

Kinetics of hydrogen atom radiation emission of the SOL plasma in ITER

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Introduction

The population of atomic hydrogen excited states responsible for radiation emission of Balmer spectral lines in the SOL plasma of ITER are under consideration. The neutral atoms penetration from the wall into plasma is calculated in the frame of ballistic model (BM) [1] which is in a good correspondence with numerical Monte-Carlo calculations [2-4]. The model decrease of neutral density is due to ionization by electron collisions and charge exchange on plasma ions. The charge exchange takes place from the ground state, so the ballistic model provides the neutral density in the ground state. It is necessary to determine the neutral excited states populations for radiation emission calculations, that is the population of the hydrogen levels $n=3$ (Balmer-alpha) and $n=4$ (Balmer-beta). The charge exchange from the excited state increases sharply (proportional to n^4) with the increase of the principle quantum number n of the excited level has to be taken into account. So the excited atoms can emit the quantum by two channels: from the states of initial atom with the velocity distribution function determined by the ballistic model, and from the states after charge exchange on plasma ions with the velocity distribution function related to the local Maxwellian temperature in the given spatial point.

Exited atomic states population kinetics

The developed kinetic model of exited atoms radiation includes the calculations of initial atoms populations by electron impact as well as calculations of secondary atoms populated by charge exchange on the initial ones. The calculations are performed in different approximations: in the frame of corona model, analytical model and numerical radiative-collisional model.

Under SOL plasma conditions considered the radiative-collisional model has a simple analytical solution:

$$\begin{aligned} N(4) &= N(1) \frac{\tilde{\gamma}_{14}\tilde{\Gamma}_5 + \tilde{\gamma}_{15}(\gamma_{54} + A_{54})}{\tilde{\Gamma}_4\tilde{\Gamma}_5 - \tilde{\gamma}_{45}(\gamma_{54} + A_{54})}, \\ N(3) &= N(1) \frac{\tilde{\gamma}_{13}}{\Gamma_3} + N(4) \frac{(\gamma_{43} + A_{43})}{\Gamma_3} \end{aligned} \quad (1)$$

where $\gamma_{nn'} = N_e \langle v_e \sigma_{nn'} \rangle$ are rate coefficients between atomic levels, $A_{nn'}$ are radiative transitions rates, the waved values designate effective relaxation constants accounting for cascade transitions.

The solution is in a good correspondence with the numerical solution of radiative-collisional kinetics.

It is natural to deviate the total populations obtained into two components – one $N_{\text{BAL}}(n) = N(n)(1-K)$ corresponds to the initial ballistic velocity distribution, another one $N_{\text{LOC}}(n) = N(n)K$ – to the local Maxwell function arising due to charge exchange of exited atoms on plasma ions. The redistribution population coefficient $K(n, T_e, N_e)$ determines the portion of particles with the local Maxwellian temperature and it depends on atomic energy number, temperature and density of surrounding plasma. It's numerical value is determined from the solution of kinetic model with account of two mentioned components.

Simple estimations of the effect in corona approximation for the third and fourth levels result in:

$$K(3, 100\text{eV}, 10^{13}\text{cm}^{-3}) \approx 0,2; K(4, 100\text{eV}, 10^{13}\text{cm}^{-3}) \approx 0,7 \quad (2)$$

which points on the noticeable contribution of charge exchange from excited states.

The values of the parameter for the levels 3,4 for typical plasma SOL ITER conditions, obtained from the total radiative-collisional system of equations are presented in tables 1,2.

Table1. The population redistribution coefficient $K(n, T_e, N_e)$ of the atomic energy level $n=3$ for different plasma temperatures and densities.

$T_e, \text{ eV} \setminus N_e, \text{ cm}^{-3}$	10^{12}	$3 \cdot 10^{12}$	10^{13}	10^{14}	10^{15}
20	0.04163	0.08648	0.1675	0.319	0.4185
50	0.0442	0.09318	0.1862	0.3746	0.491
100	0.04588	0.09774	0.1991	0.4185	0.5477
200	0.0473	0.1018	0.2106	0.4622	0.6036

Table2. The population redistribution coefficient $K(n, T_e, N_e)$ of the atomic energy level $n=4$ for different plasma temperatures and densities

$T_e, \text{ eV} \setminus N_e, \text{ cm}^{-3}$	10^{12}	$3 \cdot 10^{12}$	10^{13}	10^{14}	10^{15}
20	0.1861	0.2824	0.3735	0.4972	0.5723
50	0.2046	0.3219	0.4322	0.5798	0.6602
100	0.2169	0.3503	0.476	0.6398	0.7221
200	0.2274	0.3764	0.518	0.6953	0.7771

Radiation spectra calculations

Radiation spectra calculations were performed on the basis of population kinetic models described above. The main broadening mechanisms are Doppler and Zeeman effects. The presence of strong magnetic field with the field strength 5T typical for SOL ITER plasma was taken into account. In the frame of pointed approximations the radiation atomic spectra are described by:

$$J_n(\Delta\omega, B, T_e, T_i, N_e) = J_{BAL}^n(\Delta\omega, B, T_i) [1 - K(n, T_e, N_e)] + J_{LOC}^n(\Delta\omega, B, T_i) K(n, T_e, N_e) \quad (3)$$

where the line shapes $J_{BAL}^n(\Delta\omega, B, T_i)$ were calculated with the help of initial atomic velocity distribution function [1], and line shapes $J_{LOC}^n(\Delta\omega, B, T_i)$ - with ionic Maxwellian distribution function in a specific point.

