Bi-Maxwellian Electron Energy Distribution Function in the Vicinity of the Last Closed Flux Surface in Fusion Plasma

Preprint of Paper to be submitted for publication in Plasma Physics and Controlled Fusion
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Bi-Maxwellian electron energy distribution function in the vicinity of the last closed flux surface in fusion plasma

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Abstract. The first-derivative probe technique was applied to derive data for plasma parameters from the IV Langmuir probe characteristics measured in the plasma boundary region in the COMPASS tokamak and in the TJ-II stellarator. It is shown that in the COMPASS tokamak in the vicinity of the Last Closed Flux Surface (LCFS) the Electron Energy Distribution Function (EEDF) is bi-Maxwellian with the low-temperature electron fraction predominating over the higher temperature one, whereas in the far scrape off layer (SOL) the EEDF is Maxwellian. In the TJ-II stellarator during NBI heated plasma the EEDF in the confined plasma and close to the LCFS is bi-Maxwellian while in the far SOL the EEDF is Maxwellian. In contrast, during the ECR heating phase of the discharge both in the confined plasma and in the SOL the EEDF is bi-Maxwellian. The mechanism for the appearance of a bi-Maxwellian EEDF in the vicinity of the LCFS is discussed. The comparison of the results from probe measurements with Astra package and EIRENE code calculations suggests that the main reason of the appearance of a bi-Maxwellian EEDF in the vicinity of the LCFS is the ionization of the neutral atoms. Results for the electron temperatures and densities obtained by the first-derivative probe technique in the COMPASS tokamak and in the TJ-II stellarator were used to evaluate the radial distribution of the parallel power flux density. It is shown that in the vicinity of the LCFS where the EEDF is bi-Maxwellian, the radial distribution of the parallel power flux density is double exponential. It is pointed that in calculations of the parallel power flux density at the LCFS the energy losses from ionization mechanisms have to be taken into account.

1. Introduction

The scrape-off layer (SOL) plays an important role in the global behavior of confined plasmas. One of the frequently used tool to obtain the values of plasma parameters in the vicinity of the last closed flux surface (LCFS) and in the SOL of tokamaks and stellarators is the Langmuir probe. Langmuir probes are known for their capability of providing local measurements of the plasma

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potential and the electron energy distribution function, \( f(\varepsilon) \), (EEDF) \([1-8]\). In magnetized plasma, the interpretation of the electron part of the current-voltage \((IV)\) characteristics above the floating potential, \(U_f\), still remains difficult \([8,9]\) because the electron part of the \(IV\) characteristics is distorted due to the influence of the magnetic field. Therefore, in the strongly magnetized fusion plasmas, the ion saturation branch of the \(IV\) and the part around the floating potential are usually used when retrieving plasma parameters \([10,11]\). This classical technique assumes a Maxwellian EEDF, but in fact does not measure the real one.

In fusion plasmas, the assumption for a Maxwellian EEDF is generally valid. However, experimental evidence does exist suggesting non-Maxwellian distributions in tokamak SOL plasmas \([12]\). In ASDEX, the electron temperatures measured by a Langmuir probe assuming a Maxwellian EEDF are about twice as high as those determined by Thomson scattering \([13,14]\). The discrepancy was explained by the presence of a weakly-populated high-temperature electron fraction, together with a predominant electron population with a lower temperature. In this case, the EEDF can be considered as being bi-Maxwellian. As a result of 1D particle-in-cell modeling Chodura \([15]\), Batishchev \([16]\) and Tsakhakaya \([17]\) show non-Maxwellian distributions in SOL. It is clear that the knowledge of the real EEDF is of importance in understanding the underlying physics of the processes occurring at the SOL, plasma-wall interactions, etc.

Recently we published \([18,19,20]\) first derivative probe technique (FDPT) \([21-24]\) adapted for high temperature strongly magnetized turbulent fusion edge plasma aimed at evaluating the real EEDF. Our first investigations on the CASTOR tokamak and further on the COMPASS tokamak using the FDPT pointed the EEDF to be a bi-Maxwellian one with the low-temperature electron fraction predominating over the higher temperature one in the edge plasma. The method was successfully used in the liquid lithium divertor area of NSTX and also showed a bi-Maxwellian EEDF \([25]\).

