Advanced probe measurements of electron energy distribution functions in CASTOR tokamak plasma

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Abstract. Langmuir probes are known for their ability to provide local measurements of very important plasma parameters, namely the plasma potential, the density of the charged particles and the electron energy distribution function (EEDF). The correctness of using the probes under adverse conditions, such as presence of magnetic fields or high plasma temperature is still being questioned. In this paper we report the application of the first-derivative Langmuir probe method for processing the electron part of the volt-ampere (IV) characteristics measured in the CASTOR tokamak plasma. First results of EEDFs at different radial positions in the edge plasma are presented and the values of the plasma potential, electron temperature and electron densities are estimated. The applicability of the first-derivative Langmuir probe method in strongly magnetized, high temperature tokamak plasmas is discussed.

1. Introduction

Among the contact methods of plasma diagnostics, the electric probes are the least expensive and still the fastest and most reliable diagnostic tools allowing one to obtain the values of very important plasma parameters; Langmuir probes (LP) allow local measurements of the plasma potential, the charged particles density and the electron energy distribution functions (EEDF).

Application of these probes under adverse conditions e.g., presence of magnetic fields or high plasma temperatures, is still under discussion. On the other hand, measurements of the plasma edge temperatures and the electron densities in tokamak are generally carried out by means of LPs [1]. In single LP experiments, the electron part of the current-voltage (IV) characteristics is strongly distorted by the tokamak magnetic field. For this reason, the ion saturation part and the part around the floating potential are usually taken into account when retrieving the plasma parameters.

The recently developed kinetic theory [2, 3] may be used for calculation of the plasma parameters from the first derivative of the electron probe current. In this work we report first results of the EEDFs measurements in the CASTOR tokamak edge plasma (IPP.CR, Prague, Czech Republic) at different radial positions and present the values acquired of the plasma potential, the electron temperature and the electron densities.

Finally, we discuss the applicability of the first derivative Langmuir probe method to measurements in strongly magnetized, high temperature tokamak plasmas.

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2. First derivative Langmuir probe method

A kinetic theory in a non-local approach for processing the electron probe current in the presence of a magnetic field was published recently [2]. The theory for magnetized plasmas was developed for Langmuir probes in the case when the linear size, L_p, of the region disturbed by the probe is less than the electron energy relaxation length λ_ε :

$$\lambda_\varepsilon \approx 2\left(\frac{D}{\nu_{ee} + \delta\nu_a + \nu^*}\right)^{1/2}, \tag{1}$$

where the diffusion coefficient is $D = \mathrm{v}\ \lambda(\varepsilon)/3$, $\lambda(\varepsilon)$ is the free path of the electrons and ν_{ee}, ν_a, ν^* are the frequencies of electron-electron, electron-heavy particles elastic and inelastic collisions. $\delta = 2m/M$, where *m* and *M* are the electron and the heavy particles masses respectively.

It was shown that the electron probe current for a cylindrical probe with radius *R* and length *L* at negative probe potentials is:

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

where $W = mc^2/2 + eU$, *e* and *n* are the electron charge and density, *c* is the velocity of electrons, *S* is the probe area, *U* is the probe potential with respect to the plasma potential U_{pl}. The geometric factor $\gamma = \gamma(R/\lambda)$ assumes values in the range $4/3 \le \gamma \le 0.71$

Here $f(W)$ is the isotropic electron distribution function, normalized to 1 by:

$$\frac{4\sqrt{2}\pi}{m^{3/2}}\int_0^{\infty} f(W)\sqrt{W}dW = 1 \tag{3}$$

The diffusion parameter $\psi(W)$ for a cylindrical probe is:

$$\psi(W) = \frac{1}{\gamma\lambda(W)}\int_R^{\infty}\frac{D(W)dr}{(r/R)D(W-e\phi(r))} \tag{4}$$

In a presence of a magnetic field $\vec{B}$, the diffusion coefficient $D(W)$ in a non-local approach becomes a tensor with two components [4]:

$$D_{\parallel} = \mathrm{v}^2\lambda(W)/3 \qquad \text{and} \qquad D_{\perp} = D_{\parallel}/\rho$$

where

$$\rho = \left[1 + \frac{\lambda(W)^2}{R(W,B)_L^2}\right]^{1/2} \tag{5}$$

(R_L being the Larmor radius.) Obviously, the diffusion parameter will also depend on the orientation of the probe: If the cylindrical probe is oriented perpendicularly to the magnetic field in the case of a thin sheath ($R_L \ll \lambda$), then:

$$\psi(W)_{\perp} = \frac{R}{\gamma R_L}\ln\frac{\pi L_p}{4R}. \tag{6}$$

If the probe is oriented parallel to the magnetic field, then:

$$\psi\left(W\right)_{\mathrm{II}} = \frac{\pi L_p}{4\gamma R_L} \tag{7}$$

In equation (4), the upper limit of the integral is replaced by $4L_p / \pi$.

