A Model for Reconstruction of Hydrogen Atom Effective Temperatures in the SOL from Balmer-Alpha Asymmetric Line Shape

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1. Introduction. The asymmetry of the Balmer-alpha spectral line shape [1] caused by the broad wings due to charge-exchange neutrals and fast reflected particles is observed in tokamak experiments and simulated with kinetic codes (see, e.g., [2] and references therein). In ITER, because of a strong reflection from the main chamber metallic wall, interpretation of H-alpha diagnostic data has to cope with a strong divertor stray light (DSL) in the same spectral line [3(a)]. Analysis of D-alpha data in the recent experiments in JET with ITER-like wall supported the expectation of a strong impact of the DSL upon the H-alpha diagnostics in ITER at divertor stage of discharge [3(b)]. The algorithm of recovering the neutral hydrogen effective temperatures in the SOL with allowance for a non-Maxwellian velocity distribution function (VDF), and respective asymmetry of the SOL emission line shape, may be validated at the limiter stage of discharge when the DSL is much smaller than the SOL light [3(b)].

Here we present such an algorithm in which the line shape asymmetry parameterization is suggested by the results of the model [4] for neutral atom VDF in the SOL, tested against the EIRENE code stand-alone simulations of neutral deuterium VDF, applied on the plasma background calculated by the SOLPS4.3 (B2-EIRENE) code [5-7]. The developed "synthetic" H-alpha diagnostics for the limiter stage of discharge is tested on the example of data from predictive modeling of the flat-top of Q=10 inductive operation of ITER, with account of the poloidally resolved plasma recycling from the first wall in the frame of the "extended grid" [8].

2. Algorithm of reconstruction of hydrogen atom effective temperatures. We use a Zeeman-Doppler line shape model for the spectra of emission from the SOL. We assume that the asymmetry of the line shape is caused by the non-Maxwellian fractions of atoms (e.g., by the almost elastic reflection of relatively fast neutral atoms from the wall). Reconstruction of temperatures (for non-Maxwellian fractions, effective ones) assumes an approximation of the temperature spatial profile along the line of sight (LoS) by a histrogram in which only certain number of the temperature values (two or three) are used to fit the temperature profile which determines the measured spectral line shape. The respective inverse problem on each exposure time interval is formulated as follows:

$$\sum_{j=1}^{N}\left(S_{SOL}^{exp}(\lambda_j)-\left\{\begin{array}{l} x^0+\sum_{m=1}^{M1} x_M^m F_{Maxw}^{SOL}\left(\lambda_j,\Delta\lambda^{Zeem},C_\pi,T_M^m\right)+ \\ +\sum_{n=1}^{M2} x_N^n F_{Non-Maxw}^{SOL}\left(\lambda_j,\Delta\lambda^{Zeem},C_\pi,T_N^n,\Lambda^n\right)\end{array}\right\}\right)^2 \xrightarrow[\mathbf{x},\mathbf{T},\Lambda]{} min, \quad (1)$$

$$\begin{gathered} F_{Maxw}^{SOL}\left(\lambda_j,\Delta\lambda^{Zeem},C_\pi,T_M^m\right)=C_\pi F_{Gauss}\left(\lambda_j-\lambda_{Da},T_M^m\right)+ \\ +0.5(1-C_\pi)\left(F_{Gauss}\left(\lambda_j-\Delta\lambda^{Zeem}-\lambda_{Da},T_M^m\right)+F_{Gauss}\left(\lambda_j+\Delta\lambda^{Zeem}-\lambda_{Da},T_M^m\right)\right), \end{gathered} \quad (2)$$

$$\begin{gathered} F_{Non-Maxw}^{SOL}\left(\lambda_j,\Delta\lambda^{Zeem},C_\pi,T_N^n,\Lambda^n\right)=C_\pi F_{Gauss}\left(\lambda_j-\lambda_{Da},T_N^n\right)exp\left(-\frac{\Lambda^n}{\left|\lambda_j-\lambda_{Da}\right|}\right)\eta\left(\left(\lambda_{Da}-\lambda_j\right)(\mathbf{k}.\mathbf{l})\right)+ \\ +0.5(1-C_\pi)\times\left(\begin{array}{l} F_{Gauss}\left(\lambda_j-\Delta\lambda^{Zeem}-\lambda_{Da},T_N^n\right)\exp\left(-\frac{\Lambda^n}{\left|\lambda_j-\Delta\lambda^{Zeem}-\lambda_{Da}\right|}\right)\eta\left(\left(\lambda_{Da}-\lambda_j+\Delta\lambda^{Zeem}\right)(\mathbf{k}.\mathbf{l})\right)+ \\ +F_{Gauss}\left(\lambda_j+\Delta\lambda^{Zeem}-\lambda_{Da},T_N^n\right)exp(-\frac{\Lambda^n}{\left|\lambda_j+\Delta\lambda^{Zeem}-\lambda_{Da}\right|})\eta\left(\left(\lambda_{Da}-\lambda_j-\Delta\lambda^{Zeem}\right)(\mathbf{k}.\mathbf{l})\right)\end{array}\right), \end{gathered} \quad (3)$$

