Measurements of Plasma Convection in the SOL of JET using a Langmuir/Mach Probe

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1. Introduction. Measurements of plasma convection in the SOL (scrape-off layer) have been carried out for JET divertor discharges using a Langmuir/Mach reciprocating probe [1 , 2] with sensitive elements facing the divertor (ion drift side for normal B_ϕ) and the main SOL (electron drift side for normal B_ϕ) (see Fig.1).

Plasma convection competes with thermal conduction as a mechanism to carry energy to the divertor target and can diminish temperature gradients along the field. Convective flow also provides the basic force that favours the retention of impurities near the target. Hence, it is necessary to assess experimentally its importance in JET divertor discharges and to compare it with results from models for the SOL plasma [3], which have been validated with experimental measurements [4].

2. Experimental Measurements. Mach probe measurements in a series of upper single null discharges in various regimes have been considered (OH, L-mode, H-mode). Of the available models we use the model described in [2] that accounts for the reduction of ion flux to the side facing the divertor due to the finite size of the probe (the disturbance length for Ohmic and L-mode conditions is of about 4 m for the JET reciprocating probe, safely smaller than the 20 m from the probe to the outer divertor target for the discharges studied) and viscous and non viscous effects.

Measurements obtained for a medium density ($2.5\ 10^{19}\ m^{-3}$) low additional heating (L-mode) discharge are shown in Fig.2. The plasma flow at the reciprocating probe is directed towards the divertor all across the SOL, the ratio of the fluxes at both sides of the probe being (2.3 ± 0.2), which corresponds to a Mach number of (0.5 ± 0.03) if perpendicular viscosity is ignored and to (0.3 ± 0.03) including it. Similar values are obtained for ohmic discharges in the same density range.

The pattern of the plasma flow at the reciprocating probe is more complicated for H-mode and low density L-mode discharges. In Fig.3 the measurements obtained for a low density L-mode ($9.5\ 10^{18}\ m^{-3}$) are shown. The plasma flow is directed towards the divertor in the external part of the SOL with values for the ratio of ion fluxes on both sides of the probe similar to those obtained in the medium density case. However, close to the separatrix a region in which the flux on the ion side is larger than on the electron side is found. This is interpreted as a region in which the flow is away from the divertor at the reciprocating probe position. The reversal of the flow close to the separatrix is also found in H-mode discharges, in agreement with previous observations [5]. The ratio of ion fluxes in both sides of the probe for the external part of the SOL in H-mode discharges is similar to that found in L-mode. The radial location of the flow reversal region is more uncertain due to possible errors in the relative position of the probe to the magnetic separatrix and the fact that the profiles of plasma parameters are very steep close to the separatrix in H-modes [6].

The ion flux measurements with the probe could be affected by thermionic emission and by the presence of large negative currents close to the separatrix in JET [7]. However, these effects would affect predominantly the electron side of the probe (it suffers a higher power deposition and intercepts the electron currents), but in experiment is the ion side which shows the largest changes, indicating that flow reversal must take place.

3. Modelling of the discharges. These discharges have been modelled with EDGE1D [3] for a pure hydrogen plasma using measured plasma parameters as inputs (no shift of the relative position of the probe to the magnetic separatrix has been imposed). Assuming equal power into the SOL via electrons and ions, the calculated total power arriving at the divertor target is in agreement with the power determined from main plasma measurements (P_{targ}) in the medium density case (Fig.2). At low densities (Fig.3) the calculations account for only 30% of P_{targ}.

The calculated Mach number (modelled as constant across the SOL) at the probe is in the range (0.15 - 0.20) in reasonable agreement with experimental estimates (viscous case) for the outer regions of the SOL. The results for low densities tend to produce a smaller Mach number despite a larger neutral escape from the divertor to the main plasma (30% at low densities, 20% at high densities) due to the influence of parallel viscosity (larger at higher temperatures [8]). This is also the trend barely detectable in the experiment (compare outer SOL in Fig.2 and Fig.3).