In the case of a strong magnetic field, the diffusion parameter $\psi >> 1$ and γ~1, so that we can write for the electron probe current:

$$I_e\left(U\right) = -\frac{8\pi eSn}{3m^2}\int_{eU}^{\infty}\frac{(W-eU)\,f(W)dW}{\psi(W)}, \tag{8}$$

and, as was shown in [5], the electron energy distribution function, $f\left(\varepsilon\right)$, is then represented not by the second derivative of the electron probe current (Druyvesteyn formula), but rather by its first derivative:

$$I'(U) = -const\,\frac{eU}{\psi(\varepsilon)}\,f(\varepsilon). \tag{9}$$

For a probe oriented perpendicularly to the magnetic field we can than write [3]:

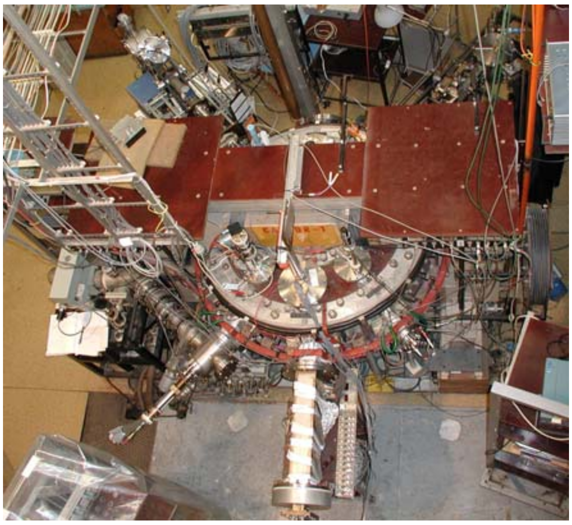
$$f(W) = -\frac{3m^2 R \ln\dfrac{\pi L_p}{4R}}{8Sne^3 R_L U}\frac{dI(U)}{dU}. \tag{10}$$

If the probe is oriented parallel to the magnetic field:

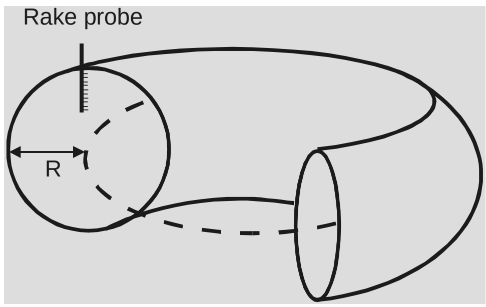
$$f(W) = -\frac{3m^2 L_p}{32Sne^3 R_L U}\frac{dI(U)}{dU}. \tag{11}$$

3. Langmuir probe measurements at CASTOR tokamak edge plasma, Institute of Plasma Physics, Association EURATOM-IPP.CR, Prague, Czech Republic.

The IV characteristics measurements at CASTOR tokamak edge plasma were carried out by using an array of 16 single Langmuir probes (rake probe), oriented perpendicular to the magnetic field (figure 1).



CASTOR-<u>C</u>zech <u>A</u>cademy of <u>S</u>ciences <u>TOR</u>us



Major radius	400 mm
Minor radius R	100 mm
Toroidal magnetic field	0.5-1.5 T
Plasma current	5-20 kA
Pulse length	<50 ms
Working gas	30-40 mPa hydrogen

Figure 1. Photograph of CASTOR tokamak (top view), Institute of Plasma Physics, Association EURATOM-IPP.CR, Prague, Czech Republic and schematic representation with its main parameters.

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Each probe tip has a length of 2 mm and radius of 0.35 mm. The probes are placed at a distance 2.5 mm from each other with a total length of 35 mm (figure 2). All probe tips are biased simultaneously by a triangular voltage *U*(*t*) with respect to tokamak chamber, which serves as a reference electrode. The time necessary to measure a single IV characteristic is typically ~ 1 ms.

