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ABSTRACT

Studies of parallel D^+ flows during detached divertor conditions in DIII–D show that the flow patterns are very complex, featuring large volume flow at Mach 1 and flow reversal regions. Perpendicular $\mathbf{E}\times\mathbf{B}_T$ drifts, which are found to be important in the attached divertor plasma, weaken during detachment.

1. INTRODUCTION

Magnetic divertors provide heat and particle exhaust and shield the main plasma from impurity contamination. Heat and particles are transported from the plasma core to the edge and scrape-off layer (SOL) plasma, whence particles are convected and heat is both conducted and convected to the divertor target. Divertor plasmas in future fusion reactors must be detached to ameliorate the high particle and heat fluxes to the divertor components. It is essential to understand divertor flows since they are intimately related to particle, impurity and heat transport and in-out asymmetries i.e. divertor operation.

The parallel heat flux is dependent on the fluid velocity and can be expressed, following Braginskii [1], in terms of the bulk fluid velocity $V_{||}$, the electron density n_e, the parallel thermal conductivity $\kappa = k_1 T_e^{5/2}$ the atomic ionization potential I_0 and the gradient along the magnetic field length:

$$q_{||} = \kappa_1 T_e^{5/2} \frac{\partial T_e}{\partial s} + n V_{||} \left[\frac{5}{2}\left(T_e + T_i\right) + \frac{1}{2} m V_{||} + I_0 \right] \quad . \tag{1}$$

When the divertor plasma detaches, the temperature is reduced to 1-5 eV as the density increases to $\sim 10^{14}\ \mathrm{cm}^{-3}$ so that recombination can become dominant, removing particles and heat and reducing the fluxes to the divertor components. Simultaneously, the temperature gradients in the divertor become negligible, eliminating conduction [first term in Eq.(1)] as a channel to deposit heat on the divertor components. The second term in Eq. (1), or convection dependent on $V_{||}$, can then dominate, thus the motivation for this work.

Additionally, chemical and physical plasma erosion of the graphite divertor components release carbon that can penetrate the plasma core and induce intolerable energy losses. The dynamics of the impurities are determined by: (1) a drag force term due to the deuteron plasma, V_b, and impurity ion $V_{||,i}$ parallel velocities, (2) a force dependent on the thermal temperature gradients along the magnetic field and (3) a parallel electric field $E_{||}$ term. The total force can be written [2] as:

$$F_z = m_z \left(\frac{V_b - V_{||,i}}{\tau_{sl}} \right) + \left(0.71\, Z_z^2 \frac{\partial T_e}{\partial s} + \beta_z \frac{\partial T_b}{\partial s} \right) + Z_z e E_{||} \tag{2}$$

where τ_{sl} is the impurity collision time with the background ions, Z_z is the charge of the impurity ion, $E_{||}$ is the parallel electric field, m_i is the ion mass, $\ln(\Lambda)$ is the Coulomb logarithm and β_z is the ion thermal gradient coefficient as given by Neuhauser, Chapman and Keilhacker [3]. The first term, or friction force, normally keeps the impurities trapped in the divertor, while the temperature gradient terms tend to pull the impurities away from the divertor. In detached divertor plasmas, the thermal forces all but vanish and the friction force dominates. A flow reversal will tend to bring impurities towards the core.

Recent numerical calculations [4] with the UEDGE plasma and gas edge simulation code, including all the classical particle drifts [5], have highlighted the importance of the drift velocity for ions and electrons produced by a gradient in the scalar electric potential, Φ:

$$v_E = E \times B / B^2 = -\nabla\Phi \times B / B^2 \approx -\nabla\Phi \times B_T / B_T^2 \quad . \tag{3}$$

The diamagnetic or $\mathbf{B}\times\nabla p/B^2$ velocity, not a true drift, transports no ions or energy and is not considered here. Recent measurements in DIII–D [6] show that poloidal $\mathbf{E}\times\mathbf{B}_T$ drifts on the private side of the separatrix circulate about 30% of the total ion flux to the target, confirming the numerical predictions.

