Ballistic Model for Neutral Hydrogen Distribution in ITER Edge Plasma

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1. Introduction. A new simple ballistic model (BM) for determination of 2D neutral distribution in coordinate and velocity spaces as well the brightness of Balmer spectral lines at given distributions of electron and ion temperature profiles and electron density in the edge plasma is developed. The initial object of the theory is the ballistic flux of neutral hydrogen isotopes molecules arising at the wall and penetrating into the plasma with velocities determined by the wall temperature. Electron collisions result in molecular dissociation and ionization. The molecular ions dissociated in their term into neutral atoms and ions by direct and dissociation recombination. Three components of neutral ballistic fluxes moving both to the plasma and to the wall directions with typical energies 0.5, 3.0 and 4.3 eV are formed at a distance from the wall. A part of neutral flux disappears due to ionization and wall absorption. The second part results in the creation of a new flux due to the charge exchange (cx) on plasma ions with a temperature corresponding to the local one at the charge exchange point. The second flux of fast neutrals also disappears partly due to the charge exchange generating a new one and so on. The neutral reflection from the wall is also taken into account. So the total neutral density is the sum of the all neutral generations. Calculations demonstrate a fast convergence due to a decrease of neutral fluxes at every step of fluxes generation.

2. Molecules. According to BM the initial flux of neutral molecules decreases along their trajectories x due to ionization and dissociation processes:

$$N_{D_2}(v_{D_2}, x) = N_{D_2}(0)P(v_{D_2})\exp\left\{-\frac{1}{v_{D_2}}\int_0^x N_e(y)\big[\langle\sigma_i v_e\rangle + \langle\sigma_d v_e\rangle\big]dy\right\}, \qquad (1)$$

where $N_{D_2}(0), P(v_{D_2})$ are molecular number density and their velocity distribution function (VDF) being the Maxwellian one with the wall temperature; the variables in the exponent are ionization and dissociation rates, $N_e(y)$ is the electron density. The ionized molecular density is determined by the local balance between ionization and dissociation processes

$$N_{D_2^+}(x, v_{D_2^+}) = N_{D_2^+}(x)P_{D_2^+}(v_{D_2^+}, x) = \frac{\langle\sigma_i v_e\rangle}{\langle\sigma_d^+ v_e\rangle}N_{D_2}(x)P_{D_2^+}(v_{D_2^+}, x) \qquad (2)$$

where $P_{D_2^+}\left(v_{D_2^+},x\right)$ is the VDF which takes into account the heating of molecular ions due to Coulomb elastic collision with charged plasma particles. The local relationship (2) accounts for the small value of ion Larmor radius as compared with the distances under consideration.

The comparison between molecular distributions from BM and Monte-Carlo calculations (MC) for outer part of horizontal chord is presented in Fig.1.
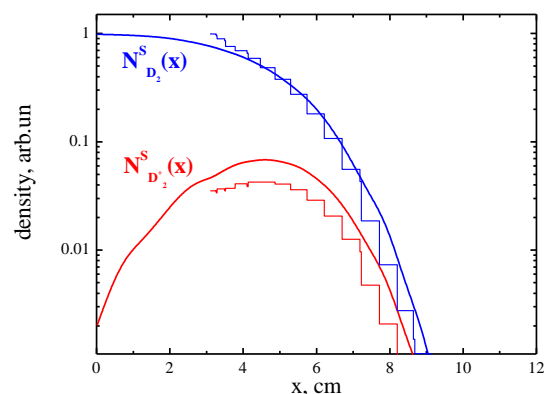

Fig.1. The comparison of space distributions of deuterium neutral and ionized molecules along the outer part of horizontal chord: solid lines – BM, step lines - B2-EIRENE code [1,3].