The calculated heat flux into the the divertor is shared between conduction (60%) and convection (40%), the Mach number at the divertor entrance (X-point) being 0.5. The conductive heat fluxes are calculated in the collisional approximation, and non-local effects can be estimated by comparison with the 'free streaming flux" ($q_{e,i} = n\, KT_{e,i} \sqrt{KT_{e,i}/m_{e,i}}$). The ratio between conductive and "free streaming flux" is about 0.07 for electrons and 1.0 for the ions. The electron heat flux is a factor 2.3 higher than that allowed by collisional theory [9] but much smaller than the collisionless flux (0.2 - 0.3 of the "free streaming flux"), hence at most a reduction of 25% in the electron conductive flux is expected due to non-local effects. These effects may be stronger for the ion conductive heat flux.

Some 2D aspects of the plasma flow were studied using the ionization source calculated in the model with the NIMBUS Monte-Carlo code [10] for various flux tubes in the SOL. Magnetic geometry effects cause the appearance of the point of maximum plasma flux onto the target at a finite distance from the separatrix [11]. This produces an ionization source with different radial dependence than the plasma density (and flux) profile (exponentially decreasing from the separatrix, in magnetic flux), shown in Fig.4. This, in turn, leads to a complicated behaviour for the ionization source along the field which causes a reversal of the flow in some flux tubes and two stagnation points for the flow between the target and the symmetry point (itself an stagnation point), also found in 2D models [12]. Flow reversal can be measured experimentally if the probe is inserted between these stagnation points. An upper estimate for the position of the stagnation point closer to the target is obtained by integrating along the field the particle source for every flux tube (momentum transfer from neighbouring flux tubes will move the stagnation points closer to the target). The distance along the field from the target to the stagnation point (ℓ_s) is

$$n_t\, c_{s\,t} = \int_0^{\ell_s} S(\ell)\, d\ell$$

where $n_t\, c_{s\,t}$ is the flux to the target and $S(\ell)$ the particle source in the flux tube. For flux tubes close to the separatrix no additional stagnation points associated with flow reversal are obtained. However, away from the separatrix additional stagnation points are found. For the higher density case the stagnation point is approximately at the position of the reciprocating probe for the flux tube number 6 (see Fig.4). For flux tubes 7 and 8 flow reversal occurs but within the divertor channel. At lower densities the results are similar but the distance to the stagnation points is longer. This is consistent with the experimental measurements in which flow reversal is only measured for the low density case. However, to obtain an exact description of this flow behaviour accurate 2D modelling is needed.

4. Conclusions. Plasma convection has been measured in the SOL of JET diverted discharges with a Mach/Langmuir reciprocating probe. The Mach number deduced at the probe position is about 0.3 within the range of densities 0.9 - 2.5 $10^{19}\ m^{-3}$ for ohmic and L-mode discharges with low additional heating. A similar Mach number is deduced for H-mode discharges. In the low density L-mode and in H-modes a flow reversal for field lines close to the separatrix is found. 1-D modelling of these discharges produces a proportion of 40% convected heat flux into the divertor and 60% conducted heat flux, although these values may change slightly due to non local effects in the ion conduction and they ignore flow reversal. A qualitative explanation of the dependence of the flow reversal observed experimentally is found in the analysis of the modelled particle sources in the various flux tubes of the SOL which are influenced by magnetic geometry effects.

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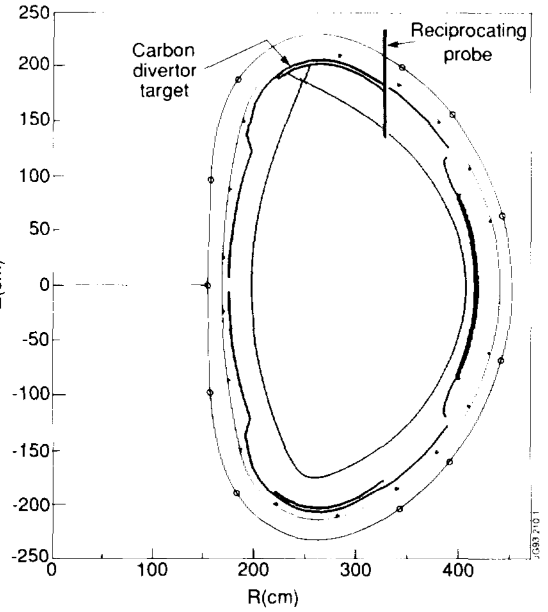

Fig.1. Position of the reciprocating probe and upper single null MHD equilibrium in JET.

