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ScienceDirect
Journal of Nuclear Materials 363–365 (2007) 764–769
journal of nuclear materials
www.elsevier.com/locate/jnucmat

Hydrogen recycling and puffing at a poloidal limiter of TJ-II

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Abstract

Hydrogen recycling and puffing through a hole in a poloidal limiter of TJ-II is studied by spatially resolved H_α-emission spectroscopy with a CCD camera. Very different emission profiles are obtained depending on whether the hydrogen enters the plasma when recycling at the carbon limiter or whether it is puffed through a hole in the limiter directly inside the last closed flux surface of the plasma. From the emission profiles, the neutral density profile of the H_α-emission precursor is deduced and compared to that calculated with the help of a simple one-dimensional model. The analysis shows, that in front of a limiter with $T_e > 30$ eV, the H_α-emission has two main sources: dissociative excitation of thermally desorbed molecular hydrogen and excitation of atomic hydrogen with kinetic energy of typically 0.3 eV. The relative importance of this last term decreases in front of a strong gas-puffing source. If the puffing rate is very strong, the plasma is measured to be locally perturbed and this can be the origin of the different emission profiles measured with and without puffing.

PACS: 52.20.Fs; 52.25.Rv; 52.25.Ya; 52.40.Hf

Keywords: Dissociation; Gas injection and Fueling; Molecular effects; Recycling; Spectroscopy

1. Introduction

The hydrogen recycling at limiters and divertor plates and its transport in the plasma edge has been and is the subject of lots of experimental and theoretical studies and care has to be taken in making generalisations and simplifications, since the atomic reactions in the plasma edge strongly depend on the plasma parameters. In other words, in different fusion devices operating at different plasma edge conditions, pulse lengths, plasma facing surface temperatures, etc., the hydrogen recycling and transport physics can be very different. Atomic reactions and surface yields have generally a very strong energy dependence in the range of 1–30 eV, so that in a high density low electron temperature divertor the dominant reactions can be irrelevant for a low density, high electron temperature plasma edge, as is the case in the present study, where at the last closed flux surface (LCFS) the electron density

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0022-3115/$ - see front matter
doi:10.1016/j.jnucmat.2007.01.061

and temperature are typically $n_e(a) = 1 - 2 \times 10^{18}\ m^{-3}$ and $T_e = 40$ eV respectively.

Spectroscopic studies of H_α Doppler line broadening and H_2 vibrational band analysis, together with Monte-Carlo codes, have been the key in understanding the dominant atomic processes in the plasma edge (see e.g. [1–7]). In these papers the authors investigate the surface and atomic physics related to neutral hydrogen atoms or molecules that are recycled at the limiter surface and that are easily re-ionised at the plasma edge due to the high electron temperature there existing ($T_e > 30$ eV). The break-up through dissociation and ionisation of the molecules is complex and the exact reactions are not completely understood to date and in the last years the role of the ro-vibrationally excited H_2 molecules has been studied intensively, especially because of its importance for the design of high density divertors as foreseen in future fusion reactors.

2. Experimental set-up

The experiments have been performed in the medium sized stellarator TJ-II, where beam-shaped plasmas of 0.2 m average minor radius and 1.5 m larger radius and of a duration of 200 ms are produced with 400 kW ECRH power. The central electron density and temperature are typically $n_e(0) \approx 0.5\text{–}1.2 \times 10^{19}\ m^{-3}$ and $T_e(0) \approx 1\text{–}1.5$ keV respectively and the corresponding values at the LCFS are $n_e(a) = 1\text{–}2 \times 10^{18}$ and $T_e(a) = 30\text{–}40$ eV. The plasma generally interacts with a helical (toroidal) limiter, but additionally two mobile poloidal graphite limiters can be inserted into the plasma. In the experiments here reported the recycling is studied in front of one of these limiters, which is inserted 1 cm into the LCFS. Gas can be puffed directly into LCFS of the plasma through a hole made in the limiter head. The puffing rate is in the range of $1\text{–}20 \times 10^{19}$ H/s, which leads to an increase in the mean electron density of $d\langle n_e\rangle/dt \approx 1\text{–}10 \times 10^{19}\ m^{-3}\ s^{-1}$.

