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Spectral profile analysis of the Dα line in the divertor region of Tore-Supra

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Abstract

The deuterium Balmer line Dα in Tore-Supra plasmas has been studied near a midplane neutraliser plate (NP) of the ergodic divertor. Line profiles are analysed with a synthetic profile method taking into account Zeeman and Doppler effects. This analysis shows that two deuterium populations with specific behaviours have to be considered: the first one (cold atoms) is composed of atomic deuterium coming from D_2 desorbed from the NP, while the second one (warm atoms) is composed of charge exchange (CX) and reflected D. The Doppler temperature of cold atoms increases with the edge electron density, n_e^{edge} (1.4 eV < T_D^c < 2.5 eV). Possible causes for this behaviour are analysed; in particular, the possible heating of cold atoms by D^+ ions is evaluated. On the other hand, the Doppler temperature of warm atoms is not influenced by edge parameter variations ($T_D^w \sim 22$ eV). The densities of reflected and CX deuterium atoms are deduced from the experimental warm component brightness, coupled to a collisional radiative model and to the TRIM code; their values are in satisfactory agreement with the results of the code EDCOLL.

Keywords: Ergodic divertor; Deuterium emission; Doppler broadening; Hydrogen density

1. Introduction

Understanding the behaviour of deuterium atoms in the divertor region is important to control fuelling and pumping in fusion plasmas. The aim of this work is to study the deuterium–neutraliser plate (NP) interaction in the ergodic divertor configuration, under various edge plasma conditions, by analysing the Dα emission profile. Similar studies have already been performed in several tokamaks [1–3]; however, the observed profile shapes are fundamentally different, depending on the tokamak. Moreover, to our knowledge, the dependence of the Dα profile on edge parameters has never been reported. Therefore, a detailed study is necessary in order to be able to use the Dα line to diagnose divertor plasmas. The spectral profile of the Dα line can be used to retrieve information on the velocity distribution of the deuterium atoms and on their basic recycling processes. In specific experimental conditions, Dα profiles with unusual assymetric Zeeman $\sigma_\pm$ components are observed. These particular lineshapes are analysed elsewhere [4].

Section 2 presents the spectroscopic diagnostic on Tore-Supra (TS) (Section 2.1), and the fitting method employed to analyse the spectra (Section 2.2). We discuss the identification of the different deuterium populations in front of the NP in Section 3.1. The physical properties of the deuterium population (Doppler temperatures, densities) are analysed in Section 3.2.

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2. Experiment

2.1. Experimental set-up

The measured spectra originate in the edge region of Tore-Supra plasmas of major and minor radius equal to 2.38 and 0.8 m, respectively, toroidal magnetic field on axis $B_T = 3.14$ T, and plasma current $I_p = 1.5$ MA. The spectral lineshape of the Balmer line Dα has been measured with a visible spectrometer, connected to in situ optical fibers (Fig. 1). Two lines of sight are used for these experiments; the first one (PJ2) is approximately parallel to the NP and located 1 cm radially away from it, whereas the angle θ of the second one $Q_2$14) with the NP is 27°. Light from the fibers is focused onto the 50 μm wide entrance slit of a Czerny–Turner spectrometer, having a focal length of 1 m and a 2000 groove/mm grating (spectral range 400–1100 nm). A 2D CCD camera is used at the exit focal plane of the spectrometer. The spectra are acquired on the plasma current plateau, at a rate of 10 Hz with an integration time of 100 ms. When necessary, the spectra are wavelength calibrated with the Dα line of a deuterium lamp. The spectra are integrated over the line of sight, and their intensities are absolutely calibrated using a halogen spherical integrating lamp. The edge electron density. n_e^{edge}, the edge electron temperature, T_e^{edge}, and the saturation current are obtained with a Langmuir probe located on the NP. The present study was performed in ohmic and lower hybrid frequency heated discharges (1 MW), with the ergodic divertor current set to 45 kA.

