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IMPACT OF EDGE CURRENT DENSITY AND PRESSURE GRADIENT ON THE STABILITY OF DIII–D HIGH PERFORMANCE DISCHARGES *

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One of the major goals of advanced tokamak research is to develop plasma configurations with good confinement and improved stability at high β. In DIII–D, various high performance configurations with H– and VH–mode edges have been produced. These include discharges with poloidal cross sections in the forms of dee and crescent shapes, single- and double-null divertors, and with various central magnetic shear profiles and current profile peakedness. All these discharges exhibit enhanced confinement in the outer plasma region which leads to a large edge pressure gradient and a large edge bootstrap current driven by this steep pressure gradient. These edge conditions often drive an instability near the edge region which can severely degrade the discharge performance [1–3]. An understanding of this edge instability is essential to sustain and enhance discharge performance.

Experimental Observations

This edge instability has been observed in DIII–D H– and VH–mode discharges with various plasma poloidal cross sections including single- and double-null divertors, dee and crescent shapes and is often preceded by a magnetic precursor with toroidal mode number $n > 1$. This is illustrated in Fig. 1. The magnetic perturbation of the precursor is localized both poloidally in the bad curvature region and toroidally with a fast growth time $\gamma^{-1} \approx$ 20–150 μs and usually rotates in the electron diamagnetic drift direction. This rotational direction is consistent with a location near the plasma edge where the **E**×**B** drift is dominated by the diamagnetic drift associated with the large edge pressure gradient. The magnetic precursor may consist of a single pulse as shown in Fig. 1(b,d) or may be preceded by a continuous n=1 or n=2 mode in the plasma core depending on the q profiles as shown in Fig. 1(f). The instability has been observed over a wide range of normalized beta β_N = 2.5-5.0 including discharges with negative or weak central magnetic shear and high ℓ_i.

As shown in Fig. 1(a,c,e) this instability may lead to a drop in the electron temperature T_e in the plasma outer region, a slight change of T_e in the plasma outer region, or a drop of T_e across the entire plasma. Consistent with these changes in T_e, equilibrium reconstructions using magnetic measurements indicate that the plasma stored energy saturates instead of continuing to rise, when the change in T_e is slight; or decreases by 10%–12% when the drop in T_e is large. Similar changes have also been observed in the soft x-ray (SXR) measurements. In the particular discharge shown in Fig. 1(e), the decrease of plasma temperature across the

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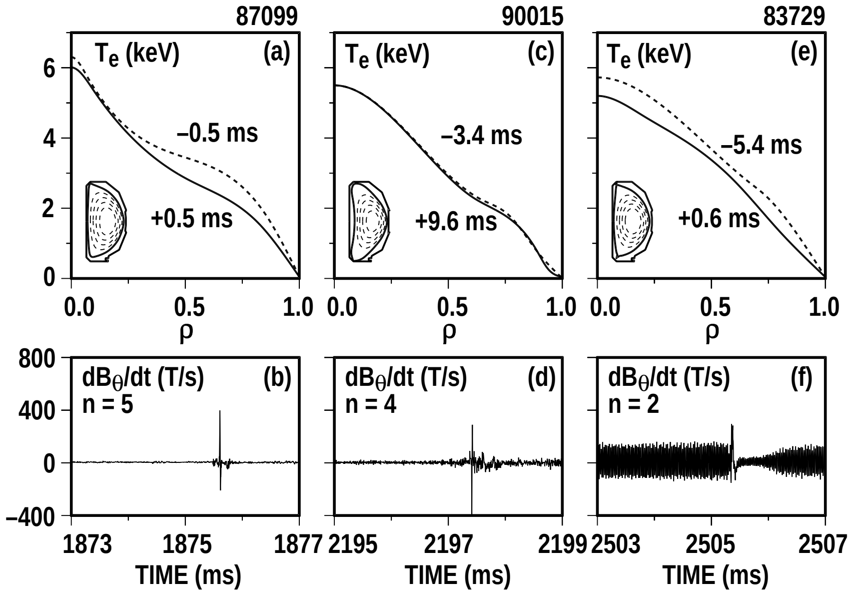

Fig. 1. Magnetic precursors and radial electron temperature profiles before (dashed) and after (solid) the edge instability.

entire plasma volume may be a result of the interaction between a continuous n=2 mode in the plasma core and the n=2 edge mode in the outer plasma region.

