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On the Evaluation of the Plasma Potential and Electron Energy Distribution Function in Tokamak Edge Plasma

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1. Introduction

The knowledge of the plasma potential, U_{pl}, is of importance for evaluating the electron energy distribution function (EEDF) and understanding the underlying physical processes occurring at the plasma edge in tokamaks, such as the formation of transport barriers, plasma–wall interactions, edge plasma turbulence, etc. Different kind of probes (emissive, ball-pen, etc) are used for direct measurement of the plasma potential [1] and the use of classical Langmuir probes for this purpose is still under discussion.

In this work we report a procedure for both plasma potential and EEDF measurements in tokamak edge plasmas by Langmuir probes. The processing of the electron probe current in the presence of a magnetic field is based on the kinetic theory in a non-local approach [2].

2. First derivative probe method

It was shown in [2] that the electron probe current for a cylindrical probe of the radius *R* and length *L* at negative potentials is given by:

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

where W is the total electron energy, $\psi(W)$ is a diffusion parameter, e, m and n are the electron charge, mass and density, S is the probe area, U is the probe potential with respect to the plasma potential. The geometric factor $\gamma = \gamma(R/\lambda)$ assumes values in the range $0.71 \le \gamma \le 4/3$. Here $f(W)$ is the isotropic EEDF, normalized by: $\frac{4\pi\sqrt{2}}{m^{3/2}}\int_0^{\infty} f(W)\sqrt{W}\,dW = \int_0^{\infty} f(\varepsilon)\sqrt{\varepsilon}\,d\varepsilon = n$. If the diffusion parameter $\psi(W)$ is negligible ($\psi << 1$), taking $\gamma = 4/3$ the equation (1) is reduced to the classical expression of the Langmuir formula for the electron probe current:

$$I_e(U) = -\frac{2\pi e S}{m^2}\int_{eU}^{\infty}(W-eU)\,f(W)\,dW \tag{2}$$

This approximation is valid for a low gas pressures and for low magnetic fields; namely when the electron mean free path or the Larmor radius is larger than the characteristic dimension of the probe sheath. When the electron mean free path is comparable with the characteristic dimension of the probe sheath and when electron motion in the probe sheath is diffusive, equation (1) must be taken into account. At strong magnetic fields (or relatively high gas pressures, > 1000 Pa), which means high diffusion parameter values (ψ >> 1), it has been shown in [2] that the EEDF, $f(\varepsilon)$, is represented not by the second derivative of the electron probe current (Druyvesteyn formula), but rather by its first derivative as:

$$f(\varepsilon) = -\frac{3\sqrt{2m}\gamma\psi(\varepsilon)}{2e^3 SU}\frac{dI}{dU} \tag{3}$$

Obviously, in order to evaluate the EEDF the values of the diffusion parameter $\psi(W)$ must be known. In the presence of magnetic field, $\psi(W)$ depends on the plasma parameters, shape, size and orientation of the probe. For a probe perpendicular to the magnetic field the diffusion parameter is given by [3]:

$$\psi_{\perp}(W) = \frac{R\ln\left(\frac{\pi L'}{4R}\right)}{16\gamma R_L(W,B)} \quad \text{and the EEDF} \quad f(\varepsilon) = -\frac{3\sqrt{2m}R\ln\left(\frac{\pi L'}{4R}\right)}{32e^3 SR_L(W,B)U}\frac{dI}{dU} \tag{4}$$

Here, $R_L(W,B)$ is the Larmor radius for electrons. For probes oriented parallel to the magnetic field the diffusion parameter is:

$$\psi_{//}(W) = \frac{\pi L'}{64\gamma R_L(W,B)} \quad \text{and the EEDF} \quad f(\varepsilon) = -\frac{3\pi\sqrt{2m}L'}{128e^3 SR_L(W,B)U}\frac{dI}{dU} \tag{5}$$

Hence the U_{pl} value must be known so that the EEDF can be measured. When the diffusion parameter $\psi(W)$ is negligible ($\psi << 1$) the electron probe current is described by equation (2) and the plasma potential may be estimated at the position of the bend of IV characteristic or at the minimum of its first derivative. As shown in [4], for a large, constant value of the diffusion parameter $\psi = \psi_0 >> 1$, the minimum of the first derivative of the IV characteristic is shifted (figure 1) by a value equal to the electron temperature (expressed in volts) towards negative probe potentials in respect to the plasma potential (set as 0 in the figures).

At strong magnetic field the diffusion parameter is large, but not constant $\psi(W) = \psi_0/\sqrt{W} >> 1$. In this case, our model calculations for a Maxwellian EEDF with different electron temperatures (figure 2) show that the minimum is shifted by a value equal to 1.5 T (T being the electron temperature). When $\psi(\varepsilon) = \psi_0/\sqrt{W} > 1$, but not too large, the minimum of the first derivative of the IV characteristic is shifted by a value in between T and 1.5 T.

