Effect of Cross-Field Drifts and Core Rotation on Flows in the Main Scrape-Off Layer of DIII-D L-mode Plasmas

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Abstract. The flow velocities of deuterons and low charge-state carbon ions have been measured simultaneously for the first time at the crown of the main SOL for low-density plasmas in DIII-D. The dependences of the flow fields on the direction of the cross-field drifts ($\mathbf{E}\times\mathbf{B}$ and $\mathbf{B}\times\nabla$B) and core plasma rotation were investigated. The measurements indicate that the carbon ion flow direction and magnitude along the magnetic field lines are not necessarily determined by the deuteron flow field, but other physics must also play a role. The deuteron velocities at the plasma crown are high (20–30 km/s) in configurations with the ion $\mathbf{B}\times\nabla$B drift toward the divertor X-point, while nearly zero in configurations with the opposite $\mathbf{B}\times\nabla$B drift direction. The flow velocities of doubly charged carbon ions are independent of the ion $\mathbf{B}\times\nabla$B drift direction, and the measurements suggest a stagnation point in the flow field at the crown of the plasma. Both deuteron and carbon ion flow velocities in the SOL were found to be independent of the direction of core plasma rotation. Simulations with the UEDGE code have been carried out to better understand the underlying physics processes. Including the cross-field drifts in the simulations produced divertor solutions that are in significantly closer agreement with the measurements. They do not, however, reproduce the measured flow fields at the crown for the configuration with the ion $\mathbf{B}\times\nabla$B drift toward the divertor X-point.

1. Introduction

Flows in the scrape-off layer (SOL) of tokamak plasmas play a critical role in the long-range migration of eroded materials from the main chamber and divertor surfaces to their final locations of net deposition [1,2]. In tokamaks with carbon-based plasma-facing components (PFCs), these flows may transport carbon sputtered from the main chamber walls to the divertor chamber, giving rise to the formation of co-deposited carbon and hydrogen on the divertor walls. Since these films do not saturate in thickness, a tritium inventory may build up which could potentially limit the duty cycle of future, long-pulse fusion devices, such as ITER [3]. Understanding flows and their impact on material migration may enable techniques for co-deposition mitigation in ITER and other future fusion devices. Plasma flows in the main SOL and private flux region (PFR) also affect the degree of divertor detachment, thereby influencing density control by divertor pumping, divertor heat load by volumetric radiation, and the impurity content of the core plasma via SOL screening [4].

This paper describes the first simultaneous flow measurements of deuteron and low-charge state carbon ions in the SOL of low-density, low-confinement (L-mode) plasmas in DIII-D. L-mode confinement was chosen as the simplest plasma condition to study, because edge-localized modes (ELMs) do not perturb the SOL and the low input power of L-modes permits reciprocating Langmuir probe measurements of the deuteron flow. In single-null (SN) configurations with the ion $\mathbf{B}\times\nabla$B drift toward the divertor X-point, the measured deuteron flow is consistent with experimental results from other tokamaks [3], i.e., the SOL is stagnant near the low field side (LFS) midplane and reaches near-sonic flow velocities (parallel Mach number ~ 0.5–1.0) in the direction of the high-field side (HFS) divertor at the crown and inner midplane of the SN configuration. In cases with the ion $\mathbf{B}\times\nabla B$ drift away from the divertor X-point, the SOL at the crown was found to be stagnant on multiple devices [5]. We define the terms 'crown' or 'top' of the plasma as the region vertically opposite the divertor X-point, midway between the inner and outer midplane. These studies on DIII-D include new measurements using passive Doppler spectroscopy [6] and two-dimensional (2-D) imaging [2] at the crown to infer the ion velocities of low charge-state carbon ions at similar poloidal locations as those of the deuterons. It is commonly assumed that impurities of low atomic number are entrained in the SOL deuteron flow. The experimental data are compared to predictions with the 2-D multi-fluid transport code UEDGE including cross-field drift terms [7,8]. The effect of cross-field drifts on the SOL flows was investigated experimentally and in the simulations by reversing the toroidal magnetic field, B_T; the effect of core rotation by reversing the toroidal torque, N_T, on the core plasma due to neutral beam injection.

