters were determined using a simple divertor code (one-dimensional fluid calculation for the plasma and two-dimensional Monte Carlo calculation for the neutral particles) from the electron temperature and density measured with the Langmuir probes at the divertor plates [10]. It was assumed that the hydrogen ions arriving at the divertor plates were reflected as hydrogen atoms or desorbed as hydrogen molecules [11]. In the collisional radiative model, the Fulcher line intensity was calculated by assuming that the populations of the $n = 3$ electronic states in the triplet system were proportional to the statistical weights. This assumption is estimated to be valid in this plasma based on an analysis using a collisional radiative model calculation for He atoms [12]. Using the observed rotational temperature (0.05 eV) and vibrational temperature (1 eV) for the $d^3\Pi_u$ state, the intensity of Fulcher $v = 1$–1 Q3 line was calculated. The calculated intensity was not sensitive to the used rotational and vibrational temperatures; even if the rotational and vibrational temperatures changed by a factor of two, the changes in the calculated intensity were estimated to be 24% and 37%, respectively. The resultant intensity profile is compared with the observed profile in Fig. 3(a). Here, two calculations are shown; the continuous line is a calculation with inclusion of dissociative attachment from the $n = 3$ state ($H_2(n = 3) + e \rightarrow H + H^-$) [4], and the broken line is a calculation without. Here, the dissociative attachment rate coefficient was assumed to be 6×10^{-5} cm^{-3} [4,13]. The observed intensity was between the intensities calculated with and without considering dissociative attachment. Although a more accurate rate coefficient is required, the agreement of the fall in the intensity profile between calculation and observation suggests that the H_2 molecule density distribution was well reproduced by the neutral particle transport calculation.

In the detached divertor plasma, the high-Rydberg ($n = 7$–10) Balmer line spectrum observed near the outer divertor plates could be reproduced by assuming a Boltzmann distribution with an electron temperature of 0.4 eV and the Stark broadening with an electron density of 1×10^{20} m^{-3}. At this electron temperature and electron density, the ratio of the H^+–e recombination rate, in which both the radiative and three-body recombination is considered, to the $H\varepsilon$ line emission rate is calculated to be ∼300. The temporal behavior of $H\varepsilon$ in Fig. 2(c) implies that the H^+–e recombination ion flux increased gradually with the electron density. The increase at the MARFE onset was stronger at the outer divertor. The ion flux loss through volume recombination (H^+–e) with the MARFE was estimated to be 55% of the ion flux incident to the divertor plates at 7.5 s, before the MARFE onset. When the MARFE appeared, the ratios of ion flux lost through volume recombination (H^+–e) to ion flux reaching the divertor plates were 1.8 and 1.0 in the inner and the outer divertor plasmas, respectively, and ∼20% of the total volume recombination (H^+–e) occurred in the vicinity of the X-point.

For the detached divertor plasma, it is difficult to obtain the spatial distribution of the plasma parameters from the Langmuir probe measurement. Here, we used the two-dimensional fluid code UEDGE [14] to provide the background plasma used by DEGAS2 for calculation of the neutral particle transport. In the UEDGE calculation, the energy flux and the electron density at the 96% flux surface were given by upstream measurements with Thomson scattering diagnostics. For calculation of MAR with DEGAS2, we added the charge exchange reaction ($H_2 + H^+ \rightarrow H_2^+ + H$) rate to the H_2^+ production rate [5,15], although the H atoms produced by the charge exchange were not tracked. The reaction rates for H_2^+ dissociation ($H_2^+ + e \rightarrow H + H^+$) and dissociative recombination ($H_2^+ + e \rightarrow H + H$) were calculated using a collisional radiative model [5,16]. MAR by means of negative ion production ($H_2 + e \rightarrow H^- + H$, $H^- + H^+ \rightarrow H + H$) was not considered, since the reaction rate is small [5].

