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Tearing modes have been stabilized in the DIII-D tokamak at pressures approaching the no-wall MHD limit by electron cyclotron current drive (ECCD). Closed-loop feedback schemes have been used to optimize the stabilization. Comparison of ECCD aiding (co) or opposing (ctr) the plasma current or pure heating show clearly the co-ECCD is most effective for stabilization.

I. Introduction

Optimal operation of tokamak plasmas requires consideration of stability with respect to tearing modes, especially for self-heated or "burning" plasmas in tokamaks. This instability results in a reduction in energy confinement, which sets an effective pressure limit for the plasma. This limit can be substantially lower than the ideal MHD pressure limit. Since fusion power in deuterium-tritium plasmas scales roughly as the square of the pressure, this lower limit significantly reduces the fusion output. The modes are aligned with the local magnetic field and longest wavelength modes, characterized by the toroidal mode number n and poloidal mode number m, yield the most detrimental effects. The m=2/n=1 tearing mode, in addition to reducing strongly the energy confinement, can lock to the wall while continuing to grow. The mode locking can lead to a complete disruption of the plasma current. For a tokamak burning plasma experiment, such disruptions represent a significant risk to the device, due to the large amount of energy stored in both the poloidal magnetic field and the plasma thermal energy.

Two roles can be envisioned for a system for stabilizing or suppressing tearing modes. First, it would represent the first line of defense against disruptions due to tearing modes. Once an m=2/n=1 mode appears, the system would be activated to reduce or stabilize the mode before it locks. Second, a system which suppressed tearing modes could lead to better tokamak fusion performance. Clearly in this role, such a system must be highly efficient and reliable.

At zero pressure, tearing modes are driven by the free energy in the poloidal magnetic field [1,2]. The mode manifests itself as helical deficits in current on magnetic surfaces with rational values of safety factor q (the change in toroidal flux with respect to poloidal flux). Poloidal projections of the magnetic field structure show "islands" in this case. At finite pressure gradient, the plasma has a pressure driven current ("bootstrap" current [3]). The islands are usually assumed to have no pressure gradient inside; therefore, the island would have an additional current deficit due to the absence of bootstrap current within the island. The stability of the zero-pressure version of the tearing mode is characterized by a parameter Δ' which represents the change in free energy in the case of a tearing mode perturbation. When $\Delta' > 0$, the mode is unstable. With the additional free energy from the pressure gradient, the possibility of solutions which are linearly stable ($\Delta' > 0$) but nonlinearly unstable exists. In the presence of a "seed" island of sufficient size, a mode can grow to a finite saturated state. This type of instability has been termed a "neoclassical" tearing mode [4].

The fact that the mode is characterized by a helical deficit of current suggests a potential means for stabilization. If this "missing" current could be replaced, the magnetic surfaces should return to their unperturbed state [5,6]. In addition, if the magnetic free energy term could be made sufficiently negative the mode should also be suppressed [7-9]. Electron cyclotron current drive (ECCD) is a prime candidate for both methods due to the potential for efficient, localized current drive at variable locations.

Stabilization of m=3/n=2 modes by ECCD has been demonstrated in several tokamaks [10-12]. The more deleterious m=2/n=1 mode has also been successfully stabilized by ECCD [13,14]. The results reported here focus on stabilization of the m=2/n=1 mode, extending the previous work. The mode has been stabilized at higher normalized pressure $\beta_N = 100\ (\langle p \rangle / 2\ \mu_0 B^2)/(I/aB)$ where $\langle p \rangle$ is the volume-averaged pressure (pascal), B is the vacuum toroidal magnetic field at the geometric center of the plasma (T), I is the plasma current (MA), and a is the plasma minor radius (m). For efficient stabilization, a new closed-loop feedback scheme has been successfully implemented. For the first time, successive discharges have been used to investigate the relative effects of heating vs. current drive and current drive aiding (co-ECCD) and opposing (ctr-ECCD) the total plasma current.

