Determination of the electron energy distribution function in the ISTTOK tokamak

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Abstract. The first derivative probe technique was applied to study the ISTTOK tokamak plasma. This technique employs the electron part of the Langmuir probe current-voltage (IV) characteristic and yields information on the plasma potential and the electron energy distribution function (EEDF). The IV characteristic was measured with new electrical probes mounted on a horizontal manipulator, one oriented in parallel and the other perpendicularly to the magnetic field lines. Using the first-derivative probe technique, the plasma potential and the EEDF at different radial positions were acquired. We show that, in the vicinity of the last close flux surface (LCFS), the EEDF is non-Maxwellian and can be approximated by a bi-Maxwellian one with a dominant cold electron population and a minority group of hot electrons. In the limiter shadow, the EEDF obtained is Maxwellian.

The comparison of the plasma parameters evaluated using the first-derivative probe technique for both probes shows a satisfactory agreement.

1. Introduction

In non-magnetized, low-density plasmas, Langmuir probes (LP) allow local measurements of the plasma potential, the charged particles density and the electron energy distribution function, \( f(E) \) (EEDF). In magnetized plasmas, the interpretation of the electron part of the current-voltage (IV) characteristic above the floating potential is difficult – the electron part of the IV characteristic is distorted due to the influence of the magnetic field. This is why a new, advanced method to solve the problem has to be applied.

The recently-developed [1,2] first-derivative probe technique (FDPT) makes use of the electron part of the Langmuir probe IV characteristic and provides information on the plasma potential and the
electron energy distribution function. Dedicated investigations aiming at evaluating the EEDF employing this method have revealed a bi-Maxwellian EEDF in the CASTOR edge plasma [2], in the COMPASS tokamak and, more recently in the liquid lithium divertor area of NSTX [3]. This technique was applied to the investigation of ISTTOK tokamak plasma.

In the ISTTOK tokamak, we acquired data on the plasma potential and the EEDFs at different radial positions using electrical probes, one oriented parallel and the other perpendicular to the magnetic field. The results demonstrated that, in the vicinity of the LCFS plasma, the EEDF is not Maxwellian, but may be approximated by a bi-Maxwellian with a dominant cold electron population and a group of hot electrons. In the limiter shadow, the EEDF obtained is Maxwellian.

2. The first-derivative probe technique for evaluation of the plasma parameters in tokamak plasma

The FDPT for evaluating the plasma potential, electron temperature and density in tokamak edge plasma was published and discussed in detail in [2]. It was shown there that the electron current flowing to a cylindrical probe negatively biased by potential \( U_p \) is given by:

\[
I_e(U) = \frac{8\pi e S}{3m e^2} \int_{eU/W}^{\infty} \frac{(W - eU) f(W)dW}{1 + \left(\frac{W - eU}{W}\right)^{(W\psi)}},
\]

where \( W \) is the electron energy; \( e \) and \( m \) are the electron charge and mass; \( S \) is the probe area; \( U \) is the probe potential with respect to the plasma potential \( U_{pl} \) (\( U = U_p - U_{pl} \)). The geometric factor \( \gamma \) assumes values in the range \( 0.71 \leq \gamma \leq 4/3 \).

The important parameter in equation (1) is the diffusion parameter \( \psi = \psi(W) \). In the presence of a magnetic field \( B \) at low gas pressures, \( \psi \) depends on the Larmor radius \( R_L(W, B) \), as well as on the shape, size and orientation of the probe with respect to the magnetic field. As it was shown [2] in strongly turbulent tokamak plasma for probes oriented perpendicular to the magnetic field lines (\( \psi_\perp \)) and for probes oriented along magnetic field lines (\( \psi_\parallel \)), the diffusion parameter can be expressed as:

\[
\psi_\perp (W, B) = \frac{R\ln(\pi L/4R)}{16\gamma R_L(W, B)} \quad \text{and} \quad \psi_\parallel (W, B) = \frac{\pi L}{64\gamma R_L(W, B)}.
\]

Here \( L \) and \( R_L(W, B) \) are the characteristic cross-section size of the turbulent structures (blobs) and the electron Larmor radius. As the number of collisions in the probe sheath increases, so does the value of the diffusion parameter. When \( \psi(W, B) \gg 1 \) (high value of the magnetic field \( B \)), the EEDF is represented by the first derivative, instead of the second derivative, of the electron probe current, as was shown in [1,2,4]:

\[
f(\varepsilon) = \frac{3\sqrt{2}\pi \gamma \psi dI_e}{2e^3S \int U dU}.
\]

3. Langmuir probe measurements in the ISTTOK tokamak

Radial measurements were performed of the current-voltage characteristics with new electrical probes, one oriented parallel and the other perpendicular to the magnetic field in the ISTTOK tokamak and mounted on a horizontal manipulator. Figure 1 shows the cylindrical Langmuir probe tips with a length of 3 mm and a diameter of 0.75 mm. The position of the manipulator was changed from shot-
to-shot; during the different shots the plasma parameters were reproducible at a toroidal magnetic field $B = 0.45$ T. The probes were biased with respect to the tokamak chamber wall by a triangular voltage $U_p(t)$ with a frequency of 1 kHz [5].

