GA–A24355

INITIAL RESULTS FROM THE NEW INTERNAL MAGNETIC FIELD COILS FOR RESISTIVE WALL MODE STABILIZATION IN THE DIII-D TOKAMAK

by
G.L. JACKSON, P.M. ANDERSON, J. BIALEK, W.P. CARY, G.L. CAMPBELL, A.M. GAROFALO, R. HATCHER, A.G. KELLMAN, R.J. LA HAYE, A. NAGY, G.A. NAVRATIL, M. OKABAYASHI, C.J. PAWLEY, H. REIMERDES, J.T. SCOVILLE, E.J. STRAIT AND D.D. SZYMANSKI

JUNE 2003

DISCLAIMER

GA–A24355

INITIAL RESULTS FROM THE NEW INTERNAL MAGNETIC FIELD COILS FOR RESISTIVE WALL MODE STABILIZATION IN THE DIII-D TOKAMAK

by

G.L. JACKSON, P.M. ANDERSON, J. BIALEK*, W.P. CARY, G.L. CAMPBELL, A.M. GAROFALO*, R. HATCHER†, A.G. KELLMAN, R.J. LA HAYE, A. NAGY†, G.A. NAVRATIL*, M. OKABAYASHI†, C.J. PAWLEY, H. REIMERDES*, J.T. SCOVILLE, E.J. STRAIT AND D.D. SZYMANSKI

This is a preprint of a paper to be presented at the 30th European Physical Society Conference on Controlled Fusion and Plasma Physics, SSt. Petersburg, Russia, July 7-11, 2003 and to be published in the *Proceedings.*

*Columbia University, New York, New York, USA
†Princeton Plasma Physics Laboratory, Princeton, New Jersey.

Work supported by
the U.S. Department of Energy under
Contract Nos. DE-AC03-99ER54463, DE-AC02-76CH03073
and DE-FG02-89ER53297

GENERAL ATOMICS PROJECT 30033
JUNE 2003

Initial Results from the New Internal Magnetic Field Coils for Resistive Wall Mode Stabilization in the DIII-D Tokamak

G.L. Jackson[1], P.M. Anderson[1], J. Bialek[2], W.P. Cary[1], G.L. Campbell[1], A.M. Garofalo[2], R. Hatcher[3], A.G. Kellman[1], R.J. La Haye[1], A. Nagy[3], G.A. Navratil[2], M. Okabayashi[3], C.J. Pawley[1], H. Reimerdes[2], J.T. Scoville[1], E.J. Strait[1], and D.D. Szymanski[1]

[1]*General Atomics, P.O. Box 85608, San Diego, California, USA*
[2]*Columbia University, New York, New York, USA*
[3]*Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA*

1. Introduction

A set of 12 internal magnetic field coils (I-coils) has recently been installed and is being used in 2003 experiments. The purpose of this new coil set is to provide stabilization of resistive wall modes (RWM) for advanced tokamak plasmas with toroidal β above the no wall stability limit. Calculations with the 3D electromagnetic code VALEN [1] predict that the performance of this system should be superior to the previously installed external compensation coils (C-coils) by providing feedback stabilization up to the ideal wall beta limit without the need for strong plasma rotation, which was required in previous DIII-D experiments [2]. Initial results have shown that with feedback this I-coil set can stabilize the RWM well above the no wall limit and simultaneously reduce the resonant field amplification (RFA) process [3] allowing high toroidal rotation. With the I-coil fewer Amp-turns are required than with the existing external C-coil set. In this paper we will discuss these results, and other uses of the I-coils.

