Determination of photon efficiencies and hydrocarbon influxes in the detached outer divertor plasma of ASDEX Upgrade

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Abstract

Hydrocarbon injection experiments with in situ calibration of spectroscopic signals have been carried out to determine the hydrocarbon flux and the chemical erosion yield under detached plasma conditions in ASDEX Upgrade. A plasma scenario was developed to detach the outer divertor in L-mode and to provide a cold ($T_e \approx 1–2$ eV) and volume recombining deuterium target plasma. A significant decrease of carbon-related intrinsic photon fluxes, in particular of the $C_2H$ Gerö and of the $C_2$ Swan band was observed in detachment. Moderate methane/ethene injections were performed through a single gas valve and an increase of carbon-related intrinsic photon fluxes was detected, which can be attributed to the amount of injected molecules. The experimentally determined effective inverse photon efficiencies are slightly larger than the ones deduced in attached plasmas. Nevertheless, the low intrinsic $CH$ and $C_2$ light observed under detached conditions can still be attributed to a reduction of the hydrocarbon flux of about one order of magnitude. The impact of detachment on the chemical erosion is discussed.

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(Some figures in this article are in colour only in the electronic version.)

1. Introduction

Carbon-fibre composite (CFC) is presently foreseen as the plasma-facing material for the ITER divertor target plates [1]. CFC is chosen to sustain the high particle and heat flux loading during a reasonable number of transient events [2]. Apart from transient events, a reduction of the particle and heat flux in normal operation is forced to ensure a long lifetime of the plasma-facing components. A fully detached inner divertor and semi-detached outer divertor plasma [3] is the proposed ITER scenario to fulfil this requirement. However, the use of CFC is connected with erosion, transport and deposition of carbon [4] which leads with respect to safety to the critical issue of tritium co-deposition [5]. Reduction of the erosion process is desirable to ensure a large number of ITER discharges without cleaning intervention [6]. The influence of divertor detachment on the hydrocarbon chemistry is the subject of present day research [7–9].

Experiments have been carried out to investigate the behaviour of the hydrocarbon particle flux and the chemical erosion yield in the outer divertor of ASDEX Upgrade under detached plasma conditions. The usually attached outer divertor leg which was recently identified to be the remaining source of carbon in ASDEX Upgrade [10] was detached on purpose. Injections of methane/ethene through a single gas valve were performed to determine effective inverse photon efficiencies or D/XB values [11–14] for different spectroscopic transitions, in particular the usually observed $CH$ Gerö band and $C_2$ Swan band and, thus to calibrate in situ the photon fluxes of the corresponding...
break-up products. The low intrinsic hydrocarbon fluxes were quantified and a comparison of hydrocarbon photon and particle fluxes deduced in attached and detached divertor plasmas is presented. The effect of detachment on the chemical erosion is discussed.

2. Experimental set-up

A plasma scenario in lower single-null configuration and medium triangularity was developed to detach the outer divertor leg in high density L-mode discharges ($I_p = 0.8$ MA, $B_t = 2.4$ T, $n_e^o = 6.0 \times 10^{19}$ m$^{-3}$, $T_e^o = 1.5$ KeV, $P_{ICRH} = 1.2$ MW) with the aid of strong deuterium fuelling. The fuelling rate that was needed to establish a fully detached divertor, was determined in set-up discharges with density ramps. The transition from an attached to a detached divertor was observed by optical emission spectroscopy, and detected by the reduction of the ion flux $\Gamma_D$, which was measured with the aid of a set of Langmuir probes (LP) [15] located in the vertical target plates. The detached scenario was density-feedback controlled, providing a long flat-top phase of more than 4 s. Several discharges with high reproducibility were performed to vary the spectrometer settings and the injected species. Additionally, the back transition from the detached to the attached regime was investigated in discharges where the deuterium fuelling was stopped on purpose. Characteristic time traces are depicted in figure 1.