3. Atoms. The first (1) generation of slow (S) atoms arises from the dissociation of molecular ions (+) and neutral (0) molecules. The ballistic motion of the neutral atoms with velocities v_D arising from molecular ions is described by the relationship:

$$N_{1S_+}(x, v_D \triangleright 0) =$$

$$\frac{1}{v_D}\int_0^\infty dv_{D_2^+}\left[P_1(v_D-v_{D_2^+})(1-k)+2kP_3(v_D-v_{D_2^+})\right]\int_0^x dN_+(y)P_{D_2^+}\left(v_{D_2^+},y\right)\exp\left[-\frac{\phi(x,y)}{v_D}\right] \quad (3a)$$

$$N_{1S_+}(x, v_D \triangleleft 0) =$$

$$\frac{1}{(-v_D)}\int_0^\infty dv_{D_2^+}\left[P_1(v_D-v_{D_2^+})(1-k)+2kP_3(v_D-v_{D_2^+})\right]\int_x^\infty dN_+(y)P_{D_2^+}\left(v_{D_2^+},y\right)\exp\left[-\frac{\phi(x,y)}{v_D}\right] \quad (3b)$$

where the atoms moving in positive (from the wall) and negative (to the wall) directions are presented, $P_{1,3}(v_D-v_{D_2^+})$ are the VDFs corresponding to different groups of dissociating atoms, factor k=0.1 represents the ratio between different dissociative channels, $\varphi(x,y)=\int_y^x dz N_e\left[\langle\sigma_{cx}v_i\rangle+\langle\sigma_{ai}v_e\rangle\right]$ is the propagation function describing the decrease of atomic densities due to ionization and dissociation; $dN_+(y)=N_{D_2}(y)N_e(y)\langle\sigma_i v_e\rangle dy$ is the atomic sourse due to ionization of neutral molecules accompanied by their dissociation which is supposed to be very fast as compared with other processes.

The next group of slow atoms arises from direct dissociation of neutral molecules:

$$N_{1S_0}(x, v_D \rhd 0) = 2\frac{1}{v_D}\int_0^\infty dv_{D_2} P_2(v_D - v_{D_2})\int_0^x dN_0(y, v_{D_2})\exp\left[-\frac{\phi(x,y)}{v_D}\right], \tag{4a}$$

$$N_{1S_0}(x, v_D \lhd 0) = 2\frac{1}{(-v_D)}\int_0^\infty dv_{D_2} P_2(v_D - v_{D_2})\int_x^\infty dN_0(y, v_{D_2})\exp\left[-\frac{\phi(x,y)}{v_D}\right], \tag{4b}$$

where $P_2(v_D - v_{D_2})$ is VDF which corresponds to the dissociation channel, $dN_0(y, v_{D_2}) = N_{D_2}(v_{D_2}, y)N_e(y)\langle\sigma_d v_e\rangle dy$ is the atomic source due to the dissociative channel. The slow atoms arising from different dissociation channels are the sources for the fast atoms generated by cx with thermal plasma ions resulting in the generation of fast (F) atoms:

$$N_{1F_+}(x, v_{DF} \rhd 0) = \frac{1}{v_{DF}}\int_0^x dN_S(y)P_F(v_{DF}, y)\exp\left[-\frac{\phi(x,y)}{v_D}\right] +$$

$$\frac{r}{v_{DF}}\int_0^\infty dN_S(y)P_F(v_{DF}, y)\exp\left[\frac{2\phi(0,y) - \phi(x,y)}{v_{DF}}\right] \tag{5a}$$

$$N_{1F_-}(x, v_{DF} \lhd 0) = \frac{1}{(-v_{DF})}\int_x^\infty dN_S(y)P_F(v_{DF}, y)\exp\left[\frac{\phi(x,y)}{v_{DF}}\right] \tag{5b}$$

