Monitoring of Detachment and the Edge using XUV Impurity Spectra from the Mark I Divertor Phase of JET

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INTRODUCTION

The XUV spectrum of CV and CVI from the edge plasma in JET is rich in diagnostic potential. Impurities in the spectral range 20-40Å are monitored with an XUV grazing incidence spectrometer. It is possible to move the spectrometer so that it can view the inner wall at any angle. The spectra analysed here were taken with the spectrometer angled at it lowest position (see insert in Figure 3). Here the spectrometer views the SOL during the ramp-up phase of the discharge, typically for the first 5 seconds. When the X-point is formed the confined plasma is seen. During radiative divertor experiments the view is just above the radiating zone. If the plasma is going to detach from the strike plates it is reflected in the spectra, which can serve as an early indicator of detachment.

SOL PARAMETERS IN RAMP-UP PHASE

In the ramp-up phase of the plasma the spectrometer views the SOL exclusively. An unusual Lyman series and CV G-ratio (intercombination / resonance line ratio) are seen in *all* discharges (Figure 1). A 'distortion' in the Lyman series appears with the Lyman γ line prominent. There is also an inversion in the He-like system G ratio. In Figure 1 the top trace shows the pre-divertor JET limiter configuration spectra (# 13571). For the JET Mark I divertor configuration the middle trace shows a typical edge spectrum in the ramp-up phase (# 32595) and the lower trace shows a radial view through the main plasma (# 30763) in the X-point phase. The difference between the pre-divertor and Mark I divertor spectra is that no n>6 C VI Lyman series lines are now observed. These lines have been attributed to charge exchange with excited deuterium produced when there is contact between the limiter and the plasma [1]. Hence the neutral deuterium is formed by Frank-Condon dissociation at ~3eV

The emission seen by the spectrometer is a slice through a 3-D volume whose parameters vary in space and time (the fall-off lengths are ~cm). The model reduces the geometry to 0-D to elucidate the important atomic processes. The extreme values of the CV G-ratio can only be explained by emission from a strongly recombining plasma. A transient, recombining, model of the emission is used. Outfluxing C^{6+}, C^{5+} and C^{4+}, from the confined plasma, enters the SOL where ionisation equilibrium does not apply. The outfluxing carbon recombines with a competition between charge exchange and radiative recombination. The residence time of carbon in SOL is set by parallel transport, where $\tau = 2L_c/c_s$ (L_c = connection length, c_s = sound speed). The outfluxing mix is adjusted to match the Ly α /CV resonance line ratio, which is a measure of the ionisation balance. The system is allowed to evolve with the integration time set to 50ms to match the spectrometer's time resolution.

The emissivities of the driving processes (excitation, recombination and charge exchange) were calculated in a collisional-radiative code which forms part of ADAS [2] at JET. All possible transitions and excitation routes for $n \leq 5$ for CVI and $n \leq 4$ for CV were included. The atomic data is mostly taken from ADAS. The charge exchange cross sections are from [3,4]. These were extended by hand to lower energies. It must be noted that there is a severe lack of cross section data at such low thermal energies.

The residence time is estimated at ~4ms. It can be modified by effects such as thermal force in the SOL, but the calculated ratios are relatively insensitive to this parameter. The prominence of the Lyman γ line is conclusive evidence of charge exchange contributions. Figure 2 shows a comparison between calculated line ratios and observations. The model requires a n_{D0}/n_e ratio of ~0.05, equivalent to a neutral density of ~$5 \times 10^{16} m^{-3}$. Neutral density fractions of 10^{-3} and above are necessary to explain the CV G ratio. Radiative and dielectronic recombination alone are not enough to account for the observations. The SOL temperature is estimated to fall in the range 50–90eV, which is consistent with all the calculated ratios.