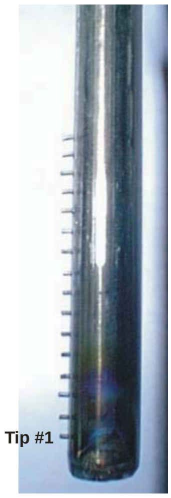

Figure 2a. Photograph of the rake probe.

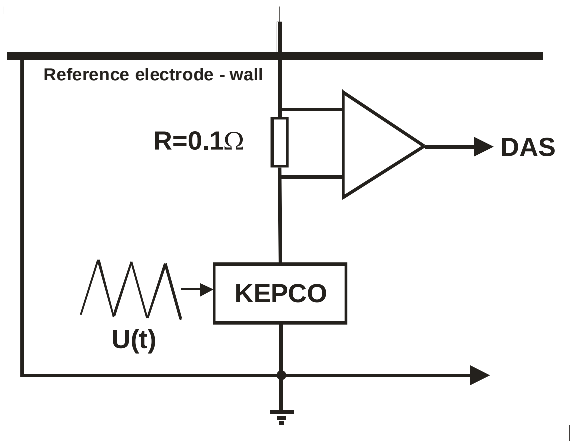

Figure 2b. Schematic diagram of the single probe circuit.

The data measured for shot # 26403; pin #8 displaced by 71.5 mm from the centre of the CASTOR poloidal cross-section are presented in figure 3:

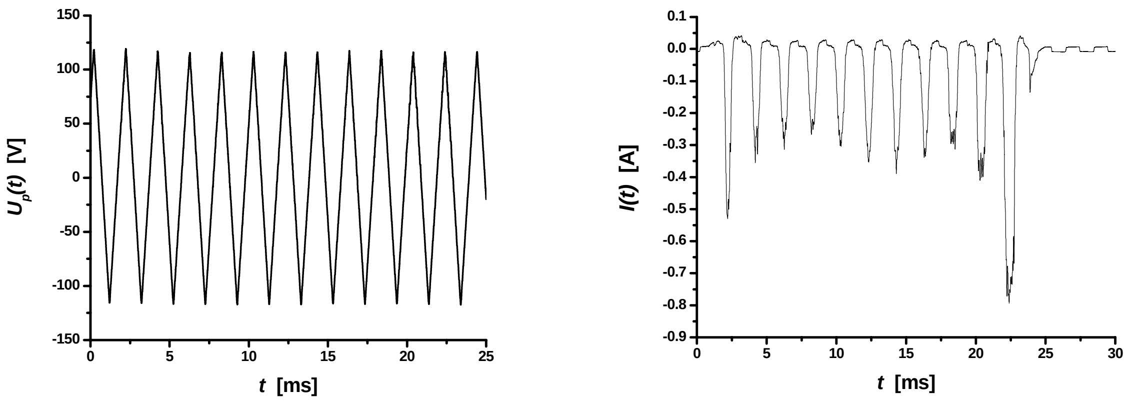

Figure 3. Probes bias *U*(*t*) and probe current *I*(*t*) during the shot #26403 for pin #8.

4. Procedure for evaluating the plasma potential, the electron temperature and the electron density using the electron part of the IV characteristics.

To demonstrate the procedure of evaluating the plasma potential, U_{pl}, the electron energy distribution function, $f(\varepsilon)$, and the electron density, *n,* we will consider a single IV characteristic at the middle (~10–11 ms) of the current pulse. The experimental data was processed by using the Origin Lab 6.1 software. The single IV characteristic was smoothed by adjacent averaging of 150 points (figure 4). As was shown (equation (10)), the EEDF is proportional to the first derivative of the electron probe current. Figure 5 presents the first derivative of the smoothed IV curve.

For further processing, one must know the value of the plasma potential.

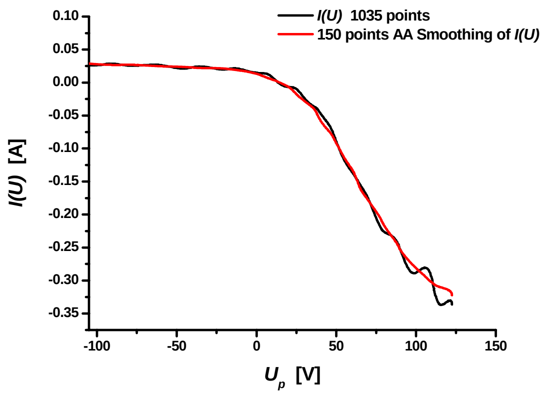

Figure 4. Single IV characteristic at the middle (~10–11 ms) of the current pulse.