In this work we report on results of radial measurements of EEDF by use of FDPT in the COMPASS tokamak and in the TJ-II stellarator. It is shown that in COMPASS tokamak in the vicinity of the LCFS the EEDF is bi-Maxwellian. In the far SOL, the EEDF is Maxwellian. The corresponding values for radial distribution of the electron densities were evaluated. For TJ-II stellarator during NBI phase the EEDF in the vicinity of the LCFS is also bi-Maxwellian while in the far SOL the EEDF is Maxwellian. In contrast, during the ECR heating phase of the discharge both in the vicinity of the LCFS and in the far SOL the EEDF is bi-Maxwellian.

The mechanism for the appearance of a bi-Maxwellian EEDF in the vicinity of the LCFS is discussed. The comparison of the results from probe measurements with those from ASTRA package and EIRENE code calculations show that an interpretation for the appearance of a bi-Maxwellian EEDF in the vicinity of the LCFS is the ionization of the neutral atoms.

Results for the electron temperatures and densities obtained by the FDPT in the COMPASS tokamak and the TJ-II stellarator were used to evaluate the radial distribution of the parallel power flux density. It is shown that in the vicinity of the LCFS where the EEDF is bi-Maxwellian, the radial distribution of the parallel power flux density is double exponential. It is pointed that in calculations of the parallel power flux density at the LCFS the energy losses from the ionization have to be taken into account.

Precise evaluations of the parallel power flux density in limiter plasma are important for prediction of the heat flux on the ITER wall during its start-up limiter phase, for the ITER blanket final design. It determines also the lifetime (erosion-rate) of the plasma-facing components during start-up plasma phases.

2. Langmuir probe measurements in the COMPASS tokamak.

To diagnose the SOL plasma in the COMPASS tokamak \([26]\) probe measurements were performed by using a vertical reciprocating probe (VRP) located at the top of the machine and a horizontal reciprocating probe (HRP) located at the outboard midplane. Series of reproducible ohmic discharges in either circular, high field side limited hydrogen plasmas or in D-shape, diverted hydrogen and deuterium plasmas were studied. The toroidal magnetic field was \(B = 1.15\) T. The probes were biased with respect to the tokamak chamber wall by a triangular voltage \(U_p(t)\) swept at a frequency of 1 kHz supplied by a KEPCO 100-4M power supply. The ramp-up/ramp-down phases lasted 0.5 ms, so that
the probe could be assumed stationary in space during each sweep cycle. The probe potential and the probe current versus time were recorded by tokamak DAQ [27].

2.1 Measurements in a circular plasma in the COMPASS tokamak

In this section are presented results from a circular ohmic discharge in hydrogen leaning on the inboard belt limiter (shot #2568), typical for the series reproducible discharges with duration of 235 ms, plasma current $I_{pl} = 120$ kA and low loop voltage $U_{loop} = 1.5$ V.

To diagnose the radial distribution of the plasma parameters VRP was used. The semi-cylindrical probe tip, made from graphite with diameter 3 mm and length 5 mm, is exposed parallel to the magnetic field lines.

Figure 1 presents a reconstruction of the magnetic surfaces by EFIT in the middle of the discharge steady-state phase ($t = 98$ ms). The LCFS is defined by the inboard belt limiter and emphasized by a bold line. Figure 2a presents the VRP position versus time. The position of the LCFS at $Z_{LCFS} = 0.203$ m in the vertical direction from the tokamak chamber centre is indicated by a dashed line. The bold line indicates the position of the probe in the time window from $t = 60$ ms to $t = 150$ ms of the steady-state phase of the discharge with a constant plasma current; the only probe data acquired during this time window were processed. Temporal evolution of plasma current for shot #2568 is presented in figure 2b.

![Figure 1: EFIT magnetic surfaces reconstruction for shot #2568 at time $t = 98$ ms. The LCFS is defined by the inboard belt limiter and emphasized by a bold line.](image1)

![Figure 2: a) Position $Z$ of the VRP tip from the tokamak chamber centre versus time for shot #2568. The bold line indicates the VRP position during the time window from $t = 60$ ms to $t = 150$ ms; these probe data were processed in this report. b) Temporal evolution of the plasma current for shot #2568.](image2)

For illustration, the EEDF in the far SOL and near the separatrix are presented in Figures 3 & 4, respectively. The first-derivative probe technique yields reliable data for the EEDF in an energy range starting from the electron temperature $T_e$ value [6,9,18]. In Figure 3 and for the 7 eV – 50 eV range, the experimental curve can be approximated by a straight line, which is indicative of a Maxwellian EEDF with electron temperature of 7 eV. The accuracy of the temperature evaluation is 10%.
Figure 3. Experimental EEDF (solid line) and the model one with electron temperature of 7 eV (dashed line) for COMPASS circular shot #2568 in the far SOL.

