Empirical Study of $\eta_e$ in H-mode Pedestal in DIII-D

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I. Introduction

There is compelling empirical [1] and theoretical [2] evidence that the global confinement of H-mode discharges increases as the pedestal pressure or temperature increases. Therefore, confidence in the performance of future machines requires an ability to predict the pedestal conditions in those machines. At this time, both the theoretical and empirical understanding of transport in the pedestal are incomplete and are inadequate to predict pedestal conditions in present or future machines.

Recent empirical results might be evidence of a fundamental relation between the electron temperature $T_e$ and electron density $n_e$ profiles in the pedestal. A data set from the ASDEX-Upgrade tokamak has shown that $\eta_e$, the ratio between the scale lengths of the $n_e$ and $T_e$ profiles, exhibits a value of about 2 throughout the pedestal, despite a large range of the actual density and temperature values [3]. Data from the DIII-D tokamak show that over a wide range of pedestal density, the width of the steep gradient region for the $T_e$ profile is about 1–2 times the corresponding width for the $n_e$ profile, where both widths are measured from the plasma edge [4]. Thus, the barrier in the density might form a lower limit for the barrier in the electron temperature.

As implied above, there is no validated theory for electron thermal transport in the pedestal. However, significant theoretical work has been done for electron temperature gradient (ETG) turbulence for conditions appropriate to the core of tokamaks. For example, linear toroidal gyrokinetic simulations have been performed for a wide range of plasma conditions and the results have been used to develop an analytic formula for the critical $T_e$ gradient at which ETG turbulence would be expected to turn on [5]. This result is

$$\left(\frac{R}{L_{T_e}}\right)_{\text{crit}} = \max \left[0.8R/L_n, F(\tau, s, q, \varepsilon, \kappa)\right],$$

where $R$ is major radius, $L_{T_e} = T_e/|\nabla T_e|$, $L_n = n/|\nabla n|$, $\tau = Z_{\text{eff}} T_e/T_i$ where $Z_{\text{eff}}$ is the effective ion charge, $T_i$ is the ion temperature, $s$ is magnetic shear, $q$ is safety factor, $\varepsilon$ is inverse aspect ratio and $\kappa$ is elongation. The function $F$ is displayed in Ref. [5]. This equation predicts that ETG turbulence will turn on when the normalized gradient of $T_e$ exceeds the larger of two terms. If the turbulence were sufficiently strong, the $T_e$ gradient would not rise significantly above the critical level. For a sufficiently strong density gradient, it would be expected that the electron density and temperature profiles would exhibit the relationship

$$\eta_e = L_n/L_{T_e} = 1.$$
For steep edge gradients, the authors of Ref. [5] state that the plasma might deviate significantly from the critical condition as expressed in Eq. (1). Specifically, the condition for the onset of strong turbulence might be substantially different than the condition for linear stability. Thus, the observed \( \eta_e \) might deviate from unity. With that caveat, the data from ASDEX-U and from DIII-D show features that are qualitatively consistent with the theory: \( \eta_e \) being about 2 and \( \nabla T_e \) being large where \( \nabla n_e \) is large. These results suggest that it would be useful to perform further empirical studies of the relation between edge \( T_e \) and \( n_e \) profiles in the H-mode pedestal. The theory embodied in Eq. (1), though not strictly applicable to the pedestal, is used to pose three questions for study. Is there evidence for a linear relation between \( L_{T_e} \) and \( L_{n_e} \) at the steepest part of the edge density gradient? If so, what are the values of \( \eta_e \)? Lastly, does this relation hold over the full extent of the density pedestal?

II. Analysis Method and Results

For the analysis presented here, the edge \( T_e \) and \( n_e \) profiles have been fit with a modified hyperbolic tangent function (tanhfit) [6] with the data being obtained from the DIII-D Thomson scattering system [7]. Long experience shows that this functional form routinely fits the data to within the measurement errors. Thus, these fits allow for a convenient way to evaluate the profiles and their gradients at arbitrary locations near the edge.

