Resistive Wall Stabilization of High Beta Plasmas in DIII–D

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Abstract. Recent DIII–D experiments show that ideal kink modes can be stabilized at high beta by a resistive wall, with sufficient plasma rotation. However, the resonant response to static magnetic field asymmetries by a marginally stable resistive wall mode can lead to strong damping of the rotation. Careful reduction of such asymmetries has allowed plasmas with beta well above the ideal MHD no-wall limit, and approaching the ideal-wall limit, to be sustained for durations exceeding one second. Feedback control can improve plasma stability by direct stabilization of the resistive wall mode or by reducing magnetic field asymmetry. Assisted by plasma rotation, direct feedback control of resistive wall modes with growth rates more than 5 times faster than the characteristic wall time has been observed. These results open a new regime of tokamak operation above the free-boundary stability limit, accessible by a combination of plasma rotation and feedback control.

1. INTRODUCTION

Many "advanced tokamak" scenarios for steady-state operation at high beta rely on wall stabilization of the ideal kink mode. Advanced tokamak scenarios have the goal of high average fusion power, which requires both high power density and steady-state operation. High fusion power density at fixed toroidal field implies high toroidal beta, while steady-state operation with a large fraction of self-generated bootstrap current implies high poloidal beta. Since $\beta_T\beta_P \propto \beta_N^2$ these lead to a requirement of high normalized beta, which may require a conducting wall for stability. In fact, the broad current density profile associated with a large bootstrap current typically leads to a relatively low free-boundary kink-mode limit in β_N, but also allows the possibility of stabilization by an ideally conducting wall. In the presence of a resistive wall, such as the DIII–D vacuum vessel, the kink mode is not completely stabilized but is converted to a slowly-growing resistive wall mode (RWM). Theory and numerical modeling predict that the RWM can be stabilized by feedback control [1] or plasma rotation [2]. RWM stabilization by strong plasma rotation may not be robust or even feasible in a burning plasma which is likely to have little or no torque from neutral beam heating, so it is important to develop both approaches.

Recent experiments in the DIII–D tokamak [3] with strong rotation have demonstrated sustained stable operation well above the free-boundary stability limit [4], as shown in Fig. 1. Earlier DIII–D experiments [5] exceeded the free-boundary limit for durations much longer than the characteristic wall time of ~5 ms, but these discharges typically showed strong damping of the rotation in the wall-stabilized regime [6], preventing sustained stabilization of the RWM by rotation. This slowing of rotation is now understood as resulting from resonant "amplification" of small magnetic field asymmetries by a marginally stable RWM [7]. Correction of the intrinsic asymmetries by means of non-axisymmetric coils has allowed rotational stabilization to be sustained for long durations. The critical rotation frequency is consistent with theoretical predictions [2].

Direct feedback control of the RWM has also been developed in DIII–D experiments [4,8] and can extend the stable operating regime. The effectiveness of feedback control depends on the choice of detection method and control algorithm. Poloidal field sensors inside the resistive wall are found to be most effective [9,10], consistent with theoretical predictions [11–13]. Modeling shows that the combined effects of rotation and feedback control can provide robust stabilization as beta increases, almost to the ideal-wall stability limit [14]. In addition to direct feedback control of the instability, the feedback system can also contribute to rotational stabilization by improving the symmetrization of the magnetic field.

Error field correction and RWM feedback control in DIII–D are performed with the “C-coil”, a six-segment set of external coils around the midplane of the tokamak [Fig. 2(a)]. These coils were originally installed for error field correction. With the addition of fast switching amplifiers, the coils are now used for simultaneous error correction and feedback stabilization. Several arrays of resistive wall mode diagnostics are available at the midplane [Fig. 2(b)] and have been used as input for the feedback system. Additional arrays above and below the midplane are used to measure the poloidal mode structure of the RWM. The arrays of radial field sensors (saddle loops) outside the vacuum vessel have been in use since 1998. Based on theoretical predictions of improved performance, new arrays of radial field sensors and poloidal field sensors (magnetic probes) were installed on the inner surface of the vessel for use in 2001.

Section 2 summarizes experimental results on the rotational stabilization of the RWM, including the effects of resonant field amplification. Section 3 compares modeling predictions for feedback control using various types of sensors, focusing on a very simple analytic model that provides qualitative understanding of the differences in behavior. Section 4 describes the results of feedback experiments, with comparison to modeling predictions. Section 5 gives a brief discussion of the performance of different types of sensors when used for feedback-controlled error field correction in a rotation-stabilized plasma. Conclusions are given in Section 6.

