Resistive Wall Mode Dynamics and Active Feedback Control in DIII–D

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Abstract. Recent DIII–D experiments have shown that the n=1 resistive wall mode (RWM) can be controlled by an external magnetic field applied in closed loop feedback using the six element error field correction coil (C-coil). The RWM constitutes the primary limitation to normalized beta in recent DIII–D advanced tokamak plasma experiments. The toroidal rotation of DIII–D plasmas does not seem sufficient to completely suppress the RWM: a very slowly growing RWM (growth rate $\gamma \ll 1/\tau_W$) is often observed at normalized beta above the no-wall limit and this small RWM slows the rotation. As the rotation decreases, there is a transition to more rapid growth ($\gamma \sim 1/\tau_W$). The application of magnetic feedback is able to hold the RWM to a very small amplitude, prolonging the plasma duration above the no-wall limit for durations much longer than the growth time of the RWM. These initial experimental results are being used to compare control algorithms, to benchmark models of the feedback stabilization process and to guide the design of an upgraded coil-sensor system for stabilization of the RWM at normalized beta values closer to the ideal-wall limit.

1. Introduction

The realization of a compact and economical fusion reactor based on any of the leading magnetic confinement concepts requires stabilization of the low toroidal mode number *n* ideal magnetohydrodynamic (MHD) kink mode [1-3]. A perfectly conducting wall placed close enough to the plasma can provide this required stabilization. However, in the presence of a real wall, the kink mode can persist as the resistive wall mode (RWM) [4], where the mode rotation and growth rate (f and γ respectively) are limited according to: $f \le 1/2\pi\tau_W$ and $\gamma \le 1/\tau_W$, with τ_W the wall resistive decay time. We will discuss here two distinct approaches to stabilization of this mode: plasma rotation and active feedback using magnetic coils.

While several theories have predicted that the presence of dissipation and rotation in the plasma can stabilize the RWM [5], the toroidal rotation achieved in DIII–D plasmas does not seem sufficient to completely suppress the instability [6,7]. Active control is needed to achieve and sustain $\beta_N > \beta_N^{\text{no-wall}}$, since the slowly growing, often bursting, RWMs limit the steady-state value of β_N to approximately the limit calculated in absence of a conducting wall [8]. [Here $\beta_N = \beta/(I/aB)$ is the normalized beta, $\beta_N > \beta_N^{\text{no-wall}}$, and $\beta_N^{\text{no-wall}}$ is the β_N limit predicted without wall stabilization]. The DIII–D experiments on feedback stabilization of the RWM [8,9] use the six element error field correction coil located at the mid-plane, outside the DIII–D vessel. An array of 6 sensor saddle loops, located outside the vessel, monitors the penetration of the n=1 helical flux through the resistive wall. Initial active feedback experiments have shown a clear suppression of the RWM by the externally applied magnetic field for durations much longer than the growth time of the RWM [8,9]. These experiments represent the first application of magnetic feedback on non-axisymmetric modes in a large tokamak. The results are examined in comparison to the predictions of several models of the feedback system. These include the electromagnetics code VALEN, which accurately models the 3-dimensional geometry of the resistive wall and the coil-sensor pairs, and a 1-dimensional simplified analytical model that includes the effects of non-ideal feedback circuit components.

2. Rotational Stabilization of the RWM

Earlier DIII–D experiments [7,10] aimed at studying the physics of the RWM developed and utilized a single-null divertor target plasma with a very low β_N limit (≤ 2) for the n=1 ideal external kink without a wall. These experiments used a plasma current ramp up to decrease the no-wall stability limit and destabilize the RWM. More recently, the RWM was observed in two new target plasmas which have the characteristics desired for advanced tokamak discharges: high normalized beta, high confinement, a large fraction of noninductive current, and nearly steady-state plasma conditions [8].

