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DETAILED OEDGE MODELING OF CORE-PEDESTAL FUELING IN DIII-D

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Abstract. The OEDGE code is used to model core fueling for attached L-mode plasmas and between edge localized modes (ELMs) for attached H-mode plasmas in DIII-D. Empirical Plasma Reconstruction has been used to determine the plasma conditions in these discharges. EIRENE is used to model the hydrogen recycling. Divertor recycling accounts for 65%–100% of the core fueling. The fraction of the total divertor target flux ionized inside the separatrix ranges from 5%–20%. The fraction of total wall flux ionized inside the separatrix ranges from 20%–50%. The probability of wall recycled deuterium ionizing in the confined plasma is larger when the wall-separatrix distance is small. Ionization in the confined plasma is concentrated below the midplane with peaks in the poloidal profiles just above the Xpoint. Radial core ionization in high density H-mode is peaked strongly near the separatrix.

PACS: 52.65 Plasma Simulation

1. INTRODUCTION

Understanding neutral recycling in the confined plasma is crucial to understanding the tokamak fuel cycle. The confined plasma must be fueled either by neutral penetration or by ion transport into the confined plasma. In addition, the distribution and magnitude of the neutral source in the confined plasma is thought to play an important role in formation of the H-mode pedestal and in determining pedestal parameters [1,2].

Several studies [3–8] have used fluid codes to model fueling of the confined plasma. In these studies, it was generally found that the divertor sources played the strong sources of ionization reported on both the high and low field sides of the confined plasma above the Xpoint [4,5]. In the present study, the OEDGE code uses the process of empirical plasma reconstruction [9,10] to generate a plasma solution. Empirical plasma reconstruction combines experimental diagnostic measurements, which are used as input or constraints, with 1-D, parallel to the field line, "onion-skin" models (OSM) of plasma behaviour to calculate the plasma conditions everywhere on the computational grid used for the simulations. Langmuir probe data, for both the inner and outer targets, are used as input to the OSM and are used to generate plasma solutions across the scrape-off layer (SOL). This ensures a good match between the calculated plasma close proximity to the recycling sources. Conditions in the confined plasma are specified based on Thomson scattering measurements of n_e and T_e for the discharges being examined. Far SOL plasma conditions and wall fluxes are constrained by reciprocating probe measurements. After the plasma solution for the computational grid has been calculated, including fluxes to surfaces, the EIRENE Monte Carlo neutral hydrogen code is used to model the hydrogen recycling from all in-vessel surfaces.

Extended computational grids were developed that allow for plasma contact to be modeled over the majority of in-vessel surfaces (Fig. 1). In addition, these grids also have a very high radial resolution just inside the confined plasma so that detailed radial profiles of pedestal ionization can be obtained from the simulation results. The radial spacing of the rings just inside the separatrix is on the order of 1 mm at the outer midplane.

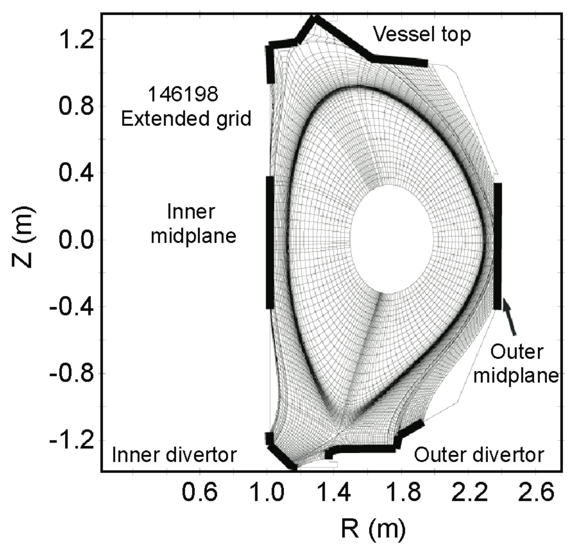

Fig. 1. Extended grid for 146198 showing modeled regions of plasma contact with vessel surfaces.

