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STABILIZATION OF NEOCLASSICAL TEARING MODES IN TOKAMAKS BY ELECTRON CYCLOTRON CURRENT DRIVE

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R.J. LA HAYE
General Atomics, P.O. Box 85608, San Diego, California 92186-5608 USA

Resistive neoclassical tearing modes (NTMs) are anticipated to be the principal limit on stability and performance in ITER as the resulting islands break up the magnetic surfaces confining the plasma. Drag from island-induced eddy currents in the resistive wall can slow plasma rotation, produce locking to the wall, and cause loss of the high-confinement H-mode and disruption. NTMs are destabilized by helical perturbations to the pressure-gradient-driven “bootstrap” current. NTMs can be stabilized by applying co-electron-cyclotron current drive (ECCD) at the island rational surface. Such stabilization and/or preemption is successful in ASDEX Upgrade, DIII-D, and JT-60U, if the peak off-axis current density is comparable to the local bootstrap current density and well-aligned.

ASDEX Upgrade has used a feed-forward sweep of the toroidal field to get ECCD alignment on the island. JT-60U has used feed-forward sweeps of the launching mirror for the same purpose, followed up by real-time adjustment of the mirror using the electron cyclotron emission (ECE) diagnostic to locate the island rational surface. In DIII-D, ECCD alignment techniques include applying “search and suppress” real-time control to find and lock onto optimum alignment (adjusting the field or shifting the plasma major radius in equivalent small steps).

Most experimental work to date uses narrow, cw ECCD; the relatively wide ECCD in ITER may be less effective if it is also cw: the stabilization effect of replacing the “missing” bootstrap current on the island O-point could be nearly cancelled by the destabilization effect on the island X-point if the ECCD is very broad. Modulating the ECCD so that it is absorbed only on the m/n=3/2 rotating island O-point is proving successful in recovering ECCD effectiveness in ASDEX Upgrade when the ECCD is configured for wider deposition.

The ECCD in ITER is relatively broad, with current deposition full width half maximum almost twice the marginal island width. This places strict requirements on ECCD alignment, with the cw effectiveness dropping to zero for misalignments as small as 2 cm. Tolerances for misalignment are presented to establish criteria for the alignment by moving mirrors in ITER for both cw and modulated ECCD.

1. Introduction

A change in the electron-cyclotron current drive (ECCD) launcher scheme in ITER from “remote” to “front” steering has narrowed the expected ECCD current density profile considerably [1], making the stabilization of neoclassical tearing modes (NTMs) — with or without modulation of the ECCD — much more certain [2]. The front steering mirror placed closer to the plasma offers the largest steering range and optimized beam focusing. Evaluation of the required EC power for either the m/n=3/2 or 2/1 modes, assuming perfect alignment of the peak ECCD on the rational surface in question, indicates that the proposed 20 MW is adequate [3]. Here, m is the poloidal mode number and n is the toroidal mode number. However, the narrower ECCD makes the alignment with the island a critical issue.

Experiment shows that the marginal island w_{marg} for NTM stabilization of the m/n = 3/2 mode is about twice the ion banana width [3], which is only 1–2 cm in ITER. This is similar for m/n = 2/1 but not as well documented. With front steering, the ECCD is still relatively broad, with current deposition full width half maximum $\delta_{eccd} \approx 2\, w_{marg}$. This places strict requirements on ECCD alignment with the cw ECCD effectiveness dropping to zero for misalignments as small as ~2 cm.

2. Model For NTM Stabilization By ECCD

A major line of research on NTM stabilization is the use of co-ECCD to drive off-axis current density j_{eccd} parallel to the total equilibrium current density j_{tot}. NTM islands are destabilized by helically perturbed bootstrap current at the rational surface $q = m/n$. The typical radial profiles of j_{tot}, with and without j_{eccd}, and that fraction of j_{tot} which is j_{boot} are shown in Fig. 1. Note that j_{boot} is approximately proportional to the plasma pressure gradient and increases with beta. ECCD has two stabilizing effects.

