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Study of ion sheath expansion and anisotropy of the electron parallel energy distribution in the CASTOR tokamak

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Abstract
A novel diagnostic, the tunnel probe, is used to investigate the edge plasma of the CASTOR tokamak. Comparison with conventional small, cylindrical Langmuir probes (typical of those usually employed for turbulence measurements in magnetized plasmas) demonstrates the superiority of the tunnel probe. The collectors of the tunnel probe are concave, eliminating in theory all uncertainty of the effective collecting area, and thereby rendering the measurement of parallel ion current density, electron temperature, and floating potential more reliable. Two tunnel probes, mounted back-to-back in a Mach probe arrangement, are used to investigate directional asymmetries of the plasma parameters. The tunnel probes are used as standard Langmuir probes by applying voltage sweeps simultaneously to all their internal conductors. The measured electron temperature is higher on the electron side than on the ion side, and the floating potential is lower. The observed asymmetries, measured at low density and collisionality in CASTOR, could be consistent with a hot tail of non-thermal electrons flowing in the counter-current direction. The ratio of ion saturation currents to the internal conductors of the tunnel probe provides a second independent measurement of electron temperature whose directional asymmetry is less pronounced, in agreement with recent theoretical predictions that tunnel probes should be less sensitive to non-thermal electrons than Langmuir probes in certain conditions.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Measurements in the edge plasma of tokamaks are needed in order to evaluate particle and energy fluxes reaching the wall. The plasma on the open magnetic flux surfaces that intersect solid objects, the scrape-off layer (SOL), plays an important role in the global behavior of the plasma. Fueling and impurity transport are both governed by the electron density and temperature as well as by the plasma flows inside the SOL. In tokamaks Langmuir probes are frequently used to characterize the edge plasma. The perturbation generated by a probe in the SOL can be described by plasma models that relate the measurements to the unperturbed quantities that would exist if the probe were absent. Generally, the models, which contain the same equations that are used to model the SOL itself, assume that the velocity distributions of charged particles are Maxwellian. This might not be true if collisionality is low enough, in which case probe measurements are strongly influenced by kinetic effects [1]. Instead of viewing this as a handicap, in this paper we will attempt to exploit directional asymmetries to obtain information about the electron distribution function in the edge plasma of the CASTOR tokamak.

In contrast to conventional probes that collect charges simultaneously from both directions along the magnetic field lines, Mach probes have directional sensitivity. In their simplest form, Mach probes consist of two Langmuir probes mounted back-to-back on either side of an insulator so as to monitor separately the charged particle fluxes that approach the probe along field lines [2]. A difference between the measured ion saturation currents (I_{sat}) is interpreted as being the signature of bulk ion flow in the unperturbed plasma. Mach probe theory, either fluid [3] or kinetic [4], provides a simple relation between the ratio of ion currents and the parallel flow velocity. A strong assumption of the theory is that the electron parallel velocity distribution is Maxwellian. If that were true, then one would expect to observe the same electron temperature on both sides, but more often than not, differences are observed. While ion saturation current asymmetries are routinely exploited to measure ion flow in tokamaks, asymmetries of electron temperature (T_{e}) and floating potential (V_{fl}) are practically never mentioned in the literature. A noteworthy exception is [5] in which strong asymmetries were observed in Alcator C-Mod. Kinetic modeling of the SOL showed that such asymmetries, observed in the TdeV tokamak, are evidence of deviations from a Maxwellian distribution [1, 6]. In that work the authors assumed that the probe is unperturbing. More recently, the effect of non-thermal electrons on Mach probe theory was investigated [7]. It turns out that the presheath of the probe can strongly affect the electron flux to each side. For example, if the electron distribution were non-thermal but isotropic (a two-temperature Maxwellian, for example), one would expect symmetric electron temperature measurements if one naively ignored the perturbing effect of the probe. However, strong upstream/downstream asymmetries of electron temperature and floating potential will be observed due to the different presheath potential drops if, in addition, ion flow is present.

The consequences of directional asymmetries of electron temperature and floating potential are significant. There is a vast body of literature concerning the measurement of turbulent radial particle flux using arrays of tiny Langmuir probes [8]. The fluctuating poloidal electric field is most often deduced from the instantaneous gradient of floating potential between two pins, assuming that electron temperature fluctuations are negligible. The upstream and downstream floating potentials can be extremely different; it is not obvious which one should be used to calculate the electric field in the unperturbed plasma. Even when fast, spatially resolved electron temperature measurements are available, standard probe theory is used to calculate the plasma potential. Knowing that probes are highly sensitive to non-thermal electrons, it would seem important to check for upstream/downstream asymmetries before using probes to make turbulence measurements, for example. It should be noted that the CASTOR plasma has low density and collisionality compared with larger tokamaks, so these observations may be particular to this experiment.

A second difficulty, encountered by all probes, concerns the effective ion collecting area. To calculate the parallel ion current density ($J_{\|,\mathrm{i}}$), the collecting area (A_c) of the probe must be known, since $J_{\|,\mathrm{i}} = I_\mathrm{sat}/A_\mathrm{c}$. It is usual to assume that both the Debye length and the ion Larmor radius are much smaller than the typical cross-field dimension of the probe, so that A_c is equal to the geometrical projection A_geo of the probe along the field lines. Most turbulence probe arrays are designed to give very good spatial resolution. The separation between tips is typically less than 5 mm, so they must be quite small in order to accommodate them in their insulating housing. Cylindrical tips of diameter 0.5–3 mm are most often used [9, 10, 11]. This is only slightly larger than the typical electrostatic sheath thickness and Larmor radius in most tokamak plasmas (0.1–1 mm), so the ion current collected by the probe is larger than the theoretical flux of ion guiding centers that would intercept the geometric projection of the probe along the field lines. In addition to finite Larmor radius effects, the strong electric field in the sheath deflects ions towards the surface and enhances the current. The parallel ion current density will therefore be overestimated. Since in most cases the electrons remain strongly magnetized under all conditions, the effective collecting area for electrons is well approximated by the geometrical projection of the probe. The unequal collecting areas for ions and electrons cause the floating potential of small probes to be more positive than that predicted by strongly magnetized probe theory [12]. To model the sheath expansion current, which is likely to depend on density, ion and electron temperature, magnetic field and probe bias, three-dimensional kinetic simulations are required. No such calculations are as yet available.

