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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 ≤ 30 keV used in fusion research. Examples are presented of analyses of JET tokamak data involving C VUV/XUV radiation. In the first, the C IV divertor emission is modelled, with agreement between theory and experiment to within the measurement accuracy of ~±10%. A second deals with C emission from the Scrape-off Layer (SOL) within the main chamber for which inconsistencies are found.

Keywords: VUV / XUV Spectra, Tokamak plasmas, C IV model.
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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. The theory involves a collisional radiative model, a low density approximation being found adequate for the C IV ionization stage. Excited states are populated by electron collisions from the ground level and by radiative cascading from higher levels. Depopulation is via radiative decay. 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), with the dominant emission expected from the plasma region outside the separatrix to the right of the X-point. The higher electron and impurity densities in the divertor result in this emission being much larger than that from the top of the vessel, which can be neglected. An accurate

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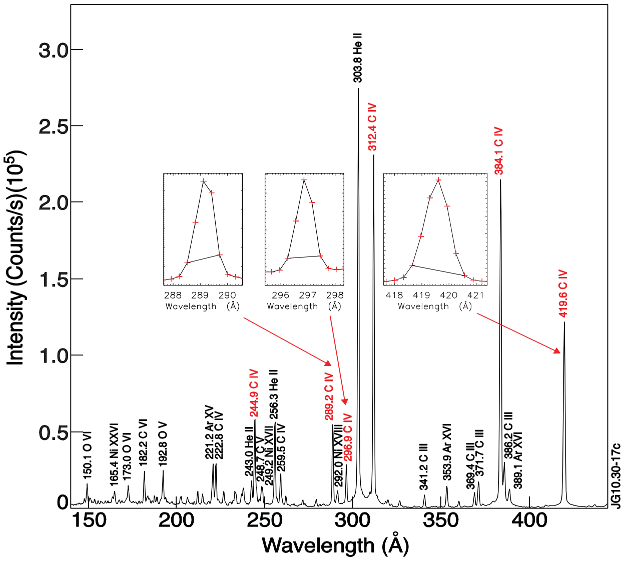

FIGURE 1. The divertor spectrum for JET pulse 69931 averaged between times 12.3 and 12.6s.

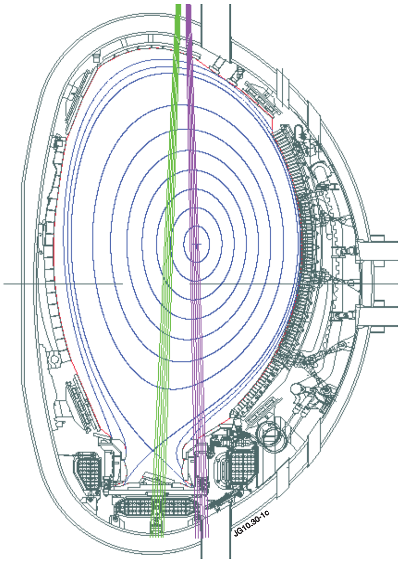

FIGURE 2. Lines-of-sight of the JET divertor viewing spectrometer.

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],

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

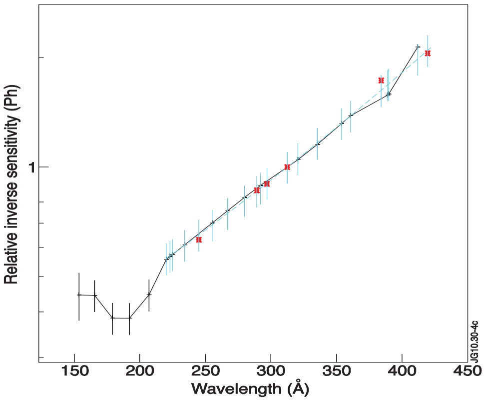

FIGURE 3. The relative inverse sensitivity calibration (S^{-1} at 312.4Å=1). + points derived from the Na- and Li-like ratios, * from C IV ratios. --- 2nd order polynomial fit.

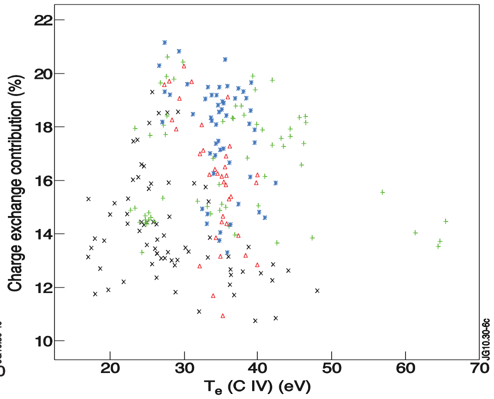

FIGURE 4. The charge exchange contributions to the 312.4Å line. x Ohmic, + L-mode, * ELMy H-mode, Δ ELM-free H-mode measurements.