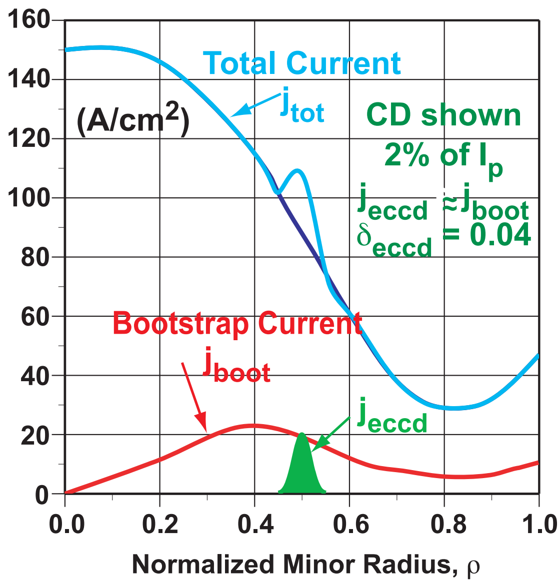

Fig. 1 Typical radial profiles of current density from an ELMing H-mode sawtoothing discharge in DIII-D for a plasma with $q_{95} \gtrsim 3$ and $\beta_N \lesssim 2$ in approximately the ITER shape. Total current density j_{tot} with (cyan) and without (blue) off-axis j_{eccd} (green) of 2% of the plasma current I_p ; half-width-half-maximum $\delta_{eccd} = 4\%$ in units of ρ. Also shown is the equilibrium bootstrap current j_{boot} (red).

The first stabilizing effect is increasing the classical linear stability, i.e., making Δ' more negative. ECCD changes the total local equilibrium current density and thus Δ' and the linear stability [4,5]. In this paper, all current drive widths of an assumed off-axis Gaussian are taken as full width half-maximum (FWHM) δ_{eccd}. Following the perturbation model of Ref. [4], the change in Δ' is

$\delta(\Delta' r) \approx -(5\pi^{3/2}/32) F\, a_2\, (L_q/\delta_{eccd})(j_{eccd}/j_{tot})$ for well-aligned co-ECCD on a rational surface $q = m/n$ where a_2 is a geometrical factor (equal to 4 for a large aspect ratio circular cylinder with constant j_{tot} within $q = m/n$). L_q is the local magnetic shear length, $q/(dq/dr)$. The factor F depends on alignment and duty factor, and is F=1 for perfect alignment and duty factor $\tau = 1$. A relative radial misalignment between the ECCD and the $q = m/n$ rational surface of as much as $|\Delta\rho/\delta_{eccd}| \approx 3/5$ would negate the stabilizing effect, i.e. $F \approx 0$, where ρ is the normalized minor radius.

The second stabilizing effect of ECCD is to replace the "missing" bootstrap current where j_{boot} is the unperturbed bootstrap current [6-8]. The modified Rutherford equation (MRE) for the island growth rate with both effects is

$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta' r + \delta(\Delta' r) + a_2\left(j_{boot}/j_{tot}\right)\left(L_q/w\right)\left[1 - \frac{w_{marg}^2}{3w^2} - K_1\frac{j_{eccd}}{j_{boot}}\right] , \qquad (1)$$

where the width of the most unstable (highest dw/dt) island is w_{marg} which arises from small island stabilizing effects; the working model is that w_{marg} is approximately twice the ion banana width, $w_{marg} \approx 2\varepsilon^{1/2}\rho_{\theta i}$ [3]. a_2 is typically fitted to experiment for the saturated island without ECCD and an assumed $\Delta' r = -m$ [3]. Here K_1 is an effectiveness parameter for replacing the missing bootstrap current. K_1 depends on the width of the ECCD with respect to the island, whether the ECCD is continuous (cw) or modulated, and on the radial misalignment of the ECCD with respect to the rational surface $q = m/n$ being stabilized.

Continuous current drive has the advantages of not having to be synchronized and can be applied preemptively without an island. A lower effectiveness K_1 is a disadvantage as the stabilizing effect of co-ECCD on the island O-point is partially cancelled by the destabilizing effect of co-ECCD on the island X-point. Modulated current drive (synchronized with the O-point) with duty factor $\tau \approx 0.5$ for example has the advantage of higher effectiveness K_1, particularly for wider ECCD. Disadvantages are a factor τ times $\delta(\Delta' r)$ and the need to synchronize the modulation with the phase of the O-point. The variations of F [4] and K_1 [8] with misalignment for cw $(\tau = 1)$ and 50/50 modulation $(\tau = 0.5)$ are shown in Figure 2. For $|\Delta\rho/\delta_{eccd}| \gtrsim 0.6 \sim 0.9$, stabilization is lost $\left(F \lesssim 0 \text{ and } K_1 \lesssim 0\right)$ for either cw or 50/50 modulation. It should be emphasized that the two stabilizing effects are additive, not mutually exclusive, and are both included in <u>all</u> calculations presented here.

