Modelling of Impurity Transport and Radiation for ASDEX Upgrade Discharges

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Introduction

During the tungsten divertor experiment at ASDEX Upgrade the global tungsten concentrations in the main plasma c_W showed only a weak correlation with the WI-fluxes in the divertor. This implies a strong dependence of the particle confinement time of tungsten on the plasma parameters. A decrease of c_W with rising plasma density and heating power and particular discharge scenarios with the tendency for tungsten accumulation could be identified [1]. In this paper a strong decrease of the tungsten confinement on the impurity concentration of light impurities is demonstrated. Neo-classical transport in the edge of the confined plasma might explain this dependence and has been investigated using the radial impurity transport code STRAHL.

Dependence of tungsten transport on carbon concentration

To asses the effect of light impurities on tungsten transport in the main plasma a type-I ELM'y H-mode discharge with a strongly varying carbon concentration has been investigated. The parameters for this deuterium discharge #8503 are $P_{NI} = 7.5MW$, $B_t = 2.5T$, $I_p = 1MA$, $q_{95} = 4$ and $n_e \approx 8 \cdot 10^{19} m^{-3}$.

Fig.1 shows the temporal behaviour of the tungsten flux in the divertor and at the mid-plane, and of the carbon and tungsten densities in the plasma bulk.

The density of fully ionized carbon in the main plasma was determined from charge exchange spectroscopy on 16 line-of-sights covering the whole plasma cross section. The neutral tungsten influx at the outer divertor plate was measured with a poloidally scanning visible spectrometer [2] and the data points are the maximum values for every scan over the outer target. The particle flux was calculated from the photon flux using S/XB-values from laboratory measurements [2]. The time trace in fig.1 represents the net influx by subtracting the calculated part of prompt redeposited particles [2]. The net influx amounts to $\approx 10\%$ of the total influx. At the mid-plane the tungsten flux has been measured as a function of time using a rotatable deposition probe. The probe was located in the open field line region between two limiters. The tungsten density at a poloidal flux label of $\rho_{pol} \approx 0.75$ was determined from the intensity of the quasi continuum at $\lambda = 5nm$

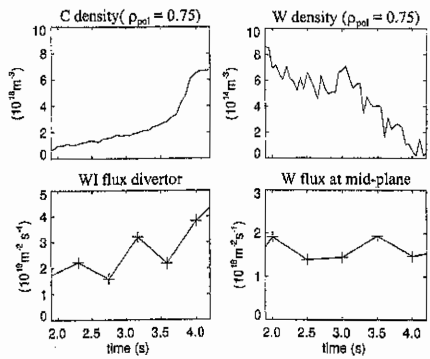

Figure 1: Time traces of carbon and tungsten densities in the plasma bulk and tungsten flux densities for discharge # 8503. The rising carbon density leads to an increased influx of W in the divertor. However, the W density in the main plasma strongly decreases.

(due to transitions of ions with charge around $Z = 28$) which was measured by a grazing incidence spectrometer on a central line-of-sight.

Towards the end of the NI-heated phase of the discharge CCD-camera observations show a bright glow from parts of the ICRH-antennas and the deposition probe leading to a strongly rising carbon density in the plasma. The rising carbon density is accompanied by an increase of the WI influx by a factor of ≈ 2 as expected from the dominance of impurity impact on the sputtering of tungsten [2]. During this phase the tungsten flux onto the probe at the mid-plane remains constant. The most prominent effect is seen from the time trace of the W density in the plasma bulk. It shows a strong decrease and falls below the detection limit at $t = 4.0s$. The line averaged electron density increases by 15% and the average temperature decreases by 15% during the shown time interval, while the radiated power fraction changes from 40% to 50%. For $t < 3.75s$ type-I ELM's are observed which change to compound ELM's for later times.

