MODIFICATION OF H–MODE PEDESTAL INSTABILITIES IN THE DIII–D TOKAMAK

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ABSTRACT

Through comparison of experiment and ideal magnetohydrodynamic (MHD) theory, modes driven in the edge region of tokamak H–mode discharges [Type I edge-localized modes (ELMs)] are shown to result from low toroidal mode number ($n$) instabilities driven by pressure gradient and current density. The mode amplitude and frequency are functions of the discharge shape. Reductions in mode amplitude are observed in discharge shapes with either high squareness or low triangularity where the low-$n$ stability threshold in the edge pressure gradient is predicted to be reduced and the most unstable mode is expected to have higher values of $n$. The importance of access to the ballooning mode second stability regime is demonstrated through the changes in the ELM character that occur when second regime access is not available. An edge stability model is presented that predicts that there is a threshold value of $n$ for second regime access and that the most unstable mode has $n$ near this threshold.
1 INTRODUCTION

The high edge-localized pressure pedestal [1] that is characteristic of the tokamak H-mode improved confinement regime [2] often results in MHD instabilities [3, 4]. These edge-localized modes (ELMs) can have a significant impact on the tokamak discharge including energy and particle loss, perturbations of the discharge that can prevent formation of core-localized transport barriers, large heat pulses into the divertor region, and the generation of seed islands for neoclassical tearing modes. In this report we show that an improved understanding of the edge stability physics has led to methods to modify the ELM frequency and amplitude. Having available methods to modify the ELM offers the possibility of optimizing the tokamak discharge between the improved confinement resulting from the edge pedestal and the detrimental effects of the edge instabilities.

The H-mode edge pressure pedestal is a steep rise in pressure that begins at the discharge boundary and extends over a region with a width which is typically less than 5% of the poloidal flux [1, 5]. The result is a narrow, edge-localized, peak in the pressure gradient. A bootstrap current proportional to the pressure gradient would be expected and, in fact, reconstructed free boundary experimental equilibria in which the pressure profile is constrained to be equal to the measured pressure profile have a current density peak that is approximately equal to the predicted level of bootstrap current [1, 5]. Both the pressure gradient and the current density are sources of free energy that can drive instabilities.

We describe here a physics model for the edge stability threshold in which the stability boundary is drawn as a threshold in the edge pressure gradient ($P'_{\text{edge}} = \partial P/\partial \psi$, $\psi$ is the poloidal flux) only. The current density in the edge region is dependent on $P'_{\text{edge}}$ and so is modeled here as equal to the predicted bootstrap current, an assumption which is reasonable for the quasistationary, continuously ELMing phase of the discharge. As illustrated in the schematic in Fig. 1, the stability threshold depends on the toroidal mode number and the discharge shape. The combination of proper discharge shape and
sufficient bootstrap current allows access in the pedestal region to the second regime of stability [6] for high \( n \) modes \([1, 5, 7, 8, 9]\). This allows the edge pressure gradient to increase, to values well above the ballooning mode first regime stability limit \([1, 5]\), until a low toroidal mode number coupled kink/ballooning mode is destabilized. The mode number of this instability and the pressure gradient threshold for instability will depend on the discharge shape. There is a threshold value of \( n \) for second regime access and the most unstable mode has \( n \) near this threshold. Comparisons are made here to ideal MHD theory which we show describes well the experimental observations, even without the possible corrections that would result from the effects of resistivity, \( E \times B \) drifts etc.

Experiments are described in which the parameters that the edge stability model predicts are keys to the ELM stability physics are varied, with the result that the character of the ELM is modified. Changes in the discharge shape, the triangularity and the squareness, and in the edge pressure gradient through injection of impurity gas or deuterium pellets, modify the edge stability and lead to variation in the mode amplitude and frequency. The importance of access to the ballooning mode second stability regime is demonstrated through the variation in the ELM character that occurs when second regime access is not available. The observed modifications to the ELMs provide support for the edge stability model.

