Abstract

H-mode experiments on DIII-D and Alcator C-Mod at high neutral opacity do not result in a degradation of the electron density pedestal. In C-Mod, these high opacity discharges (about a factor 7 higher in opacity than DIII-D) result in very high pedestal pressures and in DIII-D even at the highest achieved opacity, additional gas puffing further increases the electron pedestal density. In both machines, high opacity is achieved by operating at high current and by increasing the Scrape-Off Layer (SOL) density through gas puffing. In C-Mod, where pedestal transport is regulated by a quasi-coherent mode, typical for Enhanced D-alpha (EDA) H-mode operation, the increased gas puff had little or no effect on the pedestal density and only resulted in a small increase of the SOL density. In DIII-D, we observe the creation of a density shoulder in the SOL when the outer divertor leg
detaches. The increased SOL transport associated with shoulder formation limits the increase in SOL density at higher puff rates. On the other hand, the pedestal density continues to increase with increased gas fueling. To diagnose the role of transport, we apply a 3 Hz gas puff modulation. The electron density response to this modulation depends strongly on whether there is a density shoulder in the near SOL. During shoulder formation the amplitude of the electron density response is strongly reduced in the SOL and slightly higher inside the separatrix, compared to discharges without shoulder formation. Finally, we observe an up-down asymmetry in the electron density on closed flux surfaces close to the separatrix in these H-mode DIII-D plasmas. Increases in opacity cannot be linked to a degradation in confinement on either DIII-D or C-Mod.

1. Introduction

In future burning plasmas devices, such as ITER, the high electron density in the Scrape-Off Layer and at the separatrix will reduce the ionization to negligible levels inside the separatrix. Predictive integrated modeling, using only an outward diffusion coefficient, suggests that at high gas throughput levels, the electron density pedestal structure would disappear in ITER [1]. Consequently the electron density at the separatrix would be close to the one at the top of the ‘pedestal’. This suggests that without ionization inside the separatrix, it would be difficult to fuel a burning plasma using gas puffing. In this paper, we will show that increased opacity to neutrals as measured by an increase in SOL electron density in DIII-D and C-Mod does not result in the degradation of the pedestal electron density or structure. In fact, Alcator C-Mod achieved record plasma pressures in these EDA H-mode with very opaque Scrape-Off Layers [2] and in DIII-D while we observe a saturation in the SOL density, the pedestal density continues to increase with higher gas puff levels.

In tokamaks the main rise in opacity is the result of an increase in the electron density. This is mostly because the separatrix electron temperature is typically close to 100 eV and varies little across mid-size tokamaks. An approximation for the inverse mean free path for neutrals $1/\Delta C_x$ depends strongly on the electron density $n_e$ and less on the electron temperature, $T_e$. We can use this as a proxy for opacity: $1/\Delta C_x = \frac{1}{1.91 \times 10^{17} \frac{n_{sep}}{T_{sep}^{2/3}}}$. In ITER $1/\Delta C_x \sim 220$, using $T_{sep} \sim 200 eV$ and $n_{sep} = 4 \times 10^{20}$ and in this paper, the highest values in DIII-D was 22, while in C-Mod we achieved 162 and thus very comparable to ITER values. Raising the Scrape-Off Layer density affects more than just the neutral opacity. Higher SOL densities also affect the divertor conditions and are linked to the onset of detachment in the outer divertor [3]. These changes in divertor conditions in turn affect the SOL and pedestal conditions [4 5 6]. For example, the detachment of the outer divertor will affect the parallel conductivity, which then in turn alters the filamentary and fluctuations behavior in the SOL. The increase in fluctuations is linked to an increase in radial turbulent transport and the formation of a flat near SOL density profile, also called a shoulder. The shoulder formation itself is very effective at increasing opacity and pushing the ionization front further out into the SOL.

In this paper we will find that with increased gas fueling by discrete steps from discharge to discharge, the plasma response to these fueling changes is not always linear. There is a clear bifurcation in the electron density response to the probing gas puff modulation when the outer divertor detaches and shoulder formation occurs. This is an indication that changes in transport and divertor conditions cannot be ignored when we try to address the role of fueling versus transport in determining the electron pedestal density structure.