A fast digital CCD camera, operated at 10^4 frames per second with 64×128 pixel resolution, coupled to the view-port with a coherent fibre bundle and an interference filter centred at the H_α-line, captures the images with a tangential line of view, so that the chord each pixel observes is nearly parallel to the magnetic field in the bright light cloud in front of the poloidal limiter. Since the recycling is localised at the poloidal limiters and the neutrals returning to the plasma have a mean free path

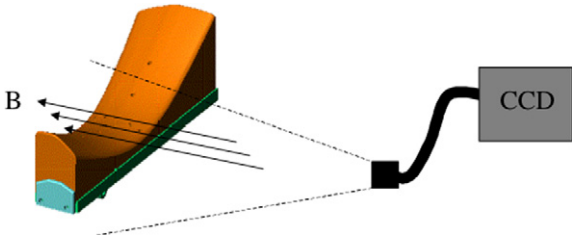

Fig. 1. Schematic view of the experimental set-up.

$\lambda < 5\text{–}10$ cm depending on the trajectory (see later), most H_α-emission comes from a 'cloud' localised in front of the poloidal limiter (see Fig. 1). The line-integrated light of each pixel principally comes from this region and since they look at directions along the magnetic field lines the integrated emission corresponds to light emitted from plasma regions with nearly constant plasma parameters. To study the local plasma perturbation in front of the puffing-source, the helium line intensity ratio technique is applied by injecting He/H_2 mixtures (see e.g. [8]). The helium line ratios are monitored with the same camera equipped with the corresponding He I interference filters and with a spectrometer which observes the plasma with the same geometry and with a spatial resolution of about 40 mm.

3. Results

Fig. 2(a) and (b) (this last with a five times lower sensitivity) shows the spectroscopic H_α-images taken without and with hydrogen puffing. The poloidal limiter is below the bright emission region and the puffing hole is between the two, due to overheating, visible Langmuir probes (the distance between both probes is 50 mm). In Fig. 3 the H_α-emission radial profiles along the white lines marked in the images is shown. They correspond to plasma radii beginning at the puffing hole and directed to the plasma centre. It can be clearly seen that the decay of the profile with puffing is much steeper than that without puffing.

For the H_α-emission intensity profile $I(r)$ integrated over the tangential viewing chord in front of the limiter we have:

$$I(r) = c n_e(r) \sum_j n_j(r) k_j, \quad \text{or}$$

$$I(r)/n_e(r) = c \sum_j n_j(r) k_j, \tag{1}$$

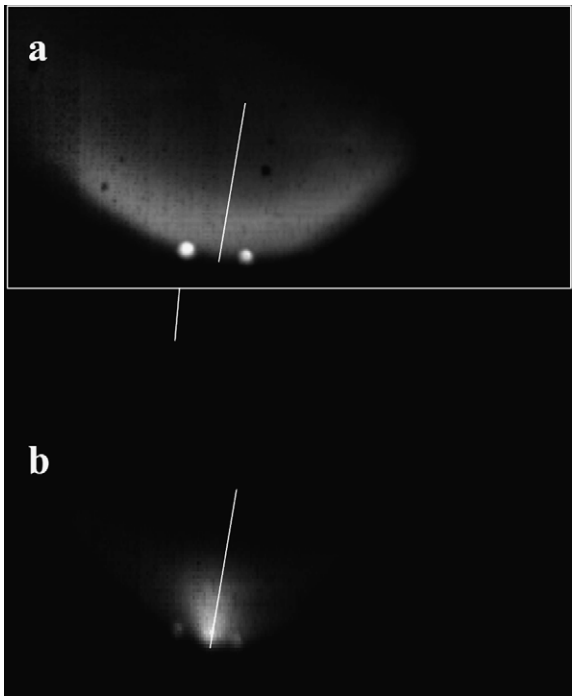

Fig. 2. H_α-emission images of (a) recycling hydrogen and (b) puffed hydrogen (with five times lower sensitivity). The white lines correspond to the radii where the profile analysis were done.