2. Measurements of Deuteron and Carbon Ion Flows in Low-Density L-mode Plasmas

The flow velocities of deuterons and low charge-state carbon ions were measured in single-null L-mode plasma at low plasma density, i.e., at densities in the range of 20% to 25% of the Greenwald density [9]. Upper single-null configurations were employed to enable flow measurements in the crown with the comprehensive diagnostic coverage in the lower divertor of the DIII-D vessel (Fig. 1). Other discharge parameters were plasma current, I_p = 1.1 MA, toroidal field, B_T = 2.0 T, edge safety factor q_{95} = 4.5, volume-averaged density, $\langle n\rangle_{vol} = 2.0-2.5\times10^{19}$ m^{-3}, and total heating power, P_{tot} = 1.0 – 1.3 MW. Without externally applied torque the core plasma rotates toroidally in the co-current direction at approximately 15 to 20 km/s at a normalized toroidal flux, Ψ_N, of 0.8. The rotation profiles were measured by charge exchange recombination spectroscopy on fully stripped carbon. At the separatrix the toroidal velocity is lower, about 5 km/s. These discharges are also characterized by the absence of active pumping in the divertor; passive pumping by the walls constitutes the only particle sink. At the separatrix at the LFS midplane, the measured plasma parameters were $n_{e,LFS} \sim 7-10\times10^{18}$ m^{-3}, $T_{e,LFS}$ ~ 50–70 eV, and $T_{i,LFS}$ ~ 150–200 eV; resulting in electron and ion collisionalities, ν_e^* and ν_i^*, of approximately 5 and 0.5, respectively. The SOL is therefore expected to be marginally collisional for the electrons, and collisionless for the ions. These plasma conditions were held constant during the 3.5 s-long density flattop, midway through which methane at a rate of ~1 Pa-m^3/s was injected in toroidally symmetric fashion for 1.5 s to enhance the carbon emission at the HFS of the crown for line-filtered imaging. The injection led to a factor of two increase in carbon emission at the LFS of the crown and, concomitantly, to a 10%–20% increase in $\langle n\rangle_{vol}$ and SOL total radiated power.

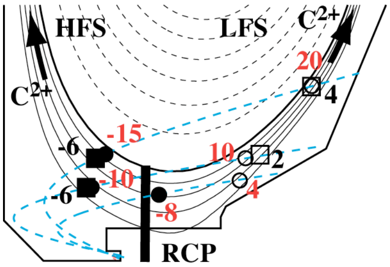

Fig. 1. Viewing geometry of 3 chords connected to an edge spectrometer (dashed cyan line) and the reciprocation path of the reciprocating Langmuir probe (thick vertical black bar). The squares and circles denote the locations for which parallel-**B** C^{2+} ion velocities were measured; the actual velocities are denoted next to the measurement locations in black (USN $V_{\nabla B\uparrow}$) and red (USN $V_{\nabla B\downarrow}$).

A summary of the measured flow velocities of the deuteron and low charge-state carbon ions for configurations with the ion $\mathbf{B}\times\nabla B$ toward (USN $V_{\nabla B\uparrow}$) and away from the X-point (USN $V_{\nabla B\downarrow}$) is given in Table 1.

2.1. Effect of Toroidal Field Direction on the Measured SOL Flows

Measurements with a reciprocating, multi-tipped Langmuir probe [10] at the HFS of the crown show in the USN $V_{\nabla B\uparrow}$ case, that the deuterons flow toward the HFS divertor with a parallel-B velocity of approximately one-half of the local ion sound speed (Fig. 2) [11]. The poloidal direction of this deuteron flow at the crown is in the direction of I_p. Using the local electron temperature measured by the probe, and assuming $T_e = T_i$, the absolute deuteron speed varies monotonically from 35 km/s at the separatrix to 15 km/s in the far SOL.

TABLE 1: SUMMARY OF THE DEUTERON AND LOW CHARGE-STATE CARBON ION FLOW VELOCITIES OBTAINED AT THE CROWN IN DIII-D LOW-DENSITY L-MODE PLASMAS. NEGATIVE FLOW VELOCITIES DENOTE FLOW TOWARD THE HFS DIVERTOR PLATE.