The attainable β values decrease when the average current density increases in the plasma outer edge region and are consistent with the previously observed operational β limit of $\beta_N \approx 4\,\ell_i$ [4,5]. This is illustrated in Fig. 2 for a group of double-null divertor discharges with plasma current I = 2–2.2 MA. Here, $\langle J \rangle_N = \langle J \rangle_{95}^{1} / \langle J \rangle_{0}^{1}$ is the average current density outside of the 95% normalized poloidal flux surface divided by the average current density across the entire plasma volume and

$$\langle J \rangle_{x_1}^{x_2} = \left[\int_{x_1}^{x_2} d\psi \oint d\ell \left(J_T / RB_p \right) \right] \Big/ \left[\int_{x_1}^{x_2} d\psi \oint \left(d\ell / RB_p \right) \right].$$

As shown in Fig. 2(a), discharges with high early beam injection tend to have larger $\langle J \rangle_N$ due to the slower penetration of the plasma current into the central core and have a lower β limit. Since ℓ_i is also a measurement of the distribution of the current density, this decrease of β_N with $\langle J \rangle_N$ can also be expressed as a variation with ℓ_i and is consistent with the previously observed operational β limit of $\beta_N \approx 4\ell_i$ [4,5]. This is shown in Fig. 2(b).

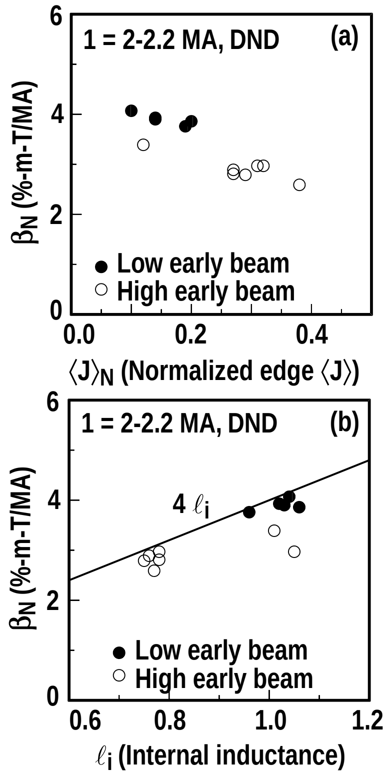

Fig. 2. Dependence of the beta limit on normalized edge current density $\langle J \rangle_N$ and ℓ_i .

Theoretical Analysis and Simulations

Near the onset of this edge instability, the discharges often have access to the second high n ideal ballooning stability regime in the plasma outer edge region but are unstable to the ballooning mode in the region near the normalized poloidal flux $\psi_N \approx 0.9$. This is illustrated in Fig. 3. As shown in Fig. 3(a,b), although the crescent and the dee shaped discharges have very different ballooning stability in the core region, near the onset of the edge instability both have access to the second ballooning stability regime in the edge region and are unstable to the ballooning mode in the region near the edge. This access to the second ballooning stability regime in the outer edge may be necessary to facilitate the development of the very steep edge pressure gradient often observed in DIII–D VH–mode discharges. Stability to the ballooning mode near the edge region $\psi_N \approx 0.9$ may play a participating role in the edge stability by further steepening the pressure gradient outside of the region. Further study is necessary to clarify the importance of the ballooning stability.