The effect of sheath expansion on J_sat and V_fl measurements was meticulously investigated quite some time ago [12]. We define here a simple way to determine whether a probe is victim to sheath expansion effects by applying a voltage ramp to it; typically the ion current will exhibit a steady increase as the voltage becomes much more negative than the floating potential, rather than saturating. It is appropriate to add an extra term to the usual three-parameter exponential fit [13]

$$I = I_\mathrm{sat}.[1 - \exp^{(e(V-V_\mathrm{fl})/kT_\mathrm{e})}], \tag{1}$$

to describe the increase of ion current with negative voltage; a sloped line is often sufficient, for example:

$$I = I_\mathrm{sat}.[1 - \exp^{(e(V-V_\mathrm{fl})/kT_\mathrm{e})}] + (\Delta I/\Delta V)(V - V_\mathrm{fl}). \tag{2}$$

With this definition, the ion component of the total current equals I_sat at floating potential. In cases where the relative increase of ion current for negative voltages is comparable to the slope of the total current (ion plus electron) near floating potential, the electron temperature can be strongly overestimated if sheath expansion is ignored. That happens because the variation of pure ion current with voltage is incorrectly interpreted as a high electron temperature by the fitting procedure. This effect is particularly noticeable for flush-mounted probes in divertor target plates where the magnetic field is near grazing [14].

Even large probes can be affected by sheath expansion effects. For example, in the Tore Supra tokamak, 14 domed Langmuir probes of 5 mm diameter were installed in the ergodic divertor until it was decommissioned in 1999, and there are now 12 in the pumping throats of the toroidal limiter. A typical I–V characteristic measured by one of these probes is shown in figure 1. The ion current clearly does not saturate. The error on $J_{\|,\mathrm{i}}$ might be acceptable for large probes (for example reasonable agreement was obtained in [15] between large probes, Thomson scattering, and Lithium beams), but by not taking account of the sheath expansion

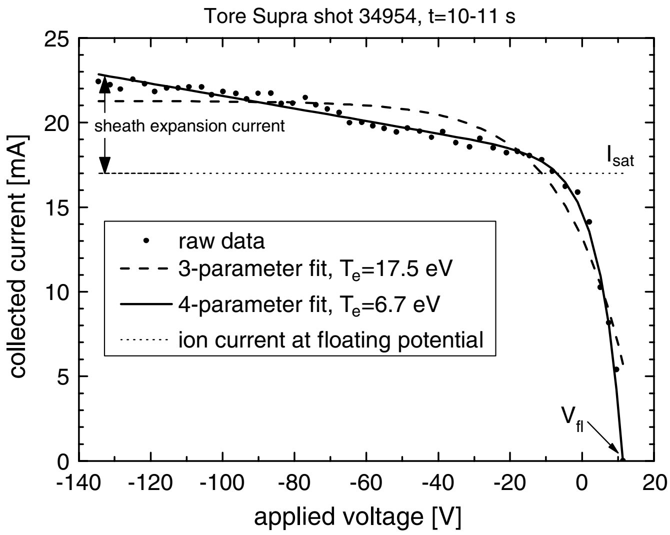

Figure 1. I–V characteristic from a 5 mm diameter dome-shaped Langmuir probe in the pumping throat of the Tore Supra toroidal limiter. Measured data are indicated by dots, the best 3-parameter fit (equation (1)) by the dashed curve, the best 4-parameter fit (equation (2)) by the full curve. The ion current at floating potential calculated by the 4-parameter fit is indicated by the thin dotted line. The increase of ion current above this level for negative voltages is due to sheath expansion.

current (i.e. by fitting equation (1) to the data), one obtains an estimate of T_e that is between two and three times as high as the value obtained from the four-parameter fit (equation (2)). This artificial increase in the measured temperature, which is basically due to an experimental blunder, can be confused with a hypothetical variation of current due to a hot electron tail. In practice it is unfeasible to separate the two effects.

Mach probe measurements could also be influenced by sheath expansion. Mach probe theory relates the ratio of upstream and downstream ion current densities to the unperturbed flow speed. If the effective collecting areas of both conductors are the same, then the Mach number should not be affected by sheath expansion effects. However, since the local density and ion temperature are different on each side of the probe (as predicted by Mach probe theory [4, 16]), and the electron temperature can also be different, it could be that the effective collecting areas of the upstream and downstream pins differ. For example, suppose that the ratio of the real upstream to downstream ion current densities is 3.5, so that the true Mach number is 0.5 according to the Hutchinson model. Let us say that an error of 0.1 on the Mach number would start to be significant. If the upstream and downstream collecting areas were different due to the local plasma conditions on each side of the probe, the ratio of ion currents would not be the same as the ratio of ion current densities. To deduce erroneously a Mach number of 0.6, the ratio of ion currents would have to be 4.5, with the collecting areas differing by roughly 25%. This hypothetical example is not implausible.

There are many reasons to treat Langmuir probe measurements with caution. It is difficult to separate sheath expansion effects, caused by probe geometry, from kinetic effects caused by departures from thermal equilibrium. In this paper we present measurements obtained with a new kind of Langmuir probe, the 'tunnel probe' [17, 18], which is totally immune to sheath expansion effects. This novel feature was already predicted by fully self-consistent kinetic simulations during the design phase of the probe, and is confirmed here experimentally by

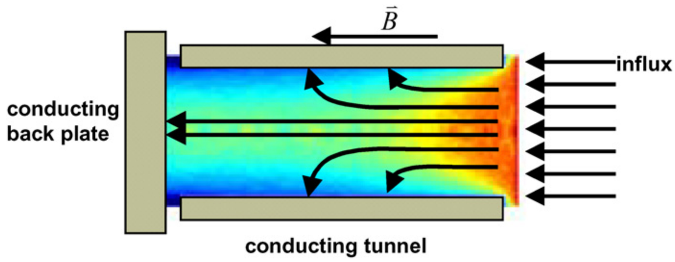

Figure 2. Schematic of the tunnel probe. Black arrows indicate the ion guiding center trajectories. The relative proportion of ion influx to the tunnel and backplate are determined by the electric field distribution inside the probe.

direct comparison with conventional, small cylindrical Langmuir tips (section 2). Two tunnel probes were mounted back-to-back in a Mach probe arrangement in order to get information about possible directional asymmetries in the edge plasma. The measured electron temperature is higher on the electron side than on the ion side, and the floating potentials are different (section 3). The observed asymmetries could be consistent with a hot tail of non-thermal electrons flowing in the counter-current direction.

2. Experimental arrangement

The CASTOR tokamak [19] has a major radius of 40 cm and a minor radius of 8.5 cm defined by a poloidal ring limiter. The magnetic field is $0.5 < B < 1.5$ T and the plasma current up to 15 kA. Both are oriented in the positive toroidal direction, that is, counter-clockwise viewed from above. The main ion species is hydrogen. The core electron density and temperature are $n_e \cong 10^{19}$ m^{-3} and $T_e \cong 180$ eV. In the edge region, where the measurements are performed, typical values of n_e and T_e are about one order of magnitude lower.