Figure 4. Bi-Maxwellian EEDF (solid line) measured at probe position 212 mm from tokamak chamber centre, i.e. 9 mm above the LCFS. It is clearly seen that the experimental EEDF (the solid line in figure 4) deviate from a Maxwellian (straight line) energy distribution. It can be approximated by a sum of two Maxwellian distributions (dashed-dotted lines) – a low-temperature one with a higher electron density (dashed line) and a high-temperature one with a lower electron density (dotted line). The accuracy of evaluating the predominant low-temperature electron fraction is ~10%, while, due to the low density of the minority high-temperature electron population, the uncertainty increases to ~25%.

Figure 5 presents the radial distribution of the electron temperatures $T_e$ and densities $n_e$ retrieved by first derivative probe techniques. The triangles and squares indicate the low and high temperatures, respectively, of the bi-Maxwellian EEDFs. The dots correspond to the Maxwellian EEDFs.

It is seen that, in the region 0-20 mm outside the confined plasma, the EEDF is bi-Maxwellian, presenting two populations of electrons with low and high energy/temperature. In the rest of the profile in far SOL the EEDF is found to be Maxwellian.
The asterisks in figure 5 a) represent the electron temperature evaluation using the classical probe technique (CPT) [10,11]. This technique uses the ion saturation branch of the measured current-voltage ($I-V$) probe characteristic and the part around the floating potential, $U_\text{f}$. The technique assumes a Maxwellian EDF for the electrons. The electron temperature is estimated by the approximation of the probe current versus probe potential $U_\text{p}$ around the floating potential by:

$$I(U) = I_\text{i} \left( 1 - \exp \left( - \frac{e(U_\beta - U_\text{f})}{kT_e} \right) \right)$$

where $I_\text{i}$ is the value of the ion saturation current. From the expression $I_\text{i} \approx 0.5e\,n_e\,A_{pr}$ the value of the electron density $n_e$ can be obtained. Here $e$ is the electron charge; $c_s = \left( k(T_e + T_i)/m_e \right)^{1/2}$ is the ion acoustic velocity; and $A_{pr}$ is the probe projection to the magnetic field lines area.

As predicted, a good agreement is observed in both $T_e$ and $n_e$ for both techniques when the distribution is found to be Maxwellian. In the case of a bi-Maxwellian EEDF, the data from the CPT are strongly influenced by the high energy tail of the electron energy distribution [18]. It is well known that in this case the part of the $I-V$ around floating potential is determined by the high energy fraction although it is a few percentage from the density of the main low energy electron group [28].

The results for the electron temperatures and densities obtained by the FDPT can be compared with those of the core Thomson scattering (TS) diagnostics [29]. Four $n_e$ and $T_e$ TS profiles, taken during the quasi-stationary phase of the discharge, were used for this comparison (figure 8).

![Figure 8](image-url)

**Figure 8.** Comparison of the TS (asterisks) electron temperatures (a) and densities (b) profiles with the VRP profile (dots, triangles and squares) obtained by the FDPT for COMPASS circular shot #2568.

The core TS results presented were obtained from the region of the tokamak chamber mid-plane to 4 mm below the separatrix position at a step of 13 mm. The spatial resolution is about 5 mm. Detailed information about the accuracy of the TS data can be found in [30]. Although the two profiles are complementary, it is seen that the TS temperature measured in the proximity of the LCFS location is close to the temperature of the low-energy electron fraction and differ by about a factor of two from the high energy electron fraction temperature. This is in agreement with the statements in [13,14], i.e. as the TS experiment assumes a Maxwellian EEDF, the results obtained match well the temperatures and densities of the predominant low-energy electron fraction yielded by the probe measurements.