The new 12 I-coil set consists of six single-turn, water cooled coils equally spaced toroidally above the outer midplane and an identical set of six coils below the midplane, shown in Fig. 1. The area of each coil is 1.1 m^2 (total DIII-D vacuum vessel area is ~70 m^2). These "window frame" coils are positioned 1.47 cm inside the Inconel vacuum vessel wall but behind graphite armor tiles. Maximum rated coil current is 7 kA which corresponds to about 9 gauss at the q=3 surface for an m/n=3/1 helical configuration. These coils can be connected in a variety of combinations, allowing for optimization of feedback control of n=1 or 2 RWM modes of variable m number. The low m spectra of various n=1 connections is shown in Fig. 2 and compared to the m spectra produced by the C-coil. For the experiments described here, the 240 deg connection was used, maximizing the m/n=3/1 component. Extensive sets of poloidal field (20 internal) and radial field (30 external, 18 internal) sensors are available for optimizing mode detection and for control algorithms,although not all sensors are used simultaneously.

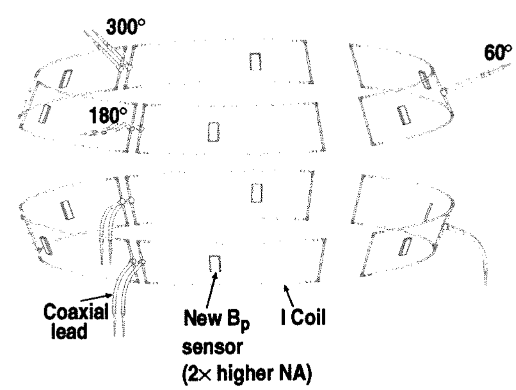

Fig. 1. Drawing of 12 I-coils and their associated poloidal field sensors. The water cooled coils are positioned 1.47 cm inside the DIII-D vacuum vessel wall above and below the midplane.

Switching power amplifiers (SPAs) are connected to the I-coils and are routinely operated from dc to 2 kHz at currents up to 4.5 kA (the full 7 kA I-coil capability has not yet been used). The upgrade to a faster CPU in the digital plasma control system has provided faster recognition of the mode onset.

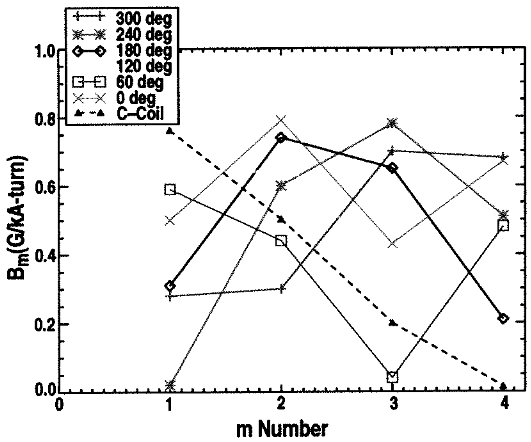

Fig. 2. Low m spectrum of the I-coils in various electrical configurations, compared to the C-coil spectrum. I-coils are inter-connected in six n=1 toroidal pairs at an external patch panel. The connections between the upper and lower sets allow different phasings, shown in the inset.

2. Results

Before feedback stabilization of RWMs was attempted, a characterization of the I-coil system was done. Part of this characterization was to demonstrate the use of I-coil feedback to reduce the plasma response from an externally applied error field. In this case, the external C-coil was used to apply an n=1 perturbation [Fig. 3(b)] and the feedback controlled I-coils were used to null the plasma response [Fig. 3(a)]. Input to the feedback system came from the midplane B_p sensors, which have no direct coupling to the radial field of the C-coil. The sign of the feedback was changed on successive discharges, demonstrating that negative feedback could reduce the plasma response to an external perturbation while positive feedback increased it, compared to the reference (no feedback) case. The three discharges shown in Fig. 3 had similar parameters and were at approximately the no wall beta limit [3].