An example of the results obtained for shot #34810 (working gas $H_2$, plasma current 4 kA and average electron density $3.5 \times 10^{18}$ m$^{-3}$) are presented in figure 2. The experimental $IV$ characteristics are measured by both probes during the steady-state plateau of the discharge at a position of 80 mm from the tokamak chamber center. Figure 3 presents the first derivative of the smoothed $IV$ curves and the fit with the model curve (first derivative of equation (1)). Using this comparison, one can evaluate the plasma potential.

![Figure 2](image1.png)  
**Figure 2.** Current-voltage characteristics for perpendicular and parallel probes at position 80 mm from the tokamak center.

![Figure 3](image2.png)  
**Figure 3.** First derivatives of the smoothed experimental $IV$ characteristics. Model curves – red lines.

Figures 4a and 4b present the EEDFs obtained by parallel and perpendicular probes and applying equation (3). It is seen that the EEDFs can be approximated by a bi-Maxwellian – i.e., by a sum of two Maxwellian EEDFs with two different electron temperatures and densities. In this case, we have the

![Figure 4a](image3.png)  
**a) parallel probe**

![Figure 4b](image4.png)  
**b) perpendicular probe**

**Figure 4.** Experimental EEDF for perpendicular and parallel probes (black curves) at probe position 80 mm from the tokamak chamber center. The blue line represents the distribution of the low-energy electron population; the red line is the high energy one. The dash-dot line is the bi-Maxwellian approximation (a sum of the blue and the red ones).
same temperatures on both probes, namely, 4 eV and 12 eV. In the limiter shadow (88 mm from the center) the EEDF is Maxwellian (figure 5) with electron temperature $T_e = 7.5 \pm 0.7$ eV and electron density $n_e = (4.8 \pm 1) \times 10^{17}$ m$^{-3}$.

4. Results and discussion
The radial distributions of the plasma potential, ion saturation current density, electron temperatures and densities are presented in figure 6a-d. The results refer to both the perpendicular and the parallel probe. Figures 6a presents the radial distribution of the ion saturation current density. Notwithstanding of different orientation of the probes, the current densities values evaluated by both of the probes practically coincide and thus we can compare other plasma parameters measured by them. Figure 6b shows the radial distribution of the plasma potential. The position of the poloidal limiter is indicated at 85 mm. Based on the position of the maximum of the plasma potential radial distribution, we concluded that the position of the LCFS is at 75 mm from the tokamak chamber center.

The accuracy of the plasma potential evaluation is ~5 V. The discrepancy in the values obtained in the confined plasma can be explained by the slightly different radial positions of the probes where the gradient of the plasma potential is large.

![Figure 5. The EEDF obtained at 88 mm probe position from the tokamak chamber center.](image)

![Figure 6. Plasma parameters at different radial positions.](image)
Figure 6c and 6d present the radial distribution of the electron temperatures and densities. The triangles correspond to the values of the more populated low-energy electron fraction, while the squares indicate the values of the suprathermal electrons from the bi-Maxwellian EEDF. The dots indicate the temperature of the Maxwellian EEDF. It is seen that the density of the hot-electron group is about 40-50% of the low-temperature one. Taking into account the uncertainties in all values measured, the temperatures of the low-energy electron group are evaluated with an accuracy of about 10%, while that for the suprathermal electrons is about 20%. The uncertainties of the electron densities are within 30%. Thus, the comparison of the parameters evaluated using the FDPT for both probes shows a satisfactory agreement.

The behavior of the electron temperature spatial distribution in the vicinity of the LCFS can be explained by the plasma turbulence and non-local kinetic effects [6]. To explain the bi-Maxwellian EEDF behaviour, a “heuristic model” accounting for the ionization of neutral hydrogen is proposed in [3]. It has to be noted that, in the limiter shadow, the EEDFs established are Maxwellian with a temperatures of about 6-7 eV which are not enough for ionization. The most probable reactions in this energetic diapason are dissociation with threshold of 4.5 eV and excitation.

4. Conclusions
The first-derivative probe technique was used to evaluate the radial distribution of the main plasma parameters (plasma potential, the electron energy distribution function and the electron densities) in the strongly magnetized turbulent ISTTOK tokamak plasmas. The measurements are performed from probe position from 60 to 90 mm in regards to the tokamak center by new electrical probes mounted on a horizontal manipulator, one oriented in parallel and the other perpendicularly to the magnetic field lines. The position of the LCFS at 75 mm from the tokamak chamber center was evaluated by the maximum of the radial profile of the plasma potential.

Radial evaluations of the EEDF show that, at the vicinity of the LCFS the EEDF is non-Maxwellian and can be approximated by a bi-Maxwellian one with a dominant cold electron fraction and a minority group of hot electrons. In the limiter shadow the EEDFs obtained are Maxwellian.

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