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Wall Stabilization of High Beta Tokamak Discharges in DIII-D

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DIII-D discharges with values of beta (the ratio of plasma pressure to magnetic pressure) up to 12.5% demonstrate that a resistive wall can stabilize low-n magnetohydrodynamic (MHD) modes. In discharges with broad current profiles, beta exceeds the ideal MHD stability limit by at least a factor of 1.3 assuming no wall, but remains below the limit calculated under the assumptions that the vacuum vessel is a perfectly conducting wall. Plasma rotation is essential to stabilization, and instabilities resembling the predicted "resistive wall mode" appear only when the rotation velocity approaches zero.

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The stabilization of ideal kink modes by a resistive wall is of great practical importance for high performance tokamak experiments. In present tokamaks, performance is often limited by long-wavelength kink instabilities at high beta, where $\beta = 2\mu_0\langle p\rangle/B^2$ is the ratio of plasma pressure to magnetic field pressure. In modeling of future "advanced tokamak" scenarios, the ideal kink mode is often assumed to be stabilized by a close-fitting, perfectly conducting wall, despite the fact that real, resistive walls are widely thought to provide stabilization only for durations less than τ_W, the magnetic field penetration time of the wall. The experiments described here suggest a resolution of this apparent inconsistency, and demonstrate that, in spite of its limitations, ideal magnetohydrodynamic (MHD) theory remains a useful method for predicting the stability limits of actual plasma discharges.

Previous experiments suggested that a nearby metal wall such as the vacuum vessel can, in fact, stabilize the ideal kink for times longer than the wall penetration time [1,2]. Stability analysis indicates that the maximum beta reached in tokamak discharges is typically greater than the calculated ideal MHD stability limit in the absence of a wall, but is consistent with the calculated limit assuming a perfectly conducting wall at the position of the vacuum vessel. However, the diagnostic measurements available in previous experiments were not sufficient to conclusively rule out other stabilizing influences, such as current density profile effects.

New theoretical developments emphasize the importance of plasma rotation in the stabilization of ideal kink modes by a resistive wall. It was previously shown that a resistive wall can stabilize resistive modes in a rotating plasma [3]. The instability rotates with the plasma at frequency ω, and is stabilized as if by an ideal wall provided $\omega\tau_W \gg 1$. Rotation is also expected to reduce the nonlinearly saturated amplitude of an unstable resistive mode to the ideal-wall value [4]. On the other hand, in the case of an ideal plasma instability which would be stable with an ideal wall but unstable without a wall, simple kink mode theory predicts two roots [5]: a rotating, stable ideal kink mode, and a stationary "resistive-wall" mode. The resistive-wall mode has a growth rate $\gamma \sim \tau_W^{-1}$, and is unaffected by plasma rotation velocities less than the Alfvén velocity [6]. However, more recent theoretical analysis [7] suggests that when finite aspect ratio and finite pressure effects are included, wall stabilization of both modes is possible if the wall is at an optimum location and the plasma rotates at only a small fraction of the Alfvén velocity.

High beta experiments have been performed in DIII-D with the purpose of obtaining clear evidence for the long time scale stabilization of kink modes by a resistive wall. These experiments were designed to maximize the gain in beta from wall stabilization. In order to improve the coupling of MHD modes to the vacuum vessel wall, a full-size double-null diverter configuration was used, with a broad current density profile and low internal inductance ℓ_i. The current profile was broadened by operating at moderate to low values of the safety factor q, and by applying neutral beam heating early in the discharge to slow the inward penetration of the current density.

The strong toroidal rotation induced by DIII-D's co-injected neutral beams, typically $f_{\mathrm{rot}} = \omega_{\mathrm{rot}}/2\pi \sim 10$ to 25 kHz at the center of the discharge, is sufficient for wall stabilization effects. The decay times τ_W for axisymmetric ($n = 0$) eigenmodes of the vacuum vessel with poloidal mode numbers $m = 2$ and $m = 3$ are calculated to be ~2 ms, and are expected to be somewhat shorter for eigenmodes with toroidal mode number $n = 1$. Nevertheless, the condition $\omega_{\mathrm{rot}}\tau_W \gg 1$ should be well satisfied for toroidal rotation frequencies $f_{\mathrm{rot}} \gtrsim 1$ kHz. Numerical calculations [7] indicate that stabilization of the resistive-wall mode requires $\omega_{\mathrm{rot}}/\omega_A \gtrsim 0.03$ to 0.05, where $\omega_A = V_A/qR$ is the Alfvén frequency. For the present experiment, this would correspond to a critical rotation frequency of a few kHz at the center of the plasma, decreasing toward the edge where q is larger.

