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WALL STABILIZATION EFFECTS IN DIII–D HIGH BETA DISCHARGES

by
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WALL STABILIZATION EFFECTS IN DIII–D HIGH BETA DISCHARGES*

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Recent high beta discharges in DIII–D, reaching values up to $\beta = 12.5\%$, demonstrate that a resistive wall can stabilize low-n MHD modes in a rotating plasma. The maximum beta values reached in discharges with broad current profiles (internal inductance $\ell_i \approx 0.7$) are up to 40% greater than the limit predicted by ideal MHD stability calculations in the absence of a wall, but are consistent with predicted limits assuming a perfectly conducting wall at the position of the vacuum vessel. This wall stabilization is observed for time scales long compared with the resistive penetration time of the wall. Plasma rotation is essential to the stabilization, and instabilities with characteristics of the predicted "resistive wall" mode are observed only when the rotation velocity approaches zero at the mode rational surface.

Introduction

The question of whether ideal kink modes can be stabilized by a resistive wall is crucial for high performance tokamaks. In present tokamaks, as well as future "advanced tokamak" scenarios, performance is often limited by low-n kink stability at high beta. In many such scenarios, the ideal kink mode is 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 times less than the resistive penetration time of the wall.

Previous experiments have suggested that the vacuum vessel wall 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 high beta 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 profile effects.

New theoretical developments emphasize the importance of plasma rotation in 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, and is stabilized as if by an ideal wall. 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:[4] a rotating, stable ideal kink mode, and a stationary "resistive wall" mode which has a growth time on the order of the wall penetration time and is unstable even in the presence of plasma rotation. However, more recent theoretical analysis[5] 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 a small but non-negligible fraction of the sound speed.

DIII–D Experiments

Recent high beta experiments in DIII–D addressed these issues: whether a real, resistive wall can provide long time scale stabilization of kink modes, whether rotation is required for this stabilization, and whether a stationary "resistive wall" mode is observed in the presence of plasma rotation.

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This series of discharges was intended to provide clear evidence by maximizing the gain in beta from wall stabilization. DIII–D's co-injected neutral beams induce a strong toroidal rotation of the plasma. In order to improve the coupling of MHD modes to the vacuum vessel wall, a full-size double-null divertor 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. A typical equilibrium reconstruction is shown in Fig. 1. This equilibrium and others used here for stability analysis include 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 8-channel motional Stark effect array.

The best discharges in this series have beta values up to 50% greater than predicted by the empirical scaling law $\beta_N = \beta\ (I/aB) = 4\ \ell_i$, as seen in Fig. 2. This relation was previously found to describe DIII–D and JET data well,[6,7] but in earlier DIII–D experiments at high β_N, calculations showed that the wall played a less significant role. The greater beta limit here is attributed to effects of wall stabilization, because of the broader current density profile.

In discharge 80108 a new record $\beta = 12.5\%$ was achieved (Fig. 1), with a value $\beta_N = 4.3$ which is 40% greater than expected from the scaling of $\beta_N = 4\ \ell_i$ (Fig. 2). MHD stability calculations show the n = 1 ideal kink mode to be unstable in this discharge in the absence of a wall. With a perfectly conducting wall at the position of the DIII–D vacuum vessel, the growth rate of the n = 1 mode becomes an order of magnitude smaller and its amplitude at the plasma edge is greatly reduced. This residual internal n = 1 instability is consistent with the observed presence of sawteeth in the discharge.

The instability which terminates the $\beta = 12.5\%$ discharge is consistent with expectations for a wall-stabilized resistive instability. An m/n = 2/1 mode rotates with a relatively small saturated amplitude, then stops rotating and grows until the discharge disrupts. Its growth time of several msec is comparable to the resistive penetration time of the vacuum vessel wall, as expected when the ideal wall-like stabilization is lost in the absence of mode rotation.

Clear evidence of wall stabilization is provided by another discharge (80111) 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

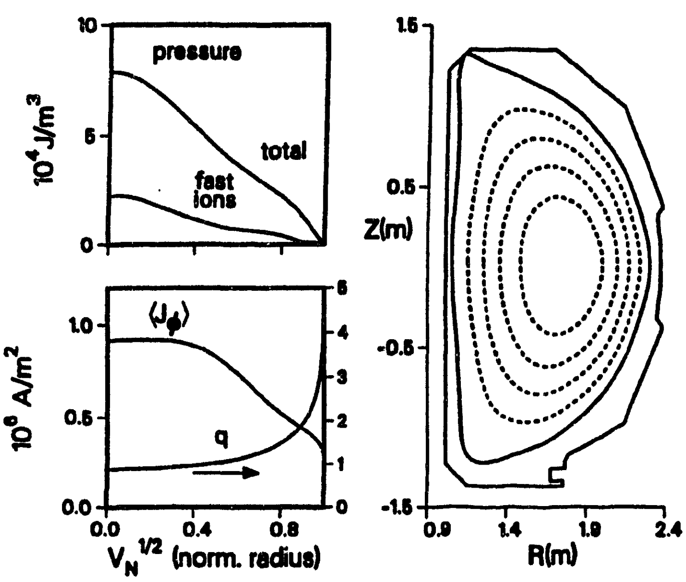

Fig. 1. High beta equilibrium reconstruction, incorporating measured plasma density, temperature, and current density profile data. Discharge 80108: $\beta = 12.6\% = 4.3\ (I/aB)$, $q_{95}=2.5$, $\ell_i = 0.71$.