2. STABILIZATION BY PLASMA ROTATION

DIII–D experiments have shown that stable operation significantly above the free-boundary ideal kink mode beta limit is possible with a resistive wall and sufficient plasma rotation. In the experiments described here, the discharge is programmed with a plasma current ramp as fast as 1.6 MA/s during the high power heating phase. The rapid current ramp maintains a broad current density profile with low internal inductance, which has a low kink mode beta limit without a conducting wall but a significantly higher beta limit with a perfectly conducting wall. In these current-ramp plasmas, both experimental evidence and stability calculations with the GATO code show that the ideal MHD stability limit without a wall is well approximated by the scaling $\beta_N \leq 2.4\ \ell_i$. (This contrasts with the more usual constant-current discharges where the ideal no-wall limit is typically $\beta_N \leq 4\ \ell_i$). Here, $\beta_N = \beta/(I/aB)$ is the normalized beta, ℓ_i is the internal inductance, $\beta = 2\mu_0 \langle p \rangle / B^2$ is the normalized plasma pressure, I is the plasma current in MA, a is the minor radius in meters, and B is the toroidal field in Tesla. When beta is above the ideal MHD no-wall limit, these discharges are subject to strong resistive wall mode instabilities that cause an early beta collapse unless there is sufficient rotation.

Experimental measurements clearly show the existence of a critical toroidal rotation frequency, above which the plasma remains stable. Figure 3(a) shows a set of similar discharges in which the rotation was allowed to decay at different rates. With sufficient rotation, the normalized beta remains above the estimated no-wall limit, and the margin above the limit increases slowly with time. However, each discharge suffers a beta collapse when the rotation frequency decays to a critical value, in this case about 6 kHz as measured at the q=2 surface.

The critical rotation frequency is consistent with theoretical expectations. Models for the rotational stabilization of an ideal kink mode require dissipation in the plasma, allowing the resistive wall mode to exert a torque on the plasma. In a series of DIII–D discharges where the toroidal field and density were varied, the critical rotation frequency for RWM stabilization was found to scale as about 2% of the Alfvén frequency [Fig. 3(b)]. (However, in this data set with roughly constant beta, an inverse scaling with the sound speed would also be consistent.) The magnitude of the critical rotation frequency is consistent with models where the dissipation takes place by sound wave coupling [2]. The variation about the fitted curve in Fig. 3(b) may indicate an additional dependence on beta.

Enhancement of small asymmetries of the external magnetic field can lead to strong damping of the rotation in stable plasmas, precisely in the regime where sustained rotation is needed for high beta stabilization. The theoretically predicted "amplification" of magnetic field asymmetries by the resonant response of a marginally stable RWM [7] has been directly observed in DIII–D experiments [15]. Figure 4(a) shows an experiment in which the C-coil was used to apply a pulsed n=1 radial magnetic field perturbation. In a plasma that was slightly above the estimated no-wall limit and stabilized by plasma rotation, there was a strong plasma response to the perturbation and a sudden slowing of the plasma rotation. In a similar plasma at lower beta, there was virtually no response to the perturbation. The response reflects the excitation of a helical plasma mode [4], although the applied n=1 field has equal right- and left-handed helical components. The response is due to excitation of a *stable* mode, since the plasma response returns to zero when the external perturbation is removed. As beta is raised above the free-boundary stability limit, the amplitude of the plasma response to the n=1 pulse increases rapidly and the measured damping rate (negative growth rate) decreases toward zero [Fig. 4(b)]. That is, plasma rotation provides only weak damping of the RWM, consistent with the strong resonant response to magnetic perturbations observed in the rotation-stabilized regime.

The resonant plasma response has been exploited in a new approach to feedback-controlled error field correction. This is one of several independent techniques using the C-coil system that have been shown to symmetrize the external magnetic field, and thereby to sustain the plasma rotation. The feedback system controls the coil currents to minimize the RWM amplitude. Thus, in the case of a stable plasma, it acts to minimize the resonant n=1 plasma response, and presumably to minimize the field asymmetries that drive that response. As shown in Fig. 5, when the same coil currents are provided by pre-programming instead of feedback control, the results are similar with respect to plasma stability. Therefore, in this case, the feedback system is primarily responding to static field asymmetries and not to an unstable plasma mode. Discharge-to-discharge optimization of the coil currents to maximize plasma rotation converges on the same currents that are found with magnetic field symmetrization by the feedback system [16].

Use of these techniques to symmetrize the external magnetic field has significantly improved the stability of DIII–D plasmas (see Fig. 5, for example). Operation above the free-boundary stability limit has been sustained for as long as 1.5 s, as also shown earlier in Fig. 1. A small additional increase in beta brings the discharge up to about twice the free-boundary limit, and results in a disruption (Fig. 6) that is consistent with having reached the ideal-wall stability limit [17]. This disruption has a fast-growing precursor with a growth time of about 300 μs, as shown in Fig. 7(a). This growth time is consistent with VALEN predictions for an RWM very near the ideal-wall stability limit [13]. The relatively rapid rotation frequency of the precursor (Fig. 7(b), $\omega\tau_{wall}$~30) also implies that the wall is acting nearly as an ideal conductor. Detailed calculations with GATO show that beta at the time of the instability differs by less than 10% from the calculated ideal-wall stability limit [Fig. 7(c)].

