

Complex Diagnostics of Electron Velocity Distribution with Thomson Scattering and Electron Cyclotron Emission in Tokamaks

P.A. Sdvizhenskii¹, P.V. Minashin¹, A.B. Kukushkin^{1,2}, G.S. Kurskiev³, E.E. Mukhin³

¹National Research Center “Kurchatov Institute”, Moscow, Russian Federation

²National Research Nuclear University MEPhI, Moscow, Russian Federation

³Ioffe Physical Technical Institute, St. Petersburg, Russian Federation

1. Introduction. Under conditions of strong auxiliary plasma heating in tokamaks a difference between temperature values obtained by Thomson scattering (TS) diagnostics and ones obtained by electron cyclotron (EC) emission spectra (from thermal EC emission on the first or second harmonics of fundamental EC frequency) is observed. The cause of this difference is often treated as a deviation of the electron velocity distribution function (eVDF) from Maxwellian one. Here we suggest a new algorithm for diagnostics of main parameters of the eVDF under condition of a substantial deviation from the Maxwellian VDF. The algorithm combines two formerly developed algorithms of the eVDF assessment: (i) from TS spectra [1] and (ii) from EC emission in the spectral range where plasma is optically thin (i.e. for moderate- or high-number harmonics of fundamental EC frequency) [2]. The work is stimulated by the search [3] for the improvement of the TS diagnostics in tokamak-reactors like DEMO (multicolor laser model, cooperation with other diagnostics of the eVDF). The important example of interpretation beyond the frame of assumption about Maxwellian VDF in present tokamak experiments with a strong auxiliary heating is given in [4]. Here we give preliminary analysis of the complex diagnostic opportunities suggested for the case of a strong deviation from the Maxwellian eVDF. We consider the case of a hypothetical experiment, where we use the current technical parameters of the core plasma TS diagnostic system in ITER and extend the method [5] of its accuracy assessment. Plasma is described by the predictive modelling data for the so-called steady-state scenario of discharge in ITER [6].

2. Complex eVDF diagnostics algorithm.

In the thermal energy range, the eVDF in each space point is the Maxwellian with the temperature T_e as a free parameter. In the weakly/moderate superthermal energy range the eVDF is assumed to be an anisotropic quasi-Maxwellian with only a couple of unknowns, $T_{e,\parallel}$ and $T_{e,\perp}$:

$$f(\mathbf{p}) = (1 - \delta_{\text{Hot}}) \cdot f_{\text{Maxw}}(\mathbf{p}) + \delta_{\text{Hot}} \cdot f_{\text{Hot}}(\mathbf{p}_{\parallel}, \mathbf{p}_{\perp}), \quad (1)$$

$$f_{\text{Hot}}(\mathbf{p}_{\parallel}, \mathbf{p}_{\perp}) = C_{\text{Hot}} \exp \left[-mc^2 \left(\frac{\sqrt{1 + (p/mc)^2} - 1}{p^2} \right) \left(\frac{p_{\parallel}^2}{T_{e,\parallel}} + \frac{p_{\perp}^2}{T_{e,\perp}} \right) \right], \quad (2)$$

where f_{Maxw} is the relativistic Maxwellian distribution; \mathbf{p}_{\parallel} and \mathbf{p}_{\perp} are the components of the momentum \mathbf{p} , respectively, parallel and perpendicular to the local magnetic field; C_{Hot} is the normalization factor (in the momentum space), and δ_{Hot} the fraction of superthermal electrons in the total electron density. At higher energies, where the most significant deviations from Maxwellian are expected and the TS diagnostics does not work, the eVDF is an arbitrary function of \mathbf{p}_{\parallel} and \mathbf{p}_{\perp} (see [2] for more details).

The TS-based eVDF diagnostic algorithm [1] includes the calculation of the number of photoelectrons, $[N_{ph-el}^{(j)}]_{Laser}$, in a given spectral channel of the detector (where j numerates spectral channels) in terms of the normalized cross-section σ of the Thomson scattering, which is averaged over the assumed model eVDF (1), (2). For each spectral channel, the difference between total $[N_{ph-el}^{(j)}]_{Total}$ and background $[N_{ph-el}^{(j)}]_{Backgr}$ signals is calculated. Randomization of input parameters is applied to estimate the diagnostic's accuracy. The values of the sought-for parameters are recovered via solving the inverse problem, which relies on the minimization of the difference between the “phantom” experimental laser-scattering signal and the respective variable calculated signal:

$$\sum_j \left\{ [N_{ph-el}^{(j)}(\xi_{assum})]_{Total} - [N_{ph-el}^{(j)}]_{Backgr} \right\}_{Random} - [N_{ph-el}^{(j)}(\xi)]_{Laser} \Big|_{\xi} \rightarrow \min, \quad (3)$$

where the summation goes over all lasers and spectral channels. Further development of the eVDF recovery algorithm [1] with the correct error assessment was continued in [5]. It was shown that the large error of recovering the parameter δ_{Hot} does not influence the accuracy of recovering the mean electron energy for the total non-Maxwellian VDF. Thus, the inverse problem solution is stable with respect to the recovery of the mean energy regardless of the particular form of the deviation from a Maxwellian in the thermal and weakly superthermal range of the electron energy. Nevertheless, for higher mean energies this statement becomes incorrect, that's why using other diagnostics data is necessary.