	USN $V_{\nabla B\uparrow}$	USN $V_{\nabla B\downarrow}$
$M_{\parallel}^{D^+}$	Crown HFS: –0.5	~ Zero
$v_{\parallel}^{D^+}$ [km/s] (w/ $T_e = T_i$)	–15 to –35 km/s	
$V_{\parallel}^{C1^+}$ [km/s]	Crown HFS: –5 to –7	HFS: –6 to –8
$V_{pol}^{C1^+}$ [km/s]	Crown HFS: –0.2 to –0.3	HFS: –0.2 to –0.3
$V_{\parallel}^{C1^{++}}$ [km/s]	Crown HFS: –5 to –10 Crown LFS: +2 to +5	HFS: –10 to –15 LFS: +8 to +20

In the USN $V_{\nabla B\downarrow}$ configuration the deuteron flow is low, with a magnitude of Mach ~ 0.1 toward the LFS divertor near the separatrix, reversing to Mach ~ 0.1 toward the HFS divertor in the far SOL.

Doubly charged carbon ions, C^{2+}, were measured to flow parallel to **B** toward the HFS divertor on the HFS of the crown, and with comparable velocities toward the LFS divertor on the LFS of the crown (Fig. 1). Improved signal strength in the recent measurements has enabled the identification of emission from two emission zones, one on the HFS and one on the LFS, which was not possible with the previous C^{2+} data [12]. The absolute magnitude of the measured C^{2+} flow velocities is 5–15 km/s, with a radial fall-off with distance from the separatrix. The C^{2+} velocity in the HFS of the crown is a factor of 2 lower than, but in the same direction as the deuteron velocity in USN $V_{\nabla B\uparrow}$ configuration. Singly charged carbon ions, C^{1+}, were previously measured to flow along **B** toward the HFS divertor at the HFS of the crown at velocities of 5–10 km/s, consistent with the more recent results for C^{2+} [12]. The carbon ion flow speeds were deduced from spectroscopic analysis of the Doppler shifts of the CII doublet (2P–2S) at 658 nm and the CIII triplet (3P–3S) at 465 nm [6]; both lines were observed along quasi-tangential chords that intersect the SOL on both the HFS and LFS of the crown (Fig. 1). The unshifted line profiles on vertical view chords were used to deduce absolute wavelength references for interpreting the shift along the quasi-tangential chords. The dependence of magnetic splitting on field strength along tangential views was used to localize the C^{1+} and C^{2+} emission zones.

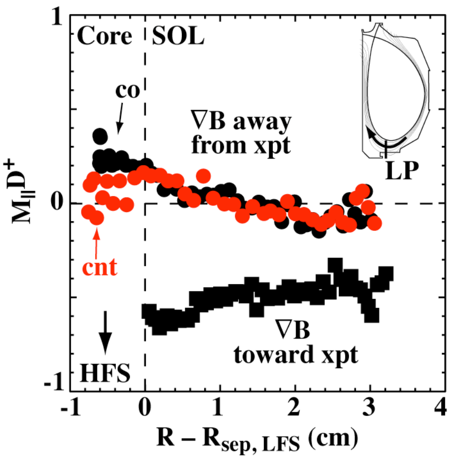

Fig. 2. Parallel-**B** flow velocities of deuterons at the HFS of the crown as a function of distance from the separatrix measured at the LFS midplane. The deuteron velocities are expressed by the Mach number. Positive Mach numbers denote flow toward the LFS divertor. Measurements in plasmas with the ion $\mathbf{B} \times \nabla B$ drift toward and away from the divertor X-point, and co-current and counter-current toroidal rotation are shown. The inset shows the magnetic configuration as calculated by EFIT and the reciprocating path of the Langmuir probe.

