GA–A26664

ERROR FIELD CORRECTION IN UNSTABLE RESISTIVE WALL MODE (RWM) REGIME

by
Y. IN, G.L. JACKSON, M. OKABAYASHI, M.S. CHU, J. HANSON, R.J. La HAYE, Y.Q. LIU, L. MARRELLI, P. MARTIN, P. PIOVESAN, L. PIRON, A. SOPPELSA and E.J. STRAIT

MAY 2010

GENERAL ATOMICS

DISCLAIMER

GA–A26664

ERROR FIELD CORRECTION IN UNSTABLE RESISTIVE WALL MODE (RWM) REGIME

by
Y. IN[1], G.L. JACKSON, M. OKABAYASHI[2], M.S. CHU, J. HANSON[3], R.J. La HAYE, Y.Q. LIU[4], L. MARRELLI[5], P. MARTIN[5], P. PIOVESAN[5], L. PIRON[5], A. SOPPELSA[5] and E.J. STRAIT

This is a preprint of a paper to be presented at the 23rd IAEA Fusion Energy Conference, October 11–16, 2010 in Daejon, Republic of Korea and to be published in Proceedings.

[1]FAR-TECH, Inc., San Diego, California
[2]Princeton Plasma Physics Laboratory, Princeton, New Jersey
[3]Columbia University, New York, New York
[4]Euratom/CCFE Fusion Association, Culham Science Centre, Abingdon, UK
[5]Consorzio RFX, Corso Stati Uniti 4, Padova, Italy

Work supported in part by
the U.S. Department of Energy
under DE-FG02-06ER84442, DE-FC02-04ER54698,
DE-AC02-09CH11466, and DE-FG02-89ER53297

GENERAL ATOMICS ATOMICS PROJECT 30200
MAY 2010

GENERAL ATOMICS

The simultaneous use of feedback control for error field correction (EFC) and stabilization of an unstable resistive wall mode (RWM) has been demonstrated in DIII-D. The RWMs that are otherwise unstable at integer edge safety factors during an inductive current ramp are used to clarify the specific roles of EFC and direct feedback (DF) [1]. Stabilization of the RWM is essential for creating and sustaining high performance fusion plasmas [2,3]. The simultaneous operation of DF with internal coils and dynamic (feedback-controlled) EFC with external coils enabled us not only to stabilize the unstable RWM but also to determine the necessary EFC in the presence of a feedback-stabilized RWM.

While the conventional EFC method addresses error fields in a pre-programmed manner, it is challenged when an unstable RWM becomes dominant, because a weakly stable or feedback-stabilized RWM becomes extremely sensitive to any small, uncorrected resonant error field. Since the DIII-D tokamak is uniquely equipped with the internal coils ("I-coils") for fast time response and the external feedback coils ("C-coils") for slower time response (due to penetration through the vessel wall) [4], independent magnetic feedback control in low and high frequency ranges allows the specific roles of EFC and DF in active RWM feedback control in *stable, marginal* and *unstable* RWM regimes.

The EFC waveform during the unstable RWM regime has been extracted using the simultaneous operation of dynamic EFC and DF. Figure 1 shows the experimental results of the simultaneous operation of the EFC and DF using the internal and external coils. While the time evolution of the edge safety factor q_{95} remains similar [Fig. 1(a)], in one case an RWM at $q_{95} \sim 3$ occurs near t = 590 ms, terminating the discharge (in black). In comparison, when the simultaneous operation of the dynamic EFC and DF is optimized (in red), the RWM at $q_{95} \sim 3$ has been feedback-stabilized. As a result, the necessary EFC waveform in the unstable RWM regime, which cannot be found without feedback, can now be determined based on the low frequency EFC as shown in the red trace in Fig. 1(d).

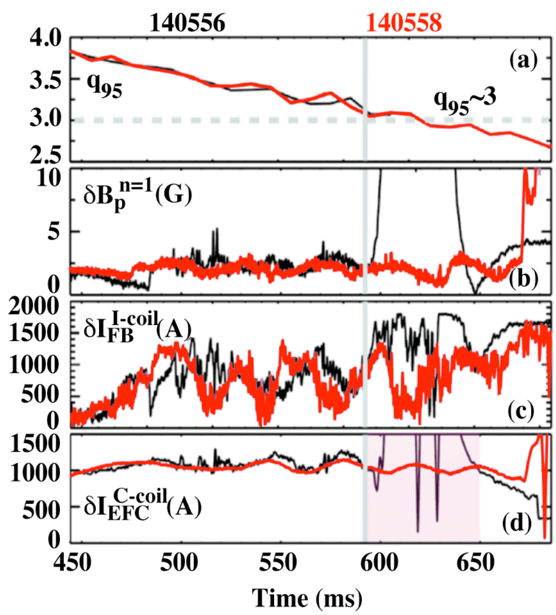

Fig. 1. Simultaneous operation of feedback-controlled EFC and DF on the unstable RWM at q_{95} ~3 with optimized gains (in red) and with lower gains (in black). Shown are the time traces of (a) edge safety factor q_{95}, (b) n=1 magnetic perturbations on poloidal field probes, (c) internal feedback coil currents, and (d) external EFC coil currents.

