SPECTROSCOPIC STUDY OF THE W-SHAPED DIVERTOR IN JT-60U

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1. Introduction

In JT-60U, spectroscopy has been used for a variety of divertor studies. In the present paper, spectroscopic study of volume recombination and behavior of He atoms in the W-shaped divertor is described. For studying of the role of volume recombination during detachment, the Balmer-series lines of deuterium atoms have been observed. The ratio of the recombination sink to the ionization source is quantitatively estimated from the line intensities. To understand the behavior of He atoms in the divertor, the spatial distribution and Doppler broadening of He I line emission have been observed and analyzed using a neutral particle transport code. The effect of elastic collisions with H^+ ions on the behavior is discussed.

2. Volume recombination

Figure 1 shows the diagnostics for the present divertor study. Emission of D_α line was observed with a fiber array, and the Balmer-series lines (2 - 5, 7, 8, 9, and 10) were observed with a visible spectrometer covering the inner and outer divertor separately.

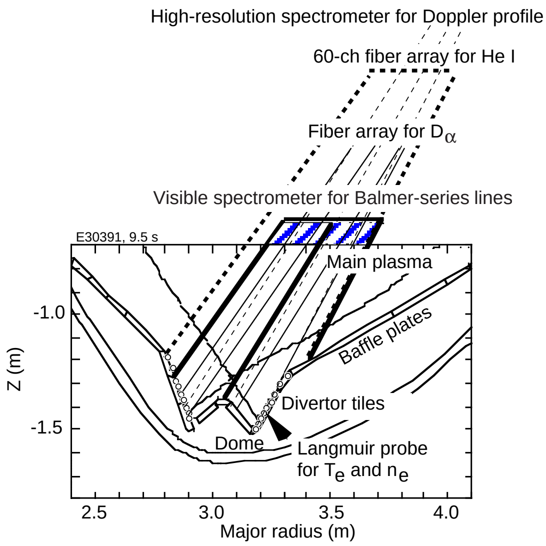

Fig. 1 Diagnostics for the present divertor study

Populations derived from the measured intensities of the Balmer-series lines are plotted in Fig. 2 for the attached and partially detached outer divertor plasmas. Calculations assuming uniform plasmas are also shown. Generally, the populations of excited levels of deuterium atoms consist of two components: ionization and recombination components. For the attached divertor plasma: Fig. 2 (a), the measured population decreases sharply as the principal quantum number increases. The populations are dominated by the ionization component. The electron temperature and density measured with the Langmuir probe located close to the strike point were 38 eV and 0.83×10^{19} m^{-3}, respectively. Thus assumptions made in the calculation agree with the Langmuir probe measurements. For the detached divertor plasma: Fig. 2 (b), the measured population does not decrease so sharply as the principal quantum number increases, compared with those for the attached case. From Langmuir probe measurement, while the outer divertor plasma was detached in the vicinity of the separatrix strike point, it was attached about 2 cm outside of the strike point. At the attached position, the electron temperature and density measured with the Langmuir probe were 19 eV and 1.7×10^{19} m^{-3}, respectively. Calculation based on the assumption that the temperature is 20 eV and the density is 2×10^{19} m^{-3} agrees with the measurements for the n = 3 level but not for the higher energy levels. Since the plasma is partially detached, a narrow layer with a low temperature might exists near the separatrix. Calculation based on the assumption that the temperature is 1 eV, the density is 8.9×10^{19} m^{-3} and the divertor plasma length along the viewing chord of the spectrometer is 0.02 m agrees with the measurements for the high energy levels. The sum of the two calculated populations can reproduce the measured populations. As a result, the populations of the n < 4 levels are dominated by the ionization component and those of the n > 6 levels are dominated by the recombination one.

