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ABSTRACT

An analytic model for the width of the electron density transport barrier shows qualitative and quantitative agreement with systematic data obtained in the DIII–D tokamak. The width of the barrier in H–mode decreases as the pedestal density increases. Moreover, for L–mode and H–mode density profiles with the same pedestal density, the gradients of the barriers are of similar magnitude even though the temperature and pressure gradients are much larger in H–mode. These results are consistent with the hypothesis that neutral penetration provides important physics which helps to set the width of the H–mode barrier for the electron density.

1. INTRODUCTION

Obtaining an understanding of the physics that controls the H–mode pedestal is an important topic for current H–mode research because the boundary conditions imposed by the H–mode pedestal have a significant effect on the global confinement of the plasma [1]. Therefore, accurate predictions of performance in future machines, from either physics-based transport models or scaling relationships, require an improved understanding of the physics processes which control the height of the pedestal [2].

There is very good evidence that the maximum attainable pressure gradient at the plasma edge is limited by MHD stability [3]. Thus, if some understanding of the width of the transport barrier for pressure could be obtained, then it is reasonable to expect that the height of the pressure pedestal will be calculable. However, in addition to MHD constraints on the pressure, there are also transport processes that provide constraints on the edge profiles of temperature and density [4]. Such constraints might be acting to limit the scale lengths for edge profiles and thus could be setting the width of the transport barrier. Thus, it is of interest to examine the barrier formation of individual profiles. For example, the electron density n_e obeys the continuity equation

$$\partial n_e / \partial t + \nabla \bullet \Gamma = S \tag{1}$$

where Γ is the particle flux and S is the source for the electrons. Because the particle source is large at the plasma edge, the source may have a significant effect on controlling the shape and the width of the n_e profile in the H–mode transport barrier. More than 20 years ago, Engelhardt produced a simple analytic solution to the coupled continuity equations for the electrons and hydrogen atoms which showed that the n_e profile should have the functional form of a hyperbolic tangent (tanh) inside the separatrix [5]. Subsequently, if has been found experimentally that the tanh functional form provides a very good fit to the edge n_e profile in both L–mode and H–mode profiles in the DIII–D tokamak [6].

More recently, direct measurements of the neutral source have been made in the Alcator C-Mod tokamak and the results have been compared to solutions of the coupled equations for electrons and neutrals [7]. The model used in that work predicts that the characteristic width of the region of steep gradient in the density profile is

$$W_{n_e} = 2\sqrt{D/2\nu_i} \tag{2}$$

and that the electron density pedestal

$$n_{ped} = n_0\sqrt{2V_n^2/D\nu_i} \tag{3}$$

with ν_i and n_0 being the ionization frequency and the neutral density at the boundary of the confined plasma, D being a fixed particle diffusion coefficient and V_n being the neutral velocity. Measurements of ν_i, a theoretical model for D and the assumption that the neutrals are uniformly distributed around the plasma were used to show that these expressions gave quite reasonable agreement with W_{n_e} and n_{ped} from direct measurements of the electron density profile in H–mode. These results provide very good evidence that neutral physics is important for shaping the edge density profile. These measurements have the caveat that a theoretical model from neoclassical theory was required to evaluate the particle diffusion coefficient. Insofar as there is no experimentally validated theory for D, the uncertainties in the model estimates for W_{ne} are unknown.

There is a complementary way of expressing the solutions for the coupled electron and neutral atom equations which provides a way to compare experimental values for the width of the density profile to the model without the need to know the particle diffusion coefficient. This approach reveals that for a given value of n_{ped}, the theoretical shape for the edge density profile is determined by the neutral penetration length and does not depend explicitly on the diffusion coefficient. It can be shown that $W_{ne} \approx 2V_n/(\sigma V_e n_{ped})$ where V_n is the mean velocity of the neutrals, perpendicular to the flux surface, V_e is the electron thermal velocity and σ is the cross section for electron impact ionization. Thus, W_{ne} is the characteristic neutral penetration length at the plasma edge. Moreover, the result implies that if the height of the density profile is given, then the shape of the profile is rather well determined. In particular, for a fixed ratio of velocities, $W_{ne} \propto 1/n_{ped}$, independently of the value of D. This approach shows that direct measurements of the edge electron density profile can be used to test the neutrals model, independently of the need to measure the neutral source or to know the particle diffusion coefficient.

