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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<1eV) and at high electron density ($n_e > 10^{20}$ 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 ne and Te 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 HLyβ at 1025.72A due to a wavelength coincidence with the $2p^4\ ^3P_2 - 2p^3(^4S)3d\ ^3D$ transition of O I at 1025.76A (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 ne 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:

$$n_e = \left[\frac{2\pi c \Delta\lambda_{FWHM}}{13.9\times10^{-14}\ \lambda_0^2 (n_i^2 - n_f^2)} \left(\frac{Z}{Z_e} \right) \right]^{3/2} \tag{1}$$

Based on this ne value, T_e is deduced from the H I / O I photoexcitation method.

1. 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 $^3P_{2,1,0}$, ^1D and ^1S levels with the upper 8 terms 3s, 4s ^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:

$$\frac{dN_i}{Z_e} = - N_e N_i \sum_{j>i} C_{ij}^e + \sum_{j>i} N_j A_{ij} - N_j \sum_{j>i} A_{ij} + \sum_{j>i} N_e \sum_{j>i} N_j - C_{ij}^d \tag{2}$$

where N_j and N_i are upper and lower levels and C^e_{ij} and C^e_{ij} are excitation and deexcitation rate coefficients respectively. A_{ij} is the spontaneous radiative rate. When photoexcitation rate R_p is added to $2p^4\ ^3P_2 - 3d\ ^3D$ transition, $1 \rightarrow 13$, the total excitation rates becomes $N_eC_{1,13} + R_p$ in equation (2). R_p can be expressed as:

$$R_p = \sigma\,(OI) \cdot I\,(HLy\beta)\ \frac{\Delta w_D\,(OI)}{\Delta w_D\,(HLy\beta)} \tag{3}$$

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

2. 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-3p ^{3}P (8446A) and 3s ^{5}S-3p ^{5}P (7774A) 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 13mm (Fig.3).

In this paper we present a study of a high density limit Pulse No: (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_α 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 ne. 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 (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 ≈2.5eV. 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~1.5×10^{20} $m^{−3}$ and R_1 ≈0.46 at 23.15s. According to Fig.2 this indicates T_e ≈0.3eV. During the H-L transition, with subsequent detachment at 25.7s, R_1 increases to 0.50. This means that T_e decreases to <0.3eV and ne increases. At 27.05s during the L mode we find n_e ≈2.5 $\times10^{20}$ $m^{−3}$ for track 1 (Fig.5) and ne around 2.2×10^{20} $m^{−3}$ for track 2. Furthermore, we note from Fig.5 that ne is rather uniform across the plasma volume covered with our line of sights. From Fig.5 we can see that ne lies between (1.5-2.5) $\times10^{20}$ $m^{−3}$ from track 1 up to 9. With R1 (Fig.4) around 0.4 during the H mode and around 0.42 during the L mode, Te is, according to calculated data (Fig.2), between 0.3 and 0.4eV 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 ne. 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 HLy_β, n_e and T_e have been measured in high density limit discharges during detachment in the divertor at JET. T_e was found < 0.3eV with ne at 2.2×10^{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 2cm from the strike plate.

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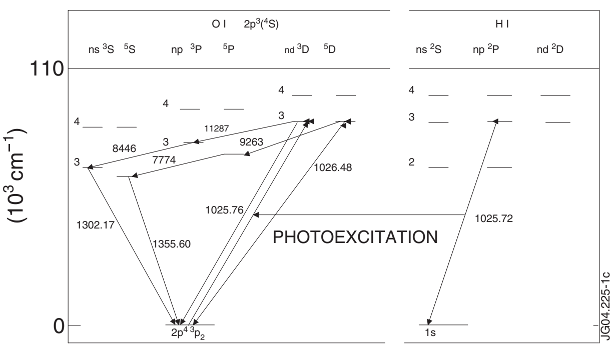

Figure 1: Partial transition scheme of the lowest excited levels of O I. The photoexcitation mechanism HLy_β /O I is indicated.

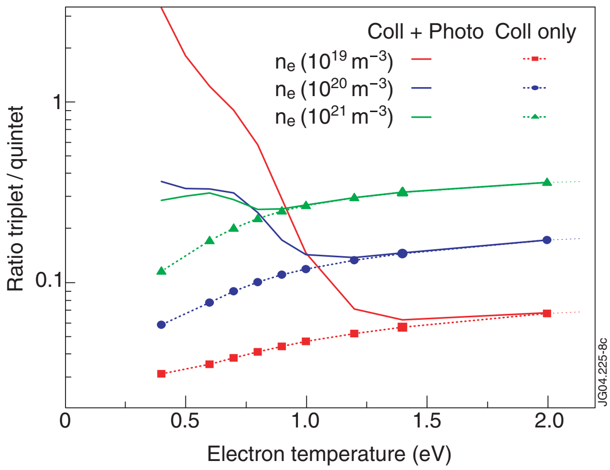

Figure 2: Calculated ratio of (3s-3p) triplet and quintet lines of O I including photo-excitation (R_p = 10/s) + collisional excitation and only collisional excitation for T_e = 0.4-2 eV.