In discharges without the strong current ramp and the lower beta limit that it leads to, rotation has allowed stable operation at normalized beta up to β_N=4.2, 50% greater than the free-boundary limit of about 2.8 for these plasmas (Fig. 8). The example shown in Fig. 8 had β_T greater than 4% and about 85% non-inductive current, and is a good candidate for development of a high-performance steady-state fusion plasma [18].

3. STABILIZATION BY FEEDBACK CONTROL: MODELING

Feedback control can improve the stability of high-beta plasmas in several ways. First, the RWM can be stabilized by direct feedback control of the mode amplitude. Second, modeling suggests that the combined effects of rotation and feedback control may provide greater stability than either one alone, given the same values of rotation frequency and feedback gain [14]. Third, as described above, the feedback system can contribute to rotational stabilization by improving the symmetrization of the magnetic field.

The advantages of internal over external radial field sensors originate primarily in their distance from the plasma, since the normal (raidal) field component is continuous across a conducting boundary. Modeling with the MARS code has shown that the feedback performance with radial field sensors is very sensitive to the position of the sensors [2]. In modeling of an advanced tokamak equilibrium with beta about 1.6 times the no-wall stability limit, the critical gain for stabilization varied by more than a factor of 2 as the radial position of the sensors was increased by about 15% of the plasma's minor radius. This is a result of the increased coupling to the control coils and reduced coupling to the plasma as the sensor radius increases, and provides motivation for placing the sensors inside the wall to reduce the distance from the plasma.

MARS modeling has also predicted superior feedback performance with poloidal field sensors as compared with radial field sensors[11,12]. In modeling of the same equilibrium, feedback control with poloidal field sensors was found to be more robust than with radial field sensors. Specifically, with poloidal field sensors, the control was much less sensitive to the poloidal width of the control coils and to the radial position of the sensors between the wall and the plasma. The poloidal field sensors were also found to require a dimensionless gain value for the feedback control about half that for radial field sensors in the optimal configuration for each. These results have been further analyzed in terms of control theory [21–23], and are attributed to the vanishing of the mutual inductance between the control coils and poloidal field sensors.

Similar results were obtained from VALEN modeling. The VALEN code [13] uses a detailed, finite-element circuit representation for the plasma mode, resistive wall, and control coils, and can model arbitrary sensor and coil configurations. In the specific geometry of the DIII–D vacuum vessel, midplane control coils, and sensors, poloidal field sensors were again found to have superior performance. As shown in Fig. 9, using the existing external control coils, external radial field sensors were predicted to extend the beta limit by about 20% of the difference between the no-wall limit and the ideal-wall limit. Internal radial field sensors were predicted to give a modest improvement, to about 30% of the difference between the no-wall limit and the ideal-wall limit, while a 50% extension was predicted with poloidal field sensors.

Although less realistic than the numerical models, analytic models with lumped parameters [8,14,19,24] can provide valuable insight into the differences between types of sensors. Such models can be reduced to a simple set of equations:

$$s - \gamma_0 + G(s)\, F(s) = 0 \quad , \tag{1}$$

$$\Phi = \Phi_P + \Phi_{PW} + \Phi_C + \Phi_{CW} \quad , \tag{2}$$

$$\Phi_P = (1+\gamma_0)\, \Phi \quad , \tag{3}$$

$$\Phi_C = -G(s)\, \Phi_S \quad , \tag{4}$$

$$\Phi_{PW,\,CW} = -\Phi_{P,C}\, s/(1+s) \quad , \tag{5}$$

where in Laplace transform notation $s = \gamma + i\omega$ represents the growth rate and real frequency of the resistive wall mode, and γ_0 is the growth rate in the absence of feedback. The limit where the plasma would be marginally stable with an ideal wall corresponds to $\gamma_0 = \infty$, since this model neglects the plasma's inertia. The dispersion relation [Eq. (1)] is to be solved for the growth rate of the instability. The total perturbed radial flux Φ at the resistive wall includes terms for the flux Φ_P produced by the plasma, the flux Φ_C produced by the control coils, and fluxes Φ_{PW} and Φ_{CW} from wall currents induced by the plasma and control coils respectively [Eq. (2)]. The plasma model [Eq. (3)] relates the plasma perturbation to the perturbed boundary condition at the wall [19]. The transfer function F(s) for the sensors relates the flux Φ_S measured by the sensors to the total perturbed flux Φ, and will be defined below. The feedback gain G(s) then relates the flux Φ_C produced by the control coils to the sensor measurement Φ_S [Eq. (4)]. The fluxes from wall currents [Eq. (5)] are driven by the rate of change of the plasma and control coil fluxes, and oppose the fluxes that drive them. Here the growth rates and frequencies are expressed in units of the wall time constant ($s\tau_{wall} \rightarrow s$). All of the perturbed fluxes, including the sensor measurements, are evaluated at the wall. The key physics is contained in the model for the unstable plasma, the gain G (which includes the characteristics of the amplifier-control coil system, and may be frequency dependent), and the sensor's transfer function F. For this discussion we will assume an idealized amplifier-coil system, with a constant proportional gain at all frequencies.

