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STABILIZATION OF NEOCLASSICAL TEARING MODES IN TOKAMAKS BY RADIO FREQUENCY CURRENT DRIVE

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Stabilization of Neoclassical Tearing Modes in Tokamaks by Radio Frequency Current Drive

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Abstract. Resistive neoclassical tearing modes (NTMs) will be the principal limit on stability and performance in the ITER standard scenario as the resulting islands break up the magnetic surfaces that confine the plasma. Drag from rotating island-induced eddy current in the resistive wall can also slow the plasma rotation, produce locking to the wall, and cause loss of high confinement H-mode and disruption. The NTMs are maintained by helical perturbations to the pressure-gradient driven "bootstrap" current. Thus, this is a high beta instability even at the modest beta for ITER. A major line of research on NTM stabilization is the use of radio frequency (rf) current drive at the island rational surface. While large, broad current drive from lower hybrid waves has been shown to be stabilizing (COMPASS-D), most research is directed to small, narrow current drive from electron cyclotron waves (ECCD); ECCD stabilization and/or preemptive prevention is successful in ASDEX Upgrade, DIII-D and JT-60U, for example, with as little as a few percent of the total plasma current if the ECCD is kept sufficiently narrow so that the peak off-axis ECCD is comparable to the local bootstrap current.

Keywords: macro-instabilities, tokamaks, plasma heating by microwaves
PACS: 52.35.Py, 52.55.Fa, 52.50.Sw

INTRODUCTION

Neoclassical tearing modes (NTMs) are resistive tearing mode islands that are sustained by a helically perturbed bootstrap current. The NTMs degrade both plasma energy and angular momentum and can lead to disruption in a high beta plasma. A toroidal plasma has a poloidal non-uniformity of the toroidally axisymmetric magnetic field that leads to two classes of particles. The interaction of these two classes of particles provide a unidirectional toroidal current, the bootstrap current, that is proportional to the radial pressure gradient. Thus, the bootstrap current is larger with increased plasma pressure. For a conventional tokamak with safety factor increasing with radius and plasma pressure decreasing with radius, a "seed" island can flatten the pressure within the island making a helical perturbation of the bootstrap current that reinforces the seed, a destabilizing effect. Small island effects can negate this destabilizing consequence. Thus, the NTM is linearly stable and nonlinearly unstable. As the bootstrap current increases with pressure, the NTM is of greater likelihood as plasma beta is increased and is therefore a high beta occurring (and limiting) instability. The physics of NTMs is reviewed in Ref. [1].

RADIO FREQUENCY (rf) CURRENT DRIVE (CD) TO INCREASE CLASSICAL TEARING STABILITY

A major line of research on NTM stabilization is the use of applied rf (or microwave frequency) waves to drive off-axis current parallel to the total equilibrium current density (co-current drive). The first stabilizing effect is increasing the classical linear stability, i.e., making Δ' more negative. Radio frequency current drive j_{cd} can change the total local equilibrium current density $j_{||}$ and thus Δ' and the linear stability [2,3]. An example of modified plasma current density profiles with different widths is shown in Fig. 1. In this paper all CD widths of an assumed off-axis Gaussian are taken as full width half-maximum (FWHM) δ_{cd} for consistency unless otherwise noted in cited work. L_q is the local magnetic shear length, $q/(dq/dr)$. Following the perturbation model of Ref. [2], the change in Δ' is $\delta(\Delta' r) \approx -(5\pi^{3/2}/32)\ a_2\ (L_q/\delta_{cd})(j_{cd}/j_{||})$ for well-aligned co-CD 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 $j_{||}$ within $q=m/n$). A radial misalignment $\Delta\rho$ of $|\Delta\rho/\ \delta_{cd}| \approx 3/5$ would negate this effect [2].

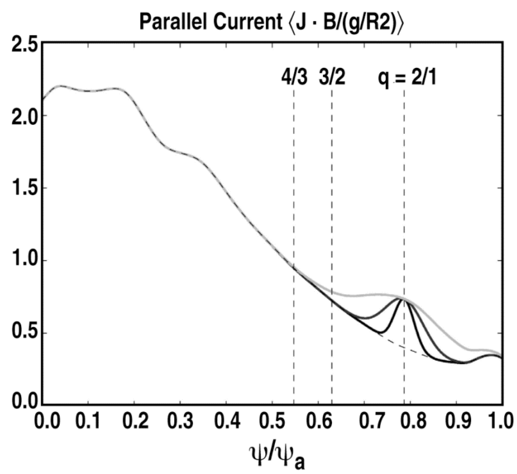

FIGURE 1. Parallel current with peaked (black), medium (dark grey), and broad (light grey) co-current drive channel about the q=2/1 rational surface. The position of the neighboring q=3/2 and q=4/3 surfaces are indicated by the vertical dashed lines. [*Reprinted courtesy of AIP, Phys. Plasmas* ***6****, 1589 (1999).*]

rf CD TO REPLACE THE "MISSING" BOOTSTRAP CURRENT

The other stabilizing effect of rf CD is to replace the "missing" bootstrap current [4-7]. The modified Rutherford equation for the island growth rate with both effects is