The DIII-D diagnostic set allows detailed comparisons with stability models. Experimental measurements of \( P'_{\text{edge}} \) are obtained with uncertainty of approximately 20% from high spatial resolution Thomson scattering measurements of the electron temperature and density and charge exchange recombination spectroscopy measurements of the ion temperature and impurity density [1]. These profile data are used along with external magnetic field and flux measurements and internal measurements of the magnetic field pitch angle from the motional Stark effect diagnostic in a self-consistent reconstruction of the tokamak equilibrium [10]. The reconstructed equilibria are used as input to stability analysis codes.
Previously, both low-n current and pressure driven kink instabilities [11, 12, 13, 14, 15] and infinite-n ballooning modes [16, 17] have been considered as causes for edge localized instabilities. Also, the effect of discharge shape [9, 12, 18, 19] and dependence of the mode growth rate on mode number [13, 14] have been studied. Here, we extend this work by showing that the mode number of the most unstable mode and the instability threshold vary continuously as the discharge shape and the H-mode pedestal width change. This variation could account for the observed differences in H-mode pedestal parameters among various tokamak experiments.

In Section 2, the role of the high-n ballooning mode is described, while Section 3 covers the role of low n coupled kink/ballooning instabilities. Further experiments to modify the edge stability using impurity and pellet injection are described in Section 4. In Section 5, we return to the discussion of the stability boundary schematic shown in Fig. 1 to summarize the correspondence between the physics model for edge stability and the theoretical and experimental results.

In this report, we consider in particular the threshold for the edge instability that is typically referred to as a Type I ELM [3]. Type I ELMs are thought to be the result of an ideal MHD instability because they occur when the tokamak heating power is well above the threshold for the L-mode to H-mode transition, the frequency increases as the heating power is increased [3], the magnetic fluctuations accompanying an ELM have a short growth time, on the order of approximately 50 $\mu$s, and the edge pedestal is characterized by high temperatures (0.5–2 keV), and thus low resistivity. Measurements of magnetic fluctuations [14] have found toroidal mode numbers for Type I ELMs in the range $2 \leq n \leq 9$. 
2 HIGH n STABILITY

The local stability to the ideal MHD ballooning mode depends on both the current density and the discharge shape. In the infinite-n limit, the ballooning stability boundaries are defined as a function of the magnetic shear ($s$) and normalized pressure gradient ($\alpha$) for each flux surface [6]. In the first stability regime, at relatively large values of $s$ and small values of $\alpha$, the pressure gradient cannot be increased indefinitely at constant shear without destabilizing the ballooning mode. However, larger values of $P_{\text{edge}}'$ produce larger values of the bootstrap current, and an increase in the local current density decreases the flux surface shear and raises the stability boundary to higher shear values. So it is possible that, as $P_{\text{edge}}'$ increases, the trajectory in $s$, $\alpha$ space will never intersect the stability boundary and the equilibrium will reach the region of relatively low shear where the second stability regime is accessible and the pressure gradient can be increased indefinitely without destabilizing the ballooning mode. The location of the stability boundary and the current density required to reach a given value of $s$ both depend on the discharge shape. So, the ability to access the second stability regime also depends on discharge shape. To facilitate comparison to $P_{\text{edge}}'$ thresholds for low-n modes, we refer to the minimum value of $\alpha$ on the first stability regime boundary curve as the “ballooning first regime limit”.

The dependence of ballooning second stability regime accessibility on discharge shape has been studied by varying the discharge squareness, $\delta_2$, illustrated in Fig. 2. Discharge shapes with very high ($\delta_2 \approx 0.5$) or low ($\delta_2 \approx 0.0$) squareness are predicted theoretically to have no access to the ballooning second stable regime near the discharge edge. The low poloidal field at the low field side “corners” weights the bad curvature region, thus increasing the current density required to reduce the magnetic shear to a low enough value.

In the experiment, a change in ballooning mode second stability regime accessibility is indicated by changes in the ELM frequency and amplitude. This is illustrated in Fig. 2 which shows results from three discharges, each with a different discharge shape.
squareness. The edge $D_\alpha$ light emission indicates the ELM frequency; each spike in the light emission is produced by an ELM. The size of the perturbation in the electron temperature near the top of the pressure pedestal is a measure of the ELM amplitude. As the squareness is increased, for example from $\delta_2 = 0.05$ [Fig. 2(a)] to $\delta_2 = 0.2$ [Fig. 2(b)], the ELM frequency increases and the amplitude decreases. With a further increase in squareness to a sufficiently high value [$\delta_2 = 0.5$, Fig. 2(c)] there is a factor of 10 increase in the ELM frequency and a corresponding decrease in ELM amplitude. This change in ELM character is abrupt, requiring only a small change in discharge shape. The same effect is observed as the squareness is reduced to very low values ($\delta_2 \approx 0.0$) [9].

