Modeling of impurity distribution and radial transport in the H-mode edge plasma

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Possible impurity accumulation is one of the crucial problems for the H-mode operation of future fusion plant. The impurity flows at the plasma edge determine the pedestal impurity density and therefore determine impurity level in the core. Here an analytical model describing the poloidal distribution of impurities and their radial fluxes is presented for high density H-mode pedestal. The discrepancies with the neoclassical predictions are emphasized. The results of the B2SOLPS5.2 [1] modeling in the ASDEX-Upgrade and Globus-M geometries with account of impurities are compared with the analytical model.

The proof of principle modeling of the impurity flows in the case of non-zero electron conductivity associated with resonant magnetic perturbations (RMPs) is also discussed.

1. Analytical model

To understand qualitatively the behavior of the impurity let us discuss the test (Z_{eff} − 1<<1) highly ionized impurity Z_a >>1 in the tokamak with $\varepsilon = r/R << 1$, circular cross section and without Shafranov shift. The toroidal coordinate system (r, θ, ϕ) is used. First, let us consider the main contributions to parallel momentum balance for impurities

$$-b_\theta\ \partial(n_a T_i)/r\partial\theta - b_\theta n_a e Z_a\ \partial\varphi/r\partial\theta + \nu_a n_a m_a (V_\parallel - V_{\parallel a}) + \alpha b_\theta n_a Z_a^2\ \partial T_i/r\partial\theta = 0 \qquad (1)$$

Pressure gradient, electrostatic force, main ion-impurity friction and thermal force with coefficient $\alpha \geq 1$ are taken into account while inertia is neglected, $b_\theta = B_\theta / B$. The term $\partial\varphi/\partial\theta$ can be found using the parallel momentum balance for electrons and the condition $\partial n_i (T_e + T_i)/\partial\theta \approx 0$. Then $V_{\parallel a}$ can be expressed using Eq. (1). Substituting this velocity into the continuity equation for impurities, where the radial fluxes are neglected, we have:

$$\frac{\partial}{\partial\theta} R\left[b_\theta n_a \left(V_\parallel - \frac{b_\theta D}{n_a}\frac{\partial n_a}{r\partial\theta} + \frac{b_\theta D^T}{T_i}(1+\beta)\frac{\partial T_i}{r\partial\theta}\right) + n_a V_\theta^E + n_a V_{a\theta}^{dia}\right] = 0 \qquad (2)$$

with $R = R_0 + r\cos\theta$, $D = T_i/(\nu_a m_a)$, $D^T = \alpha Z_a^2 T_i/(\nu_a m_a)$, $\beta = \left[Z_a T_e/(T_e + T_i) - 1\right]/(\alpha Z_a^2) \leq 1$. The parallel velocity $V_\parallel$ of the main ions is determined by neoclassical effects [2]: $b_\theta V_\parallel + V_\theta^E = -V_\theta^{dia} - (k^T - 1)R_0/(eB_0 R)\partial T_i/\partial r$, the subscript 0 denotes average values at the flux surface. This expression can be substituted into Eq.(2), and the impurity density can be sought as $n_a = n_0(r) + n_1(r)\cos\theta + n_2(r)\sin\theta$ assuming $n_0 >> n_1, n_2$, $T_i = T_{i0} - \delta T_i \sin\theta$,

$\delta T_i << T_{i0}$. The linearization of Eq.(2) gives:

$$n_1 = n_0\left[\alpha Z_a^2(1+\beta)\delta T_i / T_i - 2(A+C)\varepsilon\right]A/(1+A^2)\,,\; n_2 = -n_1 / A \tag{3}$$

with the parameters

$$A = \frac{r}{b_\theta^2 D}(V_{a\theta 0}^{dia} - V_{\theta 0}^{dia} - (k^T - 1)\frac{1}{eB_0}\frac{\partial T_i}{\partial r}), \qquad C = \frac{r}{b_\theta^2 D}(k^T - 1)\frac{1}{eB_0}\frac{\partial T_i}{\partial r}. \tag{4}$$

If $A >> 1$ then the density maximum is situated at the inner or outer midplane [3], if $A << 1$ – at the top or the bottom of the flux surface. The radial flow of the impurity can be obtained from the toroidal momentum balance. The other way is to use the diamagnetic and $\vec{E}\times\vec{B}$ drifts defined from the poloidal force balance, and it gives the same result:

$$\Gamma_r = -T_i /(Z_a eBR)\left[n_2 + \alpha\beta Z_a^2(n_0 + 0.5 n_1 / \varepsilon)\delta T_i / T_i\right].$$

Let us discuss two limiting cases: i) $A << 1$ and therefore $n_2 \sim n_0 A\varepsilon,\; n_1 << n_2$. Then

$$\Gamma_r \approx \left(\alpha Z_a^2 \delta T_i / T_i - 2(A+C)\varepsilon\right) n_0 T_i /(Z_a eBR) \tag{5}$$