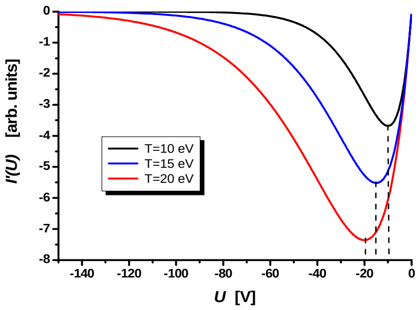

Figure 1

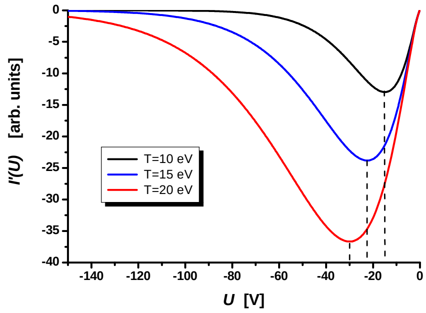

Figure 2.

The model calculations for a Maxwellian EEDF (T = 10 eV) of the electron probe current using the equation (1) are presented in figure 3. Figure 4 shows its first derivatives for different values of ψ_0 in the diffusion parameter equation $\psi(\varepsilon) = \psi_0 / \sqrt{W}$.

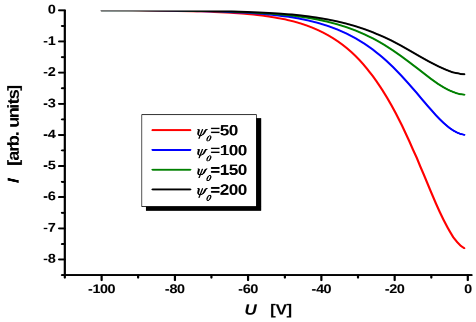

Figure 3

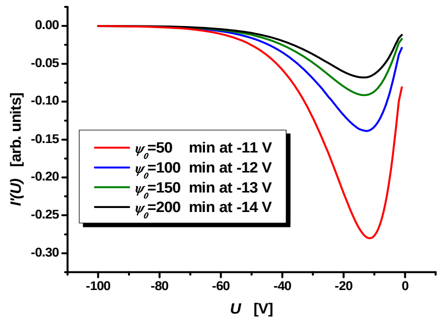

Figure 4

In this case, for an accurate evaluation of U_{pl} , hence, of the EEDF, we propose the following procedure: the electron temperature is evaluated from the slope in logarithmic scale of the first derivative of the experimental IV characteristic; the best fit using the model calculation provides the value of the plasma potential; then the EEDF may be evaluated using equation (3).

3. Results and discussion

The method was applied in the CASTOR tokamak edge plasma [5,6]. The IV characteristics were measured using an array of 11 probes oriented parallel to the magnetic field (B = 1.3 T). Each cylindrical probe tip has a length $L = 2$ mm and radius $R = 0.35$ mm, and they are radially displaced from each other by 2.5 mm. The probes were inserted into the edge plasma from the top of the tokamak.

Figure 5 presents the first derivative of the smoothed IV curve [7] during the shot #27034 for the parallel probe #1 (the deepest), displaced by 58 mm from the centre of the tokamak poloidal cross-section. In the same figure the fit using the model curve is presented, and from the comparison the plasma potential $U_{pl} = 50$ V may be evaluated. One can observe a bend (not always well pronounced) in the experimental curve. In practice, even a small increment of $I(U)$ at a probe potential U, positive with respect to plasma potential, leads to $I'(U)$ deviating from zero at U_{pl} . Additional reasons for this feature may be plasma potential fluctuations due to the plasma turbulence and biasing effects due to the smoothing of the experimental IV characteristic.

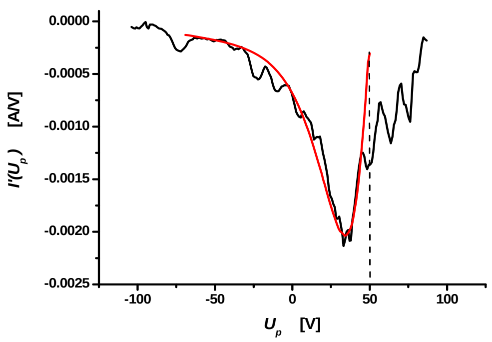

Figure 5

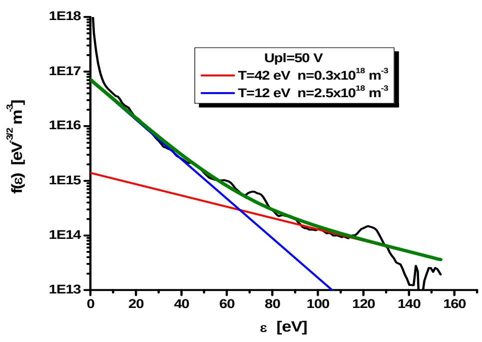

Figure 6

Figure 6 presents the EEDF obtained using equation (5). It is clearly seen that the electron energy distribution function is bi-Maxwellian, which is in accordance with our previous investigations [5,6].

4. Conclusion

The first derivative Langmuir probe method was used to process the electron part of the current-voltage characteristics measured in the CASTOR tokamak edge plasma. A procedure for the accurate evaluation of the plasma potential, respectively EEDF is presented.

Measurements were carried out by cylindrical probes parallel to the magnetic field. The values of the plasma potential, EEDF, electron temperature and electron densities are evaluated. The presented results demonstrate that the proposed procedure allows evaluating additional plasma parameters using the electron part of the current-voltage Langmuir probe characteristics in tokamak edge plasmas.

Acknowledgments

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