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 the recombining deuterium target plasma. A significant decrease of carbon-related intrinsic photon fluxes, in particular of the $CH$ 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. The impact of detachment on the chemical erosion is discussed.

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1. Introduction

Carbon-fibre composite CFC is presently foreseen as 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 subject of present day research [7,8].

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 [9] 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 [10-13] 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 develop-
oped to detach the outer divertor leg in high density L-mode discharges ($I_p = 0.8\, MA$, $B_t = 2.4\, T$, $n_e^0 = 6.0 \cdot 10^{19}\, m^{-3}$, $T_e^0 = 1.5\, KeV$, $1.2\, MW$ ICRH) 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) [14] located in the vertical target plates. The detached scenario was density-feedback controlled, providing a long flat-top phase of more than 4s. 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 fig.1.

2.1 Local plasma conditions and settings in the outer divertor

Minor-perturbing methane/ethene injections of the order of $4.0 \cdot 10^{18}\, mol./s$ were made through the gas valve T3 (tube diameter: 0.4cm) implemented in the vertical target plates ($T_{\text{target}} \simeq 350\, K$) of the outer divertor (fig.2). The injection of hydrocarbons allows to distinguish hydrogen (hydrocarbon catabolism) from deuterium (background plasma). The injected hydrocarbon did not lead to an increase of the hydrogen concentration in the plasma centre; the $H/(H+D)$ ratio lay between 3.0% to 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 10cm. 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 sweeps in one discharge. 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. Note that symmetric sweeping of the ISP and OSP is
comparable to vertical shift of the plasma column.

Local plasma parameters were measured with the aid of Langmuir probes and with Balmer spectroscopy observing the emission volume in front of the target plates (fig.2): Fig.3a 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 ionisation front which is characteristic for detached plasma conditions. $T_e$ is almost constant at about 2eV during the sweep close to the LP detection limit. Analysis and simulation of Balmer recombination lines of the background species (fig.3b) provided $T_e \simeq 1.2eV$ and $n_e \simeq 3.0 \cdot 10^{20} m^{-3}$ in the volume. The outer divertor plasma was identified to be fully recombining.

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 [15,16]. The HAR spectrometer (1.0m Czerny-Turner spectrometer, grating: 1200l/mm, spectral resolution: $R > 2.5 \cdot 10^4$, wavelength coverage: $\sim 8nm$, time resolution: 250ms) was used for the time-resolved recording of the band heads of the CH Gerö band ($A - X$ transition) and the $C_2$ Swan band ($d - a$ transition) as well as for the CII multiplets at 426.7nm and at 515.0nm. The Echelle spectrometer (cross-dispersion spectrometer, grating: 76l/mm, spectral resolution: $R > 2 \cdot 10^4$, observed wavelength range: 345nm – 645nm, exposure time: 250ms) was chosen to record the complete molecular spectra of the Gerö and Swan band; the corresponding photon fluxes were deduced from fitted and simulated spectra [17]. 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: $0.1cm$) observing the same volume in front of the gas valve as shown in fig.2. This volume (VOL, elliptical cross-section: $5.6cm$ and $4.0cm$ diameter) was chosen large enough to ensure that a major part of 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, $1cm$ 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. Fig.4a/b illustrates the reduction of the $CD$ Gerö band emission at the separatrix: the intrinsic photon flux $\phi_{A-X}^{CD int.}$ 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 ($429.5 - 431.0nm$) where nearly half the emission is resulting from $BD$. This disturbance was considered in the spectral analysis.

Injection of $CH_4$ or $C_2H_4$ in the detached plasma leads to the appearance of the $CH$ Gerö band (fig.4c). The inverse photon efficiencies for $CH$ from $CH_4$ and $C_2H_4$ related to the complete electronic transition were determined for the injection close to the separatrix to $[D/XB]_{A-X}^{CH_4\rightarrow CH} = 18 \pm 7$ and $[D/XB]_{A-X}^{C_2H_4\rightarrow CH} = 47 \pm 19$, respectively. These D/XB values were deduced from the difference of the extrinsic and intrinsic photon flux as indicated in fig.4e for the $C_2H_4$ injection. Fig.4e 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 emission of the CH Gerö band as depicted in fig.4d where \( C_2H_4 \) was injected in the attached phase of discharge \#20785 \((T_e = 14eV\) and \( n_e = 1 \cdot 10^{19} m^{-3} \) at the valve location). \([D/XB]_{A-X}^{C_2H_4 \rightarrow CH} \) amounts 19 ± 4 which is about 2.5 times lower than for detached plasma conditions. The photon efficiency for CH from \( CH_4 \) in L-mode discharges with divertor attachment \((n_e = 2...8 \cdot 10^{19} m^{-3},\ T_e = 5...15eV)\) was determined to \([D/XB]_{A-X}^{CH_4 \rightarrow CH} = 4 \ldots 15 [19]\).

