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C.J. LASNIER,[‡] R. LEHMER,[†] A.W. LEONARD, M.A. MAHDAVI,
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[†]University of California, San Diego
[‡]Lawrence Livermore National Laboratory
[◊]Sandia National Laboratories, Albuquerque
[∆]Oak Ridge National Laboratory

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Plasma Flow in the DIII–D Divertor*

J.A. Boedo,† G.D. Porter,‡ M.J. Schaffer, R.A. Moyer,† J.G. Watkins,∆ T.E. Evans, S.L. Allen,‡ N.H. Brooks, R.C. Isler,◊ C.J. Lasnier,‡ R. Lehmer,† A.W. Leonard, M.A. Mahdavi, T. Rognlien,‡ and M.R Wade◊

General Atomics, P.O. Box 85608, San Diego, CA 92186-5608

Introduction

Indications that flows in the divertor can exhibit complex behavior have been obtained from 2-D modeling [1,2] but so far remain mostly unconfirmed by experiment. An important feature of flow physics is that of flow reversal. Flow reversal has been predicted analytically [3] and it is expected when the ionization source arising from neutral or impurity ionization in the divertor region is large, creating a high pressure zone. Plasma flows arise to equilibrate the pressure.

A radiative divertor regime has been proposed in order to reduce the heat and particle fluxes to the divertor target plates. In this regime, the energy and momentum of the plasma are dissipated into neutral gas introduced in the divertor region, cooling the plasma by collisional, radiative and other atomic processes so that the plasma becomes detached from the target plates. These regimes have been the subject of extensive studies in DIII–D [4] to evaluate their energy and particle transport properties, but only recently it has been proposed that the energy transport over large regions of the divertor must be dominated by convection [5] instead of conduction. It is therefore important to understand the role of the plasma conditions and geometry on determining the region of convection-dominated plasma in order to properly control the heat and particle fluxes to the target plates and hence, divertor performance.

Owing to increased awareness of the important role of flows in the divertor, efforts are being made to characterize plasma and impurity flows in the divertor region. Divertor spectroscopy has been used to study impurity flows in ASDEX-Upgrade [6] and DIII–D [7] and probes for background plasma flow in DIII–D [8], Alcator C-Mod [9], TdV [10], and ASDEX-Upgrade [11], yet results are still partial and preliminary within a growing body [12,13] of well documented divertor physics.

Results and Discussion

We have measured the Mach number of the background plasma ion (D^+), in the DIII-D tokamak divertor, by using a fast scanning probe which is introduced vertically from the floor as shown in Fig. 1(a). The experiments were performed in lower single null divertor configuration discharges with plasma current I_p=1.4 MA, toroidal field B_T=2 T (∇B drift towards lower divertor), flat-top duration of 3.8 s. and chord-averaged density of 0.5–1.0×10^{20} m^{-3}. The discharges are heated primarily by neutral beam injection at power levels of 4–5 MW. If a strong gas puff is introduced during the discharge, the divertor plasma

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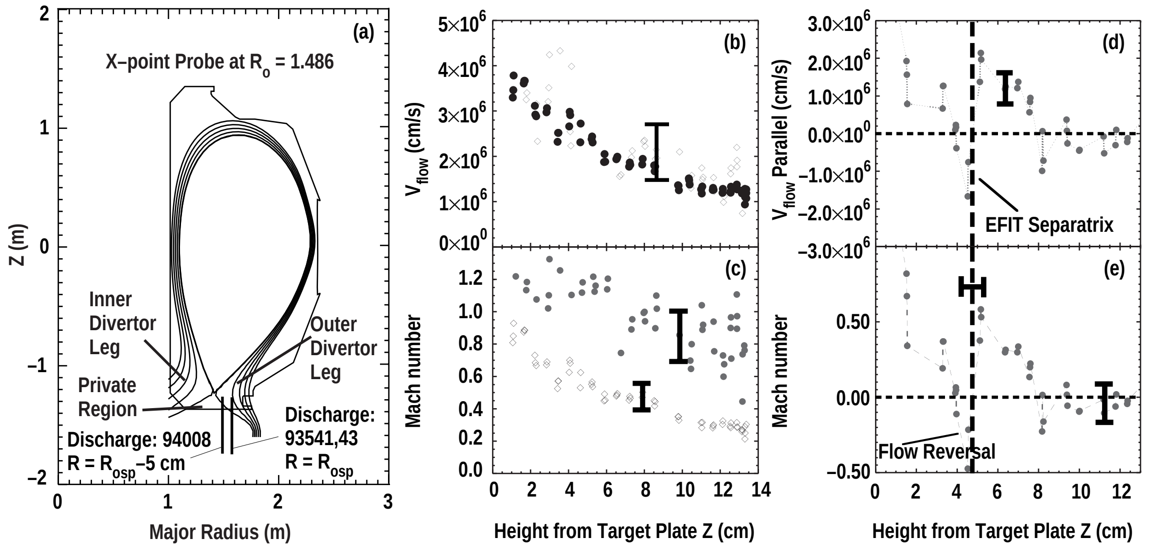