Figure 2 shows a schematic drawing of the tunnel probe (TP), which consists of a hollow conducting cylinder (the 'tunnel') a few millimeters in diameter and length. The cylindrical axis is oriented parallel to the magnetic field. The tunnel is closed at one side by an electrically insulated conducting plate (the 'back plate'). The tunnel and back plate are electrically connected together and a triangular voltage waveform (with amplitude ± 100 V and a frequency of 500 Hz) is applied to them. The precise geometry of the conductors is not important; what matters for our purposes is that the tunnel probe is concave. The collecting area of the tunnel probe is exactly known due to its concave geometry [20] and is equal to the cross section of the tunnel orifice, $A_c = \pi r_{TP}^2$, equivalent to an ideal planar disk probe, for both ions and electrons. In this concave probe, the sheath expands from the inner wall of the tunnel towards the cylindrical axis, affecting the distribution of ion current between the tunnel and back plate, but without modifying the total ion current. The sheath remains confined inside the tunnel and does not spread beyond the orifice. Numerical simulations of this configuration were performed with the 2D particle-in-cell code XOOPIC [21] for a realistic range of ion current density, temperature, and bias voltage under CASTOR conditions. It was confirmed that the total numerical current collected inside the tunnel probe was equal to that which was launched from the plasma side within 1%, for several values of applied bias voltage. In theory, we can therefore expect sheath expansion current to be totally suppressed, so the I–V characteristic can be fit by equation (1) to determine T_e, V_{fl} and I_{sat}.

Two tunnel probes oriented in opposite directions with respect to the direction of the plasma current were installed on the same manipulator, inserted from the top of the torus at a

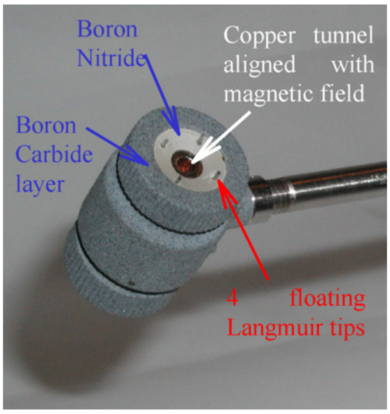

Figure 3. Picture of the CASTOR tunnel probe.

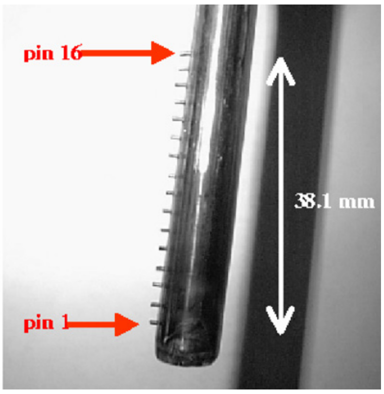

Figure 4. Picture of the CASTOR rake probe.

poloidal angle of 90° with respect to the outboard midplane. The first tunnel probe is mounted on the 'ion side' of the manipulator and it collects charges that move in the positive toroidal direction. Its radius is $r_{\mathrm{TP}}^{\mathrm{ion}} = 2.5$ mm. The second tunnel with radius $r_{\mathrm{TP}}^{\mathrm{elec}} = 2.0$ mm collects charges from the opposite direction, the 'electron side'. Two different radii were chosen in order to study the influence of tunnel radius on the distribution of ion current between tunnel and back plate as part of a separate study. This detail is not relevant to the topic of this paper. Both tunnels are 5.0 mm deep. The radial profiles were determined by changing the position of the probe head on a shot-to-shot basis. On each side of the probe head, four small, cylindrical Langmuir probe tips 0.7 mm in diameter and 2.0 mm long are arranged around a circle of radius 3.5 mm, centered on the tunnel axis, and parallel to the magnetic field (see figure 3). These tips are usually left floating, but on some occasions they were biased negatively to draw pure ion current.

A rake probe (RP), which consists of an array of 16 single Langmuir probe tips spaced by 2.5 mm in the radial direction, is inserted into the edge plasma from the top of the torus, about 40° toroidally away from the tunnel probe, and 180° from the poloidal limiter. The RP is shown in figure 4. The tips are made of molybdenum wire with a diameter of $d_{\mathrm{RP}} = 0.7$ mm and a length of $L_{\mathrm{RP}} = 2.0$ mm. For the rake probe measurements, we estimate the A_{c} as a geometrical projection of the cylindrical tip along the magnetic field, $A_{\mathrm{c}} = 2 \times L_{\mathrm{RP}} \times d_{\mathrm{RP}}$.

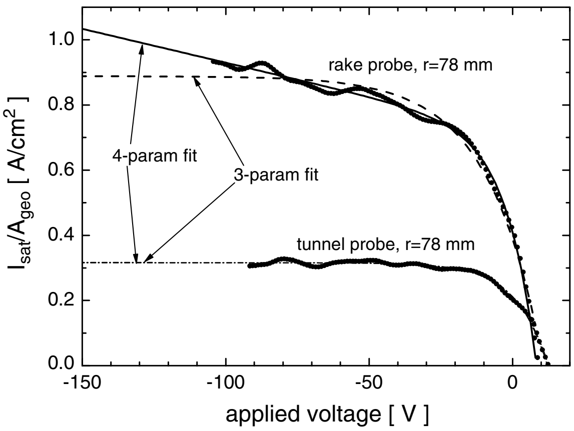

Figure 5. I–V characteristics from the tunnel probe at $r = 78$ mm and from the corresponding pin of the rake probe on another shot. The currents are normalized to their respective geometrical cross sections. The 3-parameter and 4-parameter fits are also shown.

The factor 2 comes from the fact that the probe current is the sum of the ion saturation currents collected by the ion and electron sides of each tip. A triangular voltage waveform (with the same amplitude and frequency as that applied to the swept TP) is applied simultaneously to all tips. Consequently a full radial profile can be measured during single shot.

In each shot either the rake probe or the tunnel probe was inserted into the edge plasma to avoid their mutual shadowing. In what follows, all positions will be expressed as the geometrical minor radius measured with respect to the toroidal axis of the vacuum vessel.

3. Comparison of tunnel probe with conventional probes

In order to make a convincing demonstration of the favorable properties of the tunnel probe, we compare the I–V characteristics measured by the TP at radial position $r = 78$ mm with the corresponding pin of the RP on another shot. However, in the latter case, charged particles are collected both from the upstream and downstream directions and the resulting I–V characteristics represent a sort of average of those that would be measured by the two sides of a Mach probe. All information concerning directional asymmetries is lost. To make a meaningful comparison, we added the current signals from the ion and electron sides of the TP together to simulate charge collection by a single conductor. The signal measured by each TP and the RP was normalized by its geometrical cross section (figure 5).

Both 3-parameter and 4-parameter fitting was applied to each data set. The degree of non-saturation of the ion branch is defined according to the 4-parameter fit (equation (2)) as

$$\eta = \frac{T_e}{I_{sat}} \frac{\Delta I}{\Delta V}. \tag{3}$$

The results are compiled in table 1. In agreement with visual inspection of the figure 5 data, we find that the ion branch of the TP I–V characteristic saturates (low value of η, and the same T_e from both fits), whereas that of the RP does not (high value of η and significantly higher T_e from the 3-parameter fit). Clearly, it is incorrect to apply a saturated 3-parameter fit to the RP data.

