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## ABSTRACT

The EDGE2D code with drifts can reproduce the main trends of target asymmetries observed in field reversal experiments. It also re-produces qualitatively the main feature of recent JET results obtained with double-sided reciprocating Langmuir probes introduced near the top of the torus: the reversal of parallel plasma flow with toroidal field reversal. The code results suggest that the major contributor to the observed target asymmetries is the co-current toroidal momentum generated inside the scrape-off layer (SOL) by  $j_r \times B$  forces due to the presence of large up-down pressure asymmetries. Contrary to previous expectations of the predominant role of  $E \times B$  drifts in creating target asymmetries,  $\nabla B$  and centrifugal drifts were found to be mainly responsible for both parallel flows and target asymmetries.

## 1. INTRODUCTION

The version of EDGE2D with drifts [1,2] is a predictive neoclassical code for the edge plasma, with ambipolar turbulent transport additionally specified to create realistic boundary conditions for particle and power fluxes through the separatrix. A self-consistent model for radial electric field in the core region implemented in the code yields negative electric field ( $E_r \equiv -d\Phi/dr < 0$ ) inside the separatrix, in numerical agreement with the expression from neoclassical theory for collisional plasmas [3]. It provides for the decay of poloidal rotation and satisfies the ambipolarity condition for the surface-averaged radial transport. In the SOL, the potential equation is solved which allows for current flow towards the target and non-ambipolarity of radial transport caused by drifts. Modified target boundary conditions in the SOL take account of particle drifts according to [4,5].

At present the code can satisfactorily predict main trends in target asymmetries in the field reversal experiments, despite the fact that only a pure hydrogen/deuterium version has been realised so far; radiated power inside the grid is calculated according to [6]. Introduction of individual switches for various drifts and their components in this code enabled us both to debug the code and to get a deeper insight into underlying physics of the drift effects. Contrary to some recent code calculations [7-9] and previous theoretical expectations (see e.g. [10-13]) of the predominant role of  $E \times B$  drifts in particle convection in the SOL, new EDGE2D results point to a significant role of the  $\nabla B$  and centrifugal drifts in creating both target asymmetries and parallel flows in the SOL. The code results reveal the existence of toroidal momentum in the SOL in the direction of the main plasma current, largely attributed to these drifts. This was thought previously to provide an alternative explanation (to the effect of  $E \times B$  drifts) for target asymmetries [14,15].

## 2. EXPERIMENTAL EVIDENCE FOR THE EXISTENCE OF THE SOL TOROIDAL MOMENTUM

High Mach number parallel plasma flow in the SOL was recently measured in JET [16] using double-sided Langmuir probe (Mach probe). The probe position was near the top of the torus, as shown on Fig.1. Typical Mach number profiles for the two Ohmic discharges with normal (ion  $\nabla B$  drift towards the X-point) and reversed (ion  $\nabla B$  drift away from the X-point) toroidal field direction are presented in Fig.2. The direction of the flow is from the outer to the inner target in normal, and from the inner to the outer target - in reversed field discharges. In both cases, the flow was in the direction of the main plasma current.

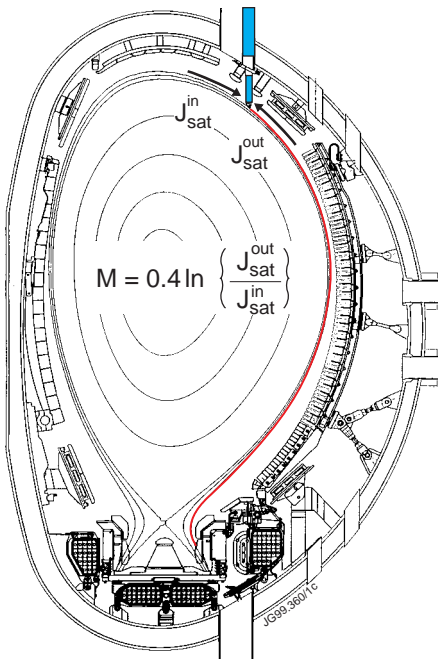


Fig.1: Reciprocating probe in JET.