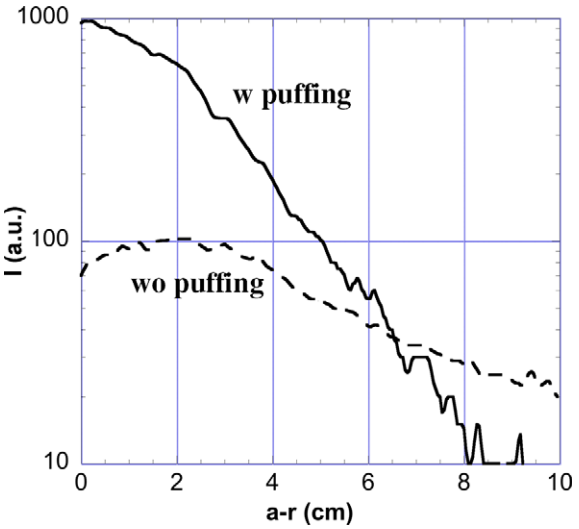

Fig. 3. H_α-intensity emission profiles without puffing (dashed line) and with puffing (continuous line) along the marked white lines of Fig. 2.

where c is a constant, and the sum is taken over all possible H_α-emission precursors with density n_j (atomic or molecular hydrogen in the ground or in a excited state) and k_j is the electron collision excitation rate of the precursor to the hydrogen atom with principal quantum number $n = 3$ normalised with the corresponding branching ratio. Since most H_α-emission is localised in front of the limiter and the view is tangential to the magnetic fields (i.e. one chord has the same plasma parameters), the profiles correspond in a first approximation to radial H_α-emission profiles. Further, the excitation rate coefficients k_j can be considered constant since they do not vary sensibly (within 20%) in the range of temperatures here considered ($40\ \text{eV} < T_e < 500\ \text{eV}$).

The continuous lines in Fig. 4(a) and (b) correspond to the ratios $I(r)/n_e(r)$, the $I(r)$ profiles being

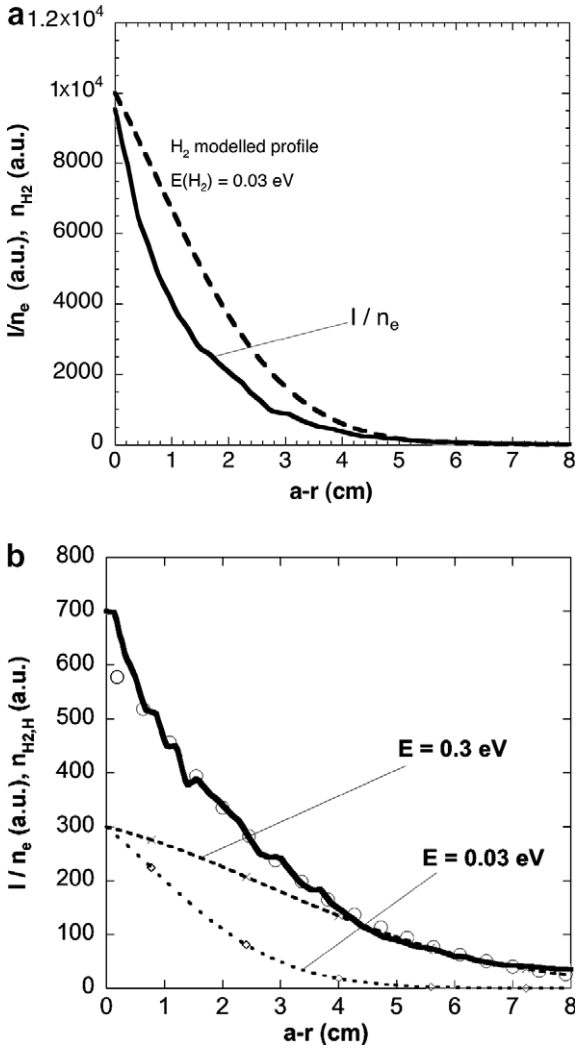

Fig. 4. Continuous traces: the H_α-intensity emission profiles of Fig. 3 divided by the measured electron density profiles (a) with and (b) without puffing. Discontinuous traces: modelled H_α-emission precursor profiles.

those of Fig. 3 and the $n_e(r)$ as obtained with plasma edge diagnostics (the discontinuous lines correspond to modelled precursor profiles later discussed). According to Eq. (1) they should be proportional to the corresponding neutral density H_α-precursor profiles. Without puffing the characteristic precursor decay lengths are typically of 3–5 cm, depending on plasma conditions, and with puffing the decay is much steeper, typically 1–2 cm.