Three discharges have been examined for this study. These discharges are 105500; a low density attached L-mode discharge and discharges 146198 and 146210; high density attached ELMy H-mode discharges. Only the inter-ELM phase neutral recycling has been examined here. All discharges are lower single null (LSN). Discharge characteristics are listed in Table 1.

Table 1
Discharge Characteristics

Shot	$\langle n_e \rangle'$ ($\times 10^{19}$ m^{-3})	P_{beam} (MW)	B_{tor} (T)	I_p (MA)
105500	2.5	2.7	–2.03	1.08
146198	11.0	11	2.15	1.98
146210	6.5	5.8	1.06	1.01

2. OEDGE MODELING

2.1. Plasma reconstruction

The plasma conditions used in the simulation are determined using the process of empirical plasma reconstruction. This involves using as much of the experimental diagnostic measurements as possible to constrain the calculation of a plasma solution. In the present study, the main diagnostics used were the Langmuir probe measurements across both the inner and outer targets, the Thomson scattering measurements of n_e and T_e in the upstream SOL and confined plasma, and reciprocating probe measurements of far SOL plasma conditions. The outer target Langmuir probe saturation currents for the three discharges are shown in Fig. 2 and the comparison to upstream Thomson measurements on the low field side of the plasma are in Fig. 3. There is generally good agreement between the calculated SOL profiles and the upstream measured plasma conditions. Mismatches at the separatrix are likely due to: (1) uncertainties in the separatrix location relative to the correct position of the Thomson profiles, and (2) deficiencies in the OEDGE model for the parallel conservation equations near the separatrix such as losses into the private flux region. These mismatches, however, have little effect on the EIRENE-calculated spatial distribution of ionization.

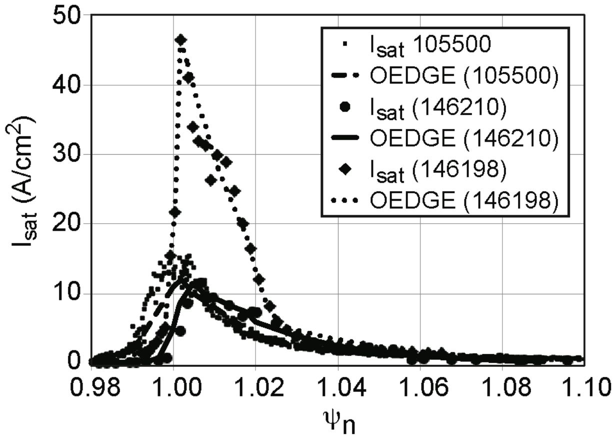

Fig. 2. Measured target I_{sat} and T_e values are used as input to OEDGE. (T_e data not shown).

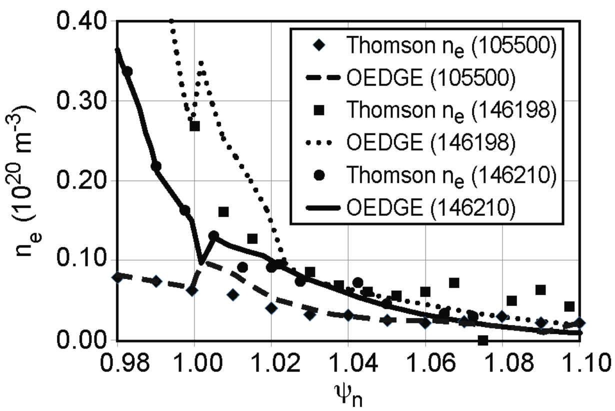

Fig. 3. Upstream outer SOL comparison of OEDGE density profiles and experimental Thomson measurements.

2.2. Fuel recycling

The deuterium recycling is calculated using the EIRENE Monte Carlo hydrogen modeling code which is integrated into OEDGE. Fluxes to surfaces are calculated based on the OEDGE plasma solution. The plasma conditions in every cell of the grid and the surface ion fluxes are supplied to EIRENE as input. EIRENE then launches deuterium molecules from these surfaces and follows the breakup of the deuterium including all charge exchange and ionization processes.

