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Spectroscopic Electron Density Measurements and Evidence of Recombination in High Density JET Divertor Discharges

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ABSTRACT

Spatially resolved measurements have been made of the deuterium Balmer series emission in the outer leg of the JET divertor using a high resolution spectrometer. At high density the excited states n=5-2 to 13-2 are observed and spectra obtained to the series limit. The high-n states are substantially broadened due to the Stark effect and there is a marked change in the continuum level between $\lambda \leq 370$ nm and $\lambda = 395$ nm. Stark broadening is analysed to obtain radial distributions of the density across the outer target plate. The maximum density exceeds 5×10^{20} m^{-3} and is observed to be correlated with the strike point (either on or outside) prior to detachment.

INTRODUCTION

Enhanced recombination and Stark broadening of the Balmer series of hydrogen in divertors has been observed near the density limit in L-mode and H-mode in several tokamaks (C-MOD[1,2], ASDEX-U[3], DIII-D[4], and JET[5,6]). These data provide insight into the physical processes occurring in the divertor and are valuable for validating 2D models of divertor physics. Evidence of recombination is obtained from the ratio of the brightness of the n=5-2 (D_γ) to 3-2 (D_α) transitions. In Ohmic and L-mode density ramp discharges recombination occurs first at the inner divertor and then, near the density limit, at the outer divertor. The presence of recombination indicates that $T_e \leq 1$ eV. Supporting evidence for these low temperatures is also obtained from the change in the bremsstrahlung continuum level near the Balmer series limit. First analysis of density distributions from Stark broadening of the hydrogen Balmer series is presented for L-mode density limit discharges (with horizontal and vertical targets) and a H-mode discharge with high gas puffing.

Fig. 1 shows the lines-of-sight (LOS) for the various diagnostics. Lines-of-sight labelled KS3O and KS3I give total D_α and D_γ intensities from the outer and inner divertor legs respectively. High-n Balmer spectra are obtained from the diagnostic KT3 which observes about 70% of the outer target with 13 mm spatial resolution, 0.1 nm spectral resolution, and an exposure time of 100 msec. Fixed Langmuir probes (KY4D) give the ion saturation current, electron temperature and density at the target surface.

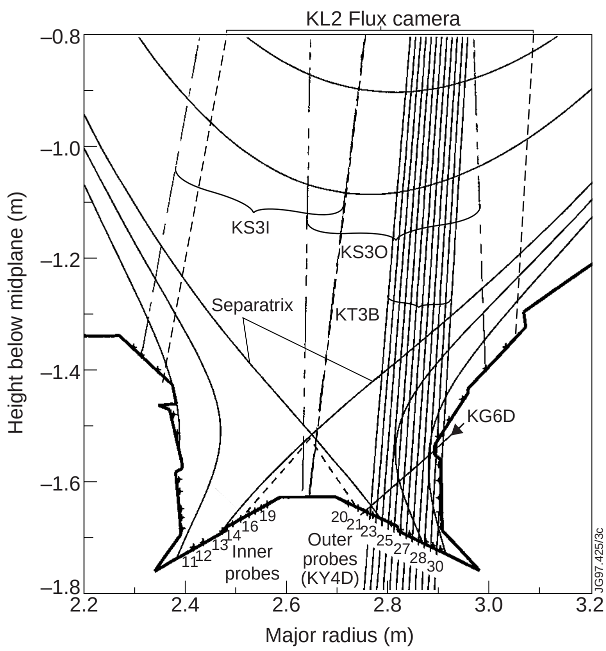

Figure 1. Diagnostic lines of sight for horizontal configuration discharge .

ANALYSIS PROCEDURE

Fig. 2 shows example spectra. Since thermal broadening and the Zeeman effect are very small compared to the Stark widths of the high-n Balmer lines at high density, the profile is well modelled by a Voigt function with the Gaussian component fixed to the instrumental width. Simultaneous fits were made to the Balmer lines (12-2, 11-2 and 10-2) and single Gaussians for the significant nearby impurity lines (mainly Be III and O III). Since the LOS averaged spectral profile is a Voigt profile, the average electron density from Stark broadening can be derived from the Holtsmark relation[7].

