GA–A23156

CHARACTERIZATION AND MODIFICATION OF EDGE-DRIVEN INSTABILITIES IN THE DIII–D TOKAMAK

by
J.R. FERRON, L.L. LAO, T.H. OSBORNE, E.J. STRAIT, A.D. TURNBULL,
R.L. MILLER, T.S. TAYLOR, E.J. DOYLE, B.W. RICE, C. ZHANG, L. CHEN,
L.R. BAYLOR, M. MURAKAMI, and M.R. WADE

JULY 1999

DISCLAIMER

GA–A23156

CHARACTERIZATION AND MODIFICATION OF EDGE-DRIVEN INSTABILITIES IN THE DIII–D TOKAMAK

by
J.R. FERRON, L.L. LAO, T.H. OSBORNE, E.J. STRAIT, A.D. TURNBULL,
R.L. MILLER, T.S. TAYLOR, E.J. DOYLE,* B.W. RICE,† C. ZHANG,‡ L. CHEN, ‡
L.R. BAYLOR,∆ M. MURAKAMI,∆ and M.R. WADE∆

This is a preprint of a paper presented at the Twenty-Sixth European Physical Society Conference on Controlled Fusion and Plasma Physics, June 14–18, 1999 in Maastricht, The Netherlands, and to be published in *The Proceedings.*

*University of California, San Diego, California.
†Lawrence Livermore National Laboratory, Livermore, California.
‡Institute of Plasma Physics, Chinese Academy of Science, Hefei, P.R. China.
∆Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Work supported by
the U.S. Department of Energy
under Contract Nos. DE-AC03-99ER54463, W-7405-ENG-48,
DE-AC05-96OR22464, Grant Nos. DE-FG03-86ER53225
and DE-FG03-94ER54371

GA PROJECT 30033
JULY 1999

Characterization and Modification of Edge-Driven Instabilities in the DIII–D Tokamak*

J.R. Ferron,[1] L.L. Lao,[1] T.H. Osborne,[1] E.J. Strait,[1] A.D. Turnbull,[1]
R.L. Miller,[1] T.S. Taylor,[1] E.J. Doyle,[2] B.W. Rice,[3] C. Zhang,[4] L. Chen,[4]
L.R. Baylor,[5] M. Murakami,[5] and M.R. Wade[5]

[1]*General Atomics, P.O. Box 85608, San Diego, California 92186-5698*
[2]*University of California, Los Angeles, California*
[3]*Lawrence Livermore National Laboratory, Livermore, California*
[4]*Institute of Plasma Physics, Chinese Academy of Science, Hefei, P.R. China*
[5]*Oak Ridge National Laboratory, Oak Ridge, Tennessee*

Abstract: The character of edge localized modes (ELMs) and the height of the edge pressure pedestal in DIII–D tokamak H–mode discharges have been modified by varying the discharge shape (triangularity and squareness) and the safety factor, increasing the edge radiation, and injecting deuterium pellets. Changes in the ELM frequency and amplitude, and the magnitude of the edge pressure gradient, and changes in the calculated extent of the region of access to the ballooning mode second stability regime are observed.

The high edge-localized pressure pedestal that is a key driver of improved confinement in "stiff" transport models of the tokamak H–mode results in edge localized MHD instabilities (ELMs) [1,2]. ELMs result in energy and particle loss and subsequent large heat pulses into the divertor region, perturbations of the discharge core that can prevent formation of internal transport barriers and triggering of neoclassical tearing modes. In order to study the tradeoffs between the improvement in confinement with pedestal height and the perturbations on the discharge caused by ELMs, and to improve understanding of the ELM mechanism, we have investigated methods to modify the ELM frequency and amplitude.

The methods for modification of ELM character that have been explored were derived from the hypothesis that typical Type I ELMs are low-n kink/peeling modes driven by the high edge pressure gradient $\left(P'_{edge}\right)$ and the associated bootstrap current density (J_{edge}). We have studied the effect on edge stability of varying the discharge shape (triangularity and squareness) and the safety factor (q_{95}), increasing the edge radiation to modify P'_{edge}, injecting deuterium pellets to change the density profile and variation in the time evolution of J_{edge}.

