Transport of deuterium-tritium neutrals in ITER divertor plasma

M.Z. Tokar, V. Kotov

Institut für Energie- und Klimaforschung - Plasmaphysik, Forschungszentrum Jülich,
Association EURATOM-FZJ, Trilateral Euregio Cluster, Germany

Introduction. In future fusion reactors, e.g. ITER [1], the plasma in the confined region and scrape-off layer (SOL) and the neutral gas in the divertor will be mixed of particles of two hydrogen isotopes, deuterium and tritium. Tritium is radioactive and its outflow to divertor target plates, amounts of particles both retained in the castellated structures of targets and exhausted by pumps, have to be kept as low as possible. As it was demonstrated in Ref.[2] such an adjustment of the isotope composition can be achieved by tuning the plasma fuelling with gas puffing and pellet injection. One of the quantities, being of importance for the analysis in Ref. [2], is the transparency of the SOL plasma for neutrals. This is defined as the probability of a neutral particle recycling from the divertor target plate to escape without ionization into the private flux region and to be pumped out. The transparencies, assumed in Ref. [2] identical for deuterium and tritium neutrals, may be dependent on the isotope kind, the isotope composition of the SOL plasma, the densities and temperatures of the plasma components. A difference in the SOL transparencies for deuterium and tritium neutrals would affect global particle balances.

Diffusion approximation. To calculate the transparencies of the divertor plasma for atoms of deuterium and tritium, whose transport is interrelated through the cross-charge-exchange with tritons and deuterons, respectively, we apply a diffusion approximation, see, e.g., [3]. This presumes that the mean free path of atoms in the plasma, determined mostly by charge-exchange interactions, is significantly smaller than the whole distance that a neutral passes before ionization. Such an approximation is appropriate for the conditions expected in the divertor of a fusion reactor where the plasma temperature should be of the order of or below the hydrogen ionization energy and, therefore, the charge-exchange rate will significantly exceed that for the ionization.

In the SOL plasma near a target plate of a poloidal divertor, Fig.1, there are several sources of deuterium and tritium neutrals: recombination of ions and electrons on the target surface and recycling of generated neutral particles into the SOL plasma, recombination of charged components within the plasma volume, refuelling through the interface with the private flux region where a residual neutral gas is present due to limited pumping rate, cross-charge-exchange of deuterium and tritium ions and atoms. The latter process interrelates transport of neutrals of different isotopes. Henceforth we distinguish these by the index l corresponding to their atomic weights, i.e. $l = 2$ stays for deuterium and $l = 3$ - for tritium particles, respectively. The densities of atoms are denoted as n_l and those of ions - as n_l^+; due to quasi-neutrality the electron density $n_e \approx n_2^+ + n_3^+$ [4]. For typical plasma conditions anticipated in the ITER divertor the mean free path length of very slow neutral molecules before disintegration through ionization, dissociation and charge-exchange is much smaller than the SOL width. Therefore we assume that neutral components are consisting of atoms only. After charge-exchange these atoms acquire the temperatures of ions; owing to coulomb collisions, being very frequent in cold and dense divertor plasma [4], deuterons, tritons and electrons have very close temperatures and we use therefore the single plasma temperature T for all components.

The stationary density n_l of neutral atoms of the isotope l is governed by a continuity equation,

$\nabla \cdot \mathbf{j}_l = -\nu_l n_l + S_l$,

where $\mathbf{j}_l$ is the density of the atom flux, $\nu_l = k_{ion} n_e + k_{cx}^* n_m^+$ is the frequency for the disappearance of atoms due to ionization by electrons and cross-charge-exchange with the ions of another isotope $m = 5 - l$, with the rate coefficients k_{ion} and k_{cx}^*, correspondingly; $S_l = (k_{cx}^* n_m + k_{rec} n_e)\, n_l^+$ is the density of the atom source due to cross-charge-exchange of the ions of the isotope in question with the atoms of another one and the volume recombination with the rate coefficient k_{rec}. The processes of ionization and charge-exchange result in the loss of the momentum of atoms described by the equation of motion,

$\nabla P_l = -m_l \left(\nu_l + k_{cx}^l n_l^+\right) \mathbf{j}_l$,

where $P_l = n_l T$ is the atom pressure, m_l the isotope mass and k_{cx}^l the rate coefficient for the charge-exchange between atoms and ions of the same isotope l. Since charge-exchange collisions tangle trajectories of atoms, their mass velocity is significantly smaller than the thermal one and the inertia term is neglected. Moreover, the average mass velocity of ions is predominantly aligned in the toroidal direction z perpendicular to the (x, y)-plane. Therefore, its projection on this plane is small compared with the velocity