The abrupt change in ELM character is consistent with an abrupt change that would be expected at a stability boundary. At the discharge squareness at which the change is observed, the bootstrap current produced by a pressure gradient equal to the first stability regime limit is calculated to be insufficient to reduce the shear to the region with second stability regime access [9]. Overall, with the change in squareness from $\delta_2 = 0.05$ to $\delta_2 = 0.5$ there is approximately a factor of 200 increase in ELM frequency and more than a factor of 200 decrease in ELM amplitude.

The measured edge pressure gradient changes along with the ELM character as the discharge squareness is varied. This is shown in Fig. 3 where the radial profiles of the measured pressure gradient are compared to the infinite-n ballooning mode stability boundaries calculated using the method of Ref. [6] as implemented in the BALOO code [20]. In the high squareness discharge [Fig. 3(a)], the peak pressure gradient value is equal to the calculated ballooning mode first regime limit and there is no region in the discharge edge where the second stability regime is predicted to be accessible. In the medium squareness discharge [Fig. 3(b)], the region outside $\psi_n \approx 0.93$ is predicted to have access to the second stability regime and in that region the measured pressure gradient exceeds the ballooning mode first stability regime limit by approximately a factor of 2. Thus the measured pressure gradient values and the calculated ballooning mode stability bound-
aries are consistent with loss of second stability regime accessibility at sufficiently high discharge squareness.

In high squareness discharges with pressure gradient limited by the ballooning mode first regime boundary, the highest toroidal mode number instabilities, those with \( k_\perp \rho_i > 0.5 \), should be stabilized by finite Larmour radius averaging (FLR) [21]. In addition, the pressure gradient limit calculated as a function of \( n \) (Fig. 4), including the finite \( n \) corrections in the ballooning equation, decreases with mode number. Therefore, the observed ELMs would be expected to result from the mode with the highest \( n \) that is not stabilized by FLR. Here, \( k_\perp \) is the wavenumber perpendicular to the magnetic field and \( \rho_i \) is the ion gyroradius. The BALMSC code [22] was used to calculate, for a model high squareness discharge, the curve in Fig. 4 and to determine that \( k_\perp / n \approx 3.3m^{-1} \). For edge parameters typical of high squareness discharges discussed here (ion temperature 0.9 keV, outboard midplane magnetic field 1.55 T), \( n > 40 \) for FLR stabilization. Figure 4 shows that for \( n = 40 \) the predicted ballooning mode first regime pressure gradient limit is only about 20% higher than that predicted for \( n = \infty \). This value is within the range of pressure gradient values measured in the experiment and the 20% uncertainty in the measurement of \( P'_{\text{edge}} \).

The instability drive resulting from the current density is important for mode numbers in the range below the FLR stabilization limit, \( n \approx 40 \) [23]. This drive results in coupling of the stability boundaries of the current-driven peeling mode to those of the pressure driven ballooning mode. A key issue for comparison to the experiment is whether access to a second regime of stability exists for \( n < 40 \) when the effect of current density is included. For mode numbers \( 10 < n < 40 \) the capability does not yet exist [24] to obtain quantitative stability boundary predictions for the full geometry of the experiment. However, in Ref. [25] it is shown that, for a high aspect ratio, shifted circle equilibrium, access to a second regime of stability is still expected to exist, provided that the magnetic well is sufficiently deep. We have used the same code used for Ref. [25] to explore the
dependence on n and magnetic well. Figure 5(a) shows the stability boundaries for the coupled ballooning/peeling instability for three values of n for a fixed value of the magnetic well parameter. The $n = 20$ stability boundaries have a gap between the peeling mode and ballooning mode branches that provides a stable path to the second stable regime, while for $n = 10$ there is no gap and there is a maximum stable value of $\alpha$ for all values of s. Thus, access to the second stability regime exists only for n above a threshold value, approximately 15 in this case. This threshold value of n varies with the magnetic well parameter [Fig. 5(b)]. Variation of the magnetic well parameter models the effect that is expected from variation of discharge shape. We expect that discharge shapes with better second stability regime accessibility as predicted by the infinite-n ballooning mode theory would have second regime access at lower mode numbers than discharge shapes, such as high squareness shapes, which are marginal for ballooning mode second regime access.
3 LOW-n STABILITY

Both the theory and experiment discussed in Section 2 indicate that for discharges with mid-range values of the squareness ($\delta_2 \approx 0.05$ to 0.2), the higher n modes should be stable because of access to the second regime of stability. Quantitative calculations of the pressure gradient threshold for model equilibria with a fixed, medium squareness shape ($\delta_2 = 0.05$) show that at relatively low mode number the threshold decreases as a function of n (Fig. 6). So, the most unstable mode will have n approximately at the threshold for second regime access.

