

Stabilization of the external kink and control of the resistive wall mode in tokamaks*

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One promising approach to maintaining stability of high beta tokamak plasmas is the use of a conducting wall near the plasma to stabilize low- n ideal magnetohydrodynamic instabilities. However, with a resistive wall, either plasma rotation or active feedback control is required to stabilize the more slowly growing resistive wall modes (RWMs). Previous experiments have demonstrated that plasmas with a nearby conducting wall can remain stable to the $n=1$ ideal external kink above the beta limit predicted with the wall at infinity. Recently, extension of the wall stabilized lifetime τ_L to more than 30 times the resistive wall time constant τ_w and detailed, reproducible observation of the $n=1$ RWM have been possible in DIII-D [Plasma Physics and Controlled Fusion Research (International Atomic Energy Agency, Vienna, 1986), p. 159] plasmas above the no-wall beta limit. The DIII-D measurements confirm characteristics common to several RWM theories. The mode is destabilized as the plasma rotation at the $q=3$ surface decreases below a critical frequency of 1–7 kHz ($\sim 1\%$ of the toroidal Alfvén frequency). The measured mode growth times of 2–8 ms agree with measurements and numerical calculations of the dominant DIII-D vessel eigenmode time constant τ_w . From its onset, the RWM has little or no toroidal rotation ($\omega_{\text{mode}} \leq \tau_w^{-1} \ll \omega_{\text{plasma}}$), and rapidly reduces the plasma rotation to zero. These slowly growing RWMs can in principle be destabilized using external coils controlled by a feedback loop. In this paper, the encouraging results from the first open loop experimental tests of active control of the RWM, conducted in DIII-D, are reported. © 1999 American Institute of Physics. [S1070-664X(99)92705-2]

I. INTRODUCTION

For the advanced tokamak confinement concept to represent an economically attractive approach to commercial fusion power, operation at high β_N is essential in order to minimize size and cost of the power core, while at the same time maximizing the bootstrap current fraction with good alignment to permit steady state operation. The negative central shear (NCS) advanced tokamak configuration^{1,2} relies on stabilization of the low- n ideal magnetohydrodynamic (MHD) kink mode by a nearby conducting wall to achieve the required high values of β_N . [Here $\beta_N = \beta/(I/aB)$, $\beta = 2\mu_0 \langle p \rangle / B_0^2$, $\langle p \rangle$ is the volume averaged pressure, B_0 is the external toroidal field at the radial center of the plasma chamber P_0 , I is the total toroidal current, and a is the plasma minor radius.]

While a perfectly conducting wall can, in principle, stabilize the kink mode, in a wall with finite conductivity the stabilizing image currents decay and the resulting unstable

resistive wall mode (RWM) essentially leaks through the wall and grows with an exponential growth time of the order of the wall resistive decay time τ_w . Experimental work on the DIII-D tokamak,^{3–5} the Princeton Beta Experiment-Modified (PBX-M),⁶ and the high beta tokamak-extended pulse (HBT-EP),^{7,8} and theoretical calculations^{9–12} that included some form of plasma dissipation, have shown, however, that the plasma can be stabilized for times much longer than τ_w if the plasma rotation rate Ω_p is sufficiently fast relative to the wall. With plasma rotation and dissipation the ideal external kink now branches into two modes: (1) a plasma mode, that rotates at speed $\omega \sim \Omega_p$ and is wall stabilized by continually regenerating the image currents for $\Omega_p > \tau_w^{-1}$, and (2) a RWM that is nearly stationary with respect to the wall ($\omega \sim \tau_w^{-1} \ll \Omega_p$) and can also be completely stabilized if the plasma rotation rate Ω_p is greater than some critical value Ω_c .