While the pedestal pressure profile in H-mode is limited ultimately by MHD, the physics processes regulating the individual temperature and density profiles are complex [7 8]. Prior research has indicated...
that various MHD and gyrokinetic instabilities regulate the separate transport channels and thus the individual profiles even in non-opaque SOL conditions. The DIII-D H-mode plasmas in this paper all have Edge Localized Modes (ELMs), and based on prior work, it is safe to assume that the pedestal pressure structure is set by the Peeling-Ballooning stability limit [1]. In the C-Mod plasmas described in this paper, there are no ELMs and the pedestal is regulated by a quasi-coherent mode [9], typical of Enhanced D-alpha (EDA) H-mode operation [10]. These pedestal transport mechanisms are important considerations in opaque SOL conditions, when plasma transport is likely to dominate the pedestal density structure and not fueling.

2. EXPERIMENTAL SETUP

2.1. DIII-D

H-mode experiments on DIII-D were conducted to investigate the role of ionization in determining the electron density pedestal structure. To reduce the ionization of neutrals inside the pedestal, we increased the SOL density using a gas puff. These experiments were performed at \( I_p = 1.7 \, \text{MA} \) and \( B_T = 2.1 \, \text{T} \), resulting in a \( q_{95} \sim 3 \). The plasmas are heated using 10–12 MW of Neutral Beam Injection (NBI), leading to discharges with a \( \beta_N \sim 1.8–2.2 \). The pedestal collisionality was high (\( \nu^* \sim 2–4 \)) since we were operating at high electron density, with pedestal electron densities ranging from \( n_e \sim 0.75 – 1.0 \times 10^{20} \, m^{-3} \), as shown in Fig. 1. This increase in \( n_e \) is the result of an increase in fueling using 0 to 300 Torr/L/s main chamber gas puffing from 2000 – 5000ms. This increase in fueling from discharge to discharge did not affect the main chamber neutral pressure, but it resulted in a large increase in the pressure under the shelf (smaller volume than main chamber), as shown in Fig. 1. Additionally, using a different gas valve we added a 3 Hz perturbative gas puff in order to measure the electron density response to this perturbation, as well as the response of 1D and 2D ionization profiles using filterscopes and fast cameras using \( D_{\alpha} \) and \( D_{\beta} \) filters. The response of the ionization as well as the electron density to this perturbation can give us information on the role of transport versus fueling in determining the pedestal structure.

Figure 2 shows that in order to reduce the effects of pumping in the divertor, the outer strike-point is up on the shelf. An additional benefit to operating with the outer strike-point on top of the shelf is that we can use the divertor Thomson Scattering system to monitor conditions close to the strike-point and inside the X-point. The upper plasma shape was optimized to have good spatial coverage of the SOL and pedestal using the core Thomson Scattering diagnostic. Moreover, the midplane filterscope measurement provide good coverage of the SOL as well as foot of the pedestal, the region we are most interesting in, for ionization profiles. In these experiments, only the lower pump was Helium cold, thus avoiding the removal of particles through the upper pumps.

2.2. C-Mod

Alcator C-Mod is a high B-field tokamak that operated until 2016. The high magnetic fields allowed for poloidal fields at or even above those in ITER. These high poloidal B-fields result in a higher Greenwald density limit and allow access to high electron density operation. The best performance at high density in C-Mod occurs typically in Enhanced D-alpha (EDA) H-modes, where a quasi-coherent mode regulates the pedestal and near-SOL transport. EDA H-mode is favored by operating with \( q_{95} > 4 \), which typically requires \( I_p \) of about 1 MA or less on C-Mod. However, to push operation to even more...
opaque SOL conditions, the plasma current was increased to 1.3 MA. The toroidal B-field is set to 5.4 T. Using ICRF heating we are able to inject 3 – 4 MW of heating power, which results in a $\beta_N \sim 1.8$. The pedestal collisionality is similar to that on DIII-D ($\nu^* \sim 2 - 4$) and we are operating at high electron density, with pedestal electron densities of $n_e \sim 3.5 \times 10^{20}$, as shown in Fig. 3. Similarly as in DIII-D, we perform a fueling scan to increase opacity and test how ionization versus transport affects the density pedestal structure.

To efficiently couple the ICRF heating at these high densities and thus neutral densities, we fueled from the low field side only during the L-mode phase and operate close to double null (the secondary X-point was outside the machine), as shown in Fig. 4. The primary X-point is in the lower divertor with strike-points on the vertical target plates. The field direction is in favorable direction, such that $\nabla B \times B$ is directed towards the lower divertor, similar to the experiments on DIII-D. In addition to the L-mode fueling from the low field side, we add a gas puff on the High Field Side into the H-mode starting at 0.8 s that is varied in size on a discharge to discharge basis. We use the edge Thomson Scattering to measure the changes in electron density and temperature and we use the $D_\alpha$ main chamber chord to assess qualitatively how the ionization has changed. Counter to DIII-D, we observe that additional gas puff does result in an increase of the midplane neutral pressure, but seems to have little effect on the line-averaged density.