2. EXPERIMENTAL ARRANGEMENT

We present measurements of ion saturation current, T_e, n_e, floating potential Φ_f and the parallel Mach number in the divertor of single null discharges in the DIII–D tokamak with plasma current I_p=1.4 MA, density n_e=2.8×10^{14} cm^{-3}, B_T=2 T at R_0=1.7 m, and power of 8.65 MW. These measurements will evaluate the convection term in Eq. (1). A gas puff is introduced at t=2200 ms [Fig. 1(b)] and detachment occurs ~100 ms later as shown by the temperature drop seen in Fig. 1(h),(i). The plasma potential Φ_p is calculated from Φ_f and T_e. The probe scans vertically from the target in approximately 250 ms along a path at major radius R = 1.486 m. The divertor Thomson scattering system, also at R = 1.486 m, provided independent T_e and n_e measurements every 50 ms at 8 vertical locations separated by 15–30 mm. The divertor plasma was stepped radially to obtain 2-D measurements over much of the heavily instrumented [7] divertor region as shown in Fig. 2.

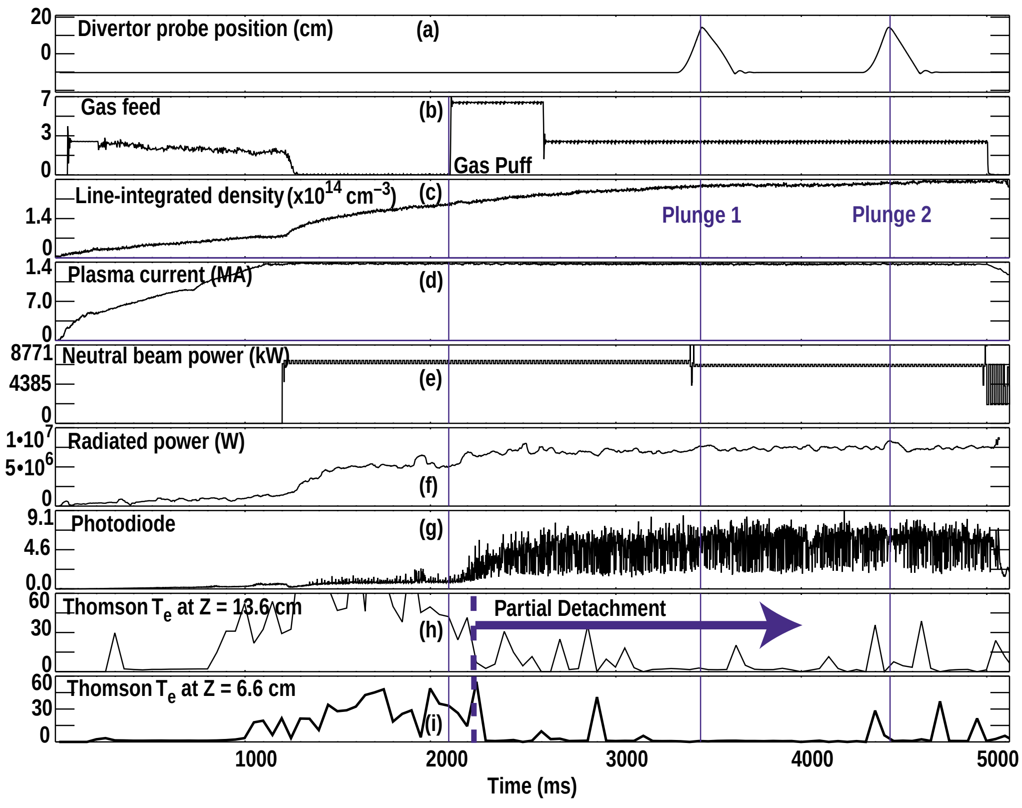

Fig. 1. Time evolution of an H–mode DIII–D discharge with a strong gas puff at t=2200 ms. The divertor plasma detaches at t=2200 ms.

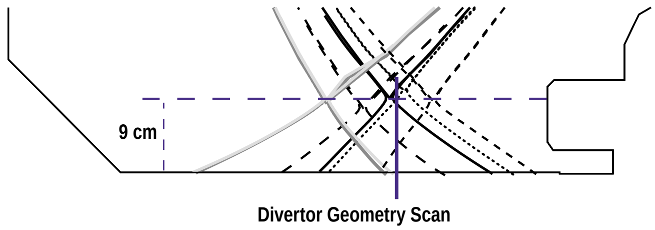

Fig. 2. The divertor magnetic geometry is swept to provide 2–D mapping capabilities to the fixed diagnostics.