A typical equilibrium reconstruction for this experiment is shown in Fig. 1. This reconstruction and others used

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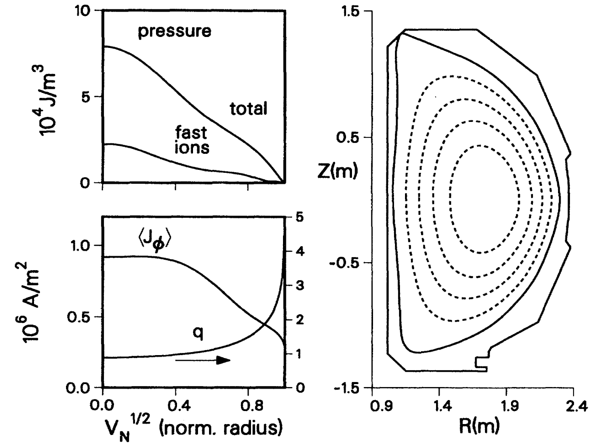

FIG. 1. High beta equilibrium reconstruction incorporating measure plasma density, temperature, and current density profile data. The figure includes radial profiles of pressure, flux-surface averaged toroidal current density $\langle j_\phi \rangle$, and safety factor q and a cross section of the reconstructed flux surfaces. Discharge 80 108: $\beta = 12.5\% = 4.3(I/aB)$, $q_{95} = 2.5$, $\ell_i = 0.71$, $B = 0.8$ T, and $I = 1.5$ MA.

here for stability analysis incorporate measured profiles of electron density from Thomson scattering and several CO_2 interferometer chords, electron temperature from Thomson scattering, ion temperature from charge-exchange recombination spectroscopy, and internal magnetic field pitch from an eight-channel motional Stark effect array, as well as external magnetic field data. The recently available current density profile information obtained from motional Stark effect measurements [8] was crucial in the analysis of this experiment.

The best discharges in this series have beta value up to 50% greater than predicted by the empirical scaling relation for the maximum beta $\beta_N = \beta(I/aB)^{-1} \leq 4\ell_i$. This relation, which includes the stabilizing effect of magnetic shear, was previously found to describe DIII-D and JET data well [9,10]. In particular, it provides a good representation of the beta limit for DIII-D discharges with $1 < \ell_i < 2$. In those earlier DIII-D experiments which reached high β_N at high ℓ_i, calculations showed that the wall had only a small stabilizing effect. However, some discharges with $\ell_i < 1$ reached values of β_N well above the $4\ell_i$ scaling, as seen in Fig. 2. These include wall-stabilization experiments of the type described here, as well as some other discharges with broad current density profiles where wall stabilization may have also played a role. Detailed stability calculations for the present experiments show that the greater beta limit at low ℓ_i is a result of wall stabilization, made possible by the broader current density profile.

In discharge 80 108 a new record $\beta = 12.5\%$ was achieved (Fig. 1) by means of wall stabilization. The normalized beta value $\beta_N = 4.3$ is 40% greater than expected from the scaling of $\beta_N \leq 4\ell_i$. MHD stability calculations show that the $n = 1$ ideal kink mode would be unstable in this discharge in the absence of a wall, but a perfectly conducting wall at the position of the DIII-D vacuum vessel stabilizes the external component of the $n = 1$ mode which might otherwise lead to a disruption. Although the $n = 1$ mode is not calculated to be completely stable with a wall, its calculated growth rate becomes an order of magnitude smaller and its amplitude at the plasma edge is greatly reduced. This residual internal instability is associated with the existence of a $q = 1$ surface within the plasma, and is consistent with the observed presence of $m/n = 1/1$ internal relaxations (sawtooth oscillations) in the discharge.

