GA–A25492

EXPERIMENTS AND MODELING USING RESISTIVE WALL MODE FEEDBACK CONTROL IN DIII–D

by
G.L. JACKSON, J.M. BIALEK, S.A. DRISKILL, A.M. GAROFALO, Y. IN, O. KATSURO-HOPKINS, A.G. KELLMAN, R.J. La HAYE, A. NAGY, G.A. NAVRATIL, M. OKABAYASHI, H. REIMERDES, J.T. SCOVILLE, E.J. STRAIT, and H. TAKAHASHI

JULY 2006

GENERAL ATOMICS

GA–A25492

EXPERIMENTS AND MODELING USING RESISTIVE WALL MODE FEEDBACK CONTROL IN DIII–D

by
G.L. JACKSON, J.M. BIALEK,* S.A. DRISKILL,†
A.M. GAROFALO,* Y. IN,‡ O. KATSURO-HOPKINS,*
A.G. KELLMAN, R.J. La HAYE, A. NAGY,§ G.A. NAVRATIL,*
M. OKABAYASHI,§ H. REIMERDES,* J.T. SCOVILLE,
E.J. STRAIT, and H. TAKAHASHI§

This is a preprint of a paper to be presented at the 33rd European Physical Society Conference on Plasma Physics, Rome, Italy, June 19-23, 2006 and to be printed in the Proceedings.

*Columbia University, New York, New York
†University of Virginia, Charlottesville, Virginia
‡FAR-TECH, San Diego, California
§Princeton Plasma Physics Laboratory, Princeton, New Jersey

Work supported by
the U.S. Department of Energy
under DE-FC02-04ER54698, DE-FG03-89ER53297,
DE-FG03-99ER82791, and DE-AC02-76CH03073

GENERAL ATOMICS PROJECT 30200
JULY 2006

GENERAL ATOMICS

Experiments in DIII-D are evaluating both feedback and rotational stabilization of the resistive wall mode (RWM) that can limit the maximum achievable toroidal β, especially in advanced tokamak (AT) scenarios. The RWM is an instability that grows on the time scale of the vessel wall time in plasmas where the ideal kink mode would be unstable without a resistive wall, but stable with a perfectly conducting wall. Previous work has demonstrated that high rotation resulting from co-injected neutral beams, typically $\Omega_\phi^{q=2}\tau_A > \sim 0.01$, can stabilize an $n=1$ RWM [1], where $\Omega_\phi^{q=2}$ is the toroidal velocity at the $q=2$ surface, τ_A is the Alfvèn time, $R_0(\mu_0 n_e m_i)^{1/2}/B_{\phi 0}$, and n is the RWM toroidal mode number. Advanced scenarios in ITER may require wall stabilization but the expected toroidal rotation is, at best, marginal for RWM stabilization [2] and therefore an alternate scheme is also being investigated in DIII-D, namely feedback stabilization using non-axisymmetric coils [3]. In support of ITER, the goal of the DIII-D RWM feedback stabilization esxperiments is sustained high beta operation, up to ideal wall β limit, with little or no toroidal rotation [4].

In order to investigate RWM feedback stabilization using co-injected neutral beams, a dissipative, or drag force is necessary to counteract the neutral beam torque, T_{NB}, and reduce rotation below the critical rotation threshold, Ω_{crit}. While an $n=1$ perturbing magnetic field can produce a very effective drag torque, this is resonant with the marginally stable RWM and creates a plasma response which increases as the rotation decreases, making control difficult. However $n=2$ and $n=3$ perturbing fields are *non-resonant* and can also create a drag torque and this has been evaluated in DIII-D and NSTX [5,6]. An example of $n=3$ magnetic braking is shown in Fig. 1. In this case a dc current, $I_{n=3}$, was applied to either the 12 internal I-coil or the 6 external C-coil non-axisymmetric set [7]. As shown in this figure, the decrease in rotation, Ω, saturated as the $n=3$ coil current, $I_{n=3}$, was increased. This is consistent with a neoclassical toroidal viscosity (NTV) model of momentum dissipation. The decrease in momentum, L, due to the applied $n=3$ perturbation can be written [8]

$$dL/dt = T_{NB} - L/\tau_M - k(\Omega - \Omega_D)\, I_{n=3}^2 \tag{1}$$

where L is plasma angular momentum, k is a constant determined from the NTV physics, τ_M is the momentum confinement time. The saturated rotation frequency, Ω_D, observed experimentally [8] agrees well with the value $\Omega_D \sim 2/3 \nabla T_i/(Z_i e B_\theta R)$ derived from a neoclassical toroidal viscosity model [9]. To our knowledge, this is the first experimental observation of this saturation effect predicted by the NTV model.