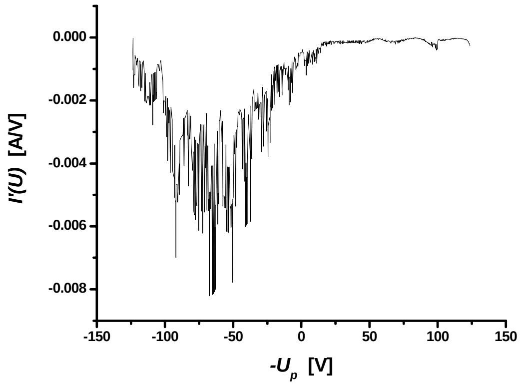

Figure 5. First derivative of the smoothed IV curve.

For an ideal IV which is saturated at probe potentials $U > 0$ with respect to the plasma potential, the plasma potential corresponds to the zero of the first derivative. In practice, even a small increment of $I(U)$ at $U > 0$ leads to $I'(U)$ deviating from zero at plasma potential. Additional reasons for this may be plasma potential fluctuations due to the turbulences and the smoothing of the experimental IV characteristic.

At $\psi >> 1$, as was shown in [6], the plasma potential is shifted before the maximum of the first derivative by a value equal to the electron temperature (in volts). In figure 5 the plasma potential is 80 V. One can observe there a more or less pronounced bend in the first derivative curve (figure 6).

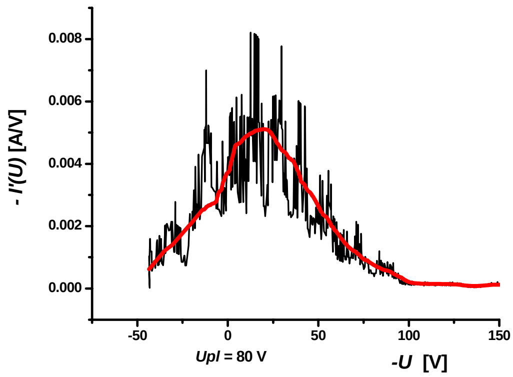

Figure 6

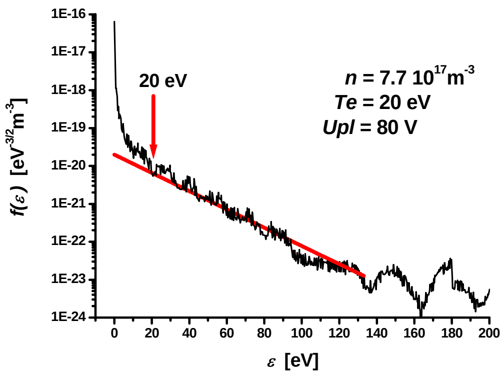

Figure 7

The electron density, n, may be obtained by comparing the best fit of the experimental distribution function to the normalized to 1 Maxwellian EEDF:

$$f_M(\varepsilon) = \frac{2}{T_e^{3/2}\sqrt{\pi}} \exp\left(-\frac{\varepsilon}{T_e}\right) \tag{12}$$

Figure 7 presents the EEDF corresponding to equation (9) (black curve). It is clearly seen that the electron energy distribution function is Maxwellian with temperature T_e = 20 eV (red line). The discrepancy in the energy interval from zero to 20 eV may be explained by the behaviour of the first derivative within the range of probe potentials $U = 0 \div -20$ V.

At electron energies exceeding 130 eV, the level of the signal is too low and only noise is registered.

5. Results and discussion.

Table 1 presents the radial distribution of the electron temperature in the CASTOR plasma. It is interesting to note that at 54, 56.5 and 59 mm from the centre, the EEDF is not strictly Maxwellian, but may be approximated by a bi-Maxwellian distribution (figure 8).

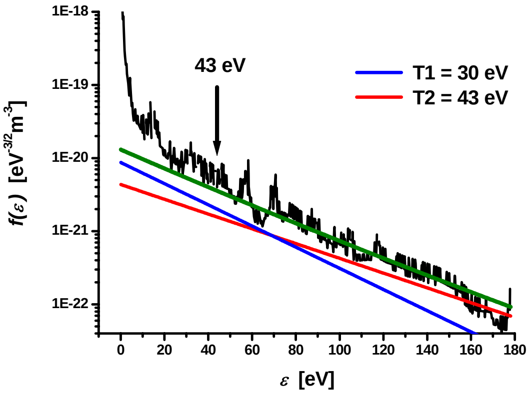

Figure 8. Experimental EEDF at 54 mm from the centre (black curve) and two-temperature approximation. The green curve is the sum of the 30 eV and 43 eV curves.