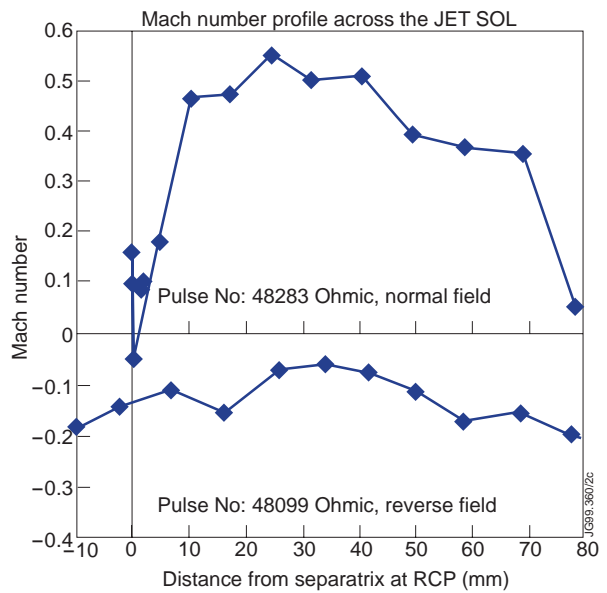


Fig.2: Mach number profiles across the JET SOL in normal and reversed toroidal field discharges.

In distinction to recent measurements on JT-60U, where a flow in the same direction, measured near the outer midplane, was interpreted as ion Pfirsch-Schlüter flow [17], estimates of the magnitude of the Pfirsch-Schlüter flow at the JET probe position have shown that it is too small to explain the measured Mach number of up to  $M_{\parallel}=0.5$  (The Pfirsch-Schlüter flow at the top of the torus is zero). Therefore, the recent JET results corroborate earlier experimental evidence for the existence of *toroidal momentum* in the SOL in the direction of the main plasma current (see e.g. [14,15] and refs. therein).

A separate piece of experimental evidence for the rotation of the SOL plasma is provided by the observation of impurity drift, apparently from the outside to the inside, in the JET SOL. A heavy deposition of carbon, with co-deposition of tritium, was observed at the inner divertor target, while the outer divertor target was clean [18]. To cause such a strong asymmetry in

impurity deposition, the parallel plasma flow has to be large enough, so as to overcome the effect of poloidal  $E \times B$  drift which in normal field discharges (the preferred JET operating mode) is directed from the inner to the outer target.

### 3. PARALLEL FLOWS IN EDGE2D CODE

The EDGE2D runs produce parallel flows and target asymmetries which are in a qualitative agreement with experimental trends. In order to discriminate drift effects from others, e.g. recycling of neutrals, and to establish the influence of individual drifts on the flows and target asymmetries, a high power case was run with input power into the grid of 6 MW through both ion and electron channels, 3 MW radiated power and  $1.5 \times 10^{19} \text{ m}^{-3}$  separatrix density. Transport coefficients, constant in flux space, were used with  $D_{\perp} = 0.2 \text{ m}^2 \text{ s}^{-1}$ ,  $\chi_e = \chi_i = 1 \text{ m}^2 \text{ s}^{-1}$  at the outer midplane, plus a constant pinch velocity of  $V_{\text{pinch}} = 6 \text{ ms}^{-1}$ . Fig. 3 shows radial profiles of the Mach number for the poloidal position shifted inwards from the JET reciprocating probe (RCP) position (indicated on Fig.4, so that the flow is actually larger at the RCP position than that shown on Fig.3). With all the drifts switched on in the core and SOL, the code reproduces the main feature of the experiment: the reversal of the parallel flow with the reversal of toroidal field. The flow peaks at  $M \approx \pm 0.2$  at about 2 cm outside of the separatrix and decays inside the core, in agreement with most of the experimental observations. The velocity of the parallel flow at the innermost core ring was set to zero, and the flow could penetrate inside the separatrix only due to perpendicular viscosity assumed to be  $\mu = nm_i D_{\perp}$ . In contrast with the experiment, however, where Mach number was much greater for normal field discharges, the code produces almost symmetrical reversal of the flow due to the field reversal. The flow is only slightly reduced when  $E \times B$  drifts are switched off in the SOL, indicating the predominant role of  $\nabla B$  and centrifugal drifts in its generation. With all the drifts switched off both in the core and SOL, the Mach number at the RCP position is small.