The different types of sensors can be characterized by their response to the different parts of the perturbed flux:

Idealized Mode Detection $\Phi_S = \Phi_P$, (6)

Smart Shell $\Phi_S = \Phi_P + \Phi_{PW} + \Phi_C + \Phi_{CW}$, (7)

DC Compensated B_r Sensor $\Phi_S = \Phi_P + \Phi_{PW} + \Phi_{CW}$, (8)

AC Compensated B_r Sensor $\Phi_S = \Phi_P + \Phi_{PW}$, (9)

B_p Sensor $\Phi_S = \Phi_P - \Phi_{PW}$. (10)

An idealized sensor [Eq. (6)] would detect the plasma perturbation and nothing else. In the "Smart Shell" control scheme [Eq. (7)] the sensor simply detects the total perturbed radial flux at the wall, with the aim of controlling it to be zero in order to mimic the response of a perfectly conducting wall [1,20]. Note that the response of a radial field sensor is the same whether it is located on the inner or outer surface of the wall. The control coil currents and their coupling to the sensors are well characterized, and their direct effects can be subtracted from the sensor signal ([Eq. (8)]. The wall response to the control coils is also predictable and can be subtracted from the sensor signal [Eq. (9)]. In DIII–D, because of the symmetry of the sensors and coils at the midplane, the poloidal field sensors are naturally decoupled from the control coils and their induced wall currents, and respond only to the plasma perturbation and the wall current that it induces [Eq. (10)]. In Eq. (10), the poloidal field sensor has been defined in terms of the perturbed *radial* flux, with an implicit 90° phase shift from the actual measured poloidal field, so that the form of the model in Eqs. (1–5) can be maintained. For poloidal field sensors inside the wall, the field from the wall current reinforces the field from the plasma perturbation, a key difference from the AC compensated radial field sensor. This change in sign of the wall response for poloidal field sensors is expressed by changing the sign of Φ_{PW} in Eq. (10), so that Eq. (5) keeps the same form for all cases.

Each of the sensor definitions [Eqs. (6–10)] can be substituted into the model of Eqs. (1–5). The dispersion relation then yields the following conditions for stability ($\gamma < 0$):

Idealized Mode Detection $\qquad G > \gamma_0/(1+\gamma_0)$, (11)

Smart Shell B_r Sensor $\qquad G > \gamma_0$, (12)

DC Compensated B_r Sensor $\qquad G > \gamma_0/(1+\gamma_0)$ and $G < 1$, (13)

AC Compensated B_r Sensor $\qquad G > \gamma_0/(1+\gamma_0)$ and $\gamma_0 < 1$, (14)

B_p Sensor $\qquad G > \gamma_0/(1+\gamma_0)$. (15)

With an idealized sensor [Eq. (11)] a feedback system *with finite gain* can reproduce the stabilizing effect of an ideal wall; that is, a mode with an arbitrarily large growth rate γ_0 can be stabilized by a finite gain ($G \geq 1$). With "Smart Shell" control [Eq. (12)], a mode with any finite growth rate can be stabilized, but the minimum required gain becomes large as the mode growth rate increases. With DC compensated radial field sensors [Eq. (13)], a mode with an arbitrarily large growth rate can be stabilized by a finite gain. However, the gain must also remain less than unity, meaning that the range of stable gain values becomes very narrow as γ_0 increases. With AC compensated radial field sensors [Eq. (14)], only modes having low growth rates ($\gamma_0<1$) can be stabilized. On the other hand, the poloidal field sensor [Eq. (15)] recovers the same stability condition as the idealized sensor. These results are summarized in Fig. 10.

This simple model suggests that poloidal field sensors can realize the same performance as an ideal mode amplitude sensor, allowing stabilization up to the ideal-wall limit with a modest feedback gain G~1. The schemes considered using radial field sensors all have significant drawbacks: a very large gain requirement, a very narrow range of stable gain values, or the capability only to control weakly unstable modes. (Of course, these responses may be modified and perhaps improved by the use of derivative gain and other techniques [8,15], but the simple model serves to illustrate the qualitative differences between detection methods.)

