# Langmuir probe diagnostics of the plasma potential and electron energy distribution function in magnetized plasma

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In this Topical lecture, methods for using Langmuir probes in magnetized plasmas are presented. The electron part of the current-voltage probe characteristics was used in order to obtain the plasma potential, the electron energy distribution function (respectively the electron temperature and the electron density).

## 1. Probe measurements in magnetized plasma

The measured $f(\varepsilon)$ (EEDF) in magnetized plasma is of a great interest due to the importance in laboratory and practical applications. A kinetic theory for processing the electron probe current in the presence of a magnetic field was published in [1,2]. The theory was developed for Langmuir probes in a non-local approach when the electrons reach the probe in a diffusion regime. It was shown that the electron probe current is expressed by an extended equation:

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

where $e$ and $m$ are the electron charge and mass, $S$ is the probe area, $W$ is the total electron energy in the probe sheath. The probe is negatively biased by a potential $U_p$, $U$ is the probe potential with respect to the plasma potential $U_{pl}$ ($U = U_p - U_{pl}$). The value of the geometric factor $\gamma$ varies monotonically from 0.71 to 4/3 [2]. $f(\varepsilon)$ is the isotropic electron energy distribution function, normalized to the electron density $n$ by:

$$\frac{4\pi\sqrt{2}}{m^{3/2}}\int_0^{\infty} f(W)\sqrt{W}dW = \int_0^{\infty} f(\varepsilon)\sqrt{\varepsilon}d\varepsilon = n \qquad (2)$$

The important parameter in equation (1) is the diffusion parameter $\psi = \psi(W)$. In the presence of magnetic field $B$, $\psi$ depends on the electron free path $\lambda(W)$ and Larmor radius $R_L(W,B)$, as well as on the shape, the size and the orientation of the probe with respect to the magnetic field.

Let us consider the limiting cases regarding the value of the diffusion parameter [3]:

**A.** When $\psi(W) << 1$, **(weak magnetic field),** neglecting the second term $\frac{(W-eU)}{W}\psi(W)$ in the denominator under the integral in equation (1) yields the classical expression for the electron probe current and the EEDF can be determined by using the second derivative of the electron probe current $I''(U)$ (Druyvesteyn formula). Although, as was shown by Swift [4], a drain of electrons to the probe is present at a finite $R/\lambda$ ratio ($R$ being probe radius), the true value of $f(\varepsilon)$ at low probe potentials differs by less than 25% from that determined by the classical theory and the EEDF is well characterized by $I''(U)$.

**B.** When $\psi(W) \sim 1$ **(intermediate magnetic field)** we have to use equation (5). Its second derivative yields the equation [3,5]:

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

The first term in equation (3) is the well-known Druyvesteyn formula. The second term describes the effect of plasma depletion around the probe surface caused by movement of the electrons in the probe sheath at presence of magnetic field.

**C.** When $\psi(W) >> 1$ **(strong magnetic field)** the EEDF is represented by the first derivative instead of the second derivative as was shown in [3,6]:

$$f(\varepsilon)=\frac{3\sqrt{2m}\gamma}{2e^{3}S}\frac{\psi}{U}\frac{dI_{e}(U)}{dU} \qquad (4)$$

It is obvious that to evaluate the EEDFs in cases **B.** and **C.**, the values of the diffusion parameter must be known. The equations for $\psi$ when the probe is placed across ($\perp$) and along ($\parallel$) to the magnetic field in the general case are presented in [1,2].

## 2. Experimental results

### 2.1 Measurements in magnetized gas discharge plasma

In [3] for practical use equations for diffusion parameter $\psi$ were simplified for homogeneous plasma in the case of $\lambda >> R_L$. For cylindrical probe with radius $R$ and length $L$, they are:

$$\psi_{\perp}(W)=\frac{R}{\gamma R_{L}(B,W)}\ln\left(\frac{\pi L}{4R}\right)=\frac{\psi_{0}^{\perp}}{\sqrt{W}}$$

and $$\psi_{\parallel}(W)=\frac{\pi L}{4\gamma R_{L}(B,W)}=\frac{\psi_{0}^{\parallel}}{\sqrt{W}} \qquad (5)$$

Here $\psi_0$ is constant with respect to the energy part of the diffusion parameter at given magnetic field $B$.

