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Particle flows in pumped DIII-D discharges

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Abstract

The dynamics of particle flows in the DIII-D tokamak for two divertor configurations is considered. Fuel and intrinsic carbon impurity flows are analyzed using experimental data and 2D fluid plasma simulations. The flows in puff and pump experiments done in open and closed divertor geometries are described. It is shown that the flow of fuel particles is sensitive to divertor geometry. The pumping efficiency of the DIII-D cryopumps is a factor of 2 higher in a closed geometry than an open. The core refueling rate of an open divertor is a factor of 2 higher than that of a closed divertor. In contrast, the flow of impurity carbon particles is insensitive to divertor geometry. Both the core carbon content and the fraction of the carbon source which penetrates to the core are unchanged between open and closed divertors. In addition, the core impurity content is found to be insensitive to the amplitude of gas puffing in the simulations. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: UEDGE; Modelling; Impurity

1. Introduction

Particle flows in the edge of a diverted Tokamak plasma are important for confinement and impurity control. Neutral penetration to the pedestal region of an H-mode plasma leads to enhanced radial particle flow, and concomitant enhanced convective power loss. In turn, this enhanced power loss affects the density and temperature in the pedestal region, and thus affects the global confinement of the core plasma. On the other hand, large radial ion fluxes across the separatrix lead to large parallel flow of primary fuel ions. These large flows are expected to control the flow of impurity ions from the divertor region by balancing the ∇T_i forces which draw impurities ions from their source in the divertor region toward the core plasma. An optimum operating point should exist which balances the negative effects of enhanced convective power losses with the positive effects of impurity control.

We explore the details of particle flows in the DIII-D tokamak by examining two discharges obtained in the so-called ‘puff and pump’ experiments. These experiments utilize primary fuel ion puffing coupled with strong pumping of the divertor plasma to enhance parallel flows of primary ions as a means of controlling impurity flow to the core plasma. The effect of divertor geometry is determined by analyzing one discharge taken with the open, lower DIII-D divertor, and the second discharge taken with the more closed upper divertor of the radiated divertor program (RDP). We use both detailed analysis of the experimental scrape-off layer (SOL) diagnostics and the 2D fluid plasma model UEDGE to determine the particle flows in both geometries.

This paper begins with a brief description of the discharges which were selected for analysis in Section 2. We present a description of the flow of primary fuel particles in Section 3 of this report, and the flow of carbon impurities introduced by wall sputtering is described in Section 4. These sections present the results of both data analysis and modeling. We close with a summary of the results in Section 5.

2. Description of puff and pump discharges

Two deuterium fueled discharges have been selected for detailed analysis for this paper. Both these discharges are pumped with the cryopumps which are

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available in the divertor regions on the DIII-D tokamak. The plasma current is similar for both discharges (1.3 MA) as is the neutral beam heating power (6 MW) and the plasma density (6×10^{19} m^{-3}). The divertor geometry differs in that one discharge is diverted to the more tightly baffled RDP divertor at the top of the DIII-D tokamak, while the second is diverted to the open lower divertor, as shown in Fig. 1. We refer to the upper single null configuration shown in Fig. 1(b) as a closed divertor because the geometry of the divertor plate is such that neutrals which originate from recycling of the ion flux are directed towards the hot SOL plasma, and thus have a high probability of being reionized near the divertor plate. This is not true for the lower single null configuration, particularly on the inner divertor leg, hence we consider this case to be an open divertor. The closed divertor discharge necessarily has a high triangularity (0.34), while the open divertor discharge has a low triangularity (0.26). The ion ∇B drift is toward the X-point for each discharge. In addition, the entrance to the pumping baffle lies on the 6 mm flux surface for each discharge so that the pumping geometry is similar. Both discharges have significant amplitude of primary fuel neutrals injected near the midplane to create parallel flows for impurity control. The amplitude of the gas puffing is sufficient to approach detachment of the plasma at the outer divertor. This required a factor of 2 higher puffing for the open divertor (1500 Amp) than for the closed (800 Amp). We use the units of atom amperes, shortened to amperes, for particle flow rates throughout this paper. This is the total particle flow rate in particles/second, multiplied by the unit charge, e. One Amp is equivalent to 6×10^{18} particles/s. Finally, both discharges operate with an ELMing H-mode plasma. The effect of ELMs is not considered explicitly in the 2D simulations. Rather, we consider the simulation to represent an average over ELMs in the sense that we match the simulated upstream density profiles to those measured over a period long relative to the ELM frequency.