In recent DIII-D experiments, reproducible wall stabilized plasmas with enhancement factors $E_w = \beta_N / \beta_N^{\text{no wall}}$ exceeding the previous maximum^{3–5} and lifetimes τ_L , during which wall stabilization was maintained, exceeding the pre-

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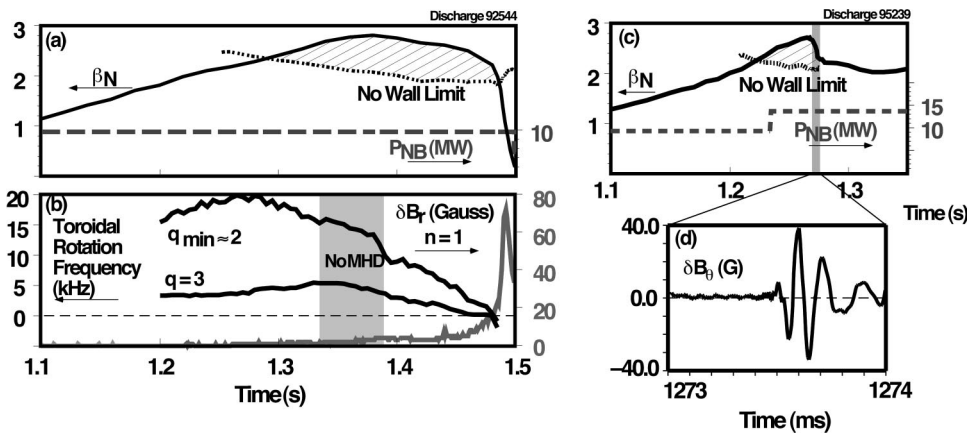


FIG. 1. Comparison of time evolution and termination of the high beta phase for discharges near the ideal wall stability limit. (a), (c) Normalized beta and neutral beam power. (b) Plasma rotation frequency at two radial locations, and the B_r amplitude of the slowly growing, slowly rotating RWM measured from saddle loops outside the vessel in discharge No. 92544. (d) B_θ amplitude of the rapidly growing, rapidly rotating ideal kink-ballooning mode in discharge No. 95239.

vious duration by a factor of 3, have been achieved using newly developed operational techniques. (Here, $\beta_N^{\text{no wall}}$ is the β_N limit predicted without wall stabilization.) The slowing of the plasma rotation noted in earlier DIII-D experiments⁴ is shown to be strongly correlated with E_w exceeding unity and persists while $\beta_N > \beta_N^{\text{no wall}}$ even in the absence of any detectable MHD activity. The critical plasma rotation for stabilization Ω_c is found to be robustly reproducible for repeated plasma conditions but is dependent on plasma conditions. Improvements in diagnostics capability and reproducibility of the discharges have furthermore made a direct identification of the RWM possible; the mode structure is measured here from electron cyclotron emission (ECE) spectroscopy and is compared directly to numerical predictions of the RWM structure.

Two promising avenues for stabilizing the RWM are being considered: active control of the plasma rotation, and active feedback using magnetic coils. Both DIII-D and HBT-EP have adopted the ‘‘smart shell’’¹³ concept as an initial approach to control the RWM using active feedback: external coils are controlled by a feedback loop designed to make the resistive wall appear perfectly conducting by maintaining a net zero radial field at the wall. A three-dimensional electromagnetic code, VALEN,¹⁴ has been developed to model active feedback control of the RWM in a tokamak. Code predictions and initial experimental tests of active control of the RWM in the DIII-D tokamak show encouraging results toward the feasibility of ultimately controlling the RWM growth.

II. PASSIVE STABILIZATION OF THE EXTERNAL KINK

Discharges exceeding the β_N limit to $n=1$ external kink calculated in absence of a wall can now be obtained reproducibly using a new technique in DIII-D. An early current ramp with some neutral beam heating is followed by a short constant current period during which the plasma is rapidly heated to high β and a transition to H mode (high confinement) is triggered. This is then followed by a second current ramp to lower the internal inductance to $\ell_i \sim 0.7$. The new technique produces single null divertor NCS target plasmas with low edge safety factor q , and broad pressure and current

density profiles that are coupled strongly to the wall.^{1,2} $E_w > 1$ is routinely achieved before other instabilities disrupt or degrade the target plasma.