Although collisional entrainment of the carbon ions in the background deuteron flow seems an obvious explanation for the measured carbon flow direction and speed in the USN

$V_{\nabla B\uparrow}$ configuration, the results obtained in the USN $V_{\nabla B\downarrow}$ case are inconsistent with collisional entrainment. A full explanation is further complicated by the fact that the carbon flow locations in the crown are displaced poloidally to the HFS and LFS from those of the deuteron flow measurements. In addition, collisional entrainment in the deuteron flow along $\mathbf{B}$ depends on how the electrostatic collision rates between the deuterons and carbon ions compare to loss rates of the carbon ions by ionization, recombination, and perpendicular transport. The Spitzer stopping time, τ_s, for electrostatic collisions between C^+ and D^+ [13] is of the order 50 μs, only one-half of the electron impact ionization time, τ_{ioniz}, for the transition from C^+ to C^{2+}. Experimental data from the reciprocating probe and divertor Thomson scattering were used to estimate these rates. Higher charge-state carbon ions couple more efficiently to the deuteron flow, because τ_s decreases with charge state Z, as $1/Z^2$. For C^{3+} ions, for example, the Spitzer stopping time is 100 times shorter than the ionization time to the next higher charge state.

During the methane injection into the HFS of the crown, the poloidal emission profiles of hydrocarbon fragments and successive ionization stages of the carbon atoms are progressively shifted toward the HFS divertor. Using the profiles of CI and CII emission (Fig. 3), and the local SOL plasma conditions to calculate the collisional and ionization rates, a poloidal C^{1+} velocity of 200–300 m/s can be deduced [Eq. (1) from [2]). The direction and magnitude of the inferred poloidal C^{1+} flow velocity, along with the pitch angles of the total magnetic field determined by EFIT equilibrium reconstruction [14] are consistent with the purely parallel-$\mathbf{B}$ motion toward the HFS divertor in the HFS of the crown measured by Doppler spectroscopy. Comparison of the CD (431 nm), CI, CII, and CIII poloidal intensity distributions do not show a discernable dependence on the ion $\mathbf{B}\times\nabla B$ drift direction (Fig. 3 showing the CI and CII profiles). Hence, the inferred poloidal velocity of C^{1+} ions is estimated to be of the same magnitude in the two ion $\mathbf{B}\times\nabla B$ drift directions and therefore independent of the $\mathbf{E}\times\mathbf{B}$ drift direction. On the other hand, the estimated magnitude of $\mathbf{E_r}\times\mathbf{B}$ drift velocity at the HFS of the crown derived from calculations of the radial electric field, $\mathbf{E_r}$, from the reciprocating Langmuir probe, is of the order 100 to 200 m/s, ~ 1/3 of the C^{1+} flow from the camera data.

Further evidence of preferential transport of the injected carbon ions from the HFS of the crown to the HFS divertor comes from images of the CII and CIII emission in HFS and LFS midplane regions with tangentially viewing cameras. In the HFS midplane SOL the emission at both wavelengths increased roughly fivefold when methane is injected, while only a 10% to 15% increase was observed at the LFS midplane.

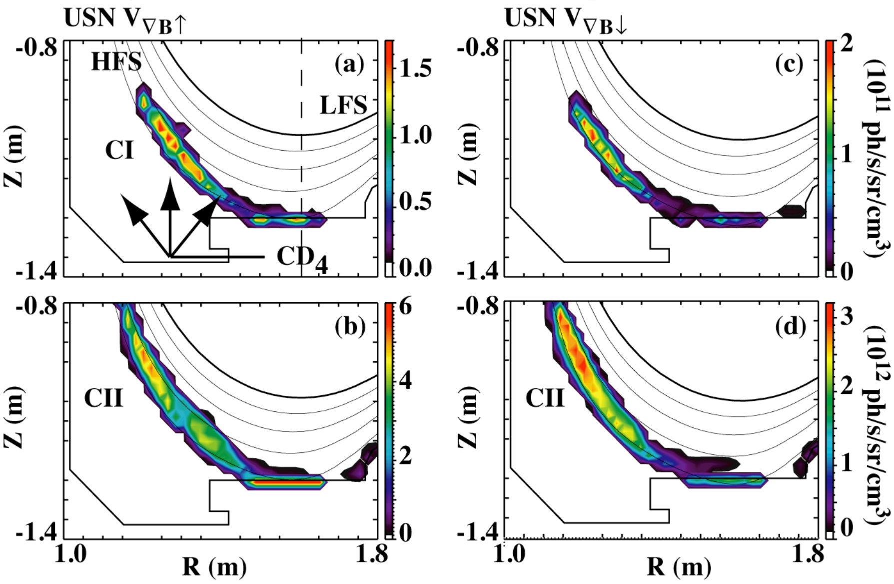

Fig. 3. Topographic reconstructions of the CI [910 nm; (a) and (c)] and CII [516 nm; (b) and (d)] emission profiles during the methane injection. The left-hand column (a,b) shows the intensity distributions in plasmas for the USN $V_{\nabla B\uparrow}$, the right-hand column (c,d) for the USN $V_{\nabla B\downarrow}$ case. The dashed vertical line (a) indicates the partition between HFS and LFS of the crown.

