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BOUNDARY MASS TRANSPORT RESEARCH ON DIII–D

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A.W. LEONARD FOR
THE DIII–D BOUNDARY RESEARCH GROUP

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GENERAL ATOMICS

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ABSTRACT

The DIII-D boundary five-year research plan is focused on understanding the physics of mass transport in the scrape-off layer (SOL) and divertor and developing techniques to affect and control the flow of particles around the boundary of divertor tokamaks. Recent experiments have measured the 2-D recycling and fueling profile with camera images and interpretation with fluid and neutrals codes. Fueling of the pedestal in low density L-mode and H-mode is found to be dominant near the X-point. The radial transport of particles due to bursty transport and edge localized modes (ELMs) have been measured in the SOL to the outer midplane wall. Divertor pumping dependence on magnetic configuration has been investigated. Impurity transport experiments included injection of Carbon-13 impurity and follow carbon transport and redeposition near the inner strike point. For impurity generation studies CI line shapes have been measured to determine the relative importance of chemical versus physical sputtering.

1. INTRODUCTION

A long-term goal of the DIII-D boundary research program is to measure and develop predictive capability for complete particle balance and 2D mass transport in the boundary of a divertor tokamak. Mass transport has important implications for several key issues for DT burning plasma devices. Transport of deuterium from the core plasma results in ion flux to the divertor surface and components throughout the vessel. The ion surface flux in turn produces recycled neutrals which fuel the core plasma, particularly the edge pedestal. We find in low density DIII-D plasmas the pedestal fueling is dominated by neutral recycling from the inboard divertor region. In addition to refueling, the ion flux to surfaces can sputter impurities into the plasma. For carbon surfaces the resulting carbon impurity is eventually redeposited where it can trap significant amounts of deuterium, or tritium, a critical issue for reactor plasmas. The carbon redeposition in DIII-D L-mode plasmas is found localized to the inboard divertor, and driven there by a strong scrape-off-layer (SOL) deuterium flow.

The mass transport research program on DIII-D consists of not only measuring and characterizing the transport of deuterium and the main impurity carbon, but also studying the underlying mechanisms driving the transport and impurity generation. In Sec. I the study of deuterium transport is described. This includes analysis of the 2D recycling profile for the neutral fueling distribution, ion fluxes to the divertor and main chamber walls, as well as particle fluxes to the divertor pumps. The radial ion transport due to SOL fluctuations and edge localized modes (ELMS) are investigated with high time resolution diagnostic systems. Section 2 describes recent efforts to characterize carbon impurity generation, flow and subsequent redeposition. Finally Sec. III discusses the results and implications for future work.

2. DEUTERIUM TRANSPORT

The transport of deuterium starts with fueling of the core plasma by neutral particles. The bulk of ionization in the main plasma occurs within the edge pedestal just inside the separatrix, and is due to neutrals recycling from ion flux to the divertor and other plasma facing surfaces. Measuring the poloidal distribution of the neutral ionization inside the separatrix is important because it is thought to play an important role in determining characteristics of the edge H-mode pedestal, and in turn, can significantly affect the core plasma performance [1-2]. In addition, the neutral ionization profile can provide valuable information about the ion flux to the divertor and main chamber surfaces which is critical for helium pumping and impurity generation issues.

On DIII-D we measure the neutral ionization rate inside the separatrix by a combination of spectroscopic imaging and plasma modeling [3]. Separate tangential camera views of the lower divertor, upper divertor and main chamber capture the 2D profile of D_{α} emission. Interpretation of the D_{α} emission profile begins by constructing a model of the pedestal, SOL and divertor plasma using the fluid code UEDGE constrained by a number of experimental measurements. For the plasma model it is very important to include plasma $E \times B$ drifts in order to obtain the observed asymmetries between the inboard and outboard divertors [4]. The profile of divertor ion flux is then launched as neutrals from the surface into the background plasma and then followed with the neutral Monte Carlo code DEGAS. This process allows us to fit the poloidal profile of the D_{α} emission peaked outside the separatrixand, through the neutral processes contained in the DEGAS code, calculate the neutral density and ionization inside the separatrix.

