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Investigation of C IV line broadening mechanisms for plasma diagnostics in magnetic fusion devices

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ABSTRACT

The $n = 5–6$ ($\lambda = 4658$ Å) and $n = 6–7$ ($\lambda = 7726$ Å) spectral lines emitted by Li-like carbon ions C^{+3} from magnetic fusion devices based on carbon material are considered for plasma diagnostic purposes. The broadening mechanisms of these lines are examined for plasma conditions relevant to Tokamak divertors (electron densities and temperatures in the ranges 10^{19}–10^{21} m^{-3} and 1–10 eV). Under these conditions, the broadening mechanisms affecting the above lines are examined with and without the retaining of the magnetic field. The uncertainties on the deduced plasma parameters are also qualitatively estimated when only Stark and Doppler effects are retained while Zeeman and fine structure effects are ignored. The results presented are based on theoretical calculations carried out with the PPP line shape code and an atomic data basis built using Cowan's code and the most accurate available atomic data for carbon.

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1. Introduction

Spectroscopic techniques play an important role in the characterization of different plasmas including those produced in magnetic fusion devices. It is known that plasma diagnostics based on spectroscopic measurements of line emission use line intensities, line shapes or both to obtain one or several plasma parameters like the densities and temperatures of the different particles (ions, electrons or/and neutrals). For instance in the JT-60U Tokamak, the electron density and temperature characterizing the plasma in the divertor region around the X-point have been deduced from the measured intensities of several C IV lines emitted by C^{+3} ions. In that case, a collisional-radiative model has been used to calculate the population densities of the C^{+3} excited levels involved in the measured C IV emission lines. The comparison of these theoretical population densities with the experimental ones (obtained from the line intensities) allows to evaluate the plasma parameters of the emissive region [1,2]. Typically, electron densities in the range 10^{20}–10^{21} m^{-3} and electron temperatures 1 eV $\leqslant T_e \leqslant$ 10 eV have been deduced for detached plasmas with a MARFE in JT-60U [1,2]. Moreover, electron densities up to 10^{22} m^{-3} have been estimated near the X-point from the measured data on this machine [1]. Such high electron densities have still to be confirmed by other independent methods, and among them Stark broadening is the most convenient. For a given species (carbon in our case), the lines which are most sensitive to Stark effect are those resulting from highly excited upper levels of the emitter which has the highest ionization stage, i.e. hydrogen-like carbon ions C^{+5} (fully stripped ions are excluded since they do not emit any line). However, H-like carbon ions are mainly present in central regions of the plasma where T_e is of the order of few hundred eVs (e.g. T_i = 100–300 eV in TEXTOR [3]). Like in other Tokamaks, the region around the X-point in JT-60U is characterized by an electron temperature of only few eVs which favours the predominance of Li-like carbon ions C^{+3} over all other ionization stages of carbon. Therefore only lines emitted by C^{+3} ions are considered in this paper. In addition to that, the higher the upper principal quantum number of the transition, the more important is the Stark effect. Our choice to study the profiles of the $n = 5–6$ and $n = 6–7$ lines is imposed by the previous considerations and the quality and availability of the spectra which have been measured in JT-60U. The ultimate aim of such a study is to compare the calculated profiles to spectra from JT-60U and other fusion devices. This work is ongoing and the results of such comparisons will be published elsewhere in the near future.

This paper is organized as follows. In Section 2, we will show how the atomic physics data basis is built. In Section 3, the broadening mechanisms affecting the considered C^{+3} lines and their profiles will be presented. The results will be discussed in Section 4 and a conclusion is drawn in Section 5.

2. Construction of the atomic physics data basis

The line shape code that we have used for this work is the PPP code [4] which is based on the standard model of Stark broaden-

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Table 1
Adopted energies of the various excited levels of C^{+3} ions implied in the $n = 5$–6 and $n = 6$–7 studied transitions compared to values found in the literature. Theoretical values are taken from [6] which reports experimental values of Bashkin and Stoner [8]. Values with superscript are taken from the NIST database [7] and are calculated as the mean value of the corresponding fine levels $^2D_{3/2}$ and $^2D_{5/2}$.

