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Analysis of Particle Flow in the DIII-D SOL and Divertor[1]

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1. Introduction

The scrape-off layer (SOL) and divertor plasma in the DIII-D tokamak has been modeled using the 2-D fluid code UEDGE[1][2][3]. The resulting simulated plasmas are compared in detail with the numerous diagnostics available on the device. Good agreement is obtained between the experimental measurements and the simulations when relatively small values of the assumed anomalous perpendicular transport coefficients are used. We use a purely diffusive model for perpendicular transport, with transport coefficients which are constant in space. The value of each of these transport coefficients is varied in the simulation to match the measured upstream density and temperature profiles. The resulting plasma parameters are then compared with all other diagnostics which measure parameters at various poloidal locations in the SOL.

One of the difficulties in this procedure arises from experimental uncertainty in determining the total particle flux from the closed flux surfaces into the SOL. One can gain confidence that the thermal diffusivities which are used to obtain consistency of the upstream temperature profiles between simulation and experiment are also consistent with the experimentally inferred power to the SOL, i.e., not only do the assumed diffusivities produce consistency in the upstream radial profile of the temperature, but the power across the separatrix, determined from a diffusive model and hence dependent on the temperature gradients, is also consistent with the power into the SOL determined experimentally. Analogously, one could test the particle diffusivity used to simulate the density profiles by comparing with the total particle flux into the SOL. Unfortunately, the particle flux is not well determined experimentally. Furthermore, the simulated density profile is determined by at least three parameters; the particle diffusivity, and the recycling coefficients for both neutrals and ions at the walls of the vessel (including the divertor plates). None of these parameters are well known. We discuss the effect of the particle flux and recycling in this paper. We begin by briefly discussing the expected particle flow channels in the plasma, and the experimental estimates of the particle flux across the separatrix in Section 2. We compare the simulations of a specific DIII-D discharge with experimental data in Section 3. We finish with discussion in Section 4.

2. Experimental estimate of particle flux

There are at least three sources of particles inside the last closed flux surface of a tokamak plasma: (1) high energy neutrals introduced by neutral beam heating; (2) neutral gas injected outside the SOL plasma to control the plasma density; and (3) neutral gas produced by recycling of ions impinging on the divertor plates. (We

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speak here only of the primary gas species, not impurity species.) The ionization source rate of energetic neutrals from the heating systems is typically a few hundred amps ($5–20 \times 10^{20}$ /s). The second source of particles, injected cold gas, is usually turned off in the H-mode plasma operation considered here. The final particle source, recycling gas, is the major source of uncertainty in determining the particle flux into the SOL. A small fraction (typically no more than a few percent) of the neutral gas which originates from recycling of the ions impinging on the divertor plates will be ionized inside the last closed flux surface, and hence be a source of particles flowing from the core into the SOL. Thus the core ionization source from recycling depends not only on the recycling coefficient at the divertor, but also on the probability of a neutral penetrating to the core and hence on the detailed plasma parameters in the SOL. At steady state all ions created by ionization of neutrals inside the separatrix must flow into the SOL and be removed. Hence the particle flux into the SOL must be equal to the total ionization rate in the core plasma.

Experimentally one can estimate the total ionization rate from all sources by examining the behavior of the density at a plasma transition such as the L- to H-mode transition. Using temporally fixed values for all parameters except the density (particle confinement time, divertor recycling coefficient, wall neutral particle albedo, and penetration probability for neutral gas sources into the core plasma), the temporal behavior of the total number of particles inside the separatrix is given by[4]

$$N_{core}(t) = N_{core}(\infty) + \left[N_{core}(0) - N_{core}(\infty)\right] \exp\left\{\frac{-t}{\tau_p^*}\right\} \quad (1)$$

Where τ_p^* is the core confinement time corrected to include sources from divertor recycling, and the equilibrium particle content, $N_{core}(\infty)$, is determined by the total ionization rate in the core plasma. One can estimate the total ionization source inside the separatrix by fitting the temporal behavior of the particle content observed at the L- to H-mode transition to Equation 1. Typically we find the experimental particle content, obtained from Thomson scattering data with the assumption of constant density on flux surfaces inside the separatrix, is described well by Equation 1 throughout the period from the transition until density equilibrium has been achieved after the onset of Edge Localized Mode (ELM) activity, suggesting that the assumptions inherent in deriving this equation are reasonable. The total ionization source inferred by this process is a few kA, or a few times 10^{22}/s, approximately an order of magnitude higher than expected from neutral beam sources.

3. Comparison of simulation and experiment

We explore the nature of recycling physics by simulation of a specific discharge on the DIII-D tokamak; a 1.6 MA lower single null configuration with neutral beam heating of approximately 6 MW. Inversion of the radiated power profile obtained from two bolometer cameras indicate 1 MW of power is radiated on the closed flux surfaces, and an additional 1.9 MW is radiated in the SOL and divertor regions. Application of the analysis described in the previous section indicates an ionization rate inside the separatrix of about 2.7 kA (1.7×10^{22}/s), decreasing rapidly as one moves inward from the separatrix. The simulation is done over a radial region between a normalized poloidal flux of 0.98 and 1.125. We assume a fixed power and density at the inner flux surface, and adjust the thermal diffusivities to match the electron temperature and density profile measured by the Thomson system, and the ion temperature profile measured by Charge Exchange Recombination. We assume the ion recycling coefficient at the divertor plate is unity except in the region which corresponds to the entrance to the pumping chamber under the outer ring of the DIII-D divertor, where we assume that only 90% of the ions are recycled as neutrals. Finally, we assume a neutral particle albedo of 0.95 on both the outer wall and the private flux wall which provides particle removal. Upon matching the upstream density and temperature profiles, the consistency between the simulation and experiment is determined by comparison of the power deposited in the divertor, measured with an IRTV system; H_α emission measured with a 7 channel array which views the divertor from above the machine; radiation profiles measured with two bolometer camera arrays; and the ion saturation current at the plate measured with a Langmuir probe array.

