Parameterization of Balmer-alpha asymmetric line shape in tokamak SOL plasmas

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Abstract. A parameterization of the Balmer-alpha spectral line shape asymmetry in the tokamak scrape-off layer (SOL) plasmas is suggested, which describes the contribution of non-Maxwellian components of the neutral atom velocity distribution function. Parameterization is needed for a fast-routine interpretation of high-resolution spectroscopy data and should be incorporated into the algorithms for the recovery of hydrogen neutral atom parameters in the SOL. We illustrate the efficiency of the parameterization on the example of spectral data calculated using the predictive modeling of the International Thermonuclear Experimental Reactor (ITER) tokamak operation.

1. Introduction

The asymmetry of the Balmer-alpha spectral line shape [1] is observed in tokamak experiments and simulated with kinetic codes (see, e.g., [2-6] and references therein). The asymmetry is manifested in the broad wings of the spectral lines and is thought to be caused by the charge-exchange neutrals and reflection of fast neutral atoms from the first wall of the vacuum chamber. These processes produce a strong non-Maxwellian component of the velocity distribution function (VDF) of hydrogen neutral atoms. A semi-analytic one-dimensional model [7,8] for neutral atom VDF in the scrape-off layer (SOL), based on the dominance of ballistic flights of neutral atoms, has shown good agreement with the EIRENE code stand-alone (Monte-Carlo) simulations of neutral deuterium VDF, applied on the divertor&SOL plasma background calculated for the International Thermonuclear Experimental Reactor (ITER) tokamak by the SOLPS4.3 (B2-EIRENE) code [9-11].

An example of a strong asymmetry may be found in the spectroscopic data from the recent experiments on the JET tokamak with the ITER-like wall (JET-ILW). An enhanced blue wing of the line shape of the central Zeeman component of the deuterium Balmer-alpha line was observed at the line-of-sight directed along major toroidal radius at the limiter stage of discharge when the toroidal plasma is attached to the inner wall limiters and the Balmer-alpha signal comes from the inner-wall SOL (see Figure 1(left) in Ref. [12]). It appears that such a wing of the line shape cannot be fitted with a set of exponential functions (Gaussians), normally used to fit the Doppler-broadened lines in the SOL plasmas, because the wing has a power-law slope.

Here we suggest a parameterization of the Balmer-alpha spectral line shape asymmetry in the tokamak SOL plasmas, which is based on the success of the model [7] and describes the contribution of non-Maxwellian components of the VDF in terms of major kinetic processes responsible for this effect. Such a parameterization is needed for a fast-routine interpretation of the Balmer-alpha high-resolution spectroscopy (HRS) data and should be incorporated into the algorithms for the recovery of hydrogen neutral atom parameters in the SOL. The parameterization has been used for analyzing the HRS D-alpha data in JET-ILW [12]. Here we show the efficiency of the parameterization on the example of spectral data [13] calculated using the SOLPS4.3 (B2-EIRENE) code predictive modeling of ITER operation, with account of the poloidally resolved plasma recycling from the first wall in the frame of the “extended grid” [14].

2. A model of neutral atom velocity distribution function

The asymmetry of the Balmer-alpha spectral line shape in the tokamak SOL plasmas originates from the substantial non-locality of particle transport. In contrast to divertor, here the mean-free-path of neutral hydrogen atom is large (see the Ballistic Model [7]) because of (i) the high rate of the resonance charge exchange of relatively cold first-generation atoms (of few-several eV temperature near the wall) with hot ions of background plasma in the SOL (of temperature up to few-several hundreds of eV in the region of the essential observed emissivity of Balmer-alpha line) and (ii) the low plasma density in the SOL. In the tokamak SOL in a strong magnetic field, the Balmer-alpha line shape is determined by the Zeeman splitting and the Doppler broadening of the Zeeman components. Under these conditions, the asymmetry of the line shape of each Zeeman component is caused by the asymmetry of inward-outward fluxes of neutrals, which is dominated by the moderate- and high-energy fractions of the neutral atom VDF. The asymmetry of the VDF is substantially enhanced by the reflection of fast atoms from the wall. In this section we suggest a simple model for the VDF and test it on the example of the data from the EIRENE code stand-alone (Monte-Carlo) simulations of neutral deuterium VDF, applied on the divertor&SOL plasma background calculated for tokamak ITER by the SOLPS4.3 (B2-EIRENE) code.

