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Modelling of asymmetric Dα line shapes for the edge of the Tore-Supra Tokamak operated with the Ergodic Divertor

M. Koubiti[1], L. Godbert-Mouret[1], L. Chérigier[1], Y. Marandet[1], R. Stamm[1], K. Touati[1], H. Capes[2], C. De Michelis[2], A. Escarguel[2], Ph. Ghendrih[2], R. Guirlet[2]

[1]*Physique des Interactions Ioniques et Moléculaires, UMR 6633 CNRS-Aix Marseille 1, centre Saint Jérôme, 13397 Marseille, France*
[2]*Département de Recherches sur la Fusion Contrôlée, Association EURATOM-CEA, CEA Cadarache, 13108 Saint Paul lez Durance cedex, France*

1. Introduction

The Tore-Supra Ergodic Divertor (ED) was designed to support high incident particle fluxes by concentrating them on cooled neutraliser plates (NPs). By randomising the magnetic field lines in the plasma periphery, the ED allows the creation of a cold and dense plasma layer extending to about 10 cm radially away from each NP surface. Such a plasma layer contains deuterium atoms and molecules in addition to deuterons and ion impurities. The D^0 neutrals are mainly produced by the following mechanisms: reflection of D^+ ions as D^0 neutrals on the NP surfaces, thermal and ion induced desorption of atomic and molecular deuterium which dissociate under various pathways (hereafter designated by Franck-Condon or FC), and charge exchange (CX) with incident ions. The analysis of the spectral lines emitted by deuterium provides some information on the neutral deuterium populations, and consequently on their production mechanisms. For that purpose, one of the NPs located in the equatorial plane is diagnosed by spectroscopic lines of sight allowing the plasma visible emission to be recorded. This paper deals with the analysis of Dα spectra measured in the low field side of Tore-Supra (TS). Asymmetric Dα profiles, constituted by 2 Doppler broadened σ components with different intensities, are sometimes observed in the edge of TS for various values of the toroidal magnetic field (B=1-2.1 T). Similar asymmetric Dα (Hα) spectra observed in other machines have already been analysed using Monte-Carlo simulation codes [1,2,3]. In this paper the asymmetry is reproduced using a model which includes a combination of initial velocity distribution functions representing the various D^0 populations which experience a thermalisation process through ion-neutral elastic collisions.

2. Spectroscopic measurements

In order to view the plasma edge in front of the equatorial NP tangentially to the magnetic field lines, 4 in situ optical fibres equipped with small telescopes and directed in the counter direction of the plasma current [4], are used. The lines of sight are close to parallel to the NP plane (6.2° at maximum). A picture of the NP constituted by 4 bars and 3 V-shaped tips and surrounded by carbon tiles is shown on figure 1. The optical fibres are connected to a high resolution Czerny-Turner spectrometer equipped with a 1200 and a 2000 gr./mm gratings and a CCD camera (4000-11000 Å), allowing the observation of 40-70 Å wide spectra with a width of 0.87 Å for the instrumental function. The electron density and temperature in the NP vicinity are deduced from a Langmuir probe located on the observed NP. The Dα spectra measured in TS are usually symmetric. Nevertheless in some discharges carried out after a wall conditioning with helium glow discharges, the observed Dα profiles were asymmetric [5]. The asymmetry of the Dα line is observable for discharges stretching out on a day or half a day. It has been observed in both low (B~1 T) and high (B~2 T) magnetic field experiments. Asymmetry appearance or disappearance has never been observed on a plasma discharge duration. All these observations suggest that the asymmetry is not related to the edge plasma conditions alone, but more probably to the wall status. Symmetric spectra were widely analysed using a multi-gaussian fit method [5,6]. This paper is focused on the asymmetric spectra analysis and the neutral thermalisation mechanism.