In all cases the plasma rotation clearly slows whenever $\beta_N > \beta_N^{\text{no-wall}}$. In the earlier experiments it was noted [10] that the electromagnetic drag from a small amplitude RWM would have been quantitatively consistent with the observed slowdown, and improved measurements now allow the detection of small amplitude modes ($\delta B_r \sim$ 1-2 G) whenever $\beta_N > \beta_N^{\text{no-wall}}$. These modes are either saturated or very slowly growing, with rate $\gamma \ll 1/\tau_W$. The new observations support the paradigm that the plasma rotation in DIII–D is not able to completely stabilize the RWM, and the previously measured threshold for stabilization of the RWM might actually mark a transition from a very slowly growing RWM (growth rate $\ll 1/\tau_W$) to a “fast” RWM growing at rate $\sim 1/\tau_W$. In Fig. 1 the rotation threshold is shown by varying the neutral beam torque in otherwise similar discharges. The torque is increased by ~20% by reducing the beam source voltage from 75 to 50 keV and increasing the number of sources to keep a constant total injected power. The discharge with greater torque applied shows faster initial rotation and longer survival until the transition to fast RWM growth and slow plasma rotation. At the transition both discharges have identical rotation profiles.

The paradigm that the RWM is linearly unstable even at high plasma rotation, although with a very slow growth rate, is in qualitative agreement with the predicted dependence of the RWM amplitude on the plasma rotation in a non linear RWM model by Gimblett and Hastie [11] where the plasma rotation is determined self-consistently from torque balance. Figure 2 shows a comparison of experimental data with a sketch qualitatively depicting the dependence of the plasma rotation on the mode amplitude as predicted by the Gimblett-Hastie model. The growth rate is small on the upper branch of the curve ($\gamma \ll 1/\tau_W$), but the plasma rotation slowly decreases as the mode amplitude increases. At the upper knee torque balance is lost, and the rotation frequency drops to the lower branch. Here the growth rate is much larger ($\gamma \sim 1/\tau_W$) leading to a minor disruption. It

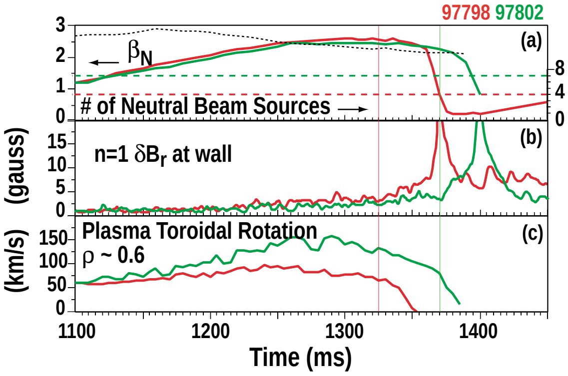

FIG. 1. Rotation threshold for the “fast” growth of the RWM shown by varying neutral beam torque at constant total injected power. Traces in red are for discharge #97798 with 4 sources of neutral beam power at 75 keV. Traces in green are for discharge #97802 with 7 sources, 6 of which at 50 keV. Shown are time traces of (a) β_N (solid lines), an approximation of the no-wall limit based on the internal inductance ($2.5\ell_i$, dotted line), and the number of neutral beam sources (dashed lines), (b) n=1 amplitude of the perturbed radial field, δB_r, at the sensor loops, and (c) plasma toroidal rotation at normalized minor radius $\rho \sim 0.6$. Vertical lines are at time of transition to “fast” RWM and slow rotation.

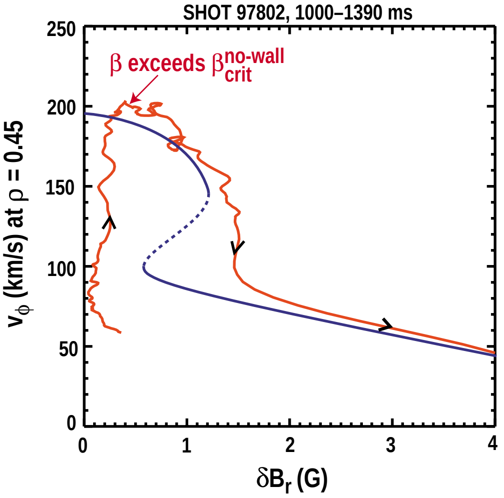

FIG. 2. Evolution of the plasma toroidal velocity vs the n=1 amplitude of δB_r measured at the wall. Shown are the experimental data for discharge 97802 (red line) and a sketch illustrating qualitatively the behavior predicted by the Gimblett-Hastie model (blue line).

should be noted, however, that the critical plasma rotation predicted by this model for the onset of the “fast” RWM is 1–2 orders of magnitude lower than the measured threshold.