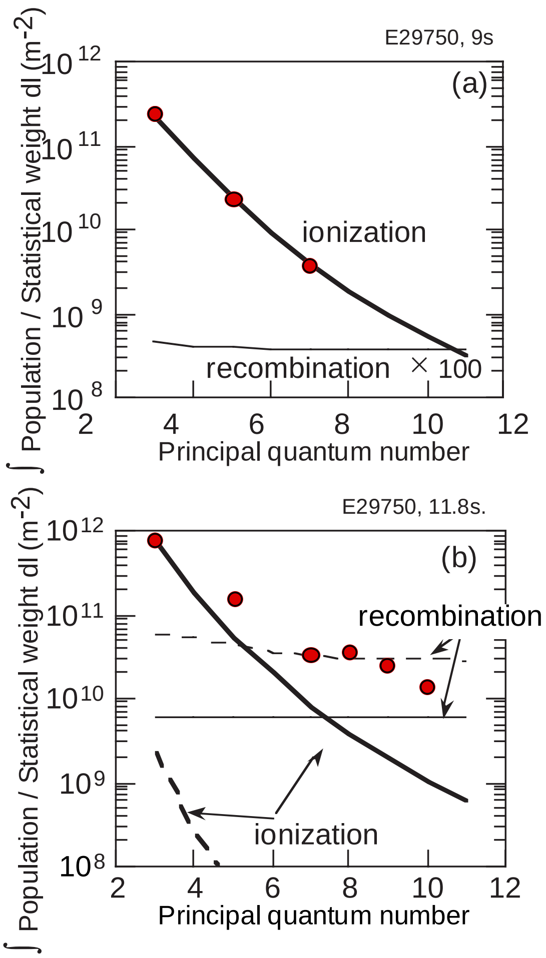

Fig. 2 Populations divided by statistical weights of excited levels of deuterium atoms in the outer divertor plasmas. The data were obtained in L-mode discharges with 4.5 MW NB heating. The points indicate the measurement and the lines indicate the calculation. The thick and thin lines illustrate the ionization and recombination components, respectively. (a) Attached divertor plasma. In the calculation, it is assumed that T_e = 50 eV, $n_e = 1 \times 10^{19}$ m^{-3}, n_D / n_e = 0.011, and the plasma length along the viewing chord of the spectrometer: Δl = 0.08 m. (b) Detached divertor plasma. Continuous line: T_e = 20 eV, $n_e = 2 \times 10^{19}$ m^{-3}, n_D / n_e = 0.018, and Δl = 0.08 m. Dashed line: T_e = 1 eV, $n_e = 8.9 \times 10^{19}$ m^{-3}, n_D / n_e = 1, and Δl = 0.02 m.

The ionization source can be estimated from the D_α line intensity, because the population of the n = 3 level is determined by the ionization component. The number of ionization events per photon of D_α line emission is about 30 at a temperature above 5 eV in this density range. On the other hand, in the detached divertor plasma, the recombination sink can be estimated from the D_ε (2 - 7) line intensity, because the population of the n = 7 level is determined by the recombination component. The number of recombination events per photon of D_ε line emission is about 200 at a temperature below 15 eV [1]. Therefore, the ratio of the recombination sink to the ionization source can be estimated from the ratio of the D_ε line intensity to the D_α line intensity. The intensity ratio increased from 0.0007 to 0.002 at the onset of detachment. From the intensity ratio, the recombination sink is estimated to be about 1 % of the ionization source in the detached plasma. The spectrum for the detached inner divertor plasma was similar to that for the detached outer divertor plasma. The ratio of the recombination sink to the ionization source was estimated to be 1 - 3 % in the detached inner divertor. The fact that the recombination sink is small agrees with Langmuir probe measurements that the ion flux in the attached area outside of the detached area increases at the onset of the partial detachment and the reduction in the total ion flux does not seem to be significant.

In summary, while the onset of the recombination is correlated with the plasma detachment, it is suggested that the recombination is not the principal cause of the detachment.

3. Behavior of He atoms

As shown in Fig. 1, the spatial distribution of the He I line (668 nm) was measured with a 60-ch fiber array, and the Doppler profile was observed with a high-resolution spectrometer. In L-mode discharges with 4.5 MW NBI heating, behavior of He atoms was studied. The working gas was hydrogen, and He gas was puffed. The helium ion density was estimated to be about 7 % of the electron density in the main plasma. Transport of He atoms and emission of He I lines were simulated by a three-dimensional neutral particle transport code (DEGAS) [2] using the electron temperature and density measured with the Langmuir probes. The code was modified to obtain the Doppler line shape, and elastic collisions between He atoms and H^+ ions [3] were added. Data presented in Ref. [4] were used for the reflection of He particles from the surface of the divertor tiles. In the discharge to be analyzed, the inner divertor plasma was detached in a narrow region around the separatrix. However, the narrow region was not considered in the simulation because it is difficult to determine the plasma parameters.

The spatial distribution of the line emission is shown in Fig. 3. The intensity decay in the vicinity of the outer strike point is reproduced by the calculation. This agreement indicates that penetration of the desorbed He atoms in the plasma is well simulated. The simulation is not so good for the inner divertor, because the detached plasma was not considered. The intensity measured between the strike points is much higher than the calculated one. The origin of the emission between the strike points is not understood. It is likely that the reflection model should be modified. It is also possible that He atoms coming from the inner divertor contributes the emission.

