Flow reversal, convection, and modeling in the DIII-D divertor

J. A. Boedo
University of California, San Diego, California 92093

G. D. Porter
Lawrence Livermore National Laboratory, Livermore, California 94550

M. J. Schaffer
General Atomics, P.O. Box 85608, San Diego, California 92186-9784

R. Lehmer and R. A. Moyer
University of California, San Diego, California 92093

J. G. Watkins
Sandia National Laboratory, Albuquerque, New Mexico 87185

T. E. Evans
General Atomics, P.O. Box 85608, San Diego, California 92186-9784

C. J. Lasnier
Lawrence Livermore National Laboratory, Livermore, California 92093

A. W. Leonard
General Atomics, P.O. Box 85608, San Diego, California 92186-9784

S. L. Allen
Lawrence Livermore National Laboratory, Livermore, California 92093

(Received 22 July 1998; accepted 11 September 1998)

Measurements of the parallel Mach number of background plasma in the DIII-D tokamak divertor [M. A. Mahdavi et al. in Proceedings, 16th International Conference, Montreal, 1996 (International Atomic Energy Agency, Vienna, 1997) Vol. I, p. 397] were performed using a fast scanning Mach probe. The parallel particle flow shows evidence of complex behavior such as reverse flow, i.e., flow away from the target plate, stagnant flow, and large scale convection. For detached discharges, measurements confirm predictions of convective flow towards the divertor target plate at near sound speed over large regions in the divertor. The resulting convected heat flux is a dominant heat transport mechanism in the divertor. For attached discharges with high recycling, particle flow reversal in a thin region at or near the outer separatrix, thereby confirming the existence of a mechanism by which impurities can be transported away from the divertor target plates. Modeling results from the two-dimensional fluid code UEDGE [G. D. Porter and the DIII-D Team, “Divertor characterization experiments and modelling in DIII-D,” in Proceedings of the 23rd European Conference on Controlled Fusion and Plasma Physics, 24–28 June 1996, Kiev, Ukraine (European Physical Society, Petit-Lancy, Switzerland, 1996), Vol. 20C, Part II, p. 699] can reproduce the main features of the experimental observations. © 1998 American Institute of Physics.

I. INTRODUCTION

Divertors are a critical component of existing and planned magnetic confinement fusion experiments. The role of the divertor is to provide heat and particle exhaust while allowing impurity entrainment. Heat is transported from the plasma core to the edge and scrapeoff layer (SOL) plasma, from where it is quickly convected to the divertor region. The heat flux thus carried impinges on the divertor components, where it must be dissipated before it can cause structural damage. Impurities, mostly carbon in present tokamak plasmas, are released from plasma-facing components through physical and chemical sputtering—processes that also damage the divertor components. Thus, there is a strong motivation to understand divertor physics in general, and, in particular, any process such as plasma flow that can affect divertor operation and design by modifying particle and power transport and fluxes to the target plates and pumping apparatus.

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 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 instead of conduction. It is, therefore, important to understand the role of the plasma conditions and geometry on determining the...
Axisymmetric Divertor Experiment.

Spectroscopy has been used to study impurity flows in the plasma and impurity flows in the divertor region. Divertor flows in the divertor, efforts are being made to characterize sure zone. Plasma flows arise to equilibrate the pressure. Ionization in the divertor region is large, creating a high pressure 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.

Indications that plasma flow in the divertor can exhibit complex behavior have been obtained from two-dimensional (2-D) modeling 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 with simple one-dimensional (1-D) modeling (not including accurate boundary conditions nor steady-state regimes) and more complete 2-D considerations and it is expected to occur 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.

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 the Axisymmetric Divertor Experiment. (ASDEX-Upgrade) and DIII-D and probes for background plasma flow in DIII-D. Alcator C-Mod. Tokamak de Varennes (TdeV), and ASDEX-Upgrade, yet results are still incomplete and preliminary within a growing body of well-documented divertor physics.

We present in this article results from plasma flow measurements obtained with scanning Mach probes in the divertor region of DIII-D. The open geometry of the divertor and the location of the probe at the divertor target plate permit access to most of the divertor region, namely, the private region, the inner and outer scrapeoff layer (SOL), and the X-point.