The gain dependence of the feedback-stabilized RWM is different from those of stable and marginal RWMs. In particular, when the EFC is not sufficient, the DF is reacting to the need to correct the residual EF, often leading to the saturation of the DF coil currents, followed by the loss of RWM control. Figure 2 shows the I-coil currents during a feedback gain scan with the pre-programmed (not feedback-controlled) C-coil EFC. The I-coil currents contribute to both DF and an additional EFC. It is clear from both experiment and modeling that stable RWMs (at $q_{95} \sim 5$ or 6) do not require high gains, while a marginal RWM (at $q_{95} \sim 4$) is insensitive to the feedback gains [1]. But, according to a prediction of a cylindrical model [5], the EFC in the unstable RWM regime requires high gain in order to approach the desired correction current [a normalized value of 1.0 in Fig. 2 (c)]. The relationship between EFC and DF is consistent with an on-going RWM feedback modeling using the MARS code [6]. A high frequency feedback control (DF), comparable to wall characteristic frequency τ_w^{-1}, is necessary for RWM stabilization and cannot be replaced by EFC, which varies in low frequency range much lower than τ_w^{-1} [1]. Here, τ_w is the wall characteristic time (2–5 ms in DIII-D).

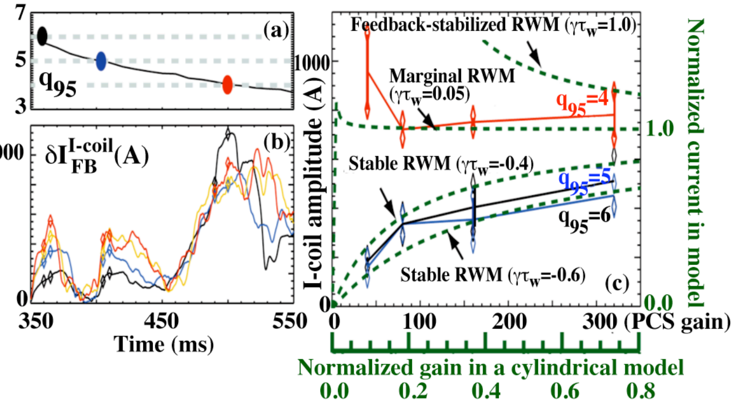

Fig. 2. Stable, marginal and feedback-stabilized RWMs. Left: time traces of (a) edge safety factor q_{95}, and (b) internal feedback coil ("I-coil") currents at various gains (G_p = 40, 80, 160 and 320 from the bottom respectively). In (c), the gain dependency of the I-coil currents varies subject to the RWM regimes, which is consistent with the predictions (dashed curves) of a cylindrical model [5].

The DF bandwidth requirement necessary for RWM feedback control is consistent with a theoretical prediction that the bandwidth should be greater than the natural (no feedback) growth rate τ_g^{-1} of the unstable mode [7]. Figure 3 shows the results of the system response time (τ_p) scan, while the C-coil EFC is pre-programmed (not feedback-controlled). The natural mode growth time τ_g is 3–4 ms, comparable to τ_w. When $\tau_p>\tau_g$ (in blue and green), the feedback system failed to suppress the mode. In contrast, when $\tau_p<\tau_g$, the RWM was stabilized (in black and red) [8]. The established methodology to determine the optimized EFC waveform with the simultaneous use of feedback control of EFC and DF is applicable for various operational scenarios with pressure beyond the no-wall ideal stability limit. In particular, it is a promising approach when the onset of unstable MHD is sensitive to the quality of EFC.

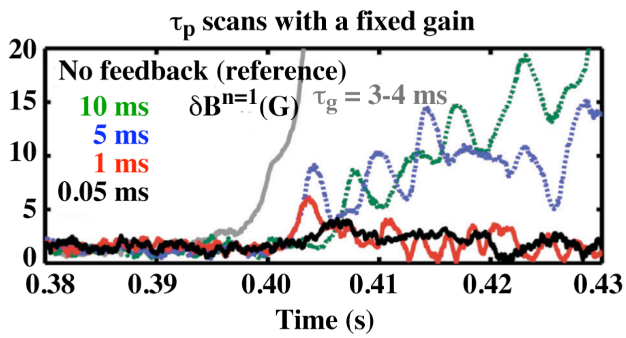

Fig. 3. Bandwidth dependency during the RWM feedback control at a fixed gain, $G_p \sim 320$.

This work was supported by the US Department of Energy under DE-FG02-06ER84442, DE-FC02-04ER54698, DE-AC02-09CH11466, and DE-FG02-89ER53297.

[1] Y. In *et al.,* Nucl. Fusion **50**, 042001 (2010)

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

[3] A.M. Garofalo *et al*., Phys. Plasmas **13**, 056110 (2006)

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

[5] M. Okabayashi, N. Pomphrey, R.E. Hatcher, Nucl. Fusion **38**, 1607 (1998)

[6] Y.Q. Liu *et al.*, Phys. Plasmas **13**, 056120 (2006)

[7] E.J. Strait *et al*., Nucl. Fusion **43**, 430 (2003)

[8] Y. In *et al.,* "Requirements for active resistive wall mode (RWM) feedback control," submitted to Plasma Phys. Control. Fusion (2010)