In addition to modeling the global recycling, EIRENE was also used to model the behaviour of several distinct regions separately. Individual EIRENE simulations were run launching particles from the inner divertor, outer divertor, outer midplane, inner midplane and top of the vessel. Differences in both fueling efficiency and radial penetration of the confined plasma for neutral sources from these regions can then be identified and used to assess the relative importance of these regions to core and pedestal fueling.

2.3. Modeling results

Poloidal Distribution. The poloidal distribution of core ionization for the three discharges is shown in Fig. 4. Most of the ionization occurs in a thin shell near the separatrix. The flux across the separatrix is calculated by radially integrating the ionization in each poloidal section of the confined plasma in order to obtain an estimate of the local neutral flux. This approximation is somewhat less accurate for cases with a significant amount of ionization deep in the confined plasma.

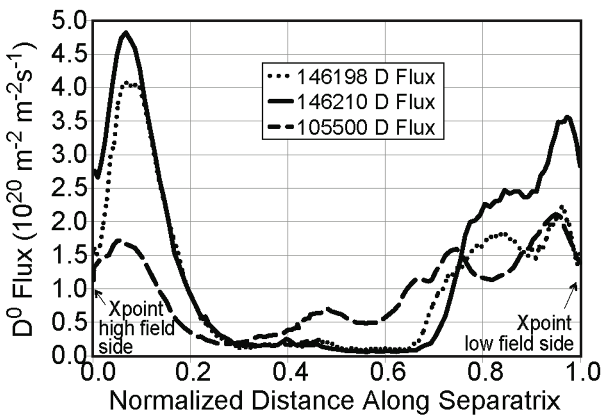

Fig. 4. Deuterium neutral flux across the separatrix for all three discharges plotted as a function of the normalized distance along the separatrix from Xpoint to Xpoint.

As in previous studies, neutral fluxes into the confined plasma and pedestal are found to be strongest just above the X-point on both the high and low field sides. This is due to the dominance of the divertor recycling source. Profiles do not peak at the Xpoint due to two effects: 1) Plasma conditions near the strike point are strongly ionizing which attenuates the neutral flux through these regions and 2) Flux expansion in the region at and below the Xpoint makes it more difficult for neutrals to penetrate this strongly ionizing region. Geometrically, the strongly ionizing region is larger near the X-point which effectively attenuates neutral penetration in this region. The thinner SOL above the X-point makes it easier for neutrals to cross the SOL and reach the confined plasma.

Radial Distribution. The radial distribution of neutral flux is calculated by integrating the total ionization within a given radius and dividing by the total plasma surface area at that radius. This yields the required neutral flux needed to account for the ionization. Results for each discharge can thus be directly compared while removing geometrical dependencies from the analysis. Figure 5 shows the radial D^0 flux for the total source from all vessel surfaces for the three discharges. The lower density of 105500 allows for much deeper overall neutral penetration into the confined plasma. In the H-mode discharges, the radial neutral flux drops quickly with about 50% of the total core fueling occurring in the first half of the pedestal for discharge 146198.

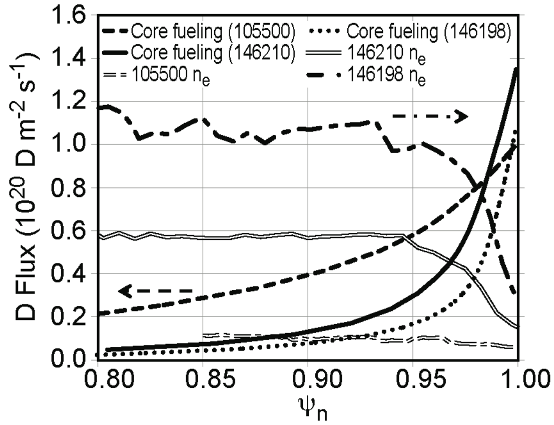

Fig. 5. Plot of the radial neutral deuterium flux (left scale) and the plasma density (right scale) for each of the three discharges.