2.1. Local plasma conditions and settings in the outer divertor

Minor-perturbing methane/ethene injections of the order of $4.0 \times 10^{18}$ molecules s$^{-1}$ were made through the gas valve T3 (tube diameter: 0.4 cm) implemented in the vertical target plates ($T_{target} \simeq 350$ K) of the outer divertor (figure 2). The injection of hydrocarbons allows hydrogen (hydrocarbon catabolism) to be distinguished from deuterium (background plasma). The injected hydrocarbon did not lead to an increase of the hydrogen concentration in the plasma; the $H/(H+D)$ ratio measured with the aid of a neutral particle analyser lay between 3.0–4.0% for all discharges with strong fuelling. Plasma parameters at the injection location were varied by sweeping the position of the outer strike point (OSP) about 10 cm. The injection was either into the private-flux region (PFR), the near or the far scrape-off layer (SOL). The long flat-top phase was sufficient to perform two strike-point sweeps in one discharge by rigidly raising and lowering the complete plasma column. One sweep was made with and one sweep without hydrocarbon injection. The later was used as reference to determine the intrinsic background under identical plasma conditions. Local plasma parameters were measured with the aid of LP and with Balmer spectroscopy observing the emission volume in front of the target plates (figure 2). Figure 3(a) shows the time evolution of the electron temperature $T_e$, the electron density $n_e$ and $\Gamma_D$ measured with LP and mapped to T3. The time points when the separatrix was on T3 are marked. The maximum in $n_e$ is observed in the SOL away from the separatrix, this indicates an upward shift of the ionization front which is characteristic for detached plasma conditions. $T_e$ is almost constant at about 2 eV or lower during the sweep and close to the LP detection limit. Analysis and simulation of Balmer recombination lines of the background species (figure 3(b)) provided $T_e \simeq 1.2$ eV and $n_e \simeq 3.0 \times 10^{20}$ m$^{-3}$ in the volume. Additionally, the Stark-broadening of Balmer-$\beta$ was measured and the maximum of the electron density was estimated to be $n_e \simeq 3 \times 10^{20}$ m$^{-3}$. These plasma parameters indicate a strong recombining outer divertor plasma.

2.2. Spectroscopic set-up

Atomic and molecular spectroscopy on hydrocarbon fragments was done with a set of fibre-coupled spectrometer systems, in particular with HAR and Echelle, which are briefly described here and in more detail elsewhere [16, 17]. The HAR spectrometer (1.0 m Czerny–Turner spectrometer, grating: 12000 mm$^{-1}$, spectral resolution: $R > 2.5 \times 10^4$, wavelength coverage: $\sim$8 nm, time resolution: 250 ms) was
used for the time-resolved recording of the band heads of the \( C H \) Gerö band \((A-X\) transition) and the \( C_2 \) Swan band \((d-a\) transition) as well as for the CII multiplets at 426.7 nm and at 515.0 nm. The Echelle spectrometer (cross-dispersion spectrometer, grating: 761 mm\(^{-1}\), spectral resolution: \( R > 2 \times 10^4 \), observed wavelength range: 345–645 nm, exposure time: 250 ms, read-out time: 1125 ms) was chosen to record the complete molecular spectra of the Gerö and Swan bands; the corresponding photon fluxes were deduced from fitted and simulated spectra [18]. Moreover, the hydrogen Balmer lines with \( n \geq 4 \) were measured simultaneously. However, the overview spectrum was recorded only for discrete time points.

All systems were equipped with one of three optical fibres (quartz, diameter: 0.1 cm) observing the same volume in front of the gas valve as shown in Figure 2. This volume (VOL, elliptical cross-section: 5.6 cm and 4.0 cm diameter) was chosen to be large enough to ensure that a major part of the emitted light from the different observed transitions was recorded. The cloud size was estimated by means of HAR, and four fibres from a set of discrete fibres (ROV, circular cross-section: 1 cm diameter) which were spatially separated over the divertor target plates. A correction factor of 1.5 to the photon fluxes deduced with VOL was applied in the case of injection into the detached plasma to take the loss of photons into account.