Figure 4 shows the Mach number of the parallel flow as a function of poloidal angle, from the outer to the inner target, for the 3<sup>rd</sup> (computational grid) ring outside of the separatrix (indicated by the arrow on Fig.3), corresponding to the radial position where the flow peaks. With all

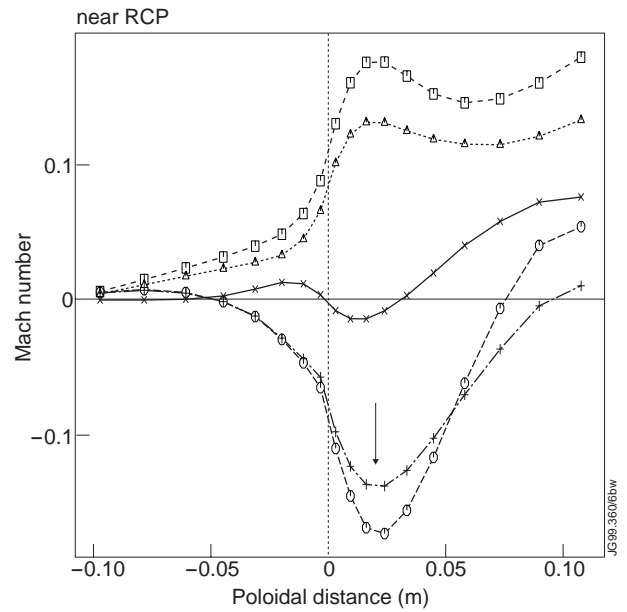


Fig.3: Radial profiles for the Mach number near the reciprocating probe position. See legend on Fig.4. Poloidal position of the probe is indicated on Fig.4 by the arrow.

the drifts switched off both in the core and SOL, the flow pattern is very simple, showing a plasma sink towards the two targets in a strong recycling regime and a stagnation point at the top of the torus. The case with  $E \times B$  drifts switched off in the SOL (leaving *all* the drifts on in the core but only  $\nabla B$  and centrifugal drifts in the SOL), clearly reveals Pfirsch-Schlüter flows superimposed on the plasma sink towards the divertor. However, the stagnation point of these flows is shifted towards the inside, so that the flow is relatively large at the RCP position. Thus, these flows consist of Pfirsch-Schlüter flows plus some extra, surface averaged flow, which is directed along the main plasma current. With all the drifts switched on both in the core and SOL, the toroidal momentum is further increased, especially in the normal field case, where the flow becomes unidirectional, from the outer to the inner target, almost in the whole SOL except for the near-target regions in the divertor. It has to be noted however that at present EDGE2D does not predict high Mach numbers of the flow for Ohmic plasmas. Although the surface-averaged flow for such plasmas is of the order of calculated Pfirsch-Schlüter flows, as in Fig.4, both these flows are significantly smaller than the flows measured experimentally.

#### 4. UP-DOWN PRESSURE ASYMMETRIES

The peaking of the parallel plasma flow inside the SOL region, both in experiment (for normal field discharges) and EDGE2D, indicates that the origin of the SOL toroidal momentum which causes it must be inside the SOL itself. We associate it with the  $\mathbf{j}_r \times \mathbf{B}$  forces exerted on the plasma due to the presence of strong up-down pressure asymmetry shown in Fig.5 for the same ring (3<sup>rd</sup> ring outside of the separatrix) as in Fig.4. The pressure is significantly larger at the bottom of the torus, near the X-point, for normal field discharges, and at the top of the torus in reversed field discharges, i.e. the pressure is larger at the side towards which the ion