Table 1. Results from the 3- and 4-parameter fits for different probe sizes and geometry.

Probe	Larmor radius (mm) for $T_i = 15$ eV	3-parameter fit		4-parameter fit		
		I_{sat} (mA)	T_e (eV)	I_{sat} (mA)	T_e (eV)	η
0.7 mm cylinder (CASTOR)	0.5 for H^+, $B = 1$ T	24.9	18.8	19.2	10.3	0.030
5 mm tunnel (CASTOR)		62.0	11.4	61.6	10.8	0.000 66
5 mm diameter dome (Tore Supra)	0.2 for D^+, $B = 4$ T	21.3	17.5	17.5	6.7	0.0141

The hard saturation of the TP I–V characteristics allows us to conclude that the non-saturation of the RP is not due to a non-thermal electron tail whose characteristic temperature would be higher than the maximum voltage of the power supply; it must be due to sheath expansion. The effective collecting area of the RP tip is an unknown function of the applied voltage, so if we naively take the geometrical cross section for A_c, we deduce different values of $J_{\parallel,i}$ for different voltages. For example, the $J_{\parallel,i}$ for $V = -100$ V is 30% higher than the value obtained by extrapolation to $V = V_{fl}$. In any case, even the latter minimum estimate is more than a factor of two higher than what the TP measures. This could imply that the actual collecting area of a cylindrical tip for these plasma conditions is more than twice as large as its geometrical projection along the field lines.

Another possibility would be that the ion current density to the TP is depressed with respect to the unperturbed value. The TP housing is not negligibly small with respect to the tokamak, so it could be possible that the presheath is connected to the poloidal limiter. That would mean that cross-field diffusive influx integrated along the flux tube would be lower than the prediction of Mach probe theory which assumes infinite connection length [22]. This is probably not the case here, because we observe similar discrepancies at all radial positions, even inside the LCFS. To investigate this issue, on shot 16342 we biased the four small pins mounted around the ion side TP to $V = -100$ V and measured the ion currents simultaneously. Taking the geometrical cross section for the effective collecting area, we obtain estimates $J_{\parallel,i} = 0.33$ A cm^{-2} and $J_{\parallel,i} = 0.77$ A cm^{-2} for the TP and pins, respectively. As we found for the RP, the small pins significantly overestimate the parallel ion current density. The fit results for the Tore Supra probe, included in table 1, remind us that large probes can be seriously affected by sheath expansion effects, too. The ratio of T_e obtained from the 3- and 4-parameter fits, respectively, is 2.6, and the ion current increases by 35% as the voltage varies between floating potential and $V = -130$ V.

The concave tunnel probe yields more accurate measurements of T_e and $J_{\parallel,i}$ than conventional convex probes due to the fact that its sheath electric field is entirely contained inside the probe and does not expand into the plasma to perturb the incoming ion orbits. It should be noted that there is no justification for using a linear term in equation (2). The dependence of sheath expansion current on voltage is unknown, and it is impossible to extrapolate the pure ion current towards the electron branch of the characteristic. Our choice is convenient because it gives qualitative information, but it is also arbitrary. The tunnel probe provides a simple, elegant solution to such difficulties.

4. Directional asymmetries

The edge profiles were measured by the TP for $B_t = 1.3$ T and $I_p = 10$ kA in a series of reproducible discharges.

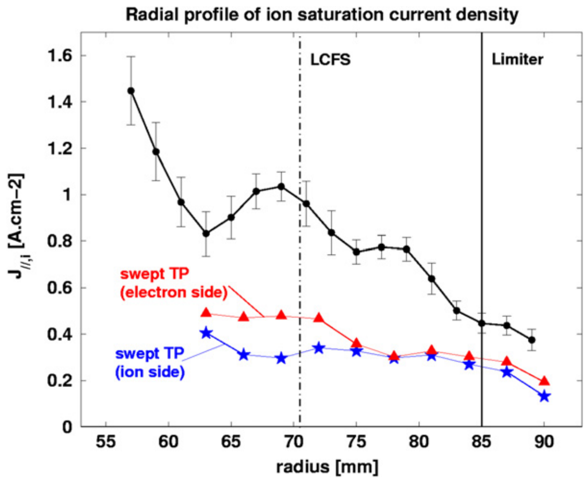

Figure 6. Radial profile of the parallel ion current density as measured by the RP (black line-dots) and by the electron (red line-triangles) and ion (blue line-stars) side of the TP. The vertical dashed–dotted line indicates the position of the last closed flux surface as deduced from the RP floating potential profile (section 4.3).

4.1. Parallel ion current density profiles and Mach number of the ion flow

The radial profiles of the parallel ion current density $J_{\parallel,\mathrm{i}}$ are shown in figure 6. The poloidal limiter and the last closed flux surface are at different positions because of a downward shift of the plasma, which will be described in section 4.3.

The asymmetry in $J_{\parallel,\mathrm{i}}$ between the electron and ion sides of the TP observed for $r < 75$ mm, is evidence of a parallel flow. The parallel Mach number can be derived from the Hutchinson model [4] according to the following formula:

$$M_{\parallel} = 0.4 \ln \left(J_{\parallel,\mathrm{i}}^{\mathrm{elec}} / J_{\parallel,\mathrm{i}}^{\mathrm{ion}}\right), \tag{4}$$

yielding $M_{\parallel} = 0.1$–0.15 for radii $r < 75$ mm. The ion flux to each side of a Mach probe is a strong function of the parallel electric field in the upstream and downstream presheaths. The model assumes that the electron distribution function is Maxwellian, which should lead to the same T_{e} measurement on both sides. We will see in the next section that this condition is not satisfied in the CASTOR's edge plasma. If the presheath electric fields are modified due to anisotropy of the electron distribution function, then equation (7) may no longer be valid, and furthermore, we no longer know how to define the ion sound speed that is needed to calculate the absolute flow speed [7].

