GA–A22033
CONF-9506282--2

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This is a preprint of a paper presented at the 22nd European Conference on Controlled Fusion and Plasma Physics, June 3–7, 1995, in Bournemouth, United Kingdom, and to be published in the *PROCEEDINGS*

Work supported by
U.S. Department of Energy
under Contract No. DE-AC03-89ER51114

GA PROJECT 3466
MAY 1995

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USE OF AN m=2, n=1 STATIC ERROR FIELD CORRECTION COIL, "THE C-COIL," ON DIII–D TO AVOID DISRUPTIVE LOCKED MODES*

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Minimizing resonant, static $n = 1$ error field with a phase steerable correction coil "the C-coil," in DIII–D allows avoidance of disruptive locked modes. Alternately, increasing $n = 1$ error field in rapidly rotating plasmas can induce magnetic braking of rotation without locking for the study of the role of rotation on stability.

Small toroidally asymmetric $m = 2$, $n = 1$ static field errors are of concern for the design of next-generation devices and for the operation of existing tokamaks. In low density ohmic plasmas for example, the torque of a small resonant error at the $q = 2$ surface can overcome the plasma inertial and/or viscous forces, stop the rotation and produce a large island which can cause disruption [1].

A toroidal torque arises at the $q = m/n$ rational surface of minor radius r_s due to an externally imposed resonant radial helical field $B_{s,vac}$

$$T_\phi \approx -\left(\frac{n}{m}\right) 4\pi^2 \frac{R_0 m^2}{\mu_0} \left(\frac{2\,m}{|\Delta_o' r_s|}\right) \frac{\omega_0' \tau_{rec}}{1+(\omega_0' \tau_{rec})^2} \left(\frac{r_s\, B_{s,vac}}{m}\right)^2 \quad , \tag{1}$$

where ω_0' is the slip frequency between the plasma and the static perturbation, τ_{rec} is the reconnection time and $|\Delta_o'|$ is the tearing stability parameter [2,3]. The helical magnetic field from the induced helical current which opposes reconnection and produces the torque T_ϕ can greatly reduce the island width such that

$$W_s = \left(\frac{16\, r_s\, R_0\, B_{s,vac}}{n\, S_s\, B_T}\right)^{1/2} \left(\frac{2\,m}{-\Delta_0' \, r_s}\right)^{1/2} \left[\frac{1}{1+(\omega_0' \, \tau_{rec})^2}\right]^{1/4} \quad , \tag{2}$$

where the first parenthesis is the vacuum island width, the second parenthesis is the enhancement (for small $\Delta_0\, r_s$) for locking, i.e., $\omega_0' \equiv 0$, and the bracket is the usually very large reduction due to the skin effect at the rational surface for $\omega_0'\, \tau_{rec} \gg 1$.

Mode locking or penetration occurs when the static error field torque overcomes the plasma inertial $(n_i M_i\, \omega_0^2\, R_0^2)$ and viscous torques $(n_i M_i\, \nu_\perp\, \omega_0 / L_r^2)$ where n_i is the ion density, $\nu_\perp$ is the viscosity and L_r is the radial scale length of the velocity gradient at $q = m/n$. In low density ohmic plasmas a critical condition (neglecting viscosity) for mode locking for the most dangerous $m, n = 2{,}1$ mode is predicted to occur either as the line-averaged density is lowered or the error field is raised [1,4,5].

$$\bar{n} \sim \left(\frac{B_T}{\omega_0}\right)^2 \left(\frac{S_s}{-\Delta_0' \, r_s}\right)^{1/2} \left(\frac{B_s}{B_T}\right)^{3/2} \quad . \tag{3}$$

Note that the unperturbed rotation ω_0 and the tearing stability parameter $\Delta_0' \, r_s$ may be explicit functions of $\bar{n}$ which along with viscosity may alter this scaling, particularly in larger tokamaks [4].

* Work was supported by the U.S. Department of Energy under Contract No. DE-AC03-89ER51114.

Provided that $\omega_0' \tau_{rec}$ remains large, the application of resonant error fields can be used to apply drag at selected rational surfaces to slow the rotation without significant islands or locking ("magnetic braking") to study the role of rotation shear on turbulence in VH–mode [6] or the role of resistive wall stabilization of high beta discharges [7].