The measurements were performed at Jožef Stefan Institute, Ljubljana, Slovenia. The plasma was produced in a stainless steel discharge tube with length 1.5 m and diameter 0.17 m (figure 1) with a hot filaments cathode.

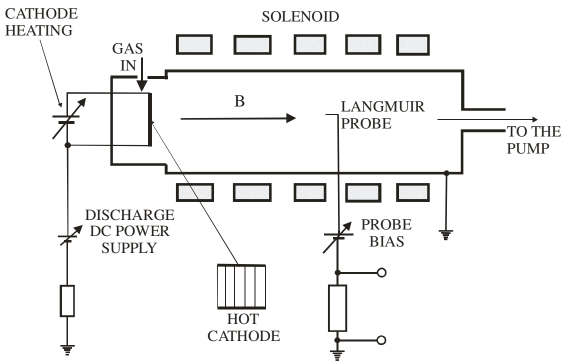


**Figure 1.** Schematic view of the experimental set-up

The wall of the discharge tube was grounded. A negative potential of −35 V was applied to the cathode while the gas discharge current was kept constant at 2 A. An axial magnetic field $B$ was created by a solenoid and was varied from 0.015 T to 0.079 T. The working gas was argon at pressure $p = 0.8$ Pa. The cylindrical Langmuir probe with $R = 1.10^{-4}$ m and length $L = 5.10^{-3}$ m was placed axially and radially at the centre of the discharge tube. The measurements were performed with the probe oriented in parallel and perpendicularly to the magnetic field. The derivatives were calculated numerically. The results of the measurements of the plasma parameters at different values of the magnetic field are presented below.

An example of the extended second derivative probe techniques application when the value of the diffusion parameter is relatively small is shown in figure 2. It has to be mentioned that the plasma potential $U_{pl}$ (set in figure as zero) does not coincide with the potential at which the second derivative is zero as it is usually assumed.

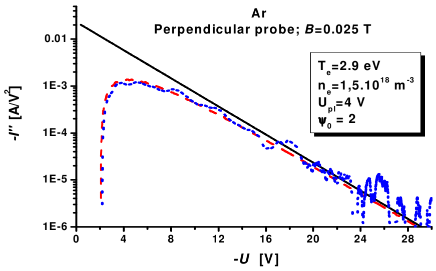


**Figure 2.** Comparison of the second derivative model curve (dashed line) for a Maxwellian EEDF ($T$=3 eV) with the experimental curve (dots) at $\psi_0^{\perp}=2$. The solid line presents the second derivative when $\psi << 1$.

The application of the extended second derivative probe method when EEDF is non-Maxwellian is more complicated: mathematically speaking, to deduce the EEDF from probe measurements under collisional conditions requires that two coupled inverse problems be solved, since the distortion of the second derivative includes an integral over the unknown EEDF and the data is convoluted by the instrumental function.

At high values of the diffusion parameter ($\psi > 30$) for evaluation of the EEDF the first derivative probe technique has to be applied. First step is to obtain the plasma potential. Figure 3 is a comparison between the experimental first derivative and the model curve in view of evaluating the plasma potential [7].

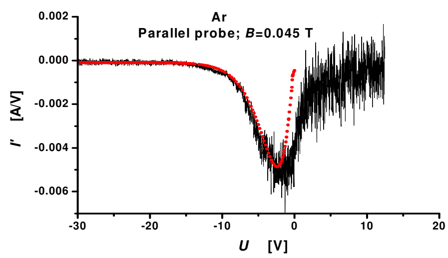


**Figure 3** Comparison between the experimental first derivative (solid line) and model curve (dots) for obtaining the plasma potential

To coincide with the model curve (where the plasma potential is set at zero) the experimental curve is shifted by 4 V, which is the value of the plasma potential. Because of the influence of the magnetic field, the minimum of the curves is shifted away from the plasma potential at a distance equal to the electron temperature value expressed in volts. The discrepancy between the model curve and the experimental curve behaviour after the minimum is due to the fact that the probe current does not saturate after the probe bias reaches the plasma potential. A more or less pronounced change of the experimental curve slope can be seen near the plasma potential.

