MEASUREMENT OF THE ION FLOW SPEED IN TORE SUPRA ERGODIC DIVERTOR EXPERIMENTS

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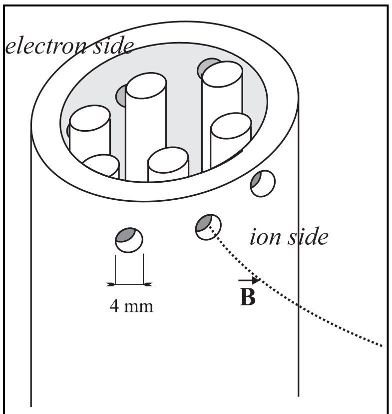

Figure 1. Tore Supra probe head.

A vertical fast scanning Langmuir probe system is installed on the top of Tore Supra. The probe head (Fig. 1) consists of a carbon fiber composite (CFC) cylindrical shell (5 mm thick, 4 cm diameter) in which are pierced six holes (4 mm diameter). Each hole is aligned with the magnetic field so that plasma incident upon the head passes through and is collected by one of six small cylindrical CFC pins (6 mm diameter). We define the upstream side of the probe (also known as the "ion side") as the side that looks toward the plasma current; the downstream side (also known as the "electron side") looks in the opposite direction. The pins are arranged inside the protective CFC shell such that three receive current from the upstream side, and three from the downstream side. The upstream pins are shadowed from the incident downstream plasma by the downstream pins themselves, and vice-versa. Two of the three probes on each side are operated in double probe mode in order to avoid the overheating that can occur when in electron collection; they provide measurements of the electron temperature and sheath-edge density, and the third probe is used to monitor the floating potential. The ratio between the upstream and downstream ion saturation currents is used to evaluate the Mach number of the parallel flow. We use the results of the kinetic simulations of Chung and Hutchinson [1] to calculate both the Mach number and the "unperturbed" electron density.

The probe assembly is driven by a hydraulic piston that is fed by an electrohydraulic valve. The pressure of the oil in the circuit is 280 bars, permitting speeds up to 2 m/s, and accelerations up to 400 m/s. The probe makes five plunges during a typical 15 second shot with a stroke length of around 20 cm and total plunge duration of around 200 ms. The probe movement is controlled in real time by feedback on the plasma position. The minor radius of the plasma is calculated every 1 ms using the poloidal field measurements. The probe position is measured with the same frequency, and with an accuracy of about ±1mm. To attain (and not exceed) a desired plunge depth, the feedback program controls the back and forth motion of the probe assembly, taking into account the inertia of the system. We estimate that the position is regulated to within ±5 mm.

We report here on measurements taken during density ramps in the ergodic divertor configuration. The magnetic flux surfaces in the edge region are destroyed by six octopolar field coils that generate local radial perturbations in the magnetic field [2]. Three principal regions can be distinguished: the unperturbed plasma core, the stochastic region of field line mixing and enhanced cross field transport [3], and the laminar region where field lines contact solid surfaces with short connection length L_c and where standard SOL edge physics is applicable [4]. The probe samples the laminar region and the outer edge of the stochastic region. To understand the probe measurements, it is helpful to consider the trajectories of individual field lines in the laminar region (Fig. 2). The radial perturbation is maximum between two current bars. A field line that passes through such a zone experiences a radial deflection. Field lines that are very close to the divertor modules can actually be diverted onto the surface of the module itself. Therefore, in each of the 42 spaces between current bars, an actively cooled divertor plate has been installed. The target plates receive field lines from either the ion or electron direction (Fig. 3) depending on the direction of the radial field perturbation, and are oriented appropriately. If a given field line arrives in front of the divertor modules with a certain resonant value of safety factor q, it can experience up to four radial deflections before it returns to the high field side.

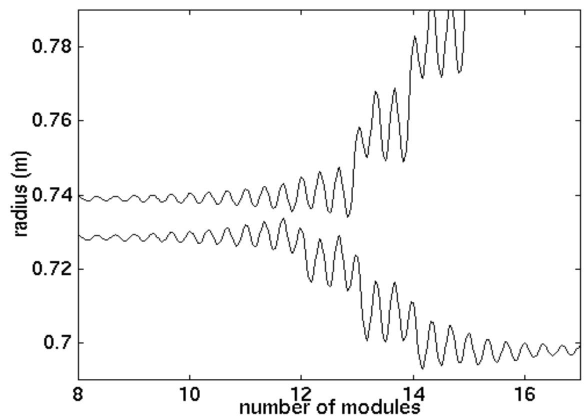

Figure 2. Radial deflection of two field lines traced from the probe position. The outer line is deflected onto a divertor module (r=0.79), while the inner one is deflected inward. One module coresponds to one sixth of a toroidal turn.

Using the MASTOC field line tracing code, we have produced maps of the radial deflection of the field lines that are sampled by the probe. The downstream map is quite simple: most of the field lines connect to the ion-facing divertor plates (L_c=10.5 m). The upstream map (Fig. 4a) is more complicated. After turning around the high field side, the field lines arrive from the bottom of the torus and pass in front of the divertor modules. We see four modulations of radial deflection, each extremum corresponding to a resonant value of q. Some of the field lines ("cold") connect to target plates, while others ("hot") are deflected inward and sample the hotter plasma in the stochastic layer.