Fig. 1. The plasma and divertor geometry and the probe paths are shown. The path labeled R_{OSP}–5 cm crosses the separatrix and the path labeled Rosp enters the SOL directly (a) Measurements of ion velocity (b) and Mach number (c) are obtained by the probe for attached (diamonds) and detached (circles) discharges. We also show the measurements of flow velocity (d) and Mach number (e) obtained at the path crossing the separatrix, and showing flow reversal.

temperature drops and the density increases as the plasma detaches from the target plate. We have studied attached and detached discharges in order to compare the flow patterns and their role in particle and energy transport. Since the fast probe is fixed in space, the divertor plasma has been scanned horizontally (in R), to allow exploration of various regions of the divertor, as shown in the two vertical cuts in Fig. 1(a).

For attached divertor conditions, in H–mode, we observe plasma flow accelerating towards the plate in the lower divertor, in agreement with classical expectations [14], as shown in Fig. 1(b,c) (diamonds). As the neutral density in the divertor increases, and the temperature is reduced, a narrow region of flow reversal at $\sim 1\times 10^6$ cm s^{-1} develops at the separatrix, as shown in Fig. 1(d,e) and extends further to the upper divertor and private region for very high neutral density conditions. The development of flow reversal [11] is strongly dependent on the particle source [3] and of great relevance for impurity transport since the impurities can then easily escape the lower divertor [15], defeating its purpose of impurity control. Impurity flow reversal (CIII) has been also observed [7] in the DIII–D divertor near the separatrix and in the upper divertor at speed comparable to that of the background plasma. This measurement confirms previous observations of impurity transport in ASDEX-U [6].

As the neutral density in the divertor is increased, the temperature in the divertor decreases further to a regime where recombination starts playing a role and the plasma is detached from the divertor plates. For detached divertor conditions, in H–mode, the plasma flows towards the divertor plate at sound speed over an extended region comprising much of the SOL as shown in Fig. 1(b,c) (circles). Heat and particle transport under these conditions are then dominated by convection [5]. By comparing the parallel convected heat flux inferred from probe data [16–18] to the total heat flux at the plate measured by an IR camera [18], we find that 80% of the heat flux can be accounted for in semi-detached plasmas and 20%–30% in attached [19] plasmas.

We have modeled all the aforementioned discharge conditions with the code UEDGE [20] in 2 dimensions as shown in Fig. 2(a). We can reproduce the main features observed [19]: 1) flow reversal, as shown in Fig. 2(b), and to be compared to Fig. 1(d,e), and 2) accelerated flow towards the plate as shown in Fig. 2(c), and to be compared to Fig. 1(b,c) (diamonds). We can also reproduce results of convective flow over large volumes of the divertor as shown in Fig. 1(b,c) (circles). The latter figures are cuts on a 2-D plot, typical UEDGE output, such as the one shown in Fig. 2(a) and meant to reproduce the probe trajectories shown in Fig. 1(a). Work is in progress to improve the accuracy of the simulations by tuning the physics of the carbon source and calculating self-consistently the electric fields (and thus drifts) in the divertor region.