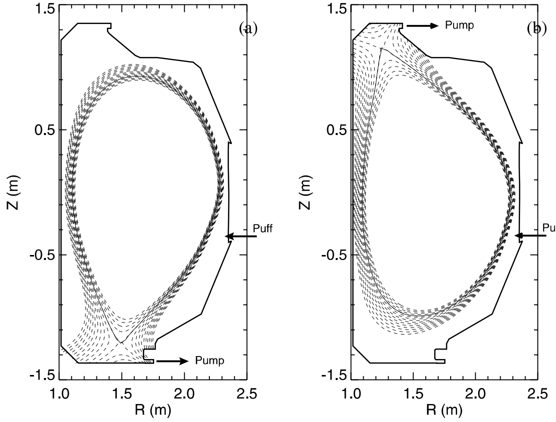

Fig. 1. Magnetic configuration for an open divertor (a) and closed divertor (b) discharge chosen for detailed analysis.

3. Behavior of fuel particles

The core ionization rate of each discharge selected for this study has been determined from the measured radial profile of the electron density and temperature near the last closed flux surface, as described previously [1]. The outward ion flux across the separatrix, and by inference the core ionization rate, is a factor of 3 higher for the open divertor configuration (2000 Amp) than for the closed divertor (700 Amp). The separatrix ion flux is large relative to the particle input from neutral beams (120 Amp) for both divertor configurations. This indicates the separatrix ion flux is derived from neutrals which originate from ions which recycle at material walls. The simulations described in this paper indicate that the measured core ionization rate is consistent with recycling at the divertor plates.

These discharges have been simulated using the 2D fluid plasma code UEDGE [2]. The effect of the walls on the fuel particle balance has been simulated by assuming all surfaces in the divertor region are saturated, hence have a recycling coefficient of unity. The wall surfaces of the main chamber are assumed to be clean, and hence have finite pumping of deuterium. (Helium glow discharge cleaning is routinely done between shots in DIII-D.) We assume that 5% of the neutral flux to the main chamber walls is pumped. We find that this wall pumping is more important for the open divertor because a larger fraction of the neutrals which originate from recycling at the divertor floor penetrate to the main chamber. The effect of the cryopump is simulated by assuming that 4% of the neutrals which impinge on the pumping baffle entrance are removed. The particle removal rate is relatively insensitive to the value assumed for this baffle removal fraction because the neutral density changes as the removal fraction is varied, keeping the exhaust rate relatively constant. The efficiency of the cryopumps is higher for the closed divertor with 2.8% of the divertor ion efflux being pumped by the cryopump for the closed divertor, and 1.3% for the open. The simulated core ionization rate for each divertor configuration is similar to that inferred experimentally. The core refueling rate (ratio of the core ionization rate to the total ion efflux to the divertors) is 4.1% for the open divertor, and 2.1% for the closed. These results indicate that the baffling of the divertor configuration has resulted in improved fuel ion control, as desired. It is interesting to note that the global energy confinement time of the closed divertor discharge is 60% better than that of the open divertor discharge (0.175 s vs 0.11 s). It is not possible to determine whether this improvement arises due to improved neutral control or to the higher triangularity of the closed divertor configuration.

The additional gas introduced by gas puffing is removed predominately by the cryopumps for both divertor configurations. Thus the simulations would appear to satisfy the conditions of the 'puff and pump' scenario, i.e., gas is puffed near the top of the SOL and removed at the bottom. This enhanced parallel flow of primary ions is expected to compensate somewhat for the adverse effect of the thermal gradient force on impurities which originate in the divertor region, thus reducing the flux of impurities to the core. The effect of gas puffing on the parallel flow velocity is shown in Fig. 2. The closed divertor discharge has a lower parallel flow velocity than the open. However, the parallel flow velocity near the *X*-point is increased very little by the introduction of gas puffing.