II. EXPERIMENTAL RESULTS

The experiments to be described have been performed at the DIII-D tokamak in lower single-null divertor configuration H-mode (high confinement) discharges with plasma current \( I_p = 1.4 \text{ MA} \), toroidal field \( B_T = 2 \text{ T} \) (\( \nabla B \) drift towards the lower divertor), flattop duration of 3.8 s, and chord-averaged density of \( \sim 1.0 \times 10^{20} \text{ m}^{-3} \), as shown in Fig. 1.

The discharges are heated primarily by neutral beam injection at power levels of 4 to 5 MW. If a strong gas puff is introduced during the discharge [as marked with the thick dashed line in Fig. 1(c)], the divertor plasma temperature drops, the density increases, and the plasma detaches from the target plate.

A fast scanning probe array featuring five domed tips is introduced vertically into the divertor plasma [Figs. 2(a) and 3(a)] with two of the tips configured as a Mach probe and two as a double probe. Since the probe is located at a fixed \( R \), the magnetic configuration in the divertor is varied to allow access of the probe to the various divertor regions. The magnetic reconstruction, used to track the probe position in the changing magnetic configuration, is obtained from the processing of many pickup coil signals performed by the code EFIT.

![FIG. 1. Time evolution for two discharges [93541 (attached) and 93543 (detached)] showing (a) plasma current, (b) timing of the probe, (c) gas puff level, and (d) line. A strong gas puff is introduced at 2 s during discharge 93543 in order to detach the plasma in the outer divertor leg. The probe is inserted at 2700 ms and 3700 ms.](image)

![FIG. 2. The magnetic geometry for two discharges (one attached and the other detached) at \( t = 2690 \text{ ms} \) is shown in (a) and the velocity (b) and Mach number (c) obtained by the Mach probe. The probe penetrates the outer SOL vertically, slightly outside the outer strike point. The attached discharge data is labeled with diamonds and the detached with circles.](image)

![FIG. 3. The magnetic geometry for the reference attached discharge at \( t = 3310 \text{ ms} \) is shown (a). The scanning probe penetrates the plasma vertically from the floor along the path shown—first entering the private region and proceeding to the outer SOL. The Mach number (c) and parallel flow velocity measured by the probe (b) are shown on the right. The probe crosses the separatrix (deduced from EFIT and marked as a dashed line) from the private region into the outer leg at 4.7 cm above the target plate. The flow reversal region is indicated.](image)

---

Downloaded 26 Nov 2001 to 132.239.1.230. Redistribution subject to AIP license or copyright, see http://ojps.aip.org/pop/popcr.jsp
The Mach tips, aligned along the parallel magnetic field, are swept at 1 kHz to prevent sustained arcing. The current drawn is digitized continuously for both tips at 1 MHz for 250 ms. The ratio of the upstream and downstream currents is calculated while at ion saturation and we utilize well-known models by Chung and Hutchinson\textsuperscript{21,22} to interpret the measured probe currents as a Mach number. We use this model with \( T_e = T_i \), as verified by spectroscopy, and with a normalized viscosity \( \alpha = 1 \). The plasma flow velocity is obtained by multiplying the local Mach number by the local sound speed \( c_s = \left[ \frac{Zk(T_e + T_i)}{m_i} \right]^{1/2} \) where \( k \) is the Boltzmann constant, \( T_e \) and \( T_i \) are the electron and ion temperature, and \( m_i \) is the ion mass. The Mach number is positive if flow is towards the target plate and negative if away from it.

The saturation current collected by the Mach tips has been favorably compared to that inferred from divertor Thomson scattering density and temperature measurements for many plasma conditions. We have found that Thomson \( T_e \) and \( n_e \) can differ from those obtained from the probe\textsuperscript{13} for low temperature, high density, divertor plasma conditions. However, the saturation current inferred from Thomson data is always in agreement with that measured by the probe. We find that the probe \( T_e \) can be up to 2 to 3 times higher than the Thomson \( T_e \), thus the flow velocity inferred from double probe measurements can be higher by a factor of 1.7 but only for semi-detached or detached conditions. In those conditions, we use Thomson data to calculate parallel velocity from the probe-measured Mach number.

A. Plasma convection in the divertor

In order to investigate the effect of detachment on divertor plasma flow, we have compared two H-mode discharges (93541 and 93543), which are identical except for the strong gas puff introduced on the latter to induce detachment, as shown in Fig. 1(c). Data from the probe and Thomson scattering indicate strong changes in the divertor plasma when detachment occurs. The density in the divertor increases from \( 2 \times 10^{13} \) to \( 6 \times 10^{13} \) cm\(^{-3} \) as the temperature decreases from 30 to 2 eV. The detached discharge features high levels of fluctuations introducing larger than usual error bars in the measurements.

