Development of a method for local electron temperature and density measurements in the divertor of the JET tokamak.

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1. Introduction

Plasma volume recombination in the divertor, a process in which charged particles recombine to neutral atoms, contributes to plasma detachment and hence cooling at the divertor target region. Detachment has been observed at JET [3] and other tokamaks and is known to occur at low electron temperatures \( T_e < 1 \) eV and at high electron density \( n_e > 10^{20} \text{ m}^{-3} \). The ability to measure such low temperatures is therefore of interest for modelling the divertor. In present work we report development of a new spectroscopic technique for investigation of local electron density \( n_e \) and temperature \( T_e \) in the outer divertor at JET. The technique is a combination of two different methods for measurements of \( n_e \) and \( T_e \) in the divertor. One of these is based on Stark effect of high lying \( n \) states of deuterium. The method is established and has previously been used at JET [1]. The process behind the other method, which recently was observed at JET and previously found by Bowen [2] as a population mechanism in nebulae, is based on photoexcitation of the \( 2p^3(4S)3d \, ^3D \) level in neutral oxygen (O I) by \( \text{H}_\lambda \) at 1025.72 Å due to a wavelength coincidence with the \( 2p^4 \, ^3P_2 - 2p^3(4S)3d \, ^3D \) transition of O I at 1025.76 Å (Fig. 1). The new method is valid for measurements of \( T_e \) and \( n_e \) from normal non-detached conditions through to detached conditions. The strategy in the present experiment has been to measure \( n_e \) from the Stark broadening of high-\( n \) Balmer series lines. \( n_e \) is measured by considering the Stark
line broadening as a Lorentzian profile by:

\[ n_e = \left[ \frac{2\pi\lambda_{FWHM}^2}{13.9 \times 10^{-14} Z^2_0 (n_x^2 - n_y^2)} \right]^{1/2} \]  

(1)

Based on this \( n_e \) value, \( T_e \) is deduced from the H I / O I photoexcitation method.

2. The model of O I.

In the O I hybrid model [4,5], applied in the present work, the ground configuration is resolved into the five \( ^3P_{2,1,0}, ^3D \) and \(^1S \) levels with the upper terms \( ^3S, ^5S, ^3p^3P, ^5P \) and \( ^3d^3D, ^5D \) terms. Level/term populations have been calculated for different electron densities and temperatures at coronal conditions by solving the statistical equilibrium equations at steady state:

\[
\frac{dN_j}{dt} = -N_j\sum \nu_j C_{j,j-1}^{\text{ex}} - \sum \nu_j A_{j,j-1}^{\text{x}} - N_j\sum \nu_{j+1}A_{j+1,j}^{\text{x}} + N_j\sum \nu_{j+1} C_{j+1,j}^{\text{em}}
\]

(2)

where \( N_j \) and \( N_i \) are upper and lower levels and \( C_{j,j-1}^{\text{ex}} \) and \( C_{j+1,j}^{\text{em}} \) are excitation and deexcitation rate coefficients respectively. \( A_{j,j-1}^{\text{x}} \) is the spontaneous radiative rate. When photoexcitation rate \( R_p \) is added to \( ^2P^4 \rightarrow ^3P_2 \rightarrow ^3D^3D \) transition, \( 1 \rightarrow 13 \), the total excitation rates becomes \( N_j C_{1,13} + R_p \) in equation (2). \( R_p \) can be expressed as:

\[
R_p = \sigma(OI)I(HLy\beta) \frac{\Delta W_d(OI)}{\Delta W_d(HLy\beta)}
\]

(3)

under these conditions calculations have been performed for \( n_e \) in the range \( 10^{16} - 10^{22} \text{ m}^{-3} \), \( 0.4 \leq T_e \leq 2.0 \text{ eV} \) and \( R_p \) between \( 10^4 \) and \( 10^2 \text{ s}^{-1} \). In Fig.2, calculations are shown for the purely collisional excitation model and the model including both collisional excitation and photoexcitation for \( T_e \) from 0.4 up to 2.0 eV for \( n_e \) between \( 10^{19} \) and \( 10^{21} \text{ m}^{-3} \) and \( R_p = 10 \text{ s}^{-1} \). The line ratio for \( T_e < 0.6 \text{ eV} \) is degenerated for \( R_p \) between 1 and 100 \text{ s}^{-1}. The calculations (Fig.2) show that photoexcitation is the most important mechanism for \( T_e < 1.0 \text{ eV} \) and electron excitation for \( T_e > 1.3 \text{ eV} \) for \( n_e \) in the range \( 1 \times 10^{19} - 1 \times 10^{21} \text{ m}^{-3} \).

