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Interpretations of the impact of cross-field drifts on divertor flows in DIII-D with UEDGE

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Simulations using the multi-fluid code UEDGE indicates that, in low confinement (L-mode) plasmas in DIII-D, poloidal projection of the ionization driven flows dominate poloidal particle flows in the divertor near the divertor plates, whereas $E \times B$ drift flows dominate the radial particle flows. In contrast, in high confinement (H-mode) conditions $E \times B$ drift flows dominate both poloidal and radial particle flows in the divertor in the vicinity of the strong gradient region near the separatrix. UEDGE indicates that the toroidal $C^{2+}$ flow velocities in the divertor plasmas are mainly entrained within 30\% to the background deuterium flow in both L- and H-mode plasmas in the plasma region where the CII 465 nm emission is measured. Therefore, UEDGE indicates that the Doppler Coherence Imaging Spectroscopy (CIS), measuring the toroidal velocity of the $C^{2+}$ ions, can provide insight to the deuterium flows in the divertor. Parallel-to-$B$ velocity dominates the toroidal divertor flow; direct drift impact being less than 1\%. Toroidal divertor flow is predicted to reverse when the magnetic field is reversed. This is explained by the parallel-$B$ flow towards the nearest divertor plate corresponding to opposite toroidal directions in opposite toroidal field configurations.

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1. Introduction

Divertor detachment is presently required for controlling power exhaust in reactor scale fusion devices [1]. Particle flows driven by recycling processes, turbulent transport, and cross-field drifts strongly impact plasma conditions and the degree of detachment at each divertor plate for given upstream plasma conditions. In this study, the multi-fluid code UEDGE [2] is used to interpret the role of drift-driven divertor flows in the overall divertor flow patterns in low and high confinement mode (L- and H-mode) plasmas in the DIII-D tokamak.

To provide spatially resolved 2D information of scrape-off layer (SOL) and divertor flow patterns, the Doppler Coherence Imaging Spectroscopy (CIS) system was developed on the DIII-D tokamak [3,4]. This system provides information about the velocity of the $C^{2+}$ ions based on the interferometrically-determined Doppler shift of the CII 465 nm line. To interpret the background deuterium flow velocity, the degree of entrainment of doubly charged carbon ion ($C^{2+}$) flow to the background deuterium flow must be understood. One of the primary purposes of this paper is to document UEDGE predictions for the degree of entrainment of $C^{2+}$ ion in the background deuterium flows in the CII 465 nm emission region in the plasma to provide a reference for the future studies with the CIS system. Similar studies for the crown of the plasma at DIII-D have been published by Groth, et al. [5].

A dedicated series of L- and H-mode plasmas with the $B \times VB$ drift direction into (FWD-$B_T$) and away (REV-$B_T$) from the divertor in the DIII-D tokamak are investigated [6,7]. H-mode plasmas were carried out in a low triangularity configuration at toroidal field strength of 1.8 T and plasma current of 0.9 MA, while the L-mode plasmas were studies in a low triangularity configuration at toroidal field strength of 2.0 T and plasma current of 1.3 MA. The total heating power in the H-mode discharges is about 3.8 MW, and in the L-mode discharges 1 MW of Ohmic with 100 ms NBI...
blips for $C^2+$ temperature and density measurements. The divertor strike points (SP) were swept to obtain 2D Divertor Thomson Scattering (DTS) profiles [8]. Extreme SP sweeps were conducted in the H-mode plasmas to cover both low and high field side (LFS/HFS) divertor legs with the DTS system [6].