2.2. Spectral analysis

Under attached edge plasma conditions ($4 \times 10^{18} < n_e^{edge} < 1.2 \times 10^{19}$ m^{-3}; 25 eV $> T_e^{edge} >$ 10 eV), the Dα profile is governed by the Zeeman and Doppler effects [5]. Therefore, the experimental lineshapes are fitted with theoretical Doppler profiles composed of a central component π and two symmetric lateral ones $\sigma_\pm$ having a B_T dependent wavelength separation. The parameters of a Doppler profile are the Doppler shift, $\Delta\lambda$, deduced from the unpertubed central wavelength value, the Doppler temperature, T_D, deduced from the full width at half maximum (FWHM), the calibrated brightness, B, and B_T deduced from the central wavelength separation of the two σ components. These parameter values are varied until the best fit is obtained using the Simplex algorithm [6]. The Hα line is situated on the red wing of Dα, but it is too weak to be treated; therefore, the minimization criterion ignores the Hα region. The measured apparatus function ($\mathrm{FWHM_{af}}$) of the spectrometer is found to be Gaussian to a good approximation. Therefore, the square of the real Doppler FWHM is equal to the difference of the synthezised FWHM^2 and FWHM^2_{af}.

Fig. 2 shows the fitting of a normalised Dα spectrum observed with the PJ2 line of sight. The angle of PJ2 with the magnetic field being less than a few degrees, only the σ components are observed on the corresponding spectra. As can be seen on this figure, to fit correctly the blue wing Hα it is necessary to consider the sum of two components with the following features: a 'cold' component (narrow line), and a 'warm' component, underlying the cold one, with respective Doppler temperatures T_D^c and T_D^w.

Helium emission lines are always detected in Tore-Supra. The He II ($n = 6 \rightarrow 4$) line is located at 6560 Å,

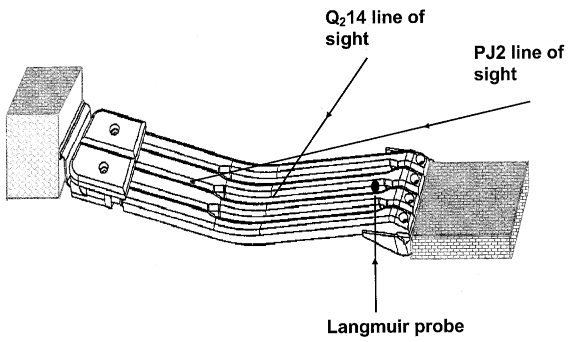

Fig. 1. Diagnostic setup on a midplane NP. The two lines of sight PJ2 and $Q_2$14 are connected to a visible spectrometer via in situ optical fibers.

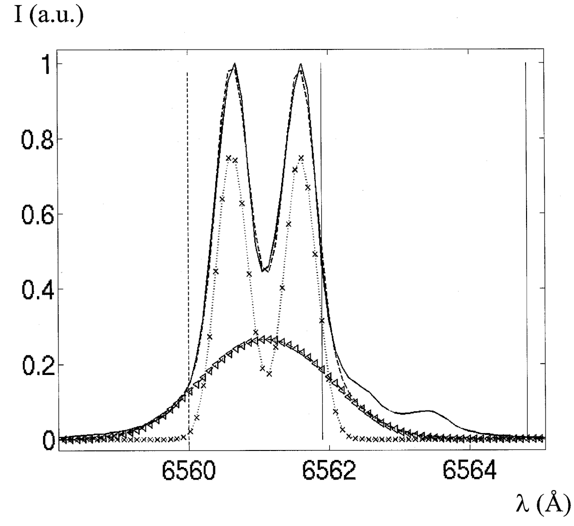

Fig. 2. Experimental Dα (solid line) fit with synthetic Doppler model (dashed line). The synthetic profile is the sum of a 'cold' (×) and a 'warm' (◁) component. The vertical full lines indicate the limit of the Hα region ignored during the fit. The vertical dotted line indicates the theoretical position of the He II(6 →4) line.

and could perturb the blue wing of the Dα line. However, no proof of its presence is seen on the lineshapes. Moreover, a detailed study, based on a collisional–radiative model, shows that its brightness is negligible compared to Dα [7].

3. Results and discussion

3.1. Identification of deuterium populations

Three different deuterium populations can contribute to the Dα emission: the atoms provided by dissociation of desorbed molecular deuterium, the reflected part of the incident D^+ flux, and the atoms created by charge exchange (CX).