The probe is inserted from the floor into the outer divertor SOL for both types of discharge, as shown in Fig. 2(a). The parallel Mach number and parallel ion velocity along the probe trajectory are obtained as shown in Figs. 2(b) and 2(c). The Mach number of the attached discharge [diamonds in Fig. 2(c)] stays near 1 over the full (14 cm) stroke of the probe. In contrast, the Mach number of the attached discharge increases monotonically (from a low value of 0.2) towards the target plate [solid circles in Fig. 2(c)]. Interestingly, the concomitant and opposite changes in the Mach number and temperature for these very different discharges results in identical flow velocities [circles and diamonds in Fig. 2(b)]. In our experiments, the parallel fluid velocity in the SOL near the divertor plate is similar in attached and detached plasmas (\( \sim 3 \times 10^6 \) cm/s).

The parallel heat flux is dependent on the fluid velocity and can be expressed, following Braginskii,\textsuperscript{24} in terms of the bulk fluid velocity \( V_{||} \), the electron density \( n_e \), the parallel thermal conductivity \( \kappa = \kappa_1 T_e^{5/2} \), the atomic ionization potential \( I_0 \), and the gradient along the magnetic field length:

\[
q_i = \kappa_1 T_e^{5/2} \frac{\partial T_e}{\partial s} + n_i V_{||} \left[ \frac{5}{2} (T_e + T_i) + \frac{1}{2} m_i V_{||} + I_0 \right].
\]

During detached divertor conditions, the conduction term in Eq. (1) is essentially zero because of the extremely low temperature and parallel temperature gradient (Leonard\textsuperscript{5}) and, therefore, the convection terms dominate. Reduction of the heat flux to the plate can be accomplished by a reduction of density or parallel fluid velocity (i.e., \( T_e \)) or temperature, because the last term, \( I_0 \), is irreducible. The temperature can be reduced by radiation, the velocity by charge exchange with the neutral background, and the density by recombination.

We have compared the total heat flux (defined as the convected, conducted, and radiated) to the divertor plate at the probe position measured by IR cameras\textsuperscript{25,26} to the convected heat flux inferred from probe measurements. For detached discharges, the convected heat flux to the plate is \( 30 \times 10^4 \) W/m\(^2 \) or \( \sim 80\% \) of the total heat flux. For attached discharges, the convected heat flux is \( 23 \times 10^4 \) W/m\(^2 \) or less than 30\% of the total. These measurements are in agreement with previous work,\textsuperscript{6} where most of the heat flux to the target plates could be explained by conduction in attached discharges and could not be explained by conduction in detached discharges.

These observations indicate that the particles and heat in a partially detached divertor are transported by convection over a larger plasma volume than otherwise expected. Therefore, the divertor volume needed to reduce the convected heat flux must be increased to allow recombination and charge exchange to reduce the momentum and density to a manageable magnitude.

B. Flow reversal and its effects on impurity transport

Flow reversal (i.e., flow away from the target plates) of the background plasma has been predicted analytically\textsuperscript{9,10} in pure deuterium plasma. The main result is that large ionization sources can be associated with flow reversal which appears, as a first approximation, near the 40 eV electron temperature contour where the ratio of the rate coefficient for electron impact ionization to the square root of the temperature \( \langle \sigma v \rangle / T_e^{1/2} \) is maximum for deuterium, resulting in a larger particle source. Simulations by UEDGE,\textsuperscript{8} a 2-D fluid plasma and neutral code, predict flow reversal in the DIII-D divertor in regions which roughly follow the 40 eV contour initially. The flow reversal volume then evolves due to impurities and 2-D effects.

