

SIMULATION OF PLASMA FLOW IN THE DIII-D TOKAMAK*

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1. Introduction

The importance of the parallel flow of primary and impurity ions in the Scrape-Off layer (SOL) of divertor tokamaks has been recognized recently because impurity accumulation on the closed flux surfaces is determined in part by their parallel flow in the SOL. In turn, the parallel transport of the impurity ions is determined in part by drag from the primary ion flow. Measurement of flow in the DIII-D tokamak has begun recently ^{1, 2}. We describe initial results of modeling plasma ion flow using the 2-D code UEDGE ³ in this paper. We assume the impurity (carbon) neutral arises from chemical and physical sputtering from the walls surrounding the DIII-D plasma and follow all six charge states. We make detailed comparison with a multitude of SOL plasma diagnostics, including the flow measurement, to verify the UEDGE physics model. We begin the paper with a brief description of the plasma and neutral models in the UEDGE code in Section 2. We then present initial results of flow simulations and compare them with experimental measurement in Section 3. We conclude with a discussion of the dominant physics processes identified in the modeling in Section 4.

2. Description of model

The UEDGE code is used to simulate the plasma in a region starting slightly inside the magnetic separatrix (typically the 96% poloidal flux surface) and extending radially outward to the poloidal flux surface which intersects a limiter. Plasma transport equations for particle, energy, and momentum, as defined by Braginskii ⁴, are solved in 2-D over this domain. Parallel transport is assumed determined by classical processes, and radial (perpendicular) transport is assumed anomalous. The code considers several species, including electron, and multiple ion species. Hydrogen (or deuterium) is considered the dominant species, and impurities are included by solving a parallel force balance equation for each charge state. A Navier-Stokes momentum equation is solved along the magnetic field, B , for the hydrogenic neutral species with diffusion perpendicular to B . Both charge exchange and elastic scattering are included. A diffusive model is included for impurity neutrals, with the diffusion coefficient evaluated from elastic scattering collision rates. Ionization, recombination and associated radiation energy

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losses are included using various atomic physics databases. Boundary conditions at the innermost flux surface are typically specified by constant density (experimentally determined), and fixed power, with equal power flowing in the electron and ion channels. Boundary conditions at the outermost flux surface is specified as zero flux for the particle and energy equations. An effective wall pumping term is specified by assuming an albedo (typically 0.95) for the neutral flux to the outer flux surface. Finally, sheath boundary conditions are used at the divertor plates.

3. Comparison with experimental measurements

Parallel flows in the SOL are determined by two diagnostics in DIII-D. The primary ion flow is determined with a retractable Mach probe². Impurity ion (and neutral deuterium) flows are spectroscopically determined using toroidally viewing optics¹. Both measurements are limited to the divertor region, typically from the position of the X-point to the divertor plates, and are generally restricted to the outer divertor leg.

The dominant adjustable variables for UEDGE simulation are anomalous radial diffusivities for particles and electron and ion thermal transport. These are determined by matching the radial profile of electron density and temperature measured by Thomson scattering near the outer midplane. Typically, these profiles can be well matched to experiment with spatially constant diffusivity⁵. Specification of thermal diffusivities, coupled with the power boundary condition at the innermost flux surface determines the gradient and amplitude of the upstream temperatures. Specification of the particle diffusivity determines the upstream density gradient, and thus the particle flux across the separatrix. This particle flux is important for simulation of the primary ion parallel flow velocities in the SOL. The simulation results described in this paper are restricted to ELMing H-mode plasmas, and the diffusivities consistent with experimental profiles are $D_{\perp}=0.1 \text{ m}^2/\text{s}$, $\chi_i=\chi_e=0.2 \text{ m}^2/\text{s}$. These diffusivities are typical of ELMing H-mode plasmas, and obtain radial particle fluxes across the separatrix on the order of 1000 A (6×10^{21} particles/s).

In addition to the radial diffusivities, we must determine the character of ion recycling at the divertor plate, and impurity sources to accurately simulate the SOL plasma. Since the ion flux to the divertor plate is large, we assume the plate is saturated and all ions recycle as neutrals, i.e. the recycling coefficient is 1.0. We assume all carbon impurities arise from chemical and physical sputtering at three surfaces: the plate, and the outermost flux surface in the common flux and private flux regions. Two sputtering models are used. The first is a simple model which assumes the flux of neutral carbon leaving the plates/walls is proportional to the incident flux of hydrogen ions and neutrals. Separate sputtering coefficients are used for chemical and physical sputtering. The second model uses empirical fits to experimental sputtering

measurements obtained at the University of Toronto⁶ with a scale factor (about 0.5) to better match the measured total radiated power.

We obtain simulations of the 2-D structure of primary and impurity ion flows using the assumptions outlined above. These flows can be compared to experiment by taking cuts across the 2-D structure at the locations of the measurements. Typical results for both the primary and impurity flows are shown in Figure 1. The primary ion flow is measured along a vertical line which goes from the divertor floor to about 15 cm above the floor, passing outside the outer strike point. The impurity flow is measured approximately half way between the floor and the X-point. Two flow rates are obtained spectroscopically, with the radial location determined by Zeeman splitting of the emission line.