The Doppler shift $\Delta\lambda$ of a spectral line is directly related to the mean speed in a given direction of the corresponding emitting species. The experimental $\Delta\lambda$ values of the cold and warm Dα components have been measured simultaneously on the PJ2 ($\theta = 0°$) and $Q_2$14 ($\theta = 27°$) lines of sight. The Doppler shift of the cold component obtained on the two lines of sight is always less than the $\Delta\lambda$ precision, which is consistent with the D atoms provided by dissociation of desorbed D_2 from the NP. Indeed, the resulting D_2 flux has approximately the temperature of the wall (~500 K), and the dissociation of D_2 gives low energy deuterium products isotropically distributed in space.

The warm component must be produced by the other two possible deuterium populations, the reflected and the CX atoms. Although this component comprises the contribution of two different populations, we have fitted it with a single Zeeman–Doppler profile (this approximation will introduce additional uncertainties which have not yet been evaluated). Reflected D atoms produced by D^+ reflection move away from the NP with an average speed V_{ref} perpendicular to it. Since the mean edge electron temperature is 23 eV for this case, the incident ionic deuterium flux on the NP has an energy of approximately 92 eV, because of the sheath acceleration. Using the TRIM code energy and particle reflection coefficients [8], we obtain $V_{ref} \sim 60$ km s^{-1} corresponding to a 0.6 Å blue shift on the $Q_2$14 line of sight. As can be seen in Fig. 3, the far blue wing of Dα is more pronounced in the $Q_2$14 case than in the PJ2 case, which corresponds to a 0.5 Å average warm component blue shift on $Q_2$14. Since the CX part of the warm component is expected to be unshifted [2], the reflected contribution of the Dα warm component must mainly contribute to this pronounced far blue wing. The mean direction of the reflected atoms perpendicular to the NP is confirmed by the warm component shift on PJ2 close to 0.

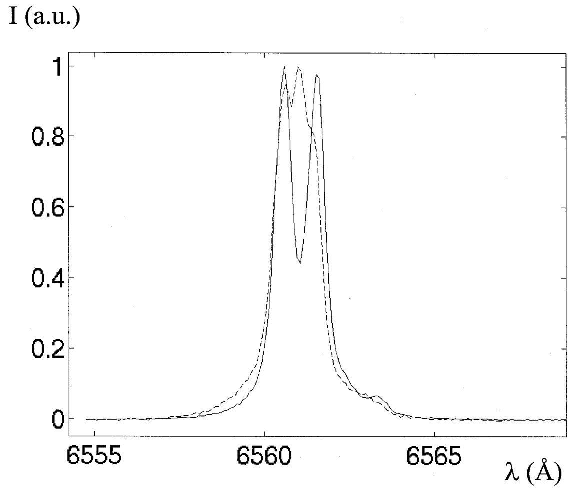

Fig. 3. Comparison of two Dα spectra obtained simultaneously with the PJ2 (solid line) and $Q_2$14 (dashed line) lines of sight. The central π component appears only in the $Q_2$14 case, because of the different lines of sight orientation in relation to the magnetic field.

3.2. Neutral temperature and density measurements

The edge electron density dependence of the Doppler temperatures, T_D^c and T_D^w, deduced from the FWHM of the cold and warm Dα components, is presented in Fig. 4 (PJ2 line of sight). The T_D^c and T_D^w uncertainties are, respectively, estimated to be ±10% and ±20%. As can be seen in Fig. 4(a), there is a clear T_D^c increase with the edge density n_e^{edge}. A similar behaviour has already been observed in JT-60U [2], but the authors could reproduce it with a Monte–Carlo simulation of the Dα spectrum.

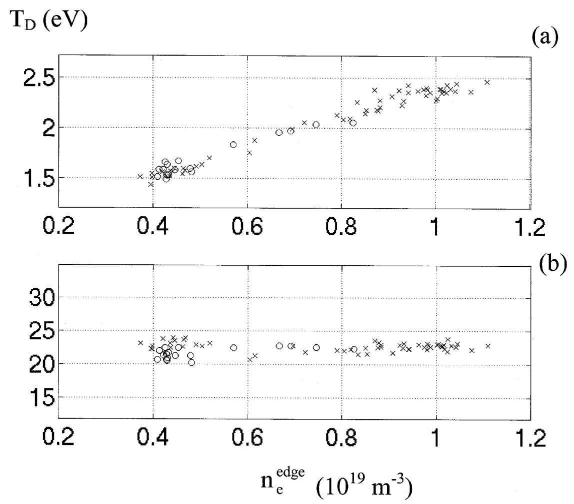

Fig. 4. Edge electron density dependence of the cold (a) and warm (b) Doppler temperatures.

