Direct Observation of the Resistive Wall Mode in a Tokamak and Its Interaction with Plasma Rotation

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Using newly developed techniques and improved diagnostics, rotating wall-stabilized discharges have been maintained in the DIII-D tokamak for 30 characteristic resistive wall decay times—significantly longer than was previously achieved. The terminating resistive wall mode has been directly identified using internal fluctuation diagnostics, and its correlation with the slowdown in the plasma rotation is established. [S0031-9007(99)09084-5]

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Stabilization of the low toroidal mode number n ideal magnetohydrodynamic (MHD) pressure-driven kink mode by a nearby conducting wall is essential to the success of many high-β magnetic confinement concepts, including the negative central shear (NCS) advanced tokamak [1,2], the spherical torus [3], the spheromak [4], and the reversed field pinch [5]. [Here, $\beta = 2\mu_0\langle p\rangle/B_0^2$, $\langle p\rangle$ is the volume averaged pressure, and B_0 is the external toroidal field. Also in the following, $\beta_N = \beta/(I/aB_0)$, where I is the total toroidal current, and a is the plasma minor radius.] However, for a wall with finite conductivity, the stabilizing image currents in the wall 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 [6–8] and theoretical work [9–12] has shown, however, that the RWM can be stabilized for times much longer than τ_w if the plasma is rotating sufficiently fast relative to the wall. The rotating kink mode continually regenerates the image currents. Although the RWM appears as another branch of the dispersion relation [13] that is locked to the wall and is unstable in an ideal plasma, finite plasma dissipation can completely stabilize this RWM branch [9] if the plasma rotation speed Ω_p is greater than some critical value Ω_c. In earlier experiments [6–8], the plasma rotation was observed to decay, and modes with the characteristic growth times and real frequencies of the RWM were observed in some discharges on external magnetic fluctuation diagnostics [6–8,14,15]. However, the evidence for the RWM in these experiments was circumstantial and the mode was not unambiguously identified.

The experiments reported here addressed several of the critical issues identified previously, and reveal a complex interdependence between the physics of the RWM and plasma rotation. Reproducible wall-stabilized plasmas have now been achieved with enhancement factors over the β_N limit predicted with no-wall stabilization, $E_w = \beta_N/\beta_N^{\text{no-wall}}$, exceeding the previous maximum [6–8] and with lifetimes τ_L, during which wall stabilization was maintained, exceeding the previous duration by a factor of 3. Improvements in diagnostic capability and reproducibility of the discharges have now made a direct identification of the RWM possible; the mode structure is measured from electron cyclotron emission (ECE) spectroscopy and is compared directly to numerical predictions of the RWM structure. The critical rotation speed Ω_c is found to be robustly reproducible for repeated plasma conditions but is dependent on the plasma conditions. The slowing of the plasma rotation noted in earlier DIII-D experiments [7] 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 discernible MHD activity. All other explanations, identified as possible causes for the slowdown in earlier experiments [7], are ruled out except those directly related to the RWM itself.

Wall-stabilized discharges can now be obtained reproducibly in DIII-D using a new technique in which 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 is triggered. This is then followed by a second current ramp to lower the internal inductance. The new technique produces single null divertor NCS target plasmas with low edge safety factor q but elevated internal q profiles that have low ℓ_i ($\ell_i \sim 0.7$) and an operationally accessible $\beta_N^{\text{no-wall}}$ limit, with $n = 1$ eigenmodes that are coupled strongly to the wall [1,2].

Using this technique, the enhancement factor has been extended to $E_w \simeq 1.4 \pm 0.1$ in discharge No. 92544. The time history for β_N is shown in Fig. 1. E_w exceeds unity in this discharge for a period of 200 ms, which is a factor of 3 greater than previously reported [6–8]. At the time that this discharge reaches its maximum β, GATO code [16] calculations show it is strongly unstable to an ideal $n = 1$ kink mode with no-wall stabilization but near marginal stability with a perfectly conducting wall at the position of the DIII-D vacuum vessel. This result is found to be insensitive to variations in the equilibrium that are consistent with the discharge diagnostics. 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 $\tau_{w0} \simeq 7$ ms. This is confirmed by estimates from the VALEN 3D electromagnetic model for the DIII-D vessel coil system, which predict $\tau_{w0} = 5.8$ ms. Wall stabilization was therefore maintained as a result of the plasma rotation for about 30 wall times in discharge No. 92544. Comparable results have also been obtained in a number of discharges with similar conditions.

