Active Control of Resistive Wall Modes in High Beta, Low Rotation DIII-D Plasmas

A.M. Garofalo 1), G.L. Jackson 2), R.J. La Haye 2), M. Okabayashi 3), H. Reimerdes 1), E.J. Strait 2), M.S. Chu 2), E.J. Doyle 4), J.R. Ferron 2), C.M. Greenfield 2), R.J. Groebner 2), Y. In 5), R.J. Jayakumar 6), G. Matsunaga 7), G.A. Navratil 1), C.C. Petty 2), J.T. Scoville 2), W.M. Solomon 3), H. Takahashi 3), M. Takechi 7) A.D. Turnbull 2), and the DIII-D Team

1) Columbia University, New York, New York, USA
2) General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA
3) Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA
4) University of California-Los Angeles, Los Angeles, California, USA
5) FARTECH Inc., San Diego, California, USA
6) Lawrence Livermore National Laboratory, Livermore, CA, USA
7) Japan Atomic Energy Research Institute, Naka-machi, Naka-gun, Ibaraki-ken, Japan

e-mail contact of main author: garofalo@fusion.gat.com

Abstract. Recent high-β DIII-D [Luxon, Nucl. Fusion **42** (2002) 64] experiments with the new capability of balanced neutral beam injection show that the resistive wall mode (RWM) remains stable when the plasma rotation is lowered to a fraction of a percent of the Alfven frequency by reducing the injection of angular momentum in discharges with minimized magnetic field errors. Previous DIII-D experiments yielded a high plasma rotation threshold (of order a few percent of the Alfven frequency) for RWM stabilization when resonant magnetic braking was applied to lower the plasma rotation. We propose that the previously observed rotation threshold can be explained as the entrance into a forbidden band of rotation that results from torque balance including the resonant field amplification by the stable RWM. Resonant braking can also occur naturally in a plasma subject to magnetic instabilities with a zero frequency component, such as edge localized modes (ELMs). In DIII-D, robust RWM stabilization can be achieved using simultaneous feedback control of the two sets of non-axisymmetric coils. Slow feedback control of the external coils is used for dynamic error field correction; fast feedback control of the internal non-axisymmetric coils provides RWM stabilization during transient periods of low rotation. This method of active control of the $n=1$ RWM has opened access to new regimes of high performance in DIII-D. Very high plasma pressure combined with elevated $q_{\rm min}$ for high bootstrap current fraction, and internal transport barriers (ITBs), for high energy confinement, are sustained for almost 2 s, or 10 energy confinement times, suggesting a possible path to high fusion performance, steady-state tokamak scenarios.

1. Introduction

ITER steady-state scenario plasmas require stabilization of the low-n magnetohydrodynamics (MHD) kink mode for operation at normalized β above the no-wall stability limit [1]. [Here $\beta_N = \beta/(I/aB)$, $\beta = 2\mu_0\langle p\rangle/B_0^2$, $\langle p\rangle$ is the volume averaged pressure, B_0 is the external toroidal field, I is the total toroidal current, and a is the plasma minor radius.] Conductive structures close to the plasma convert the kink mode into the slowly growing resistive wall mode (RWM), which theory [2] predicts can be stabilized by sufficiently rapid plasma rotation in the presence of some dissipation in the plasma. Research carried out on the DIII-D tokamak and other high β experiments has demonstrated that the RWM can be stabilized by plasma toroidal rotation [3-5] or by active feedback using magnetic coils [6-10]. There are two main issues about RWM stabilization in ITER: (1) expected plasma rotation in ITER may be insufficient to provide RWM stabilization without an active feedback system [11]. (2) The present ITER design of external non-axisymmetric error field correction coils may be marginal for RWM feedback stabilization above the no-wall stability limit [12]. Over the past few years, experimental research on DIII-D has vigorously pursued a demonstration of RWM feedback control at very low plasma rotation, both as a proof of principle of RWM feedback control without the stabilizing effect of plasma rotation, and to obtain the experimental results needed to benchmark codes which will be used to provide the physics and engineering specifications for RWM control systems in ITER.

