Diagnostics of tokamak divertor plasmas by Stark broadening of impurity emission lines

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Abstract. Line broadening by Stark and Doppler effects of some impurity spectral lines is proposed as a diagnostic tool for divertor plasmas. It is shown that the shape of the C IV n=6-7 λ~7726 Å line can be successfully used to infer the electron density averaged along the line of sight provided the electron and the ion temperatures are known. For illustrative purposes, the technique is applied to experimental data from the JT-60U tokamak. Using temperatures deduced from C IV line intensities, the line-integrated electron density and its spatial distribution around the X-point can be extracted from the shape of the C IV n=6-7 line.

1. Introduction

Peripheral regions of magnetic fusion devices such as tokamak divertors play a crucial role in the protection of the confined plasma from contamination by wall impurities as well as the extraction of the thermal power and the fusion reaction ashes in the case of fusion reactors. Therefore it is necessary to characterize such regions. For that purpose, one of the best methods is passive spectroscopy which is a non intrusive method requiring comparison of spectroscopic measurements with theoretical quantities. Passive spectroscopy relies on the use of either spectral line intensities, spectral line broadening or a combination of both. In divertors, impurities like carbon or helium neutrals and ions emit spectral lines whose shapes are governed by Stark and/or Doppler broadenings depending on the plasma conditions and the lines themselves. In addition, these lines are also subject to the Zeeman effect which can be omitted if one has to analyse spectra measured with a polarizer. Following a previous work [1], we present here comparisons between C IV n=6-7 λ~7726 Å line spectra measured in the JT-60U tokamak and theoretical profiles allowing the determination of the plasma parameters. Our results are compared to those obtained from line intensities [2]. We also consider the use of Stark broadening of the helium diffuse series He I 1s2p $^3P°$-1snd ^3D with n≥7 for diagnostic purposes in present and future magnetic fusion devices like ITER [3].

2. Stark-Doppler broadening of the C IV n=6-7 line (λ~7726 Å)

As Langmuir probes are less reliable for detached plasmas, spectroscopic methods are more convenient for diagnostics of such plasmas. To diagnose the divertor region of JT-60U, Nakano *et al* have proposed in [2, 4-5] to compare C III and C IV experimental line intensities with theoretical values calculated using a collisional-radiative model. In [2], they have used C IV line intensities measured during detachment with an X-point MARFE to infer the following plasma parameters for the recombining zone centred around the X-point: N_e=7.8x10^{20} m^{-3} and T_e=6.3 eV. A spatial characterization of the electron temperature T_e along the vertical lines of sight (Fig. 1) crossing or surrounding the X-point was also given. These temperatures have been evaluated from the C^{3+} population density ratio p(n=9)/p(n=7) for an electron density N_e=7.8x10^{20} m^{-3} [2].

To check and complete the results obtained from the carbon line intensities, we propose to analyze the shapes of the C IV n=6-7 line spectra measured in JT-60U with a linear polarizer. A line shape code called PPP [6] was used to compute the theoretical line profiles. PPP uses the usual quasi-static and impact approximations and it allows the inclusion of the ion dynamics effect through the fluctuation frequency model [6]. Other broadening mechanisms such as Doppler effect or the instrumental function can be accounted for by PPP through a convolution procedure. A theoretical investigation of the broadening mechanisms of the C IV n=6-7 line can be found in [1]. For the plasma conditions considered here (N_e~1-8x10^{20} m^{-3}, $T_e \equiv T_i$~1-10 eV), Doppler broadening competes with the Stark broadening for the C IV n=6-7 line. Due to the complexity of its profile, it is not possible to fit the measured C IV n=6-7 line spectra setting free all the plasma parameters N_e, T_e and T_i. Therefore the C^{3+} ions are assumed having the same temperature as the electrons and main ions (T_i=T_e=T).

3. Analysis of C IV n=6-7 line spectra measured in JT-60U

Using the C^{3+} excited level population density ratio p(n=9)/p(n=7) which does not depend on the electron density N_e for values higher than 3x10^{20} m^{-3}, the electron temperature T_e along the various lines of sight crossing or surrounding the X-point MARFE were estimated to be N_e=7.8x10^{20} m^{-3} [2]. These temperatures are shown in Fig.2. Spectra measured along two vertical viewing chords one crossing the X-point (chord 23) and the other one located far from it (chord 19) are compared to calculated profiles in Figs. 3 and 4. A good agreement between our calculated profile and the experimental spectrum of chord 31 is obtained for a density N_e=2.5x10^{20} m^{-3}, the temperature being T=5 eV. By varying the electron density in the calculations, we have estimated the uncertainty of the density to be $\Delta N_e \leq 5 \times 10^{19}$ m^{-3}. For the spectrum of chord 23, the agreement is not sufficiently good to allow the determination of the electron density. However, as expected the comparison indicates higher N_e values than that along chord 31. The difficulty to fit this spectrum with a single couple of plasma parameters (N_e, T_e) may be attributed to line integral effect. As for T_e, it is possible to spatially characterize the electron density in the JT-60U divertor by analyzing the C IV n=6-7 line spectra along the numerous vertical lines of sight.