Low-n modes are believed to be most important because the observed values of P'_{edge} at the Type I ELM threshold in DIII–D single and double-null divertor discharges are, with a few exceptions discussed here, above the first regime stability limit for ideal infinite-n ballooning modes predicted for low values of J_{edge} [3–5]. Values as much as 5 times the 1st regime limit are commonly observed. Theoretical calculations have shown that these conditions near the discharge edge can be unstable to low toroidal mode number ($n \geq 3$) kink/peeling modes [3], destabilized by both the current density and pressure gradient. The ballooning mode is stable because the high values of J_{edge} and the discharge shape ensure that in the region of large P'_{edge} the ballooning mode 2nd stable regime is accessible. This has been demonstrated by ballooning mode stability calculations for experimental and theoretical equilibria for a wide range of discharge shapes [3,6,7].

In the experiment, after the transition to H–mode there is a period free of ELMs during which relatively wide pedestals and good confinement develop, especially in VH–mode discharges. A large, ELM-like, relatively global low-n instability at the end of the ELM-free period often destroys the low transport edge and/or internal transport barrier. The severity of

---

*Work supported by U.S. Department of Energy under Contracts DE-AC03-99ER54463, W-7405-ENG-48, DE-AC05-96OR22464, and Grant Nos. DE-FG03-86ER53225 and DE-FG03-94ER54371.

this first ELM in these cases is consistent with theory calculations which show that the low-n mode amplitude and radial extent increase with the width of the pressure pedestal [4].

To avoid the effect of this global mode, modifications of P'_{edge} with impurity gas and deuterium pellet injection have been studied. Addition of an impurity such as krypton (Fig. 1) results in radiation of as much as 60% of the input power at the time of the peak stored energy. In this case the ELMing phase of the discharge is eliminated completely. The expectation is that reduction of P'_{edge} will result when radiation prevents a substantial fraction of the input power from flowing through the H–mode edge thermal barrier region. Modification of J_{edge} may also result from changes in edge values of n_e and T_e. There is no immediately evident difference, though, between the peak values of P'_{edge} and J_{edge} in the two discharges shown in Fig. 1, so further analysis will be necessary to understand why ELMs were not observed in the high radiation discharge.

Injection of a deuterium pellet, deliberately broken into small pieces to reduce the penetration depth, from the tokamak low field side has been observed to prematurely end the ELM-free period by triggering the start of Type I ELMs (Fig. 2). It may be possible to use a pellet to reduce the radial extent of the first ELM by triggering it at the point where the pedestal width is relatively narrow. Triggering of ELMs has also been observed with deeper penetrating, unbroken pellets injected from the high field side. In this case a delay after the pellet injection before the start of ELMs has been observed, probably resulting from the time necessary for transport of injected particles to the discharge edge.

