Simultaneous DC measurements of ion current density and electron temperature using a tunnel probe

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Abstract. The tunnel probe is a concave Langmuir probe designed to operate in strongly magnetized plasma. Due to its shape, the tunnel probe is immune to sheath expansion effects and thus provides absolutely calibrated measurements of the parallel ion current density. A two-dimensional, self-consistent kinetic model is employed to model the flow of charges within the cavity of the tunnel probe. The calculation predicts that the distribution of the ion flux onto the inner conductors depends on the electric field inside the tunnel, which in turn depends on the electron temperature. Therefore, if the tunnel is divided into two negatively biased collectors, it is possible to use the simulation results to determine the electron temperature from the measured ion current ratio. This means that a DC-biased tunnel probe can be used to provide fast, simultaneous measurements of the parallel ion current density and the electron temperature without collecting a single electron. Measurements in the CASTOR and Tore Supra tokamaks agree well with the numerical simulations.

1. Introduction
Almost invariably in tokamaks, Langmuir probes of convex geometry, such as short bits of cylindrical wire, are employed. Frequently-cited probe diameters from the literature range from 0.5 to 3 mm, and it is often incorrectly assumed that they operate in the strongly magnetized regime. In the context of probe measurements in fusion devices, “strongly magnetized” implies that the ion Larmor radius $r_L$ and Debye length $\lambda_D$ are assumed to be negligible compared to the probe size, so that the ion current to a negatively biased probe is proportional to the flux of guiding centers intersecting the geometrical projection of the probe along magnetic field lines, independent of the magnitude of the applied voltage $V_{bias}$. However, an empirical comparison of various probe geometries showed that the ion current, even that collected by 5 mm diameter domed probes, does not saturate \cite{1} with negative $V_{bias}$. It was experimentally demonstrated \cite{2} that the collecting area of small probes can be more than 2 to 4 times their geometrical projection along $B$. The effective collecting area of most convex probes used in tokamaks is thus highly uncertain, perhaps depending on the very quantities one wants to measure. Many theories have been elaborated for ion collection by convex probes in plasmas whose degree of magnetization varies from zero to infinite. Early on, such theories were applicable only to very specific, sometimes asymptotic parameter regimes. Now with modern computing power, three
dimensional simulations of spherical probes in magnetized plasmas are being performed (see [3] and references therein). Nonetheless, interpretation of convex probe data is rather cumbersome, as one must constantly take account of the particular parameter regime in which the probe operates (e.g. thin sheath vs. thick sheath, flowing vs. stagnant, magnetized vs. unmagnetized), find an appropriate model if it exists, and either extract calibration curves from figures that were printed half a century ago [e.g. 4], or be able to make the calculations oneself.

To avoid this problem, a new kind of concave Langmuir probe called the "tunnel probe" (TP) has been invented [5,6]. It consists of a hollow conducting cylinder, the "tunnel" that is closed at one end by an electrically isolated "backplate" (figure 1). The tunnel axis is parallel to the magnetic field. Plasma flows into the open orifice and the ion flux is distributed between the tunnel and the backplate. Kinetic modelling shows that despite its strong influence on the distribution of the ion flux inside the tunnel, the electric field does not penetrate into the plasma. Therefore, ion streamlines leading up to the mouth of the tunnel are totally unperturbed. That is, the effective collecting area of a concave Langmuir probe embedded in a nearly planar object is almost exactly equal to the geometrical cross-section of its orifice projected along the field lines, which means that such a probe is absolutely calibrated for the measurement of the parallel ion current density $J_{//i}$, independent of the other plasma parameters. An experimental indication that this probe has a well-calibrated effective collecting area is that the total ion current saturates perfectly (see upper panel of figure 5). In contrast to convex probes, which are difficult to calibrate because of the expansion of the sheath electric field into the plasma, concave probes are immune to such problems because the sheath electric field is contained inside the cavity. Inside the probe, however, the distribution of the ion current between the tunnel and backplate depends on the electric field, which is determined by the electron temperature $T_e$ via the Boltzmann relation. This means that a TP biased to a negative DC voltage can be used to provide fast, simultaneous measurements of $J_{//i}$ (the sum of currents to tunnel and backplate) and $T_e$ (related to the ratio of the currents).

