Measurement of Electron Temperature Fluctuations with Tunnel Probe in the CASTOR Tokamak

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ABSTRACT

The tunnel probe is a new kind of Langmuir probe for use in the tokamak scrape-off layer. Two-dimensional kinetic analysis of the ion current distribution on the concave conductors is used to calibrate the probe for measuring ion flux and electron temperature. Qualitative agreement with classical Langmuir probe measurements is found, but the electron temperature given by the tunnel probe is several times lower. This discrepancy can be caused by secondary electron emission, or the presence of suprathermal electrons. Strong reduction of ion flux and electron temperature fluctuations is observed electrode biasing.

Key Words: Plasma Diagnostics, Electrostatic Probes, Tokamak Edge Plasma

INTRODUCTION

The tunnel probe (TP)(1) is a new kind of Langmuir probe (LP) for use in the tokamak scrape-off layer. It consists of a hollow conducting tunnel a few millimetres in diameter and typically 5 mm deep that is closed at one end by an electrically isolated conducting back plate (see schematic in Fig. 1). The conductors are biased negatively with respect to the tokamak chamber to collect ions and repel electrons. 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 back plate.(2) The self-consistent interaction between the charge distribution and the electric potential inside the tunnel gives rise to two concentric layers of strong radial electric field having different characteristic radial decay lengths. The first is the positively charged electrostatic Debye sheath that lies adjacent to the tunnel surface and shields the plasma column from most of the applied probe potential. It scales as the square root of the ratio of electron temperature T_e to local electron density n_e. The second layer is the quasineutral magnetic sheath that scales as the square root of T_e. This magnetic sheath owes its existence to the radial polarization drift of ions.(3) The magnetic sheath is broader than the Deybe sheath. The structure of the electric field layers determines the current path inside the tunnel. Ions that enter the strong radial electric field gradient in either of these two regions are demagnetized and attracted to the tunnel surface. Electrons

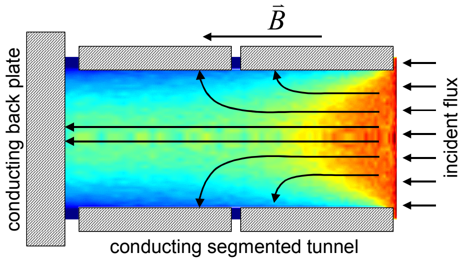

Fig. 1. Schematic of TP. The current collected by each of the three conductors is monitored separately. The ion guiding center trajectories are shown by black arrows.

remain strongly magnetized under all circumstances.

KINETIC MODELING OF THE TUNNEL PROBE

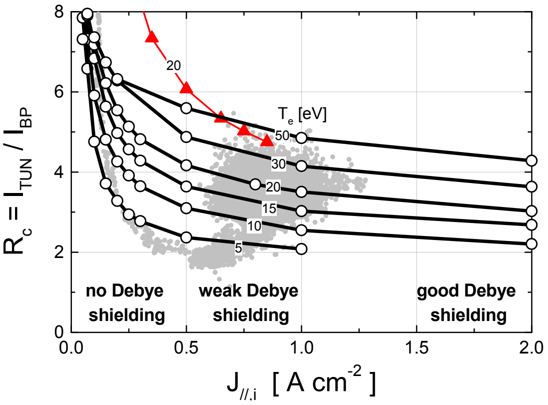

Fig. 2. The lines with open circles are tunnel-to-back-plate ion current ratios for various values of $J_{//,i}$ and T_e assuming hydrogen, B=1 T, tunnel diameter 5 mm, and applied voltage -100 V. The gray points are measured (CASTOR shot 13172). Simulation results for T_e=20 eV, V=-200V are shown for comparison (full triangles).