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 20% larger (Fig. 3). Variation of the equilibrium reconstruction within the constraints of the experimental data does not substantially alter these results. Furthermore, the discharge is wall-stabilized for at least 60 ms, more than 10 wall penetration times. A beta gain of at least 30% is achieved over the stability limit without a wall.

The good confinement phase of discharge 80111 is terminated by an m/n = 3/1 instability which has some of the characteristics expected of an ideal-plasma, resistive-wall mode stabilized by plasma rotation. 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 is slowing but remains greater than 5 kHz, sufficient to provide stabilization of the m/n = 2/1 mode. However, the plasma rotation velocity at the q = 3 surface, as determined from charge exchange recombination (CER) spectroscopy, decreases to zero shortly before the onset of the instability. This is consistent with the hypothesis that the 3/1 mode is Doppler-shifted 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 Alfven 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 ≈ 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 neutron rate. The reduction of angular momentum input as the fast ions are lost may be the reason for the slowing of the rotation.

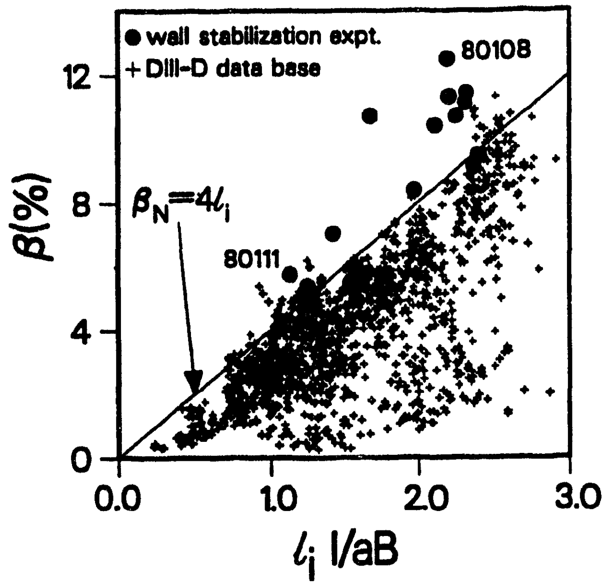

Fig. 2. Scaling of the DIII-D beta limit with ℓ_i, including the recent high beta experiments (solid circles).

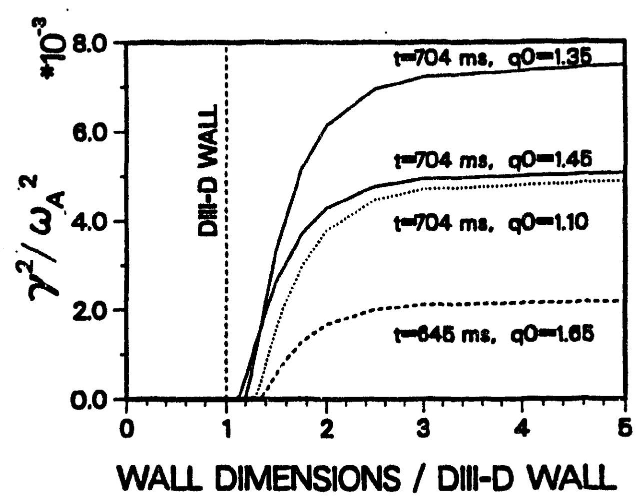

Fig. 3. Calculated ideal kink mode growth rate versus wall dimensions relative to the DIII-D vacuum vessel dimensions. Discharge 80111: β = 6.0% = 3.8 (I/aB), q_{95} = 5, ℓ_i = 0.71. Results are shown at the time of maximum beta (t = 704 ms) for the range of q_0 values allowed by the equilibrium reconstruction, and also for an earlier time in the discharge (t = 645 ms).

Discussion and Conclusions

Recent DIII–D experiments have demonstrated that a resistive wall can stabilize MHD modes for time 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 the limit calculated without a wall. These results lend credence to scenarios for future devices such as TPX[8] 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 understanding of angular momentum transport and radial electric field formation in tokamaks.

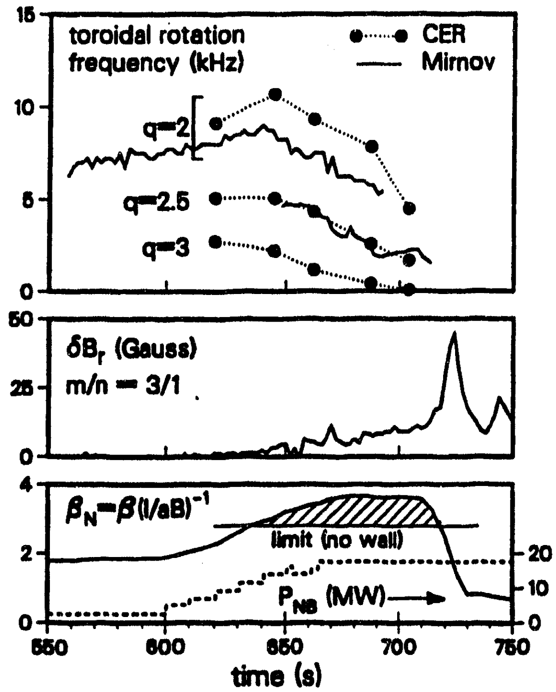

Fig. 4. Time evolution of discharge 80111, showing rotation frequencies at several rational surfaces determined from magnetic (Mirnov) oscillations and CER spectroscopy, δB_r of the non-rotating m/n = 3/1 mode from saddle loops at the midplane, normalized beta β_N, and neutral beam power P_{NB}.

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