Until the recent experimental campaign in 2006, all the neutral beam systems on the DIII-D tokamak injected power with the momentum in the same direction as the usual plasma current ("co-injection"). In these discharges with uni-directional tangential NBI heating, RWMs have only been observed when asymmetries of the magnetic field—uncorrected intrinsic or externally applied—led to a decrease of the plasma rotation Ω below the threshold value for stabilization, Ω_{crit}. This threshold was found to scale as a small fraction of the Alfven frequency, Ω_A, at the $q = 2$ surface under different conditions: 1.5-2.5% in Ref. [13], 0.7-1.5% in Ref. [14].

A recent, major modification to the DIII-D tokamak re-oriented one of the two-source beam lines to allow injecting power with the momentum opposite that of the plasma current ("counter-injection"). This modification provides the capability of injecting up to 10 MW of neutral beam power with zero momentum input to the plasma. Decoupling the injected momentum and power opens a previously inaccessible parameter space for experiments that study the effect of rotation on the RWM stability.

DIII-D experiments with the new capability of reducing the injection of angular momentum, show, surprisingly, that the RWM remains stable at β_N above the no-wall stability limit ($\beta_N^{no-wall}$) when the plasma rotation is lowered well below the previously observed threshold (~ 0.7%-2.5% Ω_A at the $q = 2$ surface) measured by braking of the plasma rotation with externally applied or intrinsic non-axisymmetric magnetic fields. The previously observed rotation threshold can be explained as the entrance into a forbidden band of rotation that results from torque balance including the resonant, non-axisymmetric field amplification by the stable RWM. Even with very low rotation requirements for RWM stabilization, active feedback control of the RWM will still be needed for reliable operation at very high β in an advanced tokamak reactor. In DIII-D, active RWM stabilization using simultaneous feedback control of the two sets of non-axisymmetric coils has opened access to new regimes of high performance, with very high plasma β combined with high bootstrap current fraction and high energy confinement, sustained for almost 2 s, or 10 energy confinement times [15].

2. RWM Stabilization by Slow Plasma Rotation

Previous DIII-D experiments [16] have demonstrated that plasma rotation in the order of a few percent of the Alfvén velocity stabilizes the RWM up to the ideal MHD ideal-wall β-limit. The recent beamline re-orientation has given DIII-D the unique capability to decouple the applied torque from the NBI heating power and generate reactor relevant low-rotation, high β plasmas and study the RWM onset in conditions of optimal correction of magnetic field asymmetries. Figure 1 illustrates an example of the use of this new capability, leading to the discovery that the plasma rotation threshold for stable operation above the no-wall β limit is much lower than previously reported. Using mixed co- and counter-injection, the NBI torque is gradually reduced from mostly co-injected to near balanced, maintaining nearly constant $\beta_N > \beta_N^{no-wall}$. The correction of the $n = 1$ non-axisymmetric field in this plasma was determined from a previous similar discharge using the technique of "dynamic error field correction", [16] i.e. using the $n = 1$ RWM feedback to detect and minimize the amplification