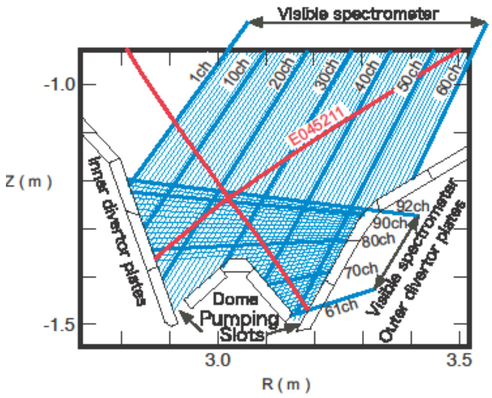

Fig. 1 A scheme showing the viewing chords of the visible spectrometer used for the measurements of spectra in JT-60U.

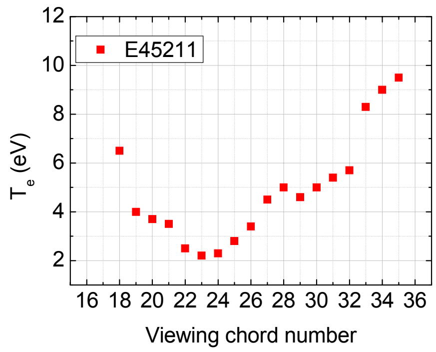

Fig. 2. Spatial characterization of T_e as a function of the vertical viewing chords of the visible spectrometer.

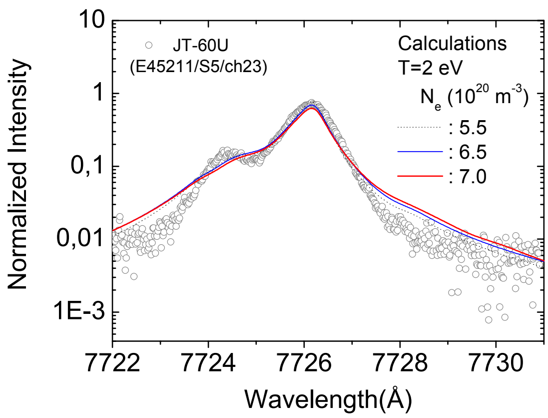

Fig. 3. Comparison of several profiles calculated for T=2 eV with an experimental spectrum of the C IV n=6-7 line measured in JT-60U with viewing chord 23 which crosses the X point.

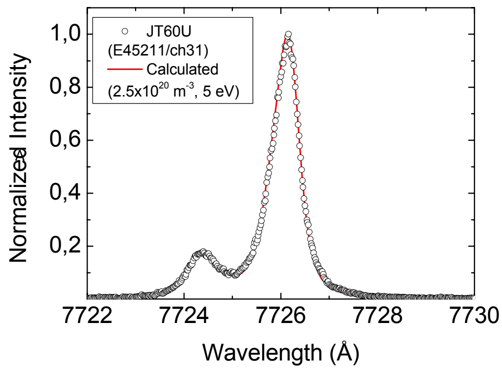

Fig. 4. Comparison of a calculated profile with an experimental spectrum of the C IV n=6-7 line measured in JT-60U along viewing chord 31 which is located far from the X-point.

4. Stark broadening of high-members of the He I diffuse series 1s2p ^{3}P°-1snd ^{3}D

Under detachment conditions, high-members of the Balmer line series of hydrogen and/or its isotopes are commonly measured and used for diagnostics purposes in several tokamaks (e.g. see [3] and references therein). The electron density is obtained from the widths and/or the shapes of such high-*n* Balmer lines which are dominated by Stark broadening. Similarly, in helium plasmas the He I 1s2p ^{3}P°-1snd ^{3}D triplet lines can be used for both electron density and temperature diagnostics. Such lines are observed in pure helium or helium-hydrogen plasmas (e.g. deuterium plasma with helium puffing in JET). The validity conditions of the impact and quasi-static approximations of the stark broadening theory for divertor plasma conditions are shown in Fig.5.

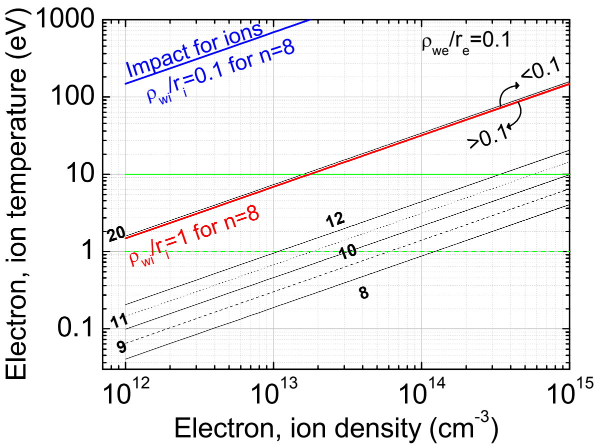

Fig. 5. Validity of the impact and quasi-static approximations for the He I 1s2p ^{3}P°-1snd ^{3}D lines for tokamak divertor plasma conditions.

From the validity conditions of these two approximations and calculations of line profiles for electron densities and temperatures in the ranges 10^{18}-10^{21} m^{-3} & 1-100 eV, it results that the He I 1s2p ^{3}P°-1snd ^{3}D lines with n=8-10 are the most convenient for plasma diagnostics as they are isolated and sensitive to Stark broadening. More details and a discussion about their use for existing and future magnetic fusion devices are given in [3].

Acknowledgements. This work is supported by the project "Radiation absorption effects" of the "Fédération de Recherche sur la Fusion par Confinement Magnétique" FR-FCM in the frame of the LRC DSM 99-14 (PIIM lab. /IRFM, CEA Cadarache).

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