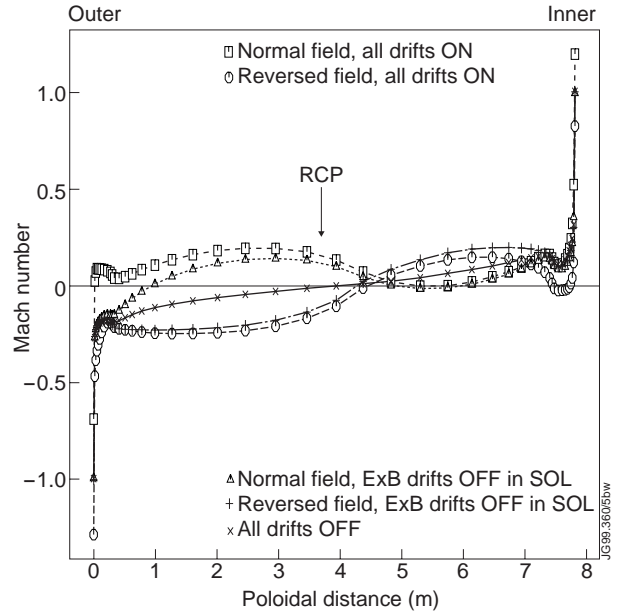


Fig.4: Poloidal distribution of Mach number of the parallel flow at the 3<sup>rd</sup> ring outside of the separatrix (indicated by the arrow on Fig.3).

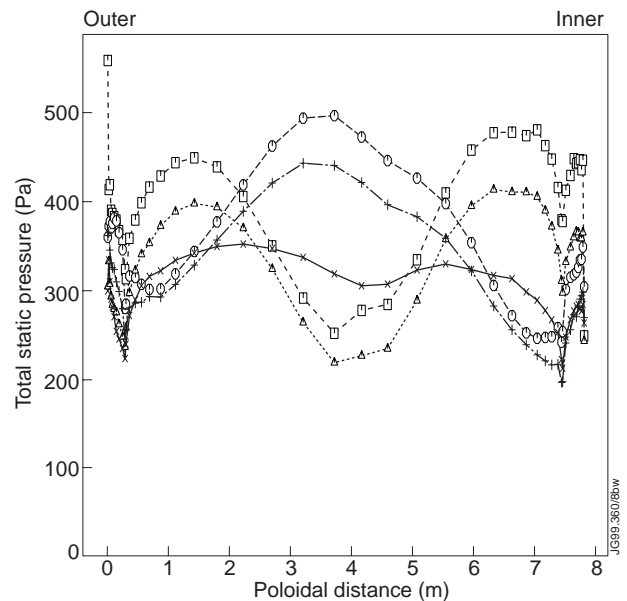


Fig.5: Poloidal distribution of total static pressure at the 3<sup>rd</sup> ring outside of the separatrix (indicated by the arrow on Fig.3). See legend on Fig.4.



$\nabla B$  drift is directed. The pressure asymmetry is similar for the case with all drifts switched on and for the case with  $E \times B$  drifts switched off in the SOL, but is much smaller for the case without drifts.

The existence of up-down pressure asymmetry creates local radial currents  $j_r = \frac{1}{B} \frac{\partial p}{r \partial \theta}$  which, due to toroidal effects of the variation of magnetic field  $B$  and surface area factor ( $\sim R$ ), give rise to a net surface-averaged radial current of density  $\langle j_r \rangle \approx \Delta p / BR$ . The latter exerts a  $RB_\theta \langle j_r \rangle$  toroidal force on the plasma in the direction of the main plasma current. This effect is specific to the SOL, since the divergence of the net radial current there can be accommodated by currents to the (electrically conducting) targets. On the core rings of the EDGE2D grid the ambipolarity condition for the radial transport ( $\langle j_r \rangle = 0$ ) yields a negative  $E_r$  which eliminates poloidal pressure variation. An explanation for plasma toroidal acceleration by  $j_r \nabla B$  forces in the SOL was first proposed in [19], but for the case of cylindrical geometry, neglecting toroidal effects and also currents passing through the magnetic pre-sheaths, as pointed out in [20].

## 5. TARGET ASYMMETRIES

Figure 6 presents the results of EDGE2D modelling of target asymmetries for the two well documented L-mode discharges with different toroidal field direction, in Mark I divertor geometry in JET [21]. In the modelling, experimental values for input and radiated powers were used ( $P_{in}=5$  MW,  $P_{rad}=1.1$  MW), with the power equally shared between ion and electron channels,  $D_\perp=0.1$  m<sup>2</sup>s<sup>-1</sup>,  $\chi_e=\chi_i=1$  m<sup>2</sup>s<sup>-1</sup> at the outer midplane, constant in the flux space, constant pinch velocity  $V_{pinch}=3$  ms<sup>-1</sup> and separatrix density  $1.1 \times 10^{19}$  m<sup>-3</sup>. The code reproduces satisfactorily the main experimental trend of higher  $n_e$  and lower  $T_e$  at the inner target in normal field discharges, with smaller changes at the outer target and more symmetric distribution of plasma parameters between the two targets in reversed field discharges [21].