C-COIL FOR $m = 2$, $n = 1$ ERROR FIELD MINIMIZATION

The new C-Coil shown in Fig. 1 on DIII–D has six sections that span the outboard midplane which with proper currents produce a nearly monochromatic $n = 1$ correcting field with both $m = 1$ and $m = 2$ components. The total $m = 2$, $n = 1$ error field to be minimized comes from the toroidal field coil (B-coil), induction coil (E-coil) and poloidal field coil (F-coil) $n = 1$ toroidal asymmetries. Ohmic double-null divertor discharges at $I_p = 1.6$ MA and either $B_T = -2.1$ T ($q_{95} = 4.6$) or -1.5 T ($q_{95} = 3.3$) were run in which the density $\bar{n}$ was allowed to drop until a locked mode, i.e., penetration of the 2,1 error field, abruptly occurred (Fig. 2). By varying the shot-to-shot amplitude and phase of the C-coil applied 2,1 error field, a database was acquired of critical density $\bar{n}$ for locked modes as a function of the 2,1 Fourier component of the C-coil and the B, F, and E currents. A nonlinear multivariate fit was made to empirically determine the 2,1 sine and cosine components of the intrinsic error field sources assuming $\bar{n}_{LM} \sim B_s^{\alpha}$ such that

$$\bar{n}_{LM} = conJ\left[(S_c + S_B + S_F + S_E)^2 + (C_c + C_B + C_F + C_E)^2\right]^{\alpha/2} \quad , \tag{4}$$

with S_c and C_c the sine and cosine components of B_s from the C-coil, where B_s is the $m = 2$, $n = 1$ helical error field, the constant $conJ = con1$ for -2.1 T ($q_{95} = 4.6$) and $con2$ for -1.5 T ($q_{95} = 3.3$) to account for the change with B_T in the relative error field, the unperturbed rotation, the tearing stability parameter, etc. A fit to $\bar{n}_{LM} \sim B_s^{\alpha}$ with $\alpha = 3/2$ was poor while $\alpha = 1/2$ gave an excellent fit with $\bar{n}_{LM} \sim (q_{95})^{-1/2}\ (B_s/B_T)^{1/2}$. The major sources of error field were the B and F coils with the E-coil error much smaller. A plot of $\bar{n}_{LM}$ versus C-coil $n = 1$ phase for near optimum C-coil $n = 1$ amplitude

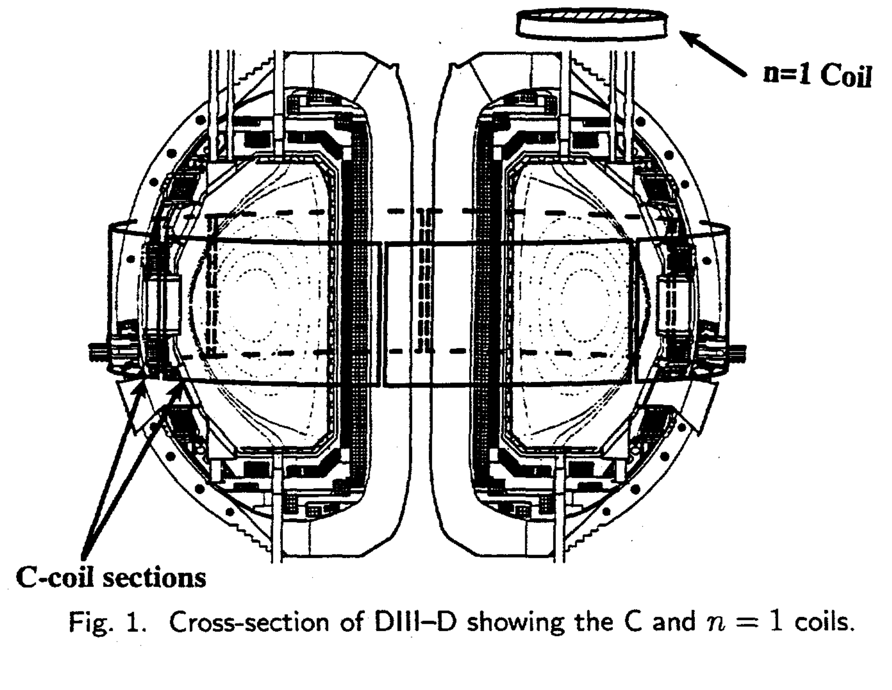

Fig. 1. Cross-section of DIII–D showing the C and $n = 1$ coils.

is shown in Fig. 3(a) while that versus C-coil amplitude is shown in Fig. 3(b). The coefficients determined from the best fit to Eq. (4) are used in real time DIII–D plasma to vary the C-coil currents for optimum correction.