II. Stabilization at Higher Pressure

Previous reports from the DIII-D tokamak showed effective stabilization of the m=2/n=1 tearing mode at $\beta_N = 2.1$ [13]. While this β_N is higher than anticipated for a tokamak burning plasma experiment [15], operation at higher β_N would lead to higher fusion power. The operational scenario employed in these DIII-D experiments used feedback control of β_N in order to induce the m=2/n=1 tearing mode reproducibly. After the mode was made, β_N was reduced to a lower level. This is a somewhat realistic scenario for a burning plasma since the confinement (and therefore the self-heating) would be reduced following the mode onset. A typical case is shown in Fig. 1. The main heating of the plasma is through neutral beam injection (NBI). The NBI power is feedback controlled [Fig. 1(a)] to maintain constant diamagnetic flux (related to pressure). The m=2/n=1 tearing mode appears at 2500 ms as indicated by the growing amplitude of the n=1 magnetic fluctuations [Fig. 1(c)]. At 3500 ms, the requested value of β_N is lowered to $\beta_N = 2.3$ [Fig. 1(b)]. The toroidal field is also lowered [Fig. 1(d)] to give a reasonable initial condition for the closed-loop feedback system used to optimize the suppression (discussed in the next section). At 4500 ms, the EC power is applied [Fig. 1(a)] and the mode amplitude begins to decrease immediately [Fig. 1(c)]. At 5200 ms, the mode is completely stabilized and does not reappear, even in the presence of sawteeth. The EC power is applied near a normalized radius ρ = 0.65. (The normalized radius ρ is $(\Phi/2\pi B)^{1/2}$, where Φ is the toroidal flux within the magnetic surface, normalized to the value at the last closed flux surface.) Note that the drop in the required NBI power is close to the applied EC power. This means that the confinement reduction due to the tearing mode is roughly the same as the reduction in the confinement of the EC power due to the off-axis deposition. For DIII-D parameters, this indicates that this scheme does not improve performance. However, it is not clear that the full power for stabilization is required continuously to avoid recurrence of the mode. Experiments to test this are planned. Also, it should be recalled that disruption avoidance is perhaps the more important role for this system. In Fig. 1, the mode amplitude is still growing until the application of the EC power. In other similar cases where EC power is not applied, the mode locks and disrupts the plasma. ECCD stabilization of the m=2/n=1 power has been obtained at β_N up to 2.8 which is ~90% of the no-wall ideal MHD n=1 pressure limit. [See Fig. 2(a) for an example.]

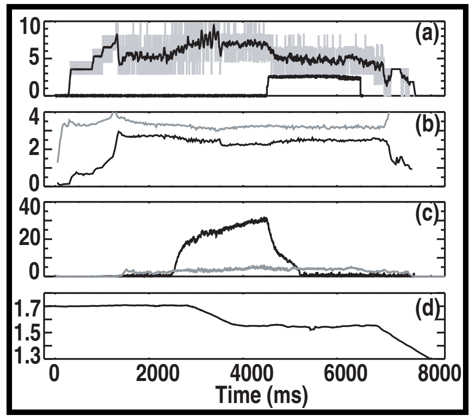

Fig. 1. Plasma parameters vs. time (ms) for a case of full suppression of an m=2/n=1 tearing mode. (a) NBI power (MW) (gray), time-averaged NBI power (MW) (black), EC power (a.u.) (lower black trace). (b) Internal inductance (ℓ_i) x4 (gray), β_N (%•mT/MA) (black). The no-wall n=1 ideal MHD limit is given approximately by $4\ell_i$. (c) n=1 magnetic fluctuation amplitude (G) (black), n=2 magnetic fluctuation amplitude (G) (gray). Both signals are obtained from measurements at the vacuum vessel. (d) Magnitude of the toroidal magnetic field (T).

III. Feedback Optimization of Stabilization

Stabilization of tearing modes by ECCD has been shown to be very sensitive to the deposition location [12,13]. The optimal location is to drive current directly at the island location. Mismatch of the deposition location from the island on the order of 1-2 cm leads to significant increases in power to reduce the mode amplitude by a similar amount. This motivates development of closed-loop feedback schemes to minimize the power required to stabilize the mode. Previous experiments successfully demonstrated a “search and suppress” scheme which would take discrete steps in the deposition location by changing the plasma location horizontally (moving the island) or changing the toroidal magnetic field (moving predominantly the deposition). The response was measured through the magnetic fluctuations, and the scheme chose to step in either direction or dwell based on