2. Kinetic model of the tunnel probe

As described in [7], experimental and numerical investigations of shielded probes in the Tore Supra tokamak [8] revealed that the magnetized sheath strongly affects the flow of charges through a small orifice whose axis is parallel to the magnetic field. It was found that the transmission factor of the orifice depends on the local plasma parameters. Since the sheath thickness scales with $\lambda_D$ and $V_{bias}$, the fraction of the incident current collected by the walls of the orifice can vary. The TP was thus proposed in order to exploit this dependence. By making kinetic simulations for a wide range of expected conditions, it was hoped that calibration factors could be derived which would allow the TP to make simultaneous, DC measurements of $J_{//i}$ and $T_e$.

Several prototype TPs of different geometries were built and tested over a few years in the CASTOR tokamak [9]. In CASTOR, the magnetic field was $B = 1$ T and the plasmas were hydrogen. To calibrate the TP, the XOOPIC code [10] was used to make a large number of simulations for expected plasma conditions. The qualitative behavior of the tunnel-to-backplate ion current distribution conformed to the prediction of the calculations, although the quantitative agreement was not so good. Typically, for a given $J_{//i}$ and $T_e$, the measured fraction of the ion current collected by the tunnel was significantly lower than expected. This behavior is now understood to be related to the boundary conditions for particle injection onto the simulation domain, which have been improved. For the CASTOR runs we injected unshifted, half-Maxwellian distributions, but this led to the formation
of a source sheath and a significant drop in the density at the tunnel entrance. Since the calibration depends on that density, as well as \( T_e \) and \( V_{bias} \), the calibration factors would require a complicated transformation to relate the current density, which is directly measured, to the sheath edge density \( n_{se} \), a quantity that must be calculated.

A PIC code that works in cylindrical geometry (on the \( R-Z \) plane) has been developed to produce calibration curves for the TP. The code is named "PICCYL", PIC code in cylindrical geometry. Standard PIC techniques such as second order leap-frog particle advance, first order grid weighting, non-uniform particle weighting, etc. have been implemented to optimize the code, and will not be discussed here. The novel aspects of the code involve, first of all, its normalization. PICCYL is designed according to the physics-based scales that determine the dynamics of the magnetized sheath, as described in [11]. The two principal parameters that contain all the physics are the Debye length \( \lambda_D = \sqrt{\epsilon_0 T_e / e n_e} \), and the magnetization strength \( \xi = \omega_p / \omega_e = \sqrt{m_e n_e / e_0 B^2} \). This makes PICCYL extremely useful for interpreting measurements in different tokamaks, with different magnetic fields, different plasma species, and different TP geometries, using a single normalized database.

The theory of Mach probes [12] is crucial to understanding how the TP works. Since the local densities at the entrances of the two TPs on either side of the Mach probe can be different in the presence of a parallel flow, the local Debye lengths can also be different. One has to account for these differences when attempting to use the TP to make DC \( T_e \) measurements. Often in the field of plasma-wall interactions, solutions are found on one of two asymptotic scales. To resolve the details of plasma flow to a probe, we are obliged to model non-neutral plasmas on the Debye scale. However, it is necessary to prescribe physically consistent boundary conditions for the plasma entering the sheath which rigorously satisfy the Bohm criterion. These boundary conditions are provided by a collisionless kinetic model [13] that solves the presheath equations in the opposite limit of vanishing \( \lambda_D \), and predicts the ion distribution function approaching the probe up until the sheath edge as a function of the background ion flow speed and the temperature. In PICCYL, the ions are launched from an injection plane towards the TP with a parallel speed distribution given by the kinetic model [13]. The distribution corresponding to \( T_i = 2 T_e \) has been used for most of our simulations, since that is a typical value for ohmic discharges in Tore Supra as measured by a retarding field analyzer [14,15]. Since the kinetic distribution satisfies the Bohm criterion, there is no artificial source sheath in front of the injection plane, and the effective local \( \lambda_D \) in the quasineutral plasma at the entrance of the tunnel is what we intend it to be. For a given \( J_{bias} \) the sheath edge density in PICCYL is higher than that obtained when injecting an unshifted, half-Maxwellian in XOOPIC. The local sheath at the tunnel surface is thus thinner, meaning that fewer ions are deflected from their guiding center trajectories, resulting in a low ion current to the tunnel. We shall see below that the improved boundary conditions remove the discrepancy observed in the first CASTOR experiments.