2.2. Effect of Core Plasma Rotation on the Measured SOL Flows

Reversal of the core plasma rotation by neutral beam injection did not significantly alter the flow velocity of deuterons (Fig. 2) [11] and low charge-state carbon ions (not shown) at the plasma crown. For these studies in L-mode, neutral beam injection was switched from co-current to counter-current at a roughly comparable torque value of 1.2 N-m. This switch caused the toroidal rotation of fully stripped C^{6+} carbon ions inside the separatrix ($\Psi_N \sim 0.8$), as measured by charge exchange recombination spectroscopy, to reverse from 15 km/s in the co-current to 20 km/s in the counter-current direction. More recent measurements indicate that at the separatrix the magnitude of the toroidal velocities are a factor 3–4 lower than at $\Psi_N \sim 0.8$, and that during the counter-injection phase the C^{6+} ions in the SOL spin in the co-current direction. Reciprocating Langmuir probe measurements show that inside the separatrix the deuterons flow in the co-current direction during co-current and counter-current neutral beam injection (Fig. 2), and that the magnitude of the deuteron flow is only slightly lower during the counter- beam phase. In the SOL, the parallel-B flow velocities of deuterons and doubly charged carbon ions, and the poloidal velocity of singly ionized carbon are unaffected by the applied torque direction.

3. Predictive SOL Simulations with UEDGE

Scrape-off layer flows were studied numerically with the 2-D multi-fluid edge code UEDGE [7], including cross-field drift terms due to $\mathbf{E}\times\mathbf{B}$ and $\mathbf{B}\times\nabla B$ [8]. In UEDGE plasma transport in the B direction is modeled using the fluid Bragiinski equations, including kinetic corrections. Perpendicular to $\mathbf{B}$, transport was assumed to be purely diffusive, and modeled with radially varying transport coefficients to match the measured outer midplane profiles of n_e, T_e, and T_i. These equations are solved on a non-orthogonal grid derived from EFIT equilibrium reconstructions, which span core, edge, and SOL regions between Ψ_N of 0.9 ($R-R_{sep,LFS}=-4$ cm) and 1.09 ($R-R_{sep,LFS}=+4$ cm). The parameter $R-R_{sep,LFS}$ is the distance from the separatrix measured at the LFS midplane. The toroidal field vector was run forward and reverse to simulate the plasma in cases with the ion $\mathbf{B}\times\nabla B$ toward and away from the X-point, respectively. Core plasma rotation was imposed as a boundary condition at the UEDGE core boundary by specifying the toroidal momentum. Deuterons striking the plates are recycled as neutrals with 100% efficiency, whereas deuterium neutrals striking the divertor target plates, the grid boundary facing the PFR, and the outermost grid boundary in the main SOL are recycled with 99% efficiency. Carbon released by physical and chemical sputtering at the plates, and by chemical sputtering at the walls is injected using published rates [15] into the computational domain as neutral atoms. Its transport is modeled using a force balance equation in the parallel-$\mathbf{B}$ direction, and diffusion in the radial direction with the same transport coefficients as for the deuterons, and collisional ionization and recombination rates are from ADAS [16].

