MODELLING OF VUV / XUV SPECTRA FROM THE JET TOKAMAK

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Abstract. The VUV/XUV spectral region is particularly rich in lines emitted by plasmas with temperatures ≤30keV used in fusion research. Three examples are presented of analyses involving JET tokamak data. In the first, the C IV divertor emission is modelled, with agreement between theory and experiment to within the measurement accuracy of ~±10%. The second deals with C emission from the Scrape-off Layer (SOL) within the main chamber for which inconsistencies are found and the third the collisional excitation of energetic α-particles in medium Z (Kr) ions.

Keywords: VUV / XUV Spectra, Tokamak plasmas, C IV model, Electron / α-particle excitation
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ANALYSIS OF C IV DIVERTOR EMISSION

A stringent test of the theory describing the passive emission from a plasma is to check the consistency of measured and theoretical intensity ratios of spectral lines emitted from the same ionization stage. This approach avoids the need for determining the plasma emission volume, an absolute sensitivity calibration of the spectrometer being used for the measurements and, in some cases, even accurate measurements of parameters such as electron density. An analysis has been carried out for the C IV emission from the JET divertor, C previously being the main low Z intrinsic impurity in JET plasmas. This ion has a simple structure as well as being useful for sensitivity calibrations. In contrast to the visible spectral region where only one useful C IV line is found, 6 lines (Fig. 1) can be observed with the JET double SPRED spectrometer. The detector used has a spectral range of 140 to 443Å and a spectral resolution of ~1Å. It observes the JET divertor along a vertical line-of-sight (left hand view of Fig. 2). An accurate relative sensitivity calibration (Fig. 3) is crucial to the analysis and this was derived using a series of Na- and Li-like line intensity ratios [1,2]. Atomic data were generated specifically for the analysis by Aggarwal and Keenan using the GRASP and DARC codes [3]. The theoretical line ratios are defined in terms of the Photon Emission Coefficient (PEC) formulation of ADAS [4],

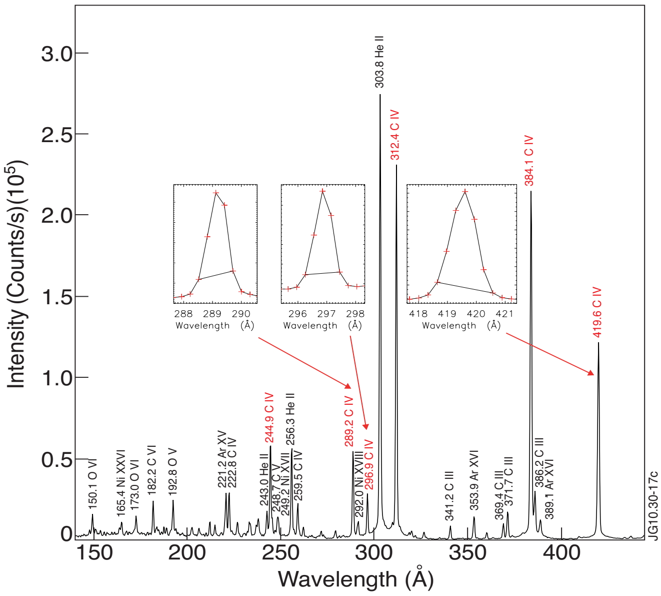

FIGURE 1. The divertor spectrum for JET pulse 69931 averaged between times 12.3 and 12.6s.