The results of Balmer-alpha and Balmer-beta line shapes calculations according the eq. (3) integrated along the different line of sights in ITER are presented on figs. 1-3.

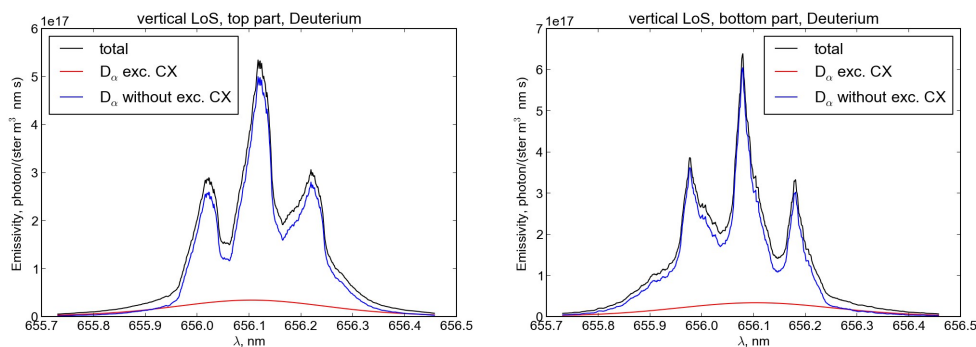


Fig.1. Left – spectral intensity of Balmer-alpha deuterium lines in SOL for the upper part of vertical observation chord ($R = 0.655$ m) in ITER regime #1514. The red line shows contribution to the radiation from neutrals obtained from charge exchange of neutrals in the excited state $n=3$ on fast ions. Blue lines – from ballistic atoms. Black line is the total spectrum. Right side – the same for the low part of vertical observation chord.

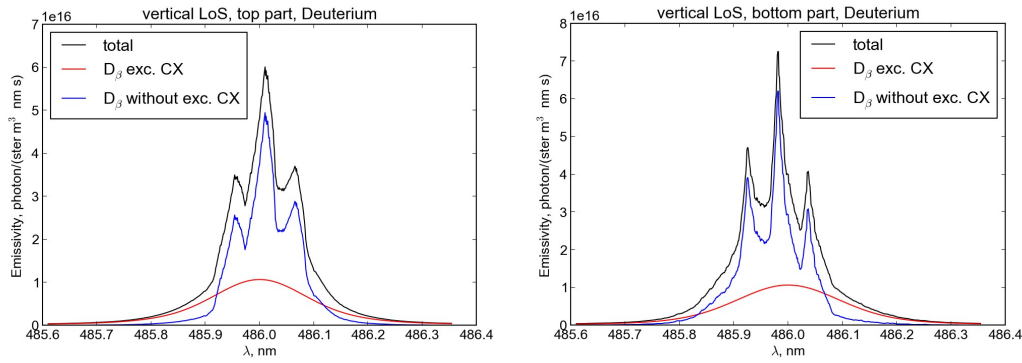


Fig.2. Left – the same as on fig.1 but for spectral intensity of Balmer-beta line. Red line shows the contribution to the radiation from neutrals obtaining as a result of neutral charge exchange in excited state $n=4$ on fast ions. The contribution is higher than one in Balmer-alpha line. Right – the same for low part of observation vertical chord.

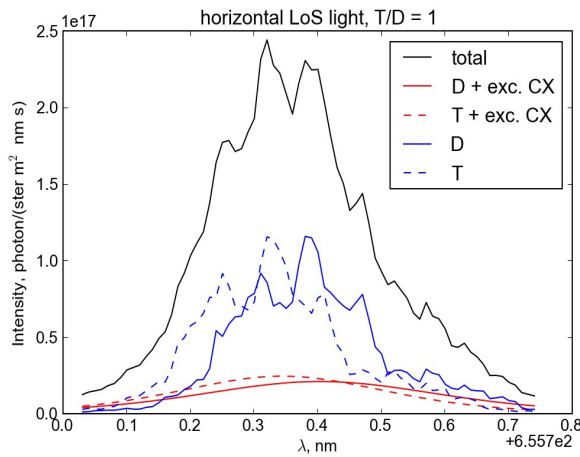


Fig.3 Contributions of deuterium and tritium into spectral intensity of H-alpha line in direct observation from SOL for horizontal chord in the scenario "d". Solid and dashed red lines – contribution of charge exchange from excited states of deuterium and tritium correspondently; blue line – contributions of ballistic deuterium and tritium atoms; solid black line - total signal.

Conclusion

1. The theoretical model of excited states population kinetics of hydrogen isotopes atoms in SOL ITER plasma are developed; the population calculations of excited state 3 (Balmer-alpha) and 4 (Balmer-beta) line of neutral hydrogen were done.
2. Two channels of Balmer line radiation were discovered: ballistic corresponding to initial velocity distribution functions and local with Maxwellian velocity distribution with local ions temperature..
3. The estimations confirmed by numerical calculations were done for population redistribution coefficient between ballistic and local fluxes of neutral hydrogen generated from charge exchange from excited states.
4. The effect of charge exchange from excited states with account of ballistic and local part on spectral shapes was calculated for SOL ITER plasma conditions.

References

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