Using this technique, the enhancement factor E_w has been extended to $E_w \sim 1.4 \pm 0.1$ in discharge No. 92544. The time history is shown in Fig. 1(a). E_w exceeds unity in this discharge for a period of ~ 200 ms, which is a factor of 3 greater than the previous duration reported in Refs. 3–5. At the time that this discharge reaches its maximum β_N , GATO code¹⁵ calculations show it is strongly unstable to an ideal kink ballooning mode with no wall stabilization, but near marginal stability with a perfectly conducting wall at the position of the DIII-D vacuum vessel (see Fig. 2). The results of the GATO stability calculations are found to be insensitive to variations in the equilibrium profiles that are consistent with the discharge diagnostics. These variations are obtained by systematically changing the number and the position of the knots in the spline representation used by the equilibrium code for the plasma profiles. This method revealed large uncertainties in the reconstruction of the edge current density. However, the $n=1$ mode predicted by GATO has a global radial structure, with large unstable components driven by the internal pressure gradients. The stability of the $n=1$

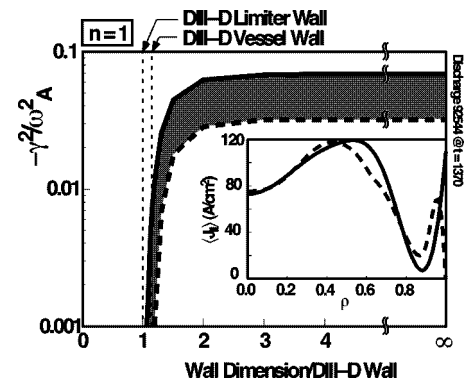


FIG. 2. Calculated growth rate of the $n=1$ ideal kink mode normalized to the Alfvén frequency vs wall dimension multiplier relative to the DIII-D limiter wall for discharge No. 92544 at the time of maximum beta ($t = 1.37$ s). Solid curve shows results for an equilibrium reconstruction allowing finite flux averaged toroidal current density $\langle J_\phi \rangle$ at the edge. Dashed curve is for case with $\langle J_\phi \rangle = 0$ at the edge. Inset shows the profiles of $\langle J_\phi \rangle$ for the two cases.

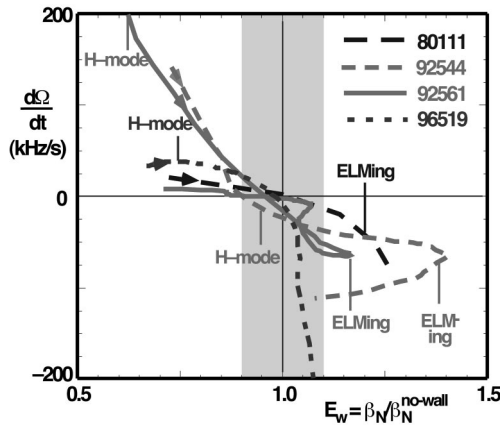


FIG. 3. Correlation of the rotation slowing rate $d\Omega/dt$ at a normalized minor radius $\rho=0.55$ for several wall stabilized discharges vs enhancement factor E_w . The H-mode transitions and ELMing onset times are also indicated.

mode is therefore essentially independent from the value of the edge current density, as shown in Fig. 2. Moreover, the stability predictions are not sensitive to variations of the minimum value of the safety factor, q_{\min} , from just below 2 to just above 2.

A two mode analysis of measurements of the time response of the vessel finds that the slowest $n=1$ eigenvalue has a time constant of $\tau_w=7$ ms. This is confirmed by estimates from the VALEN three-dimensional model for the DIII-D vessel and coil system, which predict $\tau_w=5.8$ ms. Wall stabilization was therefore maintained in discharge No. 92544 for about 30 wall times.

