

A method of interpreting the Balmer-alpha high-resolution spectroscopy for tokamak edge plasmas with account of divertor stray light

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Abstract. A method is suggested for interpreting the data from the Balmer-alpha high-resolution spectroscopy diagnostics of the edge plasma in the tokamak main chamber, which additionally uses the data from direct observation of the divertor. Such an extension of the diagnostics is motivated by the fact that in a tokamak-reactor with the metal first wall, like ITER tokamak, a significant role of the divertor stray light (DSL), which is emitted by the plasma in the divertor in the same spectral line and reflected from the first wall of the vacuum chamber to a spectrometer in the main chamber, is expected. The results of the first applications of the developed model to interpret the data from the JET-ILW tokamak experiments, which simulate the conditions of occurrence of the DSL in ITER, are discussed.

1. Introduction

The Balmer-alpha high-resolution spectroscopy in the ITER tokamak, aimed at measuring the characteristics of hydrogen isotopes in the scrape-off layer (SOL) plasma, may face the problem of the divertor stray light (DSL), which is emitted by the plasma in the divertor in the same spectral line and reflected from the first wall of the vacuum chamber to a spectrometer in the main chamber. Preliminary estimates [1] of the DSL spectrum and the numerical modeling [2] (using the ray tracing technique) of the DSL, not resolved within spectral lines shape, for the ITER Main Chamber H-alpha diagnostics have shown that the DSL in the Balmer-alpha line may exceed the Balmer-alpha light, emitted in the SOL on the observation chord in the main chamber, up to two orders of magnitude for highly reflecting walls (wall reflection coefficient $R_w \geq 0.5$) and high-power operation. The results [1, 2] have been obtained with the use of the spatial distribution of luminosity in the divertor and the SOL for the quasi-stationary stage of the inductive mode of ITER operation with the fusion gain parameter, $Q=10$ (these data were simulated by the SOLPS4.3 (B2-EIRENE) code [3-5] on an expanded numerical mesh with allowance for the poloidally resolved recycling from the first wall [6]). The first results [1] showed that a test of the elaborated approach in the currently running machines with all-metal first wall is required to benchmark the analysis method.

Here we propose a method of interpreting the data from the Balmer-alpha high-resolution spectroscopy of the edge plasma in the main vacuum chamber of a tokamak, which additionally uses

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the data from direct observation of the divertor. The method uses (i) semi-analytical model [7] for the spectral line shape of the Balmer-alpha line of hydrogen isotopes, taking into account the essential asymmetry of the spectral line shape caused by the fact that fast atoms dominate in the flow from the wall into plasma (see Ballistic Model [8,9]), and (ii) the model [10] of the recovery of basic parameters (namely, effective temperatures and relative contributions) of non-Maxwellian fractions of the velocity distribution function (VDF) of neutral hydrogen in the SOL. The method involves the following successive procedures: (i) recovery of the spatial distribution of the temperature in the divertor, using the spectra obtained via direct observation of the divertor; (ii) calculation of the DSL spectrum from the recovered distribution of temperature; (iii) solving a multi-parametric inverse problem, taking into account the contributions of the sections on the high magnetic field side (HFS) and low magnetic field side (LFS) of the observation chord in the SOL in the main vacuum chamber, and the contribution of the DSL. The results [11, 12] of the first applications of the developed model to interpret the data from the JET-ILW tokamak experiments, which simulate the conditions of occurrence of the DSL in ITER, are discussed.

2. Basic equations

A typical geometry of complex diagnostics, which includes simultaneous measurements of the emission of neutral hydrogen in the SOL plasma in the main chamber and in the divertor is shown in Figure 1 for ITER. The 2D profile of emissivity, calculated by S.W. Lisgo in the frame of the approach [3-6] for the flat-top of the so-called inductive discharge (the fusion gain $Q=10$) in a scenario with low density in the far SOL, in the L-mode regime (scenario “d”), is shown.