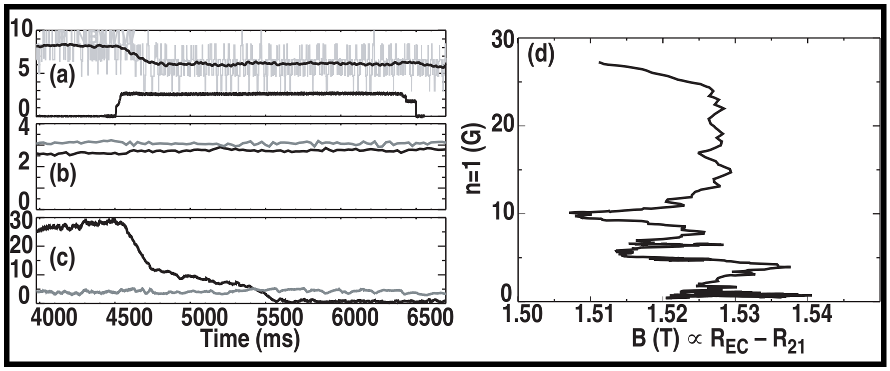

Fig. 2. (a) Applied power vs. time (ms). NBI power (MW) (gray), time-averaged NBI power (MW) (black), EC power (a.u.) (lower black trace). (b) $4\ell_i$ (gray), β_N (black). (c) n=1 magnetic fluctuation amplitude (G) (black), n=2 magnetic fluctuation amplitude (G) (gray). (d) Trajectory of the time history of the n=1 mode amplitude plotted vs. the magnitude of B selected by the feedback algorithm.

the response. While effective, this scheme can be slow, because the time required to acquire sufficient response is relatively long. In the case of stabilization of m=2/n=1 modes, faster stabilization is desirable because of the risk of mode locking, leading to disruption. Furthermore, the power required to suppress these modes at higher β_N is near the maximum EC power presently available. Therefore, efficient use of this power is important.

A new algorithm, known as "target lock", has been successfully tested in DIII-D. This algorithm makes continuous, small variations in order to find the optimum position at all times. An example of suppression at high β_N is shown in Fig. 2. As in Fig. 1, β_N is controlled by variation of the NBI power [Fig. 2(a)]. The mode growth is arrested by the application of the EC power and after about 1 s the mode is completely suppressed. The variations of the toroidal magnetic field to optimize the suppression are shown in Fig. 2(d). The initial condition is a 27 G mode with B = 1.5 T. The feedback system finds a rapid reduction of the amplitude with B = 1.528 T (~3 cm) and makes small variations in each direction throughout the rapid reduction phase, trying to optimize the reduction. As the mode reduction slows (presumably because the mode width is approaching the ECCD deposition profile width), the feedback system first tries lower B, but eventually returns to the original optimum. Eventually, the system finds that higher B leads to complete stabilization although it has a significant trend back toward the original optimum. The system does not require a physical model to successfully stabilize the mode; however, modeling the trajectory may yield interesting insights on the stabilization physics.

IV. The Role of Heating and Current Drive in Stabilization

In order to see the relative effects of heating, co-ECCD and ctr-ECCD, the EC power was applied to an existing m=2/n=1 tearing mode during a slow B ramp down. With 3 gyrotrons (~1.7 MW), significant modification of the mode amplitude is seen in each case (Fig. 3). The field ramp moves the deposition from small minor radius to larger with time. For the case of co-ECCD, a significant effect is seen even with the deposition location far from the island. As the deposition location moves toward the island location, the mode amplitude is reduced. After the island has been passed, the mode amplitude increases. In the case of pure heating, the same effect is seen; however, it is smaller and occurs over a narrower range than in the case of co-ECCD. For ctr-ECCD, the mode amplitude is increased as the current drive layer is moved closer to the island, then reduced. This effect is clearly opposite to that of co-ECCD. Current drive is clearly more effective at altering the mode amplitude than heating. Also, current in the direction to replace the "missing" current, as described in the introduction, is required to reduce the mode amplitude as expected. At five gyrotron level (~2.8 MW) ctr-ECCD leads toleads to growth and mode locking. In the case of heating, the amplitude reduction is more obvious but significantly less than the co-ECCD case, where the mode is suppressed even with varying B.