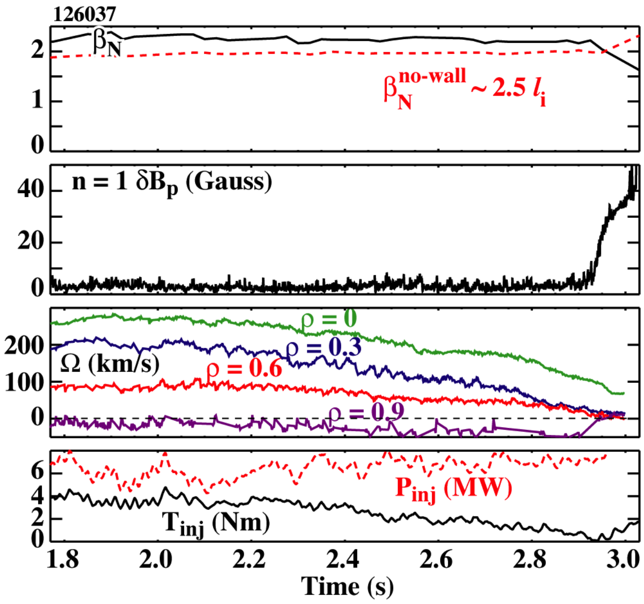

FIG. 1. RWM onset induced by controlled reduction of the neutral beam injected torque at nearly constant $\beta_N \geq 1.1\, \beta_N^{no-wall}$ with optimal correction of the n=1 non-axisymmetric field. Shown are timetraces of (a) normalized β and no-wall stability limit calculated to scale as 2.5 times the internal inductance, (b) n=1 perturbed poloidal field amplitude from midplane probe array, (c) plasma toroidal rotation measured by CER spectroscopy of impurity ion emission (C VI) at several minor radial locations, (d) neutral beam injected power and torque.

of the non-axisymmetric field by the rotationally stabilized RWM. The plasma remains stable as the total injected torque is reduced close to zero, and the plasma toroidal rotation at the $q = 2$ surface ($\rho \sim 0.6$) is slowed down from 100 km/s to about 15 km/s, or ~0.3% Ω_A. This value is about half the lowest threshold previously reported [14] and less than one third the rotation threshold for RWM onset observed by applying resonant magnetic braking in similar plasmas without counter NBI, as will be discussed in Section 3 of this paper. At even slower rotation, a nearly stationary $n = 1$ mode becomes unstable, with growth time ~12 ms, or several times the DIII–D vessel time constant estimated for penetration of an $n = 1$ kink perturbation, τ_W. This growth time is consistent with the growth rate expected for an RWM at the experimental $\beta_N \sim 1.1\, \beta_N^{no-wall}$.

Careful programming of the neutral beam torque evolution and feedback correction of the non-axisymmetric field has allowed us to demonstrate stable operation at $\beta_N \sim 1.2\, \beta_N^{no-wall}$ sustained for more than 1 s with plasma toroidal rotation $\Omega(q = 2) \leq 0.4\%\, \Omega_A$ (Fig. 2). Note that at low injected torque, the entire radial profile of the toroidal rotation lies a factor of two (in magnitude) below the threshold for RWM stabilization, $\Omega_{crit} \approx 2\%\, \Omega_A$, measured at the $q = 2$ surface using magnetic braking in a similar discharge without counter NBI (Section 3).

The ideal MHD β limit for the $n = 1$ kink mode without a conducting wall is calculated to be $\beta_N^{no-wall} \sim (2.5 \pm 0.1) l_i$ using the ideal MHD code DCON [17] on kinetic equilibrium reconstruction of several of these low-torque discharges, at several time slices.

We investigated the β dependence of the very low rotation threshold for RWM stabilization measured by controlled reduction of the neutral beam injected torque with optimal correction of the $n = 1$ non-axisymmetric field. If we limit ourselves to looking at the $q = 2$ surface, no β dependence is observed. In Fig. 3 we compare these newly measured thresholds to those measured in DIII-D using magnetic braking in previous experiments [13]. For this comparison, we use the gain in β between the calculated, ideal MHD no-wall and ideal wall stability limits as the abscissa parameter.

The new thresholds vary between 0.15-0.35 Ω_A, i.e., values about a factor of ten smaller than the old measurements and about a factor of five smaller than the MARS predictions for the