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

where the width of the most unstable (highest dw/dt) island is w_{marg} which arises from small island stabilizing effects [1]. Here K_1 is an effectiveness parameter for replacing the missing bootstrap current. K_1 depends on the width of the CD with respect to the island, whether the CD is continuous (cw) or modulated, and on the radial misalignment of the CD with respect to the rational surface $q = m/n$ being stabilized. The variation of K_1 with duty cycle for various island widths and for the unmodulated case vs island width is shown in Fig. 2; both plots assume no misalignment.

Continuous, current drive has the advantages of not having to be synchronized and can be applied pre-emptively without an island. A lower effectiveness K_1 is a disadvantage as the stabilizing effect of co-CD on the island O-point is partially cancelled by the destabilizing effect of co-CD on the island X-point.

Modulated current drive (synchronized with the O-point) with duty cycle τ has the advantages of higher effectiveness K_1, particularly for wider CD as shown in Fig. 2. Disadvantages are a factor τ smaller $\delta(\Delta' r)$ and the need to phase the modulation with the O-point.

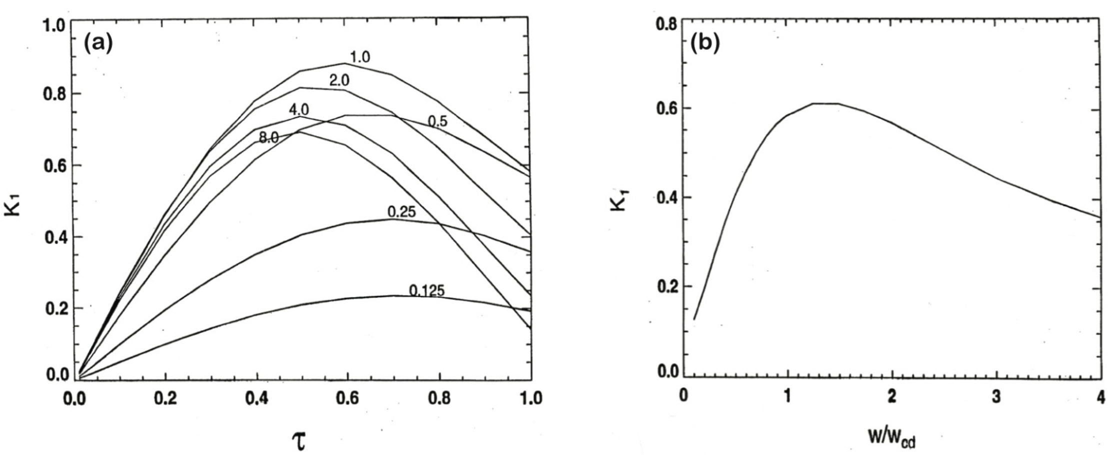

FIGURE 2. (a) K_1 versus "on"-time τ for various island widths w_{CD}/w marked on the diagram. (b) K_1 versus island width, for unmodulated ECCD ($\tau = 1.0$). [*Reprinted courtesy of EPS, Proc. of 24th Euro. Conference on Plasma Physics and Controlled Fusion, Berchtesgaden, Germany, 1997, (European Physical Society, 1997) p. 1017.*]

STABILIZATION OF NTMs WITH LOWER HYBRID CURRENT DRIVE (LHCD)

LHCD with absorption near the hybrid of the ion plasma and cyclotron frequencies is attractive because it requires much lower frequency rf power sources and can be an efficient means of current drive. Disadvantages are an inherently much broader current drive and the issues of localization and wave penetration into the core plasma.

COMPASS-D has been successful in completely stabilizing the $m/n = 2/1$ NTM and maintaining stability as long as the 1.3 GHz LHCD is on [8]. This is shown in Fig. 3. The result is consistent with a reduction in the stability index to a more negative value. As the CD is quite wide, the driven current must be large for stabilization, $I_{cd}/I_p \approx 20\%$. Further experimental investigation of LHCD is planned in JET.

STABILIZATION OF NTMs WITH cw ECCD

Heating and current drive by electron cyclotron waves is reviewed in Ref. [9]. 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 [10-13], DIII-D [7,14], 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. 4 with JT-60U as an example. 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. A misalignment of $|\Delta\rho|/\delta_{eccd}$ of ≈ 0.7 can negate any stabilizing effect [2-7].

