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Spectroscopic investigation on the impurity influxes of carbon and silicon in the ASDEX upgrade experiment

R. Pugno *, A. Kallenbach, D. Bolshukhin, R. Dux, J. Gafert, R. Neu, V. Rohde, K. Schmidtmann, W. Ullrich, U. Wenzel, ASDEX Upgrade Team

Max-Planck-Institut für Plasmaphysik, IPP–EURATOM Association, Boltzmannstrasse 2, D-85748 Garching, Germany

Abstract

Emission profiles of carbon and silicon along the heat shield (HS) were measured before and after siliconization of the vessel. Siliconization does not affect the divertor and therefore large changes in impurity concentrations and influxes cannot be attributed to it. A strong transient increase of the silicon concentration was observed immediately after the siliconization lasting for a few discharges. However, no large change was observed in the silicon influx from the HS, excluding it as possible source of the concentration increase. The fast decrease in the silicon concentration can be attributed to strong erosion at the outer limiter. The impurity influxes for C^{2+} and Si^{2+} from the HS are estimated and compared with the corresponding core concentrations. The relative contribution to the plasma impurity content from divertor, HS and outer protection limiter is discussed. Zeeman splitting analysis permits one to identify the emitting region of carbon radiation. Anomalously high silicon sputtering yields are measured, which do not however cause high core silicon content. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Plasma facing components; Spectroscopy; Siliconization

1. Introduction

Impurity influxes in tokamaks are the result of the interaction between the plasma and the plasma facing components. The main impurity production mechanisms are, in the case of carbon, physical and chemical sputtering. They depend on the energy, flux, mass and angular distribution of the particles hitting the surface. Moreover the chemical sputtering depends on the surface temperature. Despite great effort on many experiments no quantitative understanding has yet been achieved [1], due to the large number of parameters involved and to the complexity of the geometry of the plasma–wall interaction. In the ASDEX upgrade tokamak the possible sources for impurities are the divertor, the heat shield (HS) at the inner wall and the protection limiters at the outer wall. In this paper we will discuss the relative contribution of these three sources (Fig. 1(b)) to the total plasma impurity content and we do an estimate of intrinsic impurity production and screening [2–4]. The influx of silicon and carbon from the HS were determined from simultaneous measurement of the SiIII (456 nm) and CIII (465 nm) emission lines using a scanning Boundary Layer Spectrometer (BLS) [5,6]. The influxes were measured before and after the siliconization and compared with the impurity core concentrations. The spatial origin of the CIII radiation is obtained from Zeeman splitting analysis. Radial plasma shifts are performed to investigate the effect of the wall clearance.

2. Experiments

Fig. 1(b) shows the poloidal cross-section of the ASDEX upgrade tokamak and the BLS scanning range used during the measurements. The unshifted carbon and silicon photon flux profiles reveal weak intensity maxima near the center of the HS (Fig. 1(a)).

Additionally the carbon emission increases towards the divertor region, reflecting the increasing contribution

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* Corresponding author. Tel.: +49-89 32 99 2571; fax: +49-89 32 99 1812.

E-mail address: roberto.pugno@ipp.mpg.de (R. Pugno).

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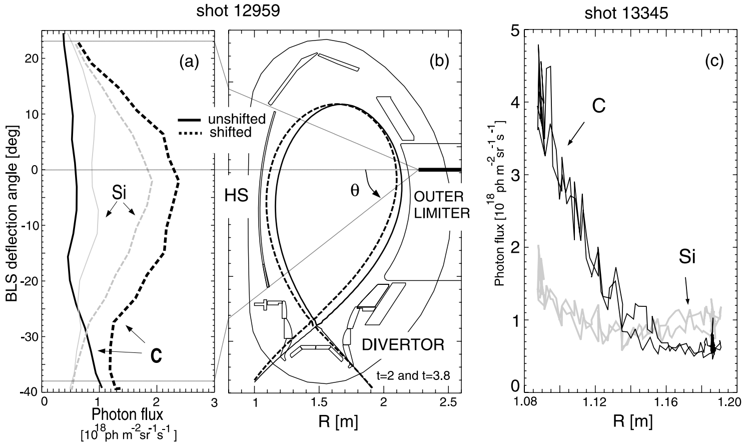

