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OVERVIEW OF H–MODE PEDESTAL RESEARCH ON DIII–D

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OVERIVEW OF H-MODE PEDESTAL RESEARCH ON DIII-D

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Introduction. Developing an understanding of the processes that control the H-mode transport barrier is motivated by the significant impact this small region (typically <2% of the minor radius) can have on overall plasma performance. Conditions at the inner edge of the H-mode transport barrier can strongly influence the overall energy confinement, and the maximum density, and therefore fusion power, that can be achieved with the typically flat H-mode density profiles [1,2]. The ELM instability, which usually regulates the pressure gradient in the H-mode edge, can result in large power loads to, and erosion of, the divertor targets in a reactor scale device [3]. The goal of H-mode pedestal research at DIII-D is to: 1) develop a physics based model that would allow prediction of the conditions at the top of the H-mode pedestal, 2) develop an understanding of processes which control Type I ELM effects in the core and divertor, and 3) explore alternatives to the Type I ELM regime.

Edge Pressure Gradient in Type I ELM Regime. There is considerable evidence from DIII-D that the ideal ballooning mode is not a good candidate for the Type I ELM instability. The pressure gradient in the majority of DIII-D discharges exceeds the ballooning mode stability limit by as much as a factor of 5. Moreover the variation of edge pressure gradient with shape is not consistent with the predictions of ballooning mode theory [Fig. 1(a)]. Observations suggest a low n, ideal, edge localized, kink/ballooning mode is responsible for the Type I ELM. Fast growing modes with 1 < n < 10 are observed as precursors to the ELMs [Fig. 1(c)]. Low n stability code calculations are in agreement with the observed variation in edge pressure gradient with shape. These calculations also predict an inverse relationship between the steep gradient (transport barrier) width and pressure gradient that tends to maintain the pedestal pressure fixed [Fig 1(b)]. There is evidence that second stability plays a role in determining the maximum edge pressure gradient [4]. Over a narrow range in *squareness* (squareness corresponds to triangularity but for the outboard side of the flux surface) the ELM frequency increases from a few hundred Hz to several kHz. This is expected for ideal ballooning modes since the current required to lower the global magnetic shear sufficiently to allow second stable access ($S \approx S_0 - j_T^{EDGE} / \langle j_T \rangle$) exceeds the available bootstrap current at high or low squareness. Second stability has also been demonstrated for intermediate n peeling/ballooning modes (n = 10-40) [4] such that there is no second stable access below a critical value of n. The critical pressure gradient for instability with self consistent bootstrap current and wall effects included decreases with increasing n. It is hypothesized then that the n for the ELM instability corresponds to the highest n mode without second stable access consistent with the actual edge current (shear). Over the next year a new lithium beam diagnostic [5] will become available on DIII-D which will greatly improve the accuracy of the edge current density and shear determination.

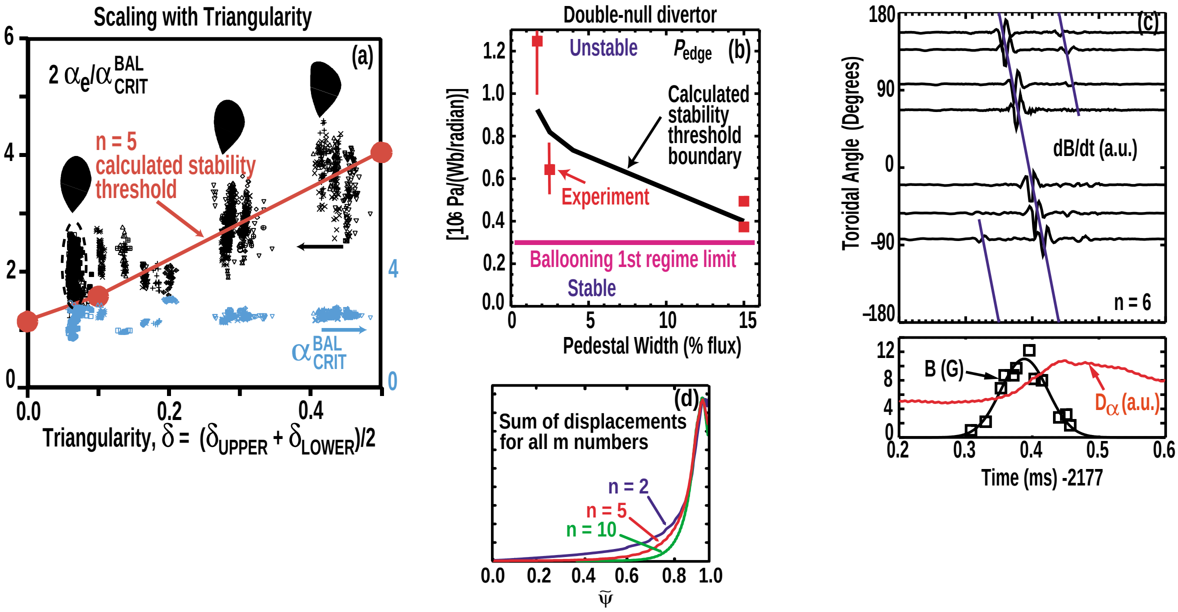

Fig. 1. (a) Edge pressure gradient before Type I ELM normalized to ideal ballooning mode limit increases with triangularity in agreement with ideal low n kink/ballooning mode calculation. Circled points correspond to variation in transport barrier width. (b) Critical edge pressure gradient for n=5 mode decreases with increasing width of the steep gradient region. (c) Fast growing low n modes observed as precursor to Type I ELM. (d) Radial modes structure of low n edge kink/ballooning mode.