Figure 2 Calculated ratio of (3s-3p) triplet and quintet lines of O I including photo-excitation (\( R_p=10/\text{s} \)) + collisional excitation and only collisional excitation for \( T_e=0.4-2 \text{ eV} \).
3. Observations of high density limit discharges

The O I spectra and the Balmer series limit spectra have been performed at JET using a vertically viewing mirror link spectroscopic system comprising three Czerny-Turner spectrometers covering the near-UV through the near-IR. We have studied the ratio ($R_1$) between 3s $^3$S-$^3$P (8446Å) and 3s $^5$S-$^5$P (7774Å) absolutely calibrated line intensities as they could be measured simultaneously on one instrument. Observations were made along twelve vertically viewing lines in the outer divertor each covering 13 mm (Fig.3).

In this paper we present a study of a high density limit discharge (58696) containing a high percentage of hydrogen ≈17% H/(H+D). In Fig.4, global and local plasma parameters are displayed. We note for tracks 2, 3 and 4 a distinct drop of $R_1$ (increase of $T_e$) at ~20.2s indicating a L-H transition, also seen by the behaviour of the $D_\alpha$ emission. During the H-mode, $R_1$ is essentially constant for each track, with a peak value for track 2 of 0.45.

For track 1, which looks up the vertical plates out of the divertor (Fig.3) $R_1$=0.2 and the L-H transition is less visible. We note that a H-L transition is takes place at ~25.7s with a subsequent detachment, visible up to track 5. The increase of $R_1$ during the H-L transition means a decrease of $T_e$ with a simultaneous increase of $n_e$. The measurement of $T_e$ has been made by an initial measurement of $n_e$ by Stark broadening of n=2-10 Balmer line. At 23.15s, that is, during the H-mode, we get (see Fig.5) $n_e$=1.5·10$^{20}$ m$^{-3}$ for track 1 and 2, going up to 1.8·10$^{20}$ m$^{-3}$ for track 9. In Fig.4 we get $R_1$=0.2 for track 1 at 23.15s. According to
calculated data not shown this gives $T_e = 2.5$ eV.

This is in accordance with what we get by the Stark broadening technique applied to present data [1]. For track 2 we get $n_e \sim 1.5 \times 10^{20}$ m$^{-3}$ and $R_1 \approx 0.46$ at 23.15s. According to Fig.2 this indicates $T_e \approx 0.3$ eV. During the H-L transition, with subsequent detachment at 25.7s, $R_1$ increases to 0.50. This means that $T_e$ decreases to $<0.3$ eV and $n_e$ increases. At 27.05s during the L mode we find $n_e \approx 2.5 \times 10^{20}$ m$^{-3}$ for track 1 (Fig.5) and $n_e$ around $2.2 \times 10^{20}$ m$^{-3}$ for track 2. Furthermore, we note from Fig.5 that $n_e$ is rather uniform across the plasma volume covered with our line of sights. From Fig. 5 we can see that $n_e$ lies between $(1.5-2.5) \times 10^{20}$ m$^{-3}$ from track 1 up to 9. With $R_1$ (Fig.4) around 0.4 during the H mode and around 0.42 during the L mode, $T_e$ is, according to calculated data (Fig.2), between 0.3 and 0.4 eV for tracks 3 up to 11 during the H mode with lower $T_e$ during the L mode (tracks 2, 3 and 4). It is interesting to note from Fig.5, that from track 6 and on we get about the same $n_e$. It is in accordance what we see in Fig 4, here we note that L and H modes can’t be distinguished according to the change of $T_e$.

**Conclusion**

By a combination of two spectroscopic methods, the Stark broadening mechanism of high lying n states of deuterium and the photoexcitation mechanism of 3d \( ^3D \) of O I by H Ly\( \beta \), $n_e$ and $T_e$ have been measured in high density limit discharges during detachment in the divertor at JET. $T_e$ was found $<0.3$ eV with $n_e$ at $2.2 \times 10^{20}$ m$^{-3}$ during the detachment in the outer divertor. The location of the HI/OI process is likely in the vicinity of the strike point flux surface and peaks around 2 cm from the strike plate.

**References**