Collisional heating of the cold deuterium population by charged particles can explain this dependence. Indeed, when the edge density increases, the plasma becomes more and more collisional [9]. Electrons, D_2^+ and D^+ ions are potential candidates for this type of interaction. However, the electrons are not heavy enough to have an efficient energy transfer to the cold atom. Moreover, since the D_2^+ ion dissociates in a very short time to give D and D^+ products, D^+ ions seem to be the more appropriate particles. Under typical edge temperatures, the rate coefficient of elastic scattering between D atoms and D^+ ions [10] is more than twice the ionisation rate coefficient of D [11]. Therefore, the lifetime of deuterium atoms does not prevent their heating by D^+.

It is possible to estimate how efficient the D^+ heating of cold D atoms is with a model [3], calculating the time evolution of the D atom temperature (T_D), heated by incident D^+ ions with density n_{D+} and temperature T_{D+}. The contribution of the ion-induced dipole and quadrupole potentials of the D^+–D elastic scattering rate coefficient is estimated considering the kinetic energy transferred to a test particle. First, it is necessary to determine the temperature and the energy level of the cold D atoms. A quick overview of the various processes between D_2 and electrons shows that the major part of the produced atoms are in the ground state [11]. Among these different reactions, an important amount of deuterium particles are produced with a mean energy of 0.3 eV [1,11]. The energy gain distribution per product atom ranges between 0 and 0.55 eV. We shall therefore consider a cold deuterium population in the ground state with an initial temperature T_0 set to 0.3 eV. The second important point is the characteristic time of heating. Its value can be estimated to be the ~1 μs time necessary for 0.3 eV D atoms, moving away from the NP, to reach the PJ2 line of sight.

The D^+ density n_{D+} has been deduced from the ion saturation current of the Langmuir probe located on the NP. In addition, we have supposed that the D^+ temperature T_{D+} is equal to T_e^{edge}. This last assumption is probably invalid in the low electron density range which is less collisional [9]. Then n_e^{edge} dependence of the resulting D atom temperature T_D is presented in Fig. 5, showing that this process can noticeably raise the cold component temperature.

The warm Doppler temperature T_D^w case is more complicated, since the warm Dα brightness is composed of two unresolved components. However, since it is essentially composed of CX contribution (see below), this temperature must be close to the temperature of CX deuterium atoms. Indeed, the mean value of T_D^w (22 eV) is close to the mean electron temperature T_e (23 eV), which can be assimilated to the D^+ ion temperature, in a first approximation.

In order to relate the warm component brightness of the Dα line and the densities of the corresponding emitting species we use the ADAS collisional-radiative model [12]. This model is not applicable to the cold component because the molecular processes are not taken into account in ADAS. The total neutral density n_{tot} obtained from the warm Dα component is the sum of the densities of the reflected and CX particles. The density of reflected D atoms (n_{ref}), deduced from the saturation current of the Langmuir probe located on the NP and from the TRIM code [8], is always lower than n_{tot}. The difference '$n_{tot} - n_{ref}$' is then interpreted as the density of the CX deuterium particles, n_{CX} (Fig. 6). The

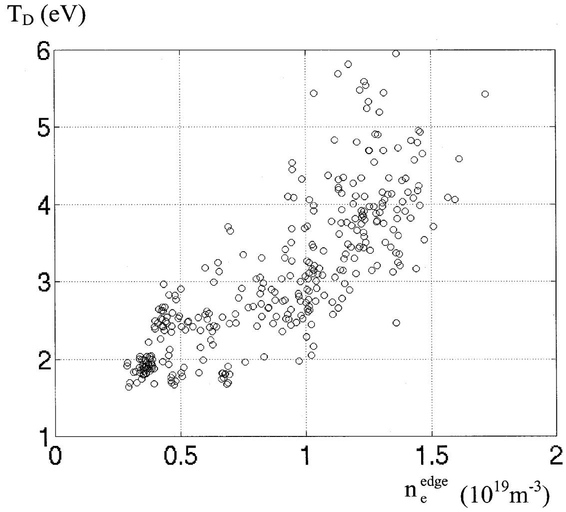

Fig. 5. Edge electron density dependence of the D atom temperature T_D, heated by D^+ ions during 1 μs.