The neutral flux crossing the separatrix for all three of the discharges examined is very similar, varying from 1.0×10^{20} to 1.5×10^{20} $D^0/m^2/s$. Total plasma surface area at the separatrix in the three cases is also very similar, ranging from 49 m^2 to 52 m^2. As a result the total neutral transport across the separatrix is also similar despite very different plasma conditions.

Core Fueling Efficiency. Although the ion fluxes to various wall components can be difficult to estimate because of the uncertainties in far SOL transport, one aspect that can be analyzed is the probability and distribution of each source contributing to core fueling.

Table 2 lists the calculated deuterium flux from distinct regions of the vessel (Fig. 1) and the fueling efficiency which is the fraction of each source which is ionized inside the confined plasma. From this table it is clear that main vessel wall sources are much more efficient at fueling the confined plasma than divertor sources. Typically the divertor fueling efficiency ranges from ~5% to ~18% for these cases while fueling from main vessel surfaces typically range from ~22–50%. In particular, outer midplane fluxes can be from 3–10 times more efficient at core fueling than the divertor.

Table 2
Contributions to Core Fueling from Vessel Sources

Shot	Source Location	Recycling D+ Source (D/s)	% Ionized in Confined Plasma (%)
105500	Total	4.3E+22	11.0
	Inner divertor	1.7E+22	5.5
	Outer divertor	2.3E+22	8.7
	Inner midplane	3.2E+20	31.7
	Outer midplane	2.8E+21	46.1
	Vessel top	5.4E+20	22.9
146198	Total	1.1E+23	5.2
	Inner divertor	3.9E+22	5.7
	Outer divertor	6.8E+22	4.2
	Inner midplane	3.7E+19	39.1
	Outer midplane	1.2E+21	34.2
	Vessel top	9.2E+20	20.4
146210	Total	4.1E+22	17.2
	Inner divertor	1.6E+22	16.2
	Outer divertor	2.4E+22	17.4
	Inner midplane	3.3E+18	45.5
	Outer midplane	9.4E+19	49.8
	Vessel top	3.3E+20	33.7

Table 3 summarizes the overall contribution to core fueling in each discharge by region. From this table, the divertor recycling dominates the neutral fueling of the confined plasma. The small main chamber contribution to fueling in 146210 is due to the low level of wall plasma fluxes obtained from matching the far SOL reciprocating probe data.

Table 3
Total Contributions to Core Fueling

	Divertor	Main Chamber
105500	65.8%	34.2%
146198	89.4%	10.6%
146210	97.7%	2.3%

3. DISCUSSION

The divertor recycling source contributes more to core fueling than the main chamber in the cases examined. Despite the attenuation of neutral transport in the divertor due to the ionizing plasma, the typically large recycling source found at the divertor strike points in attached plasma conditions still results in a substantial amount of neutral flux to the confined plasma.

Most of this transport is not directly from the strike point to the confined plasma as is demonstrated by the dip in the neutral flux in the poloidal profiles near the X-point (Fig 4). The strongly ionizing plasma near the strike point inhibits direct transport of neutrals to the confined plasma. Instead, transport to the confined plasma appears to occur mostly as a result of neutral leakage around the more intense plasma near the strike point due to the open divertor configurations on both the inside and outside. Neutrals reaching the far SOL bypass the ionizing plasma directly above the strike points and can penetrate radially across the SOL away from the divertor where the plasma is both geometrically thinner and less dense than in the region immediately above the target.