The results of ideal stability calculations are consistent with many observed features of the instability. Stability analysis using both experimental and simulated equilibria suggests the higher n modes are more unstable and both the large edge pressure gradient and high edge current density are destabilizing. This is illustrated in Fig. 4 using a sequence of simulated equilibria based on the experimental information from an actual discharge near the occurrence of this edge instability. These equilibria all have similar double-null divertor shape, q_{95} values of 5.5, ℓ_i values of 0.75, but different radial thickness of the steep pressure

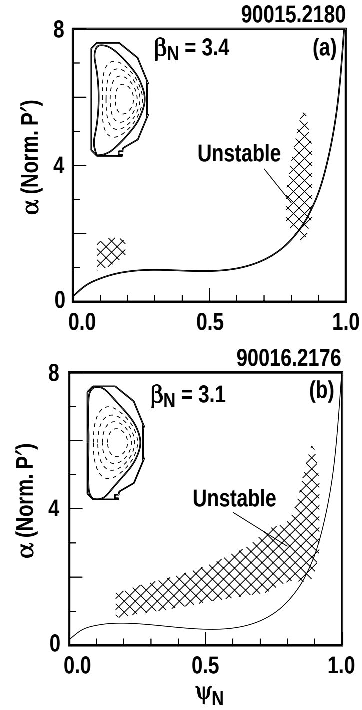

Fig. 3. Ideal ballooning stability of a crescent and a dee shaped discharge. Solid line indicates measured value.

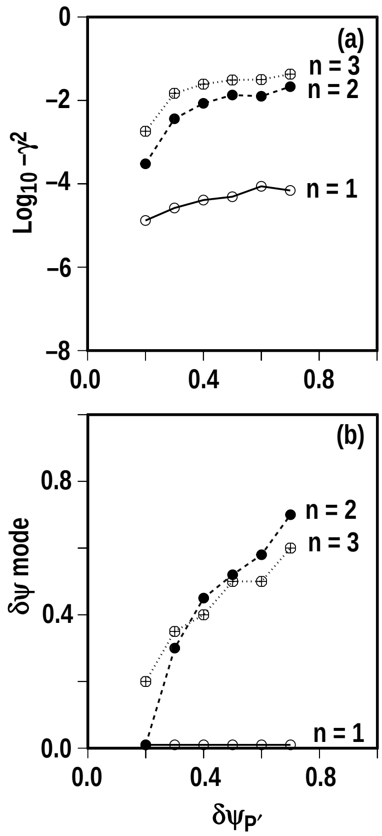

Fig. 4. Variation of growth rate and mode width with radial thickness of steep pressure gradient region.

gradient region as measured in terms of the normalized poloidal flux $\delta\psi_P$. For simplicity, the pressure gradient stream function $P'(\psi)$ is taken to have the shape of a step function with a region of small $P'(\psi)$ in the plasma core and a region of large $P'(\psi)$ in the outer edge. Both $P'(0)$ and $P'(1)$ are kept constant in the simulations. The ideal stability against the n=1,2, and 3 modes are computed using the GATO code [5] with a conducting wall at the surrounding DIII–D vacuum vessel. As shown in Fig. 4(a), the equilibria are stable to the ideal n=1 mode at all values of $\delta\psi_P$ considered but are unstable to the higher n=2 and 3 modes when $\delta\psi_P > 0.2$. Here, γ is the linear growth rate of the ideal mode. Note that both β and β_N increase with $\delta\psi_P$. Due to the finite grid size, the values of γ against the n=1 mode remain positive but small although it is stable against the n=1 mode as indicated by the radial mode structure. As shown in Fig. 4(b), the radial width of the mode $\delta\psi_{mode}$ increases with $\delta\psi_P$ which suggests that the discharge performance degradation may depend on the radial thickness of the steep pressure gradient region. Increasing $P'(1)$ tends to make the equilibria more unstable.

Summary

The performance of DIII–D high performance H– and VH–mode discharges is often limited by an edge instability which has n > 1. The attainable β values decrease with the average current density in the plasma outer edge region and are consistent with the previously reported operational β limit of $\beta_N \approx 4\,\ell_i$. The instability is driven primarily by the large edge pressure gradient and the large edge bootstrap current associated with the pressure gradient. The results of ideal stability calculations are consistent with many observed features of the instability and suggest that the performance degradation may depend on the radial thickness of the steep pressure gradient region. For sustainment and enhancement of the discharge performance it is essential to control the large edge pressure gradient and its radial thickness. Methods being proposed include use of external coils to produce an edge ergodic region and shaping of poloidal cross section to limit the edge second ballooning stability access, and reduce the first regime limit.

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