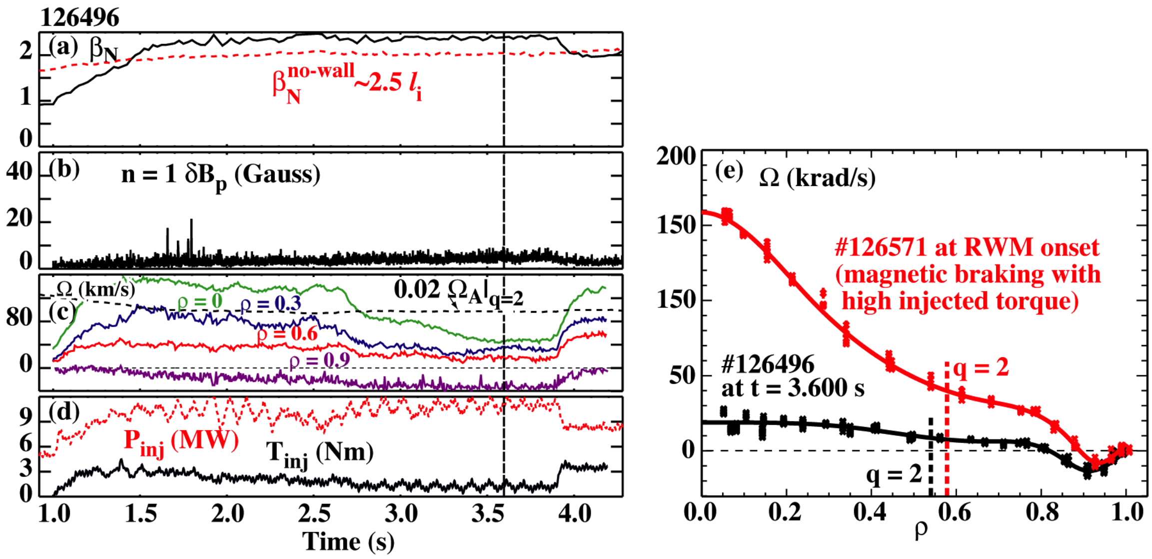

FIG. 2. (a-d) Time evolution of parameters for a discharge sustained for more than 1 s with constant $\beta_N \sim 1.2\, \beta_N^{no-wall}$ and optimal correction of the n=1 non-axisymmetric field at plasma toroidal rotation well below the threshold for RWM stabilization measured at q=2 using magnetic braking with no counter neutral beam injection [Fig. 4(a-d)]. The duration of the high-β, low-rotation phase is limited by the pulse length of one of the counter neutral beam sources. (e) Toroidal rotation profile (C VI) at t=3.6 s compared to the rotation profile at the stability threshold measured using magnetic braking in a discharge with no counter NBI (red line).

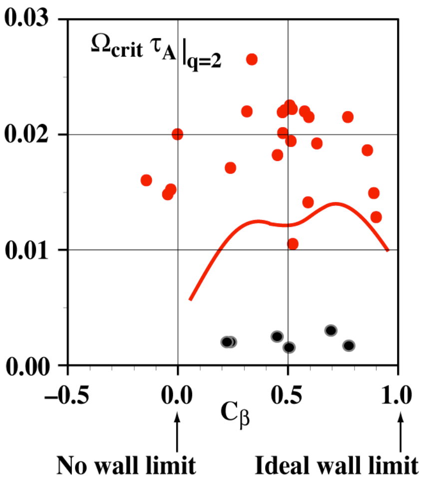

FIG. 3. Rotation threshold for RWM stabilization as a function of $C_\beta=(\beta_N-\beta_N^{no-wall})/(\beta_N^{ideal-wall}-\beta_N^{no-wall})$. Measurements obtained by reducing the input torque with minimal non-axisymmetric fields (black circles) are compared to measurements and MARS predictions of the threshold obtained using resonant magnetic braking at high input torque (red circles and line).

old experiments. It must be noted that the measurements, both the new and the old, are of the carbon impurity ion rotation (C VI emission). The rotation of the main deuterium ions is different by a correction that could be calculated using neoclassical theory, although it has been shown that the theory is not complete [18].

This low rotation threshold for RWM stabilization could have very favorable implications for ITER, but a reliable extrapolation requires a good understanding of the underlying physics. Using the MARS-F code [19], we have calculated the MHD stability predictions for an equilibrium reconstruction of the low-rotation discharge in Fig. 2, at t = 3.6 s. The MARS-F calculations can include the effects of dissipation through either a “sound wave damping” model [2] or a “kinetic damping” model [20]. MARS-F finds that the experimental rotation profile (of the carbon impurity ions) is sufficient to stabilize the plasma up to the ideal-wall β_N limit, when the kinetic damping model is used. Further investigations are needed, but these first calculations encouragingly suggest that the kinetic model for RWM damping by the plasma rotation may be adequate to make extrapolations to ITER.