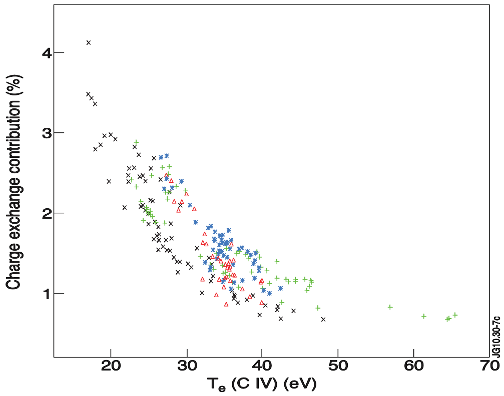

FIGURE 5. The charge exchange contributions to the 384.1Å line. x Ohmic, + L-mode, * ELMy H-mode, Δ ELM-free H-mode measurements.

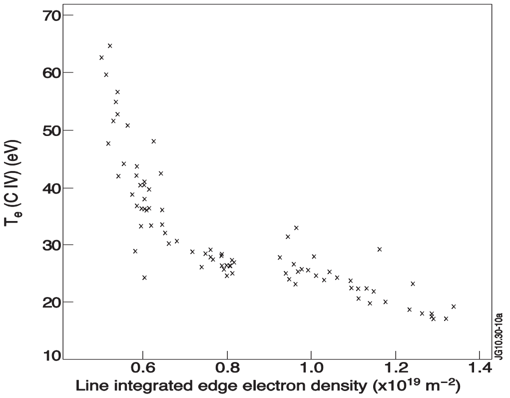

FIGURE 6. T_e (C IV) for the Ohmic database plotted against the line-integrated edge n_e.

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 excitation PEC is derived from the collisional radiative model. 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 $n_{g+1}n_D/n_gn_e$. 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 largest contributions being to the 312.4Å and 384.1Å lines, shown in figures 4 and 5 for a database of Ohmic, L- 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 to an accuracy of ~±20% at low values of T_e and ~±30% for $T_e > 50$eV. 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 an n_e of ~1.5x10^{19}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] and the study is being continued in order to gain a better understanding of the dependences and the edge transport.

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

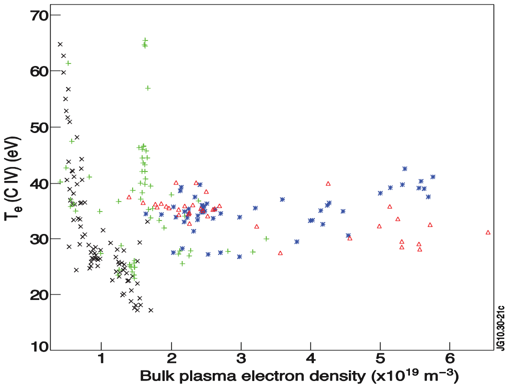

FIGURE 7. T_e (C IV) plotted against the bulk plasma n_e. x Ohmic, + L-mode, * ELMy H-mode, Δ ELM-free H-mode measurements.

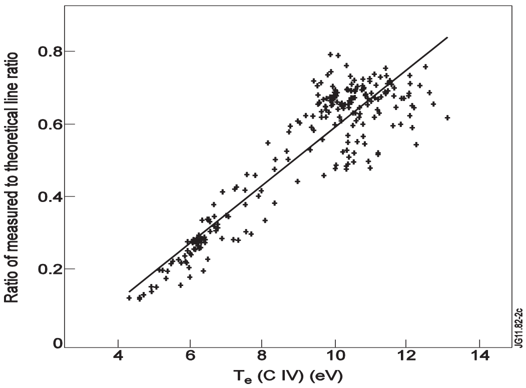

FIGURE 8. *d(T_e)* for the 419.6Å/312.4Å line intensity ratio plotted against T_e (C IV) for an Ohmic database.

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

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 ratio having a strong sensitivity to T_e with its lines close to one another, minimizing any uncertainty in the sensitivity calibration. Figure 8 illustrates $d(T_e)$ for the 419.6Å/312.4Å ratio for an Ohmic database and it can be seen that this differs significantly from unity, which would indicate consistency between the 419.6Å/312.4Å and 312.4Å/289.2Å ratios. The values of T_e found are lower than expected, while other ratios give unrealistically high values of up to ~1keV. Imposing values of T_e comparable to those found for the divertor region still results in discrepancies.

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. There is no evidence of systematic blending and it is noted that the spectra are very similar to the divertor observations for which agreement has been found.

For the collisional radiative model, transition probabilities and electron collisional excitation rates are required, the latter being a function of T_e. Since this parameter was varied in the minimization, consistency being found for a wide range of T_e for the divertor emission, these atomic data are not in question. Similarly, inaccuracies in the relative sensitivity calibration and line integrations or other unexpected instrumental effects must 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. It is noted that the analysis is not particularly sensitive to the accuracy of the charge exchange rates since the contribution to a single line (312.4Å) dominates. An error in the rates would simply lead to the minimization giving a different value of $n_{g+1}n_D/n_gn_e$.