This expression can be transformed to the neoclassical one [4]. By the order of magnitude $\Gamma_r \sim \Gamma^{\nabla B}\cdot A\cdot\varepsilon$ (here $\Gamma^{\nabla B} = n_0 T_i /(Z_a eBR)$ is impurity ∇B drift flow). The contribution to Γ_r of the $\vec{E}\times\vec{B}$ drift is small comparing to the ∇B drift.

ii) $A >> 1$, then $n_1 \sim \varepsilon n_0,\, n_1 >> n_2$ and

$$\Gamma_r \approx \frac{n_0 T_i}{Z_a eBR}\left(\frac{\delta T_i}{T_i}\frac{\alpha(1+\beta)Z_a^2}{A^2} - 2\frac{A+C}{A^2}\varepsilon - \alpha^2\beta(1+\beta)\left(\frac{Z_a^2}{\varepsilon}\frac{\delta T_i}{T_i}\right)^2\frac{\varepsilon}{2A} + \alpha\beta Z_a^2\frac{\delta T_i}{T_i}\frac{C}{A}\right) \tag{6}$$

The first two terms in the sum in the parentheses are mostly responsible for the transport of the impurity by the ∇B drift, while the electric drift corresponds to the third and fourth terms. The first two terms are of the order of $\Gamma^{\nabla B}\cdot\varepsilon / A$ while in case of the Pfirsch-Schlueter regime $\delta T_i / T_i \sim A\varepsilon / Z_a^2$ and the third and fourth terms are of the order of $\Gamma^{\nabla B}\cdot\varepsilon A / Z_a$. Increasing the value $A > \sqrt{Z_a}$ we come to the situation when the contribution of the $\vec{E}\times\vec{B}$ drift into the radial transport of impurities is bigger than that of the ∇B drift, which is not typical for standard neoclassical solution.

In the case of radial conductivity caused by RMPs two corrections are necessary:

i) the non-zero sin-like pressure perturbation for the main plasma component (ions plus electrons) $p = n_i(T_e + T_i) = p_0 - \delta p \sin\theta$ should be taken into account in the calculation of the potential poloidal perturbation. It gives rise to modification of the parameter β. The new coefficient is $\beta_1 = 1/(\alpha Z_a^2)\left[(1 - (\delta p / p)/(\delta T_i / T_i + T_e))Z_a T_e /(T_e + T_i) - 1\right]$. For A >> 1 the $\vec{E}\times\vec{B}$ drift in the radial flows should decrease due to RMPs, Eq. (6). The δp estimate through the RMP pump-out flow [5] is $\delta p \approx eBR\Gamma^{pump-out} \leq \delta T_i \; n_i T_i B_\theta^2 /(m_i r^2 \nu_i^2)$ in the Pfirsch-Schlueter regime.

ii) The poloidal rotation of the main ions deviates from the neoclassical value in the presence of RMPs. As a result the term $-(k^T - 1)/(eB_0)(\partial T_i / \partial r)$ representing the neoclassical poloidal velocity in Eq.(4) changes to the equilibrium poloidal velocity for RMPs [6]. For $A >> 1$, A decreases due to RMPs and the radial flows associated with the electric drift decrease as well.

Since the sum $A+C$ does not change with the onset of RMPs, for $A<<1$ both the density perturbation and the impurity radial flow do not change. The changes in this case can be only associated with the pump-out and consequent density gradient decrease of the main ions, which enters the $A+C$ term.

Modeling

The modeling was done for AUG with carbon impurity in the geometry of shot #17151.The parameter A was increased by rising the main ion density and corresponding decreasing of temperatures and toroidal velocities. The density, ion temperature, and C^{6+} profiles at the outer midplane are shown in Fig.1a-c. The Mach number at the inner boundary of the computational domain is 0.2 for all calculations. The values of parameter A for C^{6+} in the pedestal 2 *cm* from the separatrix at the outer midplane are 0.2, 1.5, 17 for the small, intermediate and big density of deuterium. The radial profiles of the flow components of C^{6+} ions through the flux surface are shown in Fig.2a-c. For low deuterium density the dominant in the pedestal is ∇B -drift induced flow directed outwards, Eq.(5), while for big density the $\vec{E} \times \vec{B}$ drift induced flow directed inwards gives the main contribution, Eq.(6). Radial profiles of the fluxes for the calculation with radial conductivity due to RMPs are presented in Fig.2d. The conductivity level is chosen big, so that the radial electric field changes the direction. The radial $\vec{E} \times \vec{B}$ drift induced flow in the region with RMPs is significantly decreased, in agreement with the analytical model. Still, the detailed analysis of the C^{6+} particle balance in modeling shows that the divergence of the radial diffusive flow is significant in the barrier region and therefore the analytical model can be inaccurate. The other effect which can improve the model is the inclusion of centrifugal force, leading to accumulation of both main ions and impurities at the outer midplane[7]. In the modeling the parallel momentum balance shows that this effect is not big. Still, for big toroidal velocities it can change the radial impurity flows. The modeling was also performed for spherical tokamak Globus-M shot #34439 with the central density $3.7 \cdot 10^{19}$ m^{-3} and temperature 490 eV, plasma current 114 kA. For such parameters the convective radial transport deviates from neoclassical one, Fig. 2e.