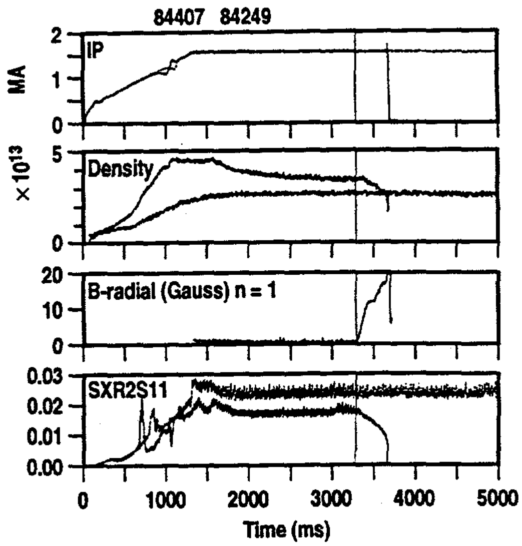

Fig. 2. Traces of discharges without (#84407, solid) and with (#84249, dashed) C-coil correction. Plasma current, line-averaged density, $n = 1$ locked mode amplitude, near central soft x-ray chord. No. 84407 has a locked mode beginning at 3280 ms and disrupts.

PLASMA ROTATION CONTROL WITH THE C-COIL

A. Magnetic Braking With Different Spectra

The C-coil allows a number of new possibilities in applying magnetic braking to the VH-mode. In conjunction with the fixed phase $n = 1$ coil [8], the C-coil $n = 1$ phase variation allows applying a nearly monochromatic 1,1 drag at $q = 1$ or a nearly monochromatic 2,1 drag at $q = 2$ or a combination. Best fits in the ELM-free VH–mode are shown in Fig. 4 for no braking, the $n = 1$ coil alone (mix of 1,1 and 2,1 modes) and the same $n = 1$ coil current as the mix but with the C-coil added either to the null the applied 1,1 field (2,1 braking) or the 2,1 field (1,1 braking). There is little difference in the rotation profiles between the mode mix and the 2,1 mode braking (with same 2,1 amplitude) while the monochromatic 1,1 mode has much less drag on the rotation in part as a result of the small $q = 1$ surface area, confirming that delta function drag can be applied at selected surfaces for tailoring the rotation profile.

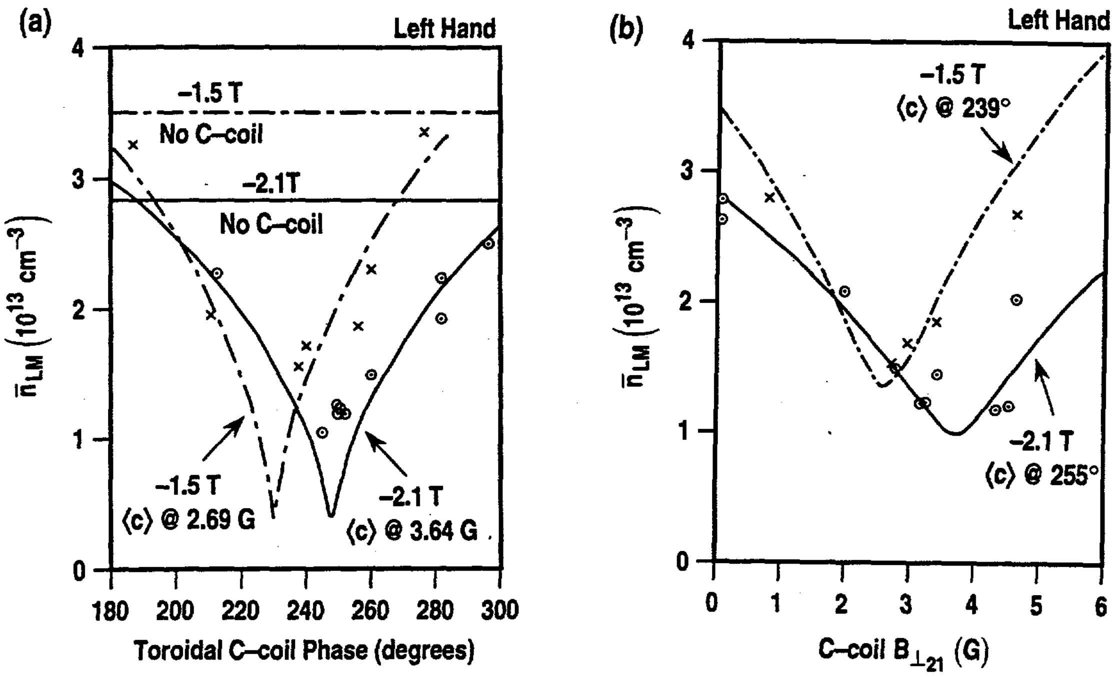

Fig. 3. (a) Critical density for locking versus C-coil phase for −1.5 T (x) and −2.1 T (⊙) at near optimum amplitude. (b) Same versus amplitude for off optimum phase.