4.2. Electron temperature profiles—evidence for anisotropy of the electron distribution

Figure 7 shows the radial profiles of the electron temperature obtained from fitting equation (1) to the TP I–V characteristics. The electron temperature measured on the electron side $T_{\mathrm{e}}^{\mathrm{elec}}$ is nearly a factor of 2 higher than that measured on the ion side, $T_{\mathrm{e}}^{\mathrm{ion}}$. The fitting parameters T_{e} are not true temperatures in the thermodynamic sense, but can be interpreted as being qualitatively representative of the typical energies of the two counterstreaming tails of the parallel electron distribution function. Since the collisionality of fast electrons is low in CASTOR, it is reasonable to suppose that the ion/electron side asymmetry is caused by the electrons that carry the plasma current, driven by the induced toroidal electric field. It would

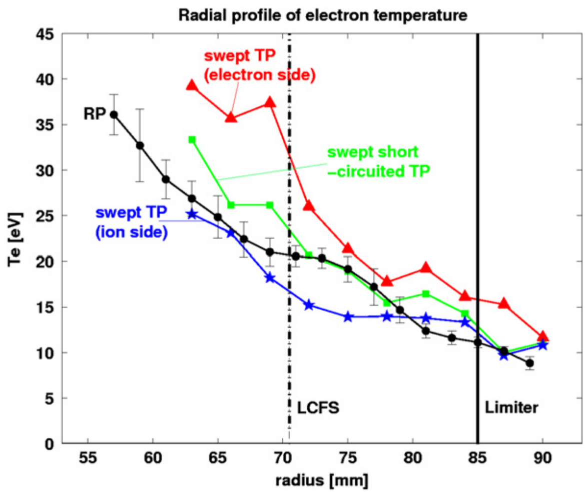

Figure 7. Radial profile of the electron temperature as measured by the RP (black line-dots) and by the electron (red line-triangles) and ion (blue line-stars) sides of the TP. The measurement obtained by short circuiting both TPs together is also shown (green line-squares).

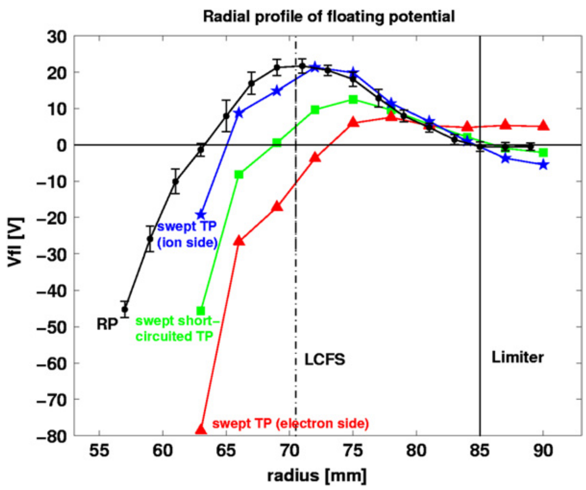

Figure 8. Radial profile of the floating potential as measured by the RP (black line-dots) and by the electron (red line-triangles) and ion (blue line-stars) side of the swept TP. The green line (squares) shows the V_{fl} measured by the short-circuited TP. The dashed–dotted line indicates the position of the last closed flux surface.

have been useful to reverse the plasma current in order to verify whether the temperature asymmetry reversed as well, but unfortunately this could not be done.

4.3. Floating potential profiles

Figure 8 shows the profiles of the floating potential. It is usually supposed in CASTOR that the maximum of V_{fl} measured by the RP indicates the position of the last closed flux surface (LCFS) [23], because it corresponds to the point where the radial electric field changes sign.

The plasma is not centered within the poloidal limiter but shifted down by several millimeters. The probe intersects the LCFS at $r = 71$ mm. The edge region on the top of the tokamak is divided into:

1. the confinement region with closed magnetic surfaces: $r < 71$ mm
2. the SOL with a long connection length of several toroidal turns: $71 < r < 85$ mm
3. the limiter shadow, where the connection length is comparable with the toroidal circumference of the plasma: $r > 85$ mm.

Now, let us focus on the radial profiles of V_{fl} measured by the double TP. It is evident from figure 8 that a toroidal anisotropy is present. Unlike the temperature asymmetry (figure 7), the floating potential asymmetry has a radial variation that can be divided into two regions, the core plasma and SOL where the electron side floating potential is lower than that measured on the ion side, and the limiter shadow where the opposite occurs.

It is not evident that one can interpret the floating potential using elementary probe theory in this case. The floating potential is governed by the balance between ion and electron particle fluxes. Usually, assuming Maxwellian electrons and neglecting secondary electron emission, one expects the floating potential of a probe (measured with respect to the plasma potential V_{p} far away from the probe) to decrease as the electron temperature increases, as given by the expression [24]:

$$V_{\mathrm{fl}} = T_{\mathrm{e}} \ln\left(\frac{J_{\|,\mathrm{i}} A_{\mathrm{i}}}{J_{\|,\mathrm{e}} A_{\mathrm{e}}}\right) + V_{\mathrm{p}}, \quad (5)$$

where $J_{\|,\mathrm{i}}$ is the parallel ion current density incident on the sheath edge, given by quasineutral presheath theory incorporating the Bohm criterion as a boundary condition for the sheath-edge parallel ion speed. $J_{\|,\mathrm{e}} = en_{\mathrm{e}}(kT_{\mathrm{e}}/2\pi m_{\mathrm{e}})^{1/2}$ is the random thermal electron flux in the unperturbed plasma far from the probe. For the calculation of the ion and electron current densities we must consider two collection areas, one for the electrons, A_{e}, and one for the ions, A_{i}. The electrons remain strongly magnetized and thus it is reasonable to assume that their collection area equals the geometric projection of the probe along the field lines ($A_{\mathrm{e}} = A_{\mathrm{geo}}$). In the case of ions whose trajectories are demagnetized in the sheath, the collection area is modified with respect to the geometric area by a factor β, which, in general, can be a function of the plasma parameters ($A_{\mathrm{i}} = \beta^* A_{\mathrm{geo}}$), the probe geometry, and the applied bias voltage. For the cylindrical tips of the rake probe, $\beta > 1$, whereas for the tunnel probe we have $\beta = 1$ [20]. The effective collecting areas for ions and electrons are equal ($A_{\mathrm{i}} = A_{\mathrm{e}} = A_{\mathrm{geo}}$) due to the concave geometry of the TP.

It is standard practice to use the probe measurement of floating potential and electron temperature to calculate the theoretical plasma potential using equation (2). The radial gradient of V_{p} gives the radial electric field, a very important quantity for turbulent transport studies. In practice, since the radial gradient of T_{e} is weak, or not even measured due to the technical difficulty of making fast temperature measurements, it is often neglected and the radial electric field is directly estimated by taking the radial derivative of the floating potential [25]. If one were to blindly apply this procedure to each side of the TP, one would obtain very different profiles of the time-averaged radial electric field. From the ion side measurement, one would find an inversion point shifted slightly outward with respect to the one measured by the RP, while on the electron side, within error bars, it is difficult to identify a clear inversion point since the floating potential profile is nearly flat in the outer region. Plasma potential and electric field cannot be multi-valued at a unique point in space. Clearly, we must delve deeper into kinetic theory to interpret these profiles.

If the electron distribution is not Maxwellian, a simple analytical expression for the floating potential cannot be easily derived. Ultimately, one would have to base the interpretation on a kinetic model of the edge plasma, as in [1]. Nonetheless, let us take equation (2) as a crude approximation of reality in order to obtain qualitative estimates. That is, we assume that each tail of the electron distribution can be described as Maxwellian, even though the effective temperatures might be different on each side.