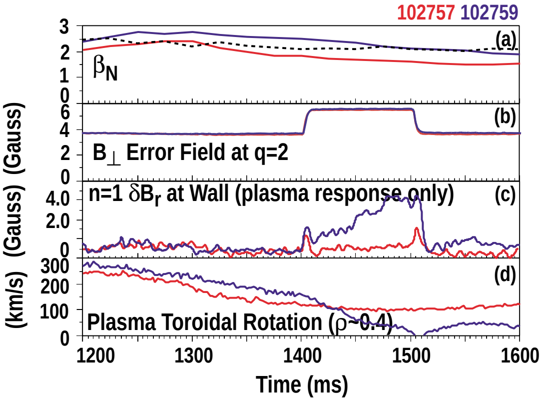

FIG. 3. Increase in external error field pulsed on and off in discharges with β_N above (102759, blue lines) and close to (#102757, red lines) the no-wall limit. Shown are traces of (a) β_N (solid lines) and $2.5\ell_i$ (dashed line), (b) resonant component of perpendicular error field at q=2 surface, (c) n=1 amplitude of δB_r due to the plasma response only, and (c) plasma toroidal rotation at normalized minor radius ρ ~ 0.4.

In a second paradigm, plasma rotation above the measured threshold is able to completely stabilize the RWM, and the presence of a slowly growing or saturated n=1 amplitude is explained as plasma response to residual static error fields resonant with the marginally stable RWM. Figure 3 shows the first clear experimental evidence in support for this theory. Two discharges were formed using the usual technique of ramping up the plasma current during high power beam injection to drive β_N above the no-wall limit. In one of the discharges, however, the injected power is lower, so that β_N is lower but close to $\beta_N^{\text{no-wall}}$. The rotation starts to slow down above $\beta_N^{\text{no-wall}}$, but no fast-growing RWM is detected for a few hundred ms. During this time we applied a square pulse to the error field correction currents, to increase the n=1 error field between t=1.4 s and t=1.5 s. The plasma response to the error field pulse is measured by the saddle loops outside the vessel, and the directly coupled field from the C-coil and its induced wall currents is removed by subtracting the signal from a vacuum shot with an identical field pulse. The plasma response is significantly larger at higher β_N. The time variation might be related to the decrease in plasma rotation, which moves the stable RWM closer to the stability boundary, and increases the resonant plasma response. The n=1 amplitude cannot be interpreted as a slowly growing, linearly unstable mode because it decays to zero on a ~τ_W timescale when the n=1 error field pulse ends.

Note that elements of the two paradigms could be combined in a theory that would explain not only plasma rotation slowing ($d\Omega/dt < 0$) for $\beta_N > \beta_N^{\text{no-wall}}$, but also why $d\Omega/dt$ decreases towards zero as β_N approaches $\beta_N^{\text{no-wall}}$, as shown in Ref. [7]. In any case, it appears that the plasma rotation cannot be maintained at $\beta_N > \beta_N^{\text{no-wall}}$ without some active means to suppress the growing n=1 perturbation, whether it is from an unstable or stable RWM.