where we have the following input and output data. **Input** data: $S_{SOL}^{exp}(\lambda_j)$ is the experimental spectrum for a certain exposure time interval; λ_j is the wavelength of the j-th spectral channel (pixel); N is the total number of pixels in the selected wavelength range; $M1$ is the total number of temperatures to be recovered; $M2$ is the total number of non-Maxwellian fractions whose effective temperatures are to be recovered; F_{Maxw}^{SOL} and $F_{Non-Maxw}^{SOL}$ are the calculated contributions to the spectrum from Maxwellian and non-Maxwellian fractions of atoms, respectively; $\Delta\lambda^{Zeem}$ is the Zeeman splitting for magnetic field in a thin layer which determines the observed spectrum; C_π is the partial contribution of the Zeeman π-component to the total line shape for a certain LoS (C_π = ½ $\sin^2\theta$, where θ is the angle between magnetic field and LoS in the region of maximal emissivity); $\eta(\lambda)$ is the Heaviside function; **k** is direction of atom flux from the wall to the SOL; **l** is direction from detector to observed section of SOL. **Output** data: T_M^m is the temperature of the m–th Maxwellian fraction of deuterium atoms; T_N^n is the effective temperature of the n-th non-Maxwellian fraction of atoms; $x_{M\,(N)}^{m\,(n)}$ is the statistical weight of the contribution of the *m*–th (*n*–th) fractions of Maxwellian (non-Maxwellian) atoms to the total intensity of the line; x^0 is a constant background; Λ^n is the characteristic wavelength shift for spectral contribution of the n-th non-Maxwellian fraction.

3. Test of algorithm on the ITER simulation data. The accuracy of reconstruction of hydrogen atoms' parameters in the SOL from the Balmer-alpha line shape should be estimated within the frame of a synthetic diagnostic. Such a diagnostic generates "phantom" experimental data, using 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 parameters. The accuracy of reconstruction cannot be estimated using the experimental data only because no diagnostic can directly measure the distribution of neutral atoms in velocity and space coordinates. A test of the algorithm may be done on the example of simulated data for velocity distribution function (VDF) for neutral atoms. These data enable one to compare the LoS-average results for temperatures (for non-Maxwellian fractions of VDF, effective ones) from the "local kinetic model" (denoted below as "L") with those recovered from the algorithm (1)-(3) which originally operates with the LoS-average parameters, "LoS-integral model" (denoted below as "I"). In the "L" model, the effective atomic temperatures are recovered from the VDFs by a procedure which is close to the recovery of the same parameters from the spectral intensity measured at a given LoS. Such a procedure enables us to plot the effective-temperature profile (histogram) along the LoS, which should be compared with the few (two or three) values of effective temperature recovered from the spectral intensity at this LoS. The results of such an analysis for the above-mentioned simulation data for ITER are presented in Figures 1,2 and Table 1.

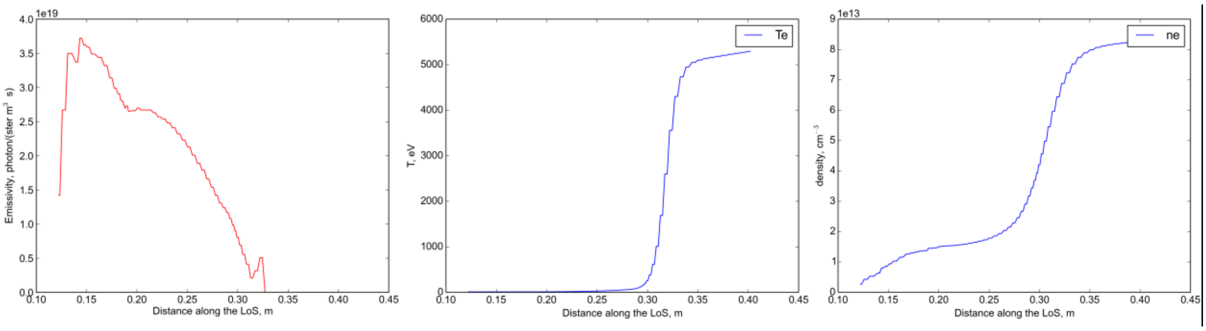

Fig. 1. Profiles of emissivity, electron temperature and density along the outer wall section of the horizontal LoS for scenario with the high density of plasma in the far SOL in the H-mode (scenario "i"). The distance is counted from the wall.