3. Modelling of asymmetric spectra

A rigorous study of a Dα (λ=6561.0 Å) line spectrum requires the knowledge of the intensity of the neighbouring He^+ Br_β line (a Brackett line with λ=6560.1 Å). Using a collisional-radiative model [5], it can be shown that the above He^+ line contribution to the blue wing of Dα is usually negligible in TS discharges. Therefore to model asymmetric spectra, we have proposed a fit method using 2 deuterium populations with maxwellian velocity distribution functions, one being Doppler blue shifted [5]. This shift was attributed to neutrals thermalised through charge exchange by deuterium ions flowing in the co-direction of the plasma current. Such an interpretation was consistent with the flow reversal of carbon impurity ions predicted by code analysis in the vicinity of the NPs [7]. Another factor which can cause a blue shift of Dα , is the contribution of reflected neutrals which originate from the NP V-shaped tips and move toward the spectrometer. Here we generalise our previous analysis [5] to include the reflected neutrals and the thermalisation of the recycled particles through neutral-ion elastic collisions. In addition to the FC population (produced by all molecular dissociation pathways) and to the fraction of reflected neutrals emitted nearly perpendicularly to the lines of sight, we assume that two distinct atomic populations also contribute significantly to the Dα line. The first one is composed by the deuterium atoms which are thermalised through charge exchange with the ions flowing towards the NP. Assuming the Mach number M<<1, the distribution of these charge exchange neutrals is considered to be a maxwellian with the same temperature as the plasma ions (T_{cx}=T_i). The second one is constituted by reflected atoms moving along B field lines in the direction opposite to the plasma current (i.e., toward the spectrometer). The main justification for these reflected atoms are the hot spots observed at the V-shaped tip locations by the endoscope camera viewing the NP. Before thermalisation by elastic collisions with ions, all reflected neutrals are assumed to be moving toward the spectrometer, and hence their initial velocity distribution function is represented by a half maxwellian.

4. Thermalisation of recycled deuterium atoms

The various D^0 neutral populations emitted by the NPs are generally not in equilibrium with the background plasma constituted mainly of ions and molecules. The neutrals may experience partial or complete thermalisation through multiple scattering processes. Among the various mechanisms able to transfer momentum between the colliding particles, we take into account here the polarisation of the D^0 dipole during the interaction with D^+ ions [8,9]. To calculate the time dependent velocity distribution function $f(v,t)$, of a neutral which moves with velocity v and experiences elastic collisions of frequency ν_c with the ions of mass M of a homogeneous background plasma at temperature T_i, we solve the following 1D Fokker-Planck equation:

$$\frac{\partial f(v,t)}{\partial t} = \nu_c \frac{\partial}{\partial v}\left[v\, f(v,t) + \frac{kT_i}{M} \frac{\partial f(v,t)}{\partial v} \right] \qquad (1)$$

Equation (1) may be easily solved by a Green function method [10]. In the following this equation is applied to only reflected neutrals. To illustrate the results of this thermalisation model, we consider a population of reflected neutrals whose velocity distribution is a half maxwellian:

$f(v,t=0)=(2/v_0\sqrt{\pi})\,H(v)\,\exp(-v^2/v_0^2)$, where $H(v)$ is the Heaviside function. The initial mean kinetic energy E_0 of these reflected atoms is related to their initial velocity v_0 by: $E_0 = m v_0^2/2 = \int_0^\infty m v^2 f(v)\,dv$. For a relaxation time τ, the resolution of the Fokker-Planck equation (1) applied to the above velocity distribution gives the following solution:

$$f(v,\tau)=\frac{1}{\sqrt{\pi}}\frac{1}{\Delta(t)}\exp\left[-v^2/\Delta^2(\tau)\right]\operatorname{erfc}\left(-\left[v_0\ \Gamma(\tau)/\left(v_\infty\,\Delta(\tau)\sqrt{1-\Gamma^2(\tau)}\right)\right]v\right), \quad (2)$$

where $\Gamma(\tau)=\exp(-\nu_c\tau)$, $\Delta^2(\tau)=v_\infty^2\left(1-\Gamma^2(\tau)\right)+v_0^2\,\Gamma^2(\tau)$, and v_∞ is the neutral thermal velocity after a complete thermalisation with the background plasma ions. For the typical plasma conditions prevailing at the edge of TS (T_e~10-50 eV, $n_i=n_e$~10^{18}-2×10^{19} m^{-3}), the elastic scattering rate coefficient <σv> can be estimated [8] between 4-6x10^{-14} $m^3.s^{-1}$. The relaxation time τ is taken equal to the time of flight, i.e., the time necessary to a D^0 neutral moving with velocity v_0 to reach the lines of sight. A reflected D^0 atom with E_0=15 eV needs τ~0.3μs to reach the closest line of sight (~2 cm), and the collisionality parameter $\nu_c\tau=n_i<\sigma v>\tau$ varies between 0.01 and 0.5 for the range of ion densities n_i indicated above. According to the value of this parameter which depends on the neutral velocity and on the ion temperature and density, the neutrals are partially or totally thermalised. For TS edge conditions reflected atoms are only partially thermalised as illustrated on figure 2 for shot #22316. On this figure, the initial velocity distribution taken as a half-maxwellian for a D^0 atom reflected with E_0=23 eV, becomes non-maxwellian after a partial thermalisation by elastic collisions with ions at a temperature T_i=15 eV. For the analysed shot, the collisionality parameter is $\nu_c\tau$=0.3 and the final mean kinetic energy E_{0f} of reflected atoms is ~19.4 eV.