Level	5 ^{2}D	5 ^{2}F	5 ^{2}G	6 ^{2}D	6 ^{2}F	6 ^{2}G	6 ^{2}H	7 ^{2}F	7 ^{2}G	7 ^{2}H	7 ^{2}I
Theoretical energy (cm^{-1})	449 889.0$^{(a)}$	449 941.3	449 945.2	471 371.0$^{(a)}$	471 402.4	471 405.8	471 406.8	484 341.9	484 345.6	484 345.8	484 346.0
Adopted energy (cm^{-1})	449 882.25	449 934.5	449 939.4	471 369.6	471 401.0	471 404.1	471 405.0	484 340.5	484 347.0	484 347.5	484 347.8
Difference (cm^{-1})	−6.75	−6.8	−5.8	−1.4	−1.4	−1.7	−1.8	−1.4	+1.4	+1.7	+1.8

ing [5]. Similarly to all other line shape codes, PPP requires an input file which contains in addition to the plasma parameters some important atomic physics data like the energies and the dipole matrix elements of the atomic transitions. To build the atomic data basis we have proceeded as follows: first we have applied the Cowan's code [6] to the C^{+3} levels for principal and angular quantum numbers $n = 4$–8 and $0 \leqslant l \leqslant n-1$, respectively. In this step, all the necessary atomic data including reduced matrix elements of the dipole *nl*–*n′l′* transitions between all *l*-levels have been calculated. Then the Cowan's values of the energy have been replaced by more recent and accurate ones taken from Quinet [7,8] and the NIST ASD database [9]. However, for the two lines studied here we have adopted slightly modified energies such that the theoretical transition wavelengths coincide with the experimental ones given by Nakano [2] (see Table 1). For the 5 ^{2}F-6 ^{2}G and 5 ^{2}G-6 ^{2}H transitions of the $n = 5$–6 line, the experimental wavelengths are respectively, 4657.75 and 4658.62 Å. On the other hand, for the 6 ^{2}F-7 ^{2}G, 6 ^{2}G-7 ^{2}H and 6 ^{2}H-7 ^{2}I transitions of the $n = 6$–7 line, the corresponding values are respectively, 7724.38, 7725.95 and 7726.26 Å. It should be noted that, for all the *nl*–*n′l′* transitions between the different *l*-levels, we have used the dipole matrix elements calculated with the Cowan's atomic package code as they are in a good agreement with the corresponding ones obtained by converting gA-values taken from the NIST ASD database [9]. In addition, a statistical equilibrium is assumed for the distribution of the population densities.

3. Broadening mechanisms and line shape calculations

We are interested here by the profiles of the $n = 5$–6 and $n = 6$–7 lines emitted by C^{+3} ions in a deuterium plasma characterized by a relatively high electron density 10^{19}–10^{21} m^{-3} and a low electron temperature 1–10 eV with the presence of a typical magnetic field $B = 1$–3.5 T. From the examination of the energies of all levels, it clearly appears that level splitting due to fine structure effect is negligible in comparison with that caused by Stark and Zeeman effects.

For clarity and simplicity, the calculations presented here have been obtained assuming the same temperature for electrons and ions $T = T_e = T_i$ (C^{+3} ions have the same temperature T_i as the D^+ ions). Note also that Zeeman effect is treated in a first approximation as a "convolution" of the Stark profiles and that the latter were calculated in the frame of the impact approximation for the plasma electrons and the quasi-static approximation for the plasma ions [5]. In the following section, we will study the competition between the different broadening mechanisms through calculations carried out with and without the inclusion of the Zeeman effect for each of the two lines. Note that similarly to our previous work [10], as a first approximation, one can simplify the line profile calculations by ignoring the Zeeman effect if comparisons are to be made with line spectra obtained with a polarizer.