The purpose of this paper is to present the model just described. A carefully designed experiment in DIII–D has been performed to test the model [8] and the results are presented. They show that the experimental widths for the density profile exhibit the qualitative decrease with increasing n_{ped} as predicted by the model. The values of the experimental widths agree with the model to better than a factor of two, which is the level of accuracy that is expected for the approach used here. Finally, L–mode and H–mode density profiles with the same value of n_{ped} have similar shapes, as would be expected from this model. This occurs even though the particle transport in L–mode and H–mode is very different [9]. Thus, these results provide evidence that neutral penetration physics plays a significant role in setting the width of the electron density barrier in H–mode.

2. MODEL

The analytical model used here is an extension of the Engelhardt model [5] and has been derived elsewhere [10]. The salient features of the model are as follows. The model is a solution in slab geometry of the coupled particle continuity equations for electrons and hydrogen atoms, with impurities neglected. The model includes a very simple treatment of the equations on the open field lines in order to allow for a finite density at the separatrix. Separate particle diffusion coefficients D_s and D_c are used in the scrape-off layer (SOL) and core, respectively. The behavior of neutrals in the SOL is not treated. For the purposes of the analytical model, it is sufficient to have an estimate of the average velocity of the neutrals at the separatrix and of the approximate poloidal distribution of the neutrals around the plasma. This latter information is required because the distance between flux surfaces varies around the plasma and therefore, the distance that a neutral can penetrate in flux space depends on its poloidal location. Insight for these issues has been gained from Monte Carlo modeling of neutrals in DIII–D plasmas [11,12]. For typical densities, the neutrals can be assumed to be equilibrated with the ions by the time they reach the separatrix. Therefore, the velocity of the neutrals perpendicular to the flux surfaces is assumed to be $V_n = V_{th} / \sqrt{2\pi}$ where V_{th} is the thermal velocity of the ions. Further diffusion of the neutrals into the plasma is ignored. This is considered to be an acceptable approach because for the moderate temperatures of interest, there is approximately one charge exchange event per ionization [13] and thus the diffusion will be small. The present version of the model is valid for temperatures in the approximate range of 0.02–0.3 keV. Monte Carlo modeling [11,12] and D_α measurements [14] indicate that the neutral source is concentrated near the X–point, although not necessarily at the X–point.

The solution for the electron density n_e is written in terms of χ, the perpendicular physical distance from the LCFS to the location of interest. The neutrals are assumed to enter the plasma from a localized region on the LCFS that is centered at the poloidal angle θ_0 and the density measurement is made at the poloidal angle θ_m, as shown in Fig. 1. Figure 1 also provides some information from a Monte Carlo calculation for an H–mode plasma in DIII–D, although this discharge had a somewhat different shape than the shape used in this study. The calculated neutral density peaked at the poloidal angle θ_0 and the FWHM for the neutral spatial distribution is also shown. In poloidal angle, the FWHM is about 55°. Because the distance between flux surfaces varies with poloidal angle, a geometric function $f(\theta) = (d\chi/d\xi)|_\theta$ is defined where ξ is a coordinate that labels the flux surfaces. The flux expansion factor $E = f(\theta_0)/f(\theta_m)$ is the ratio of the distance between two flux surfaces at the poloidal angle of the particle source and at the poloidal angle where the measurement is made. In the scrape-off layer (SOL), the solution for the density is

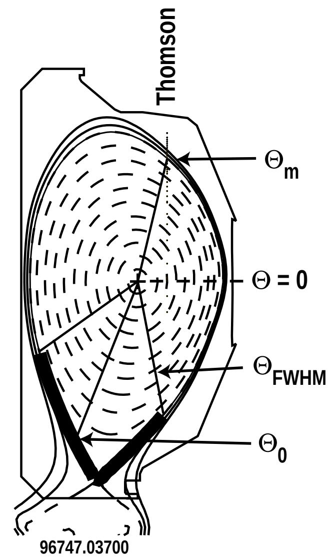

Fig. 1. Equilibrium, for DIII–D discharge 96747 at 3700 ms, showing poloidal angle θ_m of measurement along Thomson chord and angle θ_0 of peak in neutral density, as calculated with Monte Carlo code [17]. FWHM of the neutral density profile is shown by thickened region at separatrix.