These results indicate the physics model used in UEDGE, together with the assumptions required for the input parameters, are sufficient to accurately model the flow of both the primary and impurity ion species for the conditions considered in these simulations. The simulations shown here are for plasmas which are attached at the outer divertor. Simulations frequently obtain regions in which the primary ion flow is away from the divertor plate (negative in Figure 1) under these conditions. These regions of reversed flow are also seen experimentally. The C^+ flow is reversed near the separatrix, as seen in Figure 1b. Simulations of detached plasmas are also in reasonable agreement with measurement, and typically do not obtain reversed flow in the primary ions. Reversed flow of impurity ions is almost always present in some region of the plasma. The origin of this reversed carbon flow is discussed in the next section.

4. Discussion and conclusions

The flow pattern of the primary ions is determined by a combination of the particle flux across the separatrix and the amplitude of the ion recycling at the divertor plate. The flux across the separatrix is determined, in turn, by the strength of ionization sources on the closed field lines. Neutrals on closed flux surfaces originate from two sources; energetic neutrals introduced by neutral beam heating, and “cold” neutrals obtained by penetration of recycling neutrals to the

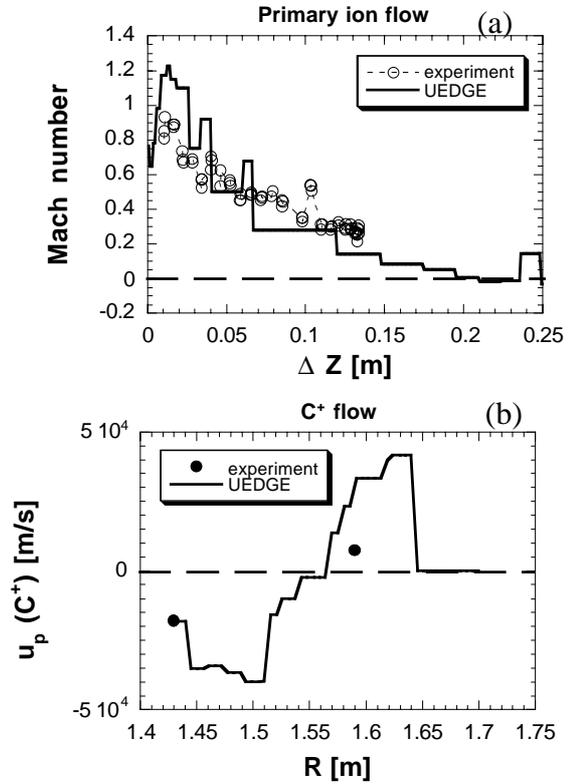


Figure 1 Comparison of simulated and measured flows for the primary ions (a) and singly ionized carbon (b) in DIII-D.

closed surfaces. As stated earlier, typical particle fluxes across the separatrix are on the order of kiloAmperes, much larger than the particle flux introduced by neutral beams (≤ 100 Amp). We conclude that the ion flux across the separatrix, and thus the parallel flow pattern of primary ions, is determined by the nature of divertor recycling, and thus by the divertor geometry and details of neutral pumping. Reversed flow of the primary ions is obtained when the local ionization source from recycled neutrals is large enough to force ions away from the plate.

The flow pattern of impurity ions, on the other hand, is determined by the source distribution and the parallel forces exerted on these ions. These forces are found to be dominated by drag with the primary ion species, and the force obtained by the gradient of the ion temperature.

The ∇T_i force is typically directed away from the divertor plates since the plates are in a region with low temperatures. The nature of these flows can be examined by considering the path by which impurity ions reach the closed flux surfaces, as shown in Figure 2. The calculated radial flux of impurity ions indicate the core is fueled (negative radial flux) by C^{4+} and C^{6+} ions flowing across the separatrix 0.5 m above the X-point on the inside.

Impurity ion losses are dominated by C^{6+} flow

near the outer midplane. The impurity ions accumulate at the point from which they flow to the core because there is force balance between the drag and ∇T_i forces at that point. Impurities coming from the divertor region are forced to the null force point from below, and prevented from flowing above the null point by drag. This balance forces a density accumulation at the null point, from which the impurities diffuse radially into the core.

5. References

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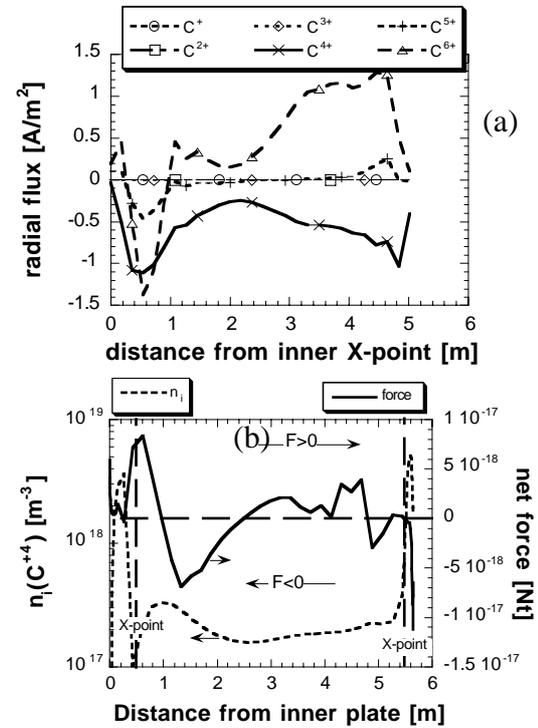


Figure 2 Simulation of the radial particle flux of impurity ions across the separatrix (a) and the poloidal variation of the parallel force on C^{4+} ions and its resulting density (b).