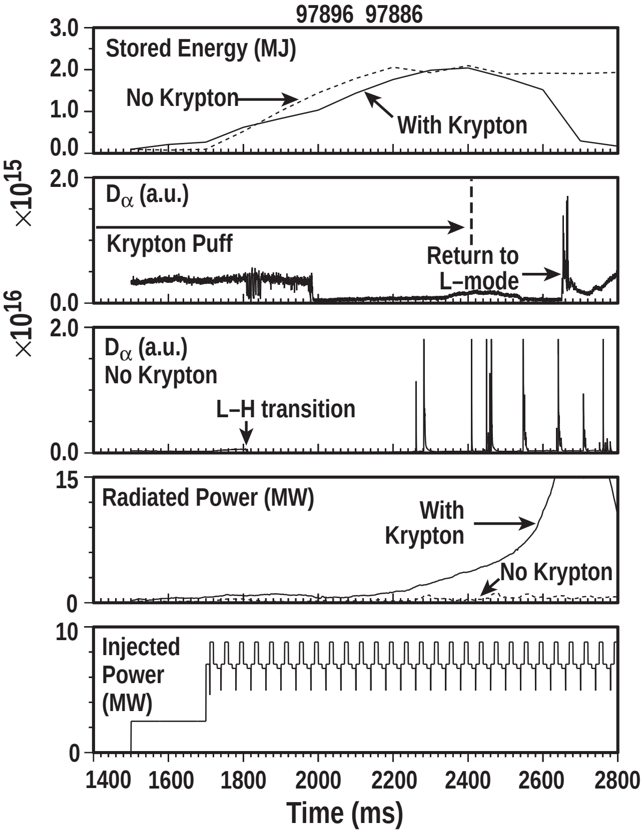

Fig. 1. Modification of edge stability through impurity radiation. Two discharges are shown, one with a krypton gas puff from 1400–2400 ms, one with no impurity gas injection.

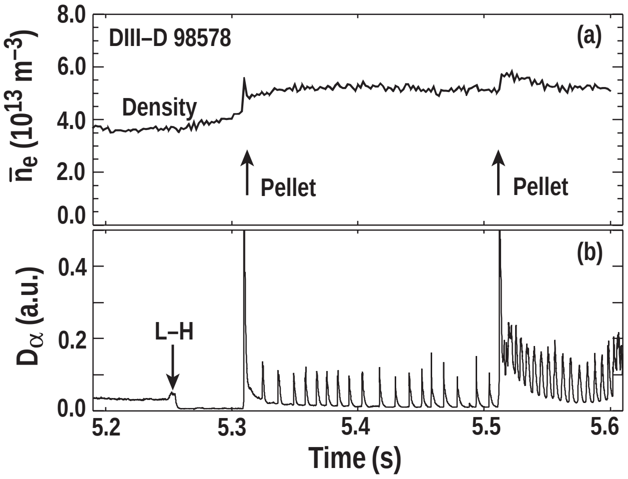

Fig. 2. Triggering of ELMs with deuterium pellet injection. (a) Line average density showing a sharp increase with pellet injection. (b) Edge D_α radiation.

Continuation of the high performance of the ELM-free phase into the phase of Type I ELMs without active discharge modification has been observed in some discharges. An example is shown in Fig. 3. A significant characteristic of this discharge is a slow rate of increase of J_{edge} during the ELM-free period. The current density in the outer 10% of the discharge, as determined from equilibria reconstructed using MSE internal magnetic field pitch angle measurements, continues to increase during the first few ELMs although P'_{edge} is approximately constant after the ELMs begin. The stored energy is maintained relatively constant. Reduced severity of the first ELMs may result from a dependence of the radial extent of the mode on J_{edge}.

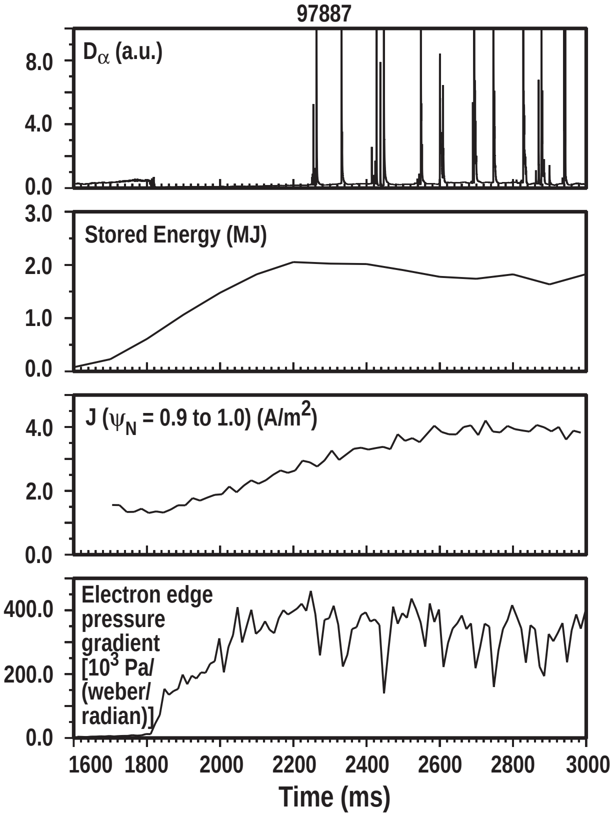

Fig. 3. Time evolution of P'_{edge} (electron pressure gradient is shown, about $P'_{edge}/2$) and J averaged over the outer 10% of the flux.

