A DC Probe Diagnostic for Fast Electron Temperature Measurements in Tokamak Edge Plasmas

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The tunnel probe (Fig. 1) is a new kind of Langmuir probe for use in the tokamak scrape-off layer (SOL). It provides simultaneous measurements of electron temperature T_e and parallel ion current density $J_{//}$ with arbitrarily high frequency at the same point in space. It consists of a hollow conducting tunnel a few millimetres in diameter, closed at one end by an electrically isolated conducting back plate (BP). Both conductors are biased negatively to collect ions and repel electrons. The tunnel axis is parallel to the magnetic field $\vec{B}$. Plasma flows into the open orifice and the ion flux is distributed between the tunnel and the BP. The ratio of the two ion currents is determined by the magnetic sheath (MS) thickness at the concave surface of the tunnel, and is therefore a strong function of T_e. The self-consistent, two-dimensional kinetic code XOOPIC [1] is used to determine the theoretical relation between the current ratio $R_C = I_{TUN} / I_{BP}$ and T_e. Combined with the measured sum of the two currents $I_{TUN} + I_{BP} = J_{//} \pi r_{TUN}^2$, n_e at the sheath entrance can also be estimated. A detailed description of the kinetic simulations and a convincing experimental validation in the Tore Supra tokamak have already been published [2]. The purpose of that study was to calibrate the effective ion
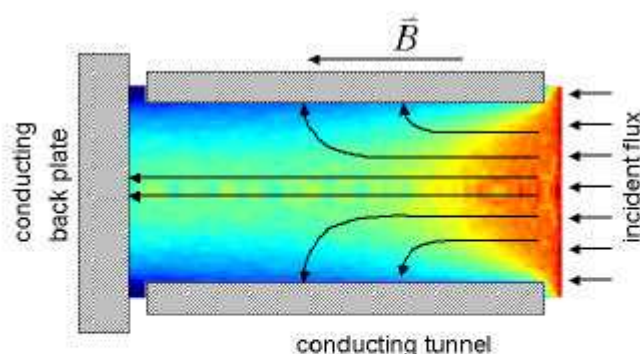

Fig. 1. Schematic of the tunnel probe. Ions near the tunnel surface are diverted from their guiding center trajectories by the strong radial electric field in the magnetic sheath. The ratio of the currents flowing to the tunnel and to the back plate is a sensitive function of electron temperature.

collecting area of a large Langmuir probe tip shielded by a thick conducting plate through which a cylindrical orifice was drilled. A large fraction of the ions flowing along $\bar{B}$ lines through the orifice are neutralized on the shield, resulting in an attenuation of the ion current measured by the pin. The calibration is needed to calculate the unperturbed $J_{//}$ incident on the shield surface. It turns out that the calibration factor depends strongly on T_e and weakly on $J_{//}$. These findings inspired the design of the tunnel probe.

Here we report on the first tests of a prototype tunnel probe in the CASTOR tokamak. The primary goals of the experiments were to find the optimal tunnel radius that gives a significant variation of R_C as a function of T_e, and to investigate the effect of angular misalignment between $\bar{B}$ and the tunnel axis. The latter cannot be tested theoretically because we do not yet have a 3D kinetic code, although 2D calculations [2] indicate that the probe should tolerate small misalignments of roughly 5°. The probe was mounted on a manipulator that could be moved radially and rotated between shots.

Tunnel diameters of 2.5 mm, 4.0 mm, and 5.0 mm were investigated. The tunnels were 5 mm long in all cases (this length must be larger than the helix length of the ion orbits for our analysis to be valid). It turns out that a good rule of thumb is to choose the tunnel radius to be roughly twice the MS thickness [3], $r_{TUNNEL} \approx 2L_{MPS} \simeq 8c_e / \omega_{ci}$ (where $c_e^2 = kT_e / m_i$ is the cold ion sound speed and ω_{ci} is the ion cyclotron frequency). In that case, the plasma inside the tunnel is divided into two regions. On axis, outside the MS boundary, the plasma flows unperturbed to the back plate. Near the concave surface inside the MS, all the ions are deviated from their guiding center trajectories by the strong radial electric field and collected by the leading edge of the tunnel. If the tunnel is too large, R_C is not sensitive enough to T_e; if it is too small, the radial electric field penetrates to the axis and the plasma remains attached to the entire length of the tunnel with the result that almost no current flows to the back plate. The following table compares the ratio of MS thickness to probe radius between the various probe diameters that were tested in CASTOR (hydrogen gas, B=1 T) and Tore Supra (deuterium gas, B=3.5 T), assuming T_e=20 eV :

probe diameter	CASTOR 2.5 mm	CASTOR 4 mm	CASTOR 5 mm	TS 3 mm
L_{MPS} / r_{TUNNEL}	1.5	0.9	0.7	0.5