Figure 1 shows an example of experimental \( T_e \) and \( n_e \) profiles from the H-mode pedestal with the model fits overlayed. This figure also demonstrates some terminology that will be used in this paper. The largest density gradient occurs at the “symmetry” point of the density profile, a location which is determined from the fit. The “knee” of the density profile is a measure of the location of the inner edge of the density barrier; in terms of fitting parameters, this position is a half-width into the plasma as measured from the symmetry point. Finally, the “foot” of the \( n_e \) profile is the location that is a half-width away from the plasma core as measured from the symmetry point. All physical coordinates in this paper are elevation along the Thomson laser chord. If projected to the outboard midplane, the widths would be compressed by about a factor of two. However, no conversion is done here.

![Fig. 1. Typical profiles of \( T_e \) and \( n_e \) in the H-mode pedestal. Data shown as function of vertical position along Thomson chord, measured relative to midplane of machine. Solid lines are fits from tanhfit function. Positions of density foot, symmetry point and knee are shown as vertical lines. Inset shows Thomson laser chord.](image-url)
A search for a relation between $L_{Te}$ and $L_{n_e}$ is presented in Figs. 2 and 3. Both figures contain data from the ELM-free phases of five discharges, which sample a wide range of DIII-D operating space. The data are evaluated at the location of the steepest density gradient under the hypothesis that that would be the place where ETG turbulence would have the best chance of manifesting some effects on the relation between the $T_e$ and $n_e$ profiles. A running boxcar average of 50 ms has been performed for all data in these figures. Figure 2, a plot of $L_{Te}$ versus $L_{n_e}$, shows evidence of a linear relationship between $L_{Te}$ and $L_{n_e}$ for a given discharge. This relationship is also apparent in Fig. 3, a plot of $\eta_e \equiv L_{n_e}/L_{Te}$ versus $\nabla T_e$. Taken as a whole, these data show that $\eta_e$ is in the approximate range of 1-3 for a range of pedestal conditions in which $\nabla T_e$ spans about an order of magnitude. For a given discharge, $\eta_e$ is approximately constant during the ELM-free phase, characterized by the variation of $\nabla T_e$.

Figure 3 shows that three of the discharges in the survey had $\eta_e$ values which were comparable and close to unity, but two discharges had significantly larger $\eta_e$ values. The two discharges with the large $\eta_e$ values both had very high upper and lower triangularity as compared to the other three discharges. However, there has not yet been sufficient study to determine if the differences in $\eta_e$ values are related to these or other characteristics of the discharges.

Figure 4 examines the relationship between $L_{Te}$ and $L_{n_e}$ over the region in which there is a large density gradient. For a VH-mode discharge, profiles of $\eta_e$ at the plasma edge are plotted and vertical lines are overlayed at the positions of the density foot and knee. These data show that in the region of steep density gradient, $\eta_e$ is in the range of about 1-3 for this...
discharge. Figure 4 also shows that inboard of the region of step density gradient, the $\eta_e$ values rise significantly above the values seen in the pedestal. This is a region of flat density gradient, and a relationship between $L_{T_e}$ and $L_{n_e}$ is not expected from the available theory.

**III. Summary and Conclusion**

A survey of $L_{T_e}$, $L_{n_e}$ and $\eta_e$ has been made in the ELM-free phases of a variety of DIII-D discharges. The $L_{T_e}$ and $L_{n_e}$ data evaluated at the location of steepest density gradient, show evidence of a linear relationship in a given discharge. The ratio of these values is not a constant; $\eta_e$ is in the range of 1-3 in the pedestal for the discharges evaluated. These results are found for other discharges that have been studied. These characteristics could be evidence that edge transport sets up a relation between the $T_e$ and $n_e$ profiles. ETG turbulence is a candidate for a mechanism to set up this relationship. Firmer conclusions on this point await the development of a theory, valid for the steep gradient region at the plasma edge, which can explain the range of $\eta_e$ values that have been observed.

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