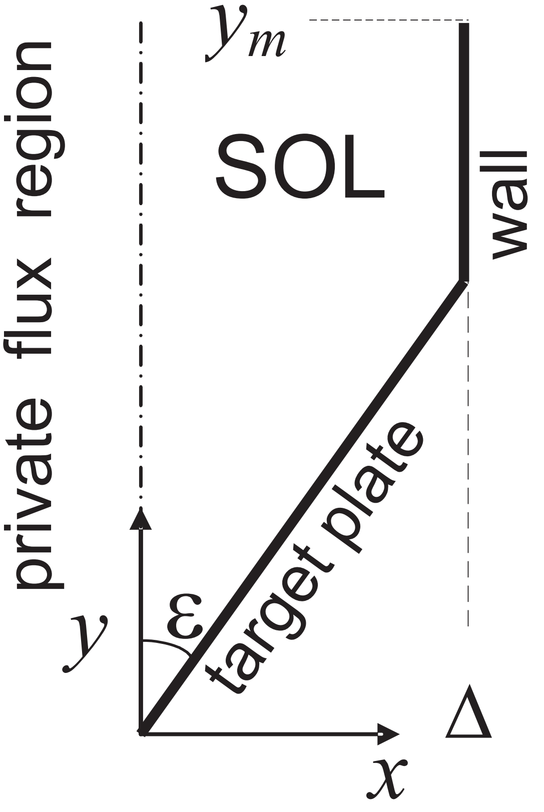

Figure 1: The poloidal cross-section of the divertor region in a tokamak.

of neutrals and is omitted in the friction force between atoms and ions. By combining continuity and motion equations one gets diffusion like equations for the neutral pressures. Assuming toroidal symmetry, i.e. independence of all parameters on the coordinate z, these equations are written as follows:

$$-\partial_x \left(D_l \partial_x P_l\right) - \partial_y \left(D_l \partial_y P_l\right) = \left(k^*_{cx} P_m/T + k_{rec} n_e\right) n^+_l - \nu_l P_l/T \tag{1}$$

where $D_l = 1/m_l/\left(\nu_l + k^l_{cx} n^+_l\right)$.

Boundary conditions. Electrons and ions recombine at the divertor target plate and generated neutrals recycle back into the plasma. It is assumed that this influx is directed perpendicular to the target surface. Thus, $D_l \partial_x P_l = \Gamma_l \sin\varepsilon\cos\varepsilon$, $D_l \partial_y P_l = -\Gamma_l \sin^2\varepsilon$ at $y = x\cot\varepsilon$, with $\Gamma_l = n^+_l V_l \sin\psi$ being the projection of the ion flux density to the target surface on the poloidal direction y, V_l the ion velocity along the magnetic field and ψ the pitch angle between the field and toroidal direction. At the interface with the private flux region atoms escape from the SOL but return back into the plasma with a finite probability ω_l because the pumping rate is limited. In order to convert this into a boundary condition for the neutral pressure we separate all atoms into two fractions of particles moving from the plasma into the private region, and of those flying in the opposite direction. Denote the densities of these particle fractions as $n_{l\Rightarrow}$ and $n_{l\Leftarrow}$, respectively, and take into account that the averaged velocities of atoms in both groups are of the thermal velocity $U_l = \sqrt{T/m_l}$. For the total particle and flux densities we have $n_{l\Rightarrow} + n_{l\Leftarrow} = n_l = P_l/T$ and $\left(n_{l\Leftarrow} - n_{l\Rightarrow}\right) U_l = -D_l \partial_x P_l$. Thus the pumping constraint above, meaning that $n_{l\Leftarrow} = \omega_l n_{l\Rightarrow}$, results in $\partial_x P_l = \lambda_l P_l$, where $\lambda_l = \left(1-\omega_l\right) U_l / \left(1+\omega_l\right) / \left(T D_l\right)$, at $x = 0$. At the wall, $x = \Delta$, we assume a perfect recycling of neutral particles with zero net flux, i.e. $\partial_x P_l = 0$. Far enough from the target plate, $y = y_m$, atoms vanish due to ionization and $P_l = 0$. The transparencies of the SOL plasma for isotope atoms are characterized by the ratio δ_l of the outflow of atoms into the private flux region, $\int_0^{y_m} D_l \frac{\partial P_l}{\partial x}\left(x = 0, y\right) dy$, to the outflow of isotope ions to the target plate, $\int_0^{\Delta} \Gamma_l \left(y = x\cot\varepsilon\right) dx$.