This is of course a crude simplification of the physics; in reality there is no sharp division between the two regions, and the MS scaling derived from 1D simulations in planar

geometry is certainly modified by the strong cylindrical curvature of the probe. Nonetheless, the rule of thumb proves to be a good guide. The importance of choosing the correct diameter is illustrated in Fig. 2. The back plate was biased to -100 V to collect ions, and the tunnel voltage was swept. For large voltages, the ion current to the 2.5 mm back plate is completely suppressed,
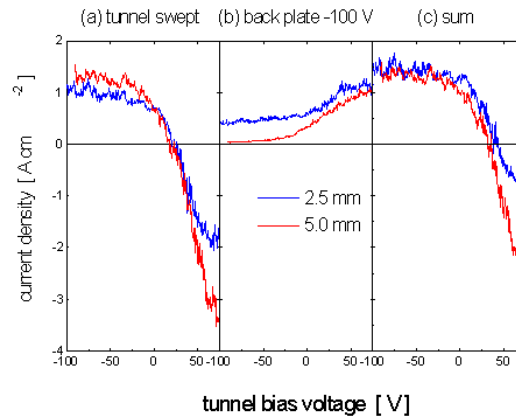

Fig. 2. Comparison of current distribution inside 2.5 mm and 5.0 mm tunnel probes. Bias voltage is swept on tunnel, fixed on back plate. (a) I-V characteristic of tunnel. (b) Current throughput to back plate. (c) Total current passing through orifice (sum of (a) and (b)). Currents are normalized by the orifice cross sectional area.

whereas it saturates to a measurable value in the 5 mm case.

The effect of angular misalignment between the tunnel axis and $\bar{B}$ was studied in detail. Magnetic shadowing by the tunnel, characterized experimentally by the ratio $\delta = I_{BP}/(I_{TUN} + I_{BP})$, impedes charge flow to the BP. As shown in Fig. 3, the geometric calculation of the magnetic shadow gives a highly peaked function, but the measurement is
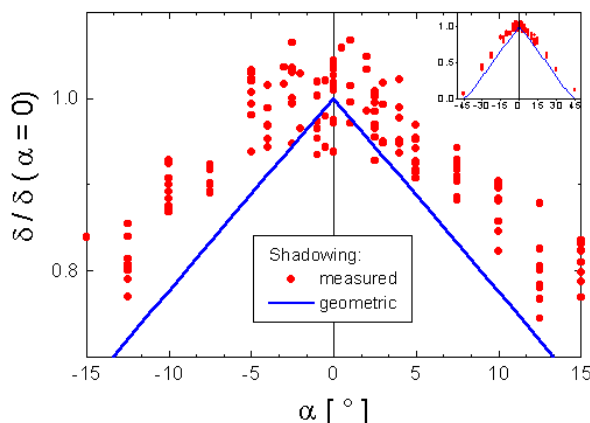

Fig. 3. Comparison of current reduction to the back plate with a geometrical calculation of magnetic shadowing as a function of the angle α between the magnetic field and the tunnel axis.

found to be insensitive to angle as long as the misalignment is less than 5°. This was predicted by 2D XOOPIC simulations in rectangular geometry and 3D Monte Carlo calculations without electric fields [2], and is due to the perpendicular motion of the ions. Such tolerances are easy to achieve, leaving a wide margin for variations of

edge saftey factor with negligible error on the measurement of R_C.

The XOOPIC code was run for the CASTOR 5 mm tunnel probe geometry over the expected ranges of plasma parameters $5 < T_e < 50 eV$ and $0.05 < J_{//} < 2.0 A cm^{-2}$. The analysis procedure is straightforward. First, one calculates $J_{//}$ from the sum of the two ion currents, and the ratio R_C. Then T_e is calculated by interpolation within the numerical results. The method is still being validated so we do not give details here. For the purpose of illustration, we show preliminary measurements from CASTOR discharge 13784 to which overlapping pulses of electrode biasing (+100V) and lower hybrid heating were applied. The 5mm tunnel probe was positioned at r=65 mm in the region of large EXB shear, facing in the ion direction. The tunnel and BP were biased to -200V and the currents were sampled at 1 MHz. The measured $J_{//}$, T_e, and n_e are plotted in Fig. 4. The relative fluctuation amplitudes of T_e and n_e are both around 20% except during the bias phase when they drop to 10%. The positive bursts that are observed on T_e are completely suppressed during the bias phase. The calculation of sheath edge density depends, as usual, on some assumed value for ion temperature. Its interpretation will be further complicated by its dependence on the Mach number of the parallel flow.
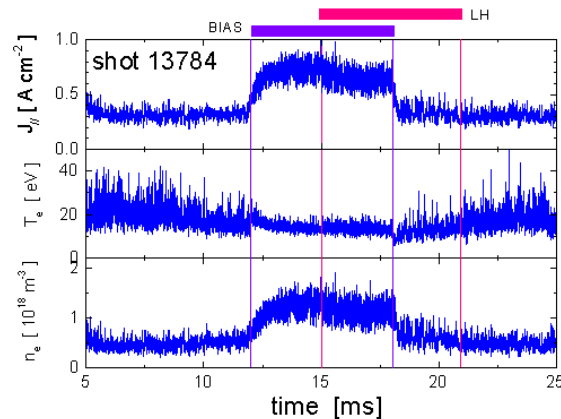

Fig. 4. Tunnel probe measurements of parallel ion current density (top panel), electron temperature (middle panel), and sheath-edge density (bottom panel) during a shot with electrode biasing and lower hybrid heating.

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