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Abstract

Fueling of the pedestal from divertor and main chamber recycling in DIII-D is assessed by a combination of experimental measurements, plasma modeling and kinetic neutral analysis. The 2D profile of surface recycling between edge localized modes in H-mode was previously determined in DIII-D from surface mounted Langmuir probes and a plasma configuration where toroidally symmetric recycling was dominant. The measured profile of recycling neutrals is launched by the DEGAS2 code into a 2D background plasma profile reconstructed by the UEDGE fluid model and constrained to match the upstream temperature and density profiles. Divertor plasmas of varying density and temperature are constructed to test sensitivity to uncertainty in the divertor plasma conditions. The pedestal ionization rate from this analysis can match the inferred outward ion flux across separatrix only for high density, detached inboard divertor conditions.

I. Introduction

In current tokamak experiments the edge H-mode pedestal, the region just inside the separatrix, is primarily fueled from recycled ion flux to material surfaces. The fueling, or ionization, profile is important as an input source term for simulation and modeling of edge pedestal plasmas. Direct measurement of pedestal ionization is difficult because the ionization profile is at least 2D in nature and hollow with the scrape-off-layer (SOL) ionization rate typically much higher than inside the separatrix. In addition, interpretation of spectroscopic measurements for the ionization rate requires the 2D profile of plasma density and temperature which can be difficult to obtain with the required accuracy. A previous modeling study of DIII-D H-mode found that pedestal fueling dominated by divertor recycling was consistent with the 2D profile of D_α emission [1]. Another DIII-D numerical study found that core and pedestal fueling from main chamber surfaces are expected to be small unless those surfaces are brought close to the separatrix [2]. However, both of these studies relied on modeling alone to determine the particle flux to surfaces outside the divertor region. Other experimental measurements indicate that the main chamber particle flux could be significantly larger than the model predictions due to radial convective transport in the SOL [3-5]. This study examines pedestal fueling by using plasma modeling to interpret the role of measured ion fluxes to plasma facing surfaces for pedestal ionization.

The main motivation for this initial study is to assess the relative role that main chamber recycling, versus divertor recycling, plays in fueling the pedestal. A secondary goal is to assess the overall efficacy of this interpretive analysis approach for determining pedestal fueling. There remain significant uncertainties in this initial study and this exercise will hopefully point the way forward for improvements. Finally, this study also examines the self-consistency of global particle balance estimates. The separatrix flux determination, for example, is based on assumptions that have not been fully tested over a wide range of conditions.

In Sec. II the interpretive analysis approach will be described. In Sec. III, the pedestal fueling results are presented. It is found that recycled neutrals from main chamber ion flux can replenish only a small part of the total outward ion flux across the separatrix. The bulk of the pedestal fueling is due to recycled ions from the inboard divertor region. The largest uncertainty in this fueling arises from modeling of the inboard divertor plasma density and temperature. In Sec. IV the results are discussed with implications for future work.

II. Analysis Approach

This study of pedestal fueling due to recycling is based on a previous examination of a density scan in H-mode with edge-localized-modes (ELMs) where the particle fluxes to all surfaces were estimated [3]. Surface mounted Langmuir probes measured the ion flux to the divertor target while the outboard main chamber ion flux was inferred from a window frame analysis [4,5] of an insertable Langmuir probe at the outboard midplane. Here the main chamber is defined as surfaces outside of the horizontal divertor target tiles for the outboard divertor and the 45 degree tile for the inboard divertor. For the quiescent period between periodic ELMs the main chamber flux fell primarily on the toroidally symmetric outboard upper and lower divertor baffles as indicated in Fig. 1. The inboard main chamber ion flux is expected to be small due to radial particle transport being primarily driven on the low field, bad curvature side [6]. While no measurement of the inboard main chamber ion flux is available, observations of negligible ion flux to the inboard divertor Langmuir probes most distant from the inner strike point are an additional corroboration of this assumption. The corresponding radial ion flux across the separatrix was determined from the separatrix density and temperature gradients and assumption of constant ratio of particle diffusivity to thermal conductivity, $\alpha = D_{\perp}/\chi_{\mathrm{eff}} = 0.25$ [7]. A summary of these ion fluxes during the quiescent period between ELMs is summarized in Fig. 2. The main chamber wall flux was found roughly equal to the separatrix flux and the divertor flux was approximately 10 times this value. The divertor flux was estimated by integrating the ion saturation current profile from the surface-mounted divertor Langmuir probes shown in Fig. 1. All of these fluxes increased strongly with increasing pedestal density.

