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Multi-ion fluid simulation of tokamak edge plasmas including non-diffusive anomalous cross-field transport

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Abstract

The two-dimensional, multi-ion, fluid code UEDGE is used to simulate the sophisticated transport of impurities in the tokamak edge plasma. The UEDGE model incorporates the effects of non-diffusive intermittent cross-field transport by using anomalous convective velocities whose spatial profile is adjusted for each ion charge state to match available experimental data. The simulations of low-confinement (L-mode) shots indicate that: (i) anomalous convective transport dominates in the far scrape-off layer; (ii) different impurity charge states have different magnitudes and signs in their convective velocities; and (iii) chamber wall sputtering is an important source of impurities.

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1. Introduction

Recent experimental and theoretical studies have shown that fast intermittent cross-field plasma transport can play the dominant role in the scrape-off layer (SOL) of many tokamaks (see Refs. [1,2] and literature cited therein). This kind of transport is associated with coherent structures (blobs) that separate from core plasma and propagate outward, i.e., the transport is convective rather than diffusive. The resulting convective plasma flux to the chamber wall enhances the recycling of neutral particles in the main chamber and increases impurity production via physical, chemical, and self- sputtering. Moreover, it is thought that other coherent structures (holes) corresponding to density depressions could propagate into the core plasma. The intermittent non-diffusive transport associated with these holes could enhance impurity ion transport and cause significant core plasma contamination.

The edge plasma physics code UEDGE [3] has been used to simulate impurity transport including anomalous intermittent cross-field convection (AICFC) for impurity and main plasma ions [4,5]. This paper presents results on further validation of the AICFC model against experimental data on carbon impurity profiles.

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2. The AICFC model

In the AICFC model incorporated into the UEDGE code, the 2D profile of convective cross-field velocity has the following form: $V_{\rm conv}(\psi_{\rm N},\theta,Z) = V_{\rm BPconv}(\psi_{\rm N},\theta)\,A_{\rm s}(Z)$. Here the profile is given in magnetic flux surface coordinates ($\psi_{\rm N}$ and θ), where $\psi_{\rm N}$ is the normalized poloidal magnetic flux, θ is viewed as the poloidal coordinate, $V_{\rm BPconv}(\psi_{\rm N},\theta)$ is the AICFC velocity of the dominant background species, and the $A_{\rm s}(Z)$ is the relative amplitude factor for each charge state Z of ion species s. The amplitude factors vary in the range; $-1 \leqslant A_{\rm s}(Z) \leqslant +1$. For the deuterium background ions, $\rm s = D^+$, we have $A_{\rm s}(Z) \equiv 1$ and $V_{\rm conv} \equiv V_{\rm BPconv}$. The $V_{\rm BPconv}(\psi_{\rm N},\theta)$ profile has been discussed in Ref. [5]. The $V_{\rm BPconv}$ strongly increases with minor radius (i.e., with $\psi_{\rm N}$) and has maximum in θ–direction at the outer mid-plane.

The positive amplitude factors correspond to charge states of impurity ions that are convected toward the wall with non-diffusive transport dominated by plasma density blobs. By contrast, the negative amplitude factors correspond to the charge states of impurities which are dominantly entrained in inwardly moving plasma density holes. In general, the amplitude factors are independent parameters. The set of values of amplitude factors for all charge state of the impurity species studied here (i.e., of carbon C^{Z+}, $Z = 1–6$, s = C) is assumed to increase monotonically with increasing Z, i.e., $A_{\rm C}(C^{Z+}) > A_{\rm C}(C^{(Z-1)+})$. The highest impurity charge states are thought to behave more like the background plasma ions, so in the paper, we use $A_{\rm C}(6) = 1$ for the fully stripped carbon ion. For convenience of discussion, the set of amplitude factors is characterized by the single parameter $\eta_{\rm CCC} = A_{\rm C}(1) + A_{\rm C}(2) + A_{\rm C}(3)$; examples are shown in Fig. 1. In numerous UEDGE runs, we scan over different sets of amplitude factors to find those sets which give the best fits to available experimental data.

