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*Columbia University, New York, New York.
†Fartech, Inc., San Diego, California.
‡Princeton Plasma Physics Laboratory, Princeton, New Jersey.

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Resistive Wall Stabilization of High Beta Plasmas in DIII–D

E.J. Strait,[1] J. Bialek,[2] N. Bogatu,[3] M. Chance,[4] M.S. Chu,[1] D. Edgell,[3] A.M. Garofalo,[2] G.L. Jackson,[1] T.H. Jensen,[1] L.C. Johnson,[4] J.S. Kim,[3] R.J. La Haye,[1] G. Navratil,[2] M. Okabayashi[4] H. Reimerdes,[2] J.T. Scoville,[1] A.D. Turnbull,[1] M.L. Walker,[1] and the DIII–D Team

[1]General Atomics, P.O. Box 85608, San Diego, California 92186-5608 USA
email: strait@fusion.gat.com
[2]Columbia University, New York
[3]Fartech, Inc., 10350 Science Center Drive, Bldg. 14, Suite 150, San Diego, California 92121
[4]Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, New Jersey 08543 USA

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 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 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 had typically shown 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

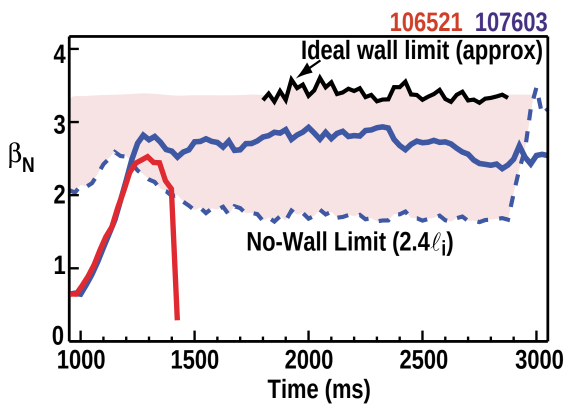

Fig. 1. Beta significantly above the no-wall kink mode stability limit is sustained for ~1.5 s (blue) with a resistive wall and plasma rotation. A similar discharge (red) without sufficient rotation has a beta collapse soon after crossing the no-wall limit.

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.

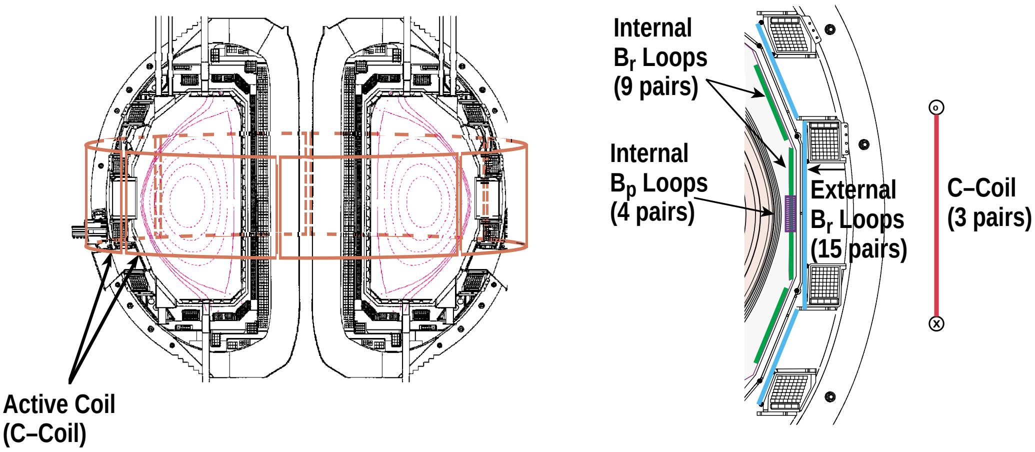

Fig. 2. (a) The 6-segment control coil (C-coil) surrounds the midplane of the DIII–D vacuum vessel. Normally the coils are connected in three opposing (odd toroidal mode number) pairs. (b) Cross-section of the large major radius side of the DIII–D vessel and coils, showing the C-coil, external and internal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

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, β_N=β/(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 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].