Calculation of tungsten transport due to impurity-impurity friction

The calculations were performed with the impurity transport code STRAHL using the measured electron density and temperature profiles. Various experimental and calculated profiles for the time $t = 3.6s$ are given in fig. 2. Electron density profiles result from defolded interferometric measurements using lithium beam measurements for the density profile at the plasma edge. Electron temperature was measured with ECE diagnostics and around the separatrix with Thomson scattering. The anomalous diffusion coefficient in fig.2 (equal for C and W) was taken from an analysis of impurity density evolution after gas puffing of helium and neon in similar H-mode discharges [3]. It represents a time averaged value including the effects of sawtooth crashes and ELM's on the impurity transport. In a first step the drift velocity for carbon v^C was determined from the measured density profiles of C^{6+} for the time interval $t = 2.0 - 3.6s$. The profile shape is almost unchanged in this phase and the density change is slow enough to evaluate the drift velocity from the slope of the density profile in the source free region ($\rho_{pol} < 0.85$). Outside that region v^C was simply kept constant at the value of $\rho_{pol} = 0.85$. The resulting drift velocity is directed inward over the whole plasma cross section being in accordance with the gas puffing results mentioned above [3]. The value of v^C for $\rho_{pol} > 0.85$ can not be checked with the measurement of C^{6+}-densities. However, there must be an inward drift to cause no contradiction between the calculated carbon density profile and the measured electron density for the time ($t > 4.0s$) with a very high carbon concentration. The drift velocity was taken to be constant for the whole time interval and the experimentally unknown carbon influx was adapted to fit the observed carbon densities.

In a second step it was checked whether neo-classical transport might explain the strong decrease of the tungsten density in the plasma bulk. The total collision frequency of W is strongly influenced by the collisions of tungsten with carbon (W-C) being a factor of ≈ 4 more frequent than collisions with deuterium (W-D) for the depicted time $t = 3.6s$ in fig.2. The plot of the collisionality ν^* times the inverse aspect ratio $\epsilon^{3/2}$ shows that tungsten is in the Pfirsch-Schlüter regime for all radii. Carbon is in the plateau regime for $\rho_{pol} < 0.75$ and in the Pfirsch-Schlüter regime outside, and deuterium is in the banana regime for most of the plasma cross-section and in the plateau regime for $\rho_{pol} > 0.9$. Thus, the neo-classical transport parameters of tungsten D^W and v^W are dominated by the Pfirsch-Schlüter terms. These terms were calculated from the formulas of Wenzel and Sigmar [4] where the deuterium density n_D was calculated from the electron density

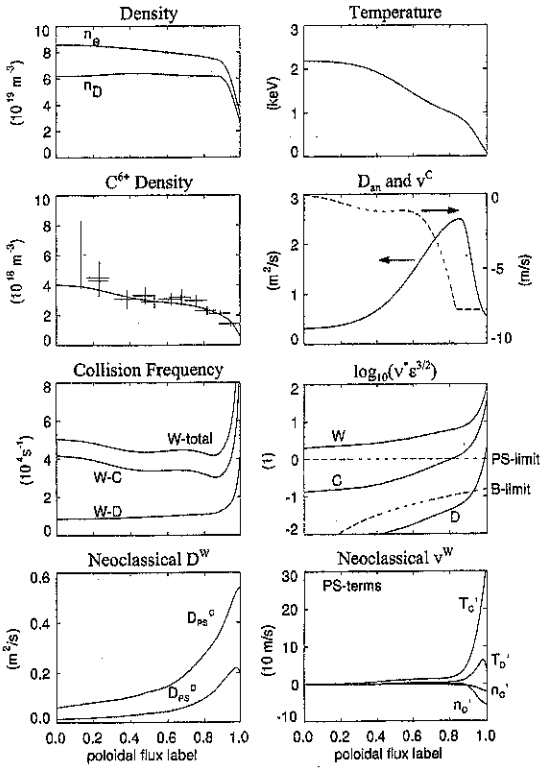

Figure 2: Various profiles for discharge #8503 at t=3.6 s versus the poloidal flux label.