Conclusions. The modeling and analytical consideration show the significant deviations of the impurity transport from the neoclassical model in the H-mode and pedestal of high density discharges. The $\vec{E}\times\vec{B}$ radial drift in combination with inner-outer midplane asymmetry of the impurity gives significant impurity inward radial flow. At the same time the neoclassical contribution associated with ∇B flow is decreased due to the smoothening of the impurity top-bottom density asymmetry by the poloidal rotation.

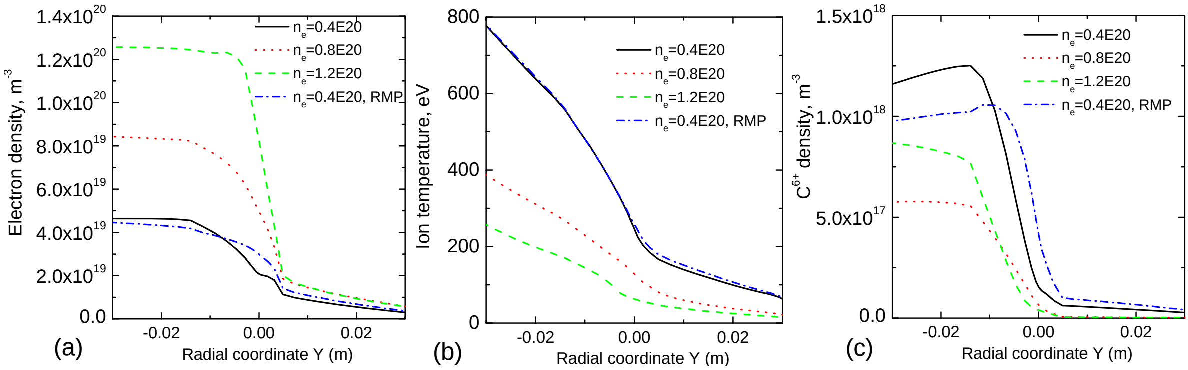

Fig.1. Radial profiles at the outer midplane (a) electron density, (b) ion temperature, (c) carbon ion density

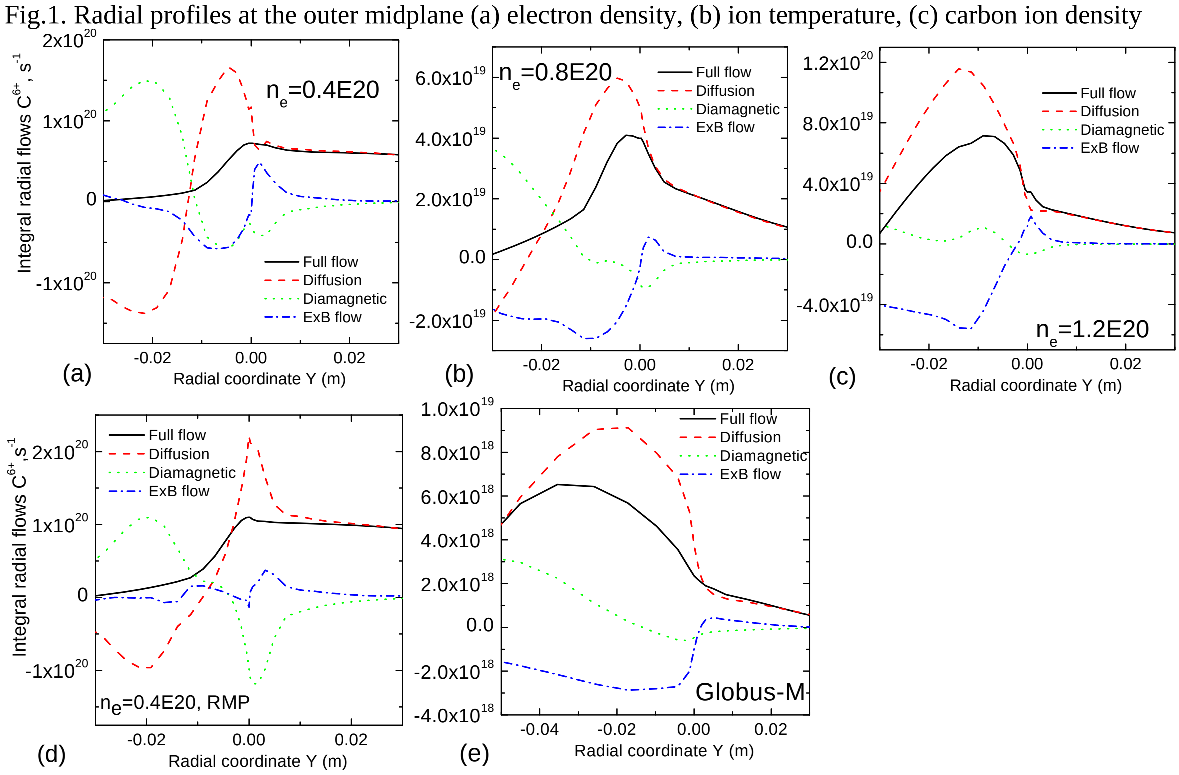

Fig. 2. Radial flows of carbon ions through the flux surface

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