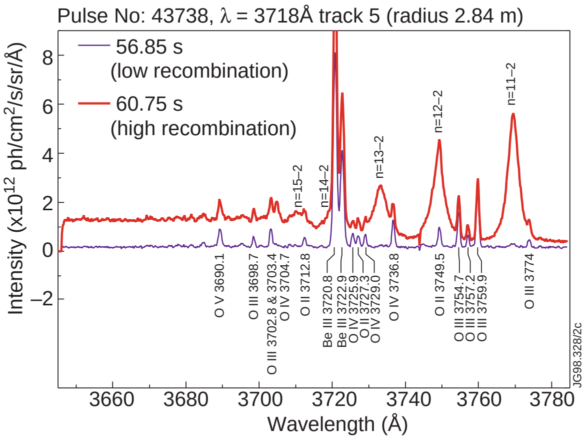

Figure 2. Example spectra from a vertical target L-mode density limit discharge with PNBI = 2 MW. $\overline{n}_e$ is about 2.3 x 10^{19} m-3 for low recombination (56.95 s, lower curve) and 3.5 x 10^{19} m^{-3} for high recombination (60.75 s) spectra.

L-MODE DENSITY LIMITS

For the horizontal target configuration, Fig. 3*left* shows the global behaviour of the discharge, and fig. 4*left* gives the density profile evolution. At the onset of outer target detachment Stark electron density profiles are peaked outside the strike point; however as the detachment progresses the density peak moves inward toward the X-point (but out of the diagnostic's LOS). This movement towards the X-point is also seen on the D_α camera and bolometry. Langmuir probes show peak density position initially at the strike point, but as detachment progresses the peak moves outward towards larger radii in opposition to the Balmer measurements. This is unlikely to be an alignment problem with the spectroscopic diagnostic; it could be a LOS averaging effect, but most probably is a real difference between what the probes measure at the target surface and what Balmer emission yields above the target. This must be resolved through modelling of the Balmer emission using DIVIMP/EDGE2D[8,9] or CRAMD[10].

For the vertical target configuration, fig. 3*right* shows the global behaviour and fig. 4*right* the density profile evolution. Prior to detachment the profiles are flat; however, the target strike point is shadowed from the LOS by a divertor tile. As with the horizontal case, at detachment the peak moves inward toward the X-point. EDGE2D simulations in a similar discharge are consistent with the observed electron density profiles both in shape and magnitude.

At the outer target the duration of the high density phase is much longer and the peak density is higher for the horizontal target case. For both discharges, densities derived from Stark broadening have been compared with Langmuir probe data at the target, fig. 5. At the onset of