Fig. 1. (a) Photon flux profiles along the heat shield for SiIII (456 nm, gray line) and CIII (465 nm, black line) for the two extreme plasma column positions (shot 12959). (b) Plasma shape for the two extreme plasma column positions. (c) CIII and SiIII photon fluxes as function of the plasma inner radius at $\Theta = 0$ (shot 13345).

of the carbon influx originated from the divertor zone. The carbon contribution from the lower part of the HS is important mainly for the standard magnetic configuration with the plasma column position far away from the HS (Fig. 1(b), solid line). The silicon does not show any increase towards the divertor. Due to the fact that the glow discharge during the siliconization does not penetrate the narrow divertor slots, the divertor is not a silicon source. When the plasma is shifted towards the inner wall (Fig. 1(b), dashed line) the photon flux from the center of the HS dominates for both impurity species. The increase of the maximum photon flux (center of the HS) during the shift is about a factor 4 for carbon and a factor 2 for silicon (Fig. 1(a)). A radial scan discharge similar to the preceding one was made, keeping the BLS line of sight fixed in the horizontal position at $\Theta = 0$. In this way the maximum emission from the HS was measured with a better time resolution. The correlation between the photon flux and the plasma inner radius is shown in Fig. 1(c). The increase in the CIII photon flux approaching the HS is larger than in the previous discharge, due to the longer time elapsed since the siliconization. The minimum distance between separatrix and HS is about 14 cm in standard configuration and 4.5 cm at the maximum inward shift. The BLS line of sight is far from the protection limiters.

The silicon concentration in the plasma core has been measured spectroscopically using the Lyman-α line emission of H-like silicon. The measurements taken during reference H-mode discharges without gas puff show an increase by more than an order of magnitude in the first discharge after the siliconization and a fast decay during the following five discharges. After approximately 50 discharges values similar to those before siliconization were reached (Fig. 2(a)). The SiIII photon flux (representative of the HS influx) for the same discharges and similar times, shows only a factor 2 increase after the siliconization (Fig. 2(b)).

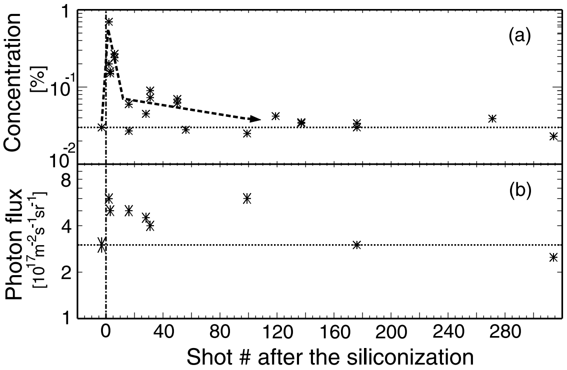

Fig. 2. (a) Silicon core concentration vs. shot number after the siliconization. (b) SiIII (456 nm) photon flux from the heat shield vs. shot number after the siliconization.

Zeeman analysis of the CIII line (465 nm), observed with a line of sight similar to the BLS at fixed angle ($\Theta = 0$), can be used to calculate the magnetic field at the emission region. In Fig. 3(b) the calculated magnetic field at the emitting region is compared with the magnetic field at the inner and at the outer separatrix obtained from magnetic measurements. The extracted magnetic field agrees well with that of the inner separatrix position during the maximum shift towards the HS (3.0–4.2 s), showing that most of the emission originates from there. By fitting the Zeeman pattern calculation to the measured profile it was found that 10–20% of the observed emission comes from the low field side in the normal magnetic configuration and only less than 1% during the shift towards the HS.

To calculate the carbon and silicon sputtering yields, the D_α radiation has been measured on a similar line of

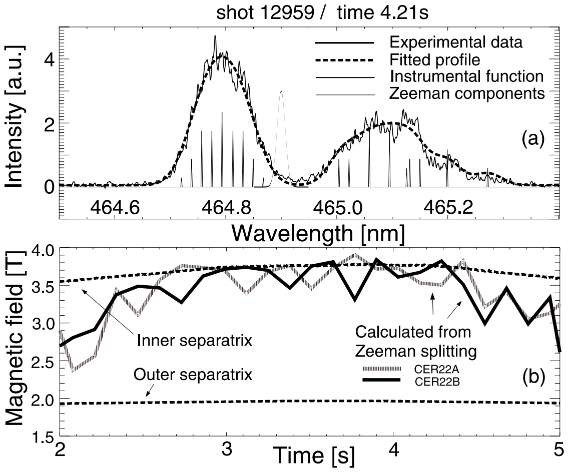

Fig. 3. (a) Experimental and fitted spectra for the CIII line. (b) Calculated magnetic field from Zeeman analysis for two independent channels and magnetic field at the outer and inner SOL in the horizontal plane.