For this “interpretive” analysis the role of measured surface ion flux is interpreted from plasma and neutral modeling. A significant assumption of this modeling is that the neutral flux recycled from plasma facing surfaces is equal to the measured incident ion flux to surfaces described above. The neutrals are followed using the Monte Carlo code DEGAS2 [7] that launches them into a background plasma model constructed by the fluid code UEDGE [8].

In constructing the background plasma with UEDGE the primary consideration is to reproduce the measured electron density and temperature profiles as accurately as possible as these parameters are most important for neutral ionization. Matching other parameters such as ion flux to surfaces, plasma flow, radiation and impurity density is of secondary concern since they do not significantly affect neutral ionization. For the upstream conditions the model densities and temperatures are accurately matched to the measured SOL profiles by adjusting the transport model diffusivity, $D_{\perp}$, and conductivities, $\chi_{e,i}$, within UEDGE. The SOL profiles are particularly important for assessing the ionization profile of the main chamber neutral flux.

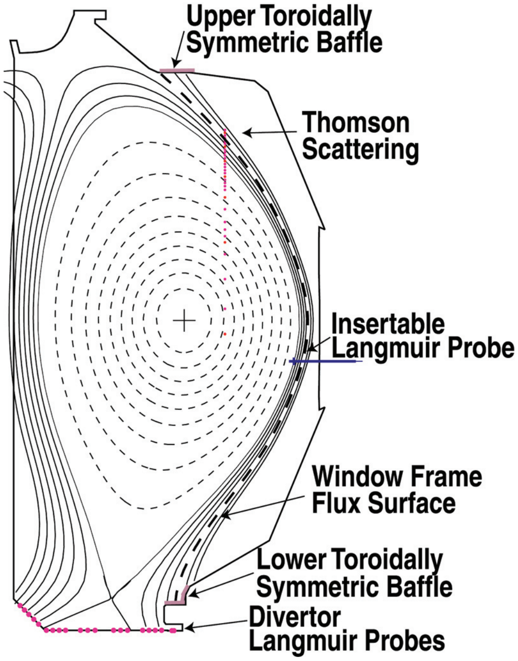

Fig. 1. DIII-D geometry showing the divertor configuration and the upper and lower baffles where most of the main chamber ion flux recycles.

The divertor plasma reconstruction, obviously important for assessing the target plate neutral flux, is more difficult and uncertain. There are typically limited experimental measurements to determine the 2D profile of electron density and temperature in the divertor that is required to assess the ionization profile of neutrals recycling from the divertor targets. For this reason a range of divertor plasmas was constructed to assess uncertainty and sensitivity. The divertor plasma state, particularly the level of inboard detachment, was varied by adjusting the recycling rate from the divertor targets and carbon impurity fraction through sputtering rate. The recycling rate, the fraction of ion flux to the target that is returned as neutral flux, was varied from 0.95 to 1.05. These variations produced a series of divertor solutions for each density case, ranging from high electron temperature at both inboard and outboard targets to an inboard divertor plasma with <5 eV electron temperature very near the X-point. These divertor solutions were compared to tangential camera images that were inverted into poloidal profiles of D_α and CIII emission [9]. The CIII emission usually peaks at 8-10 eV and is thus a good marker of where neutral deuterium ionization path lengths become shorter.