In order to study if the puffing locally perturbs the plasma parameters as was observed in TEXTOR for high puffing rates [9], a He/H_2 mixture (about 30% He) was injected through the puffing hole so as to apply the He I line intensity ratio technique to obtain the local average electron density and temperature. A visible spectrometer with the same tangential view took local spectra of the He I lines at 668, 706 and 728 nm and additionally the CCD camera was equipped in these experiments with interference filters centred at the same lines. Without gas-puffing the local plasma parameters as obtained spectroscopically were $T_e = 50$–80 eV and $n_e = 1$–2×10^{18} m^{-3} in relatively good agreement with other diagnostics (the helium in the plasma comes from surface trapping during Helium Glow Discharge conditioning). With puffing rates of the order of 5–10×10^{19} H/s a T_e decrease of 20–30% together with a n_e increase by up to a factor of 3 is observed. With low puffing rates of the order of 10^{19} H/s no sensible plasma parameters perturbation is observed.

4. Comparison of the experimental results with a simple one-dimensional neutral hydrogen transport model

A simplified one-dimensional neutral hydrogen transport model was developed based on following assumptions:

- Most hydrogen is desorbed in form of molecules perpendicularly to the surface with an energy corresponding to the surface temperature ($T = 350$ K).
- The atomic hydrogen flux reflected from the surfaces generates a uniform distribution in the vacuum chamber since its ionisation mean free path is several times the plasma radius. Its density is much lower than the local hydrogen distribution in front of the poloidal limiter and can therefore be neglected there.
- The molecular hydrogen is preferentially ionised by electron collision impact, the reaction being: $H_2 + e^- \rightarrow H_2^+ + 2e^-$. The Franck–Condon dissociation probability is at least a factor of 5 lower for our conditions ($T_e > 40$ eV).
- After being ionised, the H_2^+ disappears from the emission cloud and volume recombination is neglected.

With these conditions the radial H_2 molecule density $n_{H_2}(r)$ can be described by the following differential equation:

$$dn_{H_2}(r)/dr = v^{-1} \cdot n_{H_2}(r) \cdot n_e(r) \cdot k_{ion}(r), \quad (2)$$

where v is the surface desorption velocity and k_{ion} is the ionisation rate coefficient, which as explained above dominates over dissociation in our conditions. Fitting $n_e(r)$ (known from experimental measurements) and $k_{ion}(r)$ (known from atomic reaction databases) with second order polynomials, Eq. (2) can be analytically solved. The solution is plotted in Fig. 4(a) (dashed line) for the H_2 thermal velocity of $v = 2 \times 10^3$ m/s, corresponding to about 0.03 eV or 350 K. The similarity of the modelled H_2 profile with that of I/n_e (continuous line) indicates that molecular hydrogen is the main H_α-emission precursor when hydrogen is puffed into the plasma. The direct excitation reaction is in this case:

$$H_2 + e^- \rightarrow H_2^{**} + e^- \rightarrow H(1s) + H(n = 3) + e^-. \quad (3)$$

The discrepancy between model and experiment lies well between the acceptable limits, accounting for the simplicity of the model and local plasma perturbation due to the relatively strong gas-puffing (see above).