Recovery of the eVDF, based on the EC emission for moderate- or high-number harmonics of fundamental EC frequency, does not need the knowledge about the functional type of the eVDF. So the algorithm [2] does not recover the values of any parameters characterizing it (as it is in case of algorithm [1]), but directly recover the eVDF's values instead. Momentum space is divided into sectors, and their contributions to the EC spectrum are calculated. The spectrum is considered as a sum of two terms – contributions from Maxwellian $I_{esc}^{Maxw}(\omega)$ and hot $I_{esc}^{Hot}(\omega)$ plasma components, $I_{esc}(\omega) = I_{esc}^{Maxw}(\omega) + I_{esc}^{Hot}(\omega)$. Here

$I_{\text{esc}}^{\text{Maxw}}(\omega)$ is assumed to be known (e.g., from the TS data). To recover the eVDF, an inverse problem is solved via minimization of the sum of differences between the “phantom” experimental EC emission spectrum and the respective calculated signal.

The first stage of the present complex diagnostic is the preliminary estimation of the sought-for parameters. Their values are recovered for each space point, where a substantial contribution of superthermal electrons to the EC emission is expected. To do this the inverse problem (3) -- with the known TS spectrum and the assumed eVDF (1), (2) -- is solved. After that, the combined optimization is performed. The solution is searched closely to the preliminary estimation. Thus, the recovery from the TS data is improved due to taking into account the additional information about hot electrons from the EC emission data for moderate- or high-number harmonics of fundamental EC frequency.

Figure 1 shows the results of the estimation exclusively from the TS data.

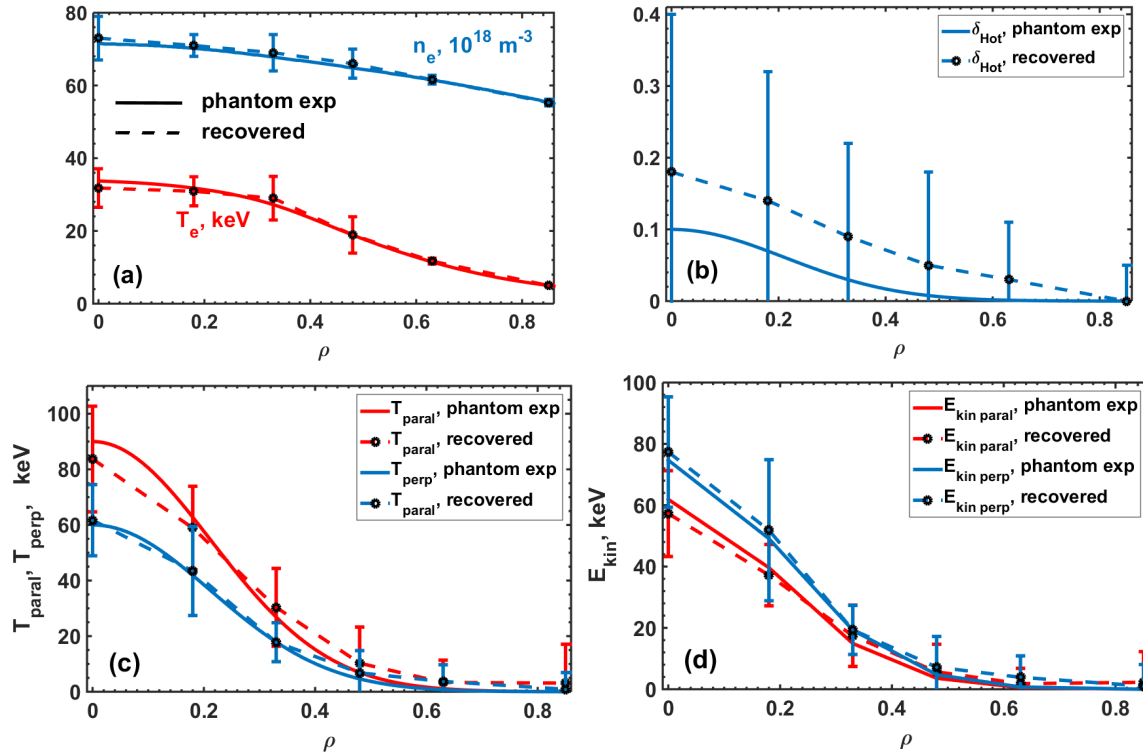


Fig. 1. The profiles as a function of effective normalized minor radius coordinate: (a) electron Maxwellian bulk's temperature and density; (b) hot electrons' fraction in the total density; (c) parallel and perpendicular effective temperatures for hot electrons; (d) their mean kinetic energies for parallel and perpendicular to magnetic field motion. Solid curves on “a” correspond to ITER steady-state scenario [6], while on “b”, “c” and “d” they are taken the Gaussians (see [2]). Dashed curves show the inverse problem solution with the error bars (2.5 standard deviation) estimated with the Monte-Carlo simulations for random input parameters (see [1, 5] for more details).