A series of simulations was completed in order to construct a database that spans a sufficiently wide parameter space to cover the range of \( J_{bias}, T_e, B, V_{bias} \), and ion mass number \( A \) typically encountered in the tokamak SOL (figure 2). The magnetization strength \( \xi \) was varied from 1 to 18.5 and the tunnel radius, from 10 \( \lambda_D \) to 170 \( \lambda_D \). For each \( (\xi, r_{TP}) \) pair, 5 to 10 values of the probe bias voltage \( \phi \) (normalized to \( T_e \)) were simulated to be able to construct \( I-V \) characteristics over the range \( -200 \leq V_{bias} - V_L \leq 0 \) V. The advantage of the normalization scheme is immediately obvious, because it allows us to reduce a 5-dimensional parameter space to a 3-dimensional one. This database covers experiments in the CASTOR tokamak (hydrogen plasma with \( B = 1 \) T), and the Tore Supra tokamak (hydrogen, deuterium, or helium plasma with \( 2 \leq B < 4 \) T). Not only is it used to interpret past experimental results, but to design TPs for future experiments.

A random selection of ion orbits is shown in figure 3 for the case of \( r_{TP} = 40 \lambda_D \) and \( \xi = 5.0 \), corresponding to \( J_{bias} = 0.66 \) A/cm\(^2\) and \( T_e = 20.7 \) eV for deuterium plasma in Tore Supra with \( B = 3.5 \) T. It can be seen that when an ion enters a region of strong radial electric field, it experiences
an azimuthal EXB drift while accelerating exponentially towards the tunnel surface, with the Larmor gyration destroyed. It is because the scale-length of the electric field gradient is shorter than $r_L$ that the magnetic moment is no longer a conserved quantity. Ions are demagnetized and can deviate from guiding center trajectories. Incidentally, it is for this reason that the ion current to convex probes is much higher than that predicted by the guiding center approximation.

3. Comparison between PICCYL simulations and measurements

The first test of the TP concept was made with a series of prototypes in the CASTOR tokamak. The TPs were mounted on a manipulator that could be moved radially between discharges. We define the experimental current ratio as the fraction of the total current which flows to the tunnel $R_{c,exp} = I_{TUN}/(I_{TUN}+I_{BP})$. The resulting PICCYL calibration curves are shown in figure 4. The typical evolution of the measurements is superimposed for CASTOR shot 13172. The analysis procedure is straightforward. One calculates $J_{ij}$ from the sum of the two ion currents divided by the cross-section of the tunnel, and the current ratio is used to calculate $T_e$ by interpolation within the numerical results. During the plasma current ramp-up phase at the beginning of the discharge, the ratio is very high and the density low. For extremely small $J_{ij}$, Debye shielding is weak and the potential distribution in the tunnel is essentially the same as the vacuum one. The current measurements give no useful information about $T_e$. This is evident from the theoretical results which all converge as $J_{ij}$ tends to zero. Fortunately, such low densities only occur during the plasma current ramp-up phase at the beginning of the discharge. The points smoothly follow the low-temperature contours until the hot flat top phase when fully developed turbulence sets in. This phase appears as a cloud of points bracketed by the ranges $20 \leq T_e \leq 40$ eV and $0.6 \leq J_{ij} \leq 1.3$ A/cm$^2$.

The physics governing the TP is fundamentally different than that of a classical LP. The voltage applied on the LP is swept in order to measure a restricted part of the electron distribution function. The
Figure 4. Theoretical tunnel-to-total current ratio predicted by the PICCYL code for the 5 mm diameter TP in hydrogen plasma in CASTOR assuming $V_{\text{bias}} = -100$ V and $B = 1$ T. Experimental results from a DC-biased probe (CASTOR shot 13172) are superimposed (grey points).

TP, on the other hand, is biased to a fixed potential that is sufficiently negative to repel all electrons. The temperature of the electrons is measured even though none are collected. It is necessary to compare the two methods. As a validation exercise, we examine measurements in CASTOR. Two copper tunnels were implemented, one facing the ion direction and the other the electron direction. The tunnel diameter was 5.0 mm and its depth was 5.0 mm. The voltage on all conductors was swept in order to measure the I-V characteristics. The averaged data that were acquired by the ion side TP on shots 16204 during the pure ohmic phase, and 16214 during the electrode bias phase, are shown in figure 5. On shot 16204 the probe was situated at $r = 83$ mm and on shot 16214 it was placed at $r = 63$ mm. We focus on these specific data because $J_{//i}$ was found to be roughly 0.5 A/cm$^2$ in both cases, while the

Figure 5. The upper panel shows I-V characteristics obtained by summing the tunnel and backplate currents together for CASTOR shots 16204 (open black circles) and 16214 (full red dots). The raw tunnel and backplate currents are shown in the lower panel. Theoretical ion currents predicted by PICCYL are superimposed on the raw data.