The high beta phase of the discharge ends with an $n=1$ mode which has the characteristics predicted for a resistive wall mode: the mode growth starts as the plasma rotation decreases; the growth time of about 8 ms matches well the wall time constant τ_w and the mode rotation ω is ~ 60 Hz from the mode onset, consistent with the predicted RWM rotation $1/2\pi\tau_w\sim 40$ Hz. Comparable results have been obtained in a number of discharges with similar conditions.

In contrast, a similar discharge, No. 95239 at about the same maximum β_N but with greater heating beam power shows an $n=1$ ideal mode growing on the Alfvénic time scale of about $40\ \mu\text{s}$ causing a beta drop [Fig. 1(c)]. The rapid growth of the mode and rapid rotation of mode is shown in Fig. 1(d). These observations are consistent with the stability calculations that show No. 92544 is near marginal stability assuming a perfect conducting wall at the DIII-D wall location (Fig. 2).

III. PLASMA ROTATION IN WALL-STABILIZED PLASMAS

It is consistently observed that the plasma rotation slows when β_N exceeds the calculated no wall limit [Fig. 1(a), for example]. The slowdown is not correlated with any observable MHD activity, although the presence of MHD activity can sometimes accelerate the slowdown. The time histories of $d\Omega/dt$ are shown for several different discharges in Fig. 3 versus $\beta_N/\beta_N^{\text{no wall}}$. The curves are for time periods with

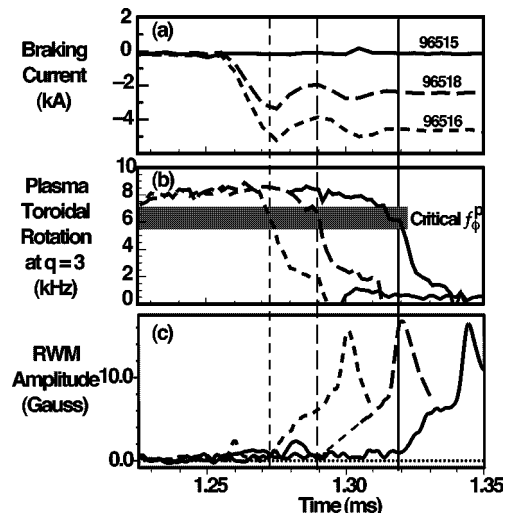


FIG. 4. Controlled variation of the RWM onset through C-coil braking of the plasma rotation in similar discharges. Time evolution of (a) C-coil current, proportional to the magnetic braking field; (b) toroidal plasma rotation at the $q=3$ surface; and (c) B_r amplitude of the RWM. The vertical lines denote the onset of the RWM, corresponding in each discharges to a $q=3$ rotation of about 6.5 kHz.

constant neutral beam heating power. In each case the plasma rotation increases [$(d\Omega/dt)>0$] while $\beta_N < \beta_N^{\text{no wall}}$ ($E_w > 1$); it starts to decrease when β_N exceeds $\beta_N^{\text{no wall}}$. One of the discharges in the figure in particular (No. 92561, solid line) illustrates clearly the correlation of the slowdown with $E_w > 1$. In this case β_N reaches a maximum, then decreases rapidly after the onset of edge-localized modes (ELMs), showing that the sign of $d\Omega/dt$ changes back to >0 when β_N decreases below $\beta_N^{\text{no wall}}$. One possible interpretation of the results is that a small amplitude, undetected RWM is always present when $\beta_N > \beta_N^{\text{no wall}}$. The electromagnetic drag from a RWM barely detectable by our sensors would be consistent with the slowdown noted. The plasma rotation slowdown could also result from electromagnetic drag from the internal continuum resonances of the wall-stabilized RWM.⁴ In any case, the RWM itself is most likely associated with the slowdown.

