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Suppression of Tearing Modes by Means of Localized Electron Cyclotron Current Drive in the DIII–D Tokamak

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The onset of tearing modes and the resulting negative effects on plasma performance set significant limits on the operational domain of tokamaks. Modes with toroidal mode number (n) larger than two cause only a minor reduction in energy confinement (<10%). Modes which have a dominant poloidal mode number (m) of three and n=2 lead to a significant reduction in confinement (<30%) at fixed power. The plasma pressure β (normalized to the magnetic field pressure) can be raised further, albeit with very small incremental confinement. Pushing to higher β often destabilizes the m=2/n=1 tearing mode which can lock to the wall and lead to a complete and rapid disruption of the plasma with potentially serious consequences for the tokamak. The β values at which these modes usually appear in conventional tokamak discharges are well below the limits calculated using ideal MHD theory. Therefore, the tearing modes can set effective upper limits on energy confinement and pressure.

Significant progress has been made in stabilizing these modes by local current generation using electron cyclotron waves. The tearing mode is essentially a deficit in current flowing helically, resonant with the spatial structure of the local magnetic field. This forms an "island" where the magnetic flux is no longer monotonic. It was predicted theoretically [1,2] that replacement of this "missing" current would return the plasma to the state prior to the instability. Experiments on the ASDEX-Upgrade [3], JT-60U [4], and DIII–D [5] tokamaks have demonstrated stabilization of m=3/n=2 modes using electron cyclotron current drive (ECCD) to replace the current in the island. Following these initial experiments, recent work on the DIII–D tokamak has demonstrated two significant advances in application of this technique – extending the operational domain stable to m=3/n=2 modes to higher β and the first suppression of the more dangerous m=2/n=1 mode.

RAISING β DURING ACTIVE STABILIZATION

The presence of an m=3/n=2 tearing mode sets limits on the achievable energy confinement and β, as discussed above. With active stabilization of the mode using ECCD, reliable operation at higher β and good confinement in present devices would add confidence in the ability of future devices designed with conventional limits to reach their performance goals. An initial step in this direction on DIII–D experiments is shown in Fig. 1. At normalized β [$\beta_N \equiv \beta/(I/aB)$] near 2.5, an m=3/n=2 mode is triggered. The neutral beam power is reduced to avoid triggering an m=2/n=1 mode. (A similar response would occur in a plasma dominated by self-heating.) The ECCD is initiated at 3.0 s and the mode is stabilized after ~0.3 s. As the mode is stabilized, the neutral beam power is increased, and after about 1.0 s the β_N rises above the value where mode was destabilized. The plasma remains at β_N~2.9 for ~0.5 s. The confinement quality as measured by the thermal confinement normalized to the ITER98y2 [6] scaling (H_{H98y2}) is > 1, even with 2.1 MW of EC power deposited at a normalized radius (ρ) of 0.56. Just before the EC and neutral beam power are stopped, a large sawtooth triggers a growing m=3/n=2 mode. The reason for the return of the mode is believed to be a growing mismatch between the ECCD location and the rational surface where the island forms, due to the increasing β and the evolution of the current profile. As discussed later, the power required for suppression is a much more sensitive function of the relative location of the ECCD and the island than it is of β. Closed-loop feedback on radial position or toroidal field has been successfully demonstrated [5] and is applied during this shot; however, in the absence of a mode, the feedback as implemented has no means of optimizing the ECCD location. Tracking the evolution of the rational surface with real-time equilibrium reconstruction or an empirical combination of measurements will be attempted in the next experimental campaign.

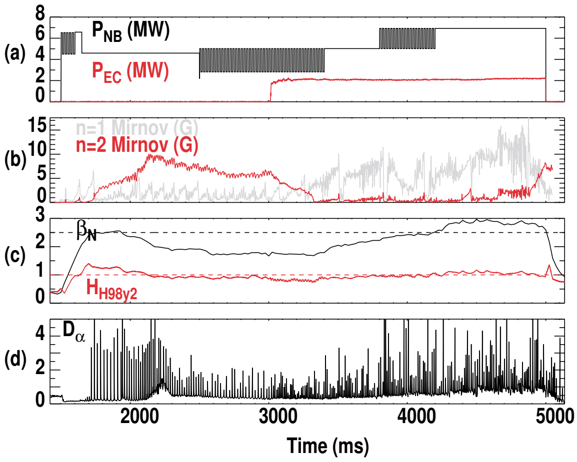

Fig. 1. Time histories of the (a) neutral beam and EC power, (b) n=1 and n=2 Mirnov amplitudes, (c) β_N *and* H_{H98y2} *and (d)* D_α *for a discharge with ECCD suppression of an m=3/n=2 tearing mode. The suppression is optimized by radial position feedback. After suppression,* β_N *rises higher than the level at which the mode was triggered and* H_{H98y2} *is ~1, even with 2.1 MW EC power at* $\rho \approx 0.56$*.*

