Correlation of H–mode Density Barrier Width and Neutral Penetration Length*

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Experimental observations and theoretical modeling show that the H–mode pedestal has a large impact on tokamak performance. Therefore, uncertainties in the scaling of the pedestal lead to significant uncertainties in the performance of next-step machines. For these reasons, understanding the physics of the H–mode pedestal has been an important topic of fusion research for the last several years, and one of the key questions in pedestal research is: What physics sets the width of the H–mode heat and density barriers?

Recent pedestal studies in the DIII–D tokamak provide evidence that the width of the density barrier depends on both plasma physics and atomic physics. The atomic physics includes the characteristics of the fueling neutrals; the plasma physics includes both the particle and heat transport. This evidence is based on a strong correlation between the width of the H–mode density barrier Δ_{ne} and the neutral penetration length λ_n. This correlation is obtained by comparing experimental n_e profiles to the predictions of a simple analytic model for the density profile. The model, obtained from a self-consistent solution of the particle continuity equations for electrons and neutral deuterium atoms, predicts that Δ_{ne} is the same as λ_n, as measured inside the separatrix. In its range of validity, this model quantitatively predicts the observed width of the n_e transport barrier, successfully predicts several qualitative experimental results, including scalings of the width (Fig. 1) and gradient of the n_e barrier (Fig. 2) and provides a unifying framework for understanding the shapes of both L–mode and H–mode edge density profiles. In the model, Δ_{ne} depends on the location, energy and flux of the fueling neutrals, on the particle transport and on the heat transport, which affects the ionization and charge exchange rates through the temperature profile. Thus, the success of the model provides evidence that the width of the density barrier depends on both plasma physics and atomic physics.

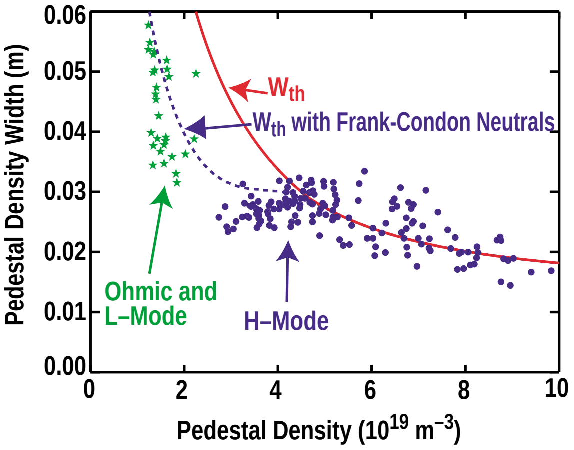

Fig. 1. Width of density barrier decreases with increasing pedestal density. Solid model curve includes only charge exchange neutrals; dashed curve also includes Frank-Condon neutrals.

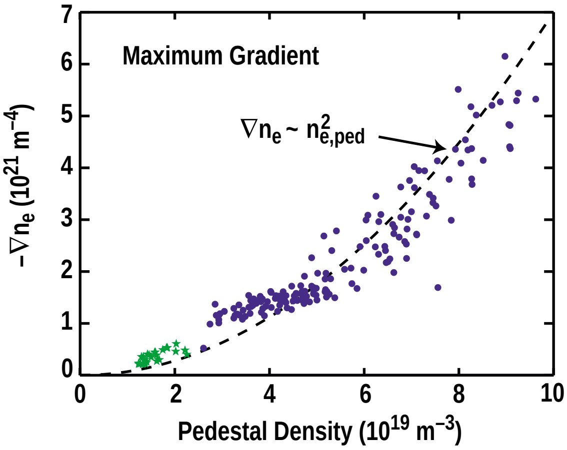

Fig. 2. Maximum density gradient of density barrier increases as square of pedestal density. dashed trend curve is proportional to square of pedestal density.

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Bench-marking of the analytic model against the much more sophisticated fluid neutrals model in the UEDGE boundary modeling code has been initiated and preliminary results show that the analytic model gives very similar results to UEDGE for the same model parameters. These results support the use of the analytic model to study trends in the plasma, despite the fact that the analytic model treats the neutral transport in a very simple way. In particular, neutrals arriving at the last closed flux surface (LCFS) are assumed to either be equilibrated with the ions, due to charge exchange process in the scrape-off layer (SOL), or to have the low energies of Frank-Condon neutrals. The ionization and charge exchange cross sections are assumed to be constant and multiple charge exchange in the plasma is ignored. This treatment restricts the validity of the model to edge temperatures in the range 0.02–0.3 keV. The analytic model assumes that the fueling is poloidally localized. A numerical factor in the model is used to account for this localization.

In its range of validity, the predictions of the model are consistent in several ways with DIII–D measurements: 1) L–mode and H–mode density profiles are predicted to have a hyperbolic tangent shape, as is observed. 2) The model predicts that the density barrier width Δ_{ne} decreases as the pedestal density $n_{e,ped}$ increases. This trend is observed experimentally over a wide range of $n_{e,ped}$, including L–mode and H–mode data (Fig. 1). These data were obtained from discharges with large gaps between the plasma and vessel wall ($\gtrsim$ 6 cm) in order to keep the fueling location as constant as possible. The widths tend to show some deviation from a strictly monotonic trend with $n_{e,ped}$. This deviation is modeled as a transition from neutrals which are primarily at the Frank-Condon energy to neutrals equilibrated with the plasma ions via charge exchange. 3) The model quantitatively predicts the experimental widths of the n_e profile (Fig 1). For the model curves shown in Fig. 1, the numerical factor used to model the localization of the fueling source has been adjusted to give a good fit. This factor is in the range of localization factors obtained from modeling with the UEDGE code. 4) The model predicts that the maximum gradient of n_e should be proportional to $(n_{e,ped})^2$, consistent with experimental results (Fig. 2). 5) The model does not distinguish between L–mode and H–mode profiles. Therefore, it predicts that L–mode and H–mode density profiles, with the same values for $n_{e,ped}$, should have approximately the same widths. This prediction is observed experimentally. However, it is necessary to apply a much higher gas puffing rate in the L–mode discharge to match the H–mode pedestal density, as expected for a larger particle diffusion coefficient in the L–mode. 6) The model nicely explains the typical changes in the density profile which occur at the L-H transition in which the width of the steep gradient region shrinks as the pedestal height increases. This phenomenology can be explained by a reduction of the particle diffusion coefficient with the particle source remaining unchanged (or increasing).

One important limitation of the analytic model is that it does not predict the observations of an increase of Δ_{ne} in plasmas that have a simultaneously increasing $n_{e,ped}$ and edge temperature. These results are obtained in plasmas with pedestal temperatures above the region of validity (0.3 keV) of the analytic model and include plasmas that evolve to the VH–mode state. It is plausible that these observations can be explained by the combination of decreasing ionization rate and increasing charge exchange rate with rising temperature. These effects result in deep penetration of the neutrals due to multiple charge exchange. If this explanation is correct, then the atomic physics of the neutrals may provide a mechanism whereby the width of the density barrier increases with the edge ion temperature.

The analysis of DIII–D H–mode data, presented here, is consistent with the hypothesis that the scale size of the H–mode density barrier is determined by a combination of plasma physics and atomic physics. If this picture is correct, there are two important implications. First, a predictive capability for the width of the density barrier requires a validated predictive capability for the particle transport. Secondly, techniques to modify the particle fueling might provide means to control the width of the density barrier. In particular, a technique which provides deeper fueling than conventional gas-puffing might produce a density barrier which is wider than conventional H–mode barriers.