### 2.2 Measurements in diverted plasmas in the COMPASS tokamak

Below the results from measurements in diverted plasmas in the COMPASS tokamak 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 vacuum chamber. Figure 7 presents a typical result of reconstruction of the magnetic surfaces by EFIT in the middle of the discharge steady-state phase, when the probe was in its deepest position.
First the results from representative for series discharges in hydrogen, shot #3912, are presented. The duration of the discharge was 250 ms with plasma current $I_p = 110$ kA and loop voltage $U_{loop} = 1.5$ V. Figure 8 a presents the HRP position versus time. The position of the LCFS at $R_{LCFS} = 0.74$ m in the horizontal direction from the tokamak chamber centre is indicated by a dashed line. Temporal evolution of plasma current for shot #3912 is presented in figure 8 b.

**Figure 7.** Typical EFIT magnetic surfaces reconstruction for diverted plasmas. The LCFS is emphasized by a bold line.

**Figure 8 a)** Position R of the HRP tip from the tokamak chamber centre versus time for shot #3912. The bold line indicates the HRP position during the time window from $t = 120$ ms to $t = 220$ ms; these probe data were processed in this report. **b)** Temporal evolution of the plasma current.

Figure 9 presents the radial distribution of the electron temperatures $T_e$ and densities $n_e$. Here and further the same symbols as for shot #2568 are used.

**Figure 9.** Radial distribution of the electron temperatures $T_e$ (a) and densities $n_e$ (b) for COMPASS diverted shot #3912 in hydrogen.

Similar results we obtained from shot #6042 in deuterium diverted plasma with duration of 225 ms, discharge current 180 kA and low loop voltage of 1 V. The distribution of the electron temperatures $T_e$ and densities $n_e$ in horizontal direction are presented in figure 10.
Here also is seen that in the vicinity of the LCFS (until 23 mm before it) the EEDF is bi-Maxwellian, while at far SOL the EEDF is found to be Maxwellian.

3. Langmuir probe measurements in the TJ-II stellarator

Measurements in the TJ-II stellarator were carried out in low line averaged density electron cyclotron resonance (ECRH; 2 x 250 kW gyrotrons, at 53.2 GHz, 2nd harmonic, X-mode polarisation) heated deuterium plasmas and high density neutral beam injection (NBI; one beam of 400 kW, port-through \( H_0 \) power at 30 kV) regimes during one shot with \( B = 1 \) T. A tungsten Langmuir probe with length 2 mm and 0.75 mm diameter was immersed at different vertical positions in regard to the LCFS (figure 11). To be able to measure at different phases of the discharge (ECR and NBI heating) here we chose a different approach than in the COMPASS tokamak: A series of reproducible discharges was made (from shot #34509 to shot #34537) in plasma with \( (a)/2\pi \approx 1.63 \). For different shots probe was immersed into the plasma at different vertical position \( Z \) – from \( Z = 40 \) mm with respect to the LCFS in the SOL to \( Z = 18 \) mm in the confined plasma.

The averaged plasma densities for the series of reproducible discharges are presented in figure 12. In the ECRH phase the densities are almost identical, whilst in the NBI phase, there is a 25% discrepancy. For each probe position plasma parameters were evaluated for ECRH phase (with duration about 60 ms) in time 1090 ms and for NBI phase (with duration about 80 ms) – in time 1160 ms as indicated with dashed lines in figure 12. Here also the probe was biased with respect to the

**Figure 10.** Radial distribution of the electron temperatures \( T_e \) (a) and densities \( n_e \) (b) for COMPASS diverted shot #6042 in deuterium.

**Figure 11.** Positions of the probe and LCFS, indicated by dotted line in TJ-II.

**Figure 12.** Averaged plasma densities in TJ-II for the series of shots #34509-#34537. The probe measurements are taken at time \( t=1090 \) ms in the ECRH phase and at \( t=1160 \) ms in the NBI phase (vertical dashed lines).
chamber wall by a triangular voltage \( U_p(t) \) swept at a frequency of 1 kHz supplied by a KEPCO 100-4M power supply. The probe current signal was filtered by 10 kHz low-pass filter and recorded by TJ-II DAQ system.