sight. To determine the fraction of the D_α flux emitted on the high field side, a small gas puff during the initial phase of the discharge was made from the outer wall. The neutral particle flux (measured by the low energy neutral particle analyser) and the D_α radiation have been measured simultaneously on similar line of sight. The increase of the neutral flux, originated from the low field side only, is proportional to the local neutral atom density, i.e., to the gas puff. The D_α radiation comes from both high and low field side and is proportional to the gas puff only if the intensity fraction from the high field side is negligible compared to the low field side. The comparison between the two measurements shows that about 85% of the D_α radiation comes from the high field side when the plasma is far away from the HS. This fraction is expected to be similar or larger during the shift of the plasma column.

3. Analysis

To derive the C^{2+} ion flux from the photon flux, the ratio ionizations/photon (S/XB) have been calculated with the STRAHL code [7] using measured edge T_e and n_e profiles. The resulting value is $S/XB_{\mathrm{CIII}} = 0.8$. For silicon a value $S/XB_{\mathrm{SiIII}} = 1.1$ has been obtained from the atomic database ADAS [8] for $T_e = 14$ eV and $n_e = 1 \times 10^{19}$ m^{-3}. The obtained ion fluxes Γ_{imp} for silicon and for carbon have been multiplied by the penetration probability of crossing the separatrix and reaching the plasma core ($\mathrm{pp}_{\mathrm{imp}}$) and by an effective HS area ($A^{\mathrm{HS}}_{\mathrm{eff}}$) which takes into account the profile shape. This integrated impurity influx from the HS $\Phi^{\mathrm{HS}}_{\mathrm{in}}$ (dashed line, Fig. 4) is then compared with the total impurity outflux Φ_{out} calculated multiplying the impurity density n_{imp} by the plasma volume V_{plasma} and dividing by the energy confinement time τ_{E} (solid line, Fig. 4):

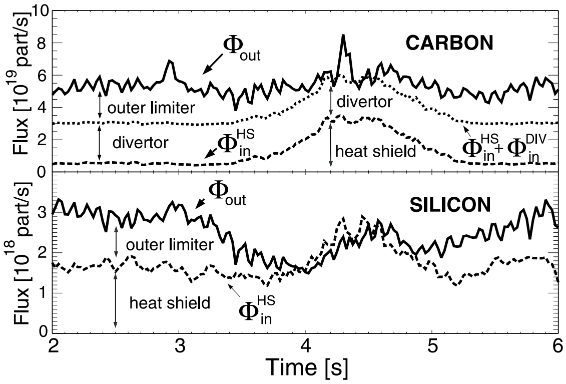

Fig. 4. Importance of the different sources compared with the inferred outflux. Flux from the core plasma (solid lines) and flux from the edge (dashed lines) for carbon (a) and silicon (b) assuming $\mathrm{pp}_{\mathrm{C}^{2+}} = 0.15$ and $\mathrm{pp}_{\mathrm{Si}^{2+}} = 0.03$.

$$\Phi^{\mathrm{HS}}_{\mathrm{in}} = \mathrm{pp}_{\mathrm{imp}} A^{\mathrm{HS}}_{\mathrm{eff}} \Gamma_{\mathrm{imp}}, \qquad \Phi_{\mathrm{out}} = n_{\mathrm{imp}}\, V_{\mathrm{plasma}}/\tau_{\mathrm{E}}.$$

From the previous silicon laser blow-off experiments [9] the core particle confinement time is known to be similar to the energy confinement time. The carbon concentration in the core plasma is measured via charge exchange recombination spectroscopy, observing the emission of CVI (529.05 nm). The inferred total carbon outflux is constant during the shift of the plasma, in spite of the strong influx increase from the HS.

From limiter shot analysis, where the HS is the only carbon source, a value $\mathrm{pp}_{\mathrm{C}^{2+}} = 0.15$ is obtained. The $\mathrm{pp}_{\mathrm{C}^{2+}}$ for a divertor plasma should be not higher than this. Assuming that 60% of the total carbon content originates from the divertor and is constant during the plasma column shift and that at the maximum shift there is no source from the outer wall, the resulting penetration probability is $\mathrm{pp}_{\mathrm{C}^{2+}} = 0.15$ (Fig. 4(a)). If the divertor source were zero, then $\mathrm{pp}_{\mathrm{C}^{2+}} = 0.5$. JET simulation results also show that the outer divertor accounts for about 50% of the carbon content for high recycling ELMy H-mode conditions [10].