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

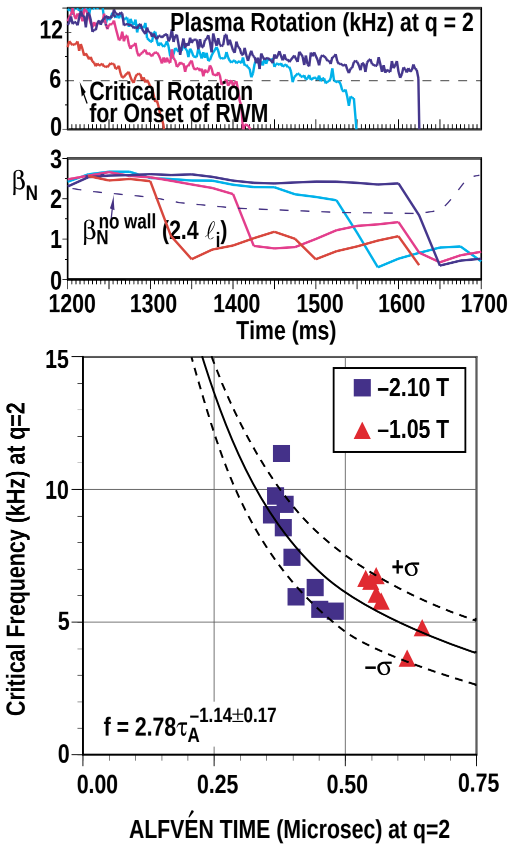

Fig. 3. (a) Several similar discharges with varying plasma rotation show a critical rotation frequency for onset of the RWM. (b) Scaling of the critical rotation frequency versus Alfvén time, for discharges with varying toroidal field and density. The q-profiles and ℓ_i are approximately the same. Solid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

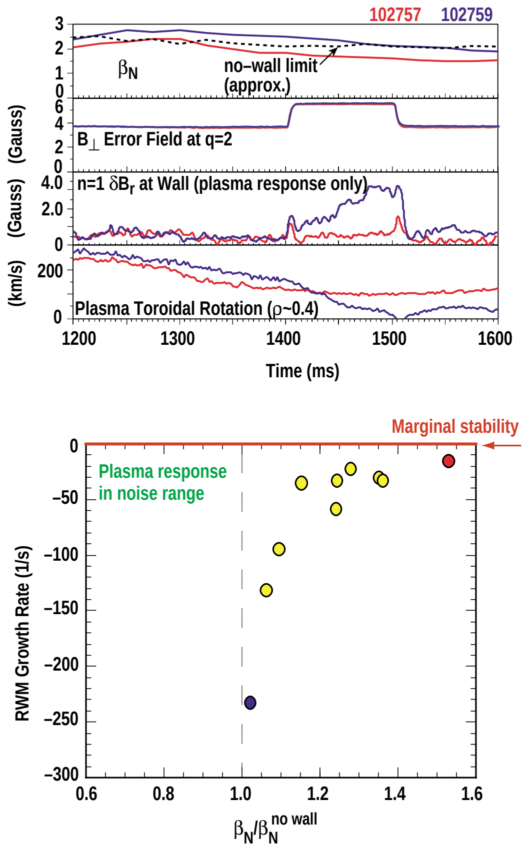

Fig. 4. (a) Pulsed n=1 magnetic perturbation produces a strong response in δB_r and rotation damping for a plasma above the no-wall limit, no response in a plasma below the limit. (b) Measured RWM damping rate (negative growth rate) in plasmas that are above the no-wall limit and stabilized by rotation.

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].

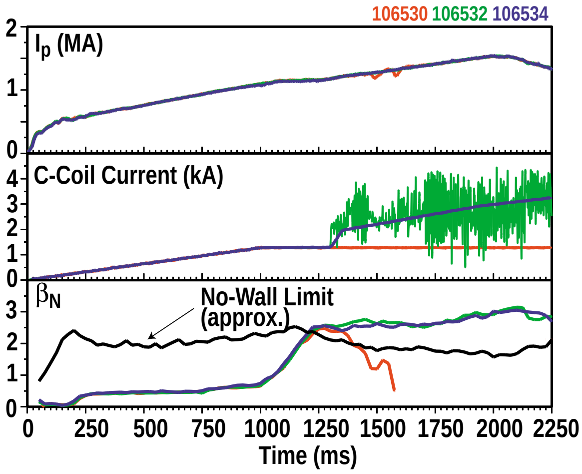

Fig. 5. Comparison of C-coil current and beta for discharges without optimum error field correction (106530), with feedback-controlled error field correction (106532), and error correction currents pre-programmed to approximate the feedback controlled currents (106534).