The reasons for the difference in performance can be understood by combining the sensor definitions [Eqs. (6–10)] with Eqs. (2), (3) and (5) to express the relationship of each type of sensor signal to the plasma perturbation:

Idealized Mode Detection	$\Phi_S = \Phi_P$	(16)
Smart Shell	$\Phi_S = \Phi_P /(1+\gamma_0)$	(17)
DC Compensated B_r Sensor	$\Phi_S = \Phi_P [1-s/(1+\gamma_0)]$	(18)
AC Compensated B_r Sensor	$\Phi_S = \Phi_P/(1+s)$	(19)
B_p Sensor	$\Phi_S = \Phi_P [1+ s/(1+s)]$	(20)

The smart shell sensor signal [Eq. (17)] decreases as the mode growth rate γ_0 increases, requiring larger gain to be used. The DC compensated signal [Eq. (18)] has a time derivative (~s) term with a destabilizing sign. The AC compensated signal [Eq. (19)] is a low-pass filtered version of the idealized sensor signal, with a bandwidth of 1. Thus it should not be expected to perform well for growth rates of $\gamma_0>1$, even though it is decoupled from the control coils. The B_p sensor [Eq. (20)] is equivalent to the idealized sensor, plus an additional high-pass filtered term that *improves* the sensitivity at high frequencies. Thus, one important conclusion is that a key advantage of poloidal field sensors over radial field sensors is their faster time response, not simply their decoupling from the control coils as is often stated.

The model also predicts a strong sensitivity to the location of radial field sensors, as did the numerical models. For simplicity, we assume here a slab geometry as in Ref. [19], but the results should apply qualitatively to other geometries. In slab geometry, the fluxes vary as exp(±kx), where x is the “radial” coordinate and k is the “poloidal” wavenumber. Therefore, if a sensor is displaced a small distance d from the wall, the radial flux that it measures will vary approximately as $(1\pm\delta)$, where $\delta = kd << 1$ and the sign depends on whether the sensor is moved nearer to or farther from the source of the flux. This modification of the model can be applied to the “smart shell” B_r sensor with $\delta<0$ (sensor displaced toward the plasma) or $\delta>0$ (sensor displaced toward the control coils), and to the B_p sensor with $\delta<0$.

Smart Shell B_r, $\delta<0$: $$\Phi_S = \Phi_P(1+|\delta|) + \Phi_{PW}(1-|\delta|) + \Phi_C(1-|\delta|) + \Phi_{CW}(1-|\delta|) \qquad (21)$$

Smart Shell B_r, $\delta>0$: $$\Phi_S = \Phi_P(1-\delta) + \Phi_{PW}(1-\delta) + \Phi_C(1+\delta) + \Phi_{CW}(1-\delta) \qquad (22)$$

B_p sensor, $\delta<0$: $$\Phi_S = \Phi_P(1+|\delta|) - \Phi_{PW}(1-|\delta|) \qquad (23)$$

In this model, a B_p sensor just outside the wall ($\delta \approx 0^+$) is equivalent to the AC compensated B_r sensor of Eq. (9), which was shown earlier to have poor performance even before displacing the sensor toward the control coils [Eq. (14)]. Therefore, the case of the B_p sensor with $\delta>0$ is omitted here.

Solving the dispersion relation yields the following conditions for stability:

Smart Shell B_r, $\delta<0$: $$G > \gamma_0/[1 + |\delta|\,(1 + 2\gamma_0)] \quad , \qquad (24)$$

Smart Shell B_r, $\delta>0$: $$G > \gamma_0/[1 - \delta\,(1 + 2\gamma_0)] \ \underline{\text{and}}\ \gamma_0 < (1-\delta)/2\delta \quad , \qquad (25)$$

B_p Sensor, δ<0: $$G > \gamma_0/[(1+\gamma_0)\,(1+|\delta|)] \quad . \tag{26}$$

It was shown earlier [Eq. (12)] that with radial sensors at the wall (δ=0), a mode with an arbitrarily large growth rate can be stabilized, but the required gain becomes large as the mode growth rate increases. If the B_r sensor is moved from the wall toward smaller radius (δ<0), the improved coupling to the plasma makes it possible to stabilize an arbitrarily large growth rate with a minimum finite gain, $G_{min} = 1/|2\delta|$, as seen in Eq. (24). The existence of a finite G_{min} is qualitatively similar to the earlier results for the idealized and poloidal field sensors [Eqs. (11) and (15)] where $G_{min} = 1$, but in the present case G_{min} may be much larger if the distance from the wall is small. On the other hand, if the B_r sensor is moved from the wall toward larger radius (δ>0), the increased coupling to the control coil places a finite upper limit to the growth rate that can be stabilized, even in the limit of very large gain [Eq. (25)]. A poloidal field sensor inside the wall is far less sensitive to position: the minimum gain required to stabilize arbitrarily large growth rates varies only as $G_{min} \approx (1 - |\delta|)$ [Eq. (26)].