Carrying out this procedure for a low density L-mode discharge in DIII-D, the poloidal profile of the neutral flux across the separatrix, plotted in Fig. 1, is seen to peak near the divertor. Appropriately integrating the profile also reveals that ~80% of the core fueling occurs in the divertor region, and most of this ionization occurs on the inboard side above the x-point. Low to moderate density H-mode exhibits a similar profile. The ionization profile arises due to two characteristics of the SOL and divertor plasma, a large ion flux to the divertor target and a cold detached inner divertor leg. The first of these, the large divertor ion flux can be seen in the D_{α} emission profile peaked in the divertor. The second of these, a cold inner divertor is confirmed by a profile of D_{α} and CIII rising from the inboard strike point to the X-point region. The cold inner divertor provides a longer ionization mean free path, allowing neutrals to penetrate inside the separatrix. Uncertainties in the modeled poloidal ionization profile also arise from uncertainties in these two factors. The measurement of the poloidal profile of D_{α} emission is assumed to be toroidally symmetric. If the emission is significantly higher at a different toroidal location than measured (due to limiters, etc.) then the neutral fueling profile could also be different. A large radial particle flux at the outer midplane, inferred from other measurements, must also be reconciled with these measurements [5]. Finally the neutral penetration above the inboard divertor depends sensitively on the plasma conditions there, though we have limited diagnostics to constrain the plasma model in that location. Radial transport carries deuterium from the pedestal onto the open field lines of the SOL where both parallel and perpendicular transport determine the eventual ion flux to surfaces. While parallel transport is well understood, perpendicular ion transport is anomalous and can distribute significant ion flux to plasma facing surfaces throughout the vessel. During H-mode the radial transport is much less than during L-mode, but ELMs provide periodic bursts of short duration, intense radial particle transport. It has been estimated that ELMs provide ~25% of the particle transport across the separatrix in H-mode [6].

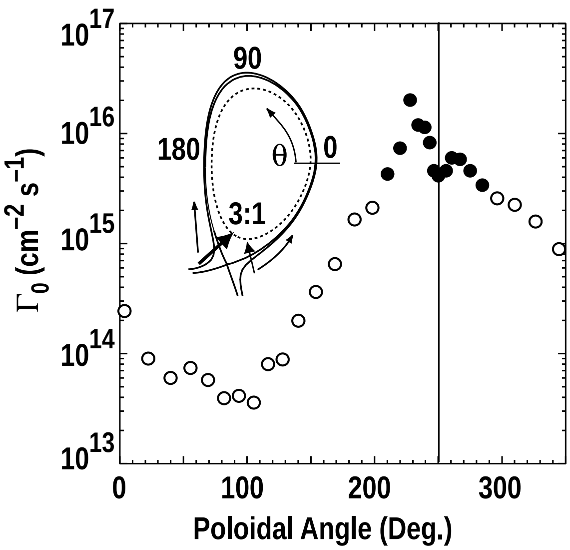

Fig. 1. The poloidal profile of the ionization source inside the separatrix as modeled by the neutral Monte Carlo code DEGAS. The source peaks in the divertor, particularly inboard just above the X-point. The colored arrows and data points define the divertor region.

In DIII-D radial transport processes are studied with insertable Langmuir probes, complemented with other fluctuation diagnostics [7,8]. The insertable probes are located at the outer midplane and in the lower divertor. They are capable of fast measurement of the electron density, temperature and the poloidal electric field, for determination of the turbulent heat and particle fluxes, both between ELMs and during ELMs. Figure 2 shows density profiles measured by the probe from the outer midplane separatrix to the wall. Notice in H-mode that during an ELM the density can rise to greater than the L-mode level. In the outer midplane SOL ~70% of the radial flux is carried by intermittent events that convect particles out towards the wall. These events are essentially filaments of higher density originating near the separatrix density gradient that propagate outward through $E \times B$ motion. Though qualitatively similar these events are of lower amplitude in H-mode than L-mode leading to a lower density SOL in H-mode. At low density the intermittent events dissipate and slow down as the propagate outward, while at higher density they travel all the way to the wall. Additional fluctuation measurements from beam emission spectroscopy and midplane D_α emission confirm the nature of intermittent transport events.

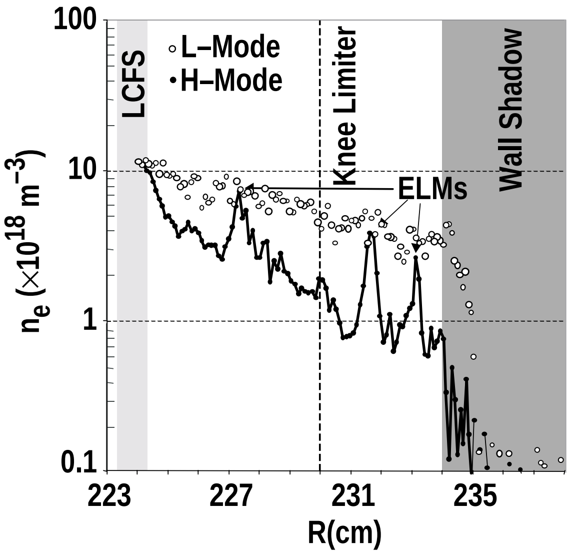

Fig. 2. Density profile at the outer midplane measured by the insertable Langmuir probe during L-mode and H-mode. Though both discharges have nearly equal separatrix density the L-mode density profile has a longer characteristic scale length with a much higher density at the outer midplane wall. In H-mode during an ELM the density can rise to a level greater than L-mode.