H-mode Transport Barrier Width. Fitting an empirical scaling law to a database of H-mode pedestal and equilibrium parameters indicates that, for a fixed plasma shape, only I_p, n_e^{PED}, and T_e^{PED} are strongly correlated with the transport barrier width as determined from the shape of the electron pressure profile, Δ_{PE}. Scaling laws of the form $\Delta_{PE}/a \propto (\beta_{POL}^{PED})^{1/2}$ or $\Delta_{PE}/a \propto (\rho_{POL}^{PED}/a)^{1/2}$ fit the data equally well. A simple argument balancing the turbulence growth rate against the E×B shearing rate also suggests a temperature dependence for the width, $\Delta/a \sim \rho_*^{1/2}$. However, a temperature dependence of the width is not consistent with discharges in which divertor pumping was used to separate the co-linearity of n_e and I_p. Modeling [6] suggests that the H-mode transport barrier width in density is determined by the edge particle source and hence a function of the neutral penetration depth. To investigate this issue and the more general question of whether or not dimensionless scaling can be applied to the H-mode pedestal region, two experiments were recently performed. In one experiment, discharges on DIII-D were run with dimensionless parameters at the top of the H-mode pedestal, ν_*, ρ_*, β, q for the electrons, as well as the discharge shape matched to those of Alcator C-Mod [Fig. 2(a)]. The resulting scaled pressure gradient was then found to also match, suggesting dimensionless scaling applies to the H-mode transport barrier, however more analysis of these discharges will be required before making a definite conclusion.

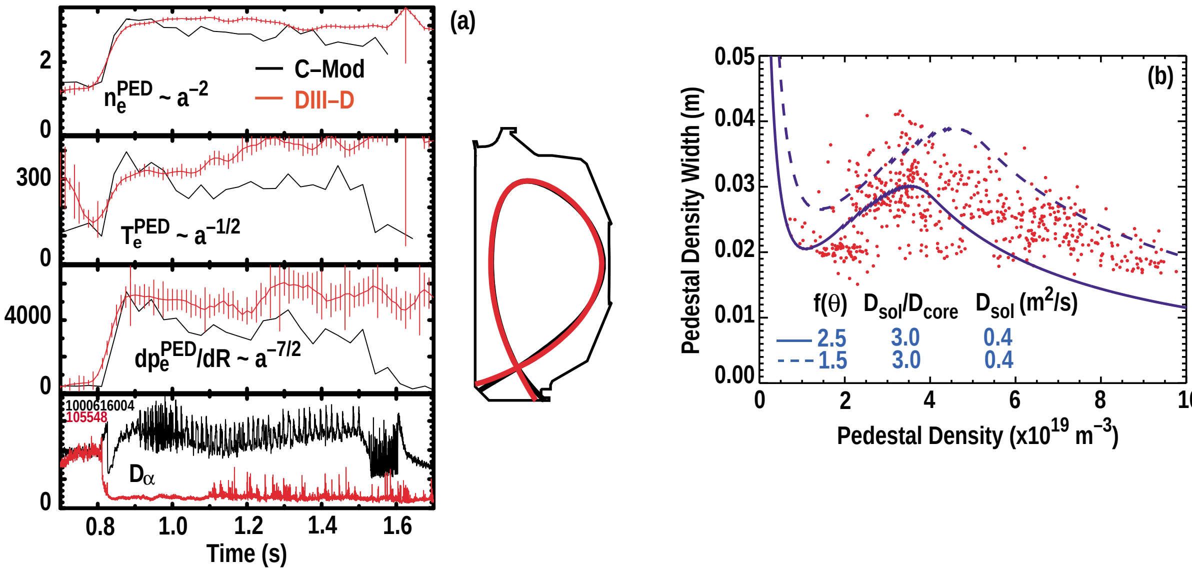

Fig. 2. (a) Scaled n_e, T_e, and plasma shape were matched and resulting pressure gradient also matched in dimensionally similar scaling experiment with Alcator C-Mod. (b) DIII-D density pedestal width is in rough agreement with neutral penetration model with flux expansion factor in the range of 1.5-2.5.