Using the FDPT for processing the experimental data we obtained that during NBI heating phase the EEDF is Maxwellian in the SOL side of the LCFS location \((Z - Z_{LCFS} \approx 10-20 \text{ mm})\). An example for probe position 20 mm above the LCFS is presented in figure 13.

\[
U_p = 36 \pm 4 \text{ V} \\
T_e = 7.0 \pm 0.7 \text{ eV} \\
\rho_e = (1.7 \pm 0.2) \times 10^{17} \text{ m}^{-3}
\]

\[
U_p = 15 \pm 2 \text{ V} \\
T_1 = 7 \pm 0.7 \text{ eV} \quad n_1 = (1.1 \pm 0.2) \times 10^{18} \text{ m}^{-3} \\
T_2 = 32 \pm 3 \text{ eV} \quad n_2 = (3.7 \pm 0.6) \times 10^{17} \text{ m}^{-3}
\]

Figure 13. Experimental EEDF (solid line) and the model one with electron temperature of 7 eV (dashed line).

Figure 14. Bi-Maxwellian EEDF (solid line) measured during shot #34531 at the plasma edge side of the LCFS \((Z - Z_{LCFS} \approx 13 \text{ mm})\).

In the vicinity of the LCFS and in the confined plasma EEDF was found to be bi-Maxwellian. Example of bi-Maxwellian EEDF as measured in 13 mm behind the LCFS is presented in figure 14. During the ECRH phase the EEDF was found to be bi-Maxwellian both in the SOL and in the confined plasma.

Follow the procedure, described in [19], the radial distributions of the plasma potential for the TJ-II stellarator during the NBI phase and during the ECRH phase are evaluated and presented in figures 15 and 16, respectively. In agreement with Langmuir probe measurements and general considerations of neoclassical transport, the NBI phase is normally characterized by higher densities and all negative radial electric fields; while the ECRH phase, due to the heating system and the typically low densities, has positive electric fields in the core plasma that sometimes reach the edge region [31,32]. It is seen that during the NBI phase the plasma potential increases in the SOL, reaching a maximum around the position of the LCFS and then decreases monotonically to negative values in the confined plasma.

Figure 15. Radial distribution in vertical direction \(Z\) with respect to the LCFS position \(Z_{LCFS}\) of the plasma potential for the TJ-II stellarator during NBI phase (high density regime)

Figure 16. Radial distribution in vertical direction \(Z\) with respect to the LCFS position \(Z_{LCFS}\) of the plasma potential for the TJ-II stellarator during ECRH phase (low density regime)
During the ECRH phase, the plasma potential increases close to the LCFS position. In the confined plasma it decreases over 5 mm and then the plasma potential starts to increase to values as high as 80 V. Deviation larger than experimental error from the smoothed radial distribution of the plasma potential can be explained by the fact that every point is from different shot, which are not exactly identical. This is valid also for the others plasma parameters evaluated from measured data in the TJ-II stellarator.

It has to be noted that probe measurements in the TJ-II stellarator during NBI phase (high density regime) yield similar results for the electron temperatures $T_e$ and densities $n_e$ like in the COMPASS tokamak – in far SOL the EEDF is Maxwellian with temperatures below 10 eV. In the vicinity of the LCFS and in the confined plasma, when the Maxwellian electron temperature exceeds 15 eV, the profile splits into two branches with a low temperature electron fraction with density higher than the high energy electrons. These results are presented in figure 17.

In contrast, during the ECRH phase the EEDF both in SOL and in the confined plasma is bi-Maxwellian (see Fig.18) – in SOL the high energy electrons have almost constant temperature of about 20 eV and increase up to 35 eV [33] in the confined plasma while low temperature fraction is with temperature 6-7 eV in the entire region of the measurements. The low temperature fraction is 2-3 times higher populated than the high energy one.

4. Discussion

All results from EEDF measurements presented in section 2 show the common feature of having two populations of electrons near the LCFS. We should point out that a more detailed analysis must be performed to clarify the origin of the low-energy fraction in the bi-Maxwellian EEDF. As a result of kinetic 1D particle-in-cell code simulations, Chodura [15], Batishchev [16] and Tskhakaya [17] state...
that in SOL the EEDF can deviate from Maxwellian in high recycling plasmas, whilst in low recycling plasmas the EEDF is mainly Maxwellian. The main reason for the origin of the EEDF deviation from a Maxwellian in stationary SOL is the ionization of neutrals by thermal electrons penetrating from the bulk plasma into the SOL. In NSTX where a bi-Maxwellian EEDF is reported in the liquid lithium divertor area, a “heuristic model” accounting for the inelastic collision effects (i.e. excitation and ionization of neutral hydrogen or deuterium) is proposed to explain this EEDF feature [25].