Spectra of the π-component of the He I line are shown in Fig. 4. The measurement is well reproduced by the calculation except for the inner strike point: Fig. 4 (c). For Fig. 4 (b), the He atom temperature corresponding to the broadening is 0.9 eV. The broadening of the calculated spectral line is attributed to elastic collisions with H^+. The broadening of the line emitted from the inner divertor can be related to the partial detachment of the inner divertor plasma.

The probability of penetration of He atoms from the outer divertor tiles into the main plasma was calculated to be 7 %. In calculation excluding the elastic collision, the probability is down to 4.5%. Thus it is expected that the elastic collision affects the He ion density in the main plasma.

In summary, the effect of elastic collisions with H^+ ions is found in the Doppler profile as calculated. The elastic collision is an important process for He atom transport.

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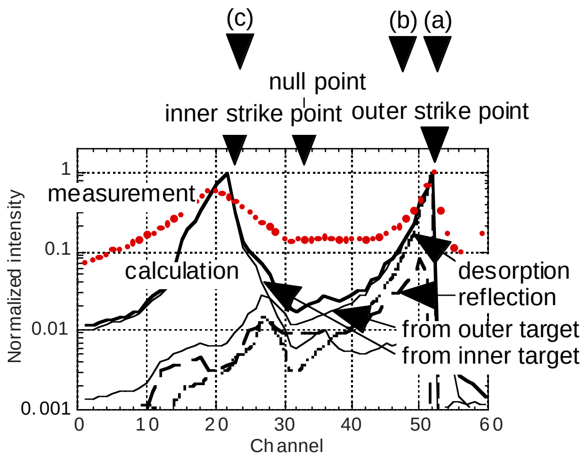

Fig. 3 Spatial distribution of He I 668 nm line emission. Points indicate the measurement and lines indicate the calculation. The electron temperature and density measured with the Langmuir probe located close to the outer strike point were 37 eV and 0.6×10^{19} m^{-3}, respectively. The inner divertor plasma was detached around the separatrix strike point. The temperature and density measured with the Langmuir probe located at the attached position just outside of the detached region are 18 eV and 2.1×10^{19} m^{-3} , respectively.

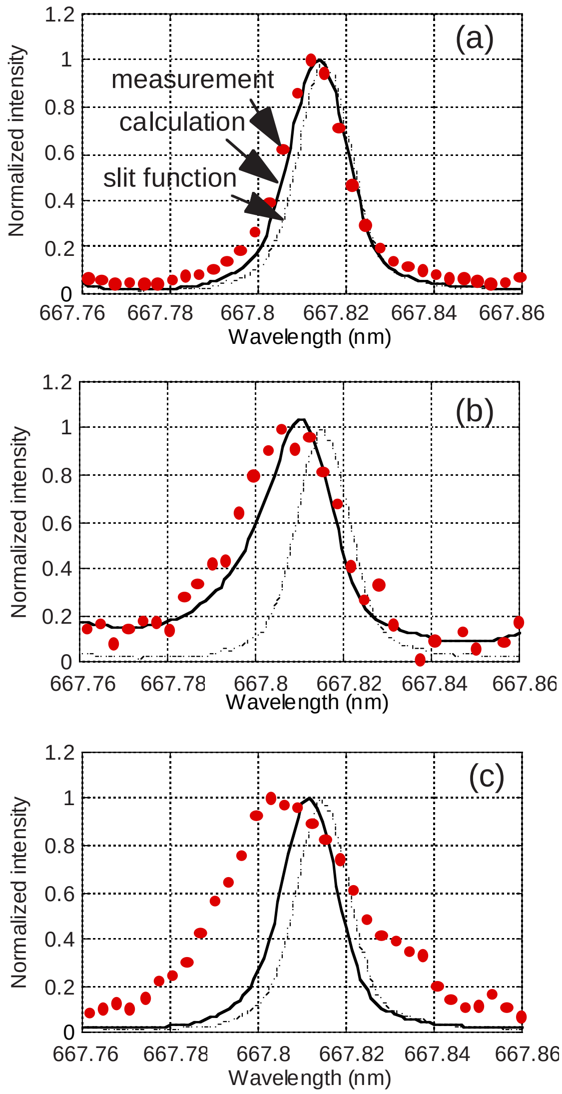

Fig. 4 Spectra of the π-component of He I 668 nm line. Points are measurement and solid lines are calculation. The slit function is indicated as broken lines. The viewing chords are indicated as (a), (b) and (c) in Fig. 3

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