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Stabilization of Tearing Modes in DIII–D by Localized Electron Cyclotron Current Drive

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Abstract. Tearing modes have been shown to limit β and confinement in conventional ELMing H–mode tokamak regimes. The tearing modes grow from a "seed" island due to the destabilizing effect of pressure flattening in the island leading to a reduction in the local bootstrap current. Recent experiments on the DIII–D tokamak have demonstrated stabilization of m=3/n=2 tearing modes in the presence of sawteeth through localized electron cyclotron current drive (ECCD). Variation of the deposition location indicates the ECCD remains localized despite the beam traversing an ELMing edge. The effect of the ECCD on the mode is consistent with predictions that the ECCD must be within the island for stabilization. The calculated EC current density (J_{EC}) is greater than the calculated local bootstrap current density (J_{BS}) also in accord with predictions. A closed-loop feedback scheme has been successfully operated for the first time using position control and magnetic signals as the actuator and sensor, respectively.

Fusion power plant performance optimizes at the highest stably achievable plasma pressure or $\beta(\propto p/B^2)$ and to a lesser extent the highest confinement time τ_E. Ideal MHD predicts β limits in the absence of a conducting wall at β_N $[\equiv\beta/(I/aB)]$ ~3.5 in conventional ELMing H–mode scenarios. However, resistive MHD instabilities known as tearing modes which involve magnetic reconnection are observed to limit the achievable β_N to as low as half of the no-wall ideal MHD limit. Perhaps even more dangerous is their propensity to slow the plasma rotation through interaction with the wall and lead to major disruptions which can damage the first wall.

These tearing modes can be stabilized by reversing the organization of the current within a flux surface into clumps which match the helical pitch of the field lines. A localized current driven by electron cyclotron waves (ECCD) only a few percent in magnitude of the total current was predicted to stabilize these modes [1,2]. Recently, experiments have demonstrated such stabilization of a m=3/n=2 tearing mode [3–5]. Increasing β_N to the ideal MHD limit would lead to increased fusion output by a factor of two.

The evolution of the radial width w of the tearing mode is governed by an equation of the form:

$$\frac{dw}{dt} = f\Delta' + g\beta_p\left[\frac{r}{w} - \frac{rw_p^2}{w^3} - \eta\frac{J_{EC}}{J_{BS}}\right] \quad . \tag{1}$$

A complete discussion of this equation can be found in Ref. [6]. A brief qualitative explanation will be given here. The first term is the classical tearing mode stability term related to the total current density gradient. The second term is a destabilizing effect of finite plasma pressure. This arises from the drop in bootstrap current due to flattening of the pressure in the island reinforcing the growing magnetic perturbation. Modes which grow even with $\Delta' < 0$ are known as "neoclassical" tearing modes due to the influence of the missing bootstrap current. The third term is the stabilizing effect of the plasma polarization current. This term sets a threshold size for some initial perturbation or "seed" to grow since it is larger than the second term when $w<w_p$. There is still considerable debate on the nature of this term; however, observations of tearing modes clearly support the notion of a threshold. Finally, the fourth term represents the influence of ECCD on the mode. The function η is proportional to $e^{-(\Delta\rho/\delta_{EC})^2}$ where $\Delta\rho$ is the location of the ECCD with respect to the island center and δ_{EC} is a characteristic width of the driven current. The form of this term predicts an influence of ECCD when it is localized within the island and when $J_{EC}/J_{BS} > 1$.

Application of ECCD clearly can suppress an m=3/n=2 tearing mode as shown in Fig. 1. At 3000 ms, 1.1 MW of EC power is applied to a sawtoothing plasma with a 3/2 tearing mode. When the driven current is placed at the optimum location, the mode amplitude goes to 0 and the β_N rises, while the plasma continues in vigorous sawtooth oscillations, unlike previous results [3,4]. For comparison, a case with no ECCD and a case with ECCD applied 2 cm away from the optimum location are shown. The β_N rise in the non-optimal ECCD case is smaller than in the suppressed case indicating the rise is not simply due to the additional auxiliary power. Counter-ECCD was also tested and found to have little effect on the mode. This may indicate the form of the EC term in Eq. (1) may not be entirely correct. The rapid drop of the mode after 3350 ms is interpreted as reaching the seed threshold. This interpretation is supported by the mode which appears after 4300 ms (after the EC pulse) at about the same level and decays very slowly for almost 100 ms before disappearing rapidly. Seed islands of similar size due to sawtooth crashes during the EC pulse are thought to decay rapidly due to the additional stabilizing influence of the ECCD. The remainder of the paper will present the evidence that the ECCD is most effective within the island and compare the observed effects on the mode with theoretical expectations.