DETACHMENT SIGNATURE

The line-of-sight of the spectrometer passes just above the divertor radiation zone. The emission line ratio of the CV resonance line to the CVI Lyman α line is an early indicator of detachment (Figure 3). As the plasma approaches detachment this ratio rises. The CV G-ratio remains relatively constant as the plasma detaches. When the plasma is fully detached the region of cold plasma becomes localised at the X-point.

During the radiative divertor phase no CVI charge exchange lines are seen, indicating that the emission is from within the confined plasma. Hence a diffusive-ionisation balance equilibrium model can be used (the neutral fraction is much lower in the confined plasma than in the SOL). The observed carbon G-ratio is ~0.7 compared with the equilibrium value of 0.45. The calculated G-ratio (figure 4) shows that in radiative divertor plasmas the plasma surrounding the X-point radiating zone is cooling as a result of the condensation in the divertor. The local temperature outside the X-point radiating zone, but from the confined plasma, cools to ~80–90eV from the 'normal' temperature of 300eV. G- ratio measurements further from the X-point show higher temperatures. This temperature gradient along the outer flux surfaces may be destabilising, possibly leading to radiative collapse of the plasma.

When a radiative divertor plasma detaches, the CV resonance to Lyman α line ratio begins a steady increase approximately 3.5s beforehand. Radiative divertor discharges which do not attain detachment do not exhibit this behaviour. Figure 4 shows this ratio calculated as a function of confinement time. The steady, monotonic, change in the line ratio as the plasma moves towards detachment is a measure of an increasing diffusion (because $\tau_p \propto a^2/D_\perp$) in the near-edge plasma. The poorer edge confinement may be caused by a degradation of the confinement mode.

CONCLUSION

It has been shown that the CV and CVI spectra can be used as diagnostics of the outer plasma region. In the SOL charge exchange with neutral deuterium is significant and amounts to ~0.05% of n_e. The temperature of the SOL is ~50-90eV. There is a lack of charge exchange cross section data at the low energies needed for this analysis. The near-edge XUV spectra provide a reproducible detachment signature. The condensation at the X-point sets up a temperature gradient along the flux surface. The ionisation balance is also affected. Enhanced diffusion or poorer edge confinement is evident well before the plasma fully detaches.

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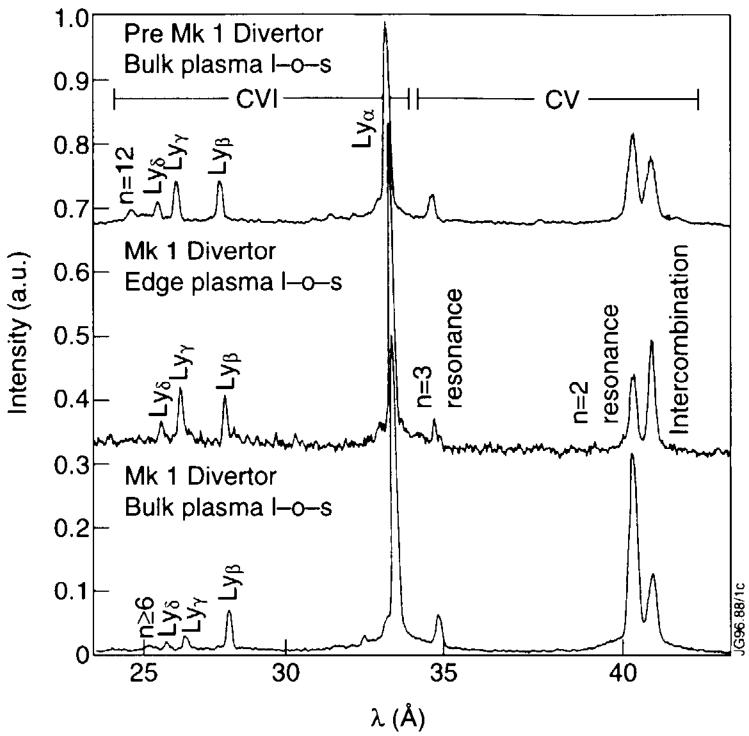

Figure 1 Comparison of observed C V and C VI spectra from the main and edge plasmas from different JET operational periods.