3. Rotation Threshold from Magnetic Braking Experiments

An important step toward predicting the rotation threshold for RWM stabilization in ITER is to reconcile the recent observations of a low rotation threshold in plasmas using low NBI torque with the higher threshold values obtained in DIII-D experiments using high NBI torque and braking of the plasma rotation with non-axisymmetric magnetic fields [13,14]. In the “magnetic braking” experiments, an externally applied non-axisymmetric field, amplified by the rotationally stabilized RWM, creates a torque which leads to a deceleration of the plasma. Eventually a threshold is reached where the deceleration of rotation and the growth of the RWM amplitude suddenly increase. Previously this threshold was interpreted as the critical rotation rate for stabilization of the RWM. We now conjecture that it represents a bifurcation in the torque-balance equilibrium of the plasma, in which the rotation must jump from a high value to a low value. In some circumstances, the critical value for RWM stabilization may lie in the intervening “forbidden” band of rotation values.

Bifurcation of the equilibrium solution for plasma rotation is well known in the “induction motor” model of error field-driven reconnection [21,22], and a conceptually similar process has been proposed involving the resistive wall mode [23]. A bifurcation can arise when the rotational drag caused by the applied field has a non-monotonic dependence on the rotation. In the induction motor model the non-monotonic dependence results from electromagnetic shielding of the error field at the singular surface as rotation increases, while in the RWM model it results from greater RWM stabilization (and hence a smaller resonant response to the error field) as rotation increases. In high β tokamak experiments, one or both of these mechanisms may be at work. Such models predict that the plasma rotation at the critical point is on the order of half of the unperturbed rotation. Higher neutral beam torque gives higher “natural” rotation frequency of the plasma, therefore a higher critical rotation at the entrance to the forbidden band of rotations.

We have confirmed that in discharges similar to the plasma of Fig. 1, reducing the toroidal rotation by applying $n=1$ magnetic braking instead of reducing the injected torque leads to the observation of a higher rotation threshold for the onset of the RWM. Figure 4 compares two discharges with $n=1$ magnetic braking at high and low NBI torque. Magnetic braking is applied by switching off the non-axisymmetric field correction while the plasma is at $\beta_N > \beta_N^{no-wall}$. At first, the rotation at the $q=2$ surface shows a slow deceleration, accompanied by an increase in the plasma response to the (increasing) $n=1$ magnetic field. Then, the rotation decay shows a sharp discontinuity at about the same time that the magnetic perturbation from the plasma transitions to a faster growth. The plasma rotation at this time has been previously interpreted as the threshold below which the mode is unstable. However, Fig. 4 shows that experiments with different amounts of injected torque in otherwise similar plasmas yield very different rotation thresholds for RWM stabilization. In the discharge of Fig. 4(a-d), without counter NBI, the observed rotation threshold measured at the $q=2$ surface is $\Omega_{crit} \approx 2\% \, \Omega_A$, consistent with the thresholds previously measured under similar conditions [13]. In the discharge of Fig. 4(e-h), using mixed co- and counter-NBI, the injected torque is reduced by about a factor of four, and the observed rotation threshold is about a factor of nine lower than in the higher torque case. The low-torque experiments therefore are inconsistent with the interpretation of the critical rotation measured with $n=1$ magnetic braking at high torque as a threshold for RWM stabilization.