Because not all the physical processes, such as particle drifts, required for accurate plasma modeling have been included, the background plasma solutions are not expected to be self-consistent in that the modeled boundary ion flux does not match the measured ion flux summarized in Fig. 2. This can lead to physically unrealistic choices for parameters such as greater than unity recycling. However these choices are deemed appropriate for the construction of a background plasma density and temperature that best matches the existing data.

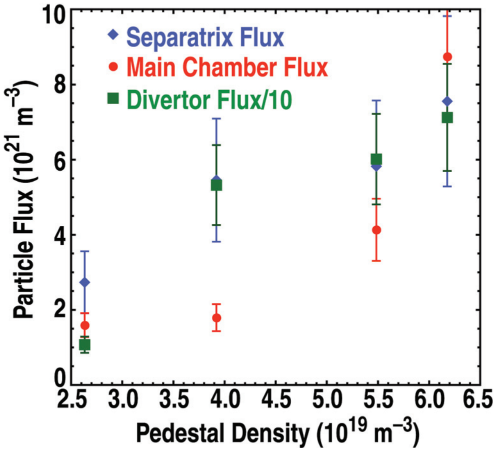

Fig. 2. A summary of ion flux versus pedestal density for the main chamber, divertor and outward ion flux across the separatrix.

Using the model plasma background solutions the measured distribution of surface ion flux is relaunched as neutrals using the DEGAS2 code. Each source, the upper baffle, lower baffle, divertor targets and the recombination source from UEDGE are launched with 10,000 flights each. The neutrals are followed until ionization and include all the relevant atomic physics processes such as charge-exchange. The resulting ionization profile is tracked separately and then summed for each recycling source. The ionization profile inside the separatrix for each source can be integrated along radial cells to provide the poloidal profile of pedestal ionization, or integrated poloidally to provide the flux-surfaced averaged radial profile of ionization.

III. Analysis Results

Four different density cases were examined, pedestal densities of 2.6×10^{19} m^{-3}, 3.9×10^{19} m^{-3}, 5.5×10^{19} m^{-3} and 6.2×10^{19} m^{-3}, representing a range of pedestal Greenwald density fraction of 0.27 to 0.64. For each of these cases the upstream SOL T_e and n_e profiles from the UEDGE model matched the experimental profiles very well, ~10%. The experimental profiles can be reviewed in Ref. [1]. For each pedestal density a less detached and a more detached divertor case was produced by varying the divertor recycling rate, typically between 0.95 and 1.05, and the carbon sputtering rate. The attached cases were adjusted to keep T_e greater than 15 eV throughout most of the inboard and outboard divertor region, while the detached cases produced a plasma with T_e less than 5 eV throughout most of the inboard divertor region. The detached inboard divertor is consistent with the images of CIII emission peaking along the separatrix just below and above the X-point. As expected the images of CIII emission exhibited extension along the separatrix toward the inboard divertor at low density and peaked emission from the X-point upward at high density.

The first observation from this analysis is that the core ionization resulting from main chamber recycling from the upper and lower baffle can account for only a small part of the ion flux across the separatrix, Fig. 3. This is consistent with the previous modeling study in a similar geometry [2]. The fraction of neutrals recycled from the main chamber baffles that penetrate across the separatrix ranges from about 15% for the low-density case to less than 10% for the higher density case. This represents slightly less than 10% of the previously estimated ion flux across the separatrix [3]. The uncertainty of determining the ion flux across the separatrix through a comparison of heat to particle transport has been previously estimated at ~30% [7]. This uncertainty was assessed over a range of H-mode conditions and encompasses effects such as profile measurement errors and averaging times, and radial transport changes over different parameter regimes. The low pedestal fueling from the main chamber appears to be a fairly robust result in that measurements well constrain both the ion flux to the baffles, ~20%, and the SOL plasma, ~10%, into which the neutrals are recycled. If anything the fraction of ion flux that is recycled as neutrals may be less than unity due to between-discharge conditioning of the plasma facing carbon tiles.