3. SHOULDER FORMATION & IONIZATION

3.1. Edge Electron Density

As shown in the time traces for DIII-D in Fig. 1, the increase in gas puffing results in an increase in the line-averaged density as well as the pedestal density, as shown in Fig. 1. In C-Mod, we observe that for gas puffs of 150 TorrL/s and higher, a density shoulder develops in the near SOL, while the outer divertor starts to detach. D. Carralero et al. [6] show that shoulder formation is often observed when the outer divertor detaches and is linked to an increase in turbulent transport in the near SOL as well as an increase in opacity. As such, we can assume that observed shoulder formation in these DIII-D H-mode plasmas will affect the ionization profile and potentially also particle transport.

In C-Mod the increase in the electron density is much more modest at any radial location as measured with the Thomson scattering system, as shown in Fig. 6 b). The increase in LFS gas puff levels has only a modest effect on the electron density profiles and only for the highest puff rate do we observe a small increase in the averaged (from 1.1 – 1.3 s) overall SOL and pedestal density. As is typical of metal wall high density operation, the steep region of the electron pedestal structure is pushed farther into the SOL with increased fueling, while in DIII-D the density pedestal is mostly located inside the separatrix. While we were able in DIII-D to increase the SOL density, which should affect the SOL opacity, in C-Mod the changes were more modest. However, based on the higher SOL densities ($n_{e,exp} = 3 \times 10^{20}$ versus $n_{e,exp} = 0.3 \times 10^{20}$) in C-Mod the opacity is about a factor 7 higher than in DIII-D and nearly reaches the opacity expected in ITER. As such, the additional gas puff in C-Mod did little to increase the SOL opacity. In the next section we want to assess whether the increase in gas puff in DIII-D did result in an increase in SOL opacity.

Figure 5: a) Average (from 2000 – 5000 ms) pedestal electron density profiles for DIII-D with increasing gas puff fueling show the appearance of a density shoulder in the SOL. b) Average (from 1.1 – 1.3 s) pedestal electron density profiles for C-Mod with increasing gas puff fueling show only a moderate increase in density for the highest fueling levels.

Figure 4: Plasma shape and location of main diagnostic measurements for the C-Mod experiments.
3.2. Ionization and opacity

The ionization rate of neutrals increases for higher \( n_e \) and \( T_e \) (up to \( T_e = 100 \) eV). In our experiments, the electron temperature from the separatrix out does not vary much and we thus increase the ionization rate predominantly by raising the electron density, thus enhancing the SOL ‘opaqueness’ to neutrals and reducing the penetration of neutrals inside the pedestal. To verify this assumption, we use the midplane filterscope system on DIII-D.

The brightness \( L_{D_\alpha} \) can be inverted to emission using the geometrical properties of the system. The emission, \( I_{D_\alpha} \) can then be related to the local neutral density, \( n_0 \), using

\[
I_{D_\alpha} = \frac{n_0}{\sigma(T_e, n_e) >},
\]

where \( \sigma(T_e, n_e) > \) is the electron excitation rate coefficient \([11] \). To first order, in order to compare the discharges to each other, we assume that the variation in the electron excitation rate coefficient is small (the electron temperature in the SOL is similar), compared to the changes in \( n_e \) from discharge to discharge. Second, since all the plasmas have the same equilibrium and the midplane filterscope diagnostic geometry does not change, we use the brightness divided by the local electron density, \( L_{D_\alpha}/n_e \), as a proxy for \( n_0 \). This means we can compare the same filterscope signals from discharge to discharge, but the radial profile in itself needs to be adjusted using the geometrical factor. Future work will include this geometrical factor as well as the correct excitation coefficient based on the local temperatures and densities.

![Figure 6: Average \( L_{D_\alpha}/n_e \) versus steady-state fueling levels for different radial midplane filterscope signals for DIII-D.](image)

We map the electron density from the core Thomson Scattering system using the equilibrium information to the midplane and interpolate the electron density to get the value for each midplane filterscope signal location. We average the electron density as well as the filterscope brightness from 2100 ms to 4900 ms for each discharge. When fueling is low and the electron density is low, the proxy for the neutral density is higher than when we increase fueling in the Scape-Off Layer, as shown in Fig. 6. In Fig. 6, the diamond shaped points are all taken from filterscope measurements located in the SOL, the circles are from measurements taken in the pedestal. This data suggests that we were able to push the ionization front further out into the SOL and increase the opaqueness to neutrals. Future work will include using the 2D cameras looking at the diverter and X-point along with the measurements from the divertor Thomson Scattering to address whether the increase of main chamber opacity affects neutral fueling from the X-point, which is thought to be dominant in DIII-D plasmas \([12] \).