3. RESULTS

It is found that the parallel D^+ divertor flows in detached plasmas approach Mach 1 towards the divertor plates (“forward flow”) over a large part of the *inner* and *outer* divertor SOL as seen in Figs. 3 and 4(b). However, the plasma flows away from the plates (“reverse flow”) in the private region and in the ***outer*** SOL regions immediately adjacent to separatrix (Fig. 3). No flow reversal is seen in the *inner* SOL or inner private region. The combination of plasma parameters is such that the convected heat flux — in the framework of Eq. (1) — dominates, transporting 80% of the remaining (reduced by a factor of 10) heat flux to the target plates. Previous measurements in attached divertor plasmas [6] showed that the D^+ parallel flow on the inner and outer divertor SOL is consistent with the classical scenarios and accelerates gradually toward the divertor target. A thin flow reversal region develops at the separatrix as the divertor plasma approaches detachment. Impurity flows measured with divertor spectroscopy [8], feature both forward flows in the SOL and reversed flows near the separatrix, following the background D^+ flow since the thermal force terms are weak. It is desirable to eliminate the flow reversal zones to avoid core contamination and to reduce $V_{||}$ as much as possible to increase divertor component protection.

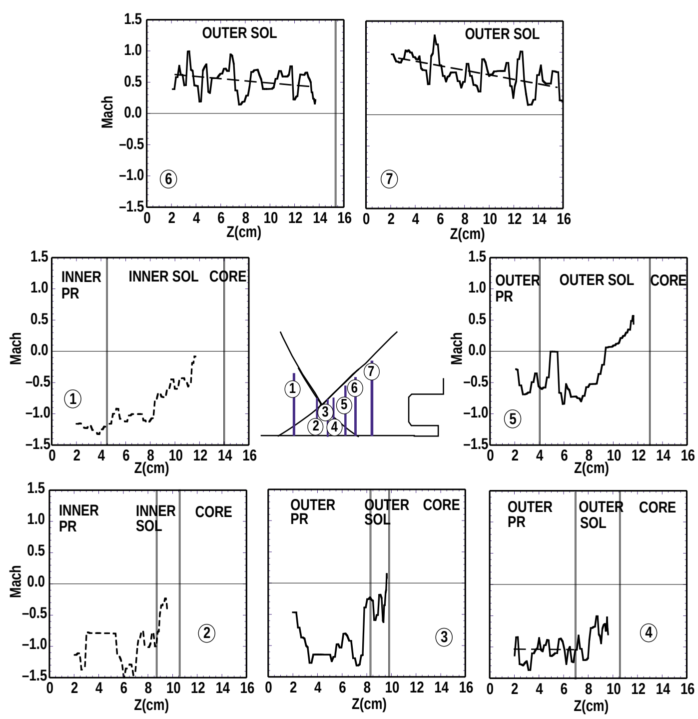

Fig. 3. Mach number versus height from the floor at t=3500 ms at various divertor locations. The flow is reversed in ③, ④, and ⑤.

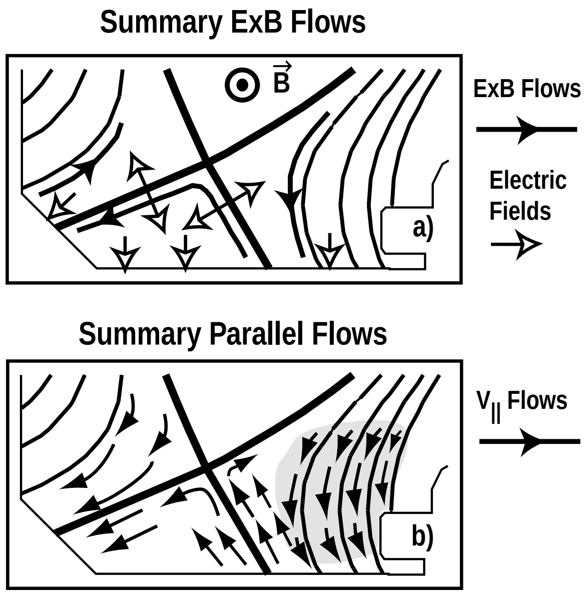

Fig. 4. Summary of (a) E×B and (b) parallel flow structure.