We consider the following model for the one-dimensional VDF in velocity v and space coordinate x in the direction perpendicular to the wall:

$$F_{VDF}\left(x,v\right)=\sum_{m=1}^{M1} n_M^m\left(x\right)F_{Gauss}\left(v,T_M^m\left(x\right)\right)+\sum_{n=1}^{M2} n_N^n\left(x\right)F_{Gauss}\left(v,T_N^n\left(x\right)\right)D_v\left(v,x\right)\eta\left(v\right), \quad (1)$$

where F_{Gauss} is the Maxwellian distribution (normalized in the velocity space); $M1$ and $M2$ are the number of, respectively, Maxwellian and non-Maxwellian fractions of the VDF; n_M^m and n_N^n are the particle density, respectively, of the m-th Maxwellian and the n-th non-Maxwellian fractions of the VDF,

$$D_v\left(v,x\right)=\exp\left(-v_{damp}\left(x\right)/v\right), \quad (2)$$

where v_{damp} is the characteristic velocity in the damping factor D_v which describes the attenuation of the inward flux, $\eta(x)$ is the Heaviside function, the x-axis is directed inward to plasma from the wall. The characteristic velocity should allow for the fact that in the SOL the inward flux of neutral atoms is attenuated mainly due to (i) ionization of neutral atoms by electron impact and (ii) their charge exchange with ions [7]:

$$v_{damp}\left(x\right)\sim\int_0^x\left[n_e\left(\tilde{x}\right)\left\langle\sigma_{ai}v_e\right\rangle\left(\tilde{x}\right)+n_i\left(\tilde{x}\right)\left\langle\sigma_{cx}v_i\right\rangle\left(\tilde{x}\right)\right]d\tilde{x}, \quad (3)$$

where n_e and n_i are the densities of, respectively, electrons and ions; σ_{ai} is the cross section of ionization; σ_{cx} is the cross-section of the charge exchange; v_e and v_i are velocities of, respectively, electrons and ions; brackets denote averaging over electron or ion Maxwellian distribution.

A comparison of the characteristic velocity v_{damp} (3) with the respective value recovered from the fitting of the EIRENE code simulation data [15] with the model VDF (1) is given in Figure 1, for two cases, namely low (the case “d” = “Low density far-SOL, L-mode pedestal” in notations of Ref. [15]) and high density of neutral deuterium (the case “i" = “High density far-SOL, H-mode pedestal”), within the case ITER SOL&divertor#1514 for background plasma (cf. [9]).