The destabilization of modes with the characteristic growth time and frequency of the RWM at low rotation is also reproducible and has been obtained in a number of discharges with β_N values near and above 2.0. Discharge No. 92544 (Fig. 1) remains stable until the plasma rotation, as determined from charge recombination spectroscopy (CER), decreases below about 1 to 2 kHz at $q = 3$, after which the $n = 1$ RWM becomes unstable. The $n = 1$ saddle-loop amplitude for the RWM shown in Fig. 1 is a direct measurement of the $n = 1$ flux through the vessel. The mode growth time is 8 ms and the mode rotates toroidally from its onset with a slow frequency of about 60 Hz, which is also in agreement with theoretical predictions [9,10] for the RWM.

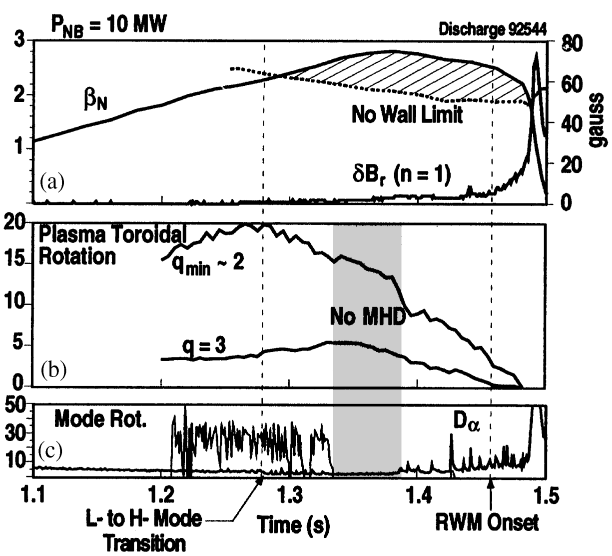

FIG. 1. Time history of discharge No. 92544 showing (a) β_N relative to the computed no-wall limit $\beta_N^{\text{no-wall}}$ and the saddle-loop amplitude δB_R of the RWM, (b) measured plasma rotation from CER at $q = q_{\min}$ and $q = 3$, and (c) MHD activity from Mirnov loops and photodiodes. For this discharge $I_p = 1.4$ MA, $\beta = 2.9\%$, $\ell_i = 0.8$, $q_0 = 2.8$, $q_{\min} = 2$, $q_{95} = 4.61$, and $B_0 = 2.1$ T at 1400 ms.

In all of the observations, RWM destabilization follows the decrease in the toroidal plasma rotation frequency below a critical value $1 \lesssim \Omega_c/2\pi \lesssim 7$ kHz at $q = 3$. The mode growth times range between 2 and 8 ms (cf. $\tau_{w0} = 7$ ms), and the mode frequencies range from nearly stationary to about 60 Hz or a few times $(2\pi\tau_{w0})^{-1}$. This is in contrast to ideal modes that are unstable with a perfectly conducting wall, whose precursors grow on time scales of at most a few hundred μs, and have real frequencies closely matching the interior plasma rotation frequency (or more correctly, the $\mathbf{E} \times \mathbf{B}$ frequency) which is typically tens of kHz. This also contrasts with resistive-plasma tearing modes which have growth times of the order of 10 ms, but which also have a frequency f that is close to the plasma rotation frequency $\Omega_p/2\pi$ while they slow down with the plasma and finally lock to the wall. Locked tearing modes are also sometimes observed in DIII-D, but again with frequency $f = \Omega_p/2\pi = 0$. In the present experiments, the modes begin growing while the plasma rotation frequency is much larger than the mode frequency.

Internal fluctuation measurements from the ECE diagnostic confirm that these slowly growing, slowly rotating modes are RWMs. At the onset of the RWM at 1331 ms, discharge No. 96519 is calculated to be just above $E_w = 1$ and the mode has near zero frequency, as observed on the toroidal and poloidal magnetic diagnostic arrays, while the plasma is still rotating between 4 kHz at $q = 4$ ($q_{95} = 4.5$) and 40 kHz in the core. Figure 2 shows the radial profile of the measured T_e fluctuations from one of the $n = 1$ growth time periods (1338 to 1339 ms) during which the change in the T_e profile (inset) due to the radial displacement from the RWM can be separated from the axisymmetric collapse which occurs as the mode grows. This agrees well with the prediction for this signal assuming that the mode responsible is the fully penetrated nonrotating ideal plasma kink mode as calculated by the GATO code [16] and that the T_e profile is convected with the mode displacement $\boldsymbol{\xi}$; i.e., $\delta T_e = -\boldsymbol{\xi} \cdot \nabla T_e$. Note that the use of the ideal mode with no wall is justified here since the ideal mode and RWM are found to be similar except in the vicinity of the resonant surfaces responsible for the damping [17,18].