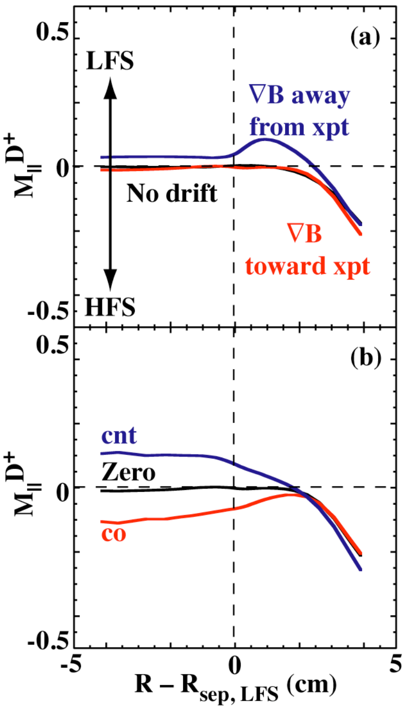

Fig. 4. Predicted parallel-$\mathbf{B}$ deuteron flow at the tip of the crown as a function of the distance from the separatrix ($R-R_{sep}$) at the LFS midplane for UEDGE cases without the drift terms and with both directions of the ion $\mathbf{B}\times\nabla B$ drifts (a), and applied toroidal momentum at the core boundary (b). The experimental data are shown in Fig. 2.

3.1. Effect of Toroidal Field Direction on the Simulated SOL Flows

The magnitude of the calculated deuteron Mach number at the crown is significantly lower than the measured Mach number in the USN $V_{\nabla B\uparrow}$ configuration, while low deuteron flow is predicted for the USN $V_{\nabla B\downarrow}$ case, as was measured [Figs. 2 and 4(a)]. For the USN $V_{\nabla B\uparrow}$ case, inclusion of the $\mathbf{E}\times\mathbf{B}$ and $\mathbf{B}\times\nabla B$ drift terms in the UEDGE simulations did not significantly change the direction and magnitude of the deuteron flow [Fig. 4(a)]. It did, however, result in solutions of the divertor plasma that are in significantly better agreement with the measurements [17]. With drift terms included, the electron temperature at the inner plate near the separatrix decreases from 20 to 3 eV, making the calculated diverter plasma more consistent with Langmuir probe and carbon emission profile measurements in the divertor.

The UEDGE simulations predict that the deuteron flow along magnetic field lines is driven by the pressure gradient between the divertor X-point and the crown produced by (1) recycling in the divertor, (2) $\mathbf{E}\times\mathbf{B}$ driven flow in the private flux region [18], and (3) ion $\mathbf{B}\times\nabla\mathrm{B}$ drifts at the crown and the divertor X-point, when the cross-field drifts are included. This flow pattern is offset by radial fluxes across the separatrix, peaking at the LFS midplane region. In both $\mathbf{B}\times\nabla\mathrm{B}$ drift directions, a stagnation point is formed near the crown, with its exact poloidal location depending on (1) – (3). In the USN $V_{\nabla B\uparrow}$ case, the radial particle flux across the separatrix is from the SOL into the core plasma domain reducing the plasma pressure at the crown: the total flow in the HFS and LFS main SOL is predominately toward the crown. In the other B_T configuration, the $\mathbf{B}\times\nabla\mathrm{B}$ driven flux at the crown is from the core into the SOL producing a pressure peak at the crown: the flow in the HFS and LFS main SOL is away from the crown. Poloidally, $\mathbf{E}\times\mathbf{B}$ driven flow can be of equal magnitude to the poloidal projection of the parallel flow, or even dominate the flow pattern, i.e., at the separatrix. The UEDGE-calculated radial electric field is negative in the SOL near the separatrix, and positive in the far SOL, thus in the USN $V_{\nabla B\uparrow}$ configuration, the poloidal $\mathbf{E}\times\mathbf{B}$ driven flow is toward the HFS divertor in the near-separatrix region, and toward the LFS divertor in the far SOL region. The direction of these flows changes with the reversal of B_T.

For USN $V_{\nabla B\downarrow}$ case the magnitude of the calculated parallel-B velocity of C^{2+} at the HFS of the crown is as high as the measurement, and increases when the drifts are included. However, the flow is toward the LFS divertor, opposite to what is observed experimentally [Fig. 5(a)]. Reversal of B_T produces C^{2+} flow velocities in the direction of the HFS divertor, but their magnitude and radial dependence (not shown) does not reproduce the experimental findings. In the LFS of the crown near the spectroscopic measurement points, the simulations show flow of C^{2+} in the direction of the LFS divertor for the cases without and with the cross-fields in both B_T configurations. A flow speed (~ 10 km/s) at the LFS of the crown is predicted for the USN $V_{\nabla B\uparrow}$ configuration, close to the measurements.