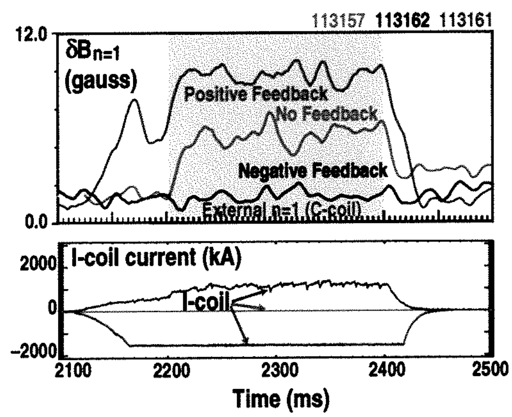

Fig. 3. Plasma response (a) to an externally applied n=1 with positive (red) or negative (blue) feedback. A reference (no feedback) discharge is shown in green. Feedback is enabled at 2125 ms, before the external n=1 perturbation beginning at 2200 ms. I-coil current is shown in (b).

After the feedback system was commissioned, active feedback stabilization of resistivewall modes above the no wall limit was investigated. In the example shown in Fig. 4, I-coil feedback is initiated at 1.3 s, before the expected onset of an RWM. The feedback was turned off for two 10 ms intervals [Fig. 4(b)]. In the first interval, a small radial field perturbation was observed, but did not grow and was again stabilized when feedback was turned back on [Fig. 4(d)]. In the second off time at 1.45 s, there was a fast growing RWM (γ^{-1}~3.3 ms) that could not be stabilized when feedback was re-enabled. Both β_N and toroidal rotation decreased [Fig. 4(a,e)], there was a transition back to L-mode [Fig. 4(c)], and the discharge subsequently disrupted.

The I-coil system has also been used for n=1 error field compensation. DIII-D static error fields, due to small mis-alignments of magnetic field coils and their current feed points, can exert drag on the plasma rotation which produces locked modes and limits plasma performance and stability [4]. These error fields were previously compensated using the external C-coil set. In recent experiments (Fig. 5), I-coil n=1 error field compensation was as effective as the C-coil in stabilizing RWMs and allowing sustained operation above the no wall stability limit. In this case, n=1 error field compensation allows high sustained toroidal rotation which, in turn, stabilizes the RWM. In Fig. 5, three similar discharges are shown: I-coil, C-coil and C-coil turned off at 1500 ms [Fig. 5(d)]. In the latter discharge, both β_N and rotation [Fig. 5(a,c)] collapse when the error field compensation is removed. The total radial field required, and the average coil current, [Fig. 5(d,e)] are similar with I-coil error field compensation, when compared to the external C-coil. The similar currents in the C-coil and I-coil in Fig. 5 are probably a coincidence. The 1 turn I-coil set consists of 12 coils, while the six C-coils each have 4 turns, but are located further from the plasma. However, we note that both sets require approximately the same m=3 radial field (at $\rho = 0.75$) for RWM stabilization above the no wall limit with high sustained toroidal rotation.

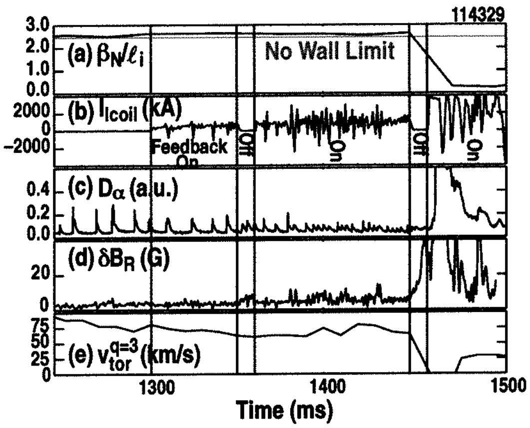

Fig. 4. RWM feedback stabilization above the no wall limit (a) Feedback is turned off for two 10 ms intervals (b) During the 2nd interval, an RWM instability occurs (d) toroidal velocity decreases, (e) and the discharge returns to L-mode (c).