3. Experimental results

3.1. Spectroscopic observation and discussion

The detached divertor plasma leads in the first place to a reduction of the intrinsic photon flux of different carbon related transitions—in particular of \( CD, C_2 \) and CII—with respect to the attached divertor. Figure 4(a) and (b) illustrates the reduction of the \( CD \) Gerö band emission at the separatrix: the intrinsic photon flux \( \varphi_{CD}^{\text{in}} \) in detachment is diminished by more than a factor of 10 with respect to the attached...
reference (#20786). Note that, the BD A–X band becomes very prominent in detachment and the P-branch interferes strongly with the CD Gerö band—in particular at the band head (429.5–431.0 nm) where nearly half the emission results from BD. This disturbance was considered in the spectral analysis in the following way: The BD A–X spectrum was calculated and fitted to the characteristic band feature of the Q-branch at about 432.7 nm. This calculated BD spectrum was subtracted from the measured mixed spectrum. The remaining CD A–X spectrum was fitted as described above.

Injection of CH$_4$ or C$_2$H$_4$ in the detached plasma leads to the appearance of the CH Gerö band (figure 4(c)). The inverse photon efficiencies for CH from CH$_4$ and C$_2$H$_4$ related to the complete electronic transition were determined for the injection close to the separatrix in the detached case to [D/XB]$^{CH_4\rightarrow CH}$ = 18 ± 7 and [D/XB]$^{C_2H_4\rightarrow CH}$ = 47 ± 19, respectively. These D/XB values were deduced from the difference of the extrinsic and intrinsic photon flux as indicated in figure 4(e) for the C$_2$H$_4$ injection. Figure 4(e) shows the temporal evolution of band head intensity during the two OSP sweeps. However, hydrocarbon injection in attached plasmas leads to a much stronger light intensity during the two OSP sweeps. However, hydrocarbon influx C$_2$H$_4$ is in the order of three for the detached plasma conditions, and thus significantly lower than the measured ones. The C$_2$ Swan band shows a similar behaviour: the intrinsic photon flux $\phi_{CH}^{int}$ is strongly suppressed in detached plasma conditions (figure 4(f) and (g)) and below the detection limit of the applied spectrometer system. Injection of C$_2$H$_4$ provides an increase of the C$_2$ Swan band emission. However, the effective inverse photon efficiencies [D/XB]$^{C_2H_4\rightarrow C_2}$ differ significantly about 25 times: 16 ± 5 for the attached and 407 ± 134 for the detached case.

3.2. Hydrocarbon particle flux

The hydrocarbon influx $\Gamma_{CD}$ is given by the photon flux of the hydrocarbon representatives CD and C$_2$ and the corresponding D/XB values. Two contributions to $\Gamma_{CD}$ usually have to be considered: one related to CD$_{2s}$ and one to CD$_{2d}$ [14]. Here, $\phi_{CD}^{int}$ is below the detection limit of the Echelle spectrometer system in detached plasma conditions and we assume that the CD$_{2d}$ contribution can be neglected with respect to the CD$_{2s}$ contribution although the inverse photon efficiency is larger than in attached conditions. $\Gamma_{CD}$ can be described solely by CD$_{2s}$, and thus, by the CD Gerö band.

In the following we focus on the hydrocarbon flux resulting from chemical erosion at the target plate close to the separatrix and 3.5 cm deep in the SOL, and thus, close
to the ionization front. \( q_{\text{CH}}^{\text{Det}} \) increases in this spatial region from 4.5 \( \times \) \( 10^{18} \) ph m\(^{-2}\) s\(^{-1}\)—close to the separatrix—to 5.1 \( \times \) \( 10^{18} \) ph m\(^{-2}\) s\(^{-1}\) in the SOL. Accordingly, the corresponding particle flux increases from 8.1 \( \times \) \( 10^{19} \) particles m\(^{-2}\) s\(^{-1}\) to 9.2 \( \times \) \( 10^{19} \) particles m\(^{-2}\) s\(^{-1}\), assuming that there is no iso-toe effect in the photon efficiencies for the \( CH \) and \( CD \) Gerö band.