Figure 4 shows the evaluated EEDF (solid line) in an argon gas discharge in the presence of a magnetic field of 0.045 T. The electron energy distribution function is generally Maxwellian. We should emphasize that the first derivative probe technique yields directly the EEDF not only in the Maxwellian case, but also when the energy distribution of the electrons deviate from the Maxwellian.

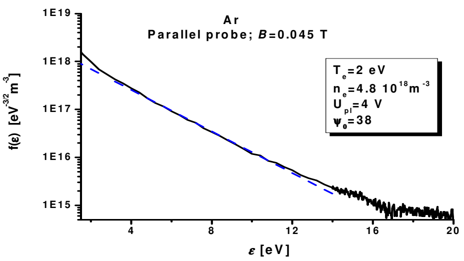


**Figure 4** Evaluated EEDF (solid line) in an argon gas discharge in the presence of a magnetic field of 0.045 T and model Maxwellian EEDF (dashed line) at electron temperature of 2 eV.

It is of interest that there is interval of values of the diffusion parameter $\psi$ ~20-30 when both of the techniques, second derivative and first derivative, can be applied for evaluating the EEDF. Example of such a situation is presented in the next figure 5.

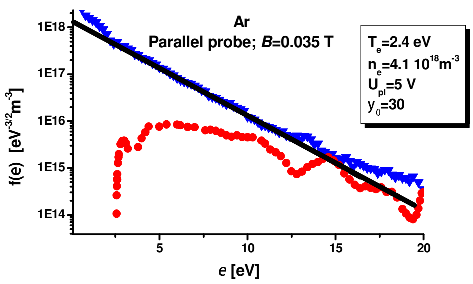


**Figure 5** Evaluated by first derivative technique EEDF (triangles) and model Maxwellian EEDF (solid line) at electron temperature of 2.4 eV. With dots is presented second derivative of the electron probe current giving the same plasma parameters.

**2.2 Langmuir probe measurements in strongly magnetized fusion plasma**

To apply the first derivative probe technique for processing the data of the probe measurements in fusion plasma the corresponding equations for diffusion parameter was estimated [8], taken into account that plasma in scrape-off layer (SOL) is strongly turbulent.

$$\psi_{\perp}(W) = \frac{R}{16\gamma R_L(B,W)} \ln\left(\frac{\pi L'}{4R}\right)$$

$$\text{and} \qquad \psi_{\parallel}(W) = \frac{\pi L'}{64\gamma R_L(B,W)} \qquad (6)$$

Here $L'$ is the characteristic cross-section size of the turbulent structures (blobs). The diffusion of the electrons from non-disturbed plasma to the probe sheath is Bohm diffusion.

Below the results from measurements in diverted plasmas in the COMPASS tokamak, IPP, CR [9] are presented. The toroidal magnetic field was $B = 1.15$ T. Measurements were performed by horizontal reciprocating probe displaced in the midplane of the COMPASS tokamak chamber. Results from representative for series discharges in deuterium, shot #6041, are presented. The duration of the discharge was 225.7 ms with plasma current $I_{pl} = 180$ kA and electron average density $5.10^{19}$ m$^{-3}$. The position of the last closed flux surface (LCFS) is $R_{LCFS} = 0.74$ m in the horizontal direction from the tokamak chamber centre.

Figure 6 present EEDF close to the tokamak chamber wall. It is Maxwellian with temperature 5 eV.