STABILIZATION OF THE m=2/n=1 TEARING MODE

Control of the m=2/n=1 tearing mode may be a mandatory safety element of future high current tokamaks. Locking of the mode to the wall and subsequent growth routinely leads to a major disruption in the tokamak. Previous attempts to suppress the m=2/n=1 mode on DIII–D achieved partial suppression. Estimates indicated about 20% more EC current was needed to achieve complete suppression. Recent experiments in the DIII–D tokamak have demonstrated full suppression of this mode as shown in Fig. 2. As in the m=3/n=2 case, the neutral beam power is dropped to avoid driving the mode to very large amplitude. The closed-loop feedback varies the toroidal field to optimize the ECCD location until suppression occurs. In this case, the neutral beam power is controlled by feedback to keep the diamagnetic flux constant, so β does not rise when the mode is suppressed. No attempt to raise β was made. The mode in this case is located near ρ=0.66. The density was lowered to increase the drive current and the aiming of the separate microwave beams to the same radius was improved relative to the previous attempts. The drop in the requested β after the mode also appears to facilitate the suppression. If validated by further experiments, this application would demonstrate ECCD at the largest ρ to date.

PROJECTION OF PRESENT RESULTS TO FUTURE TOKAMAKS

The growth rate of a tearing mode at any instant of time is assumed to obey the modified Rutherford equation [1,2,7]. Some progress has been made in verifying the form taken to describe the influence of the ECCD. It is predicted that the minimum power required for suppression should occur when the ECCD is within the island. This has been verified experimentally by using a radially-resolved electron cyclotron emission measurement to detect simultaneously the temperature perturbation due to the island and the temperature perturbation due to amplitude modulation of the EC power [8]. Under conditions where the mode is suppressed with full power, the two temperature perturbations are aligned as predicted. Small deviations from good alignment lead to lack of suppression at fixed power [Fig. 3(a)]. The model predicts correspondingly higher powers needed for complete suppression [Fig. 3(b)]. This sensitivity to the relative location of the ECCD and the island

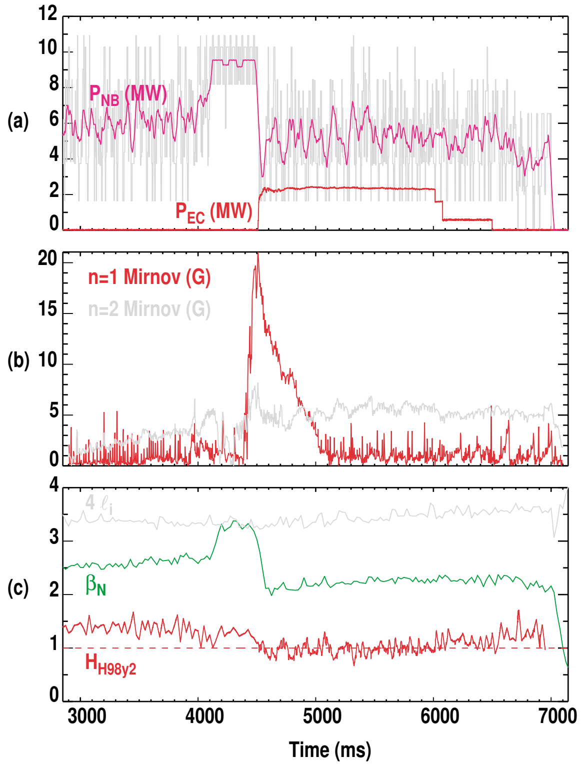

Fig. 2. Time histories of the (a) neutral beam and EC power, (b) n=1 and n=2 Mirnov amplitudes, and (c) β_N, $4\,\ell_i$, and H_{H98y2} for a discharge with ECCD suppression of an m=2/n=1 tearing mode. The suppression is optimized by toroidal field feedback control. The β value is regulated at a value of β_N~2.3 after the mode is triggered. The confinement quality (H_{H98y2}) is good even with 2.3 MW EC power at ρ=0.66.