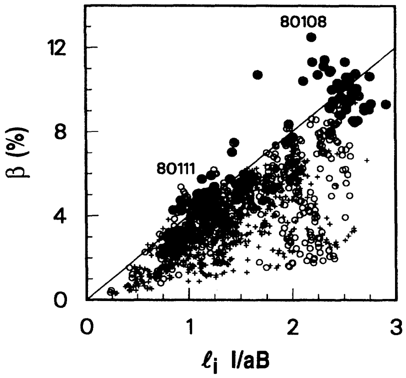

FIG. 2. Scaling of the DIII-D beta limit with ℓ_i, including (●) wall-stabilization experiments with $\ell_i < 1$, (○) other discharges with $\ell_i < 1$, and (+) discharges with $\ell_i > 1$.

Clear evidence of wall stabilization is also provided by another discharge (80 111) at lower plasma current. Here the safety factor was maintained well above unity everywhere in the discharge, thus eliminating the $m/n = 1/1$ internal kink mode. Stability calculations show that at maximum beta this discharge is stable to the ideal kink mode with a perfectly conducting wall at the position of the vacuum vessel, but would be unstable if the cross-sectional dimensions of the wall were only 10% to 30% larger (Fig. 3). Variation of the equilibrium reconstruction within the constraints of the experimental data does not substantially alter these results. Furthermore, the wall is required for stability even earlier in the discharge, as shown by the curve for $t = 645$ ms in Fig. 3. That is, the discharge is wall stabilized for at least 60 ms, more than 20 wall penetration times. Stability calculations for a series of equilibria during the earlier evolution of the discharge indicate that the stability limit without a wall is reached at $\beta_N = 2.8$, as shown in Fig. 4. The maximum normalized beta $\beta_N = 3.8$ reached in this discharge represents a gain in beta of at least 30% over the stability limit without a wall.

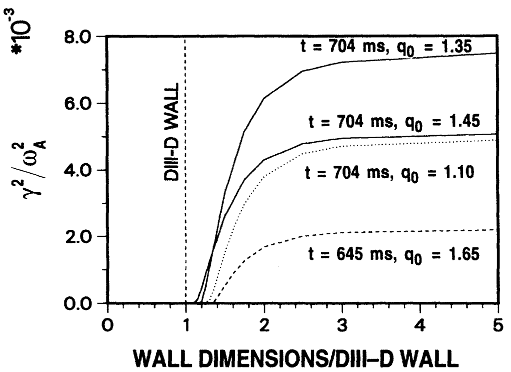

FIG. 3. Calculated ideal kink mode growth rate versus wall dimension multiplier relative to the DIII-D vacuum vessel. Discharge 80 111: $\beta = 6.0\% = 3.8(I/aB)$, $q_{95} = 5$, $\ell_i = 0.71$, $B = 0.8$ T, and $I = 0.8$ MA. Results are shown at the time of maximum beta ($t = 704$ ms) for the range of q_0 values allowed by the equilibrium reconstruction, and also at an earlier time in the discharge ($t = 645$ ms, $\beta = 4.5\%$).

Two distinct types of discharge termination were observed in these experiments, both consistent with expectations for wall-stabilized instabilities. The first type is represented by discharge 80 108, where the instability which terminates the discharge is consistent with a resistive instability whose saturated amplitude is limited by rotation in the presence of a wall. In this discharge an $m/n = 2/1$ mode rotates at $f_{\mathrm{rot}} \gtrsim 1$ kHz with a relatively small saturated amplitude; its long lifetime (more than 100 ms) in a saturated state suggests a resistive instability. Later, when this mode stops rotating, it grows until the discharge disrupts. Its growth time of several msec is comparable to the magnetic field penetration time of the vacuum vessel wall, as expected when the ideal-wall-like stabilization is lost in the absence of mode rotation.

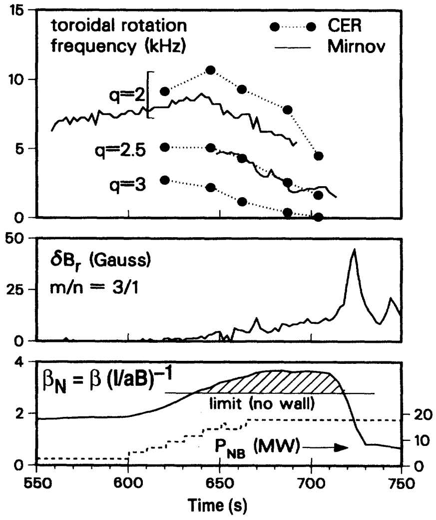

FIG. 4. Time evolution of discharge 80 111, showing rotation frequencies at several rational surfaces determined from magnetic (Mirnov) oscillations and CER spectroscopy, δB_r of the nonrotating $m/n = 3/1$ mode from saddle loops at the midplane, normalized beta β_N, and neutral beam power P_{NB}.