The ECCD is effective at suppressing the tearing mode only when applied within a narrow radial region. This is observed using two methods. The first is to move the deposition location relative to the island by ramping the toroidal field during a single EC pulse, as shown in Fig. 2. The case shows that the ECCD has an influence on the mode only over a region of width ~4 cm. Note that full suppression occurs in the static case at the maximum effect point of the ramp. The β_N recovers during the time of suppression

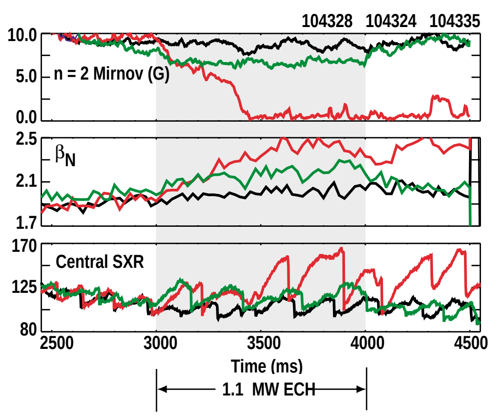

Figure 1. Time histories of the (a) n=2 Mirnov amplitude (G), (b) β_N, and (c) central SXR emission (au) for discharges with ECCD at the optimal location (solid), ECCD 2 cm off optimal (dashed), and without ECCD. The EC is applied form 3000–4000 ms (shaded) at 1.1 MW. The plasma conditions are B_T = 1.49 T, I_p = 1.18 MA, $\bar{n}$ = 4.1×10^{19} m^{-3}, P_{NB} = 5.9 MW.

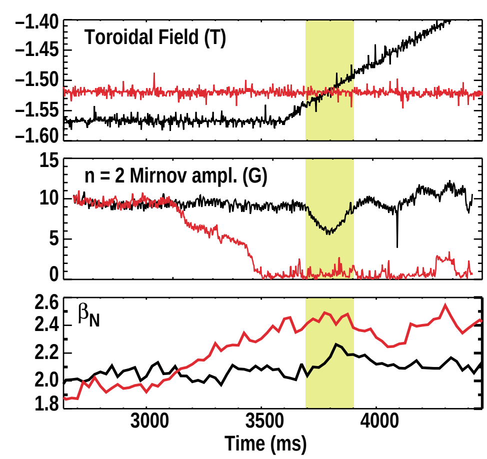

Figure 2. Time histories of (a) B_T (T), (b) n=2 Mirnov amplitude (G), and (c) β_N for a case with a B_T ramp (dark) and steady B_T at the maximum effect point (light). The shaded region shows the B_T values for which the ECCD has an influence. Other than B_T the conditions are the same as for Fig. 1.

in the B_T ramp. This implies an improvement of confinement correlated with the suppression since additional heating power is constant.

The narrow region of influence of the ECCD is also observed in shot-by-shot static variations of B_T. The width of the ECCD profile has been estimated using the simple Gaussian model for η in Eq. (1) discussed above. This indicates an ECCD profile of ~4 cm FWHM, consistent with dynamic case. Ray tracing calculations predict a slightly smaller width of ~3 cm. This level of agreement is good considering the simple model employed.

The calculated ECCD current density is slightly larger than the axisymmetric J_{BS} when the mode is suppressed, in agreement with theory. The total current density from an equilibrium reconstruction using magnetics, MSE, and kinetic profile information is shown in Fig. 3. Also shown are J_{BS} and J_{EC}. The suppression occurs when $J_{EC} > J_{BS}$ and J_{EC} is within the island as seen by ECE.

Estimates of the island width using magnetics and ECE agree very well. The fluctuating component of the electron temperature is shown in Fig. 4, converted into the physical displacement ξ. The distance between the locations of maximum ξ from the ECE analysis is ~7 cm which agrees with the mode width estimated from the inner wall magnetic probes (6.8 cm). It is puzzling, however, that the maximum ξ is only ~3 mm. This inconsistency with the 7 cm region of perturbation would imply either incomplete flattening of the temperature in the island or some over-simplification in the conversion of δT to ξ.

That the ECCD is deposited within the island can be verified unambiguously by modulating the EC power and comparing the location of the heat pulses with the location of the fluctuating T_e due to the mode. These two regions coincide as shown in Fig. 5. Both are measured at the same time and, because of the high field midplane deposition location, the mapping of the ECE channels to flux coordinates has no influence on the conclusions.

In addition to the open-loop suppression discussed above, closed-loop active feedback control has been demonstrated for the first time. To optimize the suppression, an algorithm was developed which moves the plasma radially to minimize the magnetic signature of the tearing mode. An example of successful application of this is shown in Fig. 6. Two items of particular note are the suppression in the presence of large sawtooth crashes and the return of the mode where the position feedback is turned off and the deposition location is returned to the initial condition not optimal for suppression.