4. PARTICLE BALANCE

We have to perform a particle balance to assess how many neutrals end up in the main chamber and not in the pump-plenum from the increases in gas fueling. In DIII-D, the main chamber pressure does not increase with an increase in fueling. However, in C-Mod it does, as does the pressure behind each plenum (they cryopump is located in the upper divertor) as shown in Fig. 7. While the \( D_\alpha \) light doesn’t rise for the chamber wide angle measurements, the \( D_\alpha \) main chamber radial chord shows an increase with additional fueling. Since this is a line integrated measurement and the line integrated density does not increase (Fig. 3), it is an indication of total ionization in the main chamber increasing (although enhanced signal due to reflections from the inner wall cannot be ruled out).

In DIII-D all the external fueling is through the NBI and the gas valves and in these experiments only the lower cryo-pump was Helium cold to provide the exhaust. The maximum amount of fueling is close to 500 TorrL/s where the maximum steady-state gas contribution is 300 TorrL/s, as shown in Fig. 8. The other \( \sim 200 \) TorrL/s comes from a 3 Hz 170 TorrL/s gas puff modulation and the NBI. The gas puff modulation provides an extra knob to address how the electron density and ionization respond to a change in SOL opaqueness and this will be discussed in more detail in the next section. When we compare the ratio of the fueling with respect to the exhaust we observe that this value is not constant.

![Figure 7: a) The additional LFS fueling levels result in an increase in b) the SOL density based from a tanh fit c) and \( D_\alpha \) measured by main chamber chord. The exhaust in the upper cryo-pump as well as the lower plenums increases with increased fueling for C-Mod.](image)
during the gas puff modulations. During the gas puff modulations, the ratio is much higher for the discharges that have a lower background gas puff, while the opposite can be observed in between gas puff modulations. While a small amount of the difference between the fueling and the exhaust contributes to a change in the core density, most of the difference is attributed to ‘wall loading’. Only part of this term can really be linked to wall loading, the other part is due to an increase in the SOL electron density, as shown in Fig. 8.

Based on this particle balance, only a small fraction of the added fuel actually contributes to plasma density. The average exhaust increases linearly with the increase in fueling, see figure 9a). The X-axis represents the steady-state values of the additional gas puff and this value should not be confused with the total amount of fuel that is added on average during this 3 s period. Aside from the additional steady-state gas puff, we need to also include the NBI fueling of ∼ 28 TorrL/s and the 170 TorrL/s 3 Hz gas puff modulation. Since the gas puff modulation is set to 3 Hz, on average the gas puff modulation adds 170/3 ∼ 57 TorrL/s. On average, without the steady-state gas puff, we are adding ∼ 85 TorrL/s using the NBI and the gas puff modulation from 2000 – 5000 ms. The average exhaust over this 3 s period without additional steady-state puff is ∼ 57 TorrL/s and the difference between the fueling and the exhaust (approx. ∼ 40%) is partly used to fuel the plasma while another portion gets absorbed by the walls. Figure 9a) shows that the average exhaust increases linearly with respect to the rise in steady-state fueling levels.

5. GAS PUFF MODULATION

Another way to assess how fueling affects the electron density, ionization profiles and exhaust is to apply a gas puff modulation. A Fourier decomposition of the various measurements that respond clearly with a peak in amplitude at 3 Hz allows us to extract the relative phase and amplitude to this modulation for each diagnostic. In figure 1 we can already observe that the gas puff modulation does not only affect the density, but also the $D_α$ measurements at various locations as well as the pressure under the shelf. Along with the observation that the average exhaust increases linearly with the average gas puff amount, this is an indication that on average the distribution of where the neutrals end up in the vessel and plasma remains consistent. However, while the average exhaust tracks the average fueling levels, the amplitude of the exhaust to the perturbation itself varies. There is an initial strong increase in the exhaust amplitude, although the amplitude of the gas puff modulation remains constant. The amplitude eventually saturates when we reach 150 TorrL/s. As mentioned before, this is again the fueling level at which we start to observe detachment of the outer strike-point as well as the formation of a SOL density shoulder.