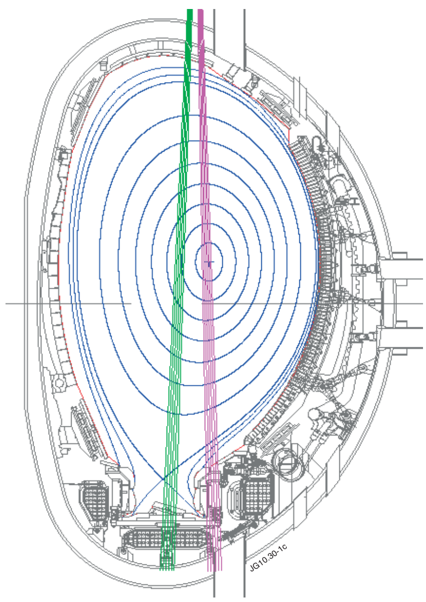

FIGURE 2. Lines-of-sight of the JET divertor viewing spectrometer.

$$\frac{I_1}{I_2} = \frac{\varepsilon_1^{exc} + \frac{n_{g+1}}{n_g}\varepsilon_1^{rec} + \frac{n_{g+1}n_D}{n_g n_e}\varepsilon_1^{cx}}{\varepsilon_2^{exc} + \frac{n_{g+1}}{n_g}\varepsilon_2^{rec} + \frac{n_{g+1}n_D}{n_g n_e}\varepsilon_2^{cx}},$$

where ε^{exc}, ε^{rec} and ε^{cx} are the excitation, free electron recombination and charge exchange PECs, respectively, and n_e, n_D and n_g indicates the electron, deuterium and ground state densities. The RMS of the differences between the measured and theoretical ratios are minimized by varying T_e, n_e, n_{g+1}/n_g and $n_{g+1}n_D/n_g n_e$. Excellent agreement to within the experimental accuracy ~±10% is found, showing the high quality of the atomic data and allowing the sensitivity calibration (Fig. 3) to be improved. The minimization was not sensitive to the local n_e nor n_{g+1}/n_g, indicating that the free electron recombination terms (dielectronic and radiative recombination being the most significant) are small. It was necessary to include charge exchange recombination, the two significant contributions being to the 312.4Å and 384.1Å lines, shown in figures 4 and 5 for a database of Ohmic, L- mode and H-mode measurements. The minimization depended on T_e, allowing the T_e for the plasma emitting C IV radiation, T_e (C IV), to be determined. T_e (C IV) was found to depend on n_e of the bulk plasma. Figure 6 shows the dependence of the Ohmic points on the line-integrated edge n_e and Fig. 7 points for all regimes on the volume averaged n_e. Here it can be seen that the L-mode points overlay the Ohmic points at low densities and the H-mode points at high densities. Since T_e (C IV) depends on the edge transport, the discontinuity observed at n_e of ~$1.5\text{x}10^{19}\text{m}^{-3}$ may indicate a change in transport behaviour between low and high densities. Further details of the analysis are given by Lawson *et al.* [5].

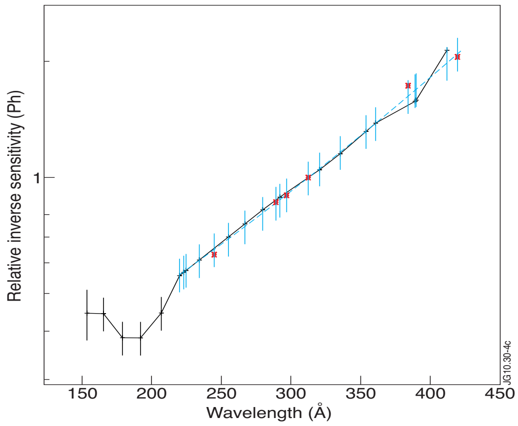

FIGURE 3. The relative inverse sensitivity calibration (S^{-1} at 312.4Å=1). + points derived from the Na- and Li-like ratios, * from C IV ratios. --- 2nd order polynomial fit.