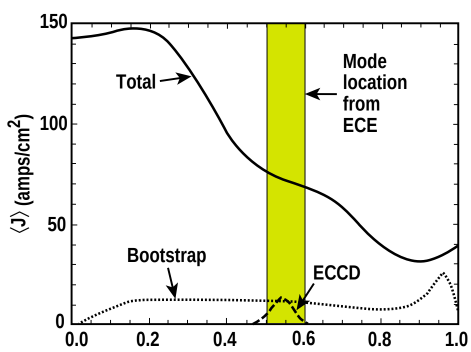

Figure 3. Profiles of the total flux-surface averaged (solid), bootstrap (dotted), and ECCD (dashed) current densities versus normalized radius. The shaded region shows the location of the mode as determined from ECE.

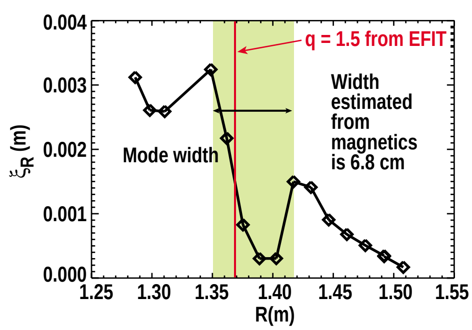

Figure 4. Mode displacement x from ECE versus major radius. The value of ξ is determined from $\xi \bullet \nabla T = \delta T$, where δT is measured by the ECE and ∇T is the unperturbed profile.

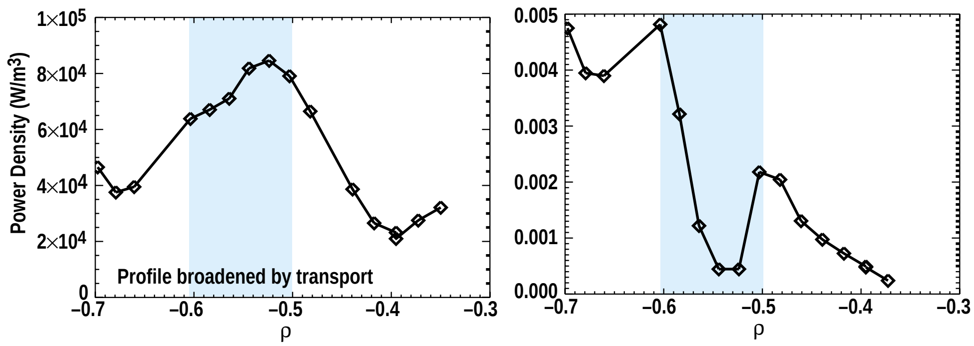

Figure 5. Comparison of the locations of the deposited EC power density (100 Hz modulation) and the fluctuating δT (12.5 kHz) due to the tearing mode versus normalized radius.

In conclusion, suppression of the 3/2 tearing mode was accomplished in sawtoothing plasmas. Closed-loop feedback using position control was demonstrated for the first time. The observation that the ECCD affects the mode only when deposited within the island is in accord with theory, as is the ratio $J_{EC}/J_{BS} \gtrsim 1$. Future plans include work to suppress the more dangerous m=2/n=1 tearing mode.

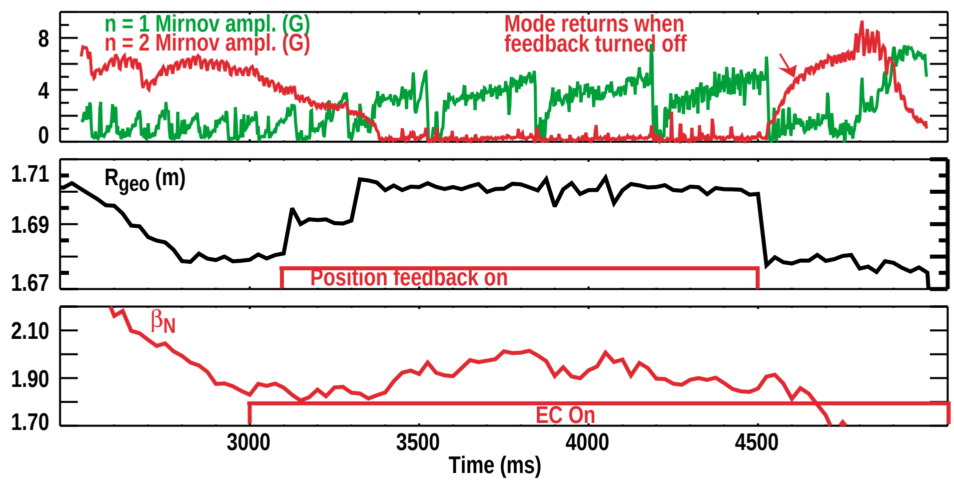

Figure 6. Time histories of (a) n=2 (dark) and n=1 (light) Mirnov amplitudes (G), (b) major radius (m), and (c) β_N. The plasma conditions are B_T = 1.53 T, I_p = 1.08 MA, $\bar{n}$ = 3.5×10^{19} m^{-3}, q_{95} = 3.6, and P_{EC} = 1.5 MW.

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