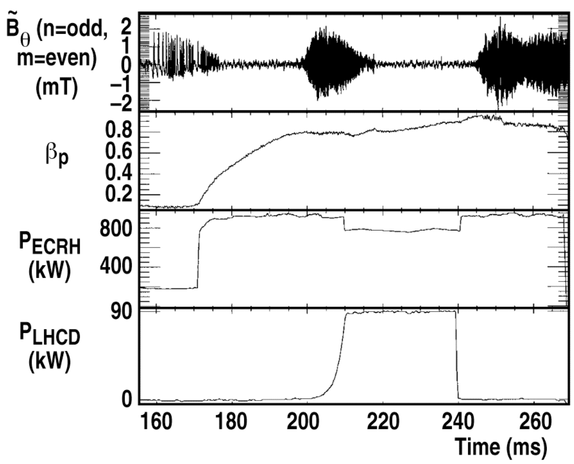

FIGURE 3. The stabilizing effect of LHCD in COMPASS-D on a naturally triggered neoclassical tearing mode (shot 28601). A clear improvement in performance (indicated by an increase in β_p) is observed during and after the mode (shown on the top trace) stabilization. [*Reprinted courtesy of APS, Phys. Rev. Lett.* ***85****, 574 (2000).*]

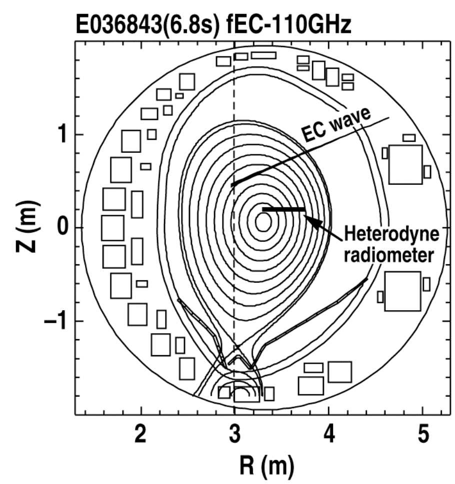

FIGURE 4. Shape of the plasma cross section in the JT-60U tearing mode stabilization experiment. Rays of EC wave and measurement range of the heterodyne radiometer are also shown in this figure. [*Reprinted courtesy of IOP, Plasma Phys. and Control. Fusion* ***42****, L37 (2000).*]

There are four possible schemes to align an NTM island and the current drive: (1) vary the toroidal field so that the ECCD eventually is aligned on the island; (2) vary the plasma major radius so that the island is placed on the ECCD; (3) vary the launching mirror tilt so that the ECCD is placed on the island, or (4) change the rf frequency to move the ECCD onto the island. The last is technologically difficult.

ASDEX Upgrade uses a slow toroidal field scan to align the ECCD [10]. 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 to put the rational surface of the island on the ECCD as shown in Fig. 5 [14]. 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%.

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. 6 [15,16]. The case shown is for predetermined fixed EC wave mirror angle. Stabilization is achieved with $I_{eccd}/I_p \approx 2\%$.

The ECCD stabilization of the m/n = 3/2 NTM in ASDEX Upgrade, DIII-D, and JT-60U all show a "sudden" stabilization when a marginal island width, shown in Fig. 7(a) from DIII-D [17], is reached. This marginal island width w_{marg} is compared in Fig. 7(b) to twice the ion banana width, $2\varepsilon^{1/2}\rho_{\theta i}$ for the representative cases from all three devices [17]. Similarity is strong with the approximate scaling of $w_{marg} = 2\varepsilon^{1/2}\rho_{\theta i}$ for the β rampdown island removal experiments (without ECCD) discussed in Ref. [17].

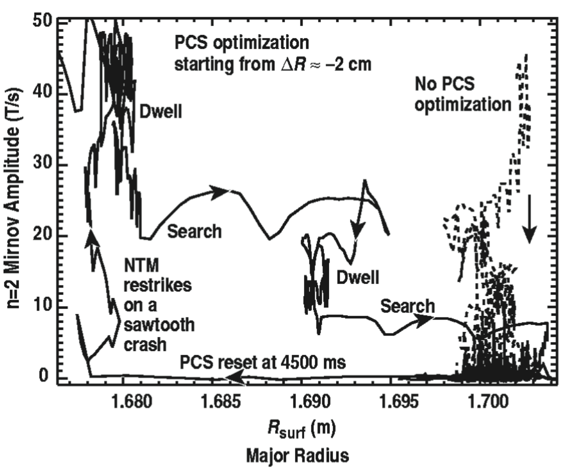

FIGURE 5. Trajectory of n=2 Mirnov amplitude in DIII-D vs plasma major radius with and without PCS real-time control of the optimum rigid plasma position (R_{surf}) for ECCD suppression of an m/n=3/2 NTM (ECCD with 3 gyrotrons, 1.5 MW, on from 3000–4800 ms, B_T –1.54 T flat-top, q_{95}=3.6 coupled sawtooth case). [*Reprinted courtesy of AIP, Phys. Plasmas* ***9****, 2051 (2002).*]