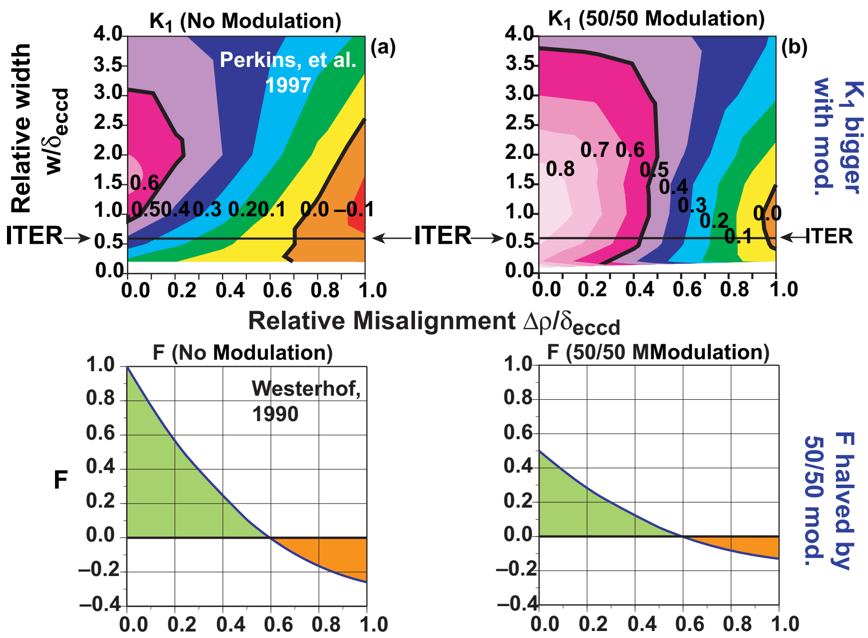

Fig. 2. Contours of effectiveness K_1 of replacing the missing bootstrap current, and the variation of the effectiveness F of making Δ' more negative. (a) cw, (b) 50/50 modulation. The models apply to any $q = m/n$ mode.

In general, the co-ECCD should be effective for NTM stabilization with : $j_{eccd} \approx j_{boot}$ at $q = m/n$, full width half maximum about twice the ion banana width ($\delta_{eccd} \approx 2\varepsilon^{1/2}\rho_{\theta i}$), modulated to drive current only on and around the O-point, particularly if $\delta_{eccd} >> 2\varepsilon^{1/2}\rho_{\theta i}$, and finally be well aligned on q = m/n, i.e., $|\Delta\rho| << \delta_{eccd}$ where $\Delta\rho = \rho_{m/n} - \rho_{eccd}$.

3. Stabilization of NTMs with CW ECCD

ECCD has the advantage of narrow current drive placed at the first harmonic cyclotron resonance (JT-60U, ITER) or at the second harmonic cyclotron resonance (ASDEX Upgrade, DIII-D). Development of high efficiency (~35%), high power (~1 MW), long pulse (~2 s to cw) gyrotrons at 110 to 170 GHz has made ECCD the choice for NTM control in ITER. Complete stabilization by cw ECCD of m/n = 3/2 NTMs is successfully proven on ASDEX Upgrade [9-12], DIII-D [13,14], and JT-60U [15,16]. The m/n=2/1 NTM has also been stabilized (or avoided) in ASDEX Upgrade and DIII-D. The advantage of narrow current drive with ECCD makes precise alignment of the peak ECCD on the rational surface being controlled a necessity.

The typical geometry is shown in Fig. 3 with JT-60U as an example. The co-ECCD (in direction of I_p) is launched with the EC wave directed in the poloidal plane to be absorbed near and just outboard of the cyclotron resonance.