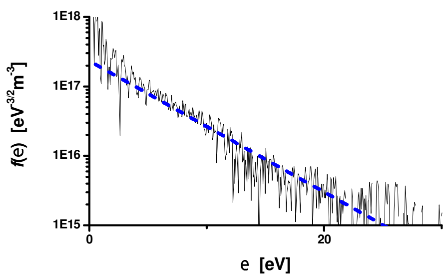


**Figure 6** Maxwellian EEDF close to the tokamak chamber wall

In the vicinity of the LCFS the EEDF was found to be bi-Maxwellian. Figure 7 presents EEDF at probe position at the LCFS with temperature of the most populated low-temperature electron fraction of 5 eV and temperature of 16 eV for the less populated high-temperature electron group.

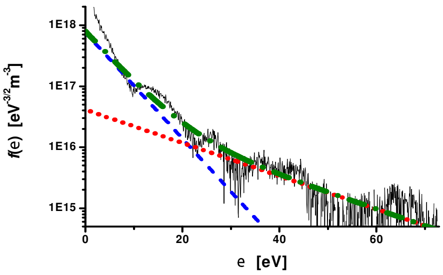


**Figure 7** EEDF at probe position at the LCFS

Figures 8, 9 and 10 presents the radial distribution of the plasma potential $U_{pl}$, electron temperatures $T_e$ and densities $n_e$ in the midplane of the COMPASS tokamak during shot #6041.

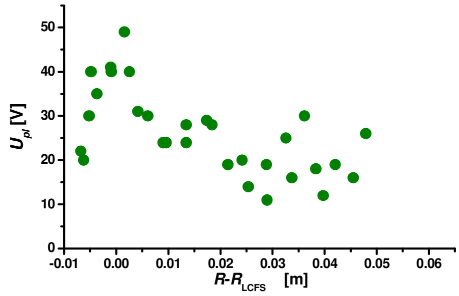


**Figure 8** Radial distribution of the plasma potential $U_{pl}$ during shot #6041

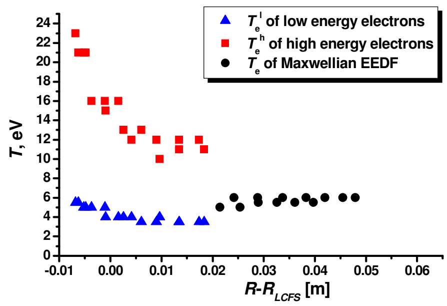


**Figure 9** Radial distribution of the electron temperatures $T_e$ during shot #6041

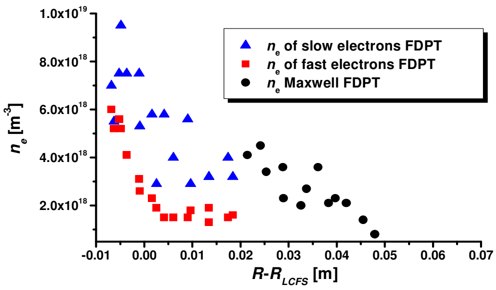


**Figure 10** Radial distribution of the electron densities $n_e$ during shot #6041

## 3. Conclusion

In this work, methods for using Langmuir probes in magnetized plasmas are presented. The electron part of the current-voltage probe characteristics was used in order to obtain the plasma potential, the electron energy distribution:

- The application of Langmuir probes to EEDF evaluation at the presence of magnetic field in the range 0.01 – 0.1 T based on the kinetic theory in a non-local approach is discussed. The diffusion parameters in an extended formula of the electron probe current are presented for cylindrical probes oriented perpendicular and parallel to the magnetic field lines. It is shown that at diffusion parameter values $\psi \sim 1$, the extended second derivative method must be used, while at $\psi >> 1$, the first derivative of the electron probe current yields a good representation of the EEDF. At intermediate values of the diffusion parameter, the two methods yield comparable results.
- First derivative probe technique is applied for processing the data of the probe measurements in fusion plasma. Results from radial distribution of the plasma potential $U_{pl}$, electron temperatures $T_e$ and densities $n_e$ in diverted plasma at the midplane of the COMPASS tokamak, IPP, CR are presented.

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