B. Magnetic Braking to Study Resistive Wall Stabilization of High Beta Resistive Modes

The low inductance of the C-coil allows rapid turn on (and off) of the full current in time as short as 20 ms for impulsive magnetic braking of transient high beta ($\beta_N > 3$) discharges [7] which have $q > 1$ everywhere. It is found that although the central rotation in these discharges remains high, the rotation at $2 < q < 3$ is greatly reduced by the localized drag. (See Fig. 5.) When the rotation frequency near the $q = 2$ and 3 surfaces is reduced below approximately 1 kHz, an unstable resistive wall mode is observed to grow and limit beta. Maintaining the plasma rotation at high beta is predicted to provide stability with a resistive wall and dissipation [9,10].

[1] La Haye R.J. et al., *Phys. Fluids B* **4** 2098 (1992)
[2] Fitzpatrick R. *Nucl. Fusion* **33** 1049 (1993)
[3] Jensen, T.H. et al., *Phys. Fluids B* **5** 1239 (1993)
[4] Fitzpatrick R. and T.C. Hender *Phys. Fluids B* **3** 644 (1991)
[5] Fishpool G.M. and P.S. Haynes *Nucl. Fusion* **34** 109 (1994)
[6] La Haye R.J. et al., "Core Flow Shear as the Cause of Very High Confinement in the DIII–D Tokamak," to be published in Nucl. Fusion
[7] Taylor T.S. et al., "Wall Stabilization of High Beta Plasmas in DIII–D," to be published in Phys. Plasmas.
[8] Scoville J.T. et al., *Nucl. Fusion* **31** 879 (1991)
[9] Bondeson A. and D.J. Ward *Phys. Rev. Lett.* **72** 2709 (1993)
[10] Chu M.S. et al. *Phys. Plasmas* **1** 1214 (1994)

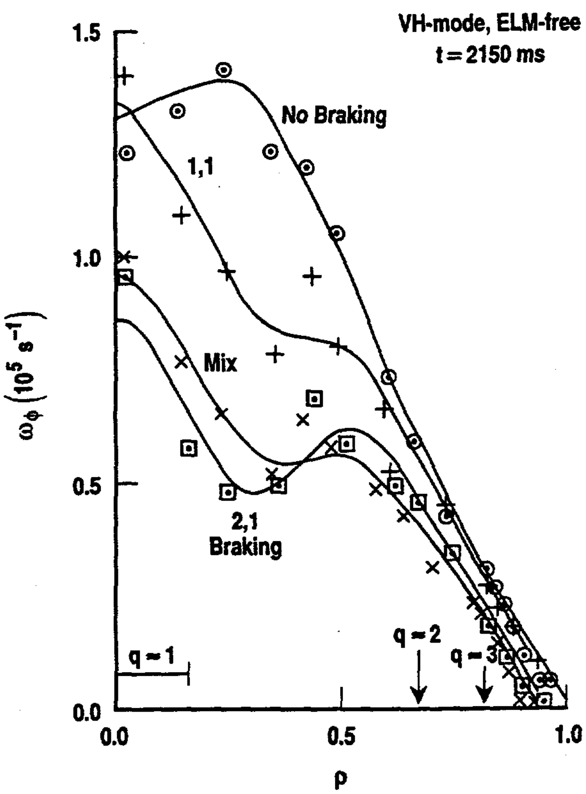

Fig. 4. Angular rotation profiles from CER during ELM-free VH–mode with either no braking or braking with a 1,1 mode, a 2,1 mode or a mix of modes.

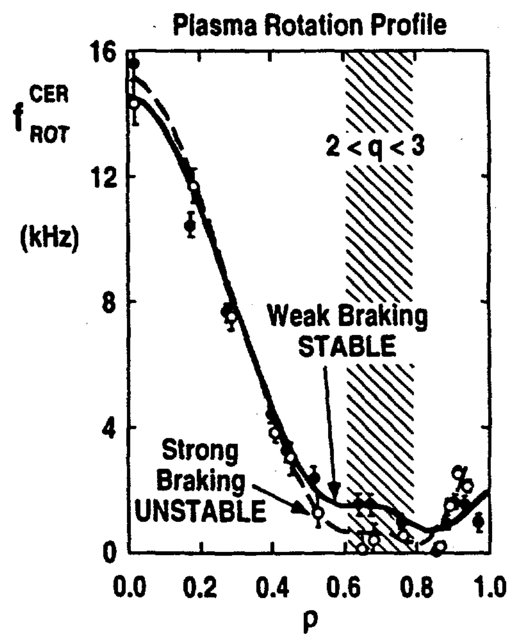

Fig. 5. Plasma rotation profiles of $\beta_N > 3$ discharges with either weak or strong C-coil braking.