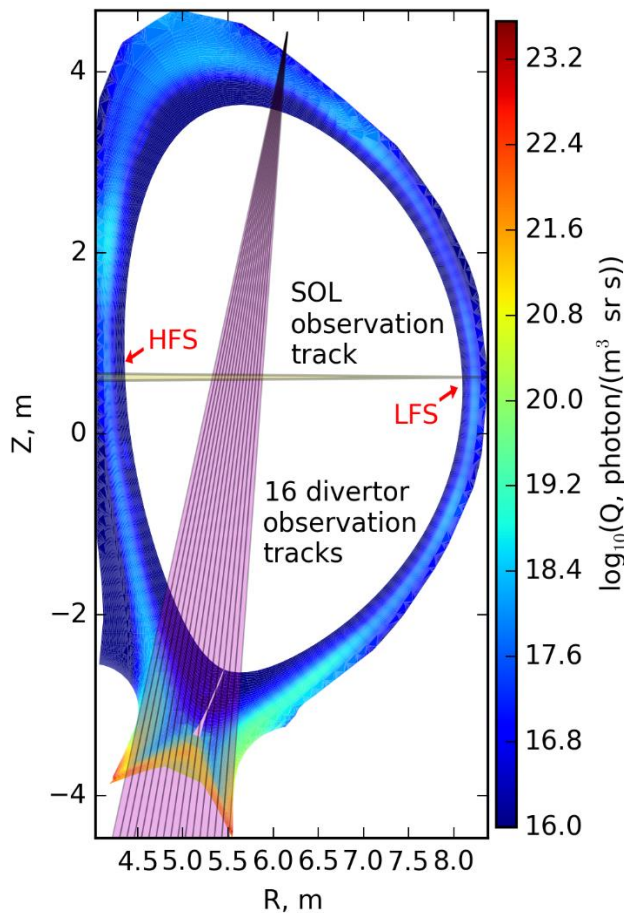


Figure 1. The 2D distribution of the Balmer-alpha emissivity in the SOL and divertor in ITER, in logarithmic scale. Possible layouts of the radial horizontal line of sight (track) from the equatorial port plug and the 16 tracks for viewing from the top port-plug down towards the divertor are shown. The HFS and LFS sections of the observation chord in the SOL in the main chamber are shown.

The Balmer-alpha spectral line shapes of hydrogen isotopes in divertor are symmetric, whereas the line shapes for emission from the SOL is asymmetric and should be described by the model [7]. Here for simplicity we assume that the σ -components of the Zeeman triplet are filtered out using the polarizers (this is the case for current experiments on JET-ILW tokamak), extension to allowance for the entire Zeeman triplet does not change the principles of the method. The inverse problem of recovering the characteristic temperature of the neutral atoms in the divertor is formulated as follows:

$$\sum_{j=1}^{N_{tr}} \left(\tilde{S}_{tr}^{\exp}(\lambda_j) - \left\{ \sum_{i=1}^M x_{tr}^{(i)} \left((1 - C_{H,tr}) \tilde{F}_{Gauss}(\lambda_j - \lambda_{D\alpha}, T_{tr}^{(i)}) \right) + C_{H,tr} \tilde{F}_{Gauss}(\lambda_j - \lambda_{H\alpha}, T_{tr}^{(i)}) \right\} \right)^2 \xrightarrow{\mathbf{x}_{tr}, \mathbf{T}_{tr}, C_{H,tr}} \min, tr = 1 : Tr_{\max}^{div}, \quad (1)$$

where λ_j is the wavelength that corresponds to the spectral channel (pixel) with number j ; N_{tr} is the total number of pixels in the Balmer-alpha spectral interval chosen for the interpretation for the track with number tr ; \tilde{S}_{tr}^{\exp} is the normalized line shape of the spectrum, measured at the current time interval on the track tr ; $\lambda_{D\alpha}$ and $\lambda_{H\alpha}$ are the wavelengths of the Balmer-alpha line center of the deuterium and hydrogen, respectively; \tilde{F}_{Gauss} is the normalized Gaussian function; i is the index of the fraction of atoms with the certain temperature; M is the total number of those fractions the temperature of which should be recovered (it is possible to recover two or three fractions); Tr_{\max}^{div} is the total number of tracks for direct observation of the divertor; $T_{tr}^{(i)}$ and $x_{tr}^{(i)}$ are, respectively, the temperature and partial contribution (statistical weight) of the i -th fraction of atoms on the track tr ; $C_{H,tr}$ is the partial contribution of the hydrogen (H) to the total (i.e. H + D) intensity observed on the track tr . Here we assume the equality of temperatures of hydrogen and deuterium atoms.