The predicted pressure gradient stability threshold values shown in Fig. 6, and in the remainder of this section, were calculated for model equilibria that were created using the method of Ref. [7]. The model equilibria have a pressure profile near the discharge edge of hyperbolic tangent form, found to be a good match to the experiment [1], and uniform pressure in the core region. In the edge region the current density is equal to the predicted bootstrap current while in the core the current profile [7] is adjusted to set the safety factor on axis to about 1.1 and to set the total discharge current to match the current used in the experiment. Equilibria with varying values of the peak pressure gradient were produced and stability for each toroidal mode number was calculated using the finite hybrid element code GATO [26] to execute a convergence study to a sufficiently dense calculation mesh (up to 620 by 1240) to resolve modes with the specified value of n.

There is good agreement between the measured pressure gradient and the predicted threshold for $n = 5$ ideal, kink/ballooning modes and similar scaling with discharge shape. Figure 7(a) summarizes the results as a function of discharge shape squareness. The data points at high and low squareness values shown as diamonds represent discharges with high frequency ELMs and no ballooning mode second stability regime access. The measured pressure gradient values for these points agree well with the calculated ballooning mode first stability regime limit for which there is little predicted variation with squareness.
The higher \( P'_{\text{edge}} \) values at the same squareness (shown as triangles) illustrate the change in edge parameters when there is a shift in second stability regime access at constant shape. This type of behavior, observed when the discharge shape is marginal for loss of second stable regime access [9], probably results from evolution of the edge region current density after the H-mode transition. For the \( \delta_2 = 0.5 \) discharge, described further in Ref. [9], the ELM frequency decreases to 300 Hz from 4kHz with a corresponding increase in the edge \( T_e \) perturbation.

In contrast to the scaling of the ballooning first regime limit, the calculated \( n = 5 \) kink/ballooning mode threshold varies significantly with discharge squareness. This is in agreement with the measured pressure gradient values [triangles, Fig. 7(a)] which increase significantly as the squareness is reduced from \( \delta_2 = 0.5 \) to \( \delta_2 = 0.15 \). Each of these experimental points is the measured pressure gradient just prior to an ELM event. The pressure gradient profile in the model equilibria used for the stability calculations was designed to be similar to the measured profile of the discharge at \( \delta_2 = 0.2 \) represented by the solid data point on Fig. 7(a). The calculated threshold pressure gradient value agrees within 40% in this case with the measured value.

Increasing the discharge shape triangularity in single null divertor discharges also results in increased edge pressure gradient [18]. This result is summarized Fig. 7(b) which shows the ratio of the measured, normalized pressure gradient to the calculated ballooning mode first stability regime limit. Measured pressure gradient values can be more than four times the ballooning mode first regime limit. The measured changes in the pressure gradient ratio shown in Fig. 7(b) do not result from changes in the ballooning first regime limit, which, as shown in the figure, varies little as the shape is changed. Here, the normalization [1] accounts for variation of the plasma current in the experimental data set. In agreement with the experimental scaling, the predicted stability threshold for \( n = 5 \) increases with triangularity, as shown in the figure. The model equilibria used for the stability threshold calculations had up/down symmetric shapes matching only the
upper half of the single null divertor discharges so this comparison with theory is only qualitative.

The pressure gradient stability threshold, both measured and calculated, is reduced as the pedestal width is increased. This is demonstrated in Fig. 8 which shows the measured peak value of $P_{\text{edge}}'$ just prior to an ELM as a function of the measured pedestal width for both a double-null divertor and a single-null divertor discharge. For a sufficient increase in pedestal width the pressure gradient stability threshold approaches the ballooning first stability regime limit. Figure 8(a) also shows the calculated pressure gradient threshold for model equilibria for $n = 5$ which is in rough agreement with the experimental data. This scaling with pedestal width is consistent with averaging of the full profiles of the pressure gradient and current density by low mode number, and thus relatively long wavelength, instabilities.
4 MODIFICATION OF THE EDGE PRESSURE GRADIENT

Deliberate modification of the H-mode edge pedestal demonstrates the importance of the edge pressure gradient in destabilization of edge localized instabilities. For instance, krypton was added to a discharge in order to reduce the pressure pedestal height by radiating part of the input power. In a similar discharge without krypton, ELMs began 400 ms after the H-mode transition, but in the discharge with krypton added there were no ELMs before the discharge returned to L-mode. In the two discharges, the parameters are very similar for the first 400 ms phase of the H-mode with the exception of an approximately 20% reduction in the electron temperature pedestal and a corresponding reduction in the edge pressure gradient. We conclude that with the krypton radiation ELMs are avoided by maintaining $P_{\text{edge}}'$ below the stability threshold.