The slowdown of the plasma rotation below a critical rotation rate Ω_c in a discharge with β_N above the no wall limit leads to an unstable RWM with growth time of the order of τ_w . The value of Ω_c is found to be robustly reproducible for repeated plasma conditions, but is dependent on plasma conditions. For discharge No. 92544 in Fig. 1, Ω_c evaluated at the $q=3$ surface is about 1 kHz, in agreement with previous DIII-D observations.^{3,5} A considerably higher value of Ω_c was reproducibly determined for a different set of discharges during a magnetic braking experiment. In this experiment a small static external $n=1$ field is applied⁵ using the error field correction coil (C-coil), to brake the plasma rotation. Figure 4 shows the results for three representative discharges with the same plasma conditions, but with varying braking current.¹⁶ A stronger braking produces an earlier deceleration of the $q=3$ surface and results in earlier onset of the RWM. In each case, however, the RWM appears when the rotation frequency at the $q=3$ surface is

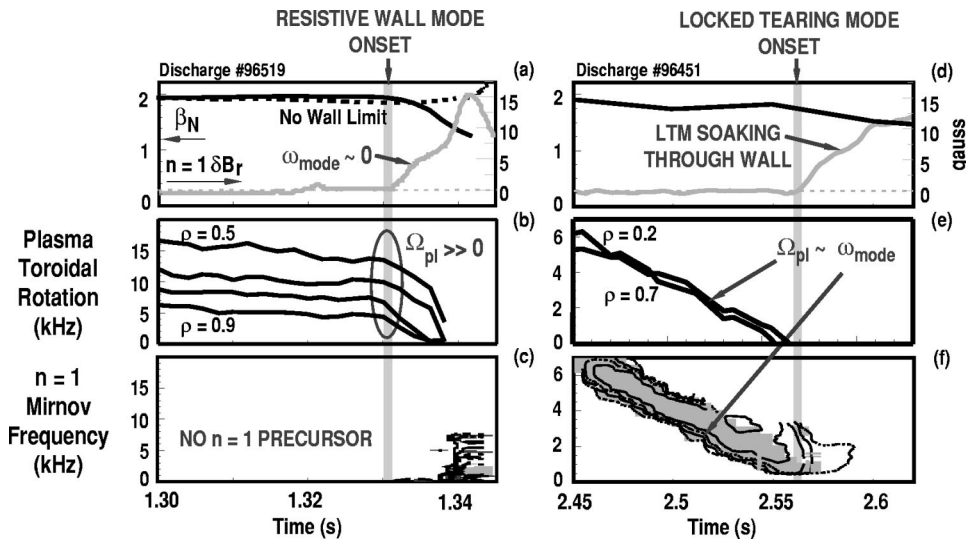


FIG. 5. Comparison of typical discharges with a resistive wall mode (a)–(c) (discharge No. 96519) and with a tearing locked mode (d)–(f) (discharge No. 96451). Time evolution of (a), (d) normalized beta and $n=1$ B_r amplitude of the mode measured outside the vessel; and (b), (e) plasma rotation frequency at several radial locations. (c), (f) Contour plot of the $n=1$ Mirnov probe signals vs time and frequency.

6.5 ± 0.5 kHz. The discharges of Fig. 4 just slightly exceed the no wall limit, and the predicted RWM structure has an edge peeling structure, unlike discharge No. 92544 for which E_w significantly exceeds 1, and the predicted mode structure is more global. These differences suggest two plausible explanations for the variation in the value of Ω_c : (1) theory and modeling have suggested that to stabilize the RWM when β is just above the no wall limit requires a more rapid plasma rotation than at somewhat higher β ,¹⁷ and (2) in discharges where the predicted RWM structure has larger internal poloidal components the RWM may couple more strongly to the rapid rotation of the core region, therefore requiring for stabilization a lower plasma rotation at the $q=3$ surface.