Flow reversal can be important for divertor operation because the main plasma flow exerts a force on impurity ions that may be present in the divertor region. Note that impurity–impurity effects are not included in Eq. (2) because the concentrations of carbon in the DIII-D divertor are less than 1\%. The force acting on the impurities (mostly carbon in present tokamaks) along the magnetic field has three main components. A drag force term depending on the difference between background deuterion plasma \( V_{||} \) and impurity ion \( V_{||,i} \) parallel velocities, a thermal force term dependent on the
thermal temperature gradients along the magnetic field and a force due to the parallel electric field $E_i$. The total force can be written as

$$F_z = m_i \left[ \frac{V_b - V_{i,b}}{\tau_{s1}} \right] + \left( 0.71Z_i^2 \frac{\partial T_e}{\partial s} + \beta_z \frac{\partial T_b}{\partial s} \right) + Z_i eE_i;$$

$$\tau_{s1} = \frac{m_i T_b (T_b/m_b)}{6.8 \times 10^4 Z_i^2 Z_e^2 n_b \ln(\Lambda) (1 + m_b/m_e)}; \tag{2}$$

where $\tau_{s1}$ is the impurity collision time with the background ions, $Z_i$ is the charge of the impurity ion, $E_i$ is the parallel electric field, $m_i$ is the ion mass, $\ln(\Lambda)$ is the Coulomb logarithm, and $\beta_z$ is the ion thermal gradient coefficient as given by Neuhauser, Chapman, and Keilhacker.

Notice that, in general, the thermal force on the ions is negative (or away from the target plate) since the temperature decreases towards the target plate. The drag force depends on the difference between the impurity and background ion flow velocity and dominates near the plate, which tends to keep the impurities trapped. These two, generally opposite, forces of the order of $10^{-17}$ N or 1 to 2 N per cubic meter of plasma where the C III density is $1 \times 10^{17}$ m$^{-3}$ are not too dissimilar in magnitude elsewhere in the divertor volume. An exception to this process occurs in the far SOL, where the long mean-free paths of neutrals and ions facilitates impurity diffusion away from the plates.

In light of the comments above, the ions will certainly experience a total force towards the midplane if fuel flow reversal is present. The situation is especially problematic if fuel flow reversal is present at the divertor separatrix since this is a direct path to the core through the X-point. Our observations show fuel flow reversal at the separatrix 4 to 5 cm above the target plate, i.e., close to the carbon source at the plates.

We have observed fuel flow reversal in H-mode discharges with attached divertor such as 94008 where the neutral pressure is high in the divertor yet no detachment is observed. The density in the divertor rises to $1\text{ to }2 \times 10^{13}$ cm$^{-3}$ compared to $2\text{ to }6 \times 10^{13}$ cm$^{-3}$ and the temperature features a significant gradient from 30 to 10 eV at the plate. For the particular geometry shown in Fig. 3(a), the probe first enters the private region and then the outer SOL after crossing the separatrix. The plasma parallel flow velocity and Mach number measured by the probe are shown in Figs. 3(b) and 3(c), respectively. We observe flow reversal (i.e., plasma flowing away from the target plate and towards the X-point) at about $-1.6 \times 10^6$ cm/s over a 1-cm thick layer, located at the separatrix between the private region and the outer SOL.

As the probe crosses the separatrix into the SOL, 5 to 6 cm from the target plate [Fig. 3(a) and 3(b)], the Mach number becomes 0.5 and the flow velocity $2 \times 10^6$ cm/s, indicating flow towards the target plate. Higher above the plate, the Mach number and flow velocity become zero corresponding to a region of stagnant flow. Thus the flow velocity in the SOL is stagnant near the X-point and increases towards the target plate consistent with classical acceleration of the plasma flow.

### III. MODELING

The plasma flow pattern in DIII-D has been modeled using the 2-D fluid plasma code UEDGE. This code is used to obtain steady-state solutions for the plasma continuity, momentum, and energy equations assuming classical parallel flow mechanisms and anomalous perpendicular flow. The perpendicular particle and thermal diffusivities are determined by matching the simulated radial profiles of plasma density and temperature to measured ones. Effects of impurity radiation are included by solving for the density of six charge states of carbon with parallel transport determined by a parallel force balance equation. The carbon is introduced by sputtering from the plasma-facing components.

Two distinct 2-D flow patterns are observed—one when the divertor plasma is attached [Fig. 4(a)], and one when the plasma is detached [Fig. 5(a)]. The sign convention used for the parallel velocity is that flow in a poloidally clockwise direction (from the inner plate to the outer plate) is assumed positive. Negative flow seen in the outer leg is termed “reversed” flow, i.e., away from the plate. Vertical cuts of Figs. 4(a) and 5(a) taken at the radius of the outer strike point ($R_{OSP}$) and 5 cm inside the outer strike point are shown in Figs. 4(b), 4(c), 5(b), and 5(c) and meant to simulate the paths taken by the X-point probe.

#### A. Attached plasma modeling

In the cut taken at the outer strike point, the attached plasma is shown to accelerate towards the plate [Fig. 4(c)] reaching $M = 1$ at the plate. This result is to be compared to the experimental data in Fig. 2(b) (diamonds). In the cut taken at inside the outer strike point ($R_{OSP}$ = 5) [Fig. 4(b)], flow reversal ($M = -0.1$) is seen in a narrow region between 5 and 7 cm off the floor. The separatrix in the simulation is located at 7 cm above the target plate. There is a region of flow towards the target plate at Mach 0.1 between 7 and 10 cm, followed by a second region of mildly reversed flow ($M \sim 0$), extending from 10 cm off the floor and above. This result is to be compared with the experimental data in Figs. 3(b) and 3(c) where a region of reversed flow at the separatrix is followed by a region of flow towards the target plate in the SOL and a second region of stagnant flow in the SOL.

These results for attached plasma compare well qualitatively with the measurements in several aspects. The region of flow reversal is narrow and located at the separatrix and the flow velocity slows down away from the target plate (in the SOL) to a stagnant flow region. In our simulations, flow reversal is a result of strong neutral recycling at the divertor plate. If the intensity of the ionization of the recycling neutrals is high enough, pressure will increase and the plasma will flow away from this source region, i.e., away from the plate.

#### B. Detached plasma modeling

The flow pattern for a plasma which is detached at both the inner and outer plates is shown in Fig. 5(a). Detachment was induced in the simulation by increasing the magnitude of upstream deuterium gas injection, as is done in the experiment. The plasma has cooled enough that three-body volume...
recombination is an important process. The reduction of available power and the recombination, which reduces the effective ion density (by acting as a particle sink that counteracts the sources) contribute to eliminate the reversed flow region in the outer leg of the divertor. Vertical cuts taken along the same radii as described above are shown in Figs. 5(b) and 5(c). The plasma flow is near Mach 1 over an extended region of the divertor and the flow velocity is maximum near the peak ionization source region, i.e., near the 3 to 5 eV electron temperature contour. There is a very small region of weak reversed flow above the X-point just outside the separatrix at 20 cm above the target plate. This region is above the extent of the X-point probe so would not be seen experimentally.

The experimental data for this type of discharge is shown in Fig. 2(c) as solid diamonds and compares favor-
ably to the simulations in that extended, rapid flow over the diverter region towards the plate is observed. A small region ($\Delta z = 1$ cm) of flow reduction at the plate seen in the simulation is not evident in the experimental results shown in Fig. 2(c), perhaps because the reduction of flow occurs over a narrow region near the strike point and will depend sensitively on the recycling condition of the plate. As shown in Fig. 5(a), this effect should be more apparent for data taken further outward from the strike point. This flow reduction arises from momentum removal via collisions and recombination between the recycling neutrals and the plasma ions, and can be seen to extend over a broad radial region in the 2-D image in Fig. 5(a).

IV. CONCLUSIONS AND DISCUSSION

We have shown that the flows in the divertor region can exhibit complex behavior such as flow reversal, stagnant flow, and bulk flow in addition to the expected presheath flow accelerating to Mach = 1 (the classical picture). We have observed that in a detached plasma, the fluid flow can approach near sonic speeds over large volumes and convect particles and heat rapidly to neighboring plasma regions and to the target plate—observation with two implications: (1) the power balance in the divertor region and the heat load to the target plate are modified; and (2) a larger divertor volume is required to assure momentum and density reduction. Flow reversal has been observed at 5 cm above the plate and its effects on the transport of impurities, such as carbon through the drag force, discussed. We have also shown that existing modeling tools can reproduce the basic features of these flows, provided the main ion and impurity sources are properly treated. The simulated results, shown in Figs. 4 and 5, indicate that (1) the discharge geometry and boundary conditions play an essential role in determining the flow pattern, and (2) the path length along a field line, or equivalently, the available volume for plasma radiation and recombination is also crucial for the transfer of momentum (by charge exchange to the neutrals), resulting on the reduction of the fluid velocity and, thus, the heat flux convected to the target plates.

ACKNOWLEDGMENTS

This work has been supported by the U.S. Department of Energy under Contract No. DE-AC03-89ER51114 and Grant No. DE-FG03-95ER54294.