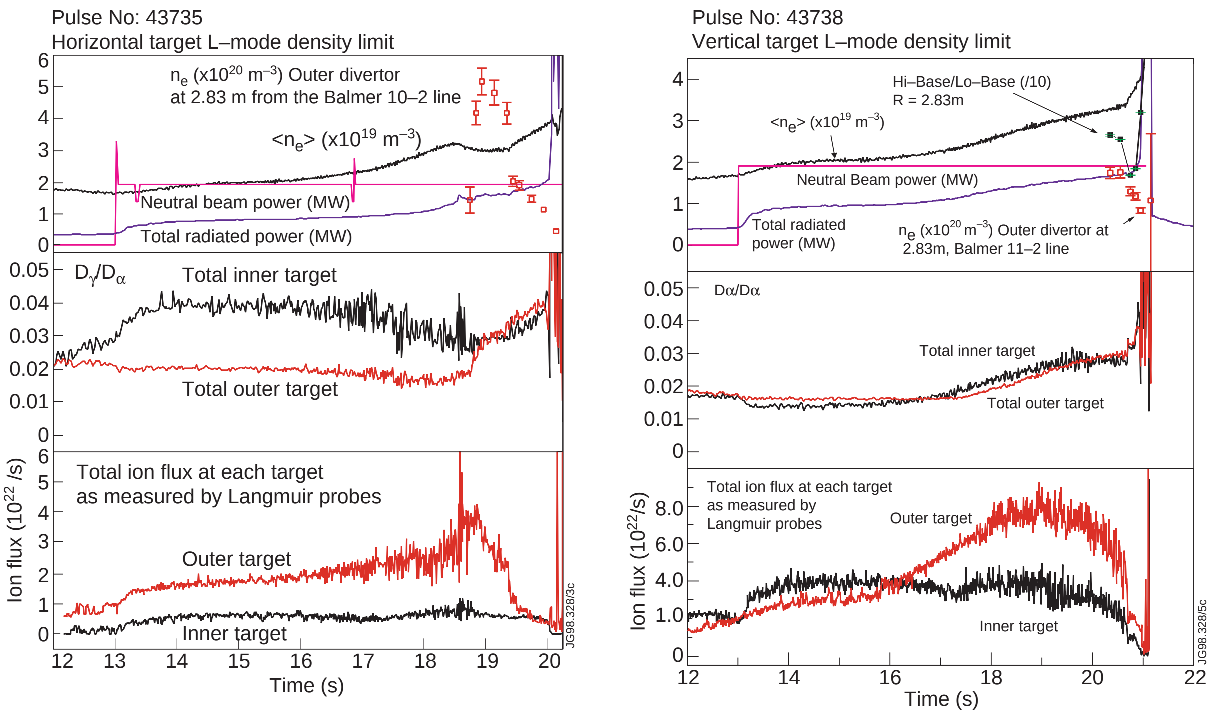

Figure 3. Global parameters for the L-mode density limits: horizontal target 43735 (left) and the vertical target 43738(right). For the horizontal target discharge, the inner target is almost always detached (bottom panel) with D_/D_ always greater than 0.025. For the vertical target, detachment and recombination are both nearly symmetrical for the inner and outer targets.

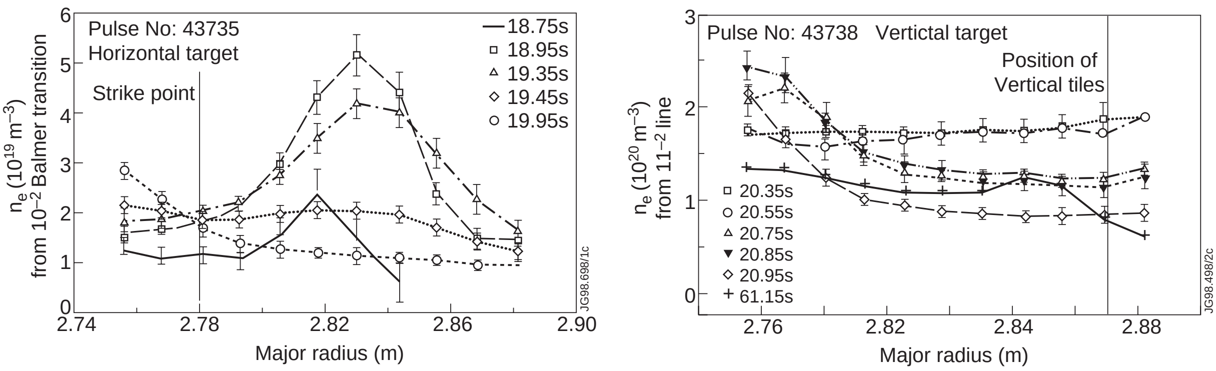

Figure 4. Balmer derived density profiles for the L-mode density limits: horizontal(left) and vertical(right) target. For the horizontal, the density is peaked outside the strike point until detachment/recombination becomes large (see fig. 3); whereas, for the vertical it is flat until recombination becomes large.

detachment the two diagnostics agree well (better for the horizontal than the vertical), but during the detached phase the spectroscopic data show higher densities than the probes, indicating that the region of maximum density is moving upwards, away from the target.

H-MODE WITH HIGH GAS PUFFING

The global characteristics of a horizontal target H-mode discharge with high gas puffing (~3x10^{22} /s) is shown in fig. 6. Only with such high gas flow rates can evidence of Stark broadening and recombination be observed. Detachment and recombination at the outer target only occurs after the confinement has significantly degraded(fig. 6*left)*. The divertor density profile retains nearly the same shape and peak position throughout the pulse(fig. 6*right*). The divertor density drops with NBI step down, while the core density drop is delayed(fig. 6*left*) coinciding with the end of gas puffing.