5. Results and discussion

We have fitted experimental Dα spectra with synthetic line profiles taking into account the relaxation mechanism described in section 4. Here only 2 spectra are presented on figures 3 and 4 corresponding to 2 different values of the edge magnetic field B=1.05 T (shot #28255) and B=2.1 T (shot #22316). Unlike the symmetric spectra where Dα emission is dominated by the FC atom component [5,6], the asymmetric ones are characterised by comparable contributions of cold (FC) and hot atoms (reflection, CX) photon emissions. In figure 3, the Dα line profile is modelled by the sum of the following contributions: 50% from FC atoms (T=1.5 eV), 17% from CX atoms (T_{cx}~10 eV) and 33% from reflected atoms (E_0=12.5 eV, E_{0f}~11.5 eV). In figure 4, these proportions are similar: 42% from FC atoms (T=5 eV), 16% from CX atoms (T_{cx}=15 eV), and 42% from reflected atoms (E_0=23 eV, E_{0f}~19.4 eV). The difference in the FC population temperatures (1.5 eV and 5 eV) can not be explained by only a thermalisation process since the collisionality parameters are very close, but it is probably due to different dissociation pathways. Note that photon emission from reflected atoms is at least twice that from the CX population. Besides the slight discrepancy in the red wing due to Hα emission which is not taken into account, note the good agreement between experimental and theoretical line profiles.

6. Conclusions

The reflected atom population produced by the NP V-shaped tips appears to be a potential candidate to explain the asymmetric Dα profiles. Unlike the symmetric spectra dominated by cold atom photon emission, the analysis of asymmetric ones indicates almost equal cold and hot populations, and reveals a partial thermalisation of the recycled neutrals with the background ions. Even populations may be due to a wall status with less desorbed molecules and/or more reflected neutrals. Note that larger values of the collisionality parameter would lead to symmetric profiles. Such values could be reached, if in addition to the recycled neutral thermalisation by ion elastic collisions, D_2 molecules could participate to the energy relaxation process. However no indication of a strong decrease of the molecular density for discharges realized after a specific wall conditioning with helium glow discharges has been observed at the edge of TS. The accuracy on the calculated proportions of CX and reflected atoms deduced from the fit may be improved using coupled collisional-radiative and transport models.

***Fig. 1**: A photograph of the neutralizer plate surrounded by carbon tiles. Its is made of 4 bars and 3 V-shaped tips visible on the right hand side (wetted by incident ion flux).*

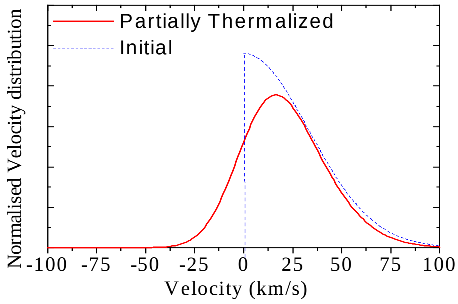

***Fig. 2:** The velocity distribution of reflected atoms (E_0=23 eV) before (dashed) and after (solid) relaxation with D^+ (T_i=15 eV), $\nu_c\tau$=0.3*

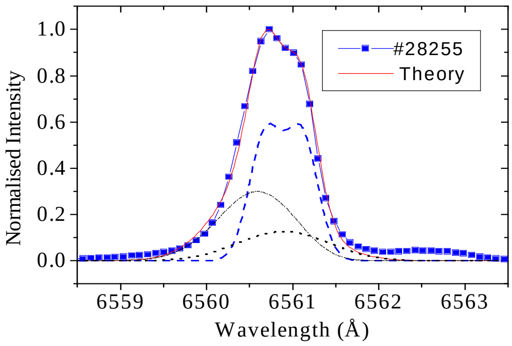

***Fig. 3.** Comparison of measured (square) and theoretical (solid) $D\alpha$ profiles. Reflected atoms with initial E_0=12.5 eV* are thermalized with D^+ (T_i=10 eV). B~1.05 T, $\nu_c\tau$=0.24.

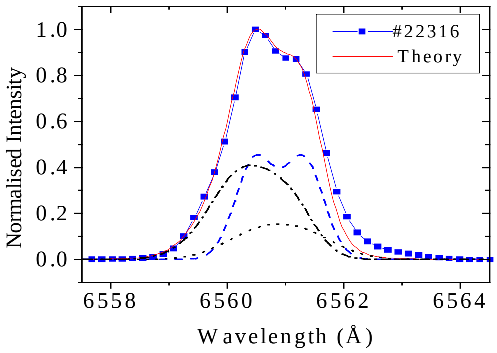

***Fig. 4**. Same as **Fig. 3**, B=2.1 T, E_0=23 eV, and $\nu_c\tau$=0.3. T_i=15 eV. Used symbols: dot* (CX), dash (FC), and dashed-dot(reflect

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