3. Active Feedback Control of the RWM

In Refs. [8,9] we reported first results of closed loop operation of a RWM feedback control system carried out on high performance AT plasmas in DIII–D. More recent feedback experiments [12] were carried out in target plasmas which used the current ramp technique to destabilize a strong, reproducible RWM. In these experiments, as in those of Refs. [8,9], the six feedback coils (which are connected so that coils 180° apart yield opposing pairs) are controlled to respond with an n=1 field to an n=1 structure extracted from the sensor signals. The “smart shell” feedback [13] responds to the total (mode plus external) radial field measured by the sensor loops, while in the “mode control” logic the external field is subtracted from the sensor signals. As shown in Fig. 4, the new experimental results are consistent with the statistical results of Ref. [8]. In the case without feedback, an RWM grows reproducibly at t~1.39 s (within about .01 s) and causes a sudden decrease in beta. In the case with smart shell feedback with time derivative gain, the onset of the RWM is postponed by about 40 ms. The feedback gain settings used are close to an upper limit beyond which the feedback system goes into a ~600 Hz oscillation. Longer stabilization periods, up to about 90 ms, are obtained with the mode control algorithm with derivative gain. In discharges 101951 and 101956, where the feedback is applied starting from t=1.35 s, fluctuations in the sensor signals and coil currents increase at t~1.4 s, consistent with the crossing of a stability threshold at this time, while the average mode amplitude is held at 2–3 G.

Stability analysis carried out using the GATO code confirms that the plasma would indeed be unstable without feedback. Stability analysis of similar discharges and related model equilibria using the GATO code shows that for these discharges β_N=2.5 ℓ_i is a good approximation to the ideal n=1 kink stability limit in the absence of a conducting wall.

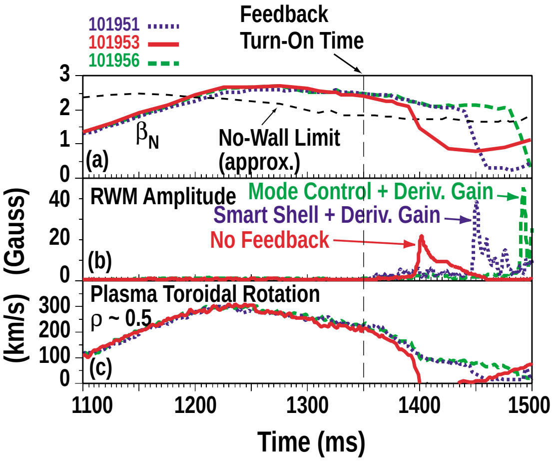

FIG. 4. Comparison between discharges with feedback applied (#101951, dotted lines, and #101956, dashed lines) and without feedback (#101953, solid lines). Shown are traces of (a) β_N and 2.5 ℓ_i, (b) n=1 amplitude of the RWM at the sensor loops, and (c) plasma toroidal rotation at normalized minor radius ρ ~ 0.5.

In a following experiment the performance of the smart shell algorithm was improved by allowing each of the three feedback coil pairs to respond to the corresponding sensor loop pair independently, so that the resulting external field can have n=1 and n=3 components. In Fig. 5(a) a scan of the derivative gain demonstrates the efficacy of the feedback system: higher derivative gain yields longer stabilization period, with an extension of up to ~120 ms with respect to the no-feedback cases. A similar connection of the feedback coils is expected to improve the performance of the mode control algorithm as well, but this is yet to be tested experimentally. The best results are obtained with feedback gain settings which had been predicted to be optimal by a 1-dimensional analytic model. The model includes the plasma, resistive wall, and control coils as current sheets, and the measured amplifier/coil frequency response with a two-pole best-fit to experimental data.

Although β_N reaches a nearly constant level in these experiments, other plasma parameters are evolving, and the equilibrium moves towards increasingly more unstable configurations: the current profile continues to broaden with time (as shown by the decreasing internal inductance ℓ_i), and the rotation continues to slow, although at a reduced rate, even during the feedback stabilized period. Control is eventually lost when the RWM no-feedback growth rate becomes exceedingly large. As shown in Figs. 4 and 5(b), the final growth rate