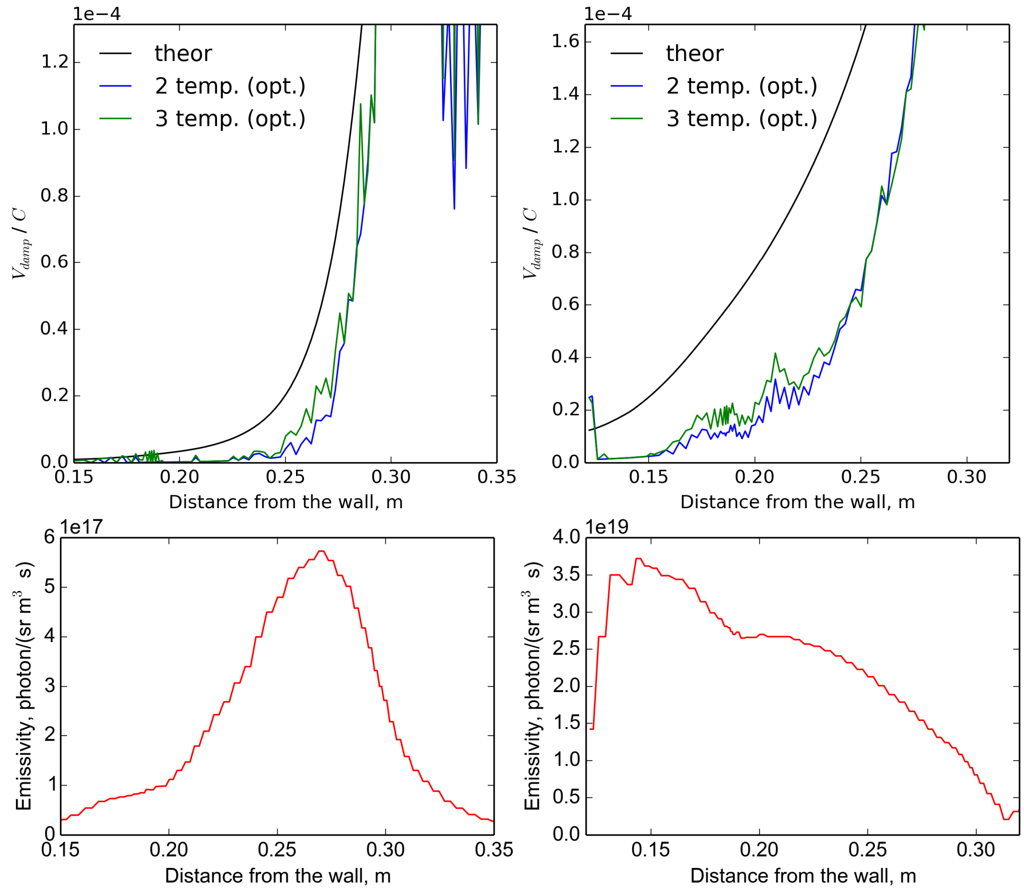

Figure 1. A comparison of v_{dump} (3), divided by the speed of light, (black curve) with the value recovered from the fitting of the EIRENE code simulation data with the model VDF in Eq. (1) in the case of low (upper left) and high density in the SOL (upper right) The results of fitting are given for the model (1) with two-temperature Maxwellian and one-temperature non-Maxwellian, $M1$=2, $M2$=1 (blue) and for the model (1) with $M1$=3, $M2$=2 (green). The respective profiles of Balmer-alpha line emissivity, in photons/(sr m^3 s), are shown in the bottom figures.

Note that the recovery is not good in the region of low emissivity: here the contribution to emissivity comes from fast particles whose Monte-Carlo modeling statistics is poor. Figure 1 suggests that the simple model (1), (2) with the v_{damp} taken as a free parameter may be used in the fitting of the VDF obtained by a numerical modeling of such a complicated kinetic problem. The success of the respective fitting is shown in Ref. [16].

3. A model of Balmer-alpha spectral line shape

The results of the above comparison enable us to suggest a simple model for the line shape of the observed signal because the latter integrates the local VDF data over a line-of-sight. This should give a reasonable parameterization of an asymmetric line shape in the SOL. We suggest the following model for the spectrum of the central (π-) Zeeman component:

$$S_{SOL}^{\pi}(\lambda)=\sum_{m=1}^{M1} S_M^m F_{Gauss}\left(\lambda-\lambda_{D\alpha},T_M^m\right)$$
$$+\sum_{n=1}^{M2} S_N^n F_{Gauss}\left(\lambda-\lambda_{D\alpha},T_N^n\right) D_\lambda\left(\lambda-\lambda_{D\alpha},\Lambda^n\right)\eta\left(\left(\lambda-\lambda_{D\alpha}\right)(\mathbf{k},\mathbf{l})\right), \quad (4)$$

where F_{Gauss} is the Gaussian line shape (normalized in the wavelength space)); S_M^m and S_N^n are statistical weights of the contribution, respectively, from the *m*-th Maxwellian and the *n*-th non-Maxwellian fractions of the VDF. The damping factor D_λ in the line shape is derived from the damping factor (2) in the VDF (1):

$$D_\lambda\left(\Delta\lambda,\Lambda\right)=\exp\left(-\frac{\Lambda}{|\Delta\lambda|}\right). \quad (5)$$