The spatial profiles of various measured and modeled plasma parameters in the detached divertor plasma are shown as functions of the distance from the outer divertor plates in Fig. 4. A detached divertor plasma solution was obtained from the UEDGE calculation, and the electron temperature and density at the separatrix were >0.6 eV and $<2 \times 10^{20}\ m^{-3}$, respectively. The temperature and density were reasonable approximation to those estimated from the observed Balmer line spectrum. The calculated $H\varepsilon$ line intensity was larger than the observed intensity, and this was ascribed to the higher calculated electron density compared with the density inferred from the Balmer spectrum. Large discrepancy between the calculated $H\varepsilon$ line intensity and that observed one near the divertor plates was ascribed to uncertainty in the distance (∼0.5 cm) and the viewing area (∼1 cm in diameter), which was not considered in the calculation, for the observation. The calculated H_2 density at the strike point was $2.2 \times 10^{19}\ m^{-3}$. The Fulcher line intensity profiles calculated with and without considering the dissociative attachment from the $n = 3$

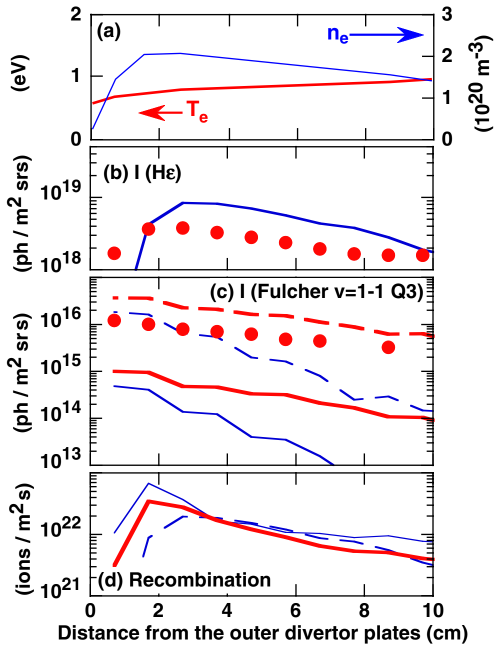

Fig. 4. Spatial profiles in the detached divertor plasma as functions of the distance from the outer divertor plates. (a) Calculated electron temperature and density along the separatrix, (b) observed (points) and calculated (line) $H\varepsilon$ line intensity, (c) observed (points) and calculated (continuous line: with dissociative attachment from the $n = 3$ state, broken line: without dissociative attachment) Fulcher $v = 1$–1 Q3 line intensity, (d) calculated MAR (continuous line) and H^+–e recombination (broken line) rate. In both (c) and (d), the thick and thin lines indicate the results obtained by assuming that the vibrational temperatures of the ground state were 0.5 eV and 1 eV, respectively.

state are compared with the observed profile. Here, the dissociative attachment rate coefficient was tentatively assumed to be as large as that used in the attached divertor plasma case, since the reliable coefficient was not available at such a low temperature. With the ground-state vibrational temperature of 0.5 eV, the calculation reproduced the logarithmic slopes in the observed intensity profile. A vibrational temperature of 0.5 eV agrees well with the ground-state vibrational temperature estimated from the vibrational population ratios of the $d^3\Pi_u$ state considering the uncertainty associated with this calculation. More accurate rate coefficients are required to reduce the error bars in this estimate. The recombination rates integrated along the viewing chords of the spectrometers are shown in Fig. 4(d). The MAR rate was calculated to be as large as the H^+–e recombination rate. In an ASDEX divertor plasma where the electron temperature was higher than 2 eV, the dissociation rate of H_2^+ was estimated to be much larger than the MAR rate [3]. In the present case, the dissociation rate of H_2^+ ions was estimated to be at a similar level of the MAR rate due to the lower electron temperature.

4. Summary

The H_2 molecule behavior has been spectroscopically studied in attached and detached divertor plasmas. It was observed that the H_2 molecules penetrated more deeply into the detached divertor plasma than into the attached divertor plasma. The fall in intensity of the H_2 Fulcher lines with distance from the divertor plates was reproduced by calculation using a neutral transport and a collisional radiative model code, although more accurate rate coefficients are required. In the detached divertor plasma, MAR was estimated to be as important as H^+–e recombination. Since the role of H_2 molecules is significant in low-temperature divertor plasmas suitable for heat and particle control, further investigation of the molecule behavior is needed and more reliable molecular data are required to facilitate the investigation.

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