In more realistic modeling there may be additional restrictions on the performance of the feedback system, including the finite bandwidth of the amplifier-coil system. However, the inclusion of a single-pole high frequency cutoff at a frequency ω_0 does not lead to qualitative changes in the results. The conditions (11–15) on the gain values remain the same. The idealized sensor, smart shell, and poloidal field sensor schemes require the bandwidth to be greater than the natural growth rate of the mode: $\omega_0 > \gamma_0$, while the “mode control” schemes with compensated radial field sensors require even larger bandwidths.

4. STABILIZATION BY FEEDBACK CONTROL: EXPERIMENTAL RESULTS

DIII–D experimental results are consistent with the modeling predictions that internal radial field sensors perform better than external radial field sensors for resistive wall mode feedback control, and that poloidal field sensors give still better performance. In these experiments, the rotation is allowed to decay below the threshold of rotational stabilization. Feedback control then prolongs the stable duration as the plasma continues to become more unstable.

Internal radial field sensors (saddle loops) are found to yield a modest improvement in feedback control over the external saddle loops, as shown in Fig. 11. In this comparison [9,10], "smart shell" control using the external saddle loops extended the duration of the high beta phase of the discharge by about 50 ms, while use of the internal saddle loops extended the duration by an additional 50 ms. This is consistent with the predictions of the analytic models and the more detailed predictions of MARS and VALEN (Fig. 9) that there is a modest improvement from moving the radial field sensors closer to the plasma.

Poloidal field sensors yield a greater improvement of RWM stability. In the discharges shown in Fig. 12, feedback using the internal saddle loops extended the high beta duration by only about 40 ms over the case with no feedback. In comparison, the use of poloidal field sensors not only extended the duration by up to 200 ms over the no-feedback case, (about 40 wall times for the n=1 mode) but also allowed the discharge to reach higher beta. With poloidal field sensors, the beta here reaches a value about 50% higher than the estimated no-wall stability limit. It is well known that plasma rotation is an important stabilizing influence on the RWM. However, in this experiment, designed to have a strongly unstable RWM, there are at least two indications that active feedback is necessary for the plasma to remain stable. First, note that the cases in Fig. 12 without feedback and with radial field feedback experience the beta collapse only after a relatively slow decay of the plasma rotation. On the other hand, there is no preliminary decay of the rotation in the cases with poloidal field feedback; that is, loss of rotation is not the reason the plasma becomes unstable. Second, in some of these discharges the feedback control was turned off for brief intervals, leaving the control-coil current constant. In the example shown in Fig. 13, the feedback is first switched off from 1350 to 1360 ms. There is no indication of an instability, as expected since the case without feedback was stable at this time. The feedback is again switched off from 1450 to 1460 ms, which is after the time when the cases without feedback and with radial field feedback became unstable. A resistive wall mode grows, reaches an amplitude of about 3 G, and then decays when the feedback is restored. A small decrease in beta also occurs during the instability. This clearly shows that feedback control is necessary for stability of the plasma.

Direct measurements of the RWM growth rate show that feedback control with poloidal field sensors stabilizes more strongly unstable resistive wall modes, as predicted by the analytic and numerical models. When the RWM becomes unstable, the control coil currents saturate early in the growth of the mode and can no longer follow the command of the feedback system. Therefore, the observed growth rate during the beta collapse should be a good approximation of the no-feedback growth rate. This observed growth rate is plotted in Fig. 14 for a set of discharges that includes those of Fig. 12. The abcissa is β_N/ℓ_i; discharges of the type used here with a fast current ramp have been found empirically and from GATO stability calculations to have a no-wall stability limit of $\beta_N/\ell_i \sim 2.4$. As expected, the RWM growth rate in Fig. 14 increases rapidly as beta is raised above the no-wall stability limit. Without feedback the RWM has a growth rate of $\gamma\tau_{wall} \sim 1$ as expected. Radial field sensors provide stability up to $\gamma\tau_{wall} \sim 2$, with little improvement in beta. However, poloidal field sensors provide stability up to $\gamma\tau_{wall} \sim 6$, with an improvement in the stability limit up to $\beta_N/\ell_i \sim 3.3$. The measured growth rates agree well with the VALEN prediction for the growth rate without feedback, as shown in Fig. 14. Here the VALEN prediction (Fig. 9) is scaled according to the no-wall and ideal-wall β_N limits of 2.1 ℓ_i and 4.2 ℓ_i, calculated with DCON for one of these discharges; there are no free parameters.