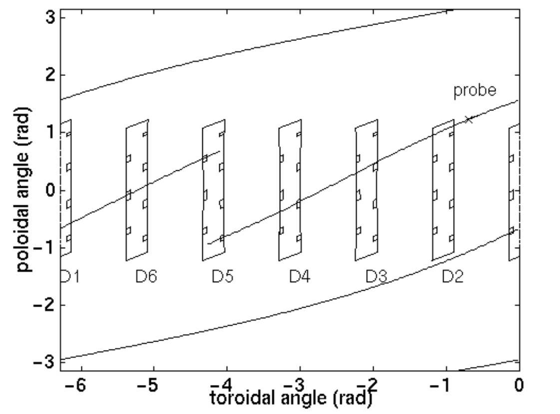

Figure 3. A typical trajectory of a field line that intersects the probe and connects to divertor modules on both the upstream and downstream sides.

Radial profiles of the plasma parameters were measured in an ohmic, diverted discharge. At low <n_e> there is a marked structure in the upstream temperature profile (Fig. 4b) that is correlated with the magnetic mapping. The outer peaks do not correspond exactly with the predicted resonances of inward radial deflection (Fig. 4a). We are presently investigating possible causes. Some candidates include errors in the magnetic measurements and/or the probe position, simplifying assumptions adopted by the MASTOC calculation, and radial drifting of the electrons. At high density, the structure is attenuated and a very flat profile around 5-10eV is measured in the outer region. Compared to the dramatic temperature modulations, the density profile (Fig. 4c) is relatively smooth. This is due to the difference in speed between ions and electrons. Cross field diffusion tends to wash out fine structures. The parallel distance over which a structure remains coherent is determined by $D_\perp$ and the parallel speed. The ion coherence length (for structures about 1 cm wide) is ~O(1 m) while for the electrons it is ~O(10^2 m). One poloidal turn corresponds to a parallel length of 45 m, so it makes sense that the probe sees the effect of distant radial deflections on the electrons, but not on the ions.

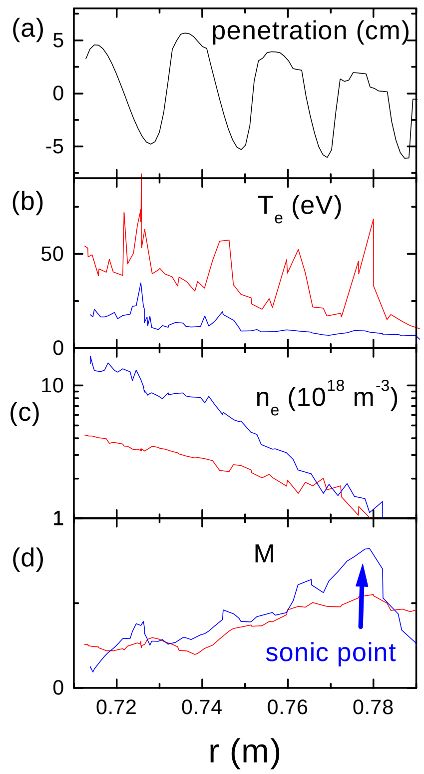

Figure 4. (a) Radial penetration of field lines relative to the probe position. Temperature (b), density (c), and Mach number (d) profiles. Red traces are taken at low central density, blue at high density.

The "temperature" measured by a Langmuir probe is representative only of the high energy tail of the electron distribution function, not the average energy of the majority [5]. In contrast to the upstream temperature profiles, the downstream temperature displays no modulated structure. In Fig. 5 are displayed the temperature at one of the peaks and at its adjacent valley, as measured by both the upstream and downstream sides of the probe. A large difference implies the presence of temperature gradients in the hot flux tubes [6], i.e. the electrons are not Maxwellian, and heat transport is nonlocal, indescribable by a classical conduction equation. The high energy electrons incident on the probe come from very far away along the field line without experiencing collisions, whereas the lower energy ones are collisional. At high density, the temperature difference becomes small at the same time as the structures disappear, indicating that even the high energy electrons' collision length is shorter than one poloidal turn.

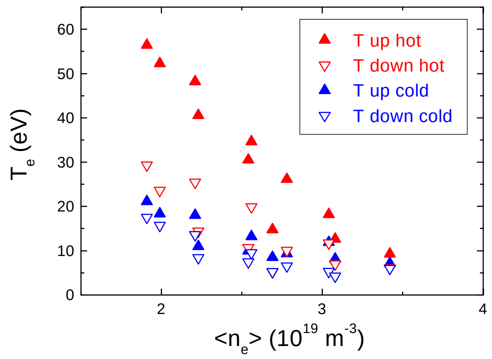

Figure 5. Fitted temperature obtained in hot and cold flux tubes by both upstream and downstream probes.

The Mach number profiles (Fig. 4d) reveal information about the distribution of sources in the edge. The Mach number is quite low at the innermost measurement point but increases to near sonic values on the outermost field lines. The direction of the flow is consistent with plasma accelerating towards the divertor modules. At high densities the Mach number shows a clear maximum. Fluid calculations [7] show that the flow should become sonic near the ionization front and then decrease in the zone near the target plate where charge exchange dominates before re-accelerating to satisfy the Bohm criterion at the sheath edge. The sonic point moves inward as the density is ramped up, indicating that the neutral density is increasing, and that the detached zone behind the ionization front becomes wider.

References

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