The experimental observations of $\Omega_c = 2\pi f \sim 10^4$ s⁻¹ disagree with predictions of ideal MHD theory that include dissipation only by resonance with the Alfvén waves,¹⁸ $\Omega_c \sim \tau_A^{-1} > 10^6$ s⁻¹, where τ_A is the poloidal Alfvén time. The observations also disagree with resistive MHD theories that require formation of islands for RWM stabilization at low rotation,^{11,12} $\Omega_c \sim \tau_w^{-1} \leq 3 \times 10^2$ s⁻¹. The observations are in somewhat better agreement with predictions of ideal MHD theories that include dissipation through toroidal coupling of the mode to sound waves,⁹ $\Omega_c \sim 0.05 \tau_A^{-1} \sim 10^5$ s⁻¹.

IV. RESISTIVE WALL MODE IDENTIFICATION IN A ROTATING PLASMA

The RWM is a mode that grows while nearly stationary with respect to the wall as the plasma is rotating: $\omega \sim \tau_w^{-1} \ll \Omega_p$. Figures 5(a)–5(c) show a clear example of this characteristic. In contrast to the RWM case, Figs. 5(d)–5(f) show a typical example of a locked tearing mode (LTM). At both the RWM onset and the LTM onset, and $n=1$ radial field essentially stationary with respect to the wall is seen to slowly penetrate through the wall [see Figs. 5(a) and 5(d)]. However, at the time of the RWM onset, the plasma rotation, measured from charge exchange recombination (CER) spectroscopy, is faster than 4 kHz over nearly the entire minor radius. It is after the onset of the RWM that the plasma rotation decreases rapidly to zero. The absence of n

$=1dB_\theta/dt$ signals from the Mirnov probes indicates that the RWM is stationary with respect to the wall from its onset. In contrast, at the time of the LTM onset the plasma rotation is already essentially zero over the entire minor radius. For this case the CER and Mirnov data show that before locking, the $n=1$ mode grows while rotating and slows down with the plasma.

Internal measurements of the mode structure from the ECE diagnostic confirm that the mode of Figs. 5(a)–5(c) is not a tearing mode. Figure 6 shows a comparison of measured and predicted radial profile of the electron temperature change caused by the $n=1$ mode. The measured change ΔT_e^m is evaluated during time periods when, based on indications from magnetics and soft x rays, only an $n=1$ perturbation is present. The predicted change, ΔT_e^p , is evaluated assuming that the mode responsible is the ideal plasma kink mode calculated by the GATO code in absence of a wall, and that the T_e profile is convected with the mode displacement ξ

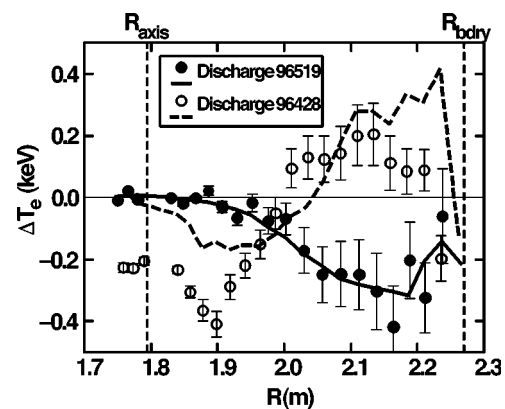


FIG. 6. Comparison of the radial profiles of the measured (solid circle data points) and predicted (solid curve) perturbed ECE T_e signal for discharge No. 96519 at 1338 ms. Also shown is the data (open circle data points) and prediction for a similar discharge No. 96428 in which the mode has a 110° phase difference from that for discharge No. 96519 according to the toroidal saddle loop array. The prediction for discharge No. 96428 is obtained by applying this phase difference to the instability for discharge No. 96519. The magnetic axis at $R \sim 1.70$ m and the plasma edge at $R \sim 2.25$ m are indicated.