In a contrasting case, a deuterium pellet was injected early in the ELM-free phase of the H-mode. The result was a rapid increase in the edge pressure gradient resulting in the start of the ELMing phase of the discharge within 50 ms. In this case the pressure gradient just prior to an ELM increased with time after the first ELM. The 7th ELM was triggered at a pressure gradient almost twice that prior to the first ELM. This increase in the ELM pressure gradient threshold occurred while a transient increase in the pedestal width generated by the pellet decayed away, consistent with the pedestal width dependence of the threshold shown in Fig. 8.
5 CONCLUSIONS

We have shown here that both theory and experiment exhibit the features of a model of the Type I ELM as an ideal MHD low-n kink/ballooning type instability driven by the edge pressure gradient and the corresponding bootstrap current. There is a threshold value of n for second regime access that is expected to vary with discharge shape and the most unstable mode has n near this threshold. The energy loss from an ELM will increase with $P'_{\text{edge}}$ [3, 27] but, in addition, higher mode number, shorter wavelength instabilities will perturb a smaller region of the discharge [4], causing a smaller energy loss. Recovery from a small energy loss is quicker resulting in higher ELM frequency. Thus the observed variation in ELM amplitude and frequency with discharge shape partially results from the variation in the value of n for the most unstable mode and partially from the change in the threshold in $P'_{\text{edge}}$ with shape. The features of the H-mode pedestal region stability in DIII-D can then, be described in terms of the threshold pressure gradient for instability as a function of toroidal mode number and discharge shape as shown in the schematic in Fig. 1.

The highest squareness discharges, those without edge region access to the ballooning mode second stability regime, are represented by the operating point number 1 in Fig. 1. The toroidal mode number of edge instabilities in this case is expected to be approximately 40, consistent with the observed 4 kHz ELMs with $T_e$ perturbation below the measurement limit, because higher mode number instabilities are stabilized by finite Larmour radius. The predicted pressure gradient limit at $n = 40$ is within 20% of the pressure gradient limit at $n = \infty$ (Fig. 4) and agrees with that measured in the experiment (Fig. 3).

A small decrease in squareness or a small increase in edge current density results in ballooning mode second stable regime access and an increase in the measured edge pressure gradient [9] [Fig. 7(a)]. This is represented by a shift to the operating point number 2 in Fig. 1. The observed factor of 10 decrease in ELM frequency to 300 Hz and corresponding increase in ELM amplitude [9] indicates a reduction in toroidal mode number which is
consistent with the theoretical prediction that an increased pressure gradient threshold would also result from a decrease in toroidal mode number (Fig. 4). The mode number in this case is estimated to be near 10 from comparison of the measured and predicted pressure gradient threshold values. Instabilities with mode number slightly larger are stable because of access to a second regime of stability. Figure 5(a) demonstrates that a second stability regime could be expected in this mode number range, despite the coupling of the peeling mode to the ballooning mode, if there is sufficient magnetic well which is analogous to choice of the correct discharge shape.

The change in shape from point number 2 to point number 3 in Fig. 1 represents either a further decrease in squareness in a double-null divertor shape or an increase in triangularity in a single-null divertor shape, either of which results in an increase in the threshold pressure gradient (Fig. 7). The dependence of the marginal value of n for second regime access on magnetic well shown in Fig. 5(b) suggests that with these shape changes even lower mode numbers should have second regime access. This is consistent with the further factor of 10 change in ELM frequency and amplitude [Fig. 2(a)] simultaneous with only a 50% change in edge pressure gradient.

In both the experiment and theory there are distinct differences between conditions where the pressure gradient is limited by the high-n ballooning mode and conditions where it is limited by low mode number coupled kink/ballooning modes. The experiments with variation in discharge shape squareness show strong evidence of a transition across a stability boundary that controls second stable regime access. In discharges where ballooning mode second stable regime access is expected, the measured pressure gradient values and the calculated pressure gradient thresholds are well above the predicted ballooning first stability regime limit. The observed and calculated strong scaling of the pressure gradient threshold with discharge shape, squareness and triangularity, are in good agreement for $n = 5$ kink/ballooning instabilities while the infinite-n ballooning mode first regime limit shows little variation with shape. Finally, the dependence of the pressure gradi-
ent threshold on the pedestal width (Fig. 8) indicates an instability that averages the full pressure gradient profile, a low n mode, rather than a high n ballooning mode that depends primarily on the local parameters near a flux surface.