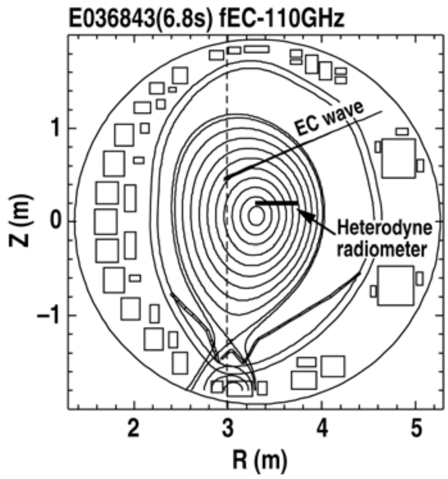

Fig. 3. Shape of the plasma cross section in the JT-60U tearing mode stabilization experiment. Rays of EC wave and measurement range of the heterodyne radiometer are also shown in this figure. [*Reprinted courtesy of IOP, Plasma Phys. and Control. Fusion 42, L37 (2000).*]

ASDEX Upgrade uses a slow toroidal field scan to align the ECCD [9]. The n=2 Mirnov amplitude decreases steadily until eventually it decays much faster to reach complete stabilization; this is the marginal condition. Stabilization occurs with $I_{eccd}/I_p \approx 1.4\%$.

DIII-D uses real-time feedback of the plasma major radius (in the presence of a mode) to put the rational surface of the island on the ECCD as shown in Fig. 4 [13]. The "search and suppress" control locks onto the optimum alignment in 1 cm steps. An alternate method in "search and suppress" uses small steps in B_T. Stabilization requires $I_{eccd}/I_p \approx 2\%$. In the absence of a mode, "active tracking" monitors the location of the q-surface in real-time to adjust the alignment and successfully avoid the mode ever occurring [17,18].

JT-60U uses a scan of the launcher mirror angle (or mirror tilt feedback on the island "node" detected by ECE radiometer) to put the ECCD on the q = 3/2 island rational surface as shown in Fig. 5 [15,16]. The case shown is for predetermined fixed EC wave mirror angle. Stabilization is achieved with $I_{eccd}/I_p \approx 2\%$.

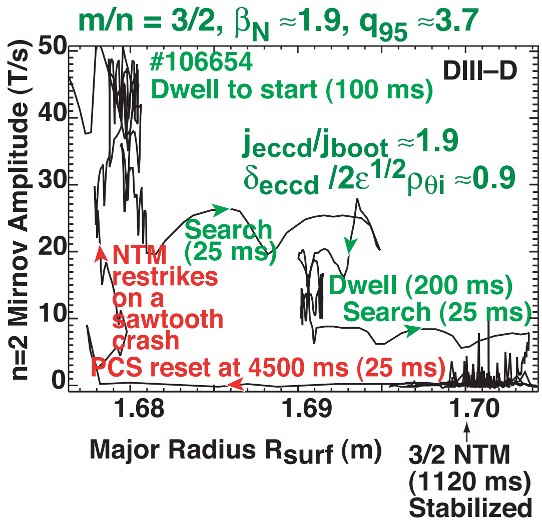

Fig. 4. Trajectory of *n*=2 Mirnov amplitude versus plasma major radius R_{surf}. Search and suppress adjusts R_{surf} in 1 cm steps interspersed with 'dwell' intervals for determination of the stabilizing effect, to find the optimum alignment and get complete m/n=3/2 NTM suppression. A reset to the initial R_{surf} value at 4500 ms, causes the mode to 'restrike'.

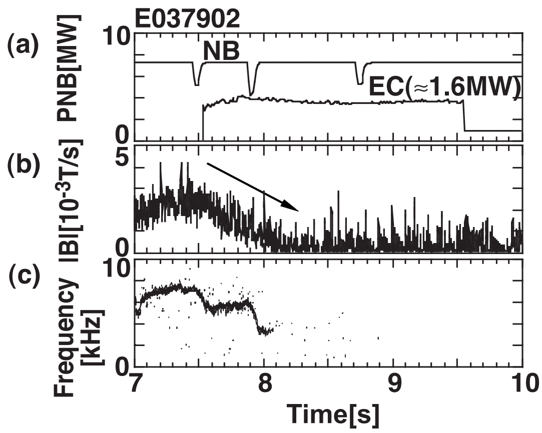

Fig. 5. (a) Time traces of NB and ECH power in JT-60U. In this discharge, the EC wave mirror angle is set at 43 degrees. (b) Time evolution of amplitude of magnetic perturbations with n=2. (c) Time evolution of frequency of electron temperature perturbations at the magnetic island. [*Reprinted courtesy of IOP, Plasma Phys. and Control. Fusion 42, L37 (2000).*]

4. Stabilization of NTMs with Modulated ECCD

ASDEX Upgrade has demonstrated control with modulated ECCD phased on the rotating O-points [19]. Mirnov probes are used in real-time whose location is mapped to where the ECCD is absorbed. When launching angles were configured for broad ECCD, the effectiveness of cw control was reduced, as expected, with only partial suppression. With O-point synchronized ECCD, complete suppression was obtained. The results are shown in Fig. 6. Changing the phase from O-point absorption to X-point greatly reduced the stabilizing effect. However, the small remaining X-point stabilization suggests the effect of more negative Δ' is active.