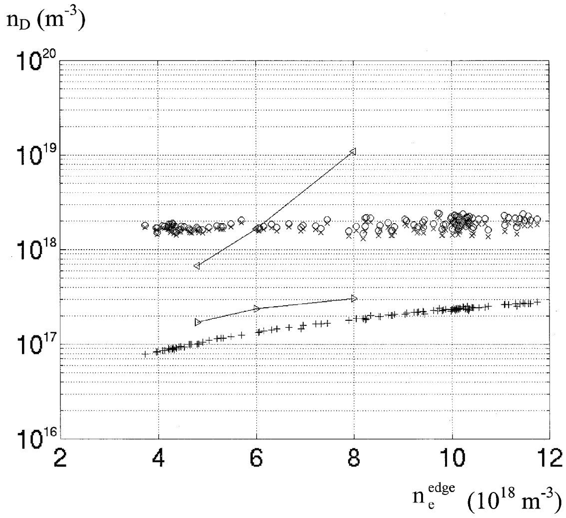

Fig. 6. Edge electron density dependence of the D atom densities: experimental total (○); experimental reflected (+); experimental CX(×); EDCOLL reflected (▷); EDCOLL CX (◁).

numerical code EDCOLL [13] is used to estimate the densities of the two deuterium populations, 1 cm radially away from the NP; these densities are also shown in Fig. 6. As can be seen, the global agreement of theory and experiment is satisfactory. However, the n_e^{edge} dependence of the CX density is more pronounced with EDCOLL than with experimental data. This can be explained by several approximations made in EDCOLL [13], or by errors possibly introduced by the ADAS code, due to uncertainties in the cross sections necessary to calculate the deuterium population equilibrium. The CX density, n_{CX}, is found to be predominant and fairly constant over the n_e^{edge} range; the average value of n_{CX}/n_{ref} is approximately 10. This must correspond to the relative contributions of reflected and CX atoms to the warm brightness.

4. Conclusion

The Dα emission line observed in Tore-Supra ergodic divertor plasmas has been studied in detail in this paper. The relation between the three deuterium emitting species and the Dα profile decomposed in two components has been studied. The first population is composed of cold D atoms provided by dissociation of D_2 desorbed from the NP, and gives rise to the cold Dα component. The corresponding measured Doppler temperature ($1.4\ \text{eV} < T_D^c < 2.5\ \text{eV}$) shows a clear increase with n_e^{edge}, which can be explained with a model, considering cold D atoms heating by elastic collisions with D^+ ions. The second and third populations are the reflected D atoms on the NP and the atoms created by CX. These two populations contribute to the Dα warm component. The densities of CX and reflected D atoms are deduced using the ADAS code. It is found that the CX contribution is predominant over the entire n_e^{edge} range ($(n_{CX}/n_{ref}) \sim 10$). These experimental results are in satisfactory agreement with the densities calculated by the code EDCOLL.

Acknowledgements

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References

[1] J.D. Hey et al., Contrib. Plasma Phys. 36 (1996) 583.
[2] H. Kubo et al., Plasma Phys. Control. Fus. 40 (1998) 1115.
[3] J.D. Hey et al., J. Phys. B 32 (1999) 3555.
[4] M. Koubiti et al., in: Proceedings of the 27th EPS Conference on Controlled Fusion and Plasma Physics, Budapest, 2000.
[5] M. Koubiti et al., in: Proceedings of the 26th EPS Conference on Controlled Fusion and Plasma Physics, Maastricht, Netherlands, vol. 23J, 1999, p. 1005.
[6] J.A. Nelder, R. Mead, Comp. J. 7 (1965) 308.
[7] R. Guirlet et al., Plasma Phys. Control. Fus., submitted.
[8] E.W. Thomas, Oak Ridge Report, ORNL-6088, 3 (1985).
[9] B. Meslin, Contrôle de la densité du plasma en présence du divertor ergodique dans le Tokamak Tore-Supra, PhD of the Paris-Sud University, France, 1998.
[10] P.S. Krstic, D.R. Schultz, Atomic and plasma–material interaction data for fusion, IAEA, Vienna 8, 1998, p. 91.
[11] R.K. Janev, Elementary Processes in Hydrogen–Helium Plasmas, Springer, Berlin, 1987.
[12] H.P. Summers, ADAS: Atomic data and analysis structure, Jet Report, Jet-IR (94)06 (1994).
[13] A. Azéroual et al., Nucl. Fus. 40 (9) (2000) 1651.