In the case of the reference attached plasma both contributions to the hydrocarbon flux have to be taken into account. Consideration of only \( \Phi_{\text{CH}}^{\text{Det}} \) and \( [D/XY]^{\text{Det}} = 10 \) would lead to 6.0 \( \times \) \( 10^{20} \) particles m\(^{-2}\) s\(^{-1}\), whereas the total hydrocarbon flux including the contribution of \( C_2D \) is for typical L-mode conditions about a factor of 1.3 larger, and amounts 7.8 \( \times \) \( 10^{20} \) particles m\(^{-2}\) s\(^{-1}\) [18].

We conclude that the strong photon flux reduction observed for these molecular transitions in the detached plasma suggest a strong reduction of the hydrocarbon particle flux coming from chemical erosion at the target. But the photon flux reduction is partially compensated by the increase of the corresponding inverse photon efficiency with respect to the attached plasma. Nevertheless a net-reduction of the hydrocarbon influx of about a factor of 8 from attached to detached occurs.

4. Discussion and conclusion about \( Y_{\text{chem}} \)

The chemical erosion yield \( Y_{\text{chem}} \) is defined by the ratio of the hydrocarbon influx, thus particles eroded at the CFC target, to the outflux of mainly fuel particles which hit (perpendicularly) the CFC target plate. The influx is reduced in detached plasmas in comparison to attached plasmas, as presented in the previous section. The questions which have to be addressed are: (i) how is the fuel outflux defined in detached plasmas and (ii) what is the impact of the hydrocarbon flux reduction on \( Y_{\text{chem}} \)?

1. The outflux has two contributions: the ion contribution \( \Gamma_{\text{D}} \) and the neutral particle contribution \( \Gamma_{\text{D}} \). Ions and neutrals can chemically erode CFC under the assumption that no energetic threshold for the erosion process exists. \( \Gamma_{\text{D}} \) is the dominating part in the case of a full ionising plasma (\( T_e > 5 \) eV) such that present in the attached outer divertor. In divertor detachment, neutrals can penetrate through the thin and cold separatrix and hit the CFC target. A large fraction of neutrals is present in the divertor and \( \Gamma_{\text{D}} \) is the dominating contribution. Typical values at the separatrix for L-mode discharges (#20784) are \( \Gamma_{\text{D}} \approx 2 \times 10^{21} \) m\(^{-2}\) s\(^{-1}\) \( < \Gamma_{\text{D}} \approx 2 \times 10^{22} \) m\(^{-2}\) s\(^{-1}\).

For a further analysis (of #20781-84), we concentrate on the local erosion yield in the region close to the separatrix and 3.5 cm in the SOL. The deuterium outflux varies between 2.75–3.10 \( \times \) \( 10^{22} \) m\(^{-2}\) s\(^{-1}\) while the major fraction of this incident flux is determined by neutrals (2.5 \( \times \) \( 10^{22} \) m\(^{-2}\) s\(^{-1}\)). Here, we estimate that the neutral flux to the target is 50% of the neutral flux measured by ionization gauges below the septum. This is reasonable nearby the thin separatrix and up to the ionization front where neutral particles cannot penetrate much further in.

2. The measured hydrocarbon flux (section 3) has to be related to the outflux discussed above to deduce the erosion yield at the CFC target. \( Y_{\text{chem}} \) varies between 2.9–3.0 \( \times \) \( 10^{-3} \) where the slightly higher yield is measured in the SOL. These values are comparable with predictions made with the outflux-dependent Roth formula [21]: \( Y_{\text{chem}}^{\text{Roth}} = 2.5–3.2 \times 10^{-3} \). These calculations were done with the total outflux and under the assumption of a constant plasma background. A detailed modelling with an erosion-deposition code with an appropriate plasma background is in preparation but is outside the scope of this paper. Note that the consideration of only \( \Gamma_{\text{D}} \) would lead to an erosion yield of 1.5–3.2 \( \times \) \( 10^{-2} \) with its maximum at the separatrix.

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