We need to know the unidirectional electron current density on both sides of the probe to calculate the logarithm term, but unfortunately there is no way to estimate it from the probe data. The electron branch of the I–V characteristic is difficult to interpret. In magnetized plasmas, it has always been observed that the electron saturation current is much lower than what one would expect, that is, much lower than $\sqrt{m_i/m_e}\, J_{\parallel,i}$. For hydrogen, the ratio of electron to ion saturation currents should be of the order of 40, but ratios between 1 and 10 are typically observed. Essentially, this happens because large positive voltages do not remain confined to the sheath, but spread into the plasma due to finite resistivity [26]. In addition, another important phenomenon causes any single Langmuir probe to act as an asymmetric double probe. In order to draw the maximum electron saturation current, a return cathode with surface area much larger than the probe is required, because the return current is limited to the ion saturation regime. Measurements in ASDEX demonstrated that, due to the low perpendicular conductivity, the electric current leaving the probe diffuses slowly onto neighbouring field lines, and returns to the surface of the probe housing immediately adjacent to the probe, or to a limiter at the far end of the connected flux tube [27]. The effective surface area of the return cathode is smaller than necessary, so the total current is limited to some value that is lower than what the random electron current can theoretically deliver, and a significant fraction of the applied voltage appears in the ion sheath of the return cathode.

Since a direct measurement of the random electron flux is not possible, we must resort to theoretical estimates. Based on electric current conservation, on open magnetic flux surfaces it is intuitively reasonable to expect that the net parallel electron flux $J^{\rm ion}_{\parallel,e} - J^{\rm elec}_{\parallel,e}$ resulting from an asymmetry of the electron distribution would be comparable in magnitude to the net ion flux, because the local parallel electric current to any surface is limited by the ion saturation current that the plasma can provide. These fluxes are negligible with respect to the random electron thermal flux, which we can therefore assume to be nearly the same on both sides of the TP, $J^{\rm ion}_{\parallel,e} \simeq J^{\rm elec}_{\parallel,e} \equiv \bar{J}_{\parallel,e}$. On closed magnetic flux surfaces, similar reasoning holds. The net electric current density in the core is roughly $J \sim I_p/\pi a^2 = 70\,{\rm kA\,m^{-2}}$. If this current density were entirely carried by a drifting electron distribution, the mean drift speed would be at most $v_e = J/en_e = 40\,000\,{\rm m\,s^{-1}}$, which is negligible compared with the electron thermal speed in the core ($v_{Te} \sim 6\times 10^6\,{\rm m\,s^{-1}}$).

The preceding assumption concerning the electron fluxes allows us to write the difference between the ion side and electron side floating potentials as

$$\Delta V_{\rm fl} = V^{\rm ion}_{\rm fl} - V^{\rm elec}_{\rm fl} = \bar{T}_e \ln\left(\frac{J^{\rm ion}_{\parallel,i}}{J^{\rm elec}_{\parallel,i}}\right) + \Delta T_e \ln \frac{\sqrt{J^{\rm ion}_{\parallel,i} J^{\rm elec}_{\parallel,i}}}{\bar{J}_{\parallel,e}}, \tag{6}$$

where $\bar{T}_e = (T^{\rm ion}_e + T^{\rm elec}_e)/2$ and $\Delta T_e = T^{\rm ion}_e - T^{\rm elec}_e$. This expression shows that ion flux asymmetries and electron temperature asymmetries can contribute to a difference in floating potential. The first term, proportional to the mean electron temperature, is zero if there is no parallel ion flow. The second term is zero if the two tails of the electron distribution have the same effective 'temperature'. Numerical fitting of the ion saturation currents given by kinetic Mach probe theory [4] yields the following empirical relation

$$\sqrt{J^{\rm ion}_{\parallel,i} J^{\rm elec}_{\parallel,i}} \simeq 0.35 e n_e c_s, \tag{7}$$

which provides the convenient result that the logarithm in the second term of equation (6) is practically constant for fixed plasma density, independent of the ion flow speed.

At all points, we measure $J_{\parallel,i}^{ion} < J_{\parallel,i}^{elec}$ (figure 6) and $T_e^{ion} < T_e^{elec}$ (figure 7). The first term of equation (6), governed by the ion current asymmetry due to parallel flow, is negative, while the second term, describing the effect of a temperature asymmetry, is positive. The observation that ΔV_{fl} changes sign could imply that the parallel flow term dominates in the limiter shadow, while the temperature asymmetry term dominates in the inner region. The postulate that the induced toroidal electric field drives the electron distribution anisotropy is consistent with these measurements. The anisotropy would naturally be very weak in the limiter shadow where the field lines are short-circuited by the limiter itself.

Since we have no knowledge of the distribution functions, the preceding discussion, even though intuitive, is largely conjecture. Nonetheless, the coincidence between low floating potential and high electron temperature in the inner region is striking. Probe measurements are dominated by the tail of the distribution function, rather than the thermal electrons that make up the bulk majority [1,6]. Both the floating potential and the fitted electron temperature are sensitive to the small fraction of electrons that have enough energy to overcome the sheath potential and strike the probe [28]. Even though precise quantitative information about the full ion and electron distributions cannot be obtained without comparison with a kinetic model of the tokamak edge plasma, the directional asymmetries measured by Mach probes give strong hints about the existence of anisotropy. As we have shown, the use of classical Langmuir probes hides the complexity of kinetic phenomena, and can lead to erroneous conclusions.

4.4. Effect of probe geometry on floating potential

We already saw that the effective collecting area of the RP tips is more than twice larger than their geometrical projection along the field lines. In addition to a large error on the calculated ion saturation current density, errors on the floating potential can be expected. In order to provide a basis for comparison, we have built the total I–V characteristic obtained by summing together the ion and electron side TP characteristics. Any differences between the fitted RP and TP characteristics can be attributed to differences in their ion collection mechanisms.