The parameters of the Maxwellian plasma component are recovered rather well (Fig. 1(a)), whereas for non-Maxwellian component the accuracy is essentially worse (Fig. 1(b)-(d)). The latter may be improved via using additionally the EC diagnostic data (Fig. 2).

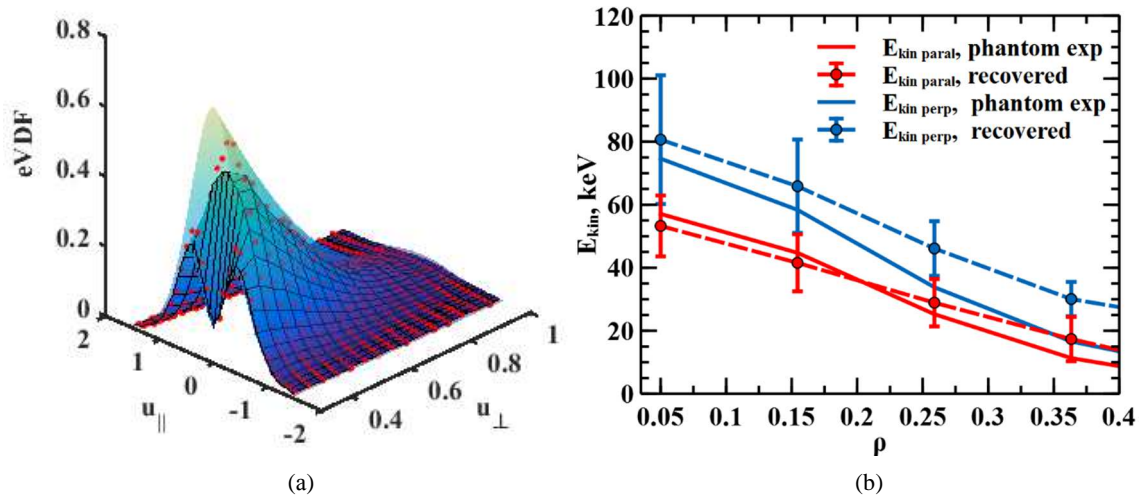


Fig. 2. The results of the eVDF recovering from the EC+TS data: (a) the eVDF for hot electrons as a function of momentum components normalized to $m_e c$; (b) mean energies of hot electrons (error bars correspond to 2.5 standard deviation).

3. Conclusions. A new algorithm is suggested for complex diagnostics of the electron velocity distribution function (eVDF) under condition of a substantial deviation from the Maxwellian eVDF. An inverse problem is formulated, which is based on the TS spectrum diagnostic and the EC emission (for moderate- or high-number harmonics of fundamental EC frequency) spectrum diagnostic. It is shown that there is a possibility to improve the recovery of the hot electrons eVDF parameters from the TS diagnostics via using the combined TS+EC diagnostics.

Acknowledgements. We thank V.I. Poznyak for helpful discussion of the EC diagnostics experimental issues. The part of work related to inverse problems solutions is supported by the Russian Foundation for Basic Research (grant RFBR-15-07-07850-a).

References

- [1] G.S. Kurskiev, P.A. Sdvizhenskii, A.B. Kukushkin, E.E. Mukhin, M. Bassan. Proc. 41st EPS Conf. Plasma Physics, Berlin, 2014, P5.009.
- [2] P.V. Minashin, A.B. Kukushkin. International Review of Atomic and Molecular Physics (IRAMP), **4** (2), 93-104 (2013).
- [3] E.E. Mukhin, et al. AIP Conf. Proceedings **1612**, 69-72 (2014).
- [4] G. Zhuang, et al. Plasma Physics Control. Fusion, **47**, 1539–1558 (2005).
- [5] G.S. Kurskiev, P.A. Sdvizhenskii, M. Bassan, P. Andrew, A.N. Bazhenov, I.M. Bukreev, P.V. Chernakov, M.M. Kochergin, A.B. Kukushkin, A.S. Kukushkin, E.E. Mukhin, A.G. Razdobarin, D.S. Samsonov, V.V. Semenov, S.Yu. Tolstyakov, S. Kajita and S.V. Masyukevich, Nucl. Fusion **55** (2015).
- [6] A.R. Polevoi, et al. Proc. 37th EPS Conf. Plasma Physics, Dublin, 2010, P2.187.