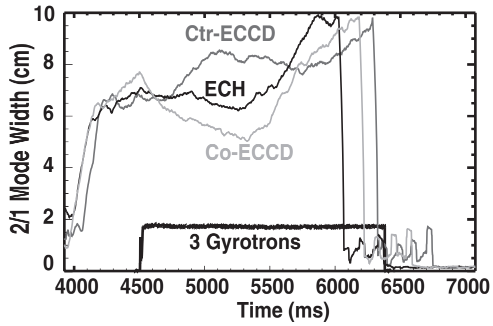

Fig. 3. n=1 mode width (cm) vs. time (ms) for three discharges with identical diamagnetic flux feedback and time-varying toroidal magnetic field. The only change is the variation of the EC aiming to give co-ECCD, EC heating only, or ctr-ECCD. The timing of the EC power (a.u.) is shown by the lower trace. The mode width is estimated by the square root of the ratio of the n=1 magnetic fluctuation amplitude to |B|. The normalization constant is obtained from comparison to mode width measured by electron cyclotron emission at one time in the discharge with ctr-ECCD.

Modeling of these dischargs has not yet been carried out, but should yield insight into the relative importance of modification of Δ' and driving current within the island. However, some basic observations can be made from the raw data. Since the pressure is feedback controlled, the average pressure gradient is roughly constant throughout the scan. The mode amplitude is large enough that the threshold effects, which strongly modify the mode behavior at small amplitude, should be negligible. Therefore, the poloidal magnetic field drive (Δ') and the current drive terms should be the only variations. The current drive effect is modeled to be symmetric on either side of the island. From Fig. 3, it appears that the location of maximum effect in the co-current and counter-current drive cases are offset in spatial location. In addition, there appears to be an asymmetry in the current drive effects in both cases as the deposition region moves across the island location. These observations may indicate that modification of Δ' (heretofore neglected in modeling) plays a significant role in the stabilization. It must be confirmed that the island location is similar in each case. It is also important to understand how the pure heating case influences the island. It may be possible that the pressure is not flat within the island, which would alter the modeling of the bootstrap current drive.

V. Conclusions

Recent experiments in the DIII-D tokamak have demonstrated stabilization of the m=2/n=1 tearing mode at high pressure (β_N up to 2.8, 90% of the no-wall ideal MHD n=1 limit). Closed-loop feedback control is essential to effectively stabilize these modes, and a second-generation algorithm to improve the stabilization has been successfully tested. While the existence of these schemes supports the possibility of implementing such a system in a burning plasma experiment such as ITER, change of B or plasma position by even small amounts is not feasible in that case. Real-time remote steering antennas with precise steering ability must be developed. The dominant role of current drive has been established in these DIII-D experiments. The data indicae the role of Δ' may need to be included in a complete model of the stabilization.

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References

[1] H.P. Furth, *et al.,* Phys. Fluids **6** (1963) 459.

[2] P.H. Rutherford, Phys. Fluids **16** (1973) 1903.

[3] R.J. Bickerton, *et al.,* Nature (London) Phys. Sci. **229** (1971) 110.

[4] R. Carrera, et al., Phys. Fluids **29** (1986) 899.

[5] C.C. Hegna, J.D. Callen, Phys. Plasmas **4** (1997) 2940.

[6] H. Zohm, Phys. Plasmas **4** (1997) 3433.

[7] E. Westerhof, Nucl. Fusion **27** (1987) 1929.

[8] E. Westerhof, Nucl. Fusion **30** (1990) 1143.

[9] A. Pletzer, F.W. Perkins, Phys. Plasmas **6** (1999) 1589.

[10] G. Gantenbein, *et al.,* Phys. Rev. Lett. **85** (2000) 1242.

[11] A. Isayama, *et al.,* Plasma Phys. Control. Fusion **42** (2001) L37.

[12] R.J. La Haye, *et al.,* Phys. Plasmas **9** (2002) 2051.

[13] C.C. Petty, *et al.,* Nucl. Fusion **44** (2004) 243.

[14] G. Gantenbein, *et al.,* Proc. 30th Euro. Conf. on Control. Fusion and Plasma Physics, Vol. 27A (European Physical Society, Geneva, 2003) P1.187.

[15] R. Aymar, *et al.,* Plasma Phys. Control. Fusion **44** (2002) 519.