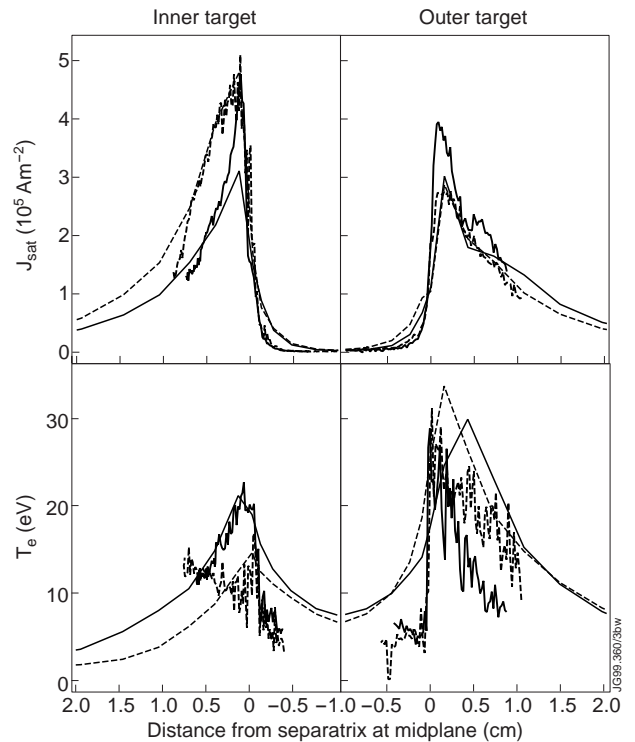


Fig.6: Experimental and modelled target asymmetries in L-mode discharges.

Figure 7 shows inner target  $n_e$  and  $T_e$  profiles for the series of runs of the case with Mach number and pressure distribution presented on Figs.3-5. In normal field cases,  $n_e$  is much larger at the inner target and  $T_e$  lower, even when  $E \times B$  drifts are switched off in the SOL. We therefore attribute changes in target asymmetries in field reversal experiments in JET mainly to the effect of  $\nabla B$  and centrifugal drifts, and, in particular, the toroidal momentum in the SOL generated by these drifts. This conclusion contrasts with previous expectations of the major role of  $E \times B$  drifts in creating target asymmetries. [10-13,21].

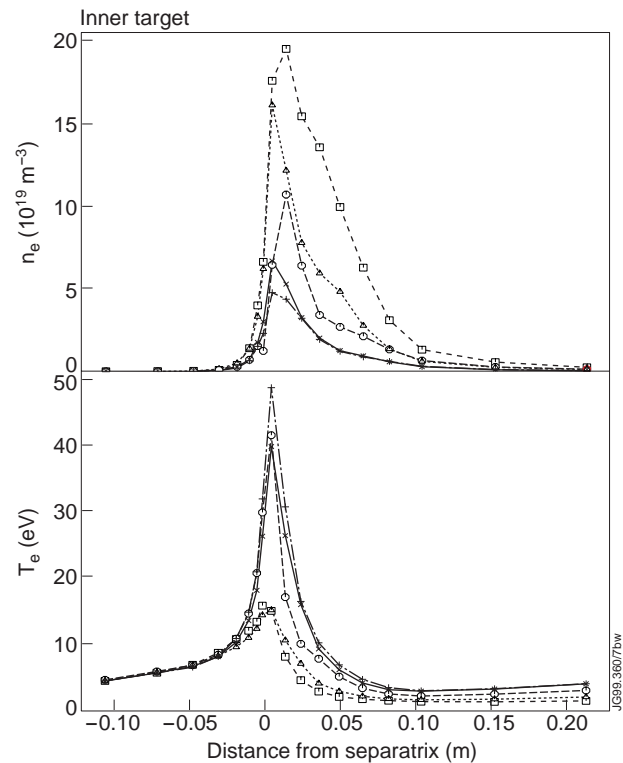


Fig.7:  $n_e$  and  $T_e$  profiles at the inner target in the series of code runs. See legend on Fig.4.

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