The current flow to the probe collectors is calculated by the two-dimensional kinetic code XOOPIC$^{(4)}$ in cylindrical geometry for a range of T_e and incident parallel ion current density $J_{//,i}$ (Fig. 2). Three parameter regimes have been identified. The first and most useful parameter regime occurs when $J_{//,i}$ is sufficiently high that the Debye sheath is much thinner than the tunnel radius (greater than about 1 A/cm^2 in CASTOR conditions), the potential drop between the tunnel surface and the plasma is efficiently shielded. In that case the potential distribution and plasma fluxes inside the tunnel are insensitive to variations of the applied potential, and the residual potential drop in the quasineutral magnetic sheath should only be sensitive to electron temperature for a given magnetic field. The probe can thus be operated in dc mode and therefore provides fast simultaneous measurements of $J_{//,i}$ and T_e. The ratio $R_c=I_{TUN}/I_{BP}$ increases with T_e because the magnetic sheath expands inward toward the cylindrical axis and diverts greater numbers of ions onto the leading edge of the tunnel. The analysis procedure is straightforward. One calculates $J_{//,i}$ from the sum of the two ion currents divided by the cross section of the tunnel, and their ratio is used to calculate T_e by interpolation within the numerical results. The second parameter regime occurs for intermediate values of $0.2<J_{//,i}<1.0$ A/cm^2. The density in the tunnel is low and the Deybe sheath thickness is significant with respect to the tunnel radius. The applied potential can penetrate into the plasma column, modifying the particle orbits. Simulations were performed in this regime for applied voltages of -100 V and -200 V with respect to the floating potential. For clarity we print the high voltage results only for T_e=20 eV in the figure, but the results for other temperatures behave the same way. It is observed that R_c is quite sensitive to applied voltage, as well as to the magnitude of $J_{//,i}$. Operation in dc mode is feasible in this regime but because fluctuations of floating potential, electron temperature, and ion current density all affect the current ratio, the floating potential must be measured simultaneously by small LP tips located near the tunnel entrance on the same magnetic flux surface. Finally, for extremely small $J_{//,i}<0.2$ A/cm^2, Debye shielding is weak and the potential distribution essentially is the same as the vacuum one. The current measurements give no information about $J_{//,i}$ or T_e. Fortunately such low densities only occur during the plasma current ramp-up phase at the beginning of the discharge. The typical evolution of the measurements is presented in Fig. 2 for CASTOR shot 13172. During the current ramp-up, the ratio is initially very high and the density low. The points smoothly follow the low temperature contours until the hot flat top phase when fully developed turbulence sets in.

EXPERIMENTAL VALIDATION OF THE NUMERICAL CALCULATIONS

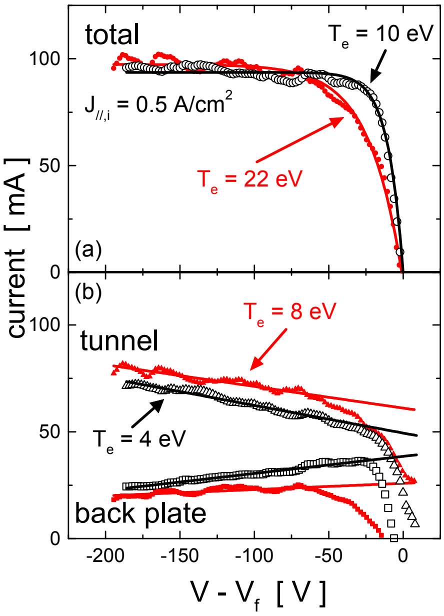

Fig. 3. (a) Total current collected by swept TP for two values of T_e. (b) Distribution of the current between the tunnel and back plate. The TP method gives lower T_e than the swept LP.

The physics governing the TP is fundamentally different than that of a classical LP. The applied voltage on the LP is swept at 1 kHz in order to measure a restricted part of the electron distribution function. The 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. In order to investigate the validity of the simulation results we built a prototype TP and installed it on the top of the CASTOR tokamak on a manipulator that could be displaced radially between discharges. 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 tunnel was split into two electrically isolated segments in order to study the axial distribution of ion current. For this experiment (shots 16200-16221) the probe axis was aligned with the magnetic field and a radial scan was performed starting at r=91 mm and reducing the probe radius by 2 mm between shots. The voltage on all conductors was swept in order to measure current-voltage (I-V) characteristics. The averaged data that were acquired by the ion side TP on shots 16204 and 16214 during the bias or ohmic phase of the discharge, respectively, are shown in Fig. 3. On shot 16204 the probe was situated at r=83 mm, roughly the radius of the poloidal limiter (r=85 mm) and on shot 16214 it was placed at r=63 mm, near the radius of the biasing electrode (r=60 mm). We focus on these specific data because $J_{//,i}$ was found to be roughly 0.5 A/cm^2, a value that we simulated with the XOOPIC code, while the electron temperatures differed by about a factor of two. The sum of the currents collected by the back plate and tunnel segments gives an I-V characteristic that is equivalent to that of an ideal disk probe with cross section equal to that of the tunnel entrance. The ion current for highly negative voltages is almost perfectly saturated, demonstrating the immunity of concave probes to sheath expansion effects, a problem that has always plagued convex LP applications. An exponential function of the form