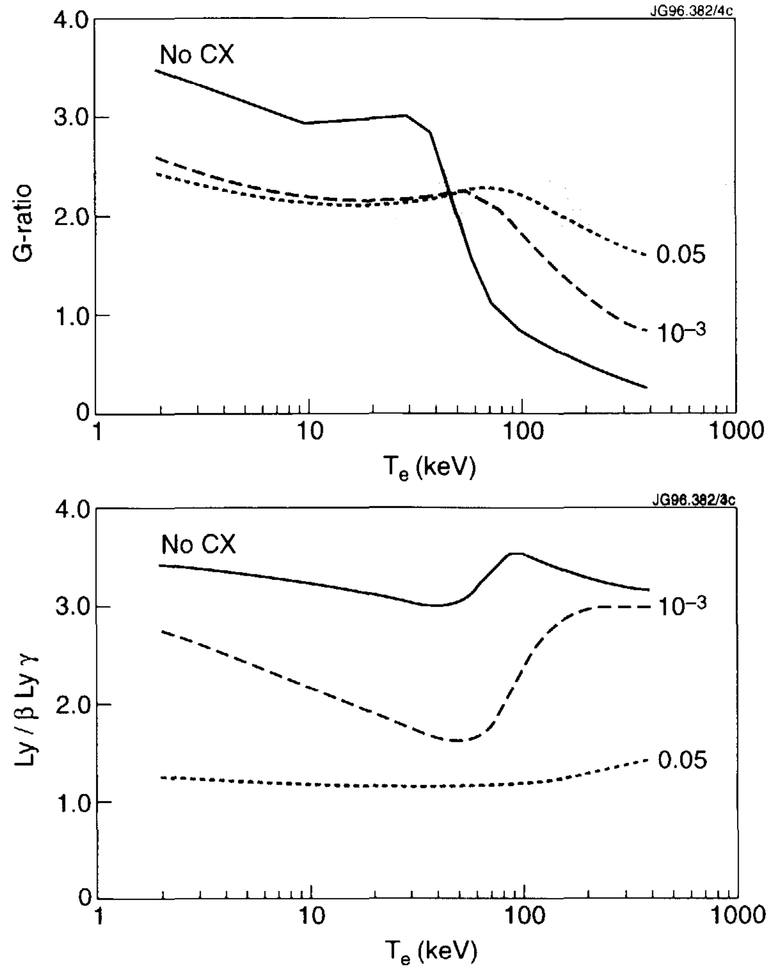

Figure 2 Comparison between observed and modelled line ratios. The spread of the observed ratio is indicated by a shaded region.