$$n_e(\chi) = n_{lcfs}\exp\left(-\chi/\sqrt{D_s\tau_{||}}\right) \tag{4}$$

where n_{lcfs} is the density at the LCFS and $\tau_{||}$ is the average particle lifetime in the SOL [15]. On the close field lines $(\chi \le 0)$, the solution is

$$n_e(\chi) = n_{ped}\tanh\left[C - (\sigma V_e/2V_n)n_{ped}E\chi\right] \tag{5}$$

with $C = 0.5\sinh^{-1}(U)$ and $U = \left[\sqrt{D_s\tau_{||}}\sigma V_e/V_n\right]En_{ped}D_c/D_s$ where n_{ped} is the asymptotic density obtained as $\chi \to -\infty$ with "ped" meaning "pedestal" and referring to the density obtained at the top of the transport barrier. Under the assumption that C can be neglected, which is approximately true for the lower densities of interest, Eq. (5) can be written as

$$n_e(\chi) = n_{ped} \tanh\left[-\chi / W_{ne}\right] \tag{6}$$

where the width

$$W_{ne} = 2V_n \Big/ \left(\sigma V_e E n_{ped}\right) \tag{7}$$

is the characteristic distance for the density to achieve its pedestal value as measured from the LCFS. This distance is also the neutral penetration length as measured at the particle source, with E = 1. This approximation reveals the basic relationship that at a fixed poloidal angle and at a fixed ratio of velocities, $W_{ne} \propto 1/n_{ped}$.

3. RESULTS

For comparisons of the experiment to the model, it is desirable to compare the widths. The experimental width parameter W_{ex} is defined as 2Δ where Δ is obtained from the fit to $\tanh\left[\left(z_{sym} - z\right)/\Delta\right]$, z is the spatial coordinate along which the measurements are performed and z_{sym} is a fit parameter. Although the theoretical and experimental functions include the tanh shape, the functions are not identical. The experimental fits extend the tanh function into the SOL, whereas the theoretical model truncates the tanh at the separatrix and uses a decaying exponential in the SOL. The simplest way to compare the model to the experiment under these conditions is to define a theoretical width W_{th} to emulate the width from the experimental fits. Thus, a theoretical width will be used here where the width is the distance from the points where the density is 88% of n_{ped} to 12% of n_{ped}. The 88% point is obtained from Eq. (5) and the 12% point will usually be obtained from Eq. (4) for the SOL. The evaluation is performed at the poloidal angle and along the chord of the Thomson scattering laser. The widths determined in this way are approximately a factor of two larger than they would be if transformed to the outside midplane. This procedure provides a reasonable and consistent way to compare the experiment and the model.

For the comparison of data to the model, nominal values of the free parameters in the model are estimated from typical experimental conditions. The particle diffusivities D_s and D_c are taken as 0.14 and 0.4 m^2/s, based primarily on results from transport modeling. The flux expansion factor E is estimated to be 2.5 (Fig. 1) from the results of Monte Carlo modeling of fuelling in DIII–D [12] and from the known measurement location. The edge ion temperature T_i is assumed to be 150 eV and the electron temperature T_e is assumed to be $T_i/2$. Knowing the exact value of T_e is not critical because the ionization rate varies weakly with T_e for the edge temperatures for which the model is valid. Sensitivity analysis of the full model [8] has confirmed the implications of Eq. (7). For a given value of n_{ped}, the theoretical width has almost no dependence on the values of the particle diffusion coefficients. Rather, the most influential parameters are the flux expansion factor E, which affects the width as about 1/E, and the ratio of ion to electron thermal velocities, which affects the width as approximately $\sqrt{T_i/T_e}$.