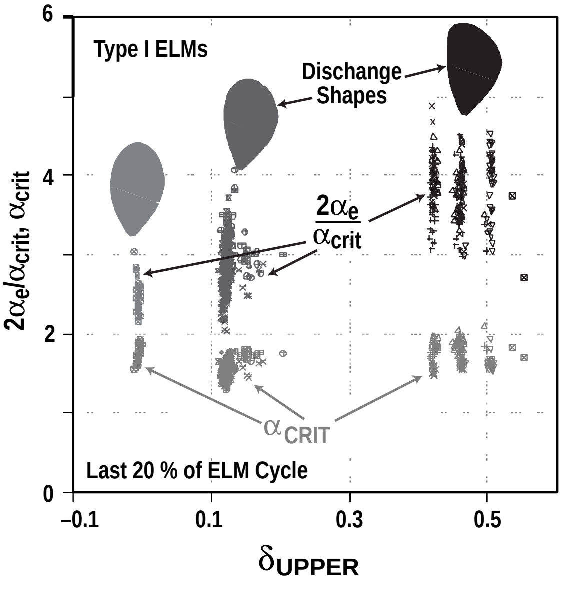

Fig. 4. Variation of P'_{edge} (expressed in terms of the normalized pressure gradient (α) commonly used in ballooning mode theory [3]) with discharge triangularity.

Modification of the pedestal height and P'_{edge} during the phase of continuous Type I ELMs is observed with changes in the triangularity (δ) of single-null divertor discharges; higher δ yields higher P'_{edge}, pedestal height and improved confinement. An increase with δ of P'_{edge} and J_{edge} at the low-n stability threshold is under study as the explanation. Figure 4 shows the variation of the ratio of the observed P'_{edge} to the critical pressure gradient for first regime ballooning stability. In all cases the ballooning first regime limit is exceeded. The figure also shows that the critical value of P'_{edge} doesn't vary significantly with δ. Little variation in the pedestal width with δ is observed. Instead, there is an increase in the pressure pedestal height by the same factor as the increase in P'_{edge}.

The largest changes in ELM character and the height of the edge pressure pedestal have been observed by eliminating edge access to the ballooning second stable regime [5]. A sharp transition, indicating loss of 2nd stable access, is observed in edge parameters if the discharge squareness is either increased or decreased sufficiently (Fig. 5). ELM amplitude is reduced dramatically, as indicated by the edge D_α fluctuations and the perturbations on the edge T_e, and the ELM frequency increases by a factor of 10. This is consistent with a shift to higher n instabilities, more like high-n ballooning than low-n kink modes, which, with shorter wave length, would be expected to produce a more localized perturbation. For the equilibria reconstructed from experimental data, there is no second stable regime access in the pedestal region either observed or predicted (Fig. 6) [5,7]. The measured P'_{edge} is equal to the first regime limit and the pressure pedestal and confinement are reduced because the pedestal width remains approximately constant. Formation and sustainment of an internal transport barrier has been observed in high and low squareness discharges with little or no ballooning second stability access at the edge during phases of continuous, low amplitude ELM activity. These discharges have confinement at or above the normal H–mode level despite the low edge pedestal height.

In summary, we have described several methods to modify the ELM character and the effect of the ELM on the discharge that are consistent with expectations from ideal MHD stability. Quantitative agreement with infinite-n, ideal ballooning mode theory is found in the elimination of second regime access by changing discharge squareness. Measured values of P'_{edge} well above the ballooning 1st stability regime limit are in agreement with calculated second regime access for ballooning modes and with low-n stability calculations performed thus far. These results suggest that large low-n ELMs can be eliminated, or their impact reduced, by control of edge profiles or high-n stability properties, and that the magnitude of the edge pedestal can be modified to impact confinement.

