IMPURITY FLOW IN THE TOKAMAK SCRAPE-OFF LAYER

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I. INTRODUCTION AND MODEL

The charge state distribution of impurities in the highly inhomogeneous tokamak boundary depends strongly on the location and composition of the impurity sources and is usually far from local coronal equilibrium. Therefore, a theoretical investigation of the impurity transport requires rather sophisticated models, the dominant physical effects being quite different for different collisionality. In the high recycling regime of present-day tokamaks like ASDEX or of future experiments like INTOR, the mean free path of all relevant particles is small compared with typical system dimensions and a fluid description may be adequate (except for the narrow electrostatic layer at the target plate which enters via boundary conditions). In view of the low impurity content measured in ASDEX /1/ and the small tolerable impurity contamination in future fusion experiments, a test fluid approach seems to be justified. This requires $n_z Z^2 \ll n_e$, where n_e is the electron density and n_z is the density of the Z times ionized impurities. In this limit we may neglect collisions between impurities and also their influence on the background hydrogen plasma.

As a first approximation we consider only the flow parallel to the magnetic field lines. Each ionization stage is then treated as a separate fluid which is coupled to neighbouring states via ionization and recombination and to the hydrogen background plasma via collisions and the ambipolar electric field E ($n_e \cdot e \cdot E = -\partial p_e / \partial s - 0.71 \cdot n_e \cdot \partial(kT_e) / \partial s$, ref. /2/; $p_e = n_e k T_e$, T_e = electron temperature, $e = 1.6 \cdot 10^{-19}$ As). For simplicity, the impurity temperature T_z is assumed to be equal to the hydrogen ion temperature T_i. Then we have to solve the following set of equations:

$$\frac{\partial n_Z}{\partial t} + \frac{\partial}{\partial s}(n_Z v_Z) = S_{Z-1} n_{Z-1} - (S_Z + R_Z) n_Z + R_{Z+1} n_{Z+1} + d_Z \; ; \qquad (1)$$

$$\rho_Z\left(\frac{\partial v_Z}{\partial t} + \frac{\partial v_Z^2}{2\,\partial s}\right) + \frac{\partial p_Z}{\partial s} - n_Z Z e E - \rho_Z \frac{(v - v_Z)}{\tau_Z} - \alpha_Z n_Z \frac{\partial (kT_e)}{\partial s} - \beta_Z n_Z \frac{\partial (kT_i)}{\partial s}$$

$$= S_{Z-1} \rho_{Z-1} v_{Z-1} - (S_{Z-1} \rho_{Z-1} + R_{Z+1} \rho_{Z+1}) v_Z + R_{Z+1} \rho_{Z+1} v_{Z+1} - m_Z v_Z d_Z \; ;$$

$$\rho_Z = m_Z n_Z \, , \; p_Z = n_Z k T_Z \; ; \quad 1 \leq Z \leq Z_{max} \qquad (2)$$

S/n_e and R/n_e are the ionization and recombination rate coefficients, v_z is the impurity flow velocity and d_z is an externally prescribed impurity source, τ_z the Spitzer slowing-down time /3/. For the electron thermal force coefficient, following the derivation of Braginski /2/, we get $\alpha_z = 0.71\ Z^2$.

For the ion thermal force coefficient β_Z, the expression given by Chapman /4/ is used, the asymptotic value for heavy impurities being $\beta_Z = 2.65\ Z^2$. The numerical solution of the time-dependent equations is similar to that described in /5/. The rate coefficients are taken from Behringer /6/.

II. RESULTS

The hydrogen background plasma parameters are taken from a one-dimensional hydrodynamic two-fluid model /7/. Typical profiles as calculated for ASDEX, assuming a total loss power of 1 MW and a particle flux of $10^{22}\ s^{-1}$ into the scrape-off are shown in Fig.1. s is the coordinate along field lines from the midplane (s = 0) to the target plates (s = 15). Because of the strong recycling in the divertor chamber ($s \gtrsim 12$m), all parameters vary appreciably along field lines, and the flow outside the divertor is subsonic (Mach number $M_p \approx 0.2$).

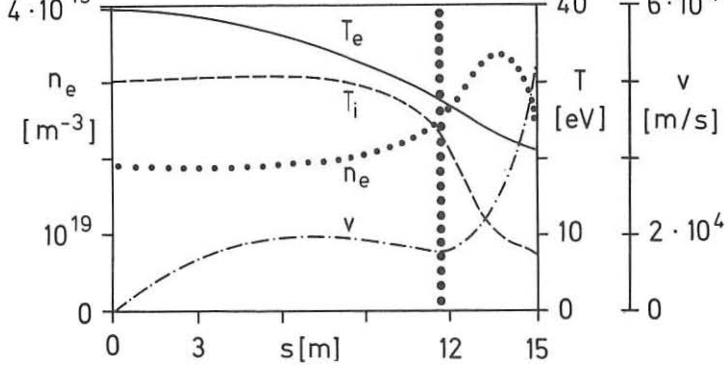

Fig. 1: Variation of the hydrogen plasma parameters along magnetic field lines for an ASDEX-type configuration.
(s=0: midplane; s=15m: target plate; $s \approx 12$m: divertor throat).