Indeed, the energy balance of the reaction

\[ H + e \rightarrow H^+ + 2e \]  

for electrons with energy by $10 - 15 \text{ eV}$ higher than the ionization energy of hydrogen (13.6 eV) is in agreement with the energy of the low-temperature electrons measured by the FDPT. The values of the rate coefficient [35] for electron temperatures in the range 20 – 30 eV are close to the maximum (figure 19). Performing a detailed energy balance necessitates that ionization through neutral hydrogen excited states be taken into account as well. On the other hand, the energy of the electrons in the far SOL is below 10 eV and the most probable reactions are dissociation with threshold of 4.5 eV and excitation.

**Figure 19.** Rate coefficient $< \sigma v >$ and cross-section $\sigma$ for atomic hydrogen ionization.

In order to validate this hypothesis, the simplified kinetic solver for neutrals included in the ASTRA package [36] has been used to calculate distributions of hydrogen atoms and electron source $S_e$ due to ionization of neutral hydrogen atoms for COMPASS configuration. Figure 20 shows a comparison between the radial distribution of the calculated electron source $S_e$ due to the ionization of the neutral Hydrogen atoms (solid line) and electron densities measured for COMPASS circular shot #2568 (symbols). The radial distribution of hydrogen atoms density for the same shot is presented in figure 21. A constant density of neutrals is assumed in the far SOL (see figure 22) and a 3 cm decay length for the electron density and temperatures. The source was estimated after fitting the experimental density profile with ad hoc transport coefficients with fixed $T_e$ and $T_i$ profiles, and considering a typical particle confinement time $\tau_p = 30 \text{ ms}$. As an output result we obtained a value for energy confinement time $\tau_E = 3.4 \text{ ms}$. It is in agreement with the value between 3 ms and 4 ms evaluated in [30].
It is clearly seen that the region in the vicinity of the LCFS where the EEDF is bi-Maxwellian corresponds to the source of electrons. In the same time the radial profile of neutrals follows the profile of the electron source in the confined plasma. These comparisons are consistent with the statement that the main reason for bi-Maxwellian EEDF observed in the vicinity of the LCFS is the ionization of the neutral hydrogen atoms.

A similar situation is observed for COMPASS Ohmic diverted deuterium plasma (shot #6042) as shown in figures 22 and 23.

Additional confirmation of the interpretation of bi-Maxwellian distribution due to ionization mechanisms can be made by comparison of the results obtain in hydrogen and deuterium plasmas with results from helium discharges. Such experiments are foreseen in COMPASS and TJ-II 2015 campaigns.

In TJ-II case, the spatial distributions of neutrals and the electron source \( S_e \) have been calculated using the EIRENE code [37] adapted for TJ-II geometries [38]. The electron sources and atom density profiles are presented in figures 24 and 25, respectively, for both NBI and ECR phases. They have been obtained taking TS profiles [39] in the main plasma complemented with He-beam data near the edge [40], and \( T_i \) following [41]. The recycling sources have been obtained for a representative value of TJ-II particle confinement times, \( \tau_p = 8.6 \) ms.
In the figures 26 and 27 the electron source $S_e$ profiles, which account for the radial locations where the ionization processes are important, are compared with the densities of the high and low temperature populations obtained with the FDPT. It is seen a good agreement in the shape and the position between calculated and experimentally obtained results.

The second main point of our discussion is how to calculate the total parallel power flux density with bi-Maxwellian EEDFs. Precise evaluations of the parallel power flux density in fusion devices is of high importance with respect to plasma-facing components life time. In limiter plasmas, the power flux is an important quantity to know for prediction of the heat flux falling on the ITER HFS first wall panels during its start-up limiter phase [42,43].

Usually the parallel power flux density is calculated by the equation [35]:

$$ Q_{||} = 7 J_{sat} T_e $$

where $J_{sat}$ is the ion saturation current density. In the case of bi-Maxwellian EEDF in the equation (3) the effective electron temperature $T_{e}^{\text{eff}}$ has to be used:

$$ T_{e}^{\text{eff}} = \frac{n_h T_{e h}^h + n_l T_{e l}^l}{n_h^e + n_l^e} $$

where the indices $l, h$ indicate the low- and high-energy components of the bi-Maxwellian distribution of the electron temperatures and densities.