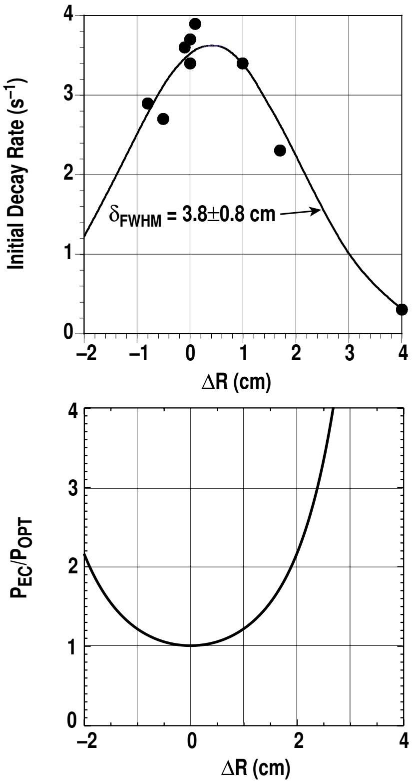

Fig. 3. (a) Initial decay rate of the m=3/n=2 tearing mode amplitude when ECCD is applied at varying positions relative to the island center (ΔR). All points have roughly equal EC power and points near ΔR=0 give full suppression. The line is a fit to δ_{EC} using the model described in [5]. (b) The increase in EC power needed to suppress the tearing mode versus location mismatch, using the same model. A mismatch of only 2 cm roughly doubles the power requirement for suppression.

has been demonstrated in both stationary discharges and discharges with variation in the toroidal field. Because of this effect, a closed-loop feedback scheme was developed to optimize the location of the ECCD [5,8]. When the mode amplitude is above a certain level, either the radial position of the plasma or the toroidal field is varied to maximize the decrease in mode amplitude. For future devices, however, varying the toroidal field or plasma position may not be acceptable. Due to longer time scales, a method for real-time steering of the EC beam or a variable frequency source could be developed. Without such a system, the suppression power requirements would likely be more than double that of the optimal value.

The optimal system for suppression also requires a match of the ECCD profile to the threshold mode width. To make this optimization requires some knowledge of the threshold physics. The present theoretical model involves both transport and polarization drift effects to set a minimum size for which islands are sustained. Below this size the growth rates are negative and the mode disappears. The present formulation indicates the polarization drift dominates the threshold behavior in DIII–D. For projections to ITER-FEAT, the polarization drift term is estimated to be greatly reduced compared to the transport term. This has the unfortunate consequence that the essential physics of the threshold at ITER-FEAT parameters can not be directly verified. Work is continuing on DIII–D and other tokamaks in concert to confirm the threshold models now in use.

The modified Rutherford equation does not describe all of the factors known to influence the stabilization. For example, in DIII–D it is more difficult to suppress the m=3/n=2 mode if its frequency locks to the m=2/n=2 component of the sawtooth precursor (Fig. 4). Theoretical models for mode coupling in the general case exist (e.g. [9]), and in some models, the presence of a second mode tends to have a stabilizing effect on the higher order mode [10]. More modeling and comparisons with experiment are required to validate a predictive model suitable for future machines. Another effect not included explicitly in the modified Rutherford equation is the self-consistent change in the axisymmetric equilibrium due to the ECCD [11]. In principle, this comes in through an equation governing the time dependence of Δ', which in present modeling is taken as a free parameter.

CONCLUSIONS

Significant progress has been demonstrated in recent experiments in the DIII–D tokamak toward two main applications of tearing mode suppression. First, the operating domain has been extended by raising β with good confinement using continuous suppression. Second, the first demonstration of complete suppression of an m=2/n=1 yields confidence that a control system to prevent disruptions due to this mode can be developed. In addition, key features of the standard theoretical model for the tearing mode have been validated. The sensitivity of the relative location of the mode and the ECCD has been demonstrated, and the clear existence of a threshold island width has been established. Further work on validating the scaling of the threshold and extension of the model to include mode coupling and current profile modification is needed.

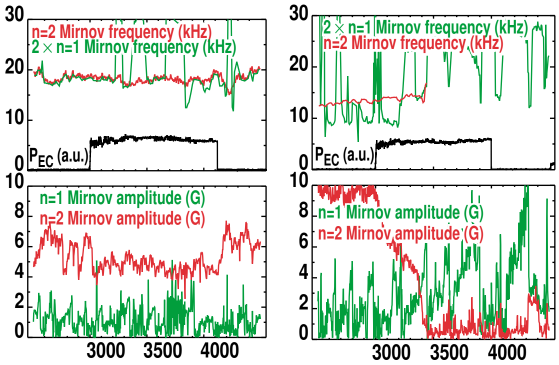

Fig. 4. Comparison of suppression effects with and without frequency locking of the n=2 and n=1 modes. The left column shows the n=2 and twice the n=1 frequency (top) and the n=1 and n=2 mode amplitudes (bottom) for a case with coupled modes. The ECCD has only a modest effect on the m=3/n=2 tearing mode. The right column shows the quantities for a case where the two modes are uncoupled. The same EC power leads to full suppression of the tearing mode. The operational difference in the two cases is a reduction in q_{95} for the uncoupled case (q_{95}=3.3) from the coupled case (q_{95}=4.2).

ACKNOWLEDGMENT

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