Attached plasma potential profiles, shown in Fig. 5(a) for the outer SOL region, feature a steep rise by ~200 V from the cold private region to the hot separatrix over 4–5 cm (5 kV/m), followed by a decrease through the SOL (~1 kV/m). The plotted traces are composites from the probe trajectories shown in insets of Fig. 5(a). The inner SOL potential variation is nearly the same as the outer SOL. These electric fields create particle ($\dot{N}=n\mathbf{E}\times\mathbf{B}_T$) drifts whose directions are sketched in Fig. 4(a) and of the order of $\dot{N}\approx 1\times10^{22}\ s^{-1}$. The ion flow to the outer and inner targets for these discharges was $\approx2\times10^{22}\ s^{-1}$ and $0.7–2\times10^{22}\ s^{-1}$ respectively, as measured by target mounted probes. Thus, the private poloidal **E**×**B** ion flow, ignored until recently [9], is ~30-40% of the total (inner plus outer) target ion flow, and is comparable to the inner target flow.

Detached plasma potential profiles, shown in Fig. 5(b), show zero gradient across the separatrix within the error bars, whereas the gradient across the near *outer* SOL, at the height of the X–point, is 100 V/m, causing $\mathbf{E}\times\mathbf{B}_T$ flows of $10^{22}\ s^{-1}$ towards the plate. Note that a small potential gradient can cause a large particle flux in these high-density detached plasmas.

The convected heat flow induced by the $\mathbf{E}\times\mathbf{B}_T$ drift is $Q_E \approx \dot{N}_e\ (5T_e+\Phi_I)$ (W). For attached plasmas, for T_e by 20 eV and Φ_I = 13.6 eV (hydrogen), the poloidal private heat flow is ~0.2 MW; which is negligible if compared to the total of 1.43 MW deposited onto the targets, as measured by IR cameras. However, the local $q_E \approx 0.48\ MW/m^2$ is comparable to peak heat fluxes to the inner and outer targets of $0.5\ MW/m^2$ and $1.4\ MW/m^2$, respectively. Therefore, q_E can be important locally.

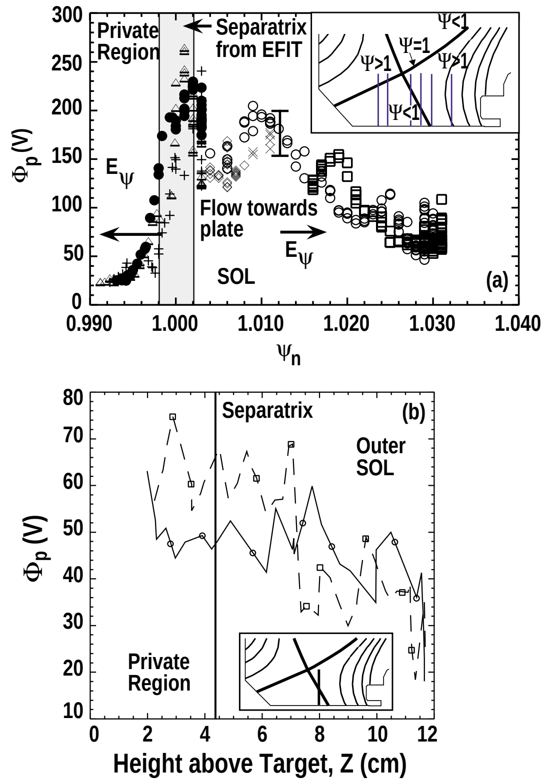

Fig. 5. Plasma potential profiles across the separatrix for attached (a) and detached (b) divertor conditions. The steep gradient across the separatrix vanishes upon detachment.

In summary, our experiments find large volume parallel flow towards the divertor in the SOL and a zone of flow reversal along the outer separatrix and private region of detached plasmas. $\mathbf{E}\times\mathbf{B}_T$ flows, of importance for divertor particle and heat transport in attached plasmas, were found to weaken in detached plasmas.

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