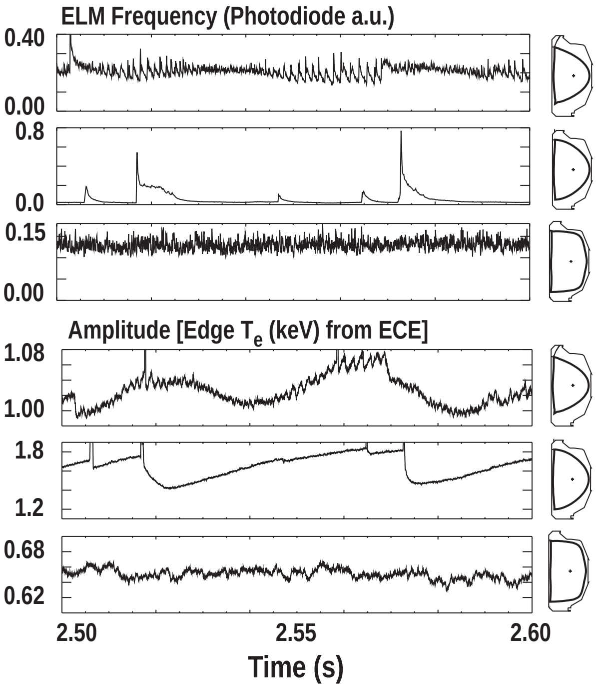

Fig. 5. D_α and edge T_e indicating ELM amplitude and frequency in 3 discharges with shape varying from low squareness (top) to high squareness (bottom). The small insets show the discharge shapes within the DIII–D vacuum vessel.

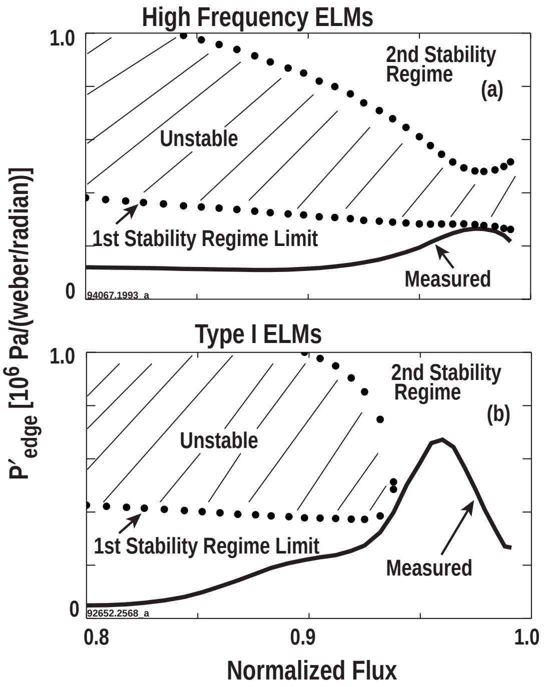

Fig. 6. Measured pressure gradient near the discharge edge and the calculated marginal stability boundaries for the ideal infinite-n ballooning mode. (a) During small amplitude ELMs in a high squareness discharge. (b) During Type I ELMs in a medium squareness discharge.

[1] H. Zohm, Plasma Phys. Control. Fusion **38**, 105 (1996).
[2] J.W. Connor, Plasma Phys. Control. Fusion **40**, 531 (1998).
[3] T.H. Osborne, *et al.*, J. Nucl. Mater. **266–269**, 131 (1999).
[4] L.L. Lao, *et al*., "Effects of Plasma Shape and Profiles on Edge Stability in DIII–D," Proc. of the 17th Int. Atomic Energy Agency Fusion Energy Conf., Yokohama, Japan (1998), to be published in Nucl. Fusion.
[5] J.R. Ferron, *et al*. "Modification of Tokamak Edge Instability Character Through Control of Ballooning Mode Second Stability Regime Accessibility," submitted to Nucl. Fusion.
[6] R.L. Miller, Y.R. Lin-Liu, T.H. Osborne, and T.S. Taylor, Plasma Phys. Control. Fusion **40**, 753 (1998).
[7] A.D. Turnbull, *et al*., Phys. Plasmas, **6** 113 (1999).