2. UEDGE setup

The multi-fluid code UEDGE was used to interpret the impact of drift-driven flows in these L- and H-mode plasmas to predict the overall divertor flow patterns in DIII-D, as well as to determine the entrainment between the $C^2+$ and $D^+$ flow. UEDGE encompasses a Braginskii fluid plasma solver with fluid neutrals model [2]. A multi charge state carbon impurity model was used assuming a force balance equation that results when impurity inertia and viscosity are neglected [9]. ADAS atomic rates were used for the carbon impurities [10]. Physical and chemical sputtering are calculated in the simulations according to published rates [11,12]. In these H-mode studies, the chemical sputtering rates of carbon are multiplied by a factor of 2 to increase the total radiated power levels in the simulations close to the experimentally measured levels. However, this approach is prone to overestimate the total amount of carbon in the computational domain and a detailed comparison to carbon spectroscopy has not been conducted for these simulations by the time of writing this report. Therefore, in this study, carbon sputtering yield is used as an adjustable control parameter to fit the total radiated power, while the ratio of carbon radiation to radiation due to other species is likely to be overestimated. Radially varying particle diffusivity in the radial direction, $D_p$, and electron and ion heat conductivity, $\chi_{ei}$, coefficients are used in the L-mode simulations to provide low field side (LFS) SOL mid-plane profiles consistent with the experimentally measured main plasma Thomson scattering profiles of electron density, $n_e$, and temperature, $T_e$. In the H-mode simulations, radially constant $D_p \sim 0.15 \text{ m}^2/\text{s}$ and $\chi_{ei} \sim 0.4 \text{ m}^2/\text{s}$ are used similar to the studies documented by Rognlien et al. in [13]. Heating power crossing the inner core boundary of the computational domain was set to 0.9 MW in the L-mode simulations and to 3.0 MW in the H-mode simulations, divided equally between electrons and ions. Cross-field drift and current model were turned on in the simulations. The densities at the core boundary of the computational domain are set as boundary conditions in the simulations, gas injections are not included in the model, and deuterium particles are assumed to recycle at the wall surfaces with an albedo of 0.99 with no poloidal dependence. The computational grid in the L-mode simulations extends 4.4 cm inside and 4.6 cm outside the separatrix at the LFS mid-plane (DIII-D shot number 160,299 at 2240 ms). The computational grid in the H-mode simulations represents the DIII-D shot number 160,997 at 4000 ms of plasma time. This latter configuration represents a far outboard point in the X-point sweep, such that both strike points are on top of the floor shelf of DIII-D. Further information about these H-mode plasmas can be found in McLean, et al. [6,14]. The H-mode plasma grid extends from 0.35 cm inside to 2.4 cm outside the separatrix at the LFS mid-plane of the plasma. In the L-mode simulations, one density level will be considered giving attached, high-recycling conditions at $n_{\text{e,SP-LFS-MP}} \sim 1.55e19 \text{ m}^{-3}$, determined at the LFS divertor plate in both FWD- and REV-B conditions. This density level is consistent with experimental estimates of $n_{\text{e,SP-LFS-MP}}$ in attached LFS conditions at the LFS plate (DIII-D #160300 FWD-B, DIII-D #160324 REV-B). These experimental estimates are obtained by shifting the main plasma Thomson Scattering profiles of electron density, $n_e$, and temperature, $T_e$, such that the separatrix temperature agrees with the UEDGE prediction of about 40 eV. This is a power balance type method to determine the separatrix location, the power balance here being calculated by UEDGE. In the H-mode simulations, one density level will be investigated, $n_{\text{e,SP-LFS-MP}} \sim 2.72e19 \text{ m}^{-3}$, corresponding to attached LFS plate conditions in the FWD-B$_1$ configuration and onset of detached LFS plate conditions in the REV-B$_1$ configuration. This value is somewhat higher than the values within the scatter of the experimental data, 2.1 – 2.5e19 m$^{-3}$, obtained when shifting the profiles radially such that the separatrix $T_e$ is consistent with the UEDGE predicted value of $\sim$80 eV (DIII-D #161005 (FWD-B$_1$) and 161146 (REV-B$_1$)). This study focuses on the radial and poloidal particle flux balances as well as on entrainment of $C^2+$ flow to the background deuterium flow in the divertor legs in these simulations. The detailed model validation studies will be reported in forthcoming publications.

3. Impact of $E \times B$ drifts on the radial and poloidal particle flows in the divertor

The net particle flows in the computational domain are always directed from source to sink, with or without cross-field drifts. The primary particle source is due to deuterium recycling and ionization distribution, and the primary sink is due to recombination at and in front of the targets (Fig. 1a). A smaller source in the global mass flow in the simulations is given by the core boundary ion flux required to maintain the requested core density. This is of the order of 4 – 10% of total ionization source in these simulations. A sink is also given by radial particle flow out of the main chamber boundary of the computational domain. This is of the order of less than a few percent of total ionization source in these H-mode simulations and 20 – 30% of the total ionization source in the L-mode simulations. These particle sources and sinks are connected by cross-field and parallel flows driven by pressure gradients, cross-field drifts, and radial anomalous transport, such that in steady state the divergence of the total particle flux is balanced by the source and sink terms (Fig. 1a, and b). Furthermore, the divertor ionization distribution is regulated by neutral deuterium conductance between the divertor legs (Fig. 1a). This conductance is presumably underestimated in the present UEDGE simulations, since neutral transport in the simulations is calculated only within the plasma grid, therefore, neglecting transport of neutrals in the far private flux region (PFR). The impact of neutral conductance of the PFR on the LFS-HFS ionization asymmetry will be investigated in forthcoming studies.