The fitted floating potentials obtained from the TP are significantly lower than those measured by the RP. The theoretical difference in floating potentials, governed by the effective collecting areas, is obtained by applying equation (2):

$$V_{fl}^{RP} - V_{fl}^{TP} = \bar{T}_e \ln\left(\frac{A_i^{RP} A_e^{TP}}{A_e^{RP} A_i^{TP}}\right) = T_e \ln \delta. \tag{8}$$

Here we use the mean temperature averaged over both sides of the TP. Assuming the mean ion saturation current density given by the TP to be correct, δ can be estimated experimentally from the ion saturation currents as

$$\delta = \frac{I_{SAT}^{RP} \pi r_{TP}^2}{I_{SAT}^{TP} L_{RP} d_{RP}}. \tag{9}$$

The two sides of equation (5) are plotted in figure 9. This tendency confirms results reported by Stangeby [12]. In this particular experiment the four floating tips mounted around each tunnel were not connected to the data acquisition due to a lack of available channels, but previous measurements confirm that the time-averaged floating potentials are more positive

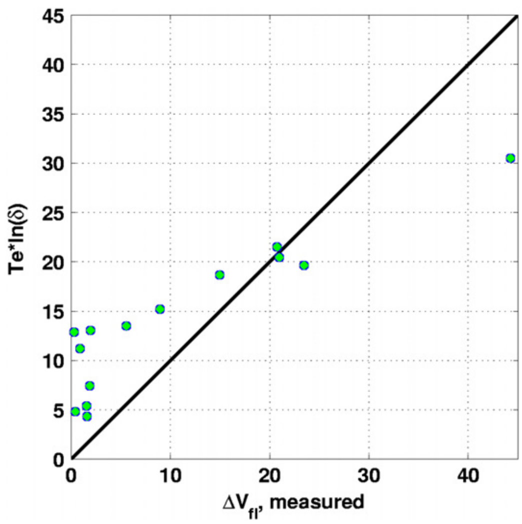

Figure 9. Comparison of the measured difference in V_{fl} between the RP and the TP with the theoretical value given by equation (8).

than that which the tunnel itself measures, in agreement with the observed differences of ion current density cited above.

4.5. More evidence for kinetic electrons

The main motivation for designing the tunnel probe was to provide a dc method to measure electron temperature. The tunnel and backplate are biased negatively to repel all electrons. The electric field distribution of the magnetized sheath determines how the incoming ion flux is distributed over the conductors. The ratio R_{c} of tunnel-to-backplate ion currents is a strong increasing function of electron temperature. Using XOOPIC simulation results for a broad range of plasma parameters, we are able to produce numerical calibration curves that yield T_{e} for a measured pair ($J_{\|,\mathrm{i}}$, R_{c}). The dc tunnel probe measurement of T_{e} is fundamentally different than the ac Langmuir probe measurement; the tunnel probe measures T_{e} without collecting significant electron current. When the tunnel probe is swept as a Langmuir probe we obtain the conventional measurement from the I–V characteristic, and using the ion branch of the same data set, we can calculate R_{c} to get a second, independent measurement.

The kinetic calculations were carried out for a 5 mm tunnel in a hydrogen plasma with $B = 1$ T. In the experiments shown above, the electron side tunnel was 4 mm in diameter; we cannot yet use it to get a dc measurement of T_{e}. However, there are several older experimental campaigns that were done with twin 5 mm tunnels. Those experiments were not as carefully executed; for example, there were several probes inserted into the plasma at once, which caused modifications of the profiles. Nonetheless, similar behavior is always observed, so it is worthwhile to examine the measurements in detail. In particular we show in figure 10 radial profiles of T_e measured simultaneously on both electron and ion sides, using both ac (Langmuir) and dc (tunnel) methods. Again, we see a strong asymmetry of the ac measurement, with a higher T_{e} on the electron side. The dc measurements are both lower in absolute value. Usually we observe that the dc measurements are more symmetric than the ac ones. In this particular case, the asymmetry is even reversed.

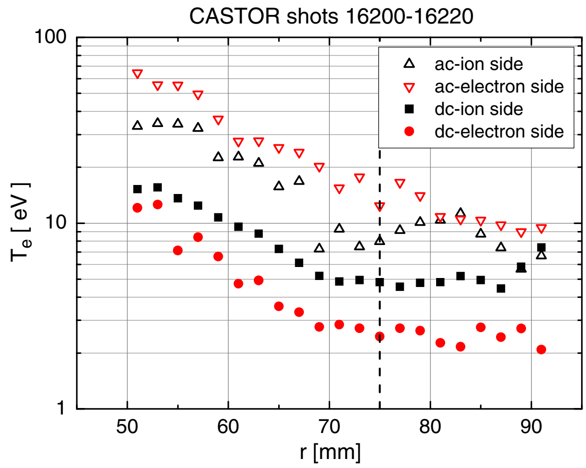

Figure 10. Radial profiles of electron temperature measured simultaneously with twin, back-to-back 5 mm tunnel probes, using ac and dc methods. The LCFS at $r = 75$ mm in indicated by a dashed line.

In general we find that the dc method always gives lower values than the ac method. Two possibilities to investigate the discrepancy have been considered. One is that secondary electron emission (by ion impact) from the backplate can artificially increase the apparent ion current, and lower the tunnel-to-backplate ion current ratio, which is the important quantity needed to deduce electron temperature. If we correct the backplate current using reasonable s.e.e. coefficients (0.3–0.4 is typical for dirty copper at these energies [29]), we obtain higher T_e, but still not as high as the Langmuir probe. The second possibility is that the Langmuir probe is detecting the typical energy of a hot tail of non-thermal electrons, whereas the tunnel probe is sensitive to the thermal bulk population. The electrons are responsible for setting up the radial electric field inside the tunnel, which determines the ratio of tunnel-to-backplate ion current. Which electrons dominate that electric field, the hot ones or the thermal ones? A recent theoretical study [30] shows that in many cases, we would expect the tunnel probe to be totally immune to or less affected by hot electrons than a Langmuir probe. The hot electrons basically stream to the backplate where they contribute to or even dominate the measured current, but in many conditions they are insufficiently numerous to influence the electric field in the tunnel.

The low absolute value of the dc measurement could be partially explained by secondary electron emission, but this should affect both tunnels the same way. It is noteworthy that the ratio of ac-to-dc measurements is around 6 on the electron side, but only 2 on the ion side, consistent with the idea of a strong anisotropy in the counter-current direction. If we take the measurements at face value, we can construct a schematic representation of the electron distribution function. Each measurement of T_e can be considered as the inverse slope of the distribution's logarithm at a given energy. The ac method measures in the high energy range of the tails, while the dc method measures in the low energy range of the bulk. The combined ac and dc measurements in both directions give us four energy ranges. In order, relative to the electron side dc measurement, the temperature ratios are roughly:

$$(T_{\text{e,ac-elec}} : T_{\text{e,dc-elec}} : T_{\text{e,dc-ion}} : T_{\text{e,ac-ion}})/T_{\text{e,dc-elec}} = (6 : 1 : 2 : 4).$$

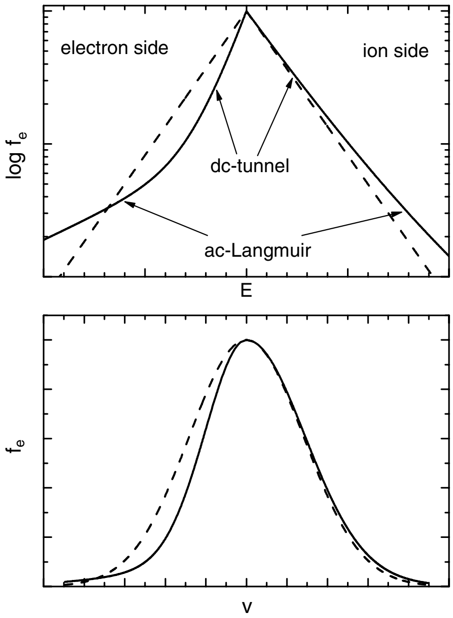

Figure 11. Schematic representation (full curve) of electron distribution function based on measurements of figure 10. A Maxwellian (dashed curve) is shown for comparison. The top panel shows the distribution on a logarithmic scale as a function of electron energy (negative energies indicate electrons that arrive on the electron side of the probe). The portion of the distribution to which each probe method is sensitive are indicated by arrows. The bottom panel shows the distribution on a linear scale as a function of electron velocity.