In order to test the model, a careful experiment was done in which n_{ped} was varied over as wide a range as possible with gas puffing to raise the density and cryopumping to reduce the density. One shape, a single-null divertor, was used to obtain the entire data set and it was carefully chosen to minimize plasma fuelling from any region except the vicinity of the X–point. Figure 2 is a plot of the measured width of the electron density profile W_{ex} as a function of n_{ped} with theoretical curves of W_{th} overlayed. The experimental data are obtained from the DIII–D Thomson scattering system [16]. Data plotted as circles were obtained during the H–mode phase of discharges with plasma current I_p = 1.2 MA (with some points obtained late in the current ramp to 1.2 MA), toroidal magnetic field B_T = 1.5–2.1 T and the neutral beam heating power P_b = 0.8–7.4 MW. The data are averaged over 100 or 300 ms, and each point represents multiple individual measurements. Data obtained during ELMs, which temporarily destroy the H–mode barrier, are eliminated. Most of the H–mode points are in the range $n_{ped} = 4–10\times10^{19}m^{-3}$ and the widths decrease with increasing n_{ped}. Data plotted as stars, all lying at $n_{ped}\leq4\times10^{19}m^{-3}$, were obtained from the ohmic and L–mode phases of a subset of these discharges with many of the points obtained during the current ramp to 1.2 MA.

The full set of data shows the general trend of width decreasing with increasing n_{ped}. The theoretical curves with E = 2 and 3 and with other parameters set to the nominal values discussed previously, bracket the H–mode data very well, showing that the model qualitatively has good agreement with the data. The experimental widths for $n_{ped}\leq4\times10^{19}m^{-3}$, which includes the ohmic, L–mode and some H–mode data, are less than expected from the theory curves. A possible explanation for this behavior is that at the lower densities that the neutrals are not fully equilibrated with the ions and thus do not penetrate as efficiently as predicted. A simple model to incorporate the effects of the low energy Frank Condon neutrals has been developed and the model provides reasonable agreement with the low density data. Even if the neutrals are

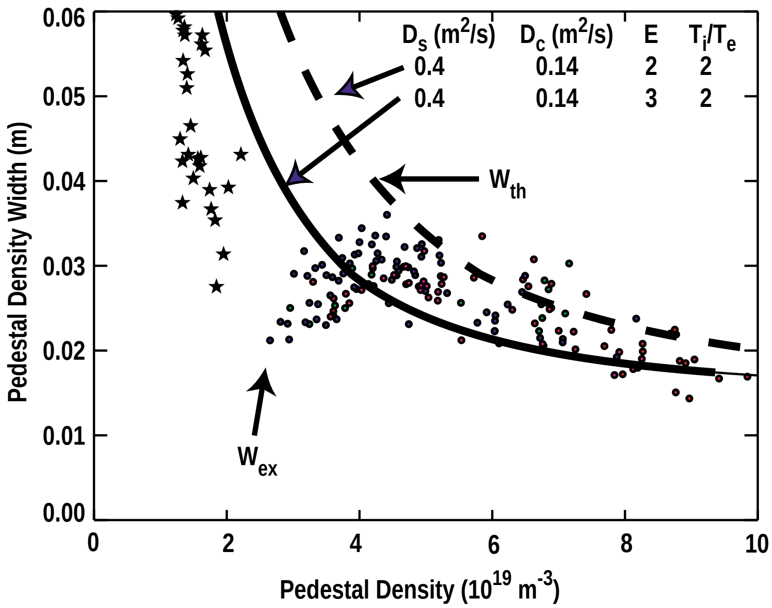

Fig. 2. Experimental widths for edge density profile as a function of pedestal density. Data with circles are from H–mode phase of discharges and data with stars are from ohmic and L–mode phase of a subset of the discharges. Overlayed curves are widths from model with E set to 2 and 3 and other parameters at nominal values.

equilibrated at the plasma edge, it is possible that the treatment of temperature effects in the model is too simple to emulate some of the trends in the data. A more thorough test of these explanations requires calculations with a neutrals code and has not yet been done.