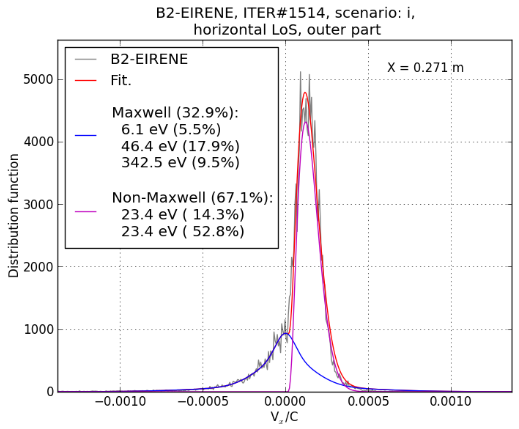

Fig. 2. The fitting of the VDF as a function of the normalized velocity v/c along the LoS (c is the speed of light), calculated by the EIRENE code for ITER #1514 case in scenario "i" in the point of maximum emissivity on the outer wall section of the horizontal LoS (here the distance from the wall is X = 0.271 m). The temperatures and their weight coefficients are obtained by solving an optimization problem for fitting the VDF for M1=3, M2=2.

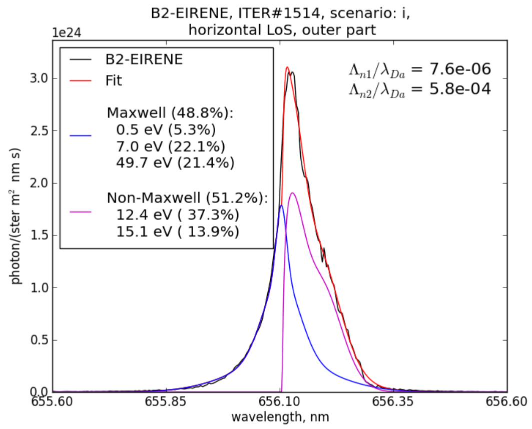

Fig. 3. The fitting of the D-alpha spectral line shape calculated using the data from simulations for ITER #1514 case in scenario "i". The temperatures and their weight coefficients are obtained by solving an optimization problem for fitting the spectrum, similarly to (1)-(3), for M1=3, M2=2. The dimensionless parameter Λ_n/λ_{Da}.describes spectral asymmetry in (3).

Table 1. Comparison of temperatures from local kinetic (“L”) and LoS-integral models (“I”) for M1=2 and M2=1 for various scenarios of predicted ITER divertor operation (see notations in [3(a)]).

		Non-Maxw. Fraction, %		Temperatures, eV				Non-Maxwellian $(T_a)_{eff}$, eV	
				Low		High			
		“L”	**“I”**	“L”	**“I”**	“L”	**“I”**	“L”	**“I”**
Regime	**d**	64.1	**64.2**	2.5	**1.1**	114.2	**80.9**	26.7	**34.8**
	e	64.7	**64.2**	1.9	**0.9**	97.1	**73**	23.2	**29.6**
	f	60.7	**59.2**	2.6	**0.7**	81.0	**54**	31.2	**50.5**
	g	60.0	**58.1**	2.0	**0.6**	72.2	**41.5**	28.0	**43.2**
	h	52.8	**51.9**	2.8	**1.4**	41.6	**26.6**	17.6	**29.6**
	i	52.1	**51.2**	2.6	**1.4**	34.3	**24.2**	20.0	**28.5**

4. Conclusions. The developed algorithm for Balmer-α diagnostic of effective temperatures of neutral hydrogen in the tokamak SOL plasmas is tested on the example of data from the EIRENE code stand-alone simulations of neutral deuterium velocity distribution function (VDF) in velocity and space coordinates in the SOL, applied on the plasma background calculated by the SOLPS4.3 (B2-EIRENE) code for the flat-top of Q=10 inductive operation of ITER. The results show reasonably good agreement of characteristic temperatures recovered in the local kinetic model, which uses the EIRENE code simulations of neutral deuterium VDF, and in the LoS-integral model which uses (i) a decomposition of the line shape of the «phantom» observed intensity to a set of Gaussians and (ii) a parameterization we suggested for the asymmetry of the Balmer-α line shape caused by an inward flux of atoms in the SOL.

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