The results from the divertor recycling, shown in Fig. 3, are consistent with the separatrix ion flux only for strongly detached plasmas for the inboard divertor. For attached plasmas, when significant fractions of both divertors have T_e above 20 eV, the total core ionization from all sources is less than the inferred separatrix ion flux varying from 0.31 to 0.44. This ionization is dominated by the divertor source. For the detached cases the core ionization significantly increases, with all cases except the lowest density, rising above the inferred separatrix ion flux. The range of core ionization for these cases is 0.64 to 1.70 of the inferred separatrix ion flux. For the detached cases the core ionization due to the recombination source also becomes significant contributing roughly an additional 2/3 of the target plate ion flux source.

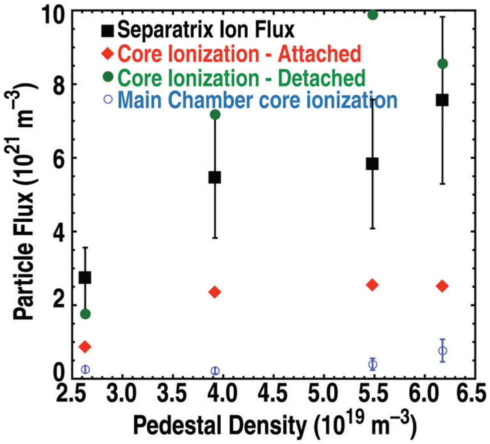

Fig. 3. Core ionization rate inside the separatrix versus pedestal density. Attached and detached divertor cases are compared to the inferred ion flux across the separatrix. The contributions of main chamber ion flux for the attached cases are also shown. The main chamber ionization rates for the detached cases (not shown) are very similar to the attached cases.

From the poloidal profile of core ionization for detached case at a pedestal density of 5.5×10^{19} m^{-3} Fig. 4(a), the increase in core ionization due to inboard detachment can clearly be seen as due to additional neutral flux in the inboard divertor region. The separatrix neutral flux was obtained by integrating the 2D ionization profile inward radially from the separatrix. The flux-surface averaged radial profile of ionization is shown in Fig. 4(b). While the overall ionization rate increases with detachment the fall off length of ionization near the separatrix also decreases with detachment. The decrease in ionization length inside the separatrix with detachment may result from a number of effects. A significant contributor is likely a lower ion temperature in the divertor and SOL resulting in a reduced neutral velocity from charge-exchange.

The uncertainty in total core ionization from this analysis is fairly large as can be seen in Fig. 3 and Fig. 4. The difference in total core ionization between attached and detached states is a factor of two to four. This should be taken as the uncertainty of the analysis at this stage of development. The levels of detachment for these cases were set rather arbitrarily with a rather limited set of divertor measurements available to constrain the UEDGE model plasmas. They detachment levels were set in an attempt to span the actual experimental case and, in fact, did span the inferred separatrix ion flux for most cases. The low-density case, 2.6×10^{19} m^{-3}, was the only instance where the detached case did not at least match the separatrix ion flux. But in fact, the inboard divertor plasma produced for the low density detached case was much hotter than the higher density detached cases with 20 eV plasma extending more than halfway from the X-point towards the divertor. While the low density inboard divertor would be expected to be more attached, this analysis together with only limited data lends uncertainty to the assumption of low density inboard divertor attachment.