4. Results and discussion

Let us start with profiles calculated without Zeeman effect. As Doppler broadening is proportional to the square root of the emitter temperature, the Doppler width increases by a factor of about 3 when *T* varies from 1 to 10 eV. On the other hand, the Stark width due to the electron contribution changes drastically (as it is proportional to the electron density) when N_e varies from 10^{19} to 10^{21} m^{-3}, the dependence of Stark broadening on the electron and ion temperatures being weak. Therefore Doppler broadening seriously competes with Stark effect for low densities as is demonstrated in Fig. 1 which shows theoretical profiles of the C IV $n = 6$–7 line calculated for a deuterium plasma with $N_e = 5 \times 10^{19}$ m^{-3}. The multi-peaks structure, characterizing the pure Stark profile (dot) calculated for $T = 1$ eV, progressively disappears with increasing *T* from 1 to 10 eV when Doppler effect is included. As mentioned before, profiles including Doppler and Zeeman effects are obtained by a convolution procedure. Those shown in Fig. 2 were obtained with an observation perpendicular to the magnetic field direction for $B = 1$–3.5 T. For this low electron density case, Zeeman effect is visible in the profiles even for $B = 1.0$ T and induces strong modifications for $B = 3.5$ T. Of course, as can be seen in Fig. 3, at higher electron densities these Zeeman "features" are completely masked by Stark broadening which even mixes the two peaks appearing in Fig. 1. Our calculations suggest that Zeeman effect should be included when the electron density is approximately lower than 10^{21} m^{-3} for the considered temperature range. Furthermore, it results from the calculations we carried out that it is not possible in the general case to quantitatively evaluate the uncertainties of the plasma parameters when using profiles without Zeeman effect in

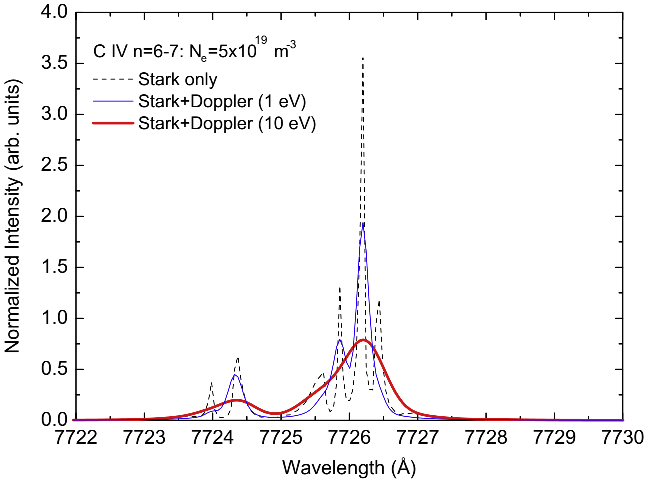

Fig. 1. Comparison of Stark and Doppler broadening on the C IV $n = 6$–7 line profiles for $N_e = 5 \times 10^{19}$ m^{-3}.

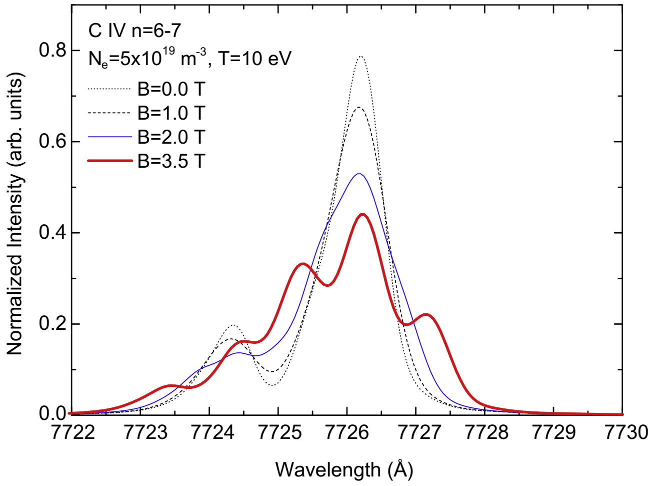

Fig. 2. Comparison of profiles of the C IV $n = 6–7$ line calculated without Zeeman effect $B = 0.0$ T (dot) and for different magnetic field values $B = 1$ T (dash), $B = 2$ T (thin line) and $B = 3.5$ T (thick line).