Because of the saturation shown in Fig. 1, $n=3$ braking was only marginally effective in producing target discharges with sufficiently low toroidal rotation for ITER-relevant RWM feedback stabilization experiments. Recently, one DIII-D neutral beamline was re-oriented to allow the capability of balanced injection up to power levels of ~ 10 MW and is now operational. Balanced injection is expected to reduce the neutral beam torque input to near zero and, in experiments planned for summer 2006, should substantially reduce the toroidal plasma rotation to values well below those required for rotational stabilization of resistive wall modes, namely $\Omega\tau_{\mathrm{ALFVEN}} < 0.01$.

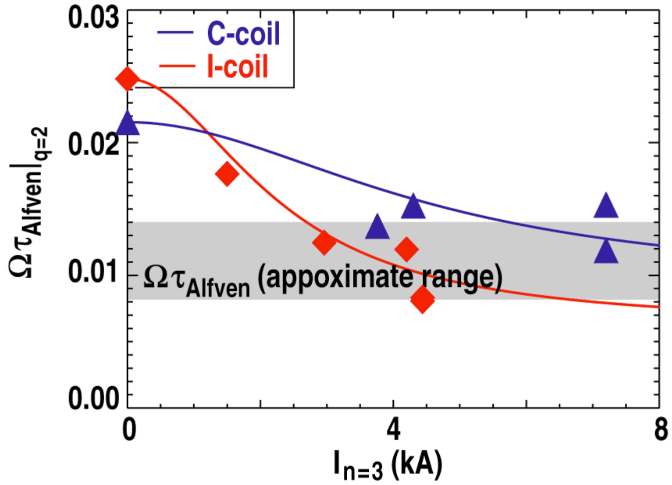

Fig. 1. Toroidal rotation at the $q = 2$ surface measured at 1.7 s after application of the $n = 3$ pulse beginning at 1.5 s. The curves represent the steady-state rotation value derived from the time-dependent fits to Eq. (1).

The RWM feedback system has also been upgraded to stabilize faster growing RWMs occurring at higher β_N. Any experimental feedback system has a finite bandwidth and a non-zero delay time due to latency in the various hardware components. VALEN-3D and other models show that as β_N increases above the no-wall limit, the growth rate, γ, ($\delta B_{RWM} \sim e^{\gamma t}$) of the resistive wall mode increases, requiring a feedback system with larger bandwidth and less system time delay for stabilization. An example is shown in Fig. 2(a), where higher bandwidth and lower system delay, modeled with the VALEN-3D code, stabilized faster growth rates than the baseline case, representing the previous RWM feedback system using switching power supply amplifiers (SPAs) and a slower control system. The effect of maximum allowable feedback system delay as a function of C_β is shown in Fig. 2(b) for 2 circuit configurations, where $C_\beta = (\beta_N - \beta_{N,NoWall})/(\beta_{N,IdealWall} - \beta_{N,NoWall})$. In a typical configuration for stabilizing the $n = 1$ RWM, the system is configured as 3 sets of 4 I-coils in series (quartets). For $n = 2$ stabilization, the system uses 6 sets of 2 I-coils (pairs). Clearly, as β_N approaches the ideal wall limit, i.e., C_β = 1, less system delay can be tolerated. Modeling also demonstrates that the use of derivative gain in the feedback circuit can increase the maximum tolerable delay [Fig. 2(b)].