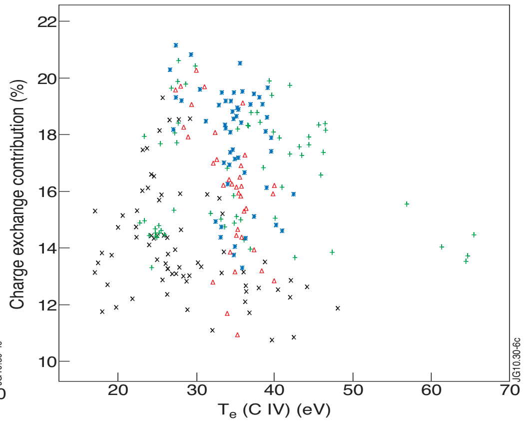

FIGURE 4. The charge exchange contributions to the 312.4Å line. x Ohmic, + L-mode, * ELMy H-mode, Δ ELM-free H-mode.

SCRAPE-OFF LAYER (SOL) EMISSION DISCREPANCY

The spectrometer used for the above measurements can be tilted to observe the plasma edge (main chamber SOL) above the throat of the divertor (right hand view of Fig. 2). In this position, with the same analysis, the expected consistency between measured and theoretical line intensity ratios is no longer found. Similar unresolved discrepancies are observed for C III and using spectrometers with horizontal lines-of-sight. The discrepancy for C IV, for which the analysis is most detailed, is defined as

$$d(T_e) = \frac{R_m}{R_t},$$

where R_m and R_t are the measured and theoretical line intensity ratios. The latter is calculated at a T_e given by the 312.4Å/289.2Å ratio (this gives values of T_e that are lower than expected; other ratios give unrealistically high values of up to ~1keV). Figure 8 illustrates $d(T_e)$ for one ratio (419.6Å/312.4Å) for an Ohmic database.

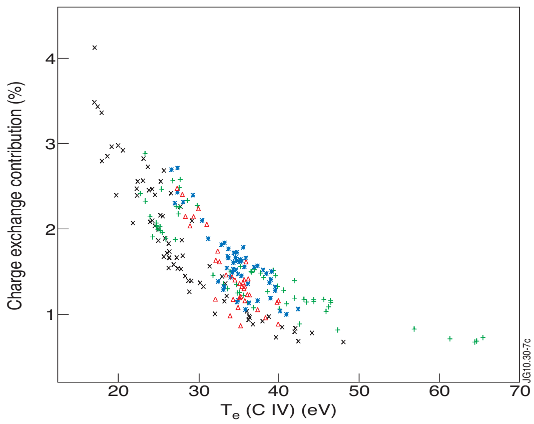

FIGURE 5. The charge exchange contributions to the 384.1Å line. x Ohmic, + L-mode, * ELMy H-mode, Δ ELM-free H-mode.

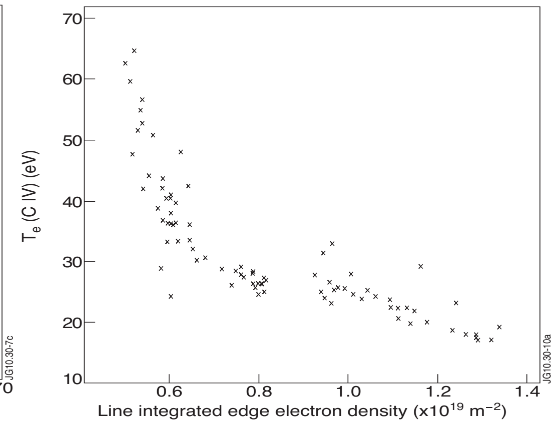

FIGURE 6. T_e (C IV) for the Ohmic database plotted against the line-integrated edge n_e.

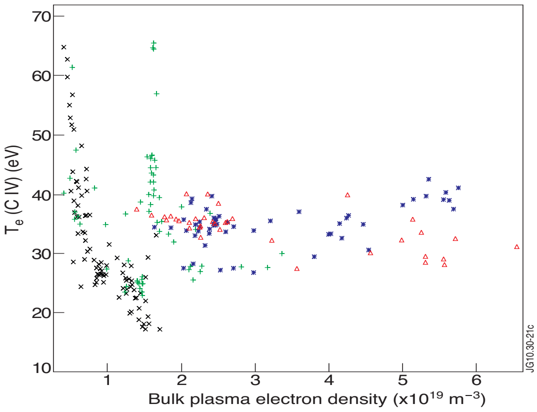

FIGURE 7. T_e (C IV) plotted against the bulk plasma n_e. x Ohmic, + L-mode, * ELMy H-mode, Δ ELM-free H-mode measurements.