A new set of twelve control coils inside the vacuum vessel, with accompanying poloidal field sensors, is being installed for operation in 2003. This system is predicted to allow feedback stabilization up to essentially the ideal wall-stabilized limit even in the absence of rotation [4].

5. FEEDBACK CONTROL OF RESONANT FIELD AMPLIFICATION

As discussed in Section 2, the resonant response of a stable RWM to a static, external n=1 field can be an important effect that causes strong damping of the plasma rotation as the plasma approaches marginal stability [7]. DIII–D experiments [4,14] have shown that feedback control can be an effective tool in reducing this "Resonant Field Amplification," thus allowing the plasma to maintain a high rotational frequency that stabilizes the RWM.

DIII–D experiments have consistently shown that feedback control to suppress resonant field amplification is much more effective with poloidal field sensors than with radial field sensors. In this case, the important factor is the decoupling of the poloidal field sensors from the control coils. Resonant field amplification is a quasi-DC process, so the time response of the sensors is not important. The difference in the sensors can be easily understood by considering a perfect feedback system (i.e., the limit of large gain). The model of Eqs. (1–5) now becomes

$$\Phi_S = 0 \quad , \tag{27}$$

$$\Phi = \Phi_P + \Phi_C + \Phi_0 \quad , \tag{28}$$

$$\Phi_P = (1+\gamma_0)\,\Phi \quad . \tag{29}$$

A perfect feedback system regulates the sensor signal to zero [Eq. (21)]. The total flux at the wall does not include induced wall currents in this quasi-DC case, but does include a constant term Φ_0 representing the static external n=1 field [Eq. (28)]. The model for the plasma response remains the same [Eq. (29)], but we now consider the stable case where $-1 < \gamma_0 < 0$ (in this model, $\gamma_0 = -1$ represents the case without plasma).

In DIII–D operation, the reference level for feedback control is typically determined after the coil currents and plasma currents are established, but before the plasma beta is raised. Therefore, to first approximation, the sensors do not detect static n=1 error fields (due to coil misalignments, for example) but do detect the plasma's response to these error fields as beta increases. In this quasi-DC case we neglect induced wall currents in Eqs. (6-10), and the sensor signals become

Idealized Mode Detection or B_p sensor $\Phi_S = \Phi_P$, (30)

Smart Shell B_r Sensor $\Phi_S = \Phi_P + \Phi_C$. (31)

The poloidal field sensor detects only the plasma perturbation and thus is equivalent to the idealized sensor. The smart shell B_r sensor detects flux from the plasma and the control coil, but not the static n=1 error field. Substituting these sensor definitions into the model of Eqs. (27–29) we find:

Idealized Mode Detection or B_p sensor $\Phi_P = 0$, (32)

Smart Shell B_r Sensor $\Phi_P = \Phi_0 (1+\gamma_0)$. (33)

For comparison, the case without feedback ($\Phi_S \neq 0$, $\Phi_C = 0$) would give

No feedback $\Phi_P = \Phi_0 (1+\gamma_0) / (-\gamma_0)$. (34)

The no-feedback case [Eq. (34)] shows the expected resonant behavior, with the plasma response becoming infinite at marginal stability ($\gamma_0 = 0$). The B_p sensor with a perfect feedback system reduces the plasma perturbation to zero [Eq. (32)]. However, the smart shell B_r sensor is only capable of reducing the plasma perturbation to a level comparable to the external error field [Eq. (33)], which could still lead to significant drag on the rotation.

In principle, the AC compensated B_r sensor [Eq. (9)] could be equivalent to the B_p sensor for suppression of resonant field amplification, despite its poorer predicted performance against unstable modes. This comparison has not yet been explored experimentally. The DC compensated B_r sensor [Eq. (8)] is limited to gains less than unity, and would be no more effective than the smart shell system.

6. DISCUSSION AND CONCLUSIONS

DIII–D experiments have shown that ideal kink modes can be stabilized at high beta by a resistive wall, with sufficient plasma rotation. The critical rotation frequency scales as a small fraction of the Alfvén frequency, and the magnitude is consistent with theoretical predictions. However, the resonant response by a marginally stable resistive wall mode to static magnetic field asymmetries can lead to strong damping of the rotation. Careful reduction of such asymmetries has allowed plasmas with beta well above the ideal MHD no-wall limit, and approaching the ideal-wall limit, to be sustained for durations exceeding one second.

Feedback control is predicted to improve plasma stability by direct stabilization of the resistive wall mode (with or without plasma rotation), or by reducing the asymmetry of the external field. DIII–D experimental results show good qualitative agreement with the predictions of simple analytic models and more realistic numerical models: internal radial field sensors provide a modest improvement over radial field sensors outside the wall, and internal poloidal field sensors provide a significant advantage over both sets of radial field sensors. The improvement with poloidal field sensors is predicted and observed for both direct feedback stabilization of the RWM and suppression of resonant field amplification. Assisted by plasma rotation, direct feedback control of resistive wall modes with growth rates more than 5 times faster than the characteristic wall time has been observed.