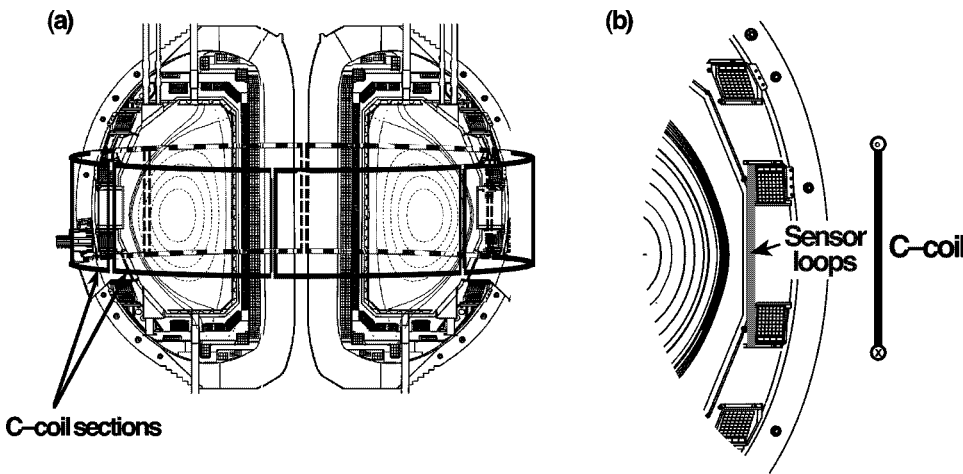


FIG. 7. Cross-section of DIII-D showing (a) the error field correction coil (C coil) used also as the active control coil during RWM stabilization experiments, and (b) the location of the sensor loops.

predicted along the ECE viewing line; i.e., $\Delta T_e^p = \xi \cdot dT_e/dR$. Examples of two similar discharges with two different toroidal phases of the mode are shown in Fig. 6. The calculation of the predicted temperature change ΔT_e^p for both discharges in Fig. 6 uses the same mode eigenfunction predicted for discharge No. 96519, with the poloidal phase of the GATO displacement chosen in each case according to the toroidal phase of the mode from magnetic diagnostics. The measured mode structure reproduces well the qualitative features of the stability calculation, showing a radially extended structure whose sign changes appropriately with the magnetic phase of the mode.

V. ACTIVE CONTROL OF THE RESISTIVE WALL MODE

The existence of a critical rotation frequency for stabilization suggests sustainment of the plasma rotation as one possible means for long time-scale stabilization of the RWM. However, the observation of a rotation slowdown in plasmas exceeding the no wall limit seems to imply that active control of the plasma rotation is required to maintain rotational stabilization. This may be achieved, for example, using rotating phased magnetic perturbations from coils internal to the vessel.

The alternative option is to feedback control the RWM using coils external to the conducting wall. This problem has been shown to be formally similar to the problem of active feedback of the axisymmetric vertical position instability.¹⁹ Active feedback stabilization of the axisymmetric mode is routinely used in DIII-D.²⁰ Several algorithms for feedback control of the RWM have been proposed, including the “smart shell”⁴ which uses externally applied magnetic perturbation to keep a zero net radial field at the wall, simulating the response of a perfectly conducting wall, and the “fake rotating shell,”²¹ where a phase shift is applied to the external magnetic perturbation to reproduce the leading phase shift response that the plasma would experience if the resistive wall were rotating toroidally.

Experimental tests have begun in DIII-D and HBT-EP using the “smart shell” approach to stabilize the RWM. Experiments in DIII-D use the existing C coil, which consists of six coils toroidally distributed at the midplane, and six radi-

ally aligned sensor loops located on the vessel wall, to cancel out the leaking radial field and mimic a perfectly conducting wall, at least in the regions covered by the sensor loops (see Fig. 7). In HBT-EP the conducting wall, internal to the vessel, is segmented to allow variation of the plasma wall separation. Recently, 10 of the original 20 aluminum wall segments have been replaced with stainless steel segments, so that also the wall time constant can now be effectively varied by inserting or retracting segments of different resistivity. Each stainless steel segment is equipped on the vacuum side with three active coils and three sensor loops for cancellation of the radial flux at the wall.