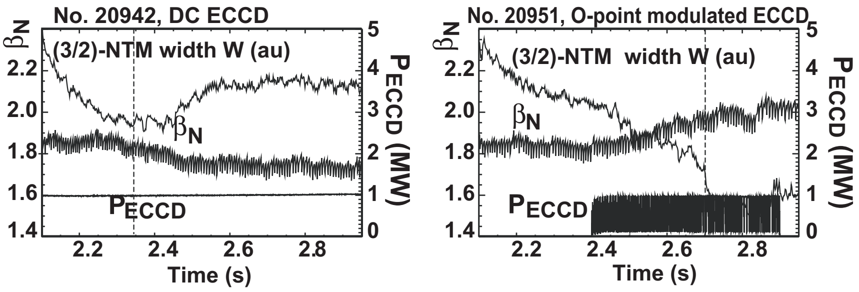

Fig. 6. Comparison between 2 nearly identical discharges with unmodulated (a) and modulated (b) broad ECCD deposition. Only the B_T ramp has been slightly adapted to match the resonance condition between ECCD and the mode. The vertical dashed lines indicate the time when the resonance is reached and the minimum island size W_{min} is taken. [*Reprinted courtesy of AIP, Phys. Rev. Lett. 98, 205009 (2007).*]

5. ECCD Stabilization of NTMs on ITER

ECCD is the primary tool planned for NTM control in ITER [20,21]. Up to 20 MW of power at 170 GHz will be injected from upper outer ports. Real-time alignment by aiming the launcher mirrors is planned. The design using "front" steering reduces the width of the ECCD in the ITER standard scenario [1]. The performance of the different options was analyzed in terms of NTM stabilization figure of merit j_{eccd}/j_{boot} in Ref. [22].

The m/n = 2/1 NTM has slower plasma rotation and closer proximity to the resistive wall allowing easier locking to the wall with subsequent loss of H-mode and disruption. Reference [3] predicts locking in ITER with a full width m/n = 2/1 island w_{lock} of only 5 cm. For "front" steering 3.5 MW is needed with perfect alignment for cw ECCD to reduce w to w_{marg} as shown in Fig. 7. The figure of merit, j_{eccd}/j_{boot}, is 0.73. Thus the 2/1 NTM is linearly and nonlinearly stable. Front steering ECCD is narrower with larger j_{eccd} per MW injected but is thus less tolerant to misalignment. Misalignment reduces the NTM control effectiveness and thus more ECCD power is needed as shown in Fig. 7 for the cw case. With $|\Delta\rho|/\delta_{eccd} \gtrsim 0.6$ and thus $|\Delta R| \gtrsim 1.5$ cm misalignment, no amount of ECCD power will suppress the 2/1 mode below the 5 cm locking limit.

Modulation requires an island for control of the O-point to modulate the gyrotrons. Thus in addition to radial alignment for cw control, island phase must be detected in real time for gyrotron control. Operation above the green curve in Figure 8 for modulated ECCD would not be possible except transiently as no saturated islands would occur. Control would have to revert to cw and "active tracking" of q = m/n location and ECCD alignment without an island as in Ref. [21]. Comparing Figures 7 and 8 for cw or modulated ECCD, one sees modulation is evaluated as similar in effectiveness to cw in ITER [22]. This is because while modulated ECCD with a duty factor $\tau = 0.5$ is more effective at replacing the missing bootstrap current, Table I, cw with a duty factor $\tau = 1$ is twice as effective at making Δ' more negative. The plasma control system (PCS) in ITER must either actively track the rational surface without the mode to 1 cm accuracy, and align the ECCD on it, or in the presence of a growing mode identify it, optimize the alignment to better than 1 cm and rapidly suppress it.

Table I. Comparison of m/n = 2/1 NTM Stabilization in ITER between cw and modulated ECCD: injected peak power of 5 MW, misalignment $|\Delta R|$=1 cm for $|\Delta\rho|/\delta_{eccd}$ = 0.4.