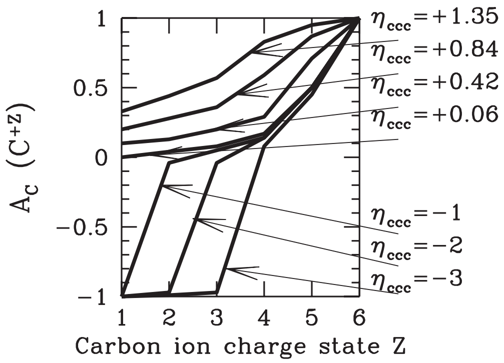

Fig. 1. Relative amplitude factors $A_{\rm C}(Z)$ of carbon ion charge states C^{Z+}.

3. Results

In Ref. [4] we have analyzed the Simple-As-Possible-Plasma (SAPP) series of low-power L-mode shots on DIII-D and presented results of multi-ion UEDGE modeling for the lowest density shots (Nos. 105500-10, $\langle n_{\rm e}\rangle \approx 2.4\times10^{13}\ {\rm cm}^{-3}$) in this series. Here, we present the results obtained for the higher density SAPP shots (Nos. 105517-19, $\langle n_{\rm e}\rangle \approx 4.5\times10^{13}{\rm cm}^{-3}$) and focus on matching the impurity profile data. We use impurity data mainly from neutral-beam charge-exchange recombination (NB CER), filterscopes (FS), and a visible multi-chord divertor spectrometer (MDS). The arrangement of these diagnostics is shown in Fig. 2.

Based on plasma profiles calculated by UEDGE, the expected signals seen by the FS, MDS, and CER diagnostics are calculated from known view-cone geometries [6]. We use atomic physics data from ADAS. The effect of visible light reflections from the chamber interior walls on FS and MDS signals is estimated using the 3D ray-tracing routine [7,8] which incorporates the measured data [7] on visible light reflectance from the DIII-D carbon tiles.

The UEDGE solutions for shot 105517 are obtained with constant $D_\perp = 0.15\,{\rm m}^2/{\rm s}$, $\chi_\perp = 0.8\,{\rm m}^2/{\rm s}$ and with the SOL averaged values of convective velocity at the wall, $\langle V_{\rm BPconv}\rangle \approx 90\,{\rm m/s}$, and at the separatrix, $\langle V_{\rm BPconv}\rangle \approx 2\,{\rm m/s}$, by matching the following: particle flux balance at the core interface consistent with the NBI fueling rate, radial profiles of $T_{\rm e}$ and $n_{\rm e}$ measured in the SOL, mid-

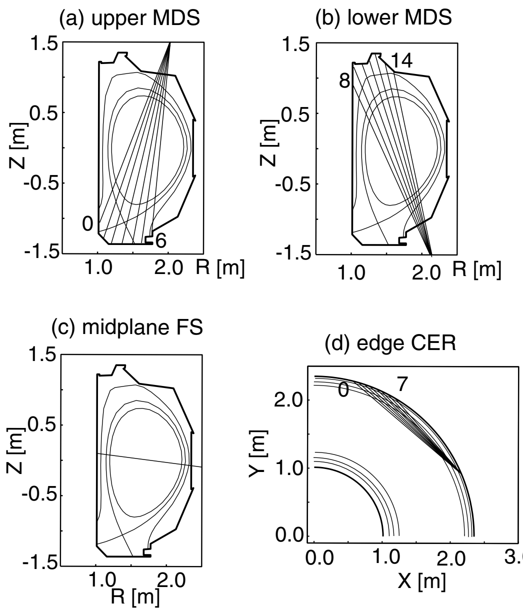

Fig. 2. Arrangement of impurity-relevant diagnostics in DIII-D.