considering the dilution due to carbon. The temperature for all species was assumed to be equal. The diffusion coefficient of tungsten due to collisions with carbon is given by $D_{PS}^C = D_{PS}^D \alpha_C \sqrt{m_C/m_D}$ where D_{PS}^D is the diffusion coefficient due to collisions with deuterium and $\alpha_C = n_C Z_C^2 / n_D$ is the impurity strength of carbon. The drift velocity of tungsten is the sum of the density gradient terms v_n^X and the temperature gradient terms v_T^X:

$$v_n^X = D_{PS}^X Z_W K_X \frac{n'_X}{n_X}$$
$$v_T^X = D_{PS}^X Z_W H_X \frac{T'_X}{T_X}$$

with $X = C$ or $X = D$. The dimensionless factors K_X and H_X are for deuterium $K_D \approx 1$ and $H_D \approx -0.5$ leading to an inward drift for the density-gradient term and an outward drift for the temperature-gradient term. For carbon these factors are $K_C \approx 1/Z_C$ and $H_C \approx H_D$. For typical density and temperature profiles the outward drift due to the temperature-gradient of carbon dominates all other terms for sufficiently high impurity strengths α_C. In these calculations tungsten could be treated in the trace limit and the dilution due to W could be neglected.

Two transport calculations for tungsten were performed: one with $D^W = D_{an} + D_{neo}$ and $v^W = v_{neo}$ and another one with $D^W = D_{an}$ and $v^W = v^C$. The influx was taken from the divertor net WI flux density and an estimated area of $0.5m^2$. The penetration of tungsten into the confined region is determined by the ionisation length, the parallel loss time and the transport parameters in the SOL. The parameter set in both cases was adapted to yield a penetration probability of $\approx 4\%$ in both cases being in accordance with investigations of the tungsten flux pattern [5]. When taking the carbon transport parameters the calculated tungsten density at $\rho_{pol} = 0.75$ (dotted line in fig.3) is too high by about an order of magnitude and the time dependence simply reflects the increasing influx. The neo-classical calculation shows the observed decrease, however, the absolute values can only be fitted when multiplying the neo-classical drift by a factor of 0.3. For a constant separatrix density of tungsten the density at $\rho_{pol} = 0.75$ is determined by the integral of v/D from the separatrix to $\rho_{pol} = 0.75$. In fig.3 the average diffusion coefficient and drift in this radius interval is given as a function of time. Even for low carbon strengths α_C the tungsten distribution is hollow. The lowest graph in fig.3 gives the calculated ratio of the W density at $\rho = 0.75$ to the density at $\rho = 1$ as a function of the carbon impurity strength.

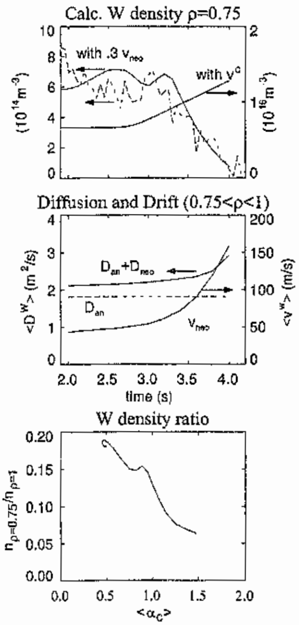

Fig. 3: Experimental and calculated W-densities for #8503 using two sets of transport parameters.

Conclusion

It has been shown by these calculations that the influence of carbon on the tungsten transport can qualitatively be described by neo-classical effects. C and W have oppositely directed drift velocities in the radial range $\rho_{pol} > 0.75$ and the tungsten profiles are hollow for the whole investigated parameter range. The outward drift resulting from the friction with medium-Z impurities is beneficial for the use of high-Z plasma facing components. However, the experimental uncertainties of densities, temperatures and carbon strength in this range and the rough estimate of the tungsten influx do not allow a quantitative check of the neo-classical transport coefficients.

References

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