Using the recovered temperature distribution in the divertor we may predict the normalized spectrum (i.e. the line shape) of the DSL as follows:

$$\tilde{S}_{DSL}(\lambda) = \sum_{tr=1}^{Tr_{\max}^{div}} \frac{S_{tr} R_{tr}}{\sum_{tr'=1}^{Tr_{\max}^{div}} S_{tr'} R_{tr'}} \sum_{i=1}^M x_{tr}^{(i)} \left(\begin{aligned} & \left(1 - \hat{C}_{H,tr} \right) \left(\frac{C_{\pi}^{(DSL)} \tilde{F}_{Gauss}(\lambda_j - \lambda_{D\alpha}, \hat{T}_{tr}^{(i)})}{2} + \frac{(1 - C_{\pi}^{(DSL)})}{2} \left(\tilde{F}_{Gauss}(\lambda_j - \lambda_{D\alpha} - \Delta\lambda_{D,tr}^{Zeem}(R_{tr}), \hat{T}_{tr}^{(i)}) + \tilde{F}_{Gauss}(\lambda_j - \lambda_{D\alpha} + \Delta\lambda_{D,tr}^{Zeem}(R_{tr}), \hat{T}_{tr}^{(i)}) \right) \right) \\ & + \hat{C}_{H,tr} \left(\frac{C_{\pi}^{(DSL)} \tilde{F}_{Gauss}(\lambda_j - \lambda_{H\alpha}, \hat{T}_{tr}^{(i)})}{2} + \frac{(1 - C_{\pi}^{(DSL)})}{2} \left(\tilde{F}_{Gauss}(\lambda_j - \lambda_{H\alpha} - \Delta\lambda_{H,tr}^{Zeem}(R_{tr}), \hat{T}_{tr}^{(i)}) + \tilde{F}_{Gauss}(\lambda_j - \lambda_{H\alpha} + \Delta\lambda_{H,tr}^{Zeem}(R_{tr}), \hat{T}_{tr}^{(i)}) \right) \right) \end{aligned} \right), \quad (2)$$

where S_{tr} is the wavelength-integrated intensity on the track tr ; R_{tr} is the major radius of the point of the maximum emissivity on the track tr (the $S_{tr} \cdot R_{tr}$ product recalculates the observation volume of the track tr to the volume of the respective emitting toroidal ring); $\hat{x}_{tr}^{(i)}$, $\hat{T}_{tr}^{(i)}$ and $\hat{C}_{H,tr}$ are the input parameters found by solving the problem (1); $C_{\pi}^{(DSL)}$ is the partial contribution of the Zeeman π -component to the total line shape of the DSL, the output parameter to be recovered from Equations (3)-(6)).

The inverse problem of interpreting the measurements in the main chamber is formulated as follows:

$$\sum_{j=1}^{N_{tr}} \left[- \sum_{p=1}^2 \left\{ \sum_{i=1}^M x_{tr}^{(i)} \left((1 - C_{H,tr}) \tilde{F}_{Maxw}^{SOL}(\lambda_j, \Delta\lambda_D^{Zeem}, \lambda_{D\alpha}, C_{\pi,tr,p}^{(SOL)}, T_{tr,p}^{(i)}) \right) + C_{H,tr} \tilde{F}_{Maxw}^{SOL}(\lambda_j, \Delta\lambda_{H,tr,p}^{Zeem}, \lambda_{H\alpha}, C_{\pi,tr,p}^{(SOL)}, T_{tr,p}^{(i)}) \right\} + \sum_{i=2}^M x_{tr}^{(M+i)} \left((1 - C_{H,tr}) \tilde{F}_{Non-Maxw}^{SOL}(\lambda_j, \Delta\lambda_D^{Zeem}, \lambda_{D\alpha}, C_{\pi,tr,p}^{(SOL)}, T_{tr,p}^{(i)}, \Lambda_{tr,p}^{(i)}) \right) + C_{H,tr} \tilde{F}_{Non-Maxw}^{SOL}(\lambda_j, \Delta\lambda_{H,tr,p}^{Zeem}, \lambda_{H\alpha}, C_{\pi,tr,p}^{(SOL)}, T_{tr,p}^{(i)}, \Lambda_{tr,p}^{(i)}) \right) \right]^2 \xrightarrow{C_{\pi,tr}^{(DSL)}, x_{tr}, T_{tr}, \Lambda_{tr}, C_{H,tr}} \min, \quad (3)$$