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)].

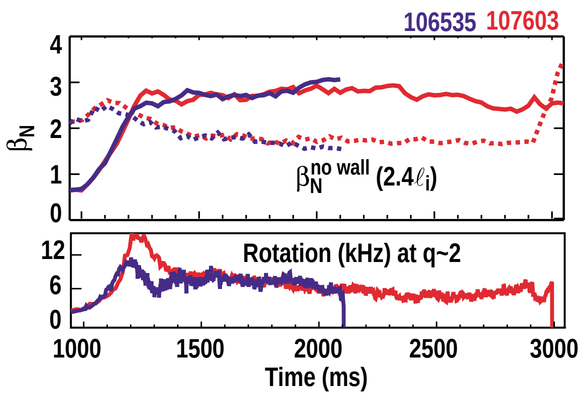

Fig. 6. Magnetic field symmetrization allows sustained operation with beta above the no-wall stability limit (107603). A similar discharge with slightly higher beta ends in a disruption (106535).

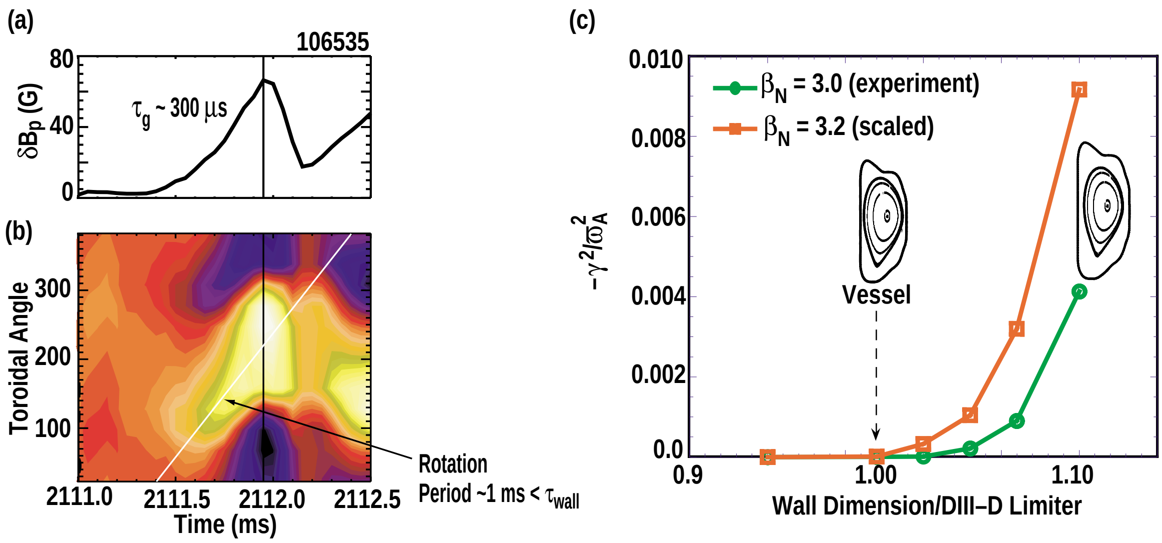

Fig. 7. (a) Growth rate and toroidal rotation of the precursor to the disruption in discharge 106535. (b) Calculated growth rate vs. assumed wall position, 40 ms before the disruption. The plasma is stable with a wall at the DIII–D wall position, but reaches marginal stability if β_N is increased slightly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

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

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.