We consider two simulations which differ in the value of the particle diffusivity. The first case has a diffusivity of $D_\perp = 0.15\ m^2/s$ with a corresponding particle flux across the separatrix of 2.2 kA, and obtains the best overall fit to the SOL data. The upstream density and temperature profiles are well matched to that obtained experimentally. The simulated peak power at the outer strike point on the divertor floor is within about 10% of that obtained from the IRTV, although the simulated power profile is somewhat narrower than measured. The simulated peak power at the inner strike point is about a factor of 4 higher than measured, and is dominated by recombination of the large ion current. The simulated ion current to the inner strike point is indeed larger than measured with the Langmuir probe array. This discrepancy suggests significant departure in the model of recycling from the behavior of the experiment. We compare the simulated H_α photo diode signals with experimental results in Figure 1. The simulated signal on the channels nearest the strike points is about 70% high on the outside, and a factor of 2 high on the inside. The simulated signals on the three channels which view the private flux region are a factor of 2 to 5 lower than the experiment. These results suggest that the mean free path for recycled neutrals is too short in the simulation,

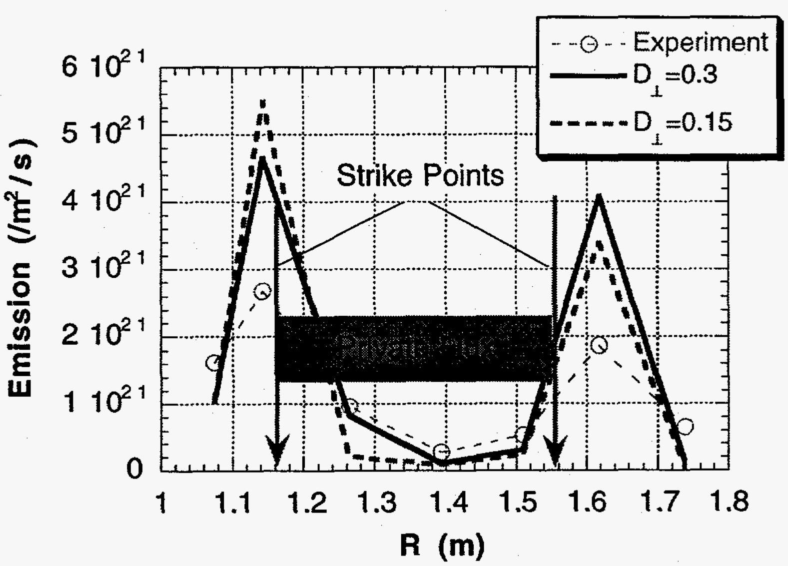

Figure 1: Comparison of simulated and measured H_α emission measured with a photo diode array viewing the divertor from above. The particle diffusivity is given in units of m^2/s.

leading to a larger particle flux amplification from the mid plane to the plate, and low neutral densities in the private flux region.

The simulated H_α signals for a second case with a particle diffusivity of 0.3 m^2/s and resulting particle flux of 3.9 kA across the separatrix is also shown in Figure 1. The large increase in the particle flux increases the convective power across the separatrix to the point that it dominates the power flow. Since the simulation is done with a fixed power, the upstream electron temperature at the separatrix has dropped from about 160 eV to about 120 eV. The combination of lower electron temperature and increased particle flow to the SOL has resulted in a significant drop in the electron temperature at the plate, particularly the inner plate. As a consequence the location of the electron temperature at which ionization of the recycling neutrals occurs (approximately the 5 eV contour) has moved a few centimeters off the inner plate for the high diffusivity case. This in turn permits penetration of the recycling neutrals into the private flux region and increases the emission seen on the photo diodes viewing this region, as seen in Figure 1. Likewise, there is better penetration of recycled gas to the SOL side of the inner divertor region, producing a cooler SOL, and in general a narrower SOL profile. All of these effects depend critically on the electron temperature at the inner plate being very low, less than 1 eV in the simulation. In contrast, interpretation of the Langmuir probe data indicate the plate temperature is 5–10 eV.

4. Discussion

Design of future divertor configurations rely upon control of recycled neutral particles, hence it is important to better model this phenomenon. The results presented here suggest we can better model the neutral particle recycling at the divertor plates, as measured by the H_α emission, with simulations which obtain plate electron temperatures below 1 eV. Such low temperatures provide a long ionization mean free path region for recycled neutrals, permitting neutral penetration around the inner strike point, and more accurate simulation of the measured emission is obtained. The existence of such low temperature regions is inconsistent with Langmuir probe data which indicate plate temperatures of 5–10 eV. Thus it would appear the Langmuir probe and H_α diagnostics are in conflict. The neutral model used in the UEDGE simulations discussed here was a simple diffusive fluid model which did not account for momentum removal via neutral interactions. As indicated here, this model overestimates the ion current to the plates, and hence overestimates recycled neutral densities. This simple model has now been upgraded to include neutral momentum effects, and is expected to permit more accurate modeling of the recycling phenomena. Validation of this improved model will require resolution of the apparent diagnostic conflict.

References

[1] Porter, G. D., et.al., Innsbruck EPS meeting

[2] Porter, G. D., et.al., Varenna PET meeting

[3]Rognlien, T. , et.al., Monterey PSI meeting

[4] This work was originally done by G. Jackson, private communication, General Atomics.