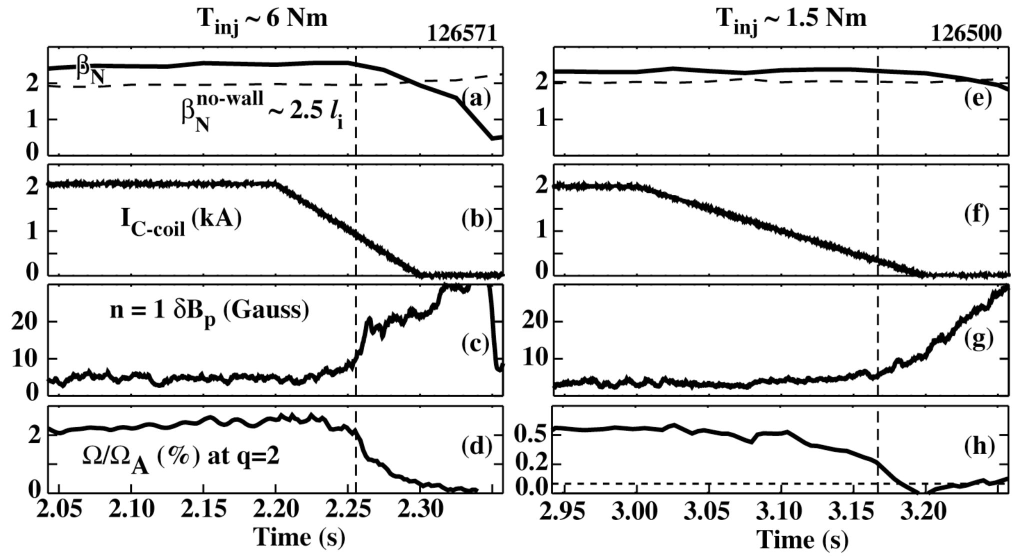

FIG. 4. RWM onset (vertical dashed lines) induced by magnetic braking of the plasma rotation, at constant injected torque, in discharges that are similar except for the injected torque: 6 Nm (a-d) and 1.5 Nm (e-h). The braking field is applied by removing the correction of the n=1 non-axisymmetric field carried out by the C-coil. The discharge with lower injected torque is stable at plasma rotation lower than the threshold measured at higher injected torque. The threshold measured at low injected torque is ~10x smaller than at high torque.

4. Control of the RWM by Magnetic Feedback

Even with very low rotation requirements for RWM stabilization, active feedback control of the RWM will probably be needed for reliable operation at very high β in an advanced tokamak reactor. This is because resonant magnetic braking can always occur naturally in a plasma subject to magnetic instabilities with a zero frequency component, such as ELMs. In DIII-D advanced tokamak plasmas, robust RWM stabilization has been achieved at very high β using simultaneous feedback control of the two sets of non-axisymmetric coils [15]. The external coils (C-coils) are used to maintain optimal error field correction so as to maintain high levels of plasma rotation for rotational stabilization of the RWM. The internal coils (I-coils) are powered by high bandwidth audio amplifiers and provide faster RWM suppression during transient periods of strong resonant braking, e.g., following a large ELM. In high β_N, high $q_{\min}$ discharges, without RWM feedback, an RWM is often observed to grow and disrupt the plasma immediately following a large ELM [15]. In the absence of active feedback, the resonant $n = 1$ component of the ELMs can lead to magnetic braking and, ultimately, unstable RWM growth. Large ELMs observed during the active feedback periods do not lead to RWM-induced disruptions.

Figure 5 shows in detail the efficacy of the RWM feedback system in one of these high-β_N discharges. The timetraces of the magnetic sensors show a low frequency $n = 1$ mode starting to grow following a large ELM at t = 1665 ms. The plasma rotation is strongly damped as the mode grows. The I-coil feedback currents respond promptly, and appear to quench the mode. High plasma rotation is re-established, and β_N is maintained above the $4\ l_i$ no-wall limit.

Simultaneous feedback control of the $n = 1$ error field and RWM has opened access to new regimes of high performance in DIII-D. Very high plasma β ($\beta > 5\%$) combined with elevated $q_{\min}$ for high bootstrap current fraction ($f_{BS} > 60\%$), and internal transport barriers

(ITBs), for high energy confinement (H_{89P} > 2.5), have been sustained for almost 2 s, or 10 energy confinement times [15] (Fig. 6).