The \( C_2 \) Swan band shows a similar behaviour: the intrinsic photon flux \( \phi_{d-a}^{C_2 \ int.} \) is strongly suppressed in detached plasma conditions (fig.4f/g) and below the detection limit of the applied spectrometer system. Injection of \( C_2H_4 \) provides an increase of the \( C_2 \) Swan band emission. However, the effective inverse photon efficiencies \([D/XB]_{d-a}^{C_2H_4 \rightarrow C_2} \) 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 \( \Gamma_{C_xD_y} \) is given by the photon flux of the hydrocarbon representatives \( CD \) and \( C_2 \) and the corresponding D/XB-values. Two contributions to \( \Gamma_{C_xD_y} \) have to be usually considered: one related to \( CD_y \) and one to \( C_2D_y \) [13]. Here, \( \phi_{d-a}^{C_2 \ int.} \) is below the detection limit of the Echelle spectrometer system in detached plasma conditions and we assume that the \( C_2D_y \) contribution can be neglected with respect to the \( CD_y \) contribution although the inverse photon efficiency is larger than in attached conditions. \( \Gamma_{C_xD_y} \) can be described solely by \( CD_y \), 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 3.5cm deep in the SOL, and thus, close to the ionisation front. \( \phi_{A-X}^{CD \ int.} \) increases in this spatial region from \( 4.5 \cdot 10^{18} \ \frac{ph}{m^2 s} \) -close to the separatrix- to \( 5.1 \cdot 10^{18} \ \frac{ph}{m^2 s} \) - in the SOL. Accordingly, the corresponding particle flux increases from \( 8.1 \) to \( 9.2 \cdot 10^{13} \ \frac{particles}{m^2 s} \), assuming that there is no isotope 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 $\phi^{CD\text{ int.}}_A - X$ and $[D/XB]^{CH_A - CH}_A - X = 10$ would lead to $6.0 \cdot 10^{20} \text{ particles m}^{-2} \text{ s}^{-1}$, whereas the total hydrocarbon flux including the contribution of $C_2Dy$ is for typical L-mode conditions about a factor 1.3 larger, and amounts $7.8 \cdot 10^{20} \text{ particles m}^{-2} \text{ s}^{-1}$ [17].

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 8 from attached to detached occurs.

4. Discussion and conclusion about $Y_{chem}$

The chemical erosion yield $Y_{chem}^{C}$ 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) which impact has the hydrocarbon flux reduction on $Y_{chem}^{C}$.

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

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 \(2.75 - 3.10 \cdot 10^{22} m^{-2} s^{-1}\) while the major fraction of this incident flux is determined by neutrals \((2.5 \cdot 10^{22} m^{-2} s^{-1})\). Here, we assume that the neutral flux to the target is about 50\% of the neutral flux measured by ionisation gauges below the septum. This assumption is reasonable nearby the thin separatrix and up to the ionisation front where neutral particles cannot penetrate further in.

(ii) The measured hydrocarbon flux (sec.3) has to be related to the outflux discussed above to deduce the erosion yield at the CFC target. \(Y_{chem} \) varies between \(2.9 - 3.0 \cdot 10^{-3}\) where the slightly higher yield is measured in the SOL. These values are comparable with predictions made with the outflux-dependent Roth formula [20]: \(Y_{chem}^{Roth} = 2.5 - 3.2 \cdot 10^{-3}\). 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 out of the scope of this paper. Note that the consideration of only \(\Gamma_{D^+}\) would lead to an erosion yield of \(1.5 - 3.2 \cdot 10^{-2}\) with its maximum at the separatrix.

Acknowledgments

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Figure captions:

Fig.1: Time traces of plasmas current, outer-strike point position, additional power, radiated power, central electron density, and neutral density in the divertor for the detached case (a) and the detached/attached case (b).

Fig.2: Schematic set-up: The range of the strike-point sweeping with respect to the injection valve T3 is indicated. The location of the Langmuir probes, the lines-of-sight of the spectroscopic systems, and the pressure gauges are presented.

Fig.3: a) Time resolved local plasma parameters at the target plates in the detached outer divertor recorded with Langmuir probes. b) Balmer-line spectrum of the fully recombining plasma. The plasma parameters in the volume in front of the target were deduced from Balmer-line ratio modelling [Wunderlich].

Fig.4: Comparison of the \( CH A - X \) (a) and the \( C_2 d - a \) spectrum (c) with and without local ethene injection under detached and attached plasma conditions, respectively. Time evolution of the \( CH \) Gerö (b) and \( C_2 \) Swan band head intensity (d) during the OSP sweep.
Figure 1:
Figure 2:
Figure 3:
Figure 4: