"Shell" model for impurity spreading from intense localized source

M. Koltunov and M.Z. Tokar

Institute for Energy and Climate Research – Plasma Physics, Research Center Jülich, Association EURATOM-FZJ, Trilateral Euregio Cluster, Germany

Introduction. Non-hydrogen impurities are unavoidably present as neutral and charged particles in plasmas of fusion devices. Under some conditions plasma facing components can be excessively demolished by hot plasma particles. In addition, impurities are deliberately introduced into fusion plasmas for various purposes, e.g., to measure plasma parameters, to redistribute the power coming from the plasma core with radiation over a larger area and reduce the heat loads onto divertor target plates, to soften consequences of discharge disruptions, etc. In these situations impurity particles are spreading, both along and across the magnetic field, from very localized sources and are involved in diverse physical processes, such as coulomb collisions with background particles, ionization, acceleration by electric fields generated in the presence of impurity itself. These processes may affect noticeably both impurity penetration process and global plasma behavior.

Basic equations. Self-consistent description of impurity spreading process and electron density response is based on the fluid equations for transfer of particles, momentum and energy for various ion species with quasy-neutrality and Coulomb collisions taken into account [1]. In the framework of the "shell model" [2] we consider spreading of impurity as a set of nested shells and approximate solutions in each shell by the set of analytical functions. In the current paper this approach is developed further to describe the radial structure of the impurity shells [3].

The evolution of the density of impurity ions, n_Z, of the charge Z is described by the particle continuity equation:

$$\partial_t n_Z - \frac{1}{r}\partial_r \left(rD_r\partial_r n_Z\right) - \partial_y \left(D_y\partial_y n_Z\right) + \partial_l \Gamma_Z = \nu^i_{Z-1} n_{Z-1} - \left(\nu^i_Z + \nu^r_Z\right) n_Z + \nu^r_{Z+1} n_{Z+1} \qquad (1)$$

where $\nu^i_Z \equiv k^Z_{ion} n_e$ and $\nu^r_Z \equiv k^Z_{rec} n_e$ are the ionization and recombination frequencies of impurity particles with k^Z_{ion} and k^Z_{rec} being the corresponding rate coefficients and the electron density n_e computed according to the plasma quasi-neutrality condition; $D_{y,r}$ are poloidal and radial components of diffusivity; Γ_Z is the density of the impurity ion flux component parallel to the magnetic field and it is determined by the momentum balance equation. In shell of Z-ions the spatial variation of the density is approximated by a parabolic profile with the maximum n_{Zs} in the source region of the width δ_{Z-1} and length l_{Z-1} and exponential decay with the decay width δ_{Zd} and length l_{Zd} out of the source.

Consider three regions of the (y,l)-surface: the total surface $0 \leq (|y|,|l|)$, y-region $\delta_{Z-1} \leq |y|, 0 \leq |l|$ and the l-region $0 \leq |y|, l_{Z-1} \leq |l|$. For the total numbers of Z-ions per unit length in r-direction in these regions we get $N_Z(t,r) = n_{Zs}\Delta_Z L_Z$, $N_{Zy}(t,r) = n_{Zs}\Delta_{Zd} L_Z$ and $N_{Zl}(t,r) = n_{Zs}\Delta_Z L_{Zd}$, respectively, where $\Delta_Z = \Delta_{Zs} + \Delta_{Zd}$, $L_Z = L_{Zs} + L_{Zd}$, with $\Delta_{Zs} = \delta_{Z-1}\frac{\delta_{Z-1}/3+\delta_{Zd}}{\delta_{Z-1}/2+\delta_{Zd}}$, $\Delta_{Zd} = \frac{\delta_{Zd}^2}{\delta_{Z-1}/2+\delta_{Zd}}$, $L_{Zs} = l_{Z-1}\frac{l_{Z-1}/3+l_{Zd}}{l_{Z-1}/2+l_{Zd}}$, $L_{Zd} = \frac{l_{Zd}^2}{l_{Z-1}/2+l_{Zd}}$ By using the definitions of N_Z, N_{Zy} and N_{Zl}, one can find the following relations for the characteristic dimensions of the shell cross-sections by magnetic surfaces: $\delta_{Zd} = \delta_{Z-1}\frac{1+\sqrt{\left(4N_Z/N_{Zy}-1\right)/3}}{2\left(N_Z/N_{Zy}-1\right)}$, $l_{Zd} = l_{Z-1}\frac{1+\sqrt{(4N_Z/N_{Zl}-1)/3}}{2(N_Z/N_{Zl}-1)}$.

In the Z-shell the Z-ions are produced mainly by ionization of the $Z-1$-ones. Total amount of these species per unit length in r-direction, $N_Z(t,r)$, is governed by equation obtained by integration of equation 1 over the magnetic surface without the term at ν_{Z+1}^r:

$$\partial_t N_Z - \partial_r\left[rD_r\partial_r\left(N_Z/r\right)\right] = \nu_{Z-1}^i N_{Z-1} - (\nu_Z^i + \nu_Z^r)N_Z \tag{2}$$

The Z-ions arising by the recombination of the $Z+1$-ones are distributed over the whole $Z+1$-shell and their amount per unit length in r-direction $N_Z^r(t,r)$ is governed by:

$$\partial_t N_Z^r - \partial_r\left[rD_r\partial_r\left(N_Z^r/r\right)\right] = \nu_{Z+1}^r N_{Z+1} - (\nu_Z^i + \nu_Z^r)N_Z^r \tag{3}$$

$N_Z^r \ll N_Z$ for the electron temperatures over several eV. Integration over y- and z-regions gives one-dimensional equations for N_{Zy} and N_{Zl}:

$$\partial_t N_{Zy} - \partial_r\left[rD_r\partial_r\left(N_{Zy}/r\right)\right] = \frac{D_y N_Z}{\left(\delta_{Z-1}/2+\delta_{Zd}\right)\Delta_Z} - \left(\nu_Z^i + \nu_Z^r\right)N_{Zy} \tag{4}$$

$$\partial_t N_{Zl} - \partial_r\left[rD_r\partial_r\left(N_{Zl}/r\right)\right] = \frac{G_Z}{\left(l_{Z-1}/2+l_{Zd}\right)m_Z} - \left(\nu_Z^i + \nu_Z^r\right)N_{Zl} \tag{5}$$

where $G_Z(t,r)$ is the total parallel momentum of Z-ions per unit length in the r-direction which is obtained from the integration of the momentum transfer equation over the area $0 \leq (|y|,|l|)$. Similarly, heat transfer equation is reduced to one-dimensional equation for the averaged ion temperatures in Z-shells.

Boundary conditions to equations (2-5) follow from the requirement of zero derivatives on the plasma axis, $r=0$: $\partial_r N_Z = \partial_r N_Z^r = \partial_r N_{Zy} = \partial_r N_{Zl} = \partial_r G_Z = 0$ and prescribed decay lengths, $\delta_{n,\Gamma,T}$ at the last closed flux surface (LCFS), $r=a$: $\partial_r N_Z = -N_Z/\delta_n$, $\partial_r N_Z^r = -N_Z^r/\delta_n$, $\partial_r N_{Zy} = -N_{Zy}/\delta_n$, $\partial_r N_{Zl} = -N_{Zl}/\delta_n$, $\partial_r G_Z = -G_Z/\delta_\Gamma$.

Solution of the total system of reduced equations together with relations for characteristic dimensions is needed for low enough charge states whose shell cross-sections by the magnetic surface are significantly smaller than the whole surface, i.e. $\delta_Z l_Z < \pi^2 rR$ with R being the surface major radius. If this condition is not satisfied the impurity charge state in question is distributed homogeneously on the surface.

Results of calculations. As an example of applications we show here the results of calculations done for the conditions of experiments with carbon impurity penetration in a relatively cold edge of Ohmic plasma of the tokamak TEXTOR and of argon injection in hot H-mode plasma of tokamak JET.

Minor and major radii of the tokamak TEXTOR are $a = 0.46$ m and $R = 1.75$ m. Into the plasma carbon atoms are injected with the temperature of 0.8 eV. In the injection cross-section of 0.015 m x 0.015 m the neutral density $n_0 = 2 \cdot 10^{19}$ m^{-3} is maintained constant at the LCFS, $r = a$. This density level corresponds to the influx of carbons of $5 \cdot 10^{19}$ s^{-1} that is below a level of 10^{20} s^{-1} where the local plasma cooling start to play a role and leads to a noticeable reduction of the electron temperature [2]. Calculations show that ions with $Z = 1, 2$ are always localized near the source. The *Li*-like ions C^{3+} are localized in the close vicinity of the LCFS but spread over the surfaces a certain time after the injection initiation and sufficiently deep in the plasma. For all considered ions their temperatures, T_Z, are saturated at the levels significantly smaller than the temperature of the main ions, T_i, because, as it was already demonstrated in [2], the life time of the impurity ions in question till their ionization is smaller than that of the temperature equilibration.

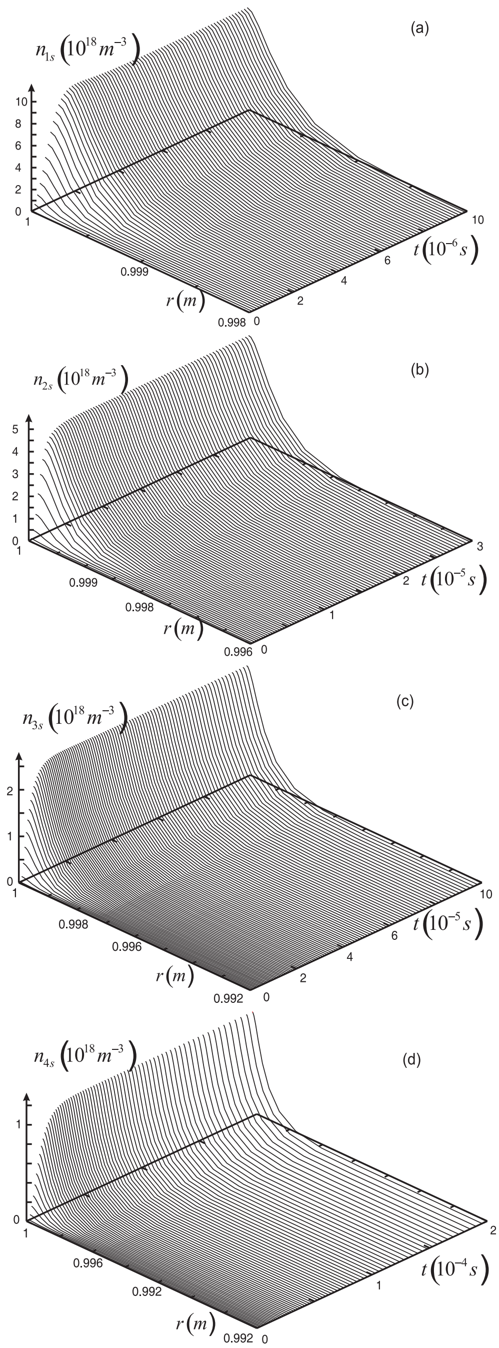

Figure 1: *Time evolution of the radial profiles of the maximum densities for argon ions of different charges: 1+ (a), 2+ (b), 3+ (c) and 4+ (d).*