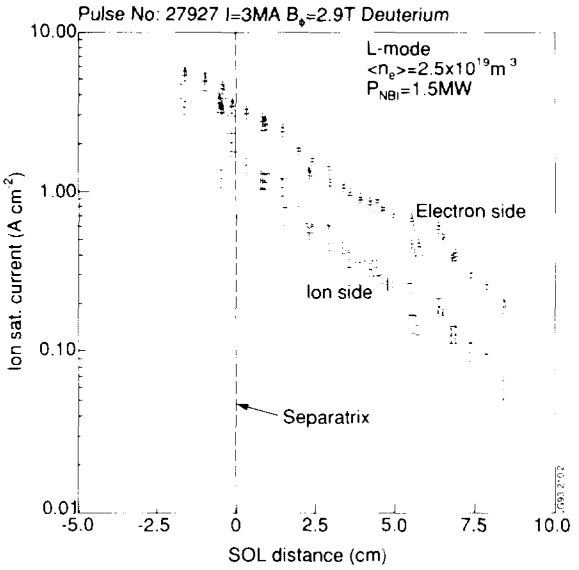

Fig.2. Measured ion fluxes versus distance normal to the flux surfaces at the probe (medium density L-mode).

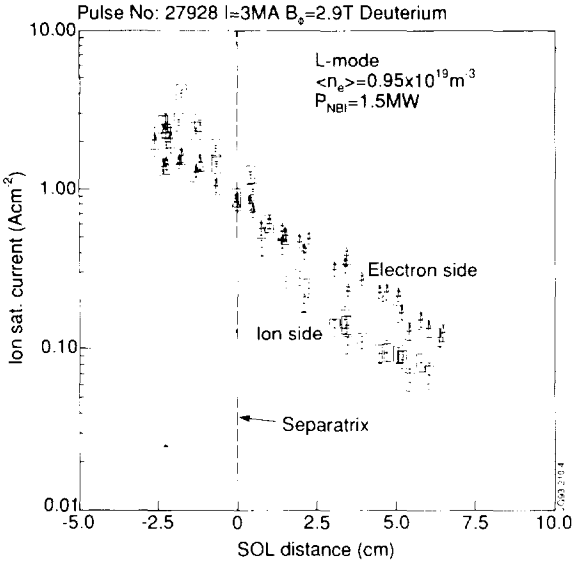

Fig.3. Measured ion fluxes versus distance normal to the flux surfaces at the probe(low density L-mode).

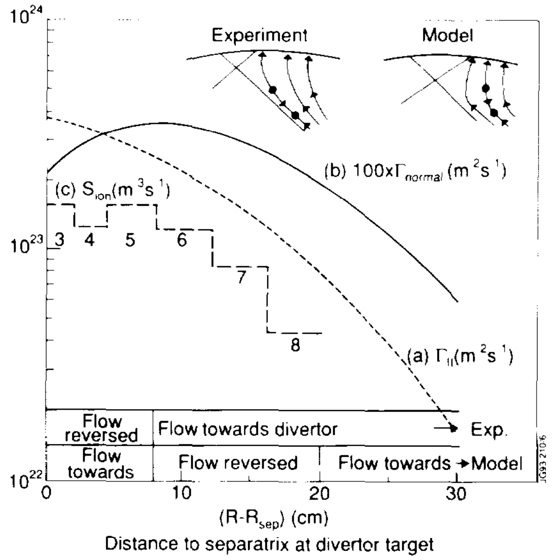

Fig.4. Modelled fluxes at the divertor target ($\Gamma_{\parallel}$, along $\vec{B}$, Γ_{normal} onto the target) and ionization source for various flux tubes. Modelled and observed regions of flow reversal are shown.