Assuming that neutral oxygen from the main chamber wall is ionized in the scrape-off near the equatorial plane (O II source around s=0) and that all oxygen ions arriving at the target plate are absorbed, we get the density and velocity profiles for individual charge states shown in Fig. 2 (left-hand side). Oxygen is quickly ionized to intermediate charge states and swept towards the divertor by the frictional drag force. Near the divertor entrance, however, the ion temperature gradient is high, while the hydrogen velocity is still low. Here, the thermal forces, directed towards high temperature, become dominant and the impurity density builds up until the resulting pressure gradient is high enough to overcome the thermal force barrier. The velocity profiles also show clearly the retardation at the divertor entrance. At the target plate, the oxygen ions arrive at nearly hydrogen sound speed and their total kinetic energy including the gain in the electrostatic Debye layer is around 600 eV with obvious consequences for the sputtering of target material.

If the thermal forces are neglected ($\alpha_Z = \beta_Z = 0$), the pronounced density peak near the divertor throat disappears and the velocity of the most prominent charge states (> III) are close to the background velocity everywhere (Fig. 2, right-hand side).

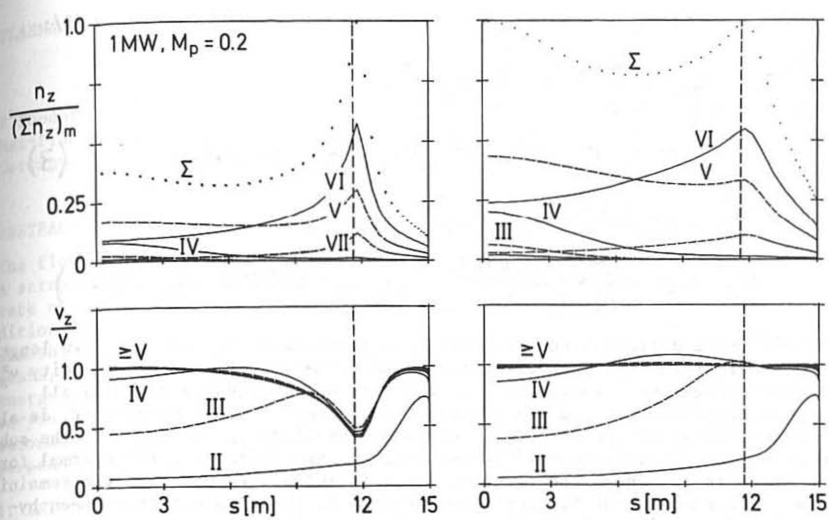

Fig. 2: Normalized density and velocity profiles for individual oxygen charge states along magnetic field lines with (left) and without (right) thermal forces. The total density is denoted by Σ.

Results for the same hydrogen plasma but other impurities (e.g. Fe, C, He) show a qualitatively similar behaviour. Because of the Z^2 dependence of the collision frequency, the accumulation peak near the divertor entrance increases sharply with Z. Changing the hydrogen background, the most important feature is that thermal forces become the more important, the lower the local Mach number is. For very low Mach number even impurity accumulation near the midplane is observed, resulting in a serious deterioration of the impurity pumping. Self-sputtering of target material was studied for iron, showing the importance of the frictional drag in addition to the electrostatic energy gain. The threshold for the onset of a self-sputtering avalanche is not a simple function of the plasma temperature at the target.

DISCUSSION

In the collisional regime, the most significant effect with respect to the impurity flow parallel to the field lines is the occurence of thermal forces. Since these are directed towards the hot central plasma, they may strongly affect the impurity removal. Considering only the collisional momentum transfer between impurities and hydrogen ions (i.e. the frictional drag and the ion thermal force), a simple criterion for impurity flow reversal is obtained: the thermal force dominates, if the local Mach number M becomes smaller than the ratio of the ion mean free path λ_i to the temperature gradient length λ_T, i.e. $M < \lambda_i/\lambda_T$. This criterion agrees roughly with the onset of density accumulation in the numerical calculations.

A simple but more complete formulation is obtained, if the inertia terms in eqs. (1) and (2) are neglected, as might frequently be justified in the subsonic region. A diffusion-drift equation is then obtained of the same form as used for empirical perpendicular transport in the central plasma /5/:

$$\frac{\partial n_z}{\partial t}-\frac{\partial}{\partial s}\left(D_z^*\frac{\partial n_z}{\partial s}\right)+\frac{\partial}{\partial s}\left(n_z v_z^*\right)$$
$$=S_{z-1}n_{z-1}-(S_z+R_z)n_z+R_{z+1}n_{z+1}+d_z \qquad (3)$$
$$D_z^*=\tau_z kT_z/m_z=\lambda_z^2/(2\tau_z)$$
$$v_z^*=v-\frac{\tau_z}{m_z}\left(\frac{\partial(kT_z)}{\partial s}-ZeE-\alpha_z\frac{\partial(kT_e)}{\partial s}-\beta_z\frac{\partial(kT_i)}{\partial s}\right)$$

The effective diffusion coefficient D_z^* is governed by the slowing down length λ_z at thermal energy. The difference between the effective drift velocity v_z^* and the background velocity v, i.e. the slip velocity (v_z^*-v) contains all temperature gradients and the electric field, which, to leading order, is also proportional to the electron temperature gradient ($p_e \approx$ const. in the subsonic region /7/). The coefficients, however, are different. The thermal forces scale as Z^2, while the electric field is multiplied by Z and the remaining term is independent of Z. Therefore, at high Z, the slip motion between hydrogen and impurities is dominated by the thermal forces, especially by the ion part. Then, setting $v_z^* \lesssim 0$, we get again the simple criterion for flow reversal mentioned above.

In the collisional regime, where our model is applicable, $\lambda_i/\lambda_T \ll 1$, holds. Therefore, at high Mach number ($M \approx 1$), the impurities are efficiently swept onto the target plates together with the hydrogen. Thermal forces become important, however, for the subsonic flow to be expected in the high recycling regime of future experiments.

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