Major and minor radii of the tokamak JET are $R = 3$ m and $a = 1$ m. Into the plasma argon atoms are injected with a thermal velocity at the room temperature, 250 ms^{-1}; their density at the injection outlet of width ≈ 0.03 m is $n_0(t, a) = 10^{20}$ m^{-3}. According to estimates in [2], this density is still low enough to guarantee weak perturbations in temperatures of the main plasma components for the conditions in question. The diffusivity of impurity ions is $[0.1 + 0.9 (r/a)^2]$ $m^2 s^{-1}$ in the core and 0.1 $m^2 s^{-1}$ in the external transport barrier with the width of 0.03 m. Figure 1 represents the time evolution of the radial profiles of the maximum densities, n_{Zs}. In the shells of ions with $Z = 1,2$ the impurity ion density is comparable with the n_e level before injection, thus the electron density is considerably disturbed by the impurity injection close to the injection outlet. Due to the high temperature of the main ions the heat exchange with the impurity ones through coulomb collisions is inefficient. Therefore, $T_Z \ll T_i$ for low charged impurity ions in question.

Impurity ion density profiles, $n_Z(t,r,y,l)$, reconstructed from calculated characteristic parameters of the shells, determine the radiation densities $w_Z = n_Z n_e F_Z$ with the latter multiplier being the cooling rates dependent on the electron temperature $T_e(r)$. Integration over the volume gives the density of the radiative flux coming from the impurity cloud through the LCFS in the vicinity of the neutral source:

$$q_{\text{rad}}(t) = \frac{1}{\pi}\sum_{Z=0}^{Z_{max}}\int_{r=0}^{a}\int_{l=0}^{\pi R}\int_{y=0}^{\pi a}\frac{(a-r)w_Z}{[(a-r)^2+y^2+l^2]^{3/2}}dydldr \qquad (6)$$

Figure 2 represents the time evolution of q_{rad} from carbon and argon species calculated for the plasma and injection conditions of discussed above. Under conditions in question the contribution to the total incident radiation flux decreases for the higher charge states, because they spread over larger distances.

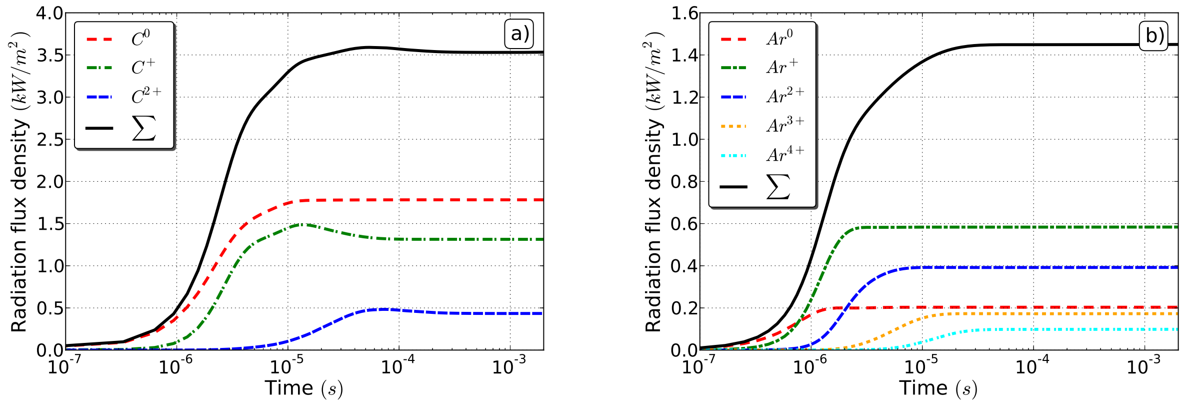

Figure 2: *Incident radiation flux density from a) carbon and b) argon species through the LCFS in the vicinity of the neutral source.*

References

[1] S.I. Braginskii *Reviews of plasma physics* (New York: Consultants Bureau) **1**, 205 (1965)

[2] M. Koltunov and M.Z. Tokar *Plasma Phys. Control. Fusion* **54**, 025003 (2012)

[3] M.Z. Tokar and M. Koltunov *Phys. Plasmas* **19** 042502 (2012)