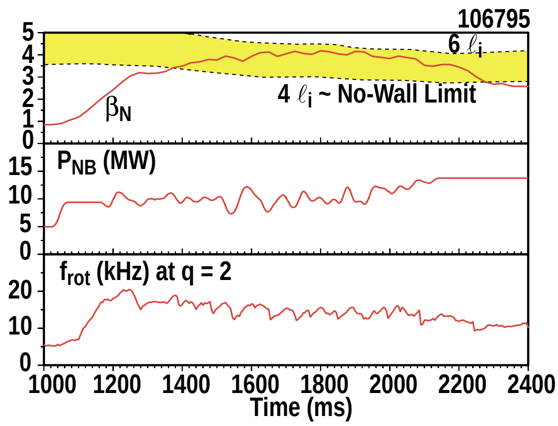

Fig. 8. RWM stabilization by plasma rotation (with feedback-controlled magnetic field symmetrization) allows sustained operation at high normalized beta in a high bootstrap fraction discharge.

Direct feedback control of the RWM using the C-coil does improve plasma stability in DIII–D [4,8]. Analytic feedback models [8,14,19] predict significant differences in performance between detection methods and control algorithms. Using radial field sensors in the originally proposed "smart-shell" feedback scheme [1,20] and assuming an ideal linear amplifier with simple proportional gain, the minimum gain to stabilize an RWM becomes large ($G > \gamma_0$) as the open-loop growth rate γ_0 increases. However, using internal poloidal field sensors the minimum gain remains of order unity [$G > \gamma_0/(\gamma_0+1)$], as a result of their faster time response and natural decoupling from the control coils. (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.) More realistic numerical modeling with MARS [11,21,22] and VALEN [13] gives similar results. In the specific geometry of the DIII–D vacuum vessel, midplane control coils, and sensors, and assuming no plasma rotation, external radial field sensors are 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 are predicted to give 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 (Fig. 9).

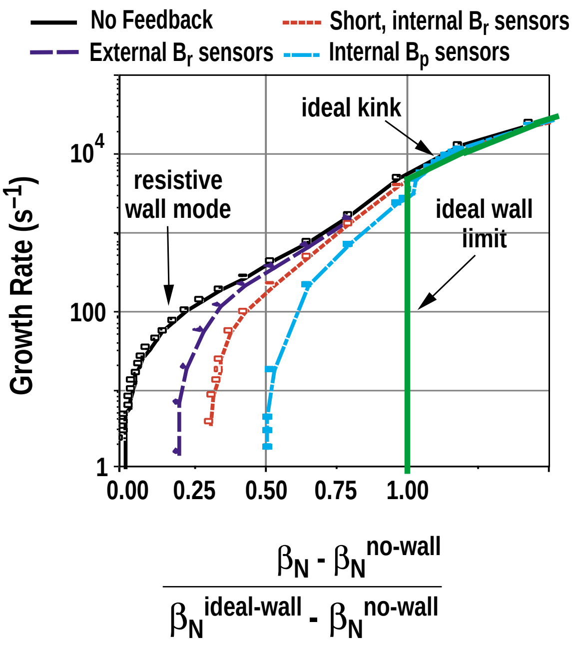

Fig. 9. VALEN predictions for kink mode stabilization in DIII–D, with feedback control using the C-coil set. Shown are cases with no feedback, external radial field sensors, internal radial field sensors, poloidal field sensors, and an ideally conducting wall.

DIII–D experiments are qualitatively consistent with the predictions of the feedback models. 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) yield a modest improvement in feedback control over the external saddle loops [9,10]. Poloidal field sensors yield a greater improvement of RWM stability. In the discharges shown in Fig. 10(a), 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 reaches a value about 50% higher than the estimated no-wall stability limit. 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. 10(b), the feedback is 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, then decays when the feedback is restored, showing that in this case feedback control is necessary for stability of the plasma.

Direct measurements of the RWM growth rate also show that feedback control with poloidal field sensors stabilizes more strongly unstable resistive wall modes, as predicted by the analytic and numerical models. The observed growth rate during the beta collapse is plotted in Fig. 11 for a set of discharges that includes those of Fig. 10. As expected, the RWM growth rate increases rapidly as beta is raised above the no-wall stability limit of $\beta_N/\ell_i \sim 2.4$. 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 rate when control is lost, is in reasonable agreement with VALEN predictions of the no-feedback growth rate.