Here $dN_S(y) = N_e\langle\sigma_{cx}v_i\rangle N_S(y)dy$ is the source of fast atoms due to cx with thermal plasma ions; $P_F(v_{DF}, y) = \sqrt{\frac{M_D}{2\pi T_i(y)}}\exp\left[-\frac{M_D v_{DF}^2}{2T_i(y)}\right]$ is the fast atoms VDF corresponding to local ion temperature. The iterative procedure can be prolonged further resulting in the appearance of fast atoms second generation and so on. But the atomic density decreases sharply for the next generations. The space distribution of neutral atoms is presented in Fig.2.
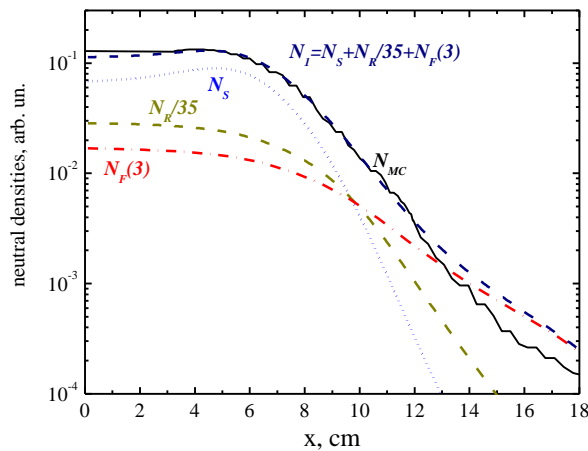

Fig.2. The spatial distribution of deuterium atoms along the outer part of horizontal chord in ITER: the contributions of slow, reflected and fast components and their sum are shown vs Monte-Carlo (MC) data.

4. Velocity distribution functions. Figure 3 displays the VDF of neutral atoms along the distance from the wall as compared with MC-data.
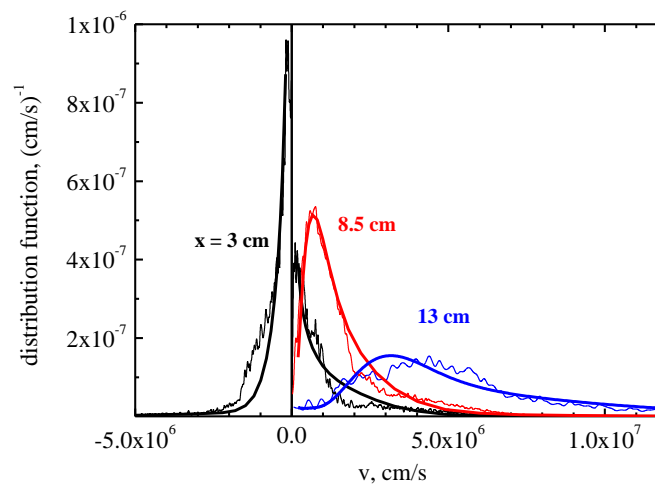

Fig.3. Atomic velocity distribution function at different distances from the wall at the outer horizontal chord: thick solid lines – ballistic model, thin lines - MC-modeling.

One can see a good agreement between two models at relatively small distances (for x < 10 cm) and some discrepancies at larger x. The discrepancy at x > 12 cm may be due to some effects don't taken into account in BM (molecular heating due to elastic collisions etc.).

So already two iterations demonstrate a good agreement with MC-simulations by SOLPS4.3 (B2-EIRENE) code [1-3]. The VDF of neutrals in the edge plasma calculated in the frame of BM is of importance for fast line shape calculations along lines of sights needed for spectral line diagnostics of neutrals in ITER.

5. Conclusions. BM describes the main properties of neutral atom distribution near the wall physically quite correct. This makes it possible to connect the observed spectral lines emissivities with neutral fluxes from the wall. The model is physically satisfactory in the plasma domains where two-dimensional flux can be approximated by a one-dimensional, i.e. where the width of neutral atom layer is small as compared with tokamak minor radius. That means that the model is applicable for the most of edge plasmas excluding the divertor region where two-dimensional transport is of importance.

References

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