The experiments described here illustrate several ways that the ELM and the effect of an ELM on the discharge can be modified or eliminated, including discharge shaping, particularly the squareness and the triangularity, impurity radiation and pellet injection. Loss of ballooning mode second stability regime access through changes in discharge squareness can reduce the ELM perturbation by more than a factor of 100. These results suggest that the impact of large, low-n ELMs on tokamak discharges can be reduced by altering parameters that determine the H-mode pedestal region stability.
References


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Fig. 1. A schematic drawing of the stability boundaries in the H–mode pedestal region for three different discharge shapes. Here, $\delta_2$ is the discharge shape squareness and $\epsilon$ represents a small value. The stability boundaries roughly represent the calculated boundaries shown in other figures, but changes in shape and position of the curves have been exaggerated for clarity.

Fig. 2. Edge light emission, $D_\alpha$, indicating ELM frequency and edge electron temperature, $T_e$, indicating ELM amplitude in three discharges with varying shape squareness. (a) $\delta_2 = 0.05$, (b) $\delta_2 = 0.2$, (c) $\delta_2 = 0.5$, where the corresponding discharge boundary shapes are shown on the right within the outline of the DIII–D limiter and $\delta_2$ is the squareness in the shape parameterization $R(\theta) = R_0 + a \cos(\theta + \sin^{-1} \delta_2 \sin \theta)$, $Z(\theta) = \kappa a \sin(\theta + \delta_2 \sin^2 \theta)$. Plasma current, $I_p = 1.2$ MA, and toroidal field $B_T = 2.1$ T.
Fig. 3. Measured pressure gradient near the discharge edge and the marginal stability boundaries for the ideal infinite-n ballooning mode calculated for the experimental equilibria using the code BALOO [20]. (a) During small amplitude ELMs in a high squareness discharge, $\delta_2 = 0.5$. (b) During Type I ELMs in a medium squareness discharge, $\delta_2 = 0.2$. $I_p = 1.2$ MA and $B_T = 2.1$ T in both cases.

Fig. 4. Finite-n ballooning mode first stability regime pressure gradient threshold as a function of toroidal mode number calculated using the BALMSC code [20] for model equilibria with $\delta_2 = 0.5$, $I_p = 1.2$ MA.
Fig. 5. (a) Stability boundaries for coupled ballooning and peeling modes in a shifted circle equilibrium for three values of the toroidal mode number (n) and fixed magnetic well parameter, \( d_m = -0.645 \). Calculated using the method of Ref. [25]. The marginal value of n for second stable regime access in this case is approximately 15. (b) The calculated marginal value of n for second stable regime access as a function of the magnetic well parameter.
Fig. 6. Pressure gradient threshold for instability as a function of \( n \) calculated using model equilibria with \( \delta_2 = 0.05, I_p = 1.2 \) MA.
Fig. 7. Measured pressure gradient just prior to an ELM as a function of (a) discharge shape squareness in double-null divertor shapes (total $P_{\text{edge}}'$) and (b) average triangularity in single-null divertor discharges (twice the normalized electron pressure gradient) with the boundary shapes shown as insets. In each case the calculated threshold in $P_{\text{edge}}'$ for $n = 5$ modes is shown. In (a), both the experimental discharges and the model equilibria for the stability threshold calculation had $I_p = 1.2$ MA.
Fig. 8. Measured pressure gradient just prior to an ELM as a function of measured pedestal width. (a) Total $P'_{\text{edge}}$ in a double-null divertor with $\delta_2 = 0.2$, $I_p = 1.2$ MA. (b) Twice the normalized electron pressure gradient in a single-null divertor discharge with average triangularity $\delta = 0.07$. These data come from the group of points circled with the dashed line in Fig. 7(b). In (a) the calculated threshold in $P'_{\text{edge}}$ for modes with $n = 5$ is also shown for model equilibria with $I_p = 1.2$ MA. In both cases a fit of the pressure profile to a hyperbolic tangent shape defines the width [1]. The width values quoted for (a) are approximate as the shape of the pressure gradient profile is not always a good match to this parameterization.