At the same time, we observe that $δn_e/n_e$ measured by the core TS goes from nearly 30% relative amplitude for the lowest density discharge in the SOL to 1% at $ρ ∼ 0.98$ and further in, see figure 10. The discharges with the lowest SOL density correspond with the discharges that have low or no additional steady-state fueling levels. There is little to no drop off in amplitude further in, where ionization is negligible. A closer inspection of the relative amplitude shows two important features. First, for the two discharges with the lowest SOL density (and fueling levels), which do not exhibit shoulder formation, the relative amplitude is largest in the SOL and lowest inside the separatrix. The main difference between these discharges at lower fueling and SOL density levels, versus all others, is that the outer strike-point is attached and there is no density shoulder formation. Second, these three discharges, with shoulder formation, show a clear increase in amplitude just inside the separatrix, from $ρ ∼ 0.98 − 1.02$. 

Figure 8: a) The total fueling levels (NBI + gas), b) the total exhaust and their c) ratio calculated using particle balance. d) Is the amount of ‘wall loading’, where we can observe that part of this increase is the result of an increase in e) SOL electron density for DIII-D.

Figure 9: a) The change in the average exhaust (blue), the adjusted level by subtracting the off-set at 0 TorrL/s (green) compared to a linear (red) relationship and b) the amplitude of the exhaust response to the perturbative 3 Hz gas puff modulation versus steady-state fueling levels for DIII-D.
6. DISCUSSION AND CONCLUSION

6.1. Poloidal electron density asymmetry

Prior results on DIII-D in L-mode show that at higher electron density there can be a poloidal asymmetry in the electron density profile on closed flux surfaces. The higher electron density region on closed flux surfaces close to the separatrix is attributed to an $E \times B$ flow in the divertor region, which dissappears in H-mode. However, there is still an up-down asymmetry in these DIII-D H-mode plasmas and the asymmetry becomes more pronounced for higher fueling levels. To avoid errors in equilibrium reconstruction to assess the asymmetry in the electron density, we assume that on a closed flux surface, the electron temperature is constant. By then graphing the electron density versus the electron temperature for the same thomson laser, we can compare the measurements taken close to the plasma crown to those close to the X-point, see figure 11. Close to the separatrix the electron density is higher near the X-point and slightly lower deeper inside and the trend is that by the time one reaches the top of the pedestal, the values are comparable. This would mean, that while the neutral densities in the divertor area are higher, the plasmas there are also more opaque. Moreover, the different radial gradients poloidally as well as the introduction of a parallel gradient in the electron density can alter turbulence and thus transport.

Since the total pressure needs to be constant on a flux surface, this indicates that the ion pressure should be slightly lower close to the X-point. Considering that divertor is an area where impurities are generated, the more likely reduction in the ion pressure should come from a drop in the ion temperature.

6.2. Role of transport

While there are some similarities between how DIII-D and C-Mod plasmas responded to more opaque plasmas, there were also some differences. In EDA H-mode plasmas on C-Mod, the pedestal density was barely affected by the increase in gas puff, while the SOL density increased a little. The lack of a response in the density profiles structure rules out a definitive statement about the relative contributions of fueling versus plasma transport, based on this experiment alone. However, coupling this with prior results, indications are that we have moved C-Mod into a regime where the pedestal structure is pre-dominantly set by transport and insensitive to neutral physics. On DIII-D an increase in opacity did not reduce our ability to increase the electron pedestal density using a gas puff. A more quantitative study is needed to determine whether additional fueling would result in a more opaque state, or a state no longer regulated by ELMs, in which the DIII-D density pedestal would saturate in the same manner as on C-Mod.

6.3. Conclusion/Summary

These results indicate that high opacity and an electron density pedestal are not mutually exclusive. The role of the SOL is not just limited to opacity when it comes to fueling, because sufficient increases in opacity/SOL density result in the detachment of the outer divertor leg. The detachment of the outer leg can change the neutral recycling regime in the divertor as well as Scrape-Off Layer transport. In order to make predictions for ITER, both of these effects need to be taken into account. These experiments show that gas puffing might be inefficient and that in opaque SOL conditions most neutrals initially are ionized in the SOL. However, these ionized neutrals become part of the SOL plasma and flow to the divertor where they recycle, providing them a new opportunity to fuel the core plasma. Dedicated SOL modeling is needed in order to address the direct and indirect effects of fueling.
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