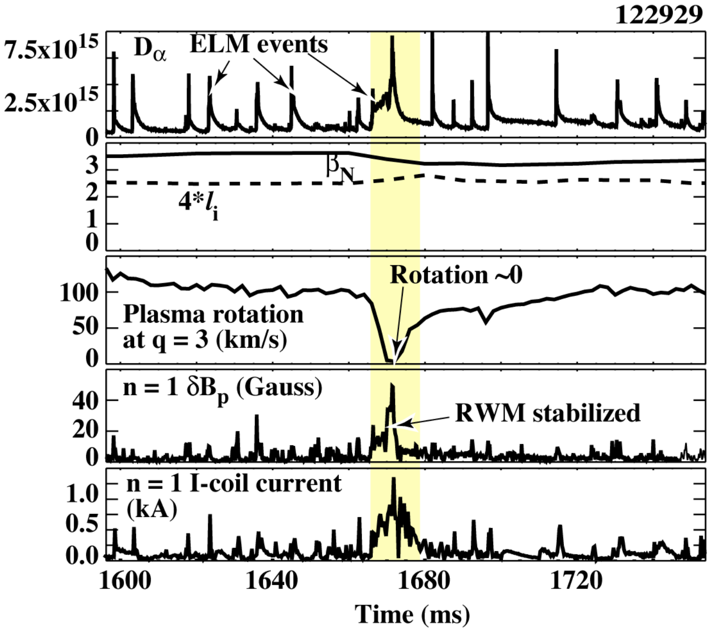

FIG. 5. Prompt response by the RWM feedback system using the I-coil to a mode growth following a large ELM and fast rotation slowdown, allows recovery of the plasma rotation and sustainment of $\beta_N > 4l_i$.

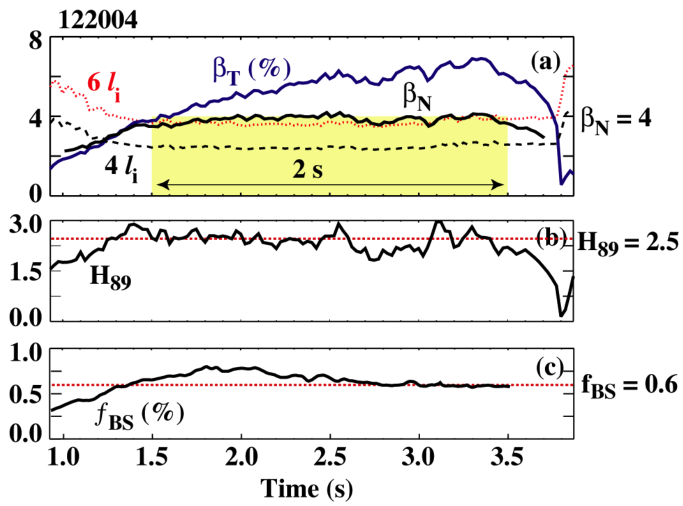

FIG. 6. Time evolution of parameters for a DIII-D discharge sustained for about two seconds at high values of (a) β and β_N, compared to 4 times and six times the internal inductance, l_i; (b) the energy confinement enhancement factor over L-mode confinement, H_{89}; (c) the bootstrap current fraction, f_{BS}.

The improvement in attained plasma pressure compared to previous plasmas with ITBs can only be achieved reliably using active feedback control of the RWM. The experimental limit to the pressure is observed to agree well with the ideal MHD, ideal-wall stability limit for low-n kink modes.

5. Discussion and Conclusions

A recent, major modification to the DIII-D tokamak provides the capability of injecting up to 10 MW of neutral beam power with zero momentum input to the plasma. DIII-D experiments with this new capability have shown, surprisingly, that the RWM remains stable at β above the no-wall stability limit when the plasma rotation is lowered to a fraction of a percent of the Alfven frequency by reducing the injection of angular momentum. With low input torque and minimal nonaxisymmetric field errors, stable DIII-D discharges have been observed with β exceeding the no-wall stability limit up to C_β=0.8 and ion rotation velocity (measured from C-VI emission) of less than 0.3% of Ω_A at the $q = 2$ surface. We propose that the rotation threshold measured using magnetic braking corresponds to a bifurcation of the torque-balance equilibrium, rather than the onset of an unstable RWM.