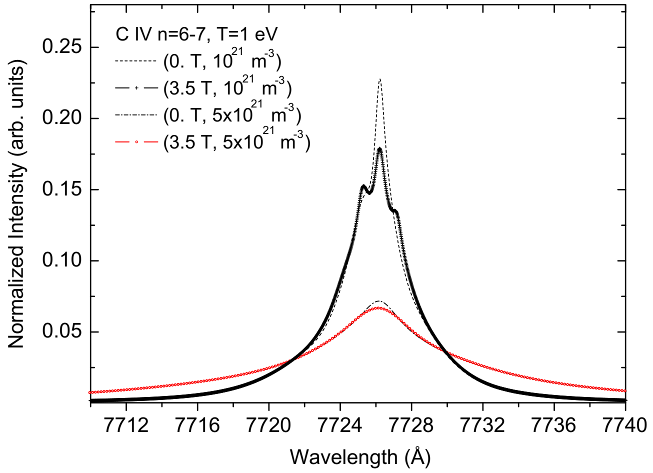

Fig. 3. Profiles of the same line as in Figs. 1 and 2 calculated for higher electron densities with and without Zeeman effect.

comparison with those taking it into account to fit measured spectra. The calculations carried out at higher electron densities and presented in Fig. 3 show that Zeeman effect can be neglected in comparison to Stark broadening. A preliminary comparison between our calculations and experimental spectra from JT-60U is illustrated in Fig. 4. As a π-polarizer has been used to record only the central component of the line, the theoretical profile has been calculated without Zeeman effect. The shown plasma conditions ($T = 5$ eV, $N_e = 5 \times 10^{19}$ m^{-3}) allow to obtain the same FWHM of $\sim$0.7 Å for the highest peak of the spectrum but don't allow to reproduce accurately the entire spectrum. According to this comparison of Fig. 4 and to profiles having a single peak (calculated for high electron densities) shown in Fig. 3, the electron density around the X-point region in JT-60U (where the measured spectra have two peaks) should not exceed values of the order of $\sim 2 \times 10^{21}$ m^{-3}. Nevertheless, more accurate comparisons with measurements (fitting spectra) are necessary for a more precise evaluation. Similar results have been obtained for the C IV $n = 5–6$ line for which Stark effect is less sensitive than for the $n = 6–7$ line at given plasma conditions.

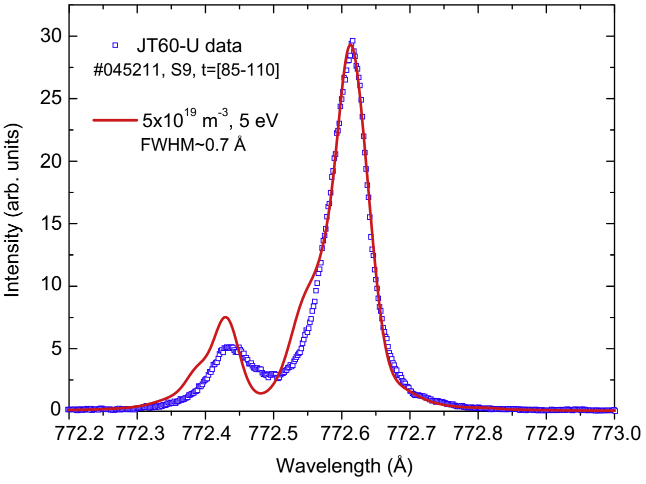

Fig. 4. An experimental spectrum of the C IV $n = 6–7$ line from JT-60U compared to a theoretical profile calculated without Zeeman effect for an electron density of 5×10^{19} m^{-3} and a temperature of 5 eV.

5. Conclusion

Line broadening mechanisms (Doppler, Stark and Zeeman effects) affecting the profiles of the C IV $n = 5–6$ and $n = 6–7$ lines have been examined for plasma conditions relevant to detached divertor plasmas. A line shape code has been used to calculate profiles with the aim of comparing them with experimental spectra from JT-60U and other fusion devices. Preliminary comparisons with published spectra from JT-60U show that the electron density in the JT-60U divertor around the X-point should not exceed 2×10^{21} m^{-3} even in the presence of a MARFE. Moreover, more and accurate comparisons with experimental data from JT-60U (fitting data) are scheduled in the future to confirm or invalidate the plasma parameters obtained using a collisional-radiative model and line intensities.

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