The relevance of the electric fields in the divertor region is under scrutiny since electric fields as large as 100 V/cm have been observed by the scanning probe across the separatrix as shown in Fig. 3. These fields are located at the boundary between the private region and the SOL and can produce $\vec{E}_\psi \times \vec{B}_\phi$ flows of the order of 0.3–1$\times 10^5$ cm/s away or towards the target plate, introducing a significant amount of poloidal velocity shear (~0.5–1$\times 10^5$ s^{-1}). The poloidal flow speed is between 10% and 40% of the parallel flow and thus can affect its direction appreciably. The particle flux induced by the poloidal flows is of the order of 2–4$\times 10^{22}$ m^{-2}s^{-1} which is larger than the estimated radial flux (5×10^{20} m^{-2} s^{-1}) inferred from UEDGE or from turbulence measurements at the midplane. The $\vec{E}_\psi \times \vec{B}_\phi$ particle flows thus can potentially affect particle balance in the divertor considerably.

Conclusions

We have observed complex structures in the deuterium ion flows in the DIII–D divertor. Features observed include reverse flow, convective flow over a large volume of the divertor and stagnant flow. We have measured large gradients in the plasma potential across the separatrix in the divertor and determined that these gradients induce poloidal flows that can potentially affect the particle balance in the divertor. Introduction of self-consistent electric fields in UEDGE is in progress.

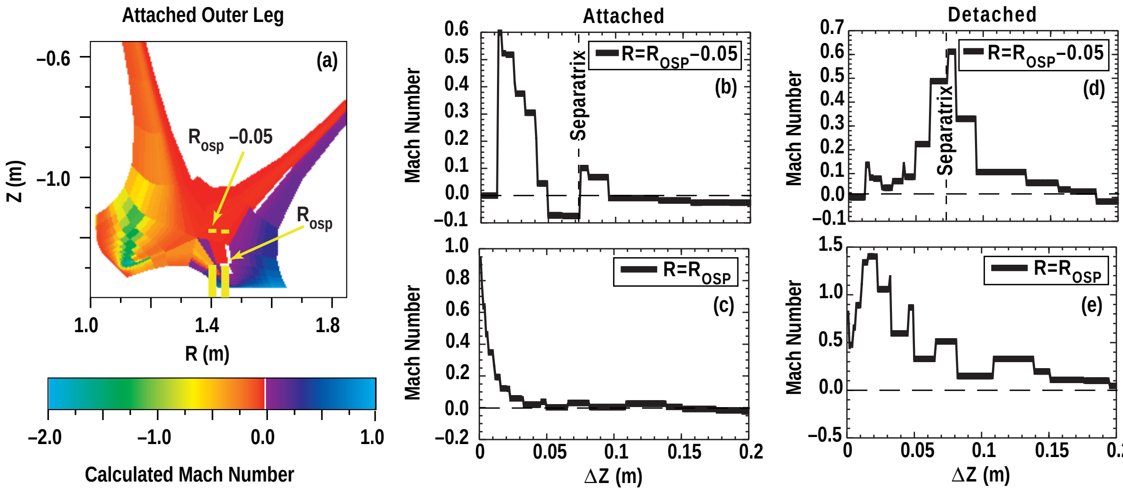

Fig. 2. The 2-D calculations of Mach number obtained by UEDGE, and two paths meant to simulate those taken by the probe are shown (a). Calculated Mach number for cuts along those paths crossing the separatrix (b) and entering the SOL directly (c) are shown for attached discharges. Calculated Mach number for the same the same paths (d–e) are also shown.

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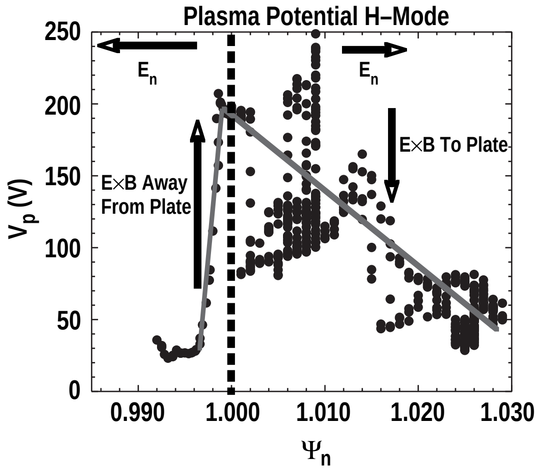

Fig. 3. Plasma potential profile (V) plotted versus normalized flux ψ_n. The separatrix is at ψ_n=1. The electric field is of the order of 200 V/cm.

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