A simple analytic model can also be applied to feedback-controlled symmetrization of the external field. In the usual scenario for DIII–D operation where the feedback system is enabled after the plasma is formed but before it reaches high beta, feedback with smart-shell radial field sensors only maintains the total field asymmetry (now including the plasma response) at its original level. That is, the feedback reduces but does not eliminate the external asymmetry, and the plasma response to the residual asymmetry may still cause significant damping of the plasma rotation. However, the model predicts that feedback with poloidal field sensors can in principle eliminate the magnetic field asymmetry. These predictions are consistent with DIII–D experiments, where feedback with the poloidal field sensors is found to be effective at sustaining plasma rotation but smart-shell feedback with radial field sensors has little or no effect on rotation [4].

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].

4. 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. In both approaches, modeling and experiments show better performance with poloidal field sensors than with radial field sensors. 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.

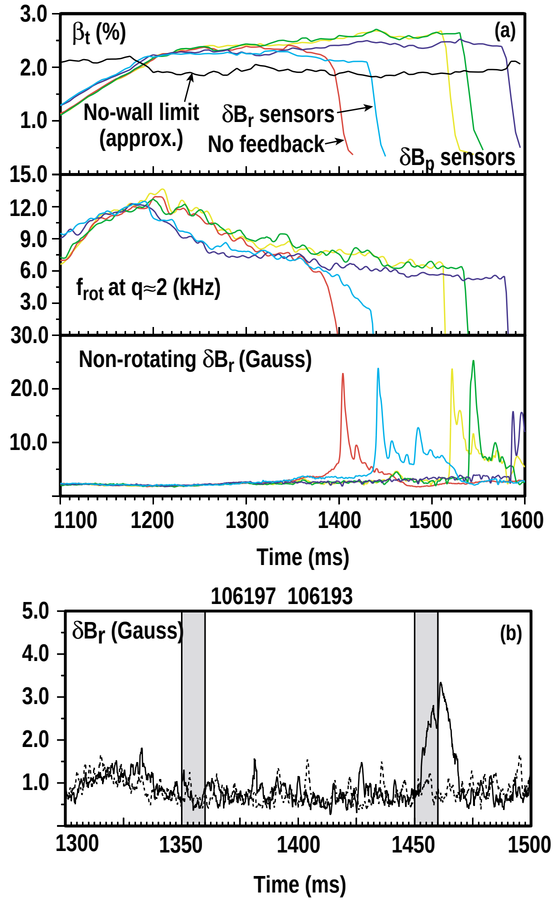

Fig. 10. (a) Comparison of feedback control with poloidal field sensors (106193, 5, 7), radial field sensors (106187), and no feedback (106196), showing the time evolution of normalized beta, toroidal rotation at the q=2 surface, and amplitude of the n=1 resistive wall mode. (b) RWM grows in the second time interval (shaded) where feedback is temporarily switched off (106197), but is stable earlier.

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.

Acknowledgment

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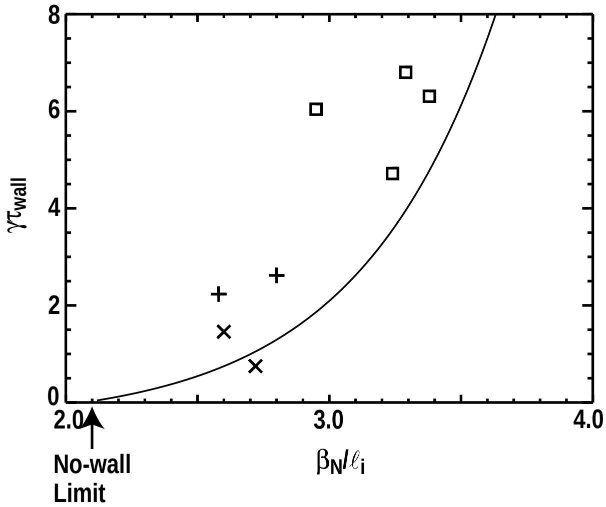

Fig. 11. Measured open-loop resistive wall mode growth rate, normalized to the wall time constant τ_{wall} ~ 5 ms, versus the stability parameter β_N/ℓ_i. Shown are cases at the maximum beta reached with no feedback (x), radial field feedback (+), and poloidal field feedback with varying amounts of derivative gain (❑). Also shown is the open-loop growth rate calculated by VALEN (solid curve).

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