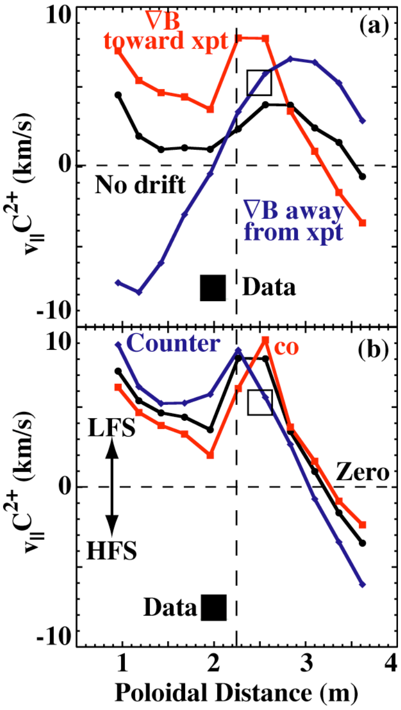

Fig. 5. Calculated parallel-$\mathbf{B}$ C^{2+} flow velocities as a function of poloidal distance from the HFS (1 m) to the LFS (3.6 m) midplane for the flux surface at distance 2 cm at the outer midplane. The grid cell representing the tip of the crown is indicated by the vertical dashed line. The experimental data are shown at the solid (HFS) and open (LFS) squares replicated from Fig. 3. UEDGE cases without the drift terms and with both directions of the ion $\mathbf{B}\times\nabla\mathrm{B}$ drifts (a), and applied toroidal momentum at the core boundary (b) are plotted.

The UEDGE simulations indicate that transport of C^{2+} ions at and near the crown is determined by the balance between the frictional drag force exerted by the deuterons, and the ion temperature gradient (∇T_i) force produced by the background plasma [19]. The simulated ion temperature in the main SOL is highest at the LFS midplane region, and falls off toward both divertor plates. Recent spectroscopic measurements of the C^{2+} ion temperatures at the crown indicated a poloidal gradient in T_i in the direction of the LFS midplane. In the simulations for USN $V_{\nabla B\uparrow}$, both the drag and ∇T_i forces push C^{2+} ions toward the crown and LFS midplane region, hence the flow is in the direction of the LFS divertor. In the opposite B_T case, the drag force exceeds the ∇T_i force at the HFS of the crown and effectively pushes C^{2+} ions toward the HFS divertor. At the LFS of the crown, both forces are toward the LFS divertor producing flow toward the LFS divertor. Poloidally, the flow of low charge-state carbon ions is dominated by the parallel flow component. The calculated $\mathbf{E_r}$ in the SOL (~ 100 V/m) is too small to play a significant role. On the other hand, the poloidal flow of higher charge-state carbon ions carrying the bulk of the total carbon flow, is determined by both the parallel-$\mathbf{B}$ and $\mathbf{E}\times\mathbf{B}$ components. For the USN $V_{\nabla B\uparrow}$ simulation, the poloidal flux of C^{4+} ions is governed by $\mathbf{E}\times\mathbf{B}$ drifts on the carbon ions in the direction of the HFS divertor for the near-separatrix part of the SOL ($0 < R - R_{sep} < 0.5$ cm). For $R - R_{sep} > 0.5$ cm the poloidal flow is determined by the parallel-$\mathbf{B}$ component pointing toward the LFS divertor.

3.2. Effect of Imposed Toroidal Rotation on the Simulated SOL Flows

Increasing the magnitude of the toroidal momentum, L_T, at the UEDGE core boundary results in a spin-up of the parallel-$\mathbf{B}$ velocity of the deuterons in the core and near-separatrix SOL region at the crown in the direction of the applied momentum [Fig. 4(b)]. The simulations indicate that the SOL region for $R - R_{sep} > 2$ cm is not affected by changes to the core rotation. Consequently, the flow velocities of C^{2+} ions calculated in the SOL are in the same direction and of similar magnitude for the three cases considered [Fig. 5(b)]. These simulations were executed for the USN $V_{\nabla B\uparrow}$ case; the results are qualitatively the same for the opposite B_T configuration. In the simulations L_T was varied from -1×10^{-2} Nms (co-current) to zero and $+1\times10^{+2}$ Nms (counter-current) resulting in toroidal deuteron velocities of –15 km/s (co-current), nearly zero, and +15 km/s (counter-current), respectively, at the LFS midplane on the UEDGE core boundary. Fully stripped carbon ions possess almost identical velocities as the deuterons. In the zero-momentum case, the SOL near the separatrix is rotating predominately in the co-current direction, while the far SOL is rotating slightly counter-current. Driving momentum in the counter-current direction at core boundary reverses the toroidal velocity at the separatrix, but only slows it down in the SOL for 0.5 cm $< R - R_{sep} < 3$ cm. Increasing the radial momentum transfer by raising the anomalous momentum diffusion by a factor of 10 broadens the toroidal velocity and parallel-$\mathbf{B}$ Mach profiles of the deuterons at the LFS midplane and crown, respectively. It does not, however, result in higher flow velocities at the crown.