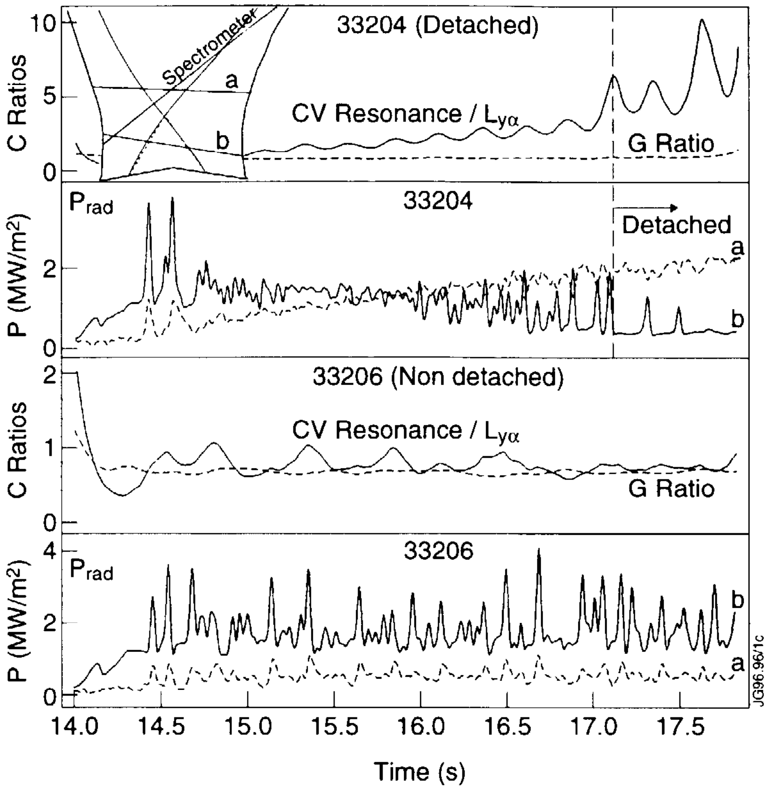

Figure 3 The spectroscopic detachment signature. The modulation of the ratios is due to divertor sweeping. Top shows a detached case with the non-detached on the bottom. Note that the G-ratios have similar values. a and b refer divertor bolometer LOS.

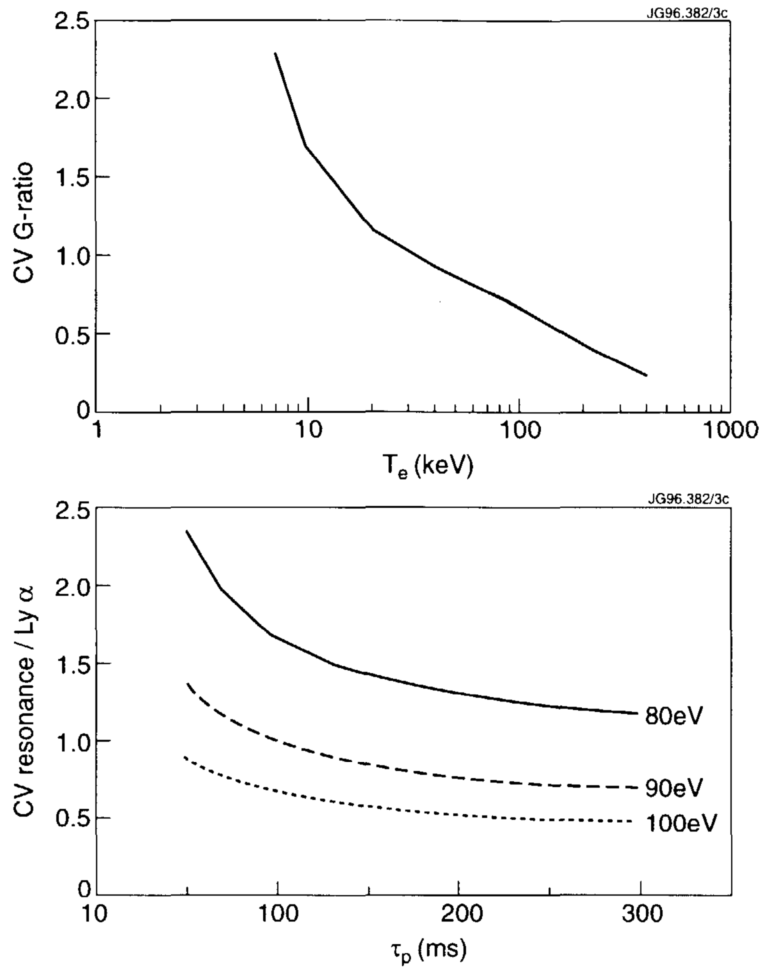

Figure 4 Top: Carbon G ratio in diffusive-ionisation balance equilibrium. The shaded region is the observed ratio. Bottom: C V resonance to C VI Lyman α emission line ratio as a function of confinement time.