In regions of steep gradients, as found at the plasma edge, the line-of-sight integrated measurement can differ from the mean value. This difference is most noticeable at low temperatures, where the atomic data is most sensitive to temperature.

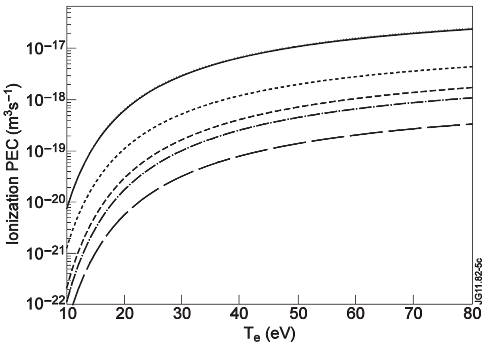

FIGURE 9. Typical C IV ionization PECs. —— 420Å, - - - - 384Å, ········ 312Å, — · — 297Å, —— - 289Å, — — 245Å lines.

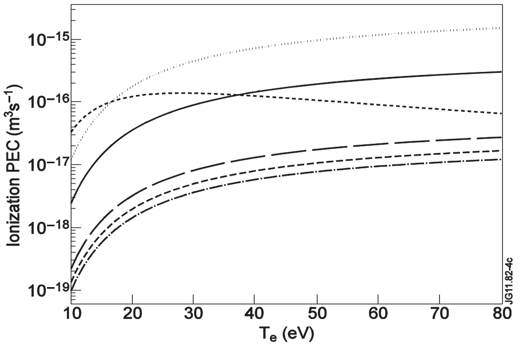

FIGURE 10. C IV ionization PECs constructed so as to give agreement. —— 420Å, - - - - 384Å, ········ 312Å, — · — 297Å, —— - 289Å, — — 245Å lines.

However, neither the temperature dependence, nor the magnitude of the effect could explain the observed discrepancy. In particular, the discrepancies for the 419.6Å/312.4Å and 419.6Å/289.2Å ratios are observed to be very similar, whereas the line-of-sight differences for these ratios have opposite gradients.

It is usual to assume a Maxwellian electron energy distribution in the SOL plasma, although this can be marginal. A check was made to see if the use of a non-Maxwellian distribution could affect the collisional excitation rates in such a way as to explain the discrepancy. A high energy tail has relatively little effect on the excitation of the C IV lines of interest. Instead, the electron distribution was divided into sections bounded by the energies of the upper levels of interest, that is in the energy range 37.6 to 50.9eV, and the contributions from each section to the collisional excitation rate varied to see if the experimental line ratios could be matched. In some cases, charge exchange recombination was included. However, no evidence of a non-Maxwellian electron energy distribution was found.

A further assumption made in deriving the energy level populations is that ionization has no effect on the excited level populations, ionization from excited levels being small compared with radiative decay and largely populating 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, these calculations also showed that ionization from C III to the C IV excited levels is not negligible. For example, 10 and 20% of ionizations go to the $1s^22p\ ^2P_{1/2}$ and $^2P_{3/2}$ levels, respectively. Ionization PECs, ε^{ion}, analogous to the ADAS recombination PECs, can be constructed, the line intensity being given by

$$I = n_e n_g \varepsilon^{exc} + n_e n_{g-1} \varepsilon^{ion}.$$

Typical PECs for the C IV lines of interest are plotted against T$_e$ in Fig. 9 for an electron and deuteron density of 10^{19}m^{-3}. In magnitude these tend to fall between the charge exchange recombination and free electron recombination PECs. Figure 10 gives an example of ionization PECs specially constructed to give agreement between the theoretical and measured line intensity ratios. Throughout most of the range of T$_e$, these are one to two orders of magnitude higher and therefore would require a higher

n_{g-1}/n_g ratio than is consistent with the present spectra for which n_{g-1}/n_g is ~1. More importantly, agreement is only found if the 384.1Å PEC has a negative gradient and this is not the case for the calculated 384.1Å PEC (Fig. 9). Nevertheless, during an impurity influx, when locally $n_{g-1}/n_g >> 1$, this populating mechanism would need to be taken into account. For the present database of steady state measurements, the effect is too small and with an incorrect temperature dependence to explain the discrepancy.

In applying the rate equations, it is assumed that the level populations reach steady state. A time dependent calculation showed that the 1/e times required for the C IV levels of interest to reach equilibrium were $\sim 6 \times 10^{-11}$- 4×10^{-10}s, close to the inverse of the radiative transition probabilities. This is 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].

CONCLUSIONS

Two examples of the modelling of JET VUV/XUV spectra are discussed. 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 the 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.

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