As it was pointed above, in most of the cases the value of the electron temperature $T_e$ is evaluated by classical probe technique. When the EEDF is bi-Maxwellian, the CPT is sensitive only to the temperature of less populated high energy electron fraction and thus the parallel power flux density.
value will be overestimated. It is clear that the effective electron temperature $T_e^{\text{eff}}$ can be evaluated only by FDPT which provide the real EEDF. Additional error in estimation of the parallel power flux density by using equation (3) can be caused by uncertainties in evaluating the ion saturation current density $J_{\text{sat}}$. As it was shown [12] in the case of small size probe the ion current at large negative probe potential do not saturate due to the sheath expansion, but increases almost linearly. This effect is less pronounced for bigger cylindrical probes with diameter ~3-5 mm. The secondary electron emission [44] due to the electron collisions with the probe surface can also increase the value of the ion saturation current density.

The calculations of the parallel power flux density can be performed by alternative way using the equation:

$$Q_{\parallel}^i = \frac{7}{2} c_s p_e$$

which is equivalent to equation (3) [35]. Here $p_e$ is the electron gas pressure. For Maxwellian EEDF it is $p_e = n_e^{\text{eq}} k T_e^{\text{eq}}$ where the values of $T_e$ are expressed in Kelvin and $k$ is the Boltzmann constant. In the case of a bi-Maxwellian, the electron gas pressure is expressed by $p_e = n_e^i k T_e^i + n_e^h k T_e^h$. When using the equation (5) we have to know the ion acoustic velocity $c_i = \left[ k (T_i + T_e)/m_i \right]^{1/2}$. To calculate ion acoustic velocity here again for the electron temperature the value of $T_e^{\text{eff}}$ has to be used. The problem is that the ion temperature has to be known or additional measurements for its evaluation have to be performed. Alternatively, for the purpose of this article an estimation of the ion acoustic velocity was done by using the values ion saturation current measured data [19]. We have to online that the $J_{\text{sat}}$ values are evaluated from $IV$ characteristics independently of the electron temperatures and densities values obtained by FDPT.

![Figure 28. Radial distribution of the parallel power flux density for shot #2568 in the COMPASS tokamak](image)

In figure 28 with squares are presented the results from the calculations of the parallel electron power flux density calculated by ion saturation current density $J_{\text{sat}}$ (equation (5)). In the same figure 29 with dots are presented data calculated by equation (3). Due to the large size of the vertical reciprocating probe in the COMPASS tokamak ion current saturate well at large negative probe potentials. It is seen that the results from equations (3) and (5) agree well. The profile of the parallel power flux density has clearly a double exponential shape. Similar results (double exponential behavior) were obtained from measurements of the parallel power flux density by infrared camera in high field side in the COMPASS tokamak [45]. The same situation is in the case of diverted plasma - in hydrogen (shot #3912, figure 29) and in deuterium (shot #6042, figure 30).
It is easy to see that first rapid slope of the parallel power flux density decay corresponds to the region where the EEDF is bi-Maxwellian. With other words we can state that the ionization of the neutrals cools the plasma electrons at the vicinity of the LCFS. Usually $P_{SOL}$ is calculated as $P_{SOL} = I_p U_{loop} - P_{RAD}$. In this equation also the losses from ionization have to be taken into account when calculate the parallel power flux density at the LCFS [46]:

$$Q_{\text{LCFS}} = \frac{P_{SOL}}{4\pi R \lambda_q (B_o / B_q)} = \frac{1}{4\pi R} \frac{P_{SOL} \lambda_{p5}}{a \lambda_q}$$  \hspace{1cm} (6)

where $R$ and $a$ are the major and minor radius.