These results open a new regime of tokamak operation above the free-boundary stability limit, accessible by a combination of plasma rotation and feedback control. This regime is favorable for steady-state plasma with high fusion gain and a high fraction of bootstrap current.

Areas where more progress is still needed include the exact physics of the dissipation mechanism involved in rotational stabilization, the related but more general issue of the plasma's response to static external magnetic perturbations, and a realistic model of feedback control in the presence of plasma rotation. DIII–D's new internal control coils should provide information on all of these questions, by allowing greater control over plasma rotation with nonresonant magnetic braking, greater flexibility in selecting the poloidal mode spectrum for magnetic perturbations, and feedback control in a new regime of fast, internal control coils.

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Figure Captions

Fig. 1. Beta significantly above the no-wall kink mode stability limit is sustained for ~1.5 s (blue) with a resistive wall and plasma rotation. A similar discharge (red) without sufficient rotation has a beta collapse soon after crossing the no-wall limit.

Fig. 2. (a) The 6-segment control coil (C-coil) surrounds the midplane of the DIII–D vacuum vessel. Normally the coils are connected in three opposing (odd toroidal mode number) pairs. (b) Cross-section of the large major radius side of the DIII–D vessel and coils, showing the C-coil, external and internal saddle loops (B_r) and internal magnetic probes (B_p).

Fig. 3. (a) Several similar discharges with varying plasma rotation show a critical rotation frequency for onset of the RWM. (b) Scaling of the critical rotation frequency versus Alfvén time, for discharges with varying toroidal field and density. The q-profiles and ℓ_i are approximately the same. Solid curve is fit to data (equation shown).

Fig. 4. (a) Pulsed n=1 magnetic perturbation produces a strong response in δB_r and rotation damping for a plasma above the no-wall limit, no response in a plasma below the limit. (b) Measured RWM damping rate (negative growth rate) in plasmas that are above the no-wall limit and stabilized by rotation.

Fig. 5. Comparison of C-coil current and beta for discharges without optimum error field correction (106530), with feedback-controlled error field correction (106532), and error correction currents pre-programmed to approximate the feedback controlled currents (106534).

Fig. 6. Magnetic field symmetrization allows sustained operation with beta above the no-wall stability limit (107603). A similar discharge with slightly higher beta ends in a disruption (106535).

Fig. 7. (a) Growth rate and toroidal rotation of the precursor to the disruption in discharge 106535. (b) Calculated growth rate vs. assumed wall position, 40 ms before the disruption. The plasma is stable with a wall at the DIII–D wall position, but reaches marginal stability if β_N is increased slightly above the experimental value.

Fig. 8. RWM stabilization by plasma rotation (with feedback-controlled magnetic field symmetrization) allows sustained operation at high normalized beta in a high bootstrap fraction discharge.

Fig. 9. VALEN predictions for kink mode stabilization in DIII–D, with feedback control using the C-coil set. Shown are cases with no feedback, external radial field sensors, internal radial field sensors, poloidal field sensors, and an ideally conducting wall.

Fig. 10. Range of gain values G (shaded) to stabilize a mode with open-loop growth rate γ_o, for various types of sensors located just inside the resistive wall.

Fig. 11. Comparison of feedback control with internal and external radial field sensors, and no feedback, showing the time evolution of (a) plasma current, (b) normalized beta, (c) toroidal rotation at the q=2 surface, and (d) amplitude of the n=1 resistive wall mode.

Fig. 12. Comparison of feedback control with poloidal field sensors (106193, 5, 7), radial field sensors (106187), and no feedback (106196), showing the time evolution of (a) plasma current, (b) normalized beta, (c) toroidal rotation at the q=2 surface, and (d) amplitude of the n=1 resistive wall mode.

Fig. 13. Effects of switching off the feedback control (shaded intervals) in discharge 106197, showing (a) RWM amplitude from the radial field sensors, (b) current in one of the C-coil pairs, and (c) the stability parameter β_N/ℓ_i. An RWM grows during the second, higher-beta interval. No mode growth occurs in discharge 106193 where the feedback was not switched off.

Fig. 14. Observed resistive wall mode growth rate, normalized to the wall time constant $\tau_{wall} \sim 5$ ms, versus the stability parameter β_N/ℓ_i. Solid curve is the growth rate predicted by VALEN, with the calculated no-wall limit of $\beta_N = 2.1\ \ell_i$ and ideal-wall limit of $\beta_N = 4.2\ \ell_i$.