For silicon, assuming that at the maximum shift towards the inner wall the HS is the main silicon source, the resulting penetration probability is $\mathrm{pp}_{\mathrm{Si}^{2+}} = 0.03$.

The C^{2+} and Si^{2+} fluxes are then divided by the deuterium flux (assuming $S/XB_{D_\alpha} = 25$) to calculate the yields (Fig. 5). The yield for carbon shows a strong dependence on the plasma column position going from 1.5% in standard configuration to 7% for the smallest distance between plasma and HS. Since the yields quoted here refer to C^{2+} and Si^{2+} ions, the underlying neutral erosion yields will be higher by the inverse of the

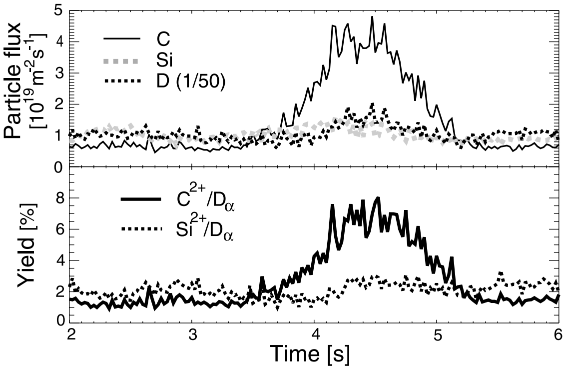

Fig. 5. (a) Particle fluxes for deuterium, carbon and silicon during the radial plasma shift. (b) Carbon and silicon sputtering yields during the radial plasma shift.

particle fraction lost due to redeposition and parallel transport losses before reaching the 2+ state.

For silicon the resulting yield is about 2%, constant during the plasma column shift. Independent measurements made in TEXTOR-94 [11] observing the SiII line at 597.9 nm have obtained yields of 2% or higher, compatible with the present results. From analysis during the startup limiter phase, a fast decrease of silicon emission in a few discharges after the siliconization and the simultaneous increase in the carbon emission suggest the formaton of a mixed C–Si layer on the HS. Nevertheless, the sputtering yield for SiC expected from charge exchange neutrals is about 0.4% [12], a factor 5 lower.

4. Discussion and conclusion

The silicon layer thickness deposited on the HS during the siliconization is about 50 nm [13] corresponding to 5×10^{21} atoms m^{-2}. Typical silicon fluxes from the inner wall are $(0.5–1.0) \times 10^{19}$ atoms m^{-2} s^{-1}. This would give a silicon coating duration (assuming no redeposition) of 500–1000 s, corresponding to about 100–200 discharges. The fast decrease of silicon core concentrations with pulse number is inconsistent with HS being the main silicon source. Because the divertor is not siliconized the only possible silicon source with a fast decay time are the outer protection limiters. It appears that a strong erosion in standard divertor configuration is present at the outer wall protection limiters, producing a strong but transient silicon concentration increase after the siliconization. This erosion is attributed predominantly to the impact of fast ions produced by the neutral beam injection. After a few discharges the silicon is totally removed from such plasma facing surfaces and the underlying carbon bulk material is eroded. The erosion at the outer wall is localized near the protection limiter, far away from the line of sight of the spectrometer, being most of the carbon radiation observed emitted at the high field side. Inspection of the outer limiter during opening of the vessel confirms the strong erosion. The HS accounts for the long term silicon source. Nevertheless, due to the low silicon concentration, no performance degradation is observed in ASDEX upgrade.

The values obtained for silicon sputtering yield are higher and the penetration probabilities lower than expected. A possible explanation could be an overestimation of the atomic data (S/XB) for the silicon line. On the other hand independent measurements from TEXTOR-94 show similar results. Therefore anomalously high sputtering yields for the silicon layer may be effective, possibly caused by the chemical composition of the Si–C–O–D surface layer. Up to now there is no clear understanding of the strong increase in the carbon sputtering yield during the plasma column shift and of the discrepancies in the silicon sputtering yields and penetration. Further analysis are in progress and a more detailed analysis will be presented in a future work.

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