$$tr = 1 : Tr_{max}^{SOL},$$

$$F_{Maxw}^{SOL}(\lambda, \Delta\lambda_D^{Zeem}, \lambda_{D\alpha}, C_{\pi}, T) = \left(\frac{C_{\pi} F_{Gauss}(\lambda - \lambda_{D\alpha}, T)}{+ \frac{1 - C_{\pi}}{2} (F_{Gauss}(\lambda + \Delta\lambda_D^{Zeem} - \lambda_{D\alpha}, T) + F_{Gauss}(\lambda - \Delta\lambda_D^{Zeem} - \lambda_{D\alpha}, T))} \right), \quad (4)$$

$$F_{Non-Maxw}^{SOL}(\lambda, \Delta\lambda_D^{Zeem}, \lambda_{D\alpha}, C_{\pi}, T, \Lambda) = \left(\frac{C_{\pi} F_{Asym}(\lambda - \lambda_{D\alpha}, T, \Lambda)}{+ \frac{1 - C_{\pi}}{2} (F_{Asym}(\lambda + \Delta\lambda_D^{Zeem} - \lambda_{D\alpha}, T, \Lambda) + F_{Asym}(\lambda - \Delta\lambda_D^{Zeem} - \lambda_{D\alpha}, T, \Lambda))} \right), \quad (5)$$

$$F_{Asym}(\Delta\lambda, T, \Lambda) = F_{Gauss}(\Delta\lambda, T) \exp(-\Lambda/|\Delta\lambda|) \eta(-\Delta\lambda(\mathbf{k}, \mathbf{l})), \quad (6)$$

where p indicates the emission section (either HFS or LFS) of the SOL; summations over i go over Maxwellian and non-Maxwellian fractions of atoms; the second sum starts with $i = 2$ because of the lack of a «cold» non-Maxwellian fraction (the temperatures of the «warm» Maxwellian and «warm» non-Maxwellian fractions are assumed to be equal); x_{tr}^{DSL} is the fraction of the DSL in the total signal and should be recovered (it varies in the range of about 10% around the universal value which is a function of the divertor emissivity, geometry of the main chamber and wall reflectivity; this value is to be found for the current intensity of divertor emission by processing the observation data from many discharges); $\Lambda_{tr,p}^{(i)}$ is the characteristic wavelength shift for the spectral contribution of the i -th fraction of non-Maxwellian atoms, which describes the attenuation of the inward flux of atoms on the track tr (see [7] for the details); $\eta(x)$ is the Heaviside function; \mathbf{k} is the direction of atomic flux from the wall to plasma in the given section of the SOL; \mathbf{l} is the direction from the detector to the observation point.

The results of the first applications of the developed model to interpret the data from the JET-ILW tokamak are presented in [11, 12]. Typical results for the D-alpha spectral line on the divertor stage of the discharge were presented for the radial and tangential tracks from the equatorial port. The recovered temperatures and the fractions of Maxwellian and non-Maxwellian atoms have been found for HFS and LFS sections of the SOL. The recovered time behavior of the fractions of different sources of the signal (HFS and LFS sections of the SOL, and the DSL) on these tracks indicated a significant fraction of the DSL (up to 50%) in the total signal throughout major part of the discharge in the JET-ILW tokamak. Extrapolation to ITER has suggested a stronger effect of the DSL in ITER.

3. Conclusions

A method is developed (and implemented on JET-ILW) for interpreting the data from the Balmer-alpha high-resolution spectroscopy in the edge plasma with account of the divertor stray light (DSL). The method uses, additionally to conventional H-alpha diagnostics in the main chamber, the data from direct observation of the divertor. The method allows to (i) separate, in the total signal, the contributions from three sources, the HFS and LFS sections on the observation chord in the main chamber, and the DSL, (ii) recover the temperature of the hydrogen and deuterium atoms, (iii) evaluate the isotope ratio in a H+D mixture.

Acknowledgements

The authors are grateful to S.W. Lisgo, A.S. Kukushkin, V.S. Lisitsa, S. Brezinsek, A.V. Gorshkov, M. von Hellermann, M.B. Kadomtsev, V. Kotov, M.G. Levashova, V.A. Shurygin, M.F. Stamp, E. Veshchev, D.K. Vukolov, K.Yu. Vukolov for their collaboration in studies on the ITER Main Chamber H-alpha (and Visible Light) Spectroscopy Diagnostics.

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