Main chamber recycling does not experience the screening effect of the strongly ionizing divertor plasma. As a result, the efficiency of wall recycled hydrogen for fueling the confined plasma is typically much higher than the divertor sources. This is a potential concern due to the uncertainties in the assessment of far SOL recycling and possible neutral gas pressure in the far SOL due to leakage. The current study examines only ion recycling sources at plasma facing surfaces with constraints imposed by matching far SOL reciprocating probe data. Further studies will add hydrogenic spectroscopic emissions to this assessment. However, direct measures of ion fluxes around the plasma will be required to more fully assess the contribution of main chamber vessel recycling to core fueling. In the cases examined, wall contributions to fueling varied from ~2%–35%. However, with fueling efficiencies of ~30%–50%, it becomes very important to accurately determine the amount of wall recycling in order to properly assess the wall contribution to total core fueling. In addition to the higher efficiency in core ionization, neutrals sourced from the outer midplane are ~2 times as effective at fueling the plasma inboard of the top of the pedestal. Figure 6 shows normalized radial flux profiles comparing the outer divertor and outer midplane sources for discharge 146198. Although the actual deep core neutral fluxes from the outer midplane are much less than from the outer divertor, the normalized profiles show that the neutrals originating from the outer midplane are roughly twice as effective at penetrating into the confined plasma beyond the pedestal.

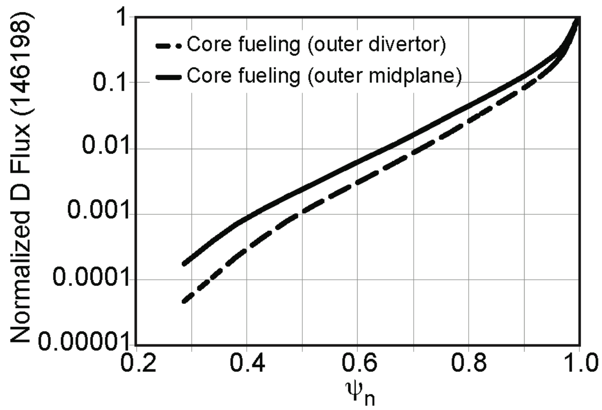

Fig. 6. Profiles of normalized radial flux for discharge 146198 for outer divertor and outer midplane sources.

There are several uncertainties in this study that need to be assessed in future work. First, a better estimate of the main chamber recycling is required. Second, the plasma conditions in the simulation inside the separatrix are assigned constant along each flux surface based on measurements from the Thomson data. Poloidal variations of the core plasma conditions are assumed to be small. Third, the effect of ELMs themselves on core fueling needs to be addressed. ELMs release a large number of particles into the SOL which may disproportionately recycle from main chamber surfaces and thus may contribute significantly to core fueling.

4. CONCLUSIONS

Detailed modeling results for three attached L and H mode discharges have are presented. In these plasmas, core fueling is dominated by neutrals originating from divertor surfaces. These divertor sources result in poloidal profiles of core fueling that are strongly peaked above the X-point, on both the high and low field sides. This result agrees with previous studies. The radial profile of core fueling is dependent on the density profile in the confined plasma. Both H-mode cases examined here had strong ionization in the pedestal region with more than half of the total ionization in the confined plasma occurring in the outer half of the pedestal.

Overall, the divertor efficiency of core fueling varies from ~5%–20% for these attached plasmas while the main chamber fueling efficiency varies from ~20%–50%. However, in these cases the divertor remained the dominant source of neutrals reaching the confined plasma due to the dominance of divertor sources in the total particle recycling.

Since the 2D spatial distribution of n_e and T_e in the divertor is estimated from target probe measurements, the magnitude of the recycling from the targets as well as the modeled neutral transport should be representative of actual experiment. Similarly, since the magnitude and spatial distribution of the wall recycling source is determined based on reciprocating probe measurements, this aspect should also be representative of the actual experiment. The efficiency of the wall recycling source for fueling the confined plasma is governed by the radial profiles of n_e and T_e in the main SOL used in the simulation, which well match the RCP and Thomson profiles. Similarly, the radial distribution of the ionization in the confined plasma is governed by the radial profiles of n_e and T_e inside the separatrix which are imposed in the simulations directly from the Thomson profiles. Thus, overall, the EIRENE-calculated spatial distribution of ionization is expected to be rather close to the actual one.

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