Results of calculations. By calculating the transport of hydrogen isotope atoms in ITER divertor we use two-dimensional profiles of the plasma density and temperature near the outer divertor target. These were calculated in Ref. [4] with the code package SOLPS4.3 for two sets of the input power into the SOL, P_{SOL}, and the pressure of deuterium neutral gas in the private flux region, P_{PFR}: case 1568 with “attached” divertor - $P_{SOL} = 80\ MW$, $P_{PFR} = 2\ Pa$, and case 1639 with “detached” divertor - $P_{SOL} = 120\ MW$, $P_{PFR} = 13\ Pa$. The relative concentration of tritons in the plasma, $\xi_3 \equiv n^+_3/n_e$, is assumed to be constant in the divertor region and is a prescribed parameter.

At a low temperature near the target plates the velocities of deuterons and tritons have to be very close to each other due to strong friction induced by often coulomb collisions; therefore V_2 and V_3 are assumed to be equal to the common ion sound velocity $c_s \equiv \sqrt{2T/(\xi_2 m_2 + \xi_3 m_3)}$. The inclination angle $\varepsilon = 23.8^0$ of the target to the poloidal direction, the variation along the target of the pitch angle ψ of the magnetic field with respect to the toroidal direction, and the pumping efficiencies of atoms in the private flux region, $1 - \omega_{2,3} = 0.0072$, are taken from Ref.[4].

In Fig.2 plasma transparencies $\delta_{2,3}$ and their ratio are displayed as functions of the triton concentration near the target. One can see that δ_3 and δ_2 differ noticeably, by a factor down to 0.64. The absolute level of $\delta_{2,3}$ is significantly larger in the "detached" case than in the "attached" one, mostly due to much stronger source of neutrals induced by the recombination of electrons and ions in the plasma volume. The difference in the SOL transparencies for deuterium and tritium atoms has to be taken into account when searching for optimum plasma compositions in a reactor.

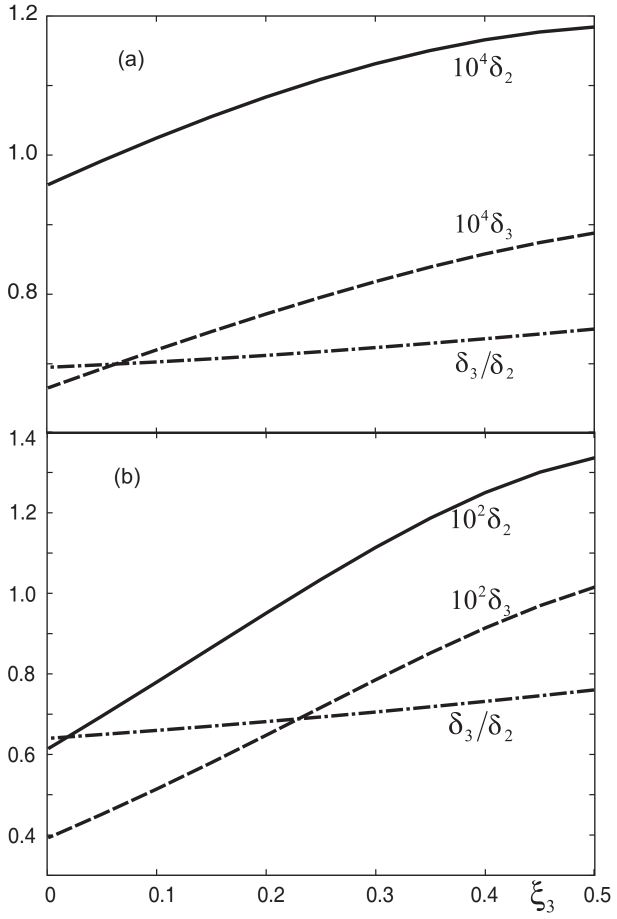

Figure 2: The dependences of the divertor plasma transparencies for deuterium and tritium atoms and of their ratio on the triton concentration computed for attached (a) and detached (b) conditions in the ITER divertor.

References

[1] A. Loarte *et al* , Nucl. Fusion **47**, S203 (2007)

[2] M. Z. Tokar and S. Moradi, Nucl. Fusion **51**, 063013 (2011)

[3] T. D. Rognlien *et al* , Contrib. Plasma Phys. **34**, 362 (1994)

[4] A. S. Kukushkin *et al* , Nucl. Fusion **49**, 075008 (2009)