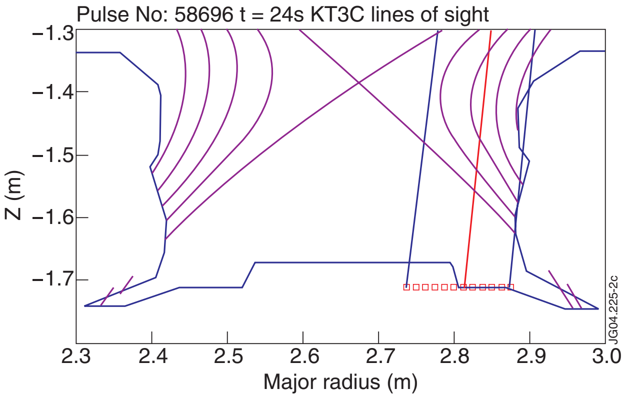

Figure 3: KT3C lines of sight at t = 24s for Pulse No: 58696 (track 1 is at 2.875m).

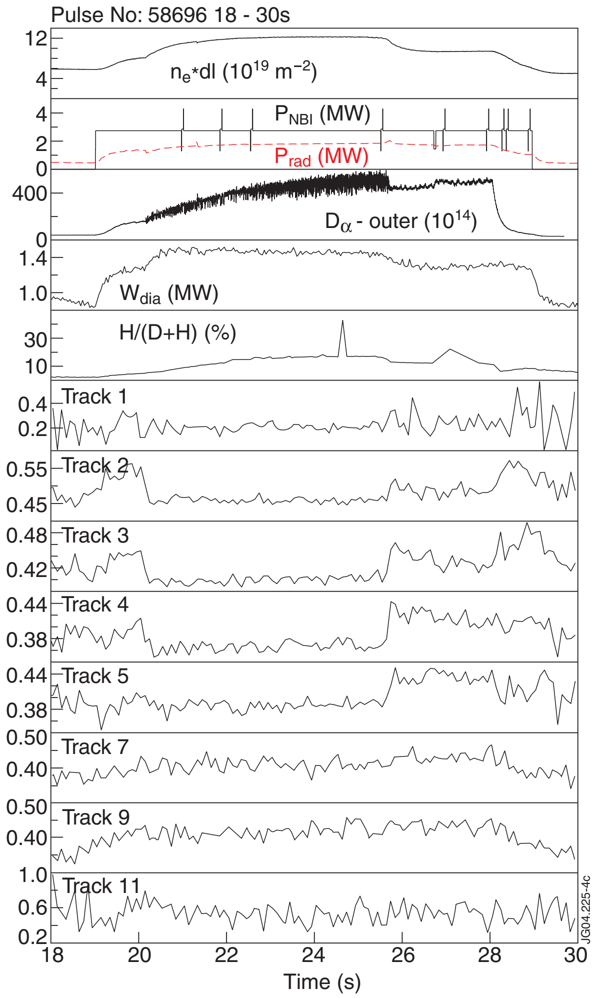

Figure 4: Some global plasma parameters for Pulse No: 58696, together with ratios of the 3s-3p triplet and quintet lines of O I for some lines of sight.

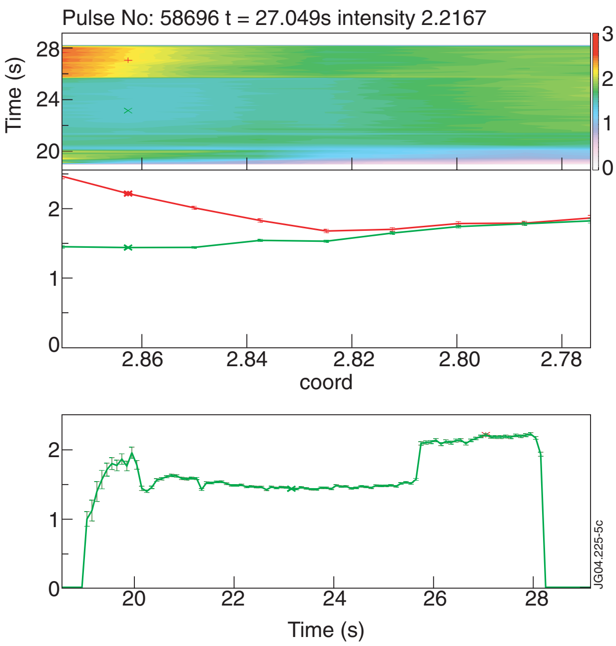

Figure 5: Measured electron density (ne) profiles at 23.15s (H-mode) and at 27.05s (L-mode) for Pulse No: 58696 in the divertor by means of the Stark broadening mechanism (scale in 10^{20} m^{-3}).