Parameter	CW	MOD	Note
$K_1\, j_{eccd}/j_{boot}$	0.38	0.59	MOD more effective
$y \equiv -a_2 \dfrac{j_{boot}}{j_{tot}} \dfrac{L_q}{w_{sat}} \left(\dfrac{K_1 j_{eccd}}{j_{boot}}\right)$	-4.18	-6.67	MOD more effective
$x = \delta\, \Delta' r$	-4.42	-2.21	CW more effective
x + y	-8.60	-8.88	Similar
w_{sat} (cm)	4.44	4.33	Similar
w_{sat}/w_{lock}	0.89	0.87	Similar

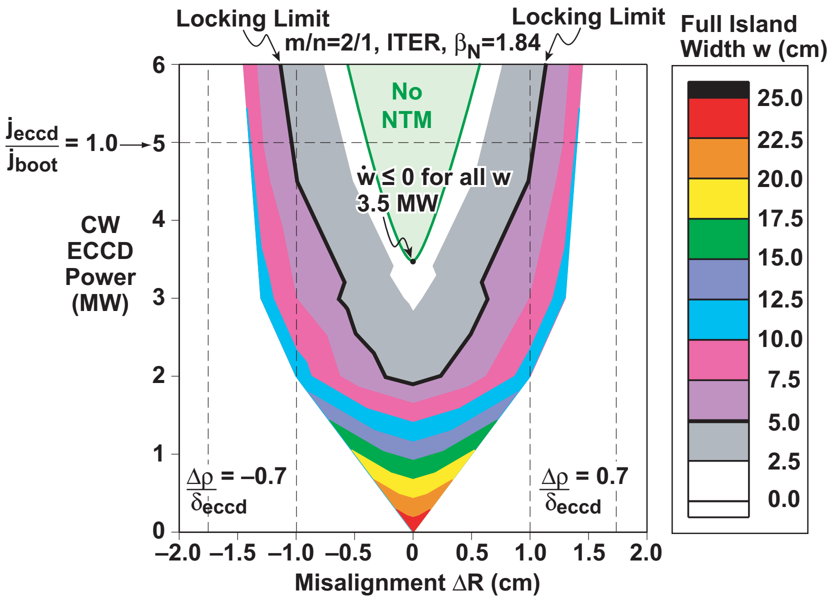

Fig. 7: Variation of m/n=2/1 island width in ITER with cw power and misalignment. For $\Delta R = 0$, 3.5 MW, j_{eccd}/j_{boot} = 0.73 is needed for complete stability. The 5 cm island locking limit is highlighted. Above the green curve, $\dot{w} < 0$ for all w and the NTM is stable.

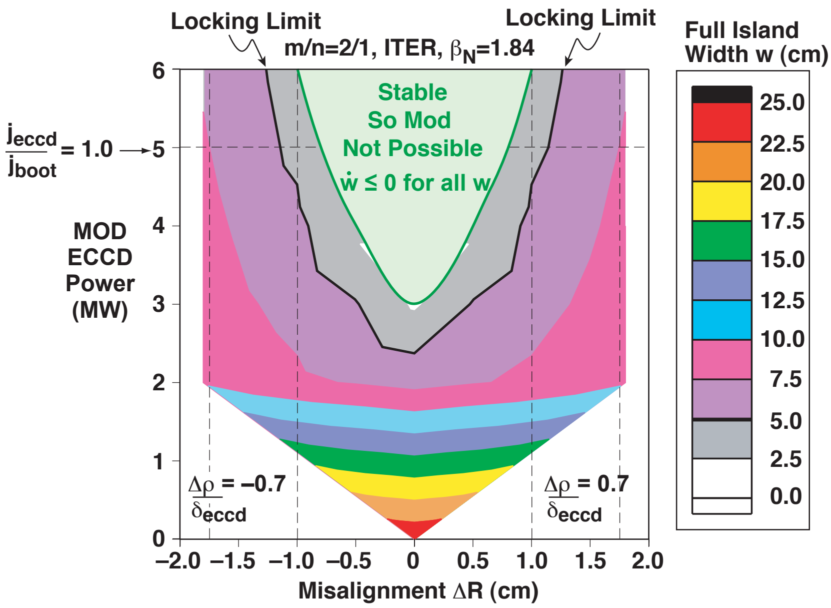

Figure 8: Same as Figure 7 but for modulated power. Above the green curve, $\dot{w} < 0$ for all w so modulation is not possible as no "saturated" island.

Acknowledgments

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