In the second experiment the variation of the width of the edge steep gradient region for the density was compared with an extension [7] of the Engelhardt-Wagner [8] model to allow for poloidal variation of the neutral source [Fig. 2(b)]. This model assumes charge exchange penetration of the neutrals and accounts for the fact that the neutral source on DIII-D is thought to be primarily from the divertor. The model predicts $n_{PED}^2 \propto n_{SEP}/f(\theta)$ and $\Delta_n \propto 1/n_{PED}$ where $f(\theta) \approx \langle\Gamma_N\rangle/\langle\Gamma_N\, d\psi/dx\rangle$ is the flux expansion weighted with the neutral source. Although this work suggests that Δ_n may be set by neutral penetration, the temperature and pressure widths are generally not correlated with the density width and thus the H-mode transport barrier width is likely set by other physics.

ELM Effects and Alternatives to Type I ELMs. The energy lost during a Type I ELM in discharges without additional gas puffing is a constant fraction ~20% of the energy in the H-mode pedestal on both DIII-D and JET [3]. As the density is raised with gas puffing the fraction of H-mode pedestal energy carried by the Type I ELM is reduced. At the same time, the n number for the ELM precursor increases and the edge pressure gradient decreases from that predicted for low n kink/ballooning modes to that predicted for infinite n ballooning. This shift to higher n is consistent with loss of access to second stability resulting from suppression of the edge bootstrap current at high collisionality. GATO results indicate that the radial width of kink/ballooning modes decreases with increasing n [Fig. 1(d)], suggesting that the size of the ELM may be set by the radial extent of the associated mode. Further evidence for this hypothesis is given by analysis of JT-60U discharges [9], which transition from large infrequent ELMs to small grassy ELMs with increased triangularity and q, where ELITE code calculations also show a decrease in radial mode width. The QH-mode [10] is an ELM-free regime with good energy confinement but without the density accumulation associated with ELM-free H-mode. QH-mode is observed at low density with divertor pumping and counter injection, and is characterized by continuous edge localized MHD oscillations which may be responsible for the density control. The H-mode pedestal conditions for QH-mode are similar to that observed for the low density branch of Type III ELMs (Fig. 3).

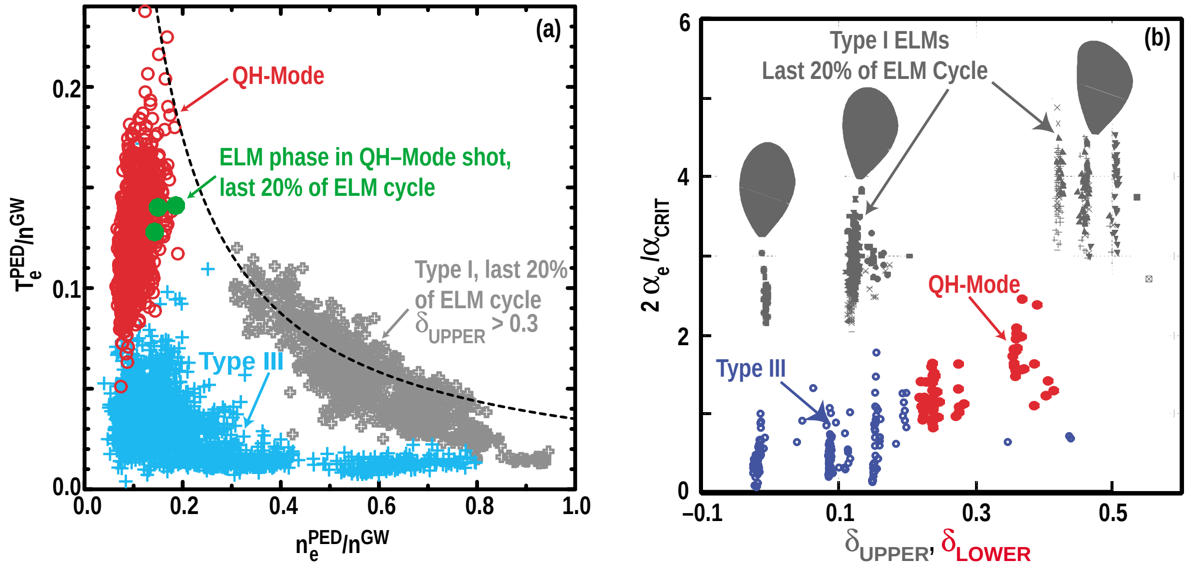

Fig. 3. Comparison of pedestal conditions in QH-mode with ELM regimes. (a) QH-mode is at low normalized density, (b) electron pressure gradient relative to ideal ballooning limit of QH-mode between Type I and III.

Conclusions. Although the low n ideal mode model seems a good candidate for the stability of the H-mode edge, building an understanding of the physics which sets the H-mode transport barrier will require continued effort. The dimensionless pedestal scaling comparison between DIII-D and C-Mod was a good step toward improved understanding in this area and more of these types of direct inter-machine comparisons could be very helpful. The coupling between the critical pressure gradient and width predicted in stability calculations, and the connection between edge E_r and the pressure gradient, suggests that a final understanding of the H-mode edge will require building a model which incorporates both transport and stability physics.

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