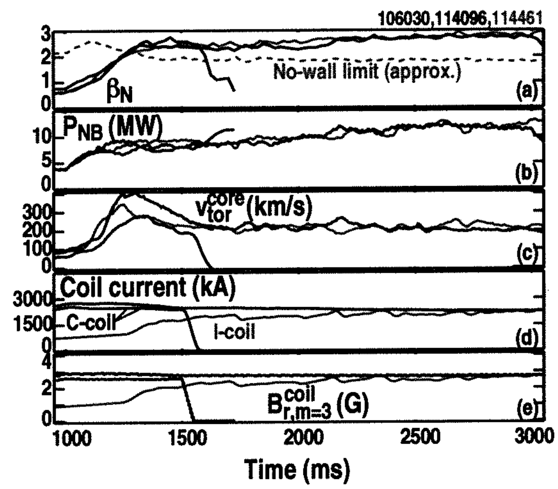

Fig. 5. n=1 error field correction with I-coils (red) is as effective as C-coils (black and blue) for stabilizing the RWM above the no wall limit (a) In one discharge (black), the error field correction is turned off at 1500 ms, producing a rapid drop in rotation (c) and an increase in neutral beam feedback controlled power (b). Also shown is the m=3 radial error field (e) produced by the correcting coil currents (d) I-Coil or C-coil current is averaged over the entire set.

3. Discussion

The new I-coil set has been successfully installed and the first experiments have been completed. I-coil feedback using the DIII-D PCS has nulled out the RFA response to an externally applied n=1 perturbation. Feedback stabilization has also been demonstrated for operation above the no wall stability limit with performance as good as previous results using the external C-coil set. Static n=1 error field correction has also been achieved with the new

I-coil set. The required m/n=3/1 radial field for RWM stabilization with high toroidal rotation [Fig. 5(e)] is similar for both C-coils and I-coils. However the C-coil produces a considerably higher m/n=1/1 component under these conditions (Fig. 2). Since RWM stabilization has been successfully achieved in both cases, this suggests that the I-coils may be better matched to the plasmas discussed here, which have no q=1 surface. The relationship between static error field correction and feedback for RWM stabilization has been discussed previously [5]. Both will be investigated in future I-coil experiments operating near the ideal wall stability limit.

Other experiments have also been done using the new I-coil set. "MHD" spectroscopy has been used to probe the plasma response to low frequency magnetic fields, 1-60 Hz [6]. Rotating fields, analogous to a three phase ac motor, have been applied from 0.1 to 2 kHz to probe the effects of viscous coupling at the m/n=3/1 surfaces. Also, perturbations have been applied with the I-coils in an n=3 configuration to produce a stochastic field at the plasma edge. The latter two experiments are still being evaluated.

An important goal of the DIII-D RWM program is to achieve long duration discharges with low rotation above the no wall limit. This scenario may be important for burning plasma devices where rotational stabilization of the RWM may not be possible. Since the I-coils can provide both error field correction and RWM feedback stabilization, the external C-coil set can now be used to independently apply an n=3 field for magnetic braking to provide a low rotation target. Such experiments are in progress and n=3 braking has reduced edge toroidal rotation by nearly a factor of two.

In the first four months of operation the DIII-D internal I-coil set has proven to be a versatile new tool for a variety of experiments. Future work will focus upon evaluating RWM stabilization with low rotation above the no wall limit, extending performance to near the ideal wall limit in advanced tokamak plasma scenarios, and directly comparing operation of the I-coil and C-coil sets.

Work supported by U.S. Department of Energy under Contract Nos. DE-AC03-99ER54463, DE-FG02-89ER53297, and DE-AC02-76CH03073.

[1] J. Bialek, A.H. Boozer, M.E. Mauel, G.A. Navratil, Phys. Plasmas **8**, 2170 (2001).
[2] A.M. Garofalo, T.H. Jensen, L.C. Johnson, et al., Phys. Plasmas **9**, 1997 (2002).
[3] A.H. Boozer, Phys. Rev. Lett. **86** 1176(2001).
[4] J.T. Scoville, R.J. LaHaye, A.G. Kellman, et. al, Nucl. Fus. **31**, 875(1991).
[5] M. Okabayashi, J. Bialek, M.S. Chance, et al., Plamsa Physics and Controlled Fusion **44** (2002) B339.
[6] H. Reimerdes, "Resistive Wall Modes and Plasma Rotation in DIII-D," this conference.