The predicted signal has an arbitrary constant phase factor corresponding to the toroidal angle origin ϕ_0, which is varied to obtain the best fit in Fig. 2. The optimum ϕ_0 also indicates that the toroidal angle of the ECE diagnostic is within 10° of the maximum in the predicted mode amplitude in this case, which is in agreement with the phase of the vacuum perturbed magnetic signal estimated from the saddle-loop array. The toroidal saddle-loop data from a similar discharge

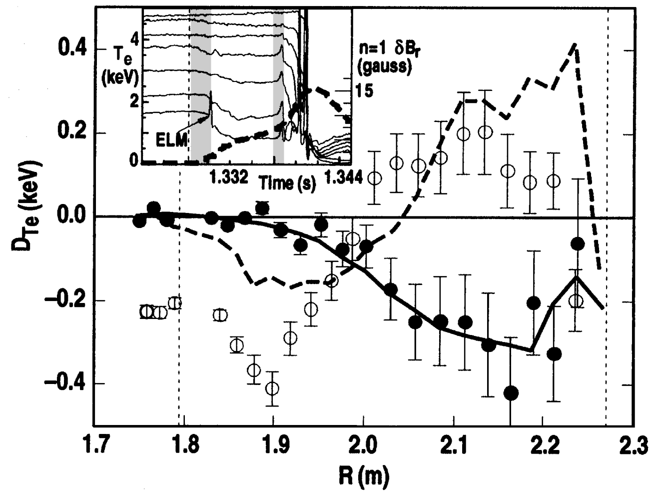

FIG. 2. Comparison of the radial profiles of the measured (solid circle data points) and predicted (solid curve) perturbed ECE T_e signal for discharge No. 96519 at 1338 ms and for a similar discharge No. 96428 (open circle data points and dashed line) in which the toroidal saddle-loop array shows a 110° phase difference from that for discharge No. 96519. The prediction for discharge No. 96428 is obtained by applying this phase difference to the instability for discharge No. 96519. The magnetic axis at $R = 1.7$ m and the plasma edge at $R = 2.25$ m are indicated. The inset shows the $n = 1$ saddle-loop amplitude and the internal ECE T_e measurements at various radial locations. The two shaded bands indicate the analysis times where the $n = 1$ displacement can be separated from the axisymmetric collapse. Analysis at either time yields similar agreement.

No. 96428 shows the RWMs to be displaced toroidally by $110° \pm 10°$ with respect to that in discharge No. 96519. Applying a 110° toroidal phase shift to the predicted mode displacement for discharge No. 96519 results in a prediction for the radial structure, which also agrees quite well with the measured fluctuation, for discharge No. 96428. This comparison is also shown in Fig. 2.

The correlation in time and toroidal angle between the ECE signal and the linear phase of the mode on the saddle-loop array, and the agreement with the predicted signal for a RWM, implies that the ECE fluctuation in Fig. 2 is a direct measurement of the displacement of the T_e profile due to the mode. Very slowly growing unstable ideal kink modes are ruled out as being responsible by the observation that, from onset, the observed mode is essentially nonrotating while the plasma is rotating at several kHz. Also, there are no phase reversals indicative of tearing mode islands which would be manifested in Fig. 2 as a sudden change in sign where the measured amplitude is near the maximum.

The competing RWM theories [9–12] vary greatly in their predictions of Ω_c, and none are in good agreement with previous observations [8] of a 1 kHz critical rotation in DIII-D. The critical rotation speed Ω_c was reproducibly determined here from magnetic braking experiments in which a small static external $n = 1$ perturbation field is applied [8] using the C coil to brake the rotation in six discharges with the same plasma conditions but with varying C-coil current [19]. The stronger braking results in earlier onset of the RWM. In each case, however, the RWM appears when the critical rotation frequency at $q = 3$ is 6.5 ± 0.5 kHz. This is considerably higher than for discharge No. 92544 in Fig. 1 and that reported for discharge No. 83034 in Ref. [8] where $\Omega_c/2\pi \sim 1$ to 2 kHz. These and other discharges show a general trend; for $E_w > 1$, lower E_w is correlated roughly with higher Ω_c. It remains to be determined whether this is due to E_w by itself, to coupling of different rotation profiles with different mode structures, or to some other parameter. Although theoretically predicted values [9–12] for Ω_c are still outside the range $1 \lesssim \Omega_c/2\pi \lesssim 7$ kHz, the observed trend with E_w is at least in qualitative agreement with some predictions [9,10] of ideal MHD theories that include dissipation through toroidal coupling of the mode to sound waves. For these theories $\Omega_c/2\pi \sim 10$ to 20 kHz. Resistive MHD theories that utilize seed island formation for stabilization [11,12] predict much smaller values for Ω_c ($\Omega_c/2\pi \sim 50$ Hz). Also, theories that rely on dissipation by resonance with Alfvén waves [20] predict much larger Ω_c ($\Omega_c/2\pi \sim 1$ to 2 MHz) than is observed.