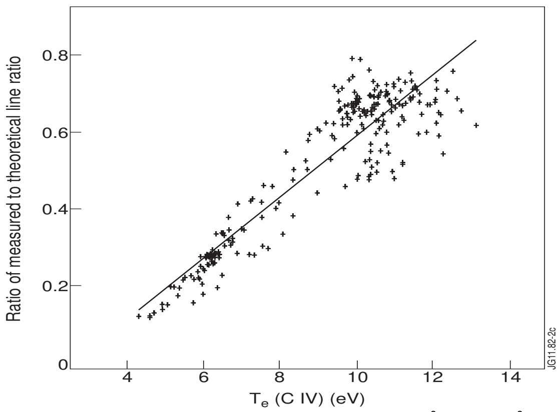

FIGURE 8. d(T_e) for the 419.6Å/312.4Å line intensity ratio plotted against T_e (C IV) for an Ohmic database.

A number of possible causes have been investigated in attempting to explain the discrepancies. The most usual cause in the VUV and XUV spectral regions is line blending, due to the limited spectral resolution possible for the wide energy range observed. This has been checked with no evidence of systematic blending being found and it is noted that the spectra are very similar to the divertor observations for which agreement has been found. Questions as to the accuracy of the atomic data, relative sensitivity calibration, line integrations or other unexpected instrumental effects must also be dismissed given the agreement found for the divertor emission.

Free electron recombination does not appear to be significant in any of the pulses studied and charge exchange recombination tends to be reduced when the discrepancy is large. In regions of steep gradients, as at the plasma edge, the line-of-sight integrated measurement can differ from the mean value, the difference being most noticeable at low temperatures. However, neither the temperature dependence nor the magnitude of the effect could explain the observed discrepancy.

It is usual to assume a Maxwellian electron energy distribution in the SOL plasma, although this can be marginal. Therefore, a check was made to see if the use of a non-Maxwellian distribution could explain the discrepancy. A high energy tail has relative little effect on the excitation of the C IV lines of interest; instead the distribution was varied particularly in the energy range 37.6 to 50.9eV, since this has the largest effect on the C IV excited level populations. No evidence of a non-Maxwellian electron energy distribution was found.

A further assumption made in deriving the energy level populations is that ionization from excited levels is small compared with radiative decay and that ionization largely populates the ground state of the next highest ionization stage. Using FAC [6] calculations of ionization cross sections, it was confirmed that ionization from the C IV excited levels is very small (<0.005% of the radiative decay). However, ionization from C III to the C IV excited levels is non-negligible. For example, 10 and 20% of ionizations go to the $1s^2 2p\ ^2P_{1/2}$ and $^2P_{3/2}$ levels, respectively. It is noted that the C IV ionization PECs were of a similar magnitude to the charge exchange recombination PECs and significantly larger than the free electron recombination PECs. During an impurity influx this populating mechanism would need to be taken into account, although for the present database, which is of steady state measurements, the effect is too small and with an incorrect temperature dependence to explain the discrepancy.