The second type of termination, represented by discharge 80 111, supports the recent prediction that the nonrotating resistive-wall mode can be stabilized by plasma rotation. The good confinement phase of the discharge ends with an $m/n = 3/1$ instability which has the characteristics expected of a resistive-wall mode: The instability has a growth time of about 5 ms, comparable to the wall penetration time, and is stationary with respect to the wall from its onset. Although the discharge dwells near the maximum beta value for about 50 ms, the rotation velocity profile is evolving during this time, as shown in Fig. 4. The rotation of the $q = 2$ surface, as determined from charge exchange recombination (CER) spectroscopy, is slowing by remains greater than 5 kHz, which is sufficient to provide stabilization of the $m/n = 2/1$ mode. However, the plasma rotation velocity at the $q = 3$ surface decreases to zero shortly before the onset of the instability. This is consistent with the hypothesis that the 3/1 mode is stabilized by the plasma rotation, becoming unstable only when the rotation ceases and the stabilizing influence becomes that of a resistive wall rather than an ideal wall.

We speculate that toroidicity-induced Alfvén eigenmodes (TAE modes) may contribute to the loss of wall stabilization of the 3/1 mode. The downturn in the rotation rate seen at $t \approx 640$ ms coincides with the onset of large-amplitude TAE activity, leading to the loss of nearly half of the neutral beam ions as estimated from the D-D fusion neutron rate. The reduction of angular momentum input as the fast ions are lost may be the reason for the slowing of the rotation.

These recent DIII-D experiments demonstrated that a resistive wall can stabilize MHD modes for times scales long compared to the resistive penetration time of the wall. The maximum beta values reached are consistent with low-n ideal stability limits calculated with a perfectly conducting wall, and are well above that limit calculated without a wall. The improvement of stability disagrees with simple ideal-plasma MHD theory but is consistent with more recent extensions of the theory. These results lend credibility to high performance tokamak scenarios for future devices such as TPX [11] which rely on wall stabilization.

These experiments also demonstrate the need for plasma rotation in order to maintain wall stabilization. Instabilities occur, leading to loss of confinement or disruption, when the rotation velocity approaches zero at the mode rational surface. Maintaining the requisite rotation across the entire minor radius of the discharge may be the most important challenge for wall-stabilized scenarios, and points to the need for an improved undertaking of angular momentum transport and radial election field formation in tokamaks.

Future experiments will be aimed at determining the rotation rate needed to maintain wall stabilization, and testing the theoretical prediction [7] that the resistive-wall mode may become more unstable as the distance from the plasma to the wall decreases.

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[1] M. Okabayashi *et al.,* Plasma Physics and Controlled Nuclear Fusion Research 1986 (Internal Atomic Energy Agency, Vienna, 1987), Vol. I, p. 275.

[2] E. J. Strait *et al.,* Plasma Physics and Controlled Nuclear Fusion Research 1988 (Internal Atomic Energy Agency, Vienna, 1989), Vol. I, p. 83.

[3] T. H. Jensen and M. S. Chu, J. Plasma Phys. **30**, 57 (1983).

[4] T. C. Hender, C. G. Gimblett, and D. C. Robinson, Nucl. Fusion **29**, 1279 (1989).

[5] L. Zakharov and S. V. Putvinskii, Sov. J. Plasma Phys. **13**, 68 (1987).

[6] C. G. Gimblett, Nucl. Fusion **26**, 617 (1986).

[7] A. Bondeson and D. J. Ward, Phys. Rev. Lett. **72**, 2709 (1994).

[8] D. Wróblewski and L. L. Lao, Rev. Sci. Instrum. **63**, 5140 (1992).

[9] E. J. Strait *et al.,* Controlled Fusion and Plasma Physics (European Physical Society, Petit-Lancy, 1991), Vol. 15C, Part II, p. 105.

[10] D. Stork *et al.,* Controlled Fusion and Plasma Physics (European Physical Society, Petit-Lancy, 1992), Vol. 16C, Part I, p. 339.

[11] R. J. Goldston *et al.,* Controlled Fusion and Plasma Physics (European Physical Society, Petit-Lancy, 1993), Vol. 17C, Part I, p. 319.