*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-2.173 (2004)*

Empirical Study of η_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 η_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

$$\left(R/L_{T_e}\right)_{\text{crit}} = \max\,[0.8R/L_n, F(\tau,\hat{s},q,\varepsilon,d\kappa/dv)] \quad , \tag{1}$$

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_{eff} is the effective ion charge, T_i is the ion temperature, $\hat{s}$ is the magnetic shear, q is safety factor, ε is inverse aspect ratio and κ 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 $\eta_e \equiv L_n/L_{T_e} \approx 1$.

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 η_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: η_e being about 2 and ∇T_e being large where ∇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 η_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.

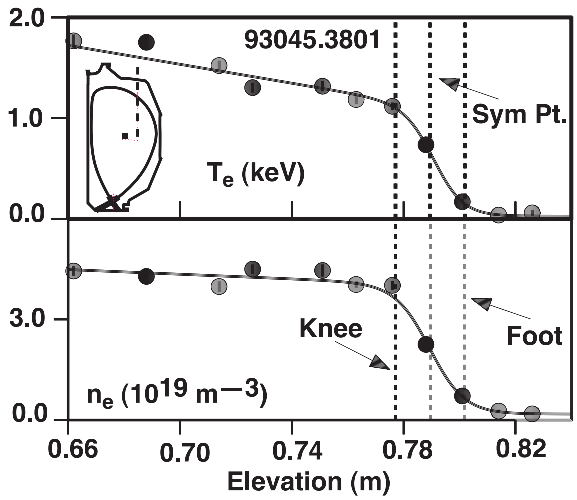

Fig. 1. Typical profiles of T_e and n_e in the H-mode pedestal. Data shown as function of vertical position along Thomson chord, measured relative to midplane of machine. Solid lines are fits from tanhfit function. Positions of density foot, symmetry point and knee are shown as vertical lines. Inset shows Thomson laser chord.

A search for a relation between L_{T_e} 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_{T_e} versus L_{n_e}, shows evidence of a linear relationship between L_{T_e} and L_{n_e} for a given discharge. This relationship is also apparent in Fig. 3, a plot of $\eta_e \equiv L_n / L_{T_e}$ versus ∇T_e. Taken as a whole, these data show that η_e is in the approximate range of 1-3 for a range of pedestal conditions in which ∇T_e spans about an order of magnitude. For a given discharge, η_e is approximately constant during the ELM-free phase, characterized by the variation of ∇T_e.

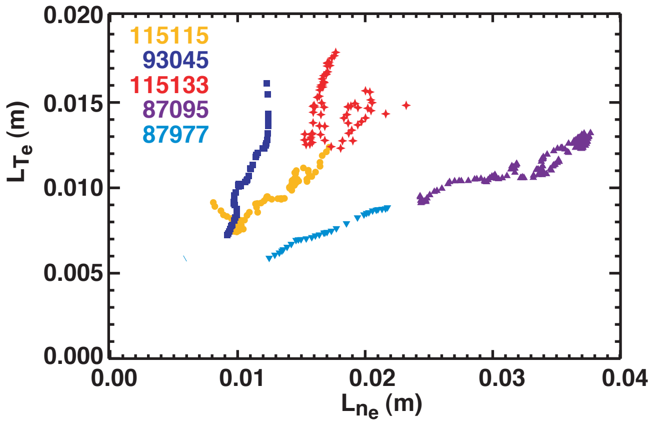

Fig. 2. Plot of L_{T_e} and L_{n_e} data, measured at point of steepest density gradient during ELM-free phases of discharges. Various discharges are differentiated by color and symbol. Scale lengths are along Thomson laser path.

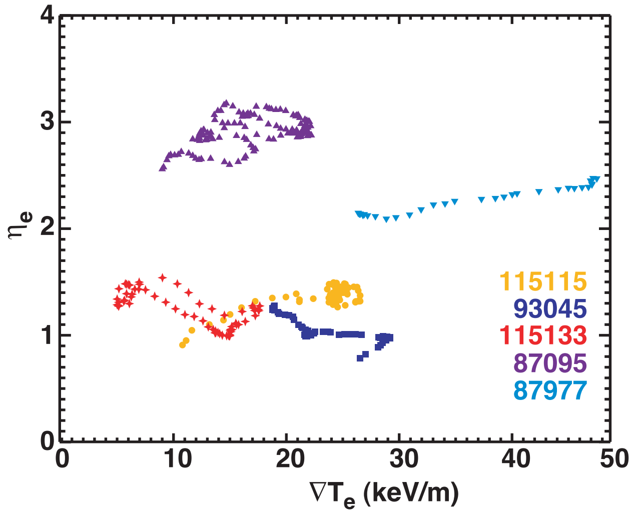

Fig. 3. Plot of η_e and ∇T_e, measured at point of steepest density gradient during ELM-free phases of discharges. Various discharges are differentiated by color and symbol. Gradient is along Thomson laser path.

Figure 3 shows that three of thedischarges in the survey had η_e values which were comparable and close to unity, but two discharges had significantly larger η_e values. The two discharges with the large η_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 η_e values are related to these or other characteristics of the discharges.

Figure 4 examines the relationship between L_{T_e} and L_{n_e} over the region in which there is a large density gradient. For a VH-mode discharge, profiles of η_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, η_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 η_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.

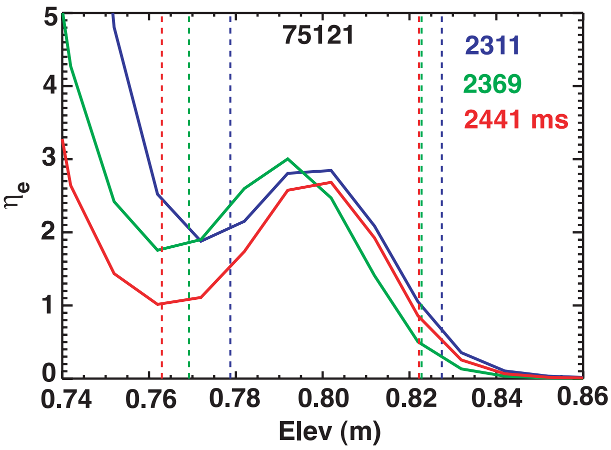

Fig. 4. Profiles of η_e along Thomson laser at three different times in the ELM-free phase of a VH-mode discharge. Vertical lines show locations of knee and foot of density profile (lower and higher elevation, respectively).

III. Summary and Conclusion

A survey of L_{T_e} ,L_{n_e} and η_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; η_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 η_e values that have been observed.

Work supported by the U.S. Department of Energy under DE-FC02-04ER54698 and W-7405-ENG-48.

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