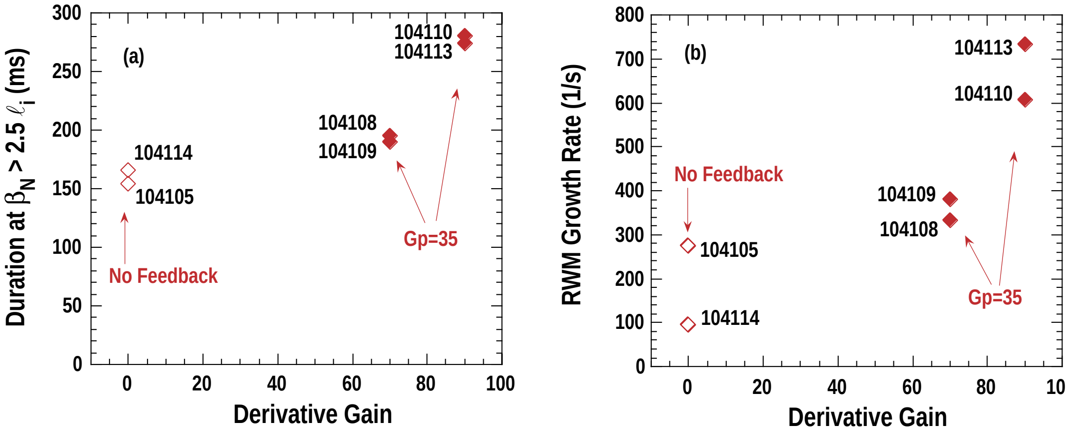

FIG. 5. Efficacy of the smart shell feedback system shown by varying the derivative gain (a proportional gain Gp=35 corresponds to a flux gain of 5.5). Plotted versus the derivative gain used are (a) the discharge duration at β_N above the approximate no-wall limit and (b) the growth rate of the RWM which terminates the duration at high beta.

increases from about 200 s^{-1} ($\sim 1/\tau_W$) without feedback to about 700 s^{-1} in the longest duration feedback stabilized case, in agreement with an MHD instability drive that increases with time.

4. Conclusions

With improved measurements, it was recently found that a very slowly growing (often $\gamma \ll 1/\tau_W$) or saturated n=1 RWM amplitude can be detected in DIII–D plasmas whenever $\beta_N > \beta_N^{\text{no-wall}}$. In one interpretation, qualitatively consistent with Gimblett and Hastie's model, the RWM is linearly unstable, although with a very slow growth rate, whenever $\beta_N > \beta_N^{\text{no-wall}}$ even at high plasma rotation. New experimental results, however, provide key evidence that a linearly stable RWM could be excited to finite amplitude by resonance with an uncorrected n=1 error field. Although it remains to be established whether rotational stabilization of the RWM is possible, the new findings strongly suggest that active control of the RWM amplitude is needed to achieve and sustain $\beta_N > \beta_N^{\text{no-wall}}$.

We have carried out an evaluation survey of several feedback schemes, using a target plasma with reproducible RWM onset and characteristics. Without feedback, these plasmas survive above the no-wall beta limit until the plasma rotation decreases below a threshold value, at which point a disruption is caused by a RWM growing with $\gamma \sim 1/\tau_W$. In discharges with feedback, the RWM appears when the same rotation threshold is crossed, but the externally applied n=1 magnetic field is able to hold the mode to a very small amplitude, prolonging the plasma duration above the no-wall limit by times much longer than the uncontrolled growth time of the RWM. Control is eventually lost when the RWM growth rate becomes large, exceeding the stabilizing capability of the present feedback system. The observations are consistent with a small increase in the beta limit with feedback control of the RWM using the present un-optimized coil set, predicted by both the VALEN code and the 1-dimensional analytical model.

Future experiments will make use of new arrays of sensors mounted inside the vessel, to measure the radial and the poloidal magnetic field. These sensors will reduce the driver-sensor coupling in favor of a larger plasma-sensor coupling, which is predicted to significantly improve the feedback efficacy. Future results will be used to continue the benchmarking of numerical models of the feedback stabilization process, necessary so that we can with confidence use these codes in the design of an upgraded RWM feedback system that will be able to demonstrate sustained operation at β_N significantly exceeding $\beta_N^{\text{no-wall}}$.

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