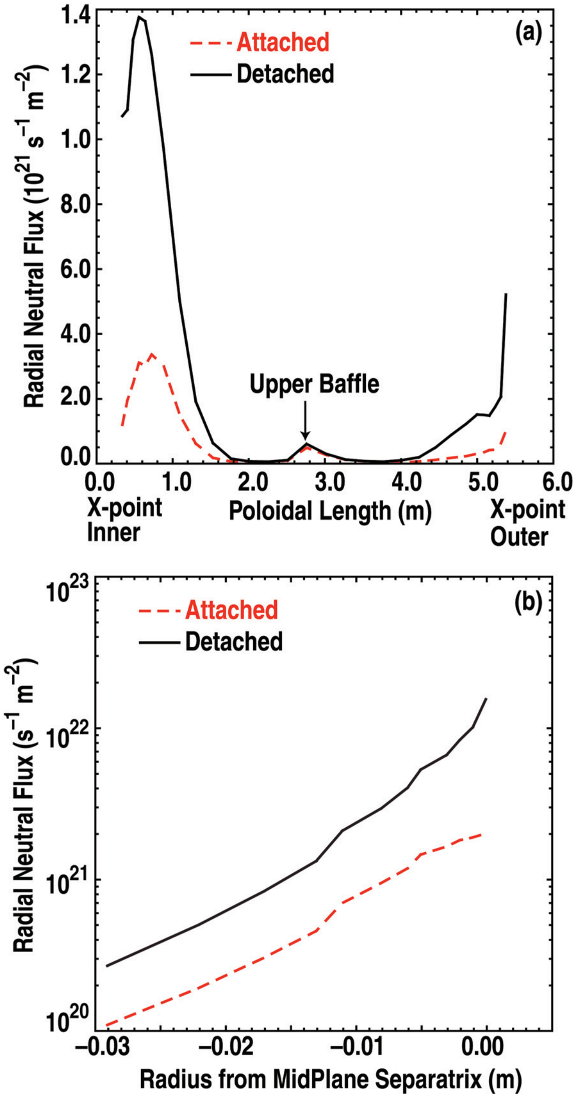

Fig. 4. The (a) poloidal profile of separatrix neutral flux and (b) the flux surface averaged radial profile of core ionization for the attached and detached cases at a pedestal density of 5.5×10^{19} m^{-3}.

IV. Discussion

While there is considerable uncertainty in the divertor solutions produced by UEDGE and the resulting core plasma ionization, there are several conclusions that can be drawn from this initial study. The first is that recycling from the main chamber, primarily off the upper and lower divertor baffles, can only account for <10% of the core ionization during the quiescent period between ELMs. This appears to be a robust result in that the surface ion flux is measured and the SOL plasma that the recycled neutrals are launched into is described accurately in the plasma model. This implies that the core and pedestal ionization source is dominated by divertor conditions for the configuration presented here.

Another conclusion is that the divertor neutral flux can account for the inferred separatrix ion flux. However this requires detached divertor conditions, particularly the inboard divertor. While a detached inboard divertor appears consistent with measurements at high density, even at the lowest density a significant degree of inboard detachment is required for consistency between the measured ion flux to plasma facing surfaces and the inferred separatrix ion flux. At this stage not enough data and analysis has been acquired to adequately assess the 2D inboard divertor conditions. Another aspect of the detached inboard divertor is that the resultant recombination neutral flux can also be a significant contributor to core ionization. The recombination source varied from insignificant for the attached divertor cases to ~35% of total core ionization for the detached cases. Additional spectroscopic measurements should help to assess this recombination source experimentally.

Also it is clear that more complete 2D divertor plasma characterization is needed to assess the core and pedestal ionization that is needed for pedestal transport simulation and modeling. Of particular importance is the location of the ~5 eV electron temperature contour in relation to the separatrix. With a very low ionization rate below ~5 eV neutral core and pedestal ionization rapidly increase as this region approaches the separatrix. Spectroscopic imaging is likely to be required for this task.

Finally while a complete physics fluid code, such as UEDGE or SOLPS [10], linked to a Monte Carlo neutrals package is necessary for a self-consistent description of recycling and ionization fueling, it is a somewhat awkward vehicle for constructing a plasma background to interpret the implications of measured fluxes. A more practical approach may be the use of interpretive models, such as OSM [11], where all available diagnostic measurements can be used to constrain the background plasma solution, into which the measured neutrals are launched.

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