UEDGE simulations indicate that, in L-mode plasmas, in both FWD-B$_1$ and REV-B$_1$ configurations, the deuterium particles flow poloidally primarily towards the nearest divertor plate in the divertor chamber below the ionization front (Figs. 2a, and d). The poloidal $E \times B$ drifts drive particle flow from the LFS to HFS in the PFR in the FWD-B$_1$ configuration and from HFS to LFS in the REV-B$_1$ configuration (Figs. 2b, and e). The simulations indicate that in L-mode conditions, the poloidal $E \times B$ flow away from the LFS target in the PFR in FWD-B$_1$ in front of the target is not, however, strong enough to overcome the ionization driven flow towards the plate (Figs. 2a, and b). Similarly in the REV-B$_1$, the poloidal $E \times B$ flow in the HFS divertor leg away from the target is not strong enough to overcome the ionization driven flow towards the HFS target (Figs. 2d, and e). Just below the X-point in PFR it can be seen that the total poloidal particle flow is dominated by the $E \times B$ flow component. In the FWD-B$_1$ configuration, this $E \times B$ flux from LFS to HFS has a magnitude of about 9% of the total LFS divertor leg ionization source, and in the REV-B$_1$ configuration the flux from HFS to LFS has a magnitude of about 5% of the LFS ionization source.

In attached conditions in the LFS divertor, the local ionization source in front of the targets and the sheath sink drive parallel to the field deuterium flow velocities of the order of a 20 – 40 km/s, corresponding to Mach numbers (ratio of parallel-B deuterium ion velocity to local deuterium ion sound speed) of about
0.5 – 1.0. These provide poloidal flow components of the order of 800 – 1500 m/s in both FWD-B\textsubscript{T} and REV-B\textsubscript{T} configurations. The predicted poloidal E × B velocities, when working against the ionization driven flow, are at most half of these ionization driven velocities in front of the targets.

In the radial direction, the particle flows are dominated by drift-driven components. In the vicinity of the strike point, the radial E × B flow velocities are predicted to be of the order of 100 – 200 m/s. The characteristic diffusive velocities are given by the ratio of cross-field diffusivity, 0.5 – 1 m²/s, to typical density scale lengths, 1 – 2 cm, at the target: 25 – 100 m/s. In FWD-B\textsubscript{T} configuration, the radial particle flows are primarily directed from the common SOL towards the private flux region (PFR) in the LFS divertor and from the PFR to common SOL in the HFS divertor. The associated particle fluxes give density profile shifts in the divertor, consistent with previously observed divertor profile shifts with field reversal experiments at DIII-D [6,7].

Unlike in the L-mode simulations, in H-mode simulations the poloidal particle fluxes in the divertor in the vicinity of the separatrix are dominated by poloidal E × B drift contributions, as can be observed by comparing the total and E × B flux figures (Figs. 3a, b, d, and e). Whereas in the L-mode simulations the poloidal E × B drift was about one half of the poloidal projection of the ionization driven particle flow, in these H-mode simulations the poloidal E × B drift can be locally up to a factor of three stronger than the ionization driven flow. In the SOL further away from the steep gradient region next to the separatrix, the poloidal flows are dominated by the standard pressure driven parallel flow. In these H-mode simulations, the PFR E × B flux from LFS to HFS in the FWD-B\textsubscript{T} configurations has a magnitude of 18% of the total LFS ionization source. The PFR E × B flux from HFS to LFS in the REV-B\textsubscript{T} configurations has a magnitude of 10% of the total LFS ionization source. Therefore, in these H-mode simulations, the relative impact of the poloidal E × B flux in the PFR on the divertor particle balance is about a factor of 2 stronger than in the investigated L-mode simulations. Similar to the L-mode simulations, the radial particle fluxes in the vicinity of the separatrix are dominated by radial E × B drifts in these H-mode simulations.