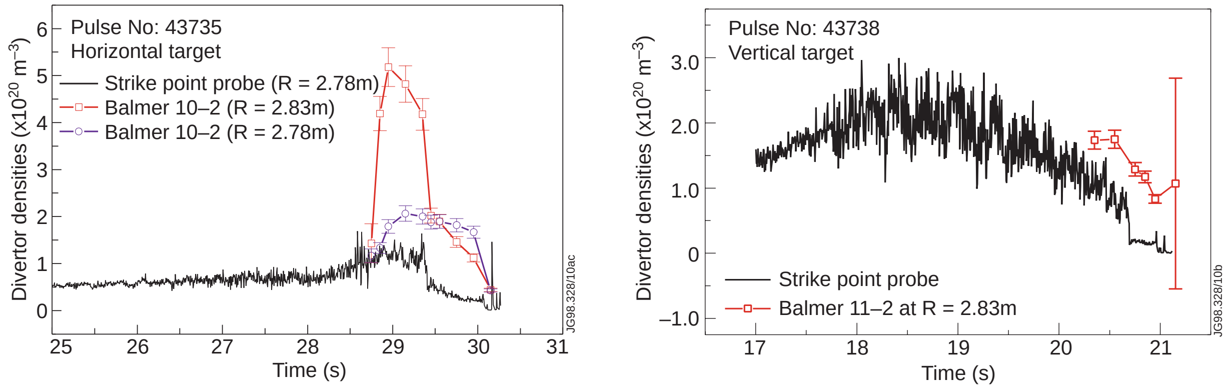

Figure 5. Comparison of electron density derived from Stark broadening to the electron density from the probe at the strike point position for the L-modes: horizontal target(left) and the vertical target(right).

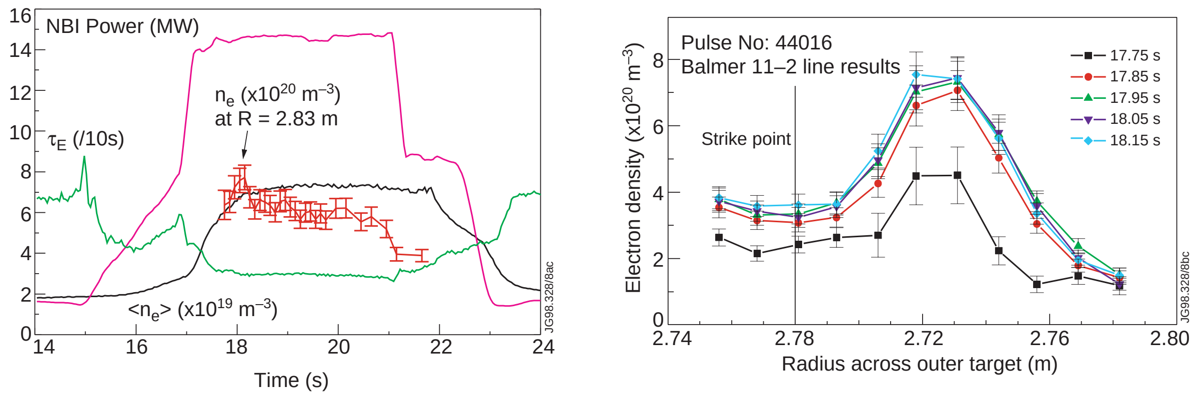

Figure 6. Time series comparison of divertor and core(left) and density profiles(right) for the high gas puffing "H-mode" 44016. The shape and position of the peak density is very stable throughout the pulse.

SUMMARY

Evidence for high electron densities in the JET outer divertor has been obtained from analysis of Stark broadened deuterium lines. In general, the peak density is radially outside the strike point, but as the density is raised the peak position moves toward the X-point. These observations were made during the detached divertor phase of L and H-mode discharges. In the H-mode, Stark broadening and recombination are only observed under conditions of very high gas puffing where the energy confinement is significantly reduced.

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