The three-dimensional electromagnetic code VALEN¹⁴ has been used to predict the efficiency of the feedback systems in DIII-D and HBT-EP. The VALEN code models any general resistive wall with a collection of thin shell, finite elements in an integral formulation. Arbitrary sensor loops and active control coils may be included in the simulation. The plasma instability is modeled by an equivalent helical current distribution on the plasma boundary.¹⁹ The VALEN results in Fig. 8 show that an improvement of about 15% in the beta limit is possible in DIII-D with active feedback using the existing C-coil. A greater increase of the beta limit is predicted with the addition of coils above and below the

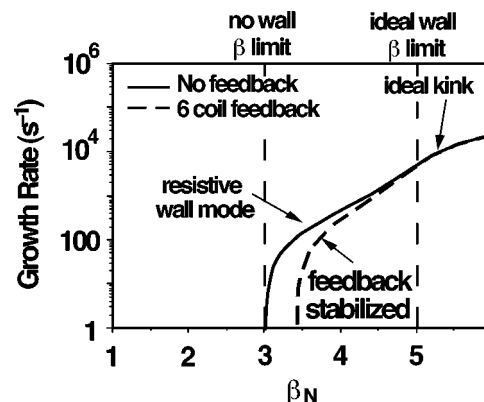


FIG. 8. Growth rate of the instability predicted by the VALEN three-dimensional code vs the normalized β for a DIII-D plasma. Different line styles denote results for the cases without feedback (solid line) and with feedback using the existing coils (dashed line).

existing C-coil for a better matching of the externally applied field to the helical structure of the RWM.

Preliminary experiments in DIII-D using open-loop active control show encouraging results. A series of discharges with reproducible RWM onset and toroidal phase were run, but one discharge included a static $n=1$ magnetic perturbation which was programmed to step on at the time of the RWM onset with a phase opposing the mode. At the time of the expected RWM onset, the plasma rotation, T_e , and β_N start to decrease rapidly in discharges without the $n=1$ opposing field, while they hesitate and then recover in the open loop discharge as the amplitude of the external field increases. Measurements of the $n=1$ mode amplitude, after correction for the applied perturbation and its induced currents, indicate that the RWM onset was postponed for greater than 20 ms.

A broad survey of active mode feedback in HBT-EP using a 30-coil smart shell with variable wall time constant has started. The results will allow the benchmark of the quantitative feedback control model VALEN, which could then be used as a tool for the design of active mode control system on a broad class of toroidal devices.

VI. SUMMARY AND DISCUSSION

New techniques and improved diagnostic capabilities have greatly extended the duration, beta enhancement factor, and reproducibility of wall-stabilized discharges in DIII-D, and have allowed the study of previously inaccessible resistive wall mode physics. The RWM has now been directly identified from external magnetic and internal diagnostic measurements. Reproducible measurements of the critical plasma rotation for stabilization of the RWM can now be compared quantitatively with the various theoretical predictions. A slowing of the plasma rotation is shown to be correlated with β_N exceeding $\beta_N^{\text{no wall}}$ and can persist even when there is no discernible MHD activity, suggesting the need for a better physics understanding of the momentum exchange between the plasma and wall when $E_w > 1$. The experimental results suggest that for stabilization of the RWM by plasma rotation, active control of the plasma rotation might be needed. Alternatively, RWM stabilization is predicted to be possible in DIII-D with active feedback using the existing error field correction coils, and preliminary experiments show encouraging results. Active control of the angular mo-

mentum profile and active feedback control of the RWM hold great promise for substantially improving the stability of high β advanced tokamak plasmas.

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