**4. Predictions of entrainment of C\textsuperscript{2+} to the background deuterium ion flow**

UEDGE simulations indicate that in the simulated conditions in L- and H-mode plasmas, the toroidal C\textsuperscript{2+}-flow is well entrained by the background deuterium flow in the region where the CIII (465 nm) emission is experimentally dominant (Figs. 4, and 5). In the CII emission region, the C\textsuperscript{2+} ions are predicted to flow in the same direction in the divertor as the deuterium ions (deuterons), and the absolute velocity of C\textsuperscript{2+} is predicted to be within 30 – 40% of the deuterion velocity (Figs. 4, and 5). The CIII 465 nm emission is localized to plasma regions of $T_e \sim 8 – 15$ eV This region occurs just at and above the deuterium ionization region. The peak parallel-B flow velocities are obtained in this region in the simulations (Figs. 4, and 5). Due to the steeper temperature
gradients in H-mode plasmas, the 2D distribution of CIII emission in the divertor leg is significantly narrower than in L-mode plasmas (Figs. 4, and 5). The primary parallel-B force components impacting the C^{2+} flow along the field line are frictional coupling to the background deuterium flow and ion temperature gradient force [15]. Investigations of the force balance in the model indicates that within the plasma regions in the model where the dominant CIII emission occurs, the frictional coupling of C^{2+} ions to the background deuterium ions balances the ion temperature gradient force when the C^{2+} ions are about 10 – 30% slower than the background plasma deuterium ions.

The toroidal projection of the drift flows due to \( E \times B \) and diamagnetic drifts, \( \sim 10 – 100 \text{ m/s} \), are less than 1% of the toroidal projection of the parallel flows, \( \sim 10 – 50 \text{ km/s} \), along the field lines, and, therefore, the direct impact of cross field drifts on the CIS measurements, observing the plasma tangentially, is unlikely to be distinguishable. Therefore, \( E \times B \) and diamagnetic drifts flows are unlikely to be directly measurable with the CIS diagnostic. However, the non-divergence free parts of these drifts change the radial and parallel plasma pressure profiles in the divertor leg, which will lead to parallel to the magnetic field return flows, such as Pfirsch-Schlüter flows. These flows are measurable with tangentially viewing systems.

The toroidal component of the C^{2+} flow in the divertor is predicted to reverse in each divertor leg when the field direction is reversed. This follows from the fact that the toroidal direction corresponding to the parallel-B flow towards the nearest targets reverses with toroidal field reversal.

In the L-mode simulations, net poloidal particle transport is primarily in the same direction as the poloidal project of the parallel-B flow interpreted from the toroidal flow profile (Figs. 2, and 4). This is caused by the pressure driven parallel-B flow dominating over the poloidal \( E \times B \) flows in the divertor leg. The poloidal \( E \times B \) flows are expected to be of the order of 50% of the recycling driven flows providing either enhancement or reduction of the total poloidal flow, depending on the field direction (Fig. 2). In the H-mode, on the other hand, the strong poloidal \( E \times B \) drifts can lead locally to net poloidal particle transport that is in opposite direction than the poloidal projection of the parallel flux interpreted from the toroidal flow profile (Figs. 3, and 5).
5. Conclusions

In L-mode plasmas, the edge fluid code UEDGE predicts that ionization driven flow components dominate poloidal particle transport over poloidal $\mathbf{E} \times \mathbf{B}$ driven components, whereas $\mathbf{E} \times \mathbf{B}$ driven radial flows dominate over diffusion driven flows in the vicinity of the separatrix. In H-mode plasmas, UEDGE predicts that both poloidal and radial flows are dominated by $\mathbf{E} \times \mathbf{B}$ drifts over the ionization and diffusion driven flows in the strong gradient region near the separatrix. In both L- and H-mode plasmas UEDGE predicts that $C^2+$ is entrained to a parallel velocity within 30% to the background deuterium flow in the region where the dominant CIII 465 nm emission occurs. Simulations indicate that in both L- and H-mode plasmas, the toroidal flow component measured by a tangentially viewing system in the divertor is dominated by parallel-$\mathbf{B}$ flow. The toroidal component of the cross field drift flows is about 1% of the toroidal component of the flow parallel to the field line, and therefore challenging to measure. Toroidal divertor flow is predicted to reverse when the magnetic field direction is reversed. This is caused by the fact that parallel-$\mathbf{B}$ flow towards the nearest divertor plate, driven by the sheath-sink action, corresponds to the opposite toroidal direction in opposite toroidal field configurations. Whereas in the L-mode the poloidal projection of the parallel-$\mathbf{B}$ flow estimated from the toroidal flow profile is in the same direction as the net poloidal particle transport, in H-mode the net poloidal particle transport can be locally in opposite direction than the poloidal component of the parallel-$\mathbf{B}$ plasma flow, due to strong poloidal $\mathbf{E} \times \mathbf{B}$ flows.

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