$$I = I_{SAT}\left(1-\exp\left(\frac{V-V_f}{T_e}\right)\right) \tag{1}$$

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 current to the back plate and the total of the two tunnel segments are measured at -100 V and -200 V with respect to floating potential. From the low temperature characteristic (open symbols on the figure) the ratios of those currents are R_c=2.1 and 3.3 respectively, and interpolation within the XOOPIC results gives T_e values of 3.6 eV and 4.2 eV. From the high temperature characteristic (full symbols on the figure) the ratios are R_c=3.1 and R_c=4.1, giving T_e=9.9 eV and 7.3 eV. From each characteristic we get three simultaneous and independent estimates of T_e that may be compared. The two values derived from the TP technique agree reasonably well with each other but they are generally a few times lower than the LP value. LPs are often accused of producing falsely high T_e measurements. If the electron distribution is not thermal, a small population of suprathermal electrons may be collected, and it is the characteristic energy of those electrons to which a swept LP is sensitive.$^{(5)}$ Further problems can arise due to rectification of plasma fluctuations and plasma resistivity in the current channel between the probe and the reference electrode. On the other hand, secondary electron emission from ion bombardment of copper would lead to apparently high values of back plate ion current, which would cause the TP to underestimate the electron temperature. If we assume that the LP value is correct and calculate the secondary emission coefficient γ that would be needed to make the TP agree, we find $\gamma \approx 0.5$. This value is of the correct order of magnitude if we compare with published experimental studies.(6) More XOOPIC simulations are needed to quantify the effect of additional electrons, whether they be suprathermals emitted by the plasma or cold secondary electrons emitted by the back plate, on the electric field distribution inside the tunnel.

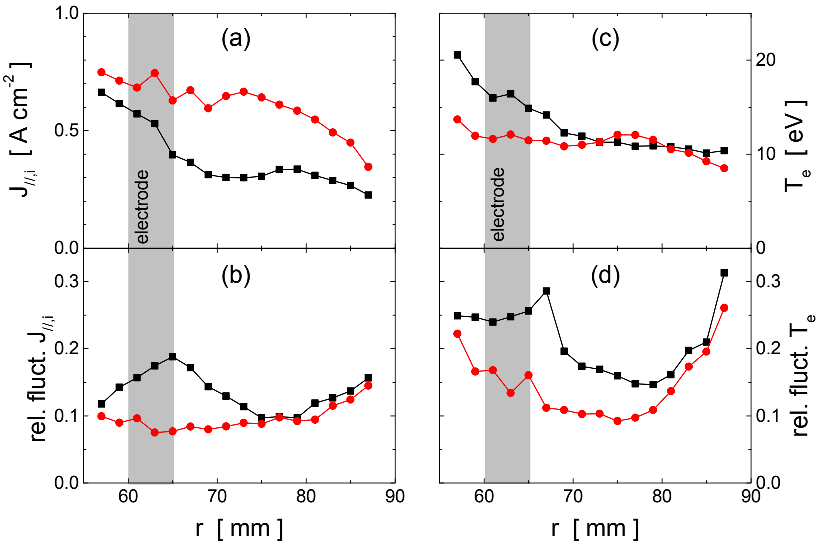

Fig. 4. Tunnel probe measurements from ion side during ohmic phase (squares) and bias phase (circles) of the discharge. The biasing electrode was placed at r=60 mm. The displayed quantities are (a) parallel ion current density and (b) its relative fluctuation amplitude, and (c) electron temperature and (d) its relative fluctuation amplitude. A secondary electron emission coefficient γ=0.5 was assumed.

The first analysis of electron temperature and ion current density fluctuations measured by the TP indicates a strong reduction of the level of turbulence during electrode biasing (Fig. 4). In this experiment, the biasing electrode was placed inside the plasma (r=60 mm) and biased to +100 V. The strongest reduction is observed in the vicinity of the electrode radius with further reduction in the SOL behind the electrode.

CONCLUSIONS AND FUTURE WORK

Because of the simple geometry of theTP, it is possible to carry out precise kinetic simulations in order to calibrate it. Even with a highly idealized model, we have seen that the simulation results behave remarkably like the experimental measurements, indicating that we have correctly identified the essential physics. Further simulations including suprathermal electrons and secondary electron emission are expected to explain the discrepancy between LP and TP T_e measurements. Preliminary measurements of the radial profiles of ion current density and electron temperature fluctuations reveal a strong reduction of ion and electron turbulence in the EXB shear layer during electrode biasing.

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