In the absence of any external braking, all discharges calculated to be significantly above the no-wall limit are observed to slow down while $E_w > 1$. The slowdown is not correlated with any observable MHD activity. This is demonstrated clearly in discharge No. 92544 shown in Fig. 1. The slowdown near $q_{\min}$ in Fig. 1(b) begins just after the transition to H mode at 1280 ms when β_N exceeds $\beta_N^{\text{no-wall}}$, and is largely unperturbed as the discharge evolves through several MHD phases. The $\frac{5}{2}$ tearing mode present well before 1280 ms, when the rotation was increasing, was restabilized and disappeared at 1330 ms with no detectable change in the rotation profile. From 1330 until 1390 ms, there was no MHD activity detected on any of the diagnostics. When edge-localized mode (ELM) activity commenced at 1390 ms, the slowdown continued at the same rate, except for an initial small loss of angular momentum, which was recovered within a few ms. Although the general slowdown begins close to the H-mode transition, this is not generally a feature of the transition in non-wall-stabilized discharges; usually the edge rotation increases after the transition as can be seen at the $q = 3$ surface in Fig. 1. Also, in other discharges, the slowdown is clearly separated from the H transition.

The correlation between the onset of the slowdown and E_w exceeding unity holds in all of the cases analyzed so far. In contrast, there is no consistent correlation between the onset of the slowdown with the H transition or with any observed MHD activity, although the presence of other MHD activity can sometimes accelerate the slowdown. The time histories of $d\Omega/dt$ versus E_w for

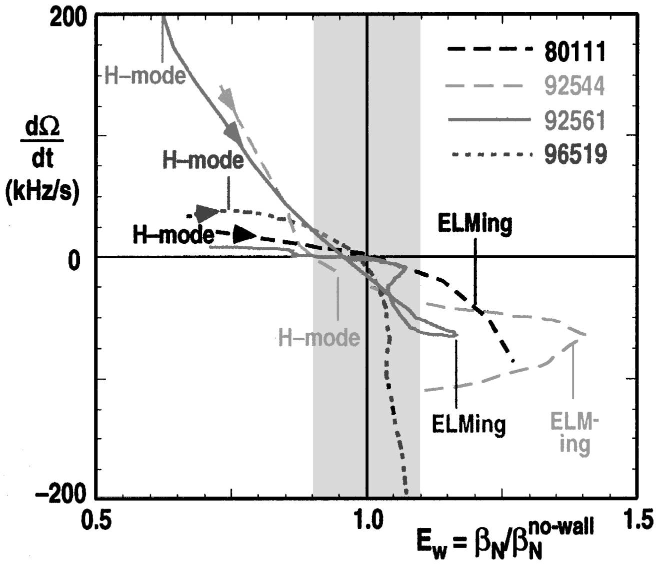

FIG. 3. Correlation of the rotation slowing rate $d\Omega/dt$ at a normalized radius of $\rho = 0.55$ for several wall stabilization discharges versus enhancement factor E_w. The H-mode transitions and onset of ELMs are also indicated.

several different discharges are given in Fig. 3 and show the correlation with $E_w > 1$ clearly; when $E_w \simeq 1$, the sign of $d\Omega/dt$ changes in each case.

This result suggests the existence of new physics in which the RWM is implicated in the slowdown. The possible explanations are naturally divided into two classes: the existence of an undetectable small amplitude (possibly saturated) RWM *always* present whenever $\beta_N > \beta_N^{\text{no-wall}}$, or a conjectured electromagnetic drag from the internal continuum resonances of the stable RWM [7]. The observed slowdown is marginally consistent with estimates of $df/dt \sim \delta B_r^2$ with the coefficient obtained from the braking experiments and a mode with δB_r below the experimental noise level of $\delta B_r \sim 10$ G at $q = 3$. However, this is difficult to reconcile in the context of the present linear theories [9–12] that predict *stabilization* of the linear RWM by plasma rotation. At present, neither possibility can be ruled out, and either explanation requires a significant modification of current understanding.

In summary, new techniques and improved diagnostic capabilities have greatly extended the duration, 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 rotation speed can now be compared quantitatively with the various theoretical predictions. The slowdown in the 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. This has important ramifications for stabilization of the RWM by plasma rotation and implies the need for a better physics understanding of the momentum exchange between the plasma and wall when $E_w > 1$.

The observation that the RWM itself is closely coupled to the rotation dynamics leads to several promising strategies for eventually fully stabilizing the mode. Direct control of the angular momentum profile is one possibility. This might be partially achieved by increasing the angular momentum-energy ratio of the neutral beams to spin the plasma edge harder, for example, or rotating phased magnetic perturbations. The alternative option is to actively control the RWM itself using external coils. Experiments in DIII-D using both open-loop and closed-loop feedback control are planned to pursue this further.

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