We have shown here that these recent results are consistent with the leading RWM stabilization theory embodied in the MARS-F code. The new results and the new interpretation of the previous magnetic braking results suggest that wall stabilization of high β plasmas in ITER and other future devices may be possible with relatively modest rotation. However, maintaining even a small rotation with low injected torque may require very small magnetic field errors at β above the no-wall limit.

Active feedback control of the RWM will probably be needed even with moderate plasma rotation, for reliable operation at very high β in an advanced tokamak reactor. This is because resonant magnetic braking can always occur naturally in a plasma subject to magnetic instabilities with a zero frequency component, such as ELMs. Robust RWM stabilization can be achieved in DIII-D using simultaneous feedback control of the two sets of non-axisymmetric coils. This method of active control of the RWM has opened access to new regimes of high performance, with very high plasma pressure combined with elevated $q_{\min}$, and ITBs, sustained for about 10 energy confinement times. These results, and the predictions [15] that the ideal-wall β limits increase with $q_{\min}$ increasing above 2, suggest the possibility to generate DIII-D plasmas with $\beta \sim 6\%$ with RWM stabilization, and indicate a path toward the demonstration of steady-state tokamak operation with high fusion performance and large bootstrap current fraction.

Acknowledgments

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References

[1] HENDER et al., "MHD stability, operational limits, and disruption", Chapter 3 of the Progress in the ITER Physics Basis, to be published in Nucl. Fusion.
[2] BONDESON, A., and WARD, D., Phys. Rev. Lett. **72** (1994) 2709.
[3] TAYLOR, T.S., et al., Phys. Plasmas **2** (1995) 2890.
[4] GAROFALO, A.M., et al., Phys. Plasmas **9** (2002) 1997.
[5] SABBAGH, S.A., et al., Nucl. Fusion **46** (2006) 635.
[6] CATES, C., et al., Phys. Plasmas **7** (2000) 3133.
[7] GAROFALO, A.M., et al., Nucl. Fusion **41** (2001) 1171.
[8] OKABAYASHI, M., et al., Phys. Plasmas **8** (2001) 2071.
[9] SABBAGH, S.A., et al., Phys. Rev. Lett. **97** (2006) 045004.
[10] STRAIT, E.J., et al., Phys. Plasmas **11** (2004) 2505.
[11] LIU, Y., et al., Nucl. Fusion **45** (2005) 1131.
[12] MEADE, D.M., et al., Fusion Energy (Proc. 20th Int. Conf. Villamoura, 2004) IAEA, Vienna, CD-ROM file FT/P7-23.
[13] La HAYE, R.J., et al., Nucl. Fusion **44** (2004) 1197.
[14] REIMERDES, H., et al., Phys. Plasmas **13** (2006) 056107.
[15] GAROFALO, A.M., et al., Phys. Plasmas **13** (2006) 056110.
[16] GAROFALO, A.M., et al., Phys. Rev. Lett. **89** (2002) 235001.
[17] GLASSER, A.H., and CHANCE, M.S., Bull. Am. Phys. Soc. **42** (1997) 1848.
[18] REIMERDES, H., et al., Phys. Rev. Lett. **93** (2004) 135002.
[19] SOLOMON, W.M., et al., Phys. Plasmas **13** (2006) 056116.
[20] LIU, Y.Q., et al., Phys. Plasmas **7** (2000) 3681.
[21] JENSEN, T.H., Phys. Fluids B **5** (1993) 1239.
[22] FITZPATRICK, R., Phys. Plasmas **5** (1998) 3325.
[23] FITZPATRICK, R., Phys. Plasmas **9** (2002) 3459.