The values Λ^n in Eq. (4) are the free parameters which have to be determined by the fitting the experimental line shape. The argument of the Heaviside function allows for mutual direction of the line-of-sight, defined by the unit vector **l** from pupil to plasma, and the direction of atom inward flux in the SOL, defined by the unit vector **k** either at inner or outer part of the inner wall of the toroidal vacuum chamber. The total contribution of all Zeeman components takes the form:

$$S_{SOL}(\lambda)=C_\pi S_{SOL}^{\pi}(\lambda)+\frac{1-C_\pi}{2}\left(S_{SOL}^{\pi}\left(\lambda-\Delta\lambda^{Zeem}\right)+S_{SOL}^{\pi}\left(\lambda+\Delta\lambda^{Zeem}\right)\right), \quad (6)$$

where $\Delta\lambda^{Zeem}$ is the Zeeman splitting for magnetic field in a rather thin layer of essential emissivity in the SOL (see Figure 1, bottom figures). The factor $C_\pi = ½ \sin^2\theta$ is determined by the angle θ between the line-of-sight and the above-mentioned magnetic field.

The first application of the above model has been made to interpret the data from tokamak JET-ILW experiments at the limiter stage of discharge (see Figure 1(left) in Ref. [12]). Here we illustrate the fitting of the line shapes for the case of ITER predictive modeling data [15], [9] used in Figure 1.

The test of the above model can be made only in the frame of a "synthetic" diagnostic. Such a diagnostic generates "phantom" experimental data from the results of predictive numerical modeling of plasma parameters and allows direct comparison of the pristine (i.e. taken as known) and the recovered values of main parameters. The estimation of accuracy cannot be made using experimental data only because no diagnostic can directly measure the distribution of neutral atoms in velocity and space coordinates. The data [15], [9] enabled us to compare the results for temperatures (for non-Maxwellian fractions of the VDF, the effective ones, see the second term in the right hand side of Eq. (1)) averaged over the line-of-sight in the local kinetic model with those recovered from an algorithm of interpretation the observed signal, which originally operates with parameters averaged over the line-of-sight. The respective results are presented in Ref. [12], and in more detail in Ref. [16], they show good enough agreement of assumed and recovered values of temperatures.

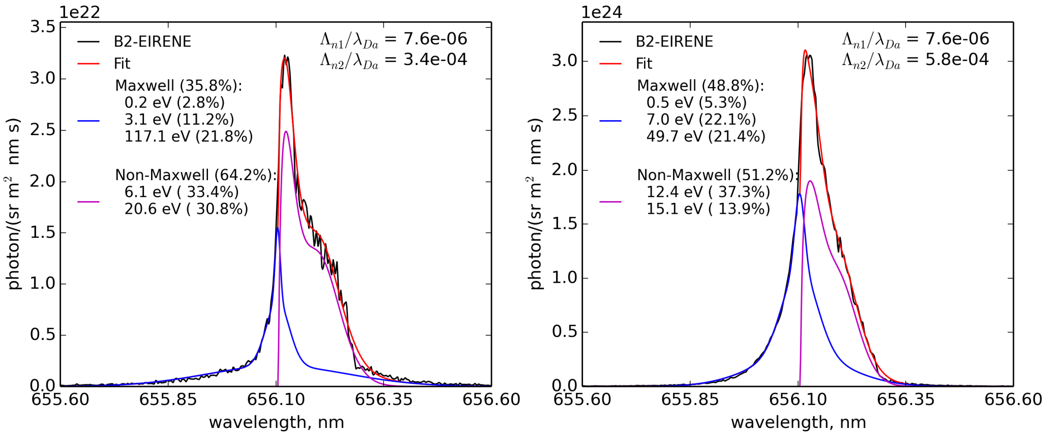

Figure 2. The results of fitting the deuterium Balmer-alpha line shape with the model (4) for the cases defined in Figure 1. The temperatures and relative particle densities of various fractions of neutral atoms, as well as the values of Λ in the damping factor (5), are indicated.

4. Conclusions

The models (1) and (2) for neutral hydrogen velocity distribution function (VDF) with the ν_{damp} taken as a free parameter may be used for fitting the VDF obtained with the numerical modeling (the success of such a fitting is shown in Ref. [16]). The models (4) and (5) for the Balmer-alpha line shape may be effective in fitting the spectral intensity of Balmer-alpha emission in the tokamak SOL plasmas under condition of a strong spectral asymmetry not treatable with the standard (set-of-Gaussians) model. The parameterization of the line shape is tested on the data of predictive modeling of ITER operation.

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