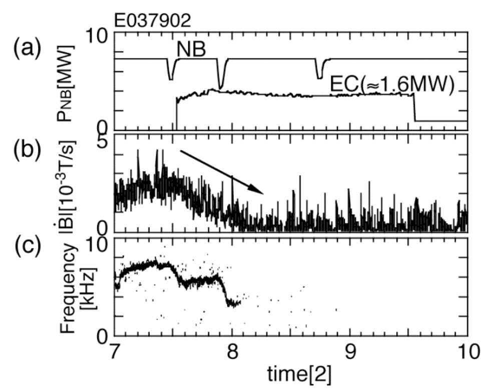

FIGURE 6. (a) Time traces of NB and ECH power in JT-60U. In this discharge, the EC wave mirror angle is set at 43 degrees. (b) Time evolution of amplitude of magnetic perturbations with n=2. (c) Time evolution of frequency of electron temperature perturbations at the magnetic island. [*Reprinted courtesy of IOP, Plasma Phys. and Control. Fusion* ***42****, L37 (2000).*]

Experiments have also been successful in avoiding the m/n=3/2 mode occurring [18,19]. Early "pre-emptive" application of ECCD is applied on JT-60U [18] with the best estimate of the mirror angle for alignment based on previous discharges. Pre-emptive ECCD on DIII-D [19] uses real-time MHD equilibrium reconstruction to determine the q=3/2 surface location and place it on the peak ECCD. The deleterious, long wavelength m/n=2/1 mode has also been completely stabilized or avoided by ECCD in DIII-D [20,21] and ASDEX Upgrade [22].

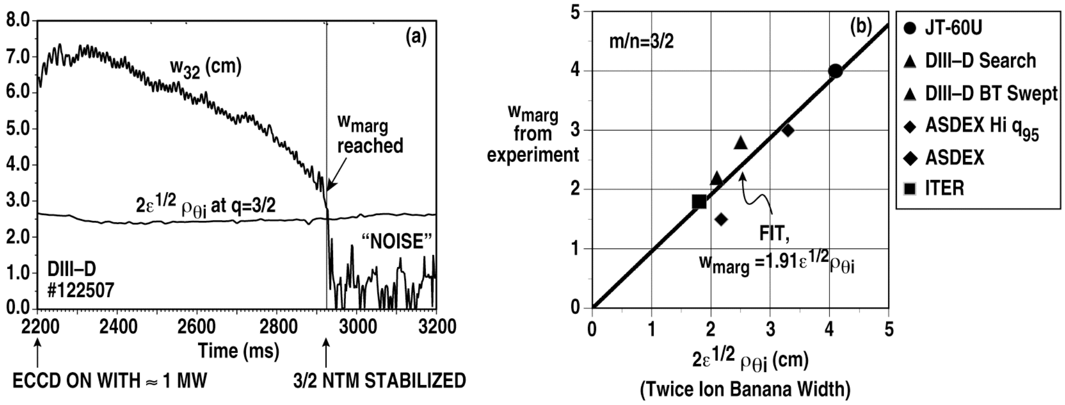

FIGURE 7. (a) Stabilization of an m/n=3/2 NTM in DIII-D by ECCD. The island width w_{32} (from Mirnov analysis calibrated by ECE radiometer) decreases steadily until the marginal condition at just above twice the ion banana width ($2\varepsilon^{1/2}\rho_{\theta i}$) is reached. (b) Marginal island widths for ECCD removal in ASDEX Upgrade (both high q_{95} and ITER similar q_{95}), DIII-D (both with search and suppress alignment and with toroidal field B_T swept as in ASDEX Upgrade), and JT-60U versus twice the ion banana width. Best linear fit has correlation = 0.84. The ITER value of ($2\varepsilon^{1/2}\rho_{\theta i}$) at q=3/2 is also shown. [*Reprinted courtesy of IOP, Nucl. Fusion* ***45****, 451 (2006).*]

STABILIZATION OF NTMs WITH MODULATED ECCD

ASDEX Upgrade has demonstrated control with modulated ECCD phased on the rotating O-points [23]. 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. 8.