Using the approximation

$$Q_c = Q_{\text{LCFS}} \exp \left( -\frac{Z - Z_{\text{LCFS}}}{\lambda_q} \right)$$  \hspace{1cm} (7)

$\lambda_q$ and $Q_{\text{LCFS}}$ can be obtained from data, presented in figures 29, 30 and 31. Results from experimentally obtained $Q_{\text{LCFS}}$ data and calculations of $Q_{\text{LCFS}}$ using equation (6) without taking into account the ionization losses are presented in table 1:

<table>
<thead>
<tr>
<th>Shot #</th>
<th>$\lambda_q$ [m]</th>
<th>$Q_{\text{LCFS}}$ [MW/m$^2$]</th>
<th>$Q_{\text{LCFS}}$ [MW/m$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2568</td>
<td>0.01 0.06</td>
<td>2</td>
<td>37</td>
</tr>
<tr>
<td>3912</td>
<td>0.006 0.026</td>
<td>9.5</td>
<td>95</td>
</tr>
<tr>
<td>6042</td>
<td>0.005 0.036</td>
<td>12.5</td>
<td>140</td>
</tr>
</tbody>
</table>

| Table 1 Comparison between experimentally obtained $Q_{\text{LCFS}}$ data and calculations of $Q_{\text{LCFS}}$ without taking into account the ionization losses |

It is seen that without taking into account the energy losses from ionization, the calculated and experimentally estimated values of the parallel power flux density at the LCFS differ with an order of magnitude.
In the TJ-II stellarator during NBI phase in SOL the distribution of the parallel power flux density has also double exponential behavior (figure 31) with $\lambda_q = 4$ and 46 mm and $Q_{\text{LCFS}}^{\exp} = 0.1$ and 0.05 MW/m$^2$. Again the first, rapid slope correspond to the region where the EEDF is bi-Maxwellian.

During the ECRH phase, the radial distribution of the parallel power flux density (figure 32) is exponential with $\lambda_q = 0.033$ m and $Q_{\text{LCFS}}^{\exp} = 0.1$ MW/m$^2$ (the dashed line in figure 41) in the entire SOL, where the EEDF is bi-Maxwellian.

**Conclusions**

The plasma boundary region has been investigated in the COMPASS tokamak and TJ-II stellarator. The first-derivative probe technique was applied to derive data for the plasma parameters from the IV probe characteristics measured, with the following results:

- It is shown that in the COMPASS tokamak in the vicinity of LCFS EEDF is bi-Maxwellian with the low-temperature electron fraction predominating over the higher temperature one. In far SOL, EEDF is Maxwellian. The corresponding values for radial distribution of the electron densities were evaluated.
- For stellarator TJ-II during NBI heating phase the EEDF in the confined plasma and close to the LCFS is bi-Maxwellian while in the far SOL the EEDF is Maxwellian. In contrast, during the ECR heating phase of the discharge both in the confined plasma and in the SOL the EEDF is bi-Maxwellian.
- The mechanism for the appearance of a bi-Maxwellian EEDF in the vicinity of the LCFS is discussed. The comparison of the results from probe measurements with these from ASTRA package and EIRENE code calculations show that the main reason of the appearance of a bi-Maxwellian EEDF in the vicinity of the LCFS is the ionization of the neutral atoms.
- Results for the electron temperatures and densities obtained by the first-derivative probe technique in tokamak COMPASS and stellarator TJ-II were used to evaluate the radial distribution of the parallel power flux density. It is shown that in the vicinity of the LCFS where the EEDF is bi-Maxwellian, the radial distribution of the parallel power flux density is double exponential. It is pointed that in calculations of the parallel power flux density at the LCFS the energy losses from the ionization have to be taken into account.

**Acknowledgements**

The authors wish to thank Dr. J. Gunn, Dr. V. Fuchs and Dr. Tskhakaya for the fruitful discussions, to the COMPASS tokamak and TJ-II teams for the technical assistance.

This research has been partially supported by the European Community under the contract of Association between EURATOM/IPP.CZ and EURATOM/INRNE.BG; by the Bulgarian National Science Fund through the Association EURATOM-INRNE; by the International Atomic Energy Agency (IAEA) Research Contract No 17125/R0, R1 and R2 as a part of the IAEA CRP F13014 on
“Utilisation of a Network of Small Magnetic Confinement Fusion Devices for Mainstream Fusion Research” 5th and 6th IAEA Joint Experiment; by the JOINT RESEARCH PROJECT between the Institute of Plasma Physics v.v.i., AS CR and the Institute of Electronics BAS BG; by grant project GA CR P205/12/2327; and by MSMT Project # LM2011021 and this work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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