4. Discussion and Summary

Measurements of the flow velocities of deuterons and low charge-state carbon ions (C^{1+}, C^{2+}) at the crown of L-mode plasmas in DIII-D showed that carbon is not necessarily entrained in background plasma flow. Physics processes other than frictional drag must influence carbon transport in the main SOL. These new results must be considered when interpreting previous carbon transport studies in DIII-D using isotopically tagged carbon (^{13}C), and they challenge our present understanding of material migration in tokamaks. These studies were performed in low-density, marginally collisional SOL plasmas. In configurations with the ion $\mathbf{B}\times\nabla B$ drift toward the X-point, both the deuterons and C^{2+} ions were measured to flow at 20–30 km/s and 5–15 km/s toward the HFS divertor at the HFS of the crown. In the case with the ion $\mathbf{B}\times\nabla B$ drift away from the X-point, the deuteron flow is zero, but carbon ions flow at 5–15 km/s toward the HFS divertor. At the LFS of the crown C^{2+} ions were measured to flow at up to 20 km/s toward the LFS divertor, hence a stagnation point for C^{2+} ions exists at the tip of the crown. Poloidally, the C^{1+} velocities at the HFS were measured to be consistent with parallel-$\mathbf{B}$ motion; the $\mathbf{E}\times\mathbf{B}$ flow component appears too small compared to the poloidal projection of parallel-$\mathbf{B}$ flow. Driving toroidal rotation in the core does not significantly change the flows of deuterons and C^{2+} in the SOL at the crown, hence momentum coupling between the core plasma inside $\Psi_N \sim 0.8$ and the SOL is small. Plasma simulations with the multi-fluid edge code UEDGE do not predict the strong deuteron and C^{2+} flows measured in the configuration with the ion $\mathbf{B}\times\nabla B$ drift toward the X-point. The simulations include the cross-field terms due to $\mathbf{E}\times\mathbf{B}$ and $\mathbf{B}\times\nabla B$. While including these terms does not significantly change the predicted flow fields in the vicinity at the crown, their inclusion does lead to plasma solutions in the divertor that are more consistent with measurements than in simulations without them. The simulations indicate that the deuteron flow along **B** is determined by pressure imbalance between the divertor X-point and the crown: due to the $\mathbf{B}\times\nabla B$ drift the crown is either a pressure sink (USN $V_{\nabla B\uparrow}$) or pressure hill (USN $V_{\nabla B\downarrow}$). Consequently, in the former case, the SOL flow is predominately from the X-point to the crown, in the latter case from the crown toward the X-point. The simulations also show the transport of low charge state carbon ions in the main SOL is determined by both electrostatic coupling to the deuterons and the ion temperature gradient force. A poloidally peaked ion temperature profile is predicted by UEDGE, with its maximum at the LFS midplane, pushing carbon ions from the HFS X-point toward the crown. Depending on the direction of the deuteron flow at and around the crown, C^{2+} ions are predicted to flow either toward the LFS divertor only (USN $V_{\nabla B\uparrow}$), or toward the HFS and LFS divertor at either side of the crown (USN $V_{\nabla B\downarrow}$). Imposing toroidal momentum at the UEDGE core boundary, or poloidally peaked pressure profiles at the LFS midplane, do not significantly change the predicted flow of deuterons and low charge state carbon ions at the crown. Kinetic effects due to ion orbit losses across the separatrix may play a role in driving flows in the SOL; their effect is yet to be studied.

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