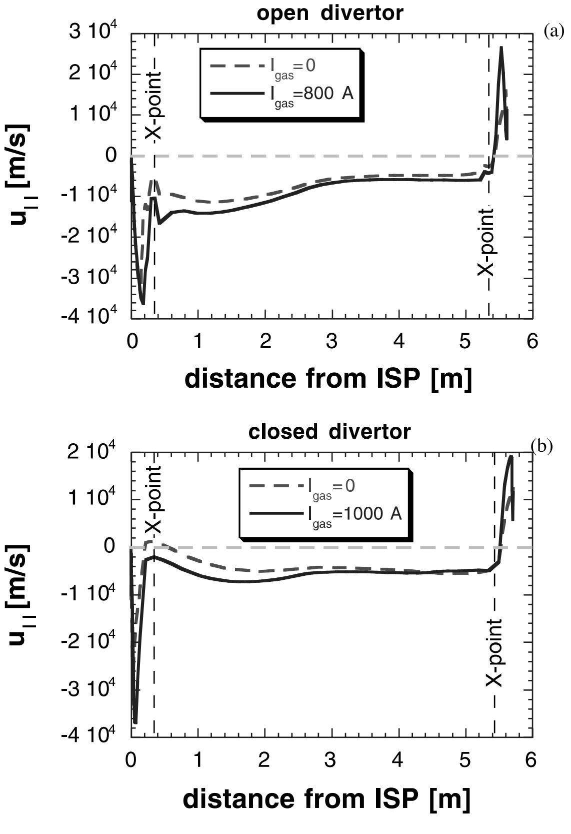

Fig. 2. The variation of the parallel flow velocity near the separatrix with gas puff amplitude for the open divertor (a) and closed divertor (b) geometries. The abscissa is the distance from the inner strike point (ISP). Positive velocity denotes flow from the inner to the outer strike point.

4. Behavior of carbon particles

The behavior of the intrinsic carbon impurities is modeled using a force balance model for the parallel transport, and an anomalous radial transport with perpendicular diffusivity set to the same value used for the primary fuel ions [3]. All six ionization states of carbon are included. The source of carbon is assumed to be physical and chemical sputtering from the divertor plates and walls [4]. Carbon is assumed to be non-recycling. A zero density gradient boundary condition is imposed for impurity ions at the private flux and outer walls. Since this means there is no ion flux to these walls, all carbon impurities are removed by flow to the divertor plates. Note, however, that the private flux and outer walls act as sources for carbon through chemical sputtering from the neutral deuterium flux.

The critical measure of the ability to control the flow of carbon to the closed flux surfaces is the equilibrium carbon density in the core. We simulate only the poloidal flux surfaces between the 96% and 110% surfaces. The average carbon density at the outer midplane between the 96% surface and the separatrix is used as a measure of the core carbon content. The dependence of this core carbon content on the amplitude of fuel gas injection is shown in Fig. 3 along with the total carbon source strength. The total carbon production rate is relatively independent of gas puffing amplitude. Although the ion flux to the plates increases with gas puff amplitude, the plate electron temperature is reduced, hence the carbon yield is reduced. This keeps the total carbon source strength relatively independent of gas puff amplitude. In addition, the parallel flow velocity in the divertor is relatively insensitive to gas puffing, consistent with experimental observation [5], leading to a weak effect of gas puffing on the impurity drag force. The combination of these two effects means that the core carbon content decreases slightly with gas puffing, particularly for the open divertor configuration. However, the effect is quite small suggesting that gas puffing and pumping are not particularly effective ways to control non-recycling impurity flow to the close field lines.

The pattern of normalized flows of total carbon (ions plus neutrals) is shown in Fig. 4. The numbers next to the arrows on this figure represent the total carbon flux across each surface, normalized to the total carbon source amplitude for each configuration. (The total carbon source amplitude differs by only a few percent for the two configurations.) For example, the total source of carbon from the inner plate in the open divertor (Fig. 4(a)) is 41% of the total carbon source. The total carbon flux from the SOL to the closed field lines is 3.8% of the total source in the open divertor configuration and 4.1% for the closed. The primary difference found for the open and closed configurations is the amplitude of the carbon source from the outer wall,