The ELM radial particle flux is contained in a series of high density filaments propagating outward at up to 500 m/s. At low density the ELM filament density dissipates only slightly as it travels all the way to the outer wall. The ELM also represents a significant fraction of the time averaged ion flux to the outer wall. At high density the ELM filaments propagate more slowly and dissipate more quickly, representing a smaller fraction of the outer wall ion flux.

The ELMs also affect impurity transport in the pedestal. Fast charge exchange recombination spectroscopy (CER) measurements reveal a significant expulsion of the carbon impurity from the pedestal [9]. The ELMs play a key role in determining the balance between SOL impurity transport and the level of core plasma impurity contamination.

Another important aspect of deuterium transport is divertor pumping for helium and density control. Density control is important in current experiments for studying advanced tokamak issues. To assess aspects of pumping in a double null configuration the particle flux to both the upper inboard and outboard divertor pumps was measured as the magnetic topology was varied [10]. The flux to the upper inner divertor pump is significantly reduced for a balanced double-null configuration compared to an upper single-null. While typically the outboard divertor flux is greater than the inboard, this asymmetry is particularly enhanced with the $B\times\nabla B$ drift direction toward the lower divertor. These results are consistent with two particle transport effects. First, the particle flux across the separatrix is dominated by flux to the low field side because of the greater area, steeper density gradients due to flux surface compression, higher fluctuation levels due to bad magnetic curvature and ELMs. Thus, the particle flux to the inboard divertor significantly decreases when it loses connection to low field side in a double-null configuration. The second effect arises from electric fields in the SOL due to radial temperature gradients. The $E \times B$ drift drives particle flux from the outboard toward the inner when the $B \times \nabla B$ drift is directed toward the divertor and in the opposite direction when the $B \times \nabla B$ drift is away from the divertor. These two effects must be accurately modeled for design and performance prediction for divertor pumping in future tokamaks.

3. CARBON TRANSPORT

With graphite coverage of the first wall, carbon is the dominant impurity in DIII-D. As such it is important to understand its generation and transport analysis of DIII-D discharges. It is also important for future tokamaks, where the issue of tritium retention due to codeposition of eroded carbon is a critical issue. To address the topic of carbon transport and deposition, $^{13}CH_4$ was injected into 22 identical lower single-null L-mode discharges from a toroidally distributed gas injection system located at the top of the vessel [11]. The DIII-D divertor diagnostic set was used to characterize the SOL and divertor conditions into which the $^{13}CH_4$ was injected. Immediately following these discharges a set of 29 tiles distributed throughout the vessel were removed. Surface analysis of the tiles revealed that the injected ^{13}C was predominately deposited near the inboard divertor strike point, Fig. 3 [12]. This deposition pattern is similar to that previously observed in JET [13].

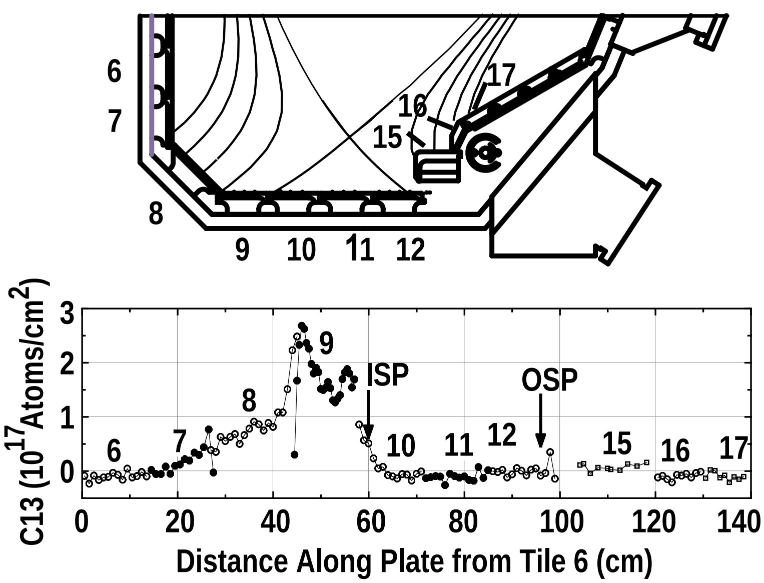

Fig. 3. Profile of deposited ^{13}C on the DIII-D graphite tiles due to $^{13}C_4$ injection. Measurable ^{13}C was found only on tiles near the inboard strike point.

