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Collisional transport and poloidal asymmetry distribution of impurities in tokamak plasmas, with application to WEST

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The use of metallic walls as plasma facing components in tokamaks puts severe constraints on the control of impurity contamination. Heavy impurities like Tungsten are of particular concern due to the high level of radiative losses they can induce. Moreover, their high sensitivity to neoclassical transport mechanisms exacerbated by toroidal rotation or electrostatic potential asymmetry generally explains experimental cases of strong accumulation in the plasma core. The poloidal distribution of the impurity modulates the amplitude of this neoclassical transport [Angioni14], with an asymmetry that often leads to enhancement, but that can also result in a reduction of the flux [Helander98].

We report in this contribution on the development of an analytic model for a self-consistent determination of the poloidal asymmetry, collisional flux and steady state profile of heavy impurities [Maget20], with application to Tungsten transport in the WEST tokamak. The model is compared with nonlinear axisymmetric simulations with the XTOR code [Lütjens10,Ahn17,Maget20], and with computations using the drift-kinetic code NEO [Belli08]. Three main mechanisms drive the poloidal asymmetry of the impurity: centrifugal forces, electrostatic potential asymmetry and collisional friction with the main ion. In a geometrical formulation of this problem, the horizontal and vertical asymmetry parameters of the impurity density (n_a) move along a circle, with a centre and radius determined from the ion density and temperature gradients, and the angular position given by collisionality.

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In figure 1, the horizontal (δ) and vertical (Δ) asymmetry parameters, with $\eta_i = \partial_r \ln T_i/\partial_r \ln N_i$ the poloidal angle, are plotted at a given radial position for a flat and a peaked ion temperature profile when increasing the friction with the main ions ($\delta = [n_a^{\theta=0} - n_a^{\theta=\pi}]/[n_a^{\theta=0} + n_a^{\theta=\pi}]$, with $\Delta = [n_a^{\theta=\pi/2} - n_a^{\theta=-\pi/2}]/[n_a^{\theta=\pi/2} + n_a^{\theta=-\pi/2}]$).

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The impurity flux is reduced by the growing negative horizontal asymmetry that originates from collisional friction with the main ion when the ion density profile is peaked (fig.2, right plots). A similar reduction also arises for a flat ion density case with the formation of a positive horizontal asymmetry. Simulations with XTOR, where the impurity behaviour is described via density and parallel momentum equations, confirm these results via an artificial collisionality scan, as shown in figure 3.

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It can be shown that in the absence of toroidal rotation or anisotropic electrostatic potential, the steady state impurity distribution is however symmetric, so that the reduction of the flux affects the impurity profile in a transient way. Nonlinear simulations also reproduce the theoretical trajectory of the poloidal asymmetry during the evolution to steady state.

The analytical model also covers the effect of the electrostatic potential asymmetry, and allows computing the effect of a minority species with an anisotropic temperature, as driven during Ion Cyclotron Resonance Heating. If we isolate the effect of temperature anisotropy (disregarding ion temperature heating), we find, in agreement with NEO computations, that Tungsten is pushed toward the plasma core as the horizontal asymmetry is becoming negative, except in a narrow window where θ is just above unity (fig. 4). This indicates that, in the absence of toroidal rotation, ion temperature heating has to compensate (via the increase of ion temperature screening effect) for a tendency to Tungsten accumulation.

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