Table 1. Radial distribution of the electron temperature in the CASTOR plasma**.**

Radial position [mm]	Electron temperature [eV]
54	30
	43
56.5	24
	40
59	23
	33
61.5	31
64	30
66	26
68	23
71.5	20
74	18
76.5	16
79	13
81.5	14
84	13
86	13
89	12
91	12

The results obtained are compared to those evaluated by the Stangeby method [1] (figure 9). It is seen that our data in the interval 56-80 mm are somewhat lower. This may be explained by the fact that in processing the data by the Stangeby method the average values from the consecutive IV characteristics during current pulse are taken.

We must also point out that in Stangeby method a Maxwellian EEDF of the electrons is assumed, but not measured.

The best fit with the experimental EEDF was obtained with an accuracy of 5%. Taking into account all factors affecting the accuracy, the uncertainty in the electron temperatures evaluated by the first derivative method are in the range of $\pm$ 4 eV.

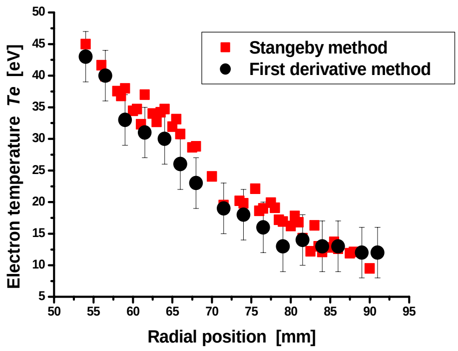

Figure 9.

The next figure (figure 10) shows the radial distribution of the plasma potential.

Figure 11 presents the radial distribution of the electron densities. The uncertainty in the values evaluated does not exceed $\pm$50%. For comparison, in figure 12 we give Stangeby method values acquired from different shots.

In general, the results obtained by the two methods are in good agreement. However, the first derivative method allows one to obtain in addition the real EEDF and the plasma potential values.

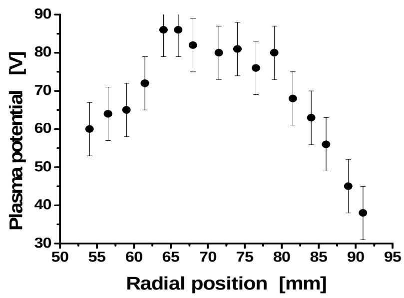

Figure 10.

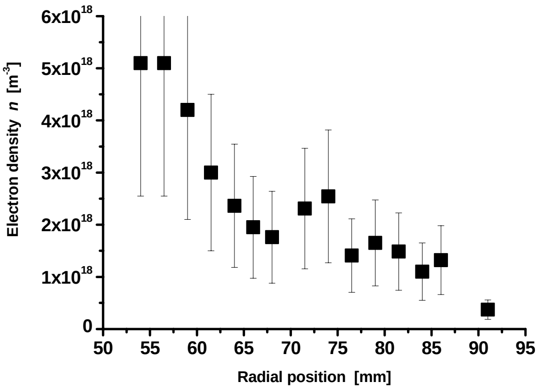

Figure 11. Radial distribution of the electron density in the CASTOR plasma (this work).

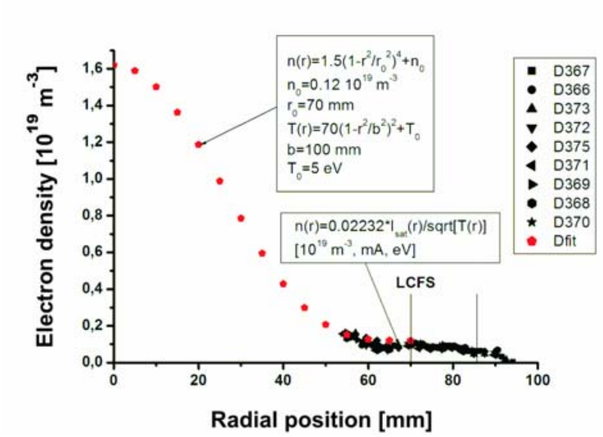

Figure 12. Electron density values acquired from different shots by Stangeby method.