For the recycled hydrogen (i.e. without puffing), the emission precursor/s profile/s is more complicated to interpret. As shown in Fig. 4(b) (continuous line), the I/n_e-profile (which should be proportional to the H_α-emission precursor profile) has a much longer penetration into the plasma than that of the case with gas-puffing. This indicates that before the emission process, at least a significant fraction of the desorbed molecules are dissociated into atoms, which gain energy in the dissociation process and penetrate more deeply into the plasma. These atoms, which have energies typically from 0.3 eV up to 7 eV depending on the exact dissociation process, are the main contributors of the H_α-emission in the deeper plasma edge (some centimetres inside the LCFS). In order to investigate which is the dissociation process, Eq. (2) was solved again with higher precursor velocities in order to get a better fit (the mass of the

precursor was taken to be that of atomic hydrogen). A good fit to the tail was found for an energy of about $E = 0.3$ eV. Fig. 4(b) shows the two precursor curves as calculated with Eq. (2) for $E = 0.03$ eV and H_2 as precursor and $E = 0.3$ eV with H as precursor (dotted and dashed lines respectively). The curve plotted with circles, which fits very well to the I/n_e-profile, is the sum of both curves with equal weight. Consequently, it seems that the source of the H_α-emission for the case of recycling at the limiter has at least two precursors: The first one is the thermally desorbed molecular hydrogen (see Eq. (3)), which is important only in the very first cms. The second one is most probably atomic hydrogen, which is excited after the H_2 molecule is dissociated with reaction products having energies of about 0.3 eV. This is the case for the following reaction ([10], reaction 2.2.6):

$$H_2 + e^- \rightarrow H_2^{**} + e^- \rightarrow H(1s) + H(2s) + e^-. \qquad (4)$$

This reaction has for $T_e > 25$ eV a higher rate coefficient than the H_2 dissociation to ground state level atoms (which produces 3–5 eV Franck–Condon atoms) and will therefore be the preferential H_2-dissociation route in the TJ-II plasma edge. Furthermore, the 3–5 eV atoms will penetrate the plasma with much higher velocity and disperse much more, so that they will contribute less to the region just above the limiter. The dissociation of H_2^+ into low energy (about 0.3 eV) H atoms (in the ground state or directly to the $n = 3$ level) can also be a possible source term and its relative importance will be studied in future with the EIRENE code.

The reason why the atomic H source term with 0.3 eV energy is absent in the case of puffing can be that the electron temperature decrease in front of the puffing, as measured here with the He I line intensity ratio technique, favours the H_2 dissociation to ground state level atoms of 3–5 eV Franck–Condon atoms, which disperse much more deeply into the plasma. This is the thesis claimed by the TEXTOR group [7,9]. We can however not exclude that the one-dimensional modelling and interpretation of the results is too simple for the puffing case. This 'geometrical' effect will be checked next with the 3-D code EIRENE, that is know being implemented for TJ-II.

5. Conclusions

- The H_α-emission profile analysis with the here proposed experimental set-up can help in understanding the atomic physics in the plasma boundary. This is because the velocity or energy of the H_α-emission neutral precursor, which gives information of the atomic break-up reaction, is directly proportional to its characteristic decay length in the plasma and this can be easily measured as is done here.
- The local plasma perturbation in front of a puffing-source has been measured with the He I line intensity ratio technique. For our conditions ($F = 5–10 \times 10^{19}$ H/s) a T_e decrease of 20–30% together with a $n_e$increase by up to a factor of 3 is observed.
- The H_α-emission directly in front of the limiter due to recycled hydrogen has two main sources: the electron impact dissociative excitation of H_2 molecules (see Eq. (3)) and the electron impact excitation of ground state atoms (perhaps also atoms in the $n = 2$ level) with energies of about 0.3 eV which are produced by dissociation of H_2 molecules following e.g. the reaction shown in Eq. (4).
- The H_α-emission in front of a hydrogen puffing-source at the LCFS has only thermal H_2 molecules as main precursor. The reason of the absence of the atomic route is unclear until now, but there are strong indications that the local plasma perturbation (T_e decrease 20–30%, n_e increase by up to a factor of 3 and neutral hydrogen increase by more than a factor of ten) is responsible for the disappearance of this source term.
- The EIRENE code is being implemented for TJ-II and first results comparing H_α-emission profiles with those simulated by the code will be presented in the near future. It will be useful to check if the simplified 1-D model is correct. The absolute neutral density distribution will be also calculated and used to compute CX-losses of ECRH and NBI plasmas as well as those of non-thermalised fast ions in TJ-II.

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