The model presented here should apply equally to L–mode and H–mode discharges. Thus, L–mode and H–mode density profiles with the same values of n_{ped} would be expected to have approximately the same shape. In practice, it is difficult to find such matched discharges because H–mode densities tend to be higher than L–mode densities. However, some examples of nearly equal n_{ped} values in L–mode and H–mode have been found in DIII–D and one example is shown in Fig. 3. This figure shows that although the edge gradients of electron pressure and temperature are higher by about an order of magnitude in the H–mode discharge than in the L–mode discharge, the gradients of the electron density are very similar, differing by ~40%. The widths of the two density profiles are also similar, with the L–mode profile having a slightly larger width than the H–mode profile. The modest differences in the profiles might be due to the particle source being more uniformly distributed around the plasma in the L–mode than the H–mode plasma a difference which would imply a smaller *E* in the model. This comparison is in stark contrast to standard comparisons of L–mode and H–mode density profiles for which the gradients differ by about an order of magnitude [8]. In those comparisons, the n_{ped} values are also substantially different.

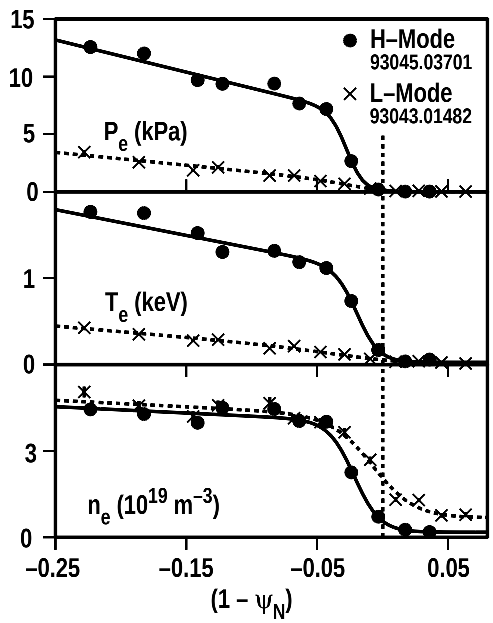

Fig. 3. Comparison of edge P_e, T_e and n_e profiles for L–mode and H–mode (I_p = 1.5 MA) discharges with nearly equal values of density on pedestal. Data are plotted as function of the normalized poloidal flux function. Dashed line shows location of LCFS, determined from equilibrium reconstructions. Lines through the data are fits from TANH function.

4. CONCLUSIONS AND DISCUSSION

The coupled continuity equations for electrons and hydrogen atoms can be solved with simple assumptions to show that the width of the steep gradient region of the edge electron density profile is the characteristic penetration length for neutrals. This simple model is consistent with several observations from the DIII–D tokamak: 1) the edge density profile in L–mode and H–mode has the hyperbolic tangent shape; 2) the model successfully predicts that the width of the steep gradient region decreases as the pedestal value for the density increases; 3) for moderate to high densities, the model predicts the width of the H–mode profiles to better than a factor of two, the level of accuracy expected for this model; 4) L–mode and H–mode discharges with approximately equal values for the pedestal density have similar shapes for the steep gradient region of the density profile. These results strongly suggest that neutral penetration plays an important role in setting the width of the electron density transport barrier in H–mode.

Although the role of neutrals has been emphasized here, Eqs. (2) and (3), presented in Ref. [7], remain valid of course and show that the width of the density barrier is controlled by particle transport as well as the atomic physics associated with neutral fueling. The model presented here goes one step further and shows that there is a canonical shape to the density profile so that the height and width of the barrier have a relationship that is nearly independent of transport and depends on the neutral penetration length. Thus, testing of the model is possible with very poor quantitative knowledge of the particle transport.

An alternate hypothesis to the one presented here is that the steep gradient in the density profile is due primarily to the shape of the diffusion coefficient and is little influenced by the particle source. In this view, the diffusion coefficient is small where the gradient is large and diffusion is large inboard of the steep gradient region. To the extent that heat and particle transport are linked, this model implies that the inner edges of the temperature and density barriers should occur at the same location. There are examples from DIII–D in which the inner edge of the T_e barrier extends further into the core than the inner edge of the n_e barrier. These results appear to be contradict the alternate hypothesis. However, a satisfactory treatment of this topic requires analysis and data which are beyond the scope of this work and remains an important topic for future study.

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