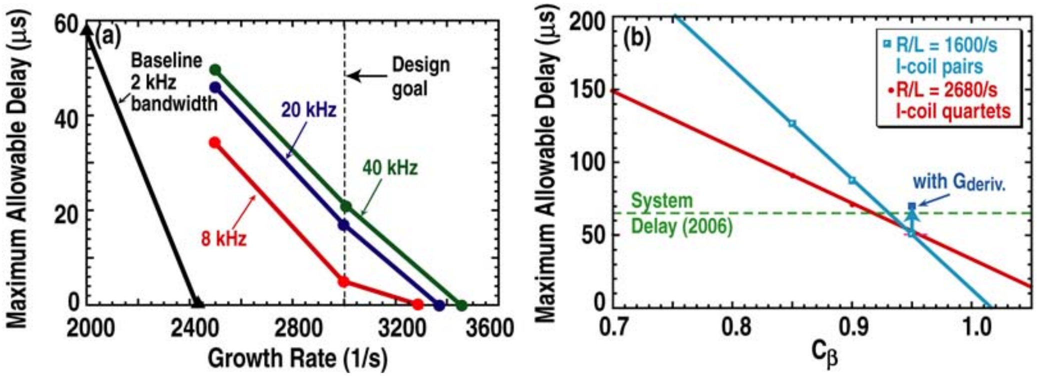

Fig. 2. VALEN-3D modeling of maximum allowable delay as a function of RWM growth rate (a), and C_β (b). Addition of derivative gain to the feedback circuit is shown for one case, allowing larger maximum delay. R/L represent typical values of resistance and inductance for the feedback power system. Upgraded system is shown as blue and red curves in (b).

Another design consideration is that the current available from the amplifiers must be sufficient to stabilize an RWM in the presence of ELMs and noise. ELMs in DIII-D produce low n magnetic field components that are detected by the magnetic sensors. This has been modeled using the VALEN-3D time-dependent code with noise and ELM inputs from a typical DIII-D discharge, plotted in Fig. 3. Shown in Fig. 3 is the measured $n=1$ perturbation of an RWM which begins at $t=0$ and is allowed to grow until feedback is applied at t = 1.1 ms. After an initial current of 320A, the RWM is stabilized and the system responds primarily to ELMs and noise. The coil current shown in Fig. 3(b) is for one of the I-coils, but the temporal response is typical of the entire 12 I-coil set. Based on this modeling, a design criteria for the maximum current was chosen, namely $I_{amplifier} > 2\ I_{rms}$, where I_{rms} is the maximum root mean square value of the coil current when ELMs and noise are modeled for anticipated RWM scenarios in DIII-D. We note that work in progress is aimed at reducing the “ELM noise” by techniques such as Kalman filtering [10].

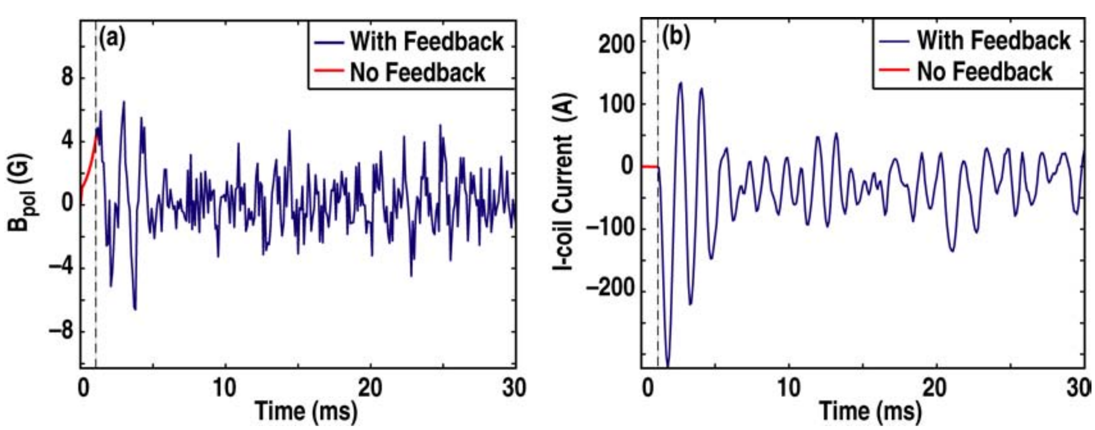

Fig. 3. Control current response calculated from the VALEN-3D code using typical DIII-D sensor inputs for noise and ELMs. B_{noise} ~ 1.5 G (rms), $R/L = 2700\ \mathrm{s}^{-1}$, system delay= 65 μs. An RWM initially grows until control system is enabled at 1.1 ms (vertical dashed line).