Representing each half of the distribution as double Maxwellians using these ratios, we obtain the hypothetical distribution shown in figure 11. We arbitrarily choose the hot electron concentration on each side to be 10% of the total.

5. Summary

Two main themes were developed in this paper. The first concerns the physics of charge collection by Langmuir probes in strongly magnetized, tokamak edge plasmas. By comparing the tunnel, the rake probe, and the four small tips mounted around each tunnel, we demonstrate that the proper selection of the collecting area of a cylindrical Langmuir probe plays an important role in calculation of the parallel ion current density. Equating the effective collecting area of a cylindrical Langmuir probe tip with its geometrical projection along the field lines seems to lead to an overestimation of $J_{\|,i}$ by a factor of 2 for the CASTOR plasma parameters, assuming that the effective collecting area of the tunnel probe is precisely known. The difference between the two probes is due to their respective geometries. The conventional cylindrical probe is subject to enhanced ion collection due to the strong electric field in the magnetized sheath that surrounds the convex pin. Three-dimensional kinetic simulations would be needed to model the problem, taking into account the electron temperature, density, applied probe voltage, and bulk flow velocity of the plasma. Such simulations are not within reach today, so one must simply accept that ion current density measurements by conventional probes are highly inaccurate. The concave geometry of the tunnel probe ensures its immunity to sheath expansion effects, thus providing a precise calibration of the parallel ion current density.

In the case of cylindrical probes, the effective collecting area for ions is larger than for electrons due to their different degrees of magnetization. However, the two collecting areas are identical for the tunnel probe. This means that the floating potential of cylindrical probes should be more positive, as was indeed observed in the experiment. Care should be taken when using standard sheath theory to calculate the difference between the floating potential of a probe and the plasma potential. Furthermore, since the sheath expansion current is an unknown function of the plasma parameters, the magnetic field, and the probe bias, we should expect that fluctuations of those quantities can contribute to fluctuations of ion current and floating potential. There could be important consequences for turbulent flux measurements. In principle, as a first step towards quantifying this effect, the tunnel probe could be used simultaneously with conventional turbulence probes to provide a calibration of their effective collecting area.

The second theme concerns directional asymmetries of the measured ion saturation current, electron temperature, and floating potential. Ion current asymmetries are routinely exploited to estimate the Mach number of the parallel flow in many tokamaks, but asymmetries of the other two quantities are generally ignored. In CASTOR, the electron side of the tunnel probe measures higher electron temperature and lower floating potential than the ion side. The existence of an asymmetry could imply that the parallel electron distribution function is anisotropic. This would automatically mean that the electrons are not Maxwellian; if they were, one would expect to measure the same temperature on both sides of the TP. These two observations are consistent with a hot tail of suprathermal electrons streaming in the counter-current direction. The dc measurements of electron temperature using the new method do not show the same asymmetry as the ac Langmuir method, in agreement with theoretical predictions that tunnel probes should be less sensitive to a hot electron tail. The presence of anisotropic, non-Maxwellian electron distributions in the edge plasma can have important consequences, especially in low collisionality regimes as expected in ITER, so it is useful to be able to obtain even qualitative information about them. It is therefore preferable to employ directional probes rather than conventional probes that average over both directions.

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References

[1] Shoucri M *et al* 1998 *Contrib. Plasma Phys.* **38** 225
[2] Hutchinson I H *Principles of Plasma Diagnostics* (Cambridge: Cambridge University Press)
[3] Hutchinson I H 1987 *Phys. Fluids* **30** 3777
[4] Chung K S and Hutchinson I H 1988 *Phys. Rev.* A **38** 4721
[5] LaBombard B *et al* 2004 *Nucl. Fusion* **44** 1047
[6] Batishchev O V *et al* 1997 *Phys. Plasmas* **4** 1672
[7] Gunn J P and Fuchs V 2007 *Phys. Plasmas* **14** 032501
[8] Zweben S J 2007 *Plasma Phys. Control. Fusion* **49** S1
[9] Garcia-Cortes I *et al* 2000 *Plasma Phys. Control. Fusion* **42** 389
[10] Kirnev G S *et al* 2004 *Plasma Phys. Control. Fusion* **46** 621
[11] Mizuuchi T *et al* 2005 *J. Nucl. Mater.* **337–339** 332
[12] Stangeby P C *et al* 1984 *J. Vac. Sci. Technol.* A **2** 702
[13] Stangeby P C and McCracken G M 1990 *Nucl. Fusion* **30** 1232

[14] Gunn J P *et al* 1995 *Rev. Sci. Instrum.* **66** 154
[15] Erents S K *et al* 2004 *Plasma Phys. Control. Fusion* **46** 1757
[16] Laux M *et al* 1989 *J. Nucl. Mater.* **162–164** 200
[17] Gunn J P *et al* 2004 *Rev. Sci. Instrum.* **75** 4328
[18] Gunn J P *et al* 2005 *Czech. J. Phys.* **55** 255
[19] Stockel J *et al* 2005 *Plasma Phys. Control. Fusion* **47** 635–43
[20] Gunn J P 2001 *Phys. Plasmas* **8** 1040
[21] Verboncoeur J P *et al* 1995 *Comput. Phys. Commun.* **87** 199
[22] Hutchinson I H 1991 *Phys. Fluids* B **3** 847
[23] Gunn J P *et al* 2001 *Czech. J. Phys.* **51** 1001
[24] Bohm D 1949 The characteristics of electrical discharges in magnetic fields 1949 *Nat. Nucl. Energy Series* **5** 77
[25] Endler M *et al* 1995 *Nucl. Fusion* **35** 1307
[26] Stangeby P C 1995 *Plasma Phys. Control. Fusion* **37** 1337
[27] Weinlich M 1995 *Ph.D. Thesis* Technical University, Munich
[28] Stangeby P C 1995 *Plasma Phys. Control. Fusion* **37** 1031
[29] Kyslyakov A I *et al* 1975 *Zh. Tekh. Fiz.* **7** 1545
[30] Van Rompuy T *et al* 2007 *Plasma Phys. Control. Fusion* **49** 619–29