The assumption that steady state has been reached was also checked. It was found that the C IV levels of interest reached equilibrium in ~10^{-10} - 10^{-11}s, significantly faster than characteristic edge flow or transport times or of plasma effects. Searches have been made for dependences on various plasma parameters, although to date none have been found. The large Ohmic database illustrated in Fig. 8 has still to be analysed in this way. If found, such dependencies may help resolve the discrepancy, which to date remains unexplained. Further details of these analyses are given by Lawson *et al.* [7]

COLLISIONAL EXCITATION BY FAST α-PARTICLES

The dominant mechanism exciting ions in tokamak plasmas is electron collisional excitation. In medium to high Z ions, collisions by thermal heavy ions, either D or T fuel or He ash, can excite levels close to the ground state, such as those that result in optically forbidden transitions. The question arose as to whether the energetic α-particles produced in DT reactions increased the excitation of the forbidden transitions to the extent that line intensity ratios involving these transitions could be used as a diagnostic of the alpha particles. F- and B-like Kr, whose ions are well-separated in the JET plasma, are being used to investigate this possibility and assess the atomic data. Instead of α-particles, Kr spectra were recorded when He neutral beams were injected into JET.

The effect is expected to be small and so accurate atomic data are essential. A-values and electron excitation collision strengths were generated by Aggarwal *et al.* using the GRASP and DARC codes [8,9,10] and Reid provided heavy particle excitation cross-sections for these ions using the IFXN code. Figure 9 shows the α-particle cross sections between the lowest 3 levels ($2s^22s^5\ {}^2P_{3/2,1/2}$ and $2s2s^6\ {}^2S_{1/2}$) of F-like Kr. Those to level 3, in particular, which result in optically allowed transitions, remain significant throughout the energy range of the α-particles (≤3.52MeV). To judge the likely effect of such cross sections in burning plasma experiments, simulated α-particle velocity distributions for ITER discharges [11] have been used to derive

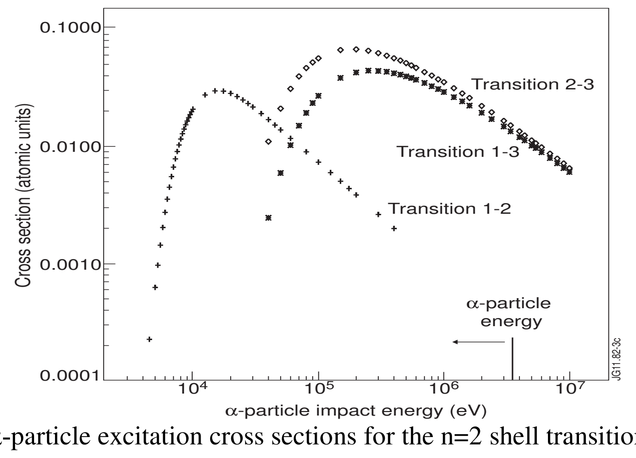

FIGURE 9. α-particle excitation cross sections for the n=2 shell transitions of F-like Kr

excitation rates. For F-like Kr, the excitation rates for the allowed transitions are ~20x higher than for the forbidden transition. It follows that the diagnostic use of line intensity ratios to determine, say, the α-particle density is not confined to the use of forbidden transitions. Indeed, line intensity ratio techniques as for electrons and, for example, as used above for C IV, should be possible.

Atomic data for higher temperature ions expected to be found towards the plasma centre, such as He-like Kr, are required to determine whether the technique will be sensitive enough to provide a useful diagnostic in future machines.

CONCLUSIONS

An analysis of C IV emission from the JET divertor shows excellent agreement with theory (~±10%). The importance of charge exchange recombination is seen (≤21% contribution to the 312.4Å line), although free electron recombination is small for all pulses studied. The analysis allows the determination of T_e of the C IV emitting plasma to an accuracy of ~±20-30% and it is shown that this temperature depends on n_e of the bulk plasma. Inconsistencies are found when the same analysis is applied to the main chamber SOL emission and various possible causes have been investigated, as yet without resolution. It suggests that the description of the passive impurity emission from the main chamber SOL is incomplete, which can affect any use made of the lines. Collisional excitation by α-particles in medium to high Z elements is being investigated through a study of F- and B-like Kr line intensity ratios on JET. The high α-particle energies result in significant excitation to all energy levels, not only those close to the ground level as is expected for thermal heavy particles.

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