When considering the results obtained using a Langmuir probe in the presence of a strong magnetic field, the spatial resolution of the measurements must also be discussed. For a large negative probe potential (with respect to the plasma potential) the probe-disturbed length for the ions [1] along the magnetic field lines is:

$$L_p^i = \frac{Ac_s}{8D_\perp}, \qquad (13)$$

where A is projection of the probe in the $\vec{B}$ direction and $c_s = \left[(T_e + T_i)/m_i\right]^{1/2}$ is the (isothermal) ion acoustic velocity. In the presence of plasma turbulences, the diffusion coefficient must be set equal to the Bohm diffusion value [1] $D_\perp = D_\perp^{Bohm} = 0.06T_e[eV]/B[T]$.

In a similar way, for a probe potential corresponding to the electron part of the IV characteristic the electron probe-disturbed length is:

$$L_p^e = \frac{A\bar{c}_e}{16D_\perp}\exp\left(-\frac{eU}{kT_e}\right), \qquad (14)$$

where $\bar{c}_e = \left(8kT_e/\pi m_e\right)^{1/2}$ is the thermal electron velocity.

The probe projection is 2 × (2 mm × 0.7 mm) → $A = 2.8 \times 10^{-6}$ m^2, so that for a magnetic field $B = 1.3$ T in the range of interest of electron temperatures ($T_e \geq T_i$) we have:

Table 2. The electron and ion probe-disturbed length.

T_e (eV)	L^i_p (m)	L^e_p (m)
40	17 10^{-3}	0.39
10	31 10^{-3}	0.76

In the discussion of the probe-disturbed length, the characteristic dimension of the turbulent structures must be taken into account. Such measurements have been performed on CASTOR by means of the 2D array of Langmuir probes [8], figure 13 show a snap shot of the projection of potential structures to a fraction of the poloidal cross section.

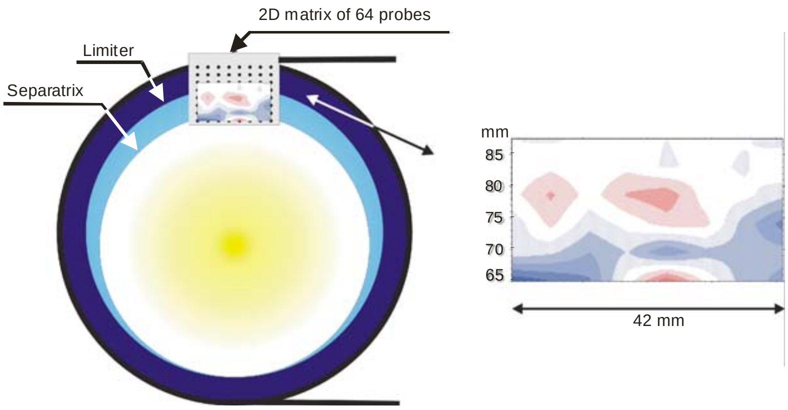

Figure 13.

It is seen that the characteristic dimension of the disturbed area is in the order of L_P = 2 – 10 mm, which is comparable to the probe length. This value must be assumed as the upper limit of the integral for the diffusion parameter in equation (4) and further in equations (6), (7) etc.

Another problem in Langmuir probe measurements is the availability of sufficient reference probe area. The reference probe surface area must be large enough to withstand all the current collected from the measuring probe without a noticeable potential drop [7]. In practice, in a number of tokamaks, installing the probes involves mounting the probes within an existing edge structure, such as limiter, with the probe face flush to the main surface [1]. Then, if the probe-disturbed length is larger than the distance between the probe and the reference solid surface, the requirement for a sufficient probe/reference probe surface may be not satisfied and the charged particles collection may be impeded.

In our case, the rake probe is inserted into the edge plasma from the top of the torus, 180^0 toroidally away from the poloidal limiter and the probe-disturbance length is much less than the probe-limiter distance for the temperature ranges of interest.

6. Conclusion

The first derivative Langmuir probe method is used for processing the electron part of the current-voltage (IV) probe characteristics measured in the CASTOR tokamak edge plasma (Institute of Plasma Physics, Association EURATOM-IPP, Prague, Czech Republic).

First results of EEDFs for real tokamak plasma at different radial positions in the edge plasma are acquired and the values of the plasma potential, electron temperature and electron densities are evaluated. It is shown that close to the bulk plasma the EEDF is not strictly Maxwellian.

The comparison of the results obtained with the results given by the Stangeby method yields a satisfactory agreement.

The applicability of the first derivative Langmuir probe method in strongly magnetized, high temperature tokamak plasmas is discussed.

The results presented demonstrate that the procedure proposed allows one to acquire additional plasma parameters using the electron part of the current–voltage Langmuir probe characteristics in tokamak edge plasma measurements.

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