Based on the modeling discussed above the DIII-D RWM feedback system has recently been upgraded and consists of 12 high-speed transistor amplifiers (dc to 40 kHz) driving internal non-axisymmetric coils (I-coils). Amplifiers can be paralleled for higher current, e.g., in a quartet configuration each set is driven by four amplifiers and maximum current is 720A, exceeding the design criteria discussed above. In addition, the digital feedback system has been upgraded to provide higher processing speed (~90 kHz), and shorter system time delays (65 μs) which should allow RWM stabilization near the ideal wall limit [Fig. 2(b)].

A prototype system of the upgrade described above, consisting of 6 amplifiers and a system delay of 160 μs was used in 2005 to help stabilize discharges well above the no wall β limit, i.e., $\beta_N \sim 4$ for durations up to 1.5 s. A novel combination of I-coils, driven by these high speed amplifiers, and external coils (C-coils) driven by (SPAs) with slower time response provided dynamic error field correction, $n = 3$ braking, and fast RWM stabilization [4]. An example is shown in Fig. 4 and compared to a discharge without RWM I-coil stabilization that developed RWMs leading to lower confinement and lower β_N.

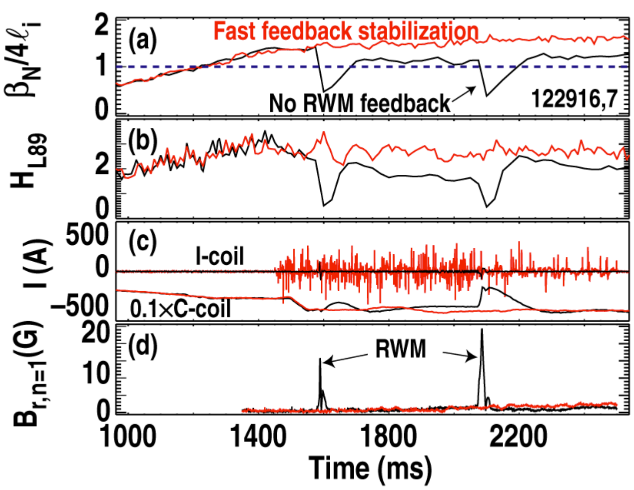

Fig. 4. Comparison of two discharges with (red) and without (black) RWM feedback using the prototype 6 amplifier system. Both discharges exceed the no wall limit, $\beta_N/4\ell_i \sim 1$ (a), and have similar confinement (b), until an RWM starts (d). Coil currents are shown in (c) where the dynamic stabilization is provided by a combination of fast response internal I-coils and slower external C-coils.

With the new amplifier system driving I-coils and balanced beam injection to provide low rotation targets, feedback stabilization of RWMs at high β_N, approaching the ideal wall β limit, and for long durations will be evaluated in ITER-relevant conditions of low plasma rotation in future experiments on DIII-D.

REFERENCES

[1] H. Reimerdes, et al., Nucl. Fusion **45**, 368 (2005).

[2] Y. Liu, et al., Nucl. Fusion **45**, 1131 (2005).

[3] G.L. Jackson, et al., Proc. 30th EPS Conf. on Controlled Fusion and Plasma Physics, St. Petersburg, Russia, 2003, CD-ROM P-4.47.

[4] M. Okabayashi, et al., Nucl. Fusion **45**, 1715 (2005).

[5] S.A. Sabbagh, et al., Nucl. Fusion **46**, 635 (2006).

[6] W. Zhu, S.A. Sabbagh, R.E. Bell, et al., Phys. Rev. Lett. **96**, 225002 (2006).

[7] E.J. Strait et al., Phys. Plasmas **11**, 2505 (2004).

[8] S. Driskill, et al., Bull. Am. Phys. Soc. **50**(8), 152 (2005).

[9] K.C. Shaing, et al., Phys. Fluids **29**, 521 (1986).

[10] Y. In, et al., “Model-based Dynamic Resistive-Wall-Mode (RWM) Identification and Feedback Control in the DIII-D Tokamak,” accepted for publication in Phys. Plasmas (2006).

ACKNOWLEDGMENT

Work supported by the U.S. Department of Energy under DE-FC02-04ER54698, DE-FG03-89ER53297, DE-FG03-99ER82791, and DE-AC02-76CH03073.