Figure 6. Comparison of theoretical tunnel-to-total current ratios calculated by the PICCYL code with the measured ratios from each I-V characteristic having $J_{//i} > 0.1$ A/cm$^2$. The ratios were taken 100 V below floating potential. For all cases, sheath potential $\phi_{\text{sh}} = -2T_e$ and ion temperature $T_i = 2T_e$ were assumed. Blue dots and red triangles correspond to electron-side and ion-side tunnels, respectively.
electron temperatures differed by about a factor of two. An exponential function is fit to the data to obtain estimates of $T_e = 10$ eV and $T_e = 22$ eV using the classical swept LP technique. Then the ion currents to the backplate and the tunnel are calculated by extrapolation within the PICCYL database. The theoretical ion currents agree quite well with the measurements both in absolute value and in their voltage dependence.

4. Measurements in the Tore Supra tokamak

The Mach probe used in an experiment dedicated to SOL flow studies in Tore Supra [16] was in fact composed of two back-to-back TPs. The SOL profiles exhibited a wide range of $J_{\parallel,i}$, $T_e$, and $M_\parallel$ and thus provide a challenging test of the TP theory. The profiles of $J_{\parallel,i}$ and $T_e$ were measured on both sides of the probe, with the core density increased shot by shot until the radiative density limit. The radiated power fraction evolved from approximately 40-50 % on the first discharge, to 100 % on the fourth discharge, resulting in an order of magnitude variation of $T_e$. The variation of the plasma contact point with respect to the region of ballooning-type radial transport lead to strong variations of the parallel flow. From each I-V characteristic the resulting $J_{\parallel,i}$ and $T_e$ are used to calculate the local values of $\xi$ and $r_{TP}/\lambda_D$, and the theoretical I-V characteristic is constructed by interpolation within the normalized database. The theoretical and experimental current ratios are compared for $V_{bias} - V_I = -100$ V for all $J_{\parallel,i} > 0.1$ A/cm$^2$ in figure 6. Independently of which side of the Mach probe produced each measurement, and independently of the reciprocation, there is a fairly decent correlation between theory and experiment. One can remark that the theoretical ratio is a bit higher than the measurement for the smallest values, which correspond to the lowest measurements of $T_e$. The normalized database was built using the unique value $\tau = T_i/T_e = 2$. However, it has already been observed in Tore Supra (and many other devices) that the ion-to-electron temperature ratio in the SOL can vary strongly with the local plasma density. At low densities, the two tend to be decoupled due to low ion-electron collision rate. At higher densities, the collision rate can be sufficient to bring about temperature equipartition. Therefore, even though no $T_i$ measurements were made, we hypothesize that $\tau$ decreases significantly as the core density increases in our experiment. As a result of the smaller ion Larmor radius, less current flows to the tunnel than is predicted by the PICCYL simulations.

5. Concluding remarks

It was convincingly demonstrated that for simple $J_{\parallel,i}$ measurements the TP is superior to classical convex Langmuir probes because it is not subject to sheath expansion effects. For turbulence measurements, this means that the TP measures the true $J_{\parallel,i}$ fluctuations, whereas the classical probe signals are contaminated by sheath expansion current which depends on the other plasma parameters. Standard Langmuir probes cannot separate density fluctuations from temperature fluctuations. New schemes to measure temperature fluctuations without fast voltage sweeping have been proposed, usually involving probe arrays (for example triple probes) or more sophisticated types of probes, for example combined Langmuir and ball-pen probes. Given the positive results of the present study, the TP method can be
proposed as a new technique that can be added to the arsenal of tools available for measuring plasma turbulence. What makes the TP potentially interesting is that the current density and temperature fluctuations can be made simultaneously at the same location, using cheap DC electronics.

As an illustration of the kind of results one can obtain with the TP, we show measurements that were made with the ion-side tunnel on the vertical reciprocating probe during a supersonic molecular beam injection [17,18] on Tore Supra deuterium discharge 47771 with plasma current 1.2 MA (figure 7). A supersonic gas pulse was released from an injector on the high field side of the tokamak. The tunnel and backplate were biased to $-150$ V and the DC currents were measured at a rate of 1 MHz. The magnetic field at the probe location was 3.5 T. Following the arrival of the gas pulse, the local density increased several times, and the SOL cooled to a few eV. MHD activity was also triggered, visible as the long-time scale pulses which last a few ms.

**Acknowledgements**

This work, supported by the European Communities under the contract of Association between EURATOM and CEA, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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