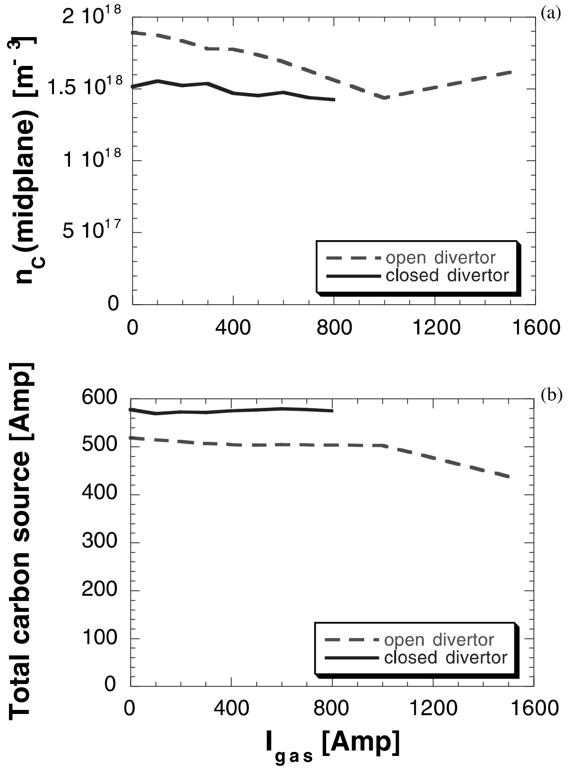

Fig. 3. Variation of core carbon content (a) and total carbon source (b) with primary ion gas puff amplitude.

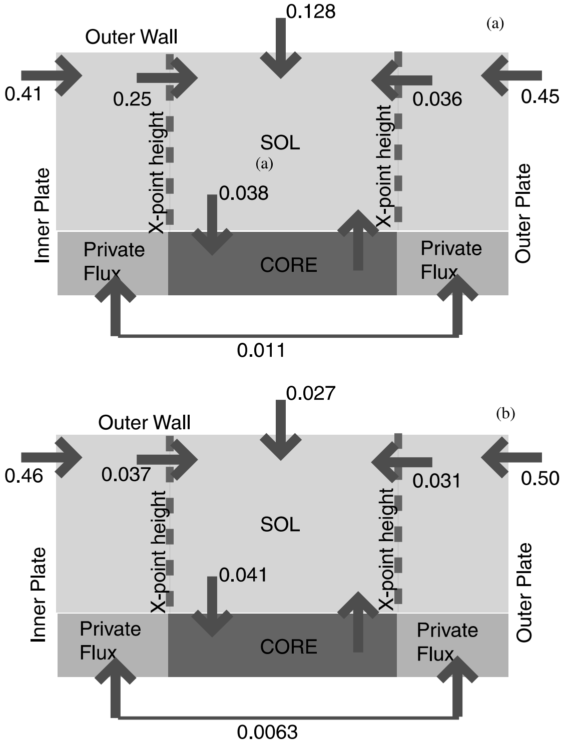

Fig. 4. Carbon flow patterns for an open divertor (a) and closed divertor (b) configuration. The efflux numbers are normalized to the total carbon source.

12.8% for the open and only 2.7% for the closed. This represents the difference in the neutral hydrogen flux on the outer wall, and the concomitant carbon created via chemical sputtering. However, this is a small fraction of the total carbon source and does not have a big effect on the flux of carbon to the closed flux lines. The dominant carbon sink is ion flow to the divertor plates for both configurations.

5. Summary

The flow of fuel and impurity particles in puff and pump experiments in DIII-D has been analyzed for two divertor geometries. It has been shown that adding baffling to the divertor region controls the flow of fuel ions as expected. The core refueling fraction has been reduced by a factor of 2 by baffling. In addition, the pumping efficiency of the DIII-D cryopumps is a factor of 2 higher for a baffled divertor. It is found that adding fuel gas puffing has a relatively small effect on the parallel velocity of fuel ions.

Adding baffling to the divertor is shown to have a relatively small effect on transport of carbon generated by sputtering from the plasma facing surfaces to the core. Approximately 4% of the carbon originating from the walls is transported to the core for both geometries. The core carbon content is only slightly reduced by gas puffing in these pumped discharges. This is consistent with the observation that gas puffing has a small effect of the primary ion flow velocity in the SOL.

Acknowledgements

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