Implications of the ^{13}C deposition were studied using the interpretive edge analysis code OEDGE [14]. This code reconstructs the background plasma using an "onion-skin" model constrained by experimental measurements. Singly charge carbon ions, $^{13}C^+$, are then launched into the background plasma near the gas injection site, and followed until deposition on a surface. The experimentally observed deposition of ^{13}C could only be reproduced in the analysis by imposing a flow of M ~ 0.5 on the background SOL plasma from outer divertor towards the inboard divertor. This flow was also consistent with an imaged plume of CIII near the gas injection site which showed the CIII emission was directed from the injection site toward the inboard divertor [15]. DIVIMP modeling of $^{13}CH_4$ breakup and carbon ion transport also reproduced CIII emission only if a M ~ 0.5 flow was imposed on the SOL plasma derived from OEDGE.

The source of carbon observed in the DIII-D discharges is also under study. Carbon can be released from the surface either by direct physical sputtering due to ion impact, or by chemical sputtering from neutral interaction with the carbon surface. The relative contribution of these two processes can be obtained from a shift and broadening of the CI line emission. While chemically sputtered hydrocarbon molecules result in an isotropic velocity distribution from molecular breakup, physically sputtered carbon atoms acquire an anisotropic velocity distribution from the ion impact on the surface, resulting in a Doppler shift of the CI emission. Analysis of the CI line shape at the outer strike point during low power L-mode discharges reveals that only about 10% of the carbon arises from physical sputtering with the rest due to chemical sputtering. During high power H-mode discharges the level of physical sputtering rises to 50% of the carbon generation [16]. This observation must still be reconciled with previous measurements of reduced chemical sputtering inferred from very low CD-band emission in the divertor [17].

4. DISCUSSION AND FUTURE WORK

Progress is being made understanding the transport of deuterium in DIII-D. Analysis of the 2D emission profile of D_α indicates that fueling of the pedestal occurs primarily near the X-point in low to moderate density plasmas. However, some additional diagnostic measurements are needed to refine this assessment. While significant radial particle flux has been measured at the outer midplane, neutral modeling did not need to invoke this flux to reproduce the outer midplane D_α emission. This may be due to the toroidal asymmetry of the vessel outer wall structure. A D_α measurement near the limiter surface nearest the outer midplane would help to quantify the localization of the midplane neutral flux. A fundamental understanding of bursty transport and ELMs that can lead to ion flux on surfaces other than the divertor will require development of high time resolution diagnostic systems.

The other important region for fueling is the inboard divertor region near the X-point. The cold plasma in this region allows neutrals to penetrate for pedestal fueling. Confirmation of the low electron temperature in this region is necessary for confidence in determination of the fueling profile.

The fueling profile described above has implications for the deuterium flow in the SOL. Numerous experimental observations indicate that particle flux through the separatrix occurs at the low field side [18]. This represents a source of particles into the SOL. The results described above indicate the primary location of loss of particles from the SOL occurs by ionization of neutrals penetrating the separatrix on the high field side above the X-point. The most straightforward path between this particle source and sink is through parallel flow in the SOL from the outer midplane, over the top of the plasma and into the inboard divertor. For H-mode plasmas, this flow would need to be M ~ 0.5 to account for the observed ionization rate and SOL parameters. This flow rate is consistent with the observed CIII plumes on DIII-D and flow rates measured on other tokamaks [19]. However, further work is needed to evaluate the driving mechanism for this SOL flow. Another possible path for particle flux includes flow from the midplane to the outboard divertor where $E \times B$ drifts [20] and neutrals can transport a significant flux of particles. Additional measurements of flow at other locations in the SOL and divertor are also needed to address this topic.

Progress has also been made in the study of carbon generation and transport. The SOL flow described above was found to be important in the deposition of carbon impurity. An important aspect of carbon transport that needs further work is the profile of carbon generation due to physical and chemical sputtering. This will require measurements of ion and neutral flux at other plasma facing surfaces, particularly during ELMs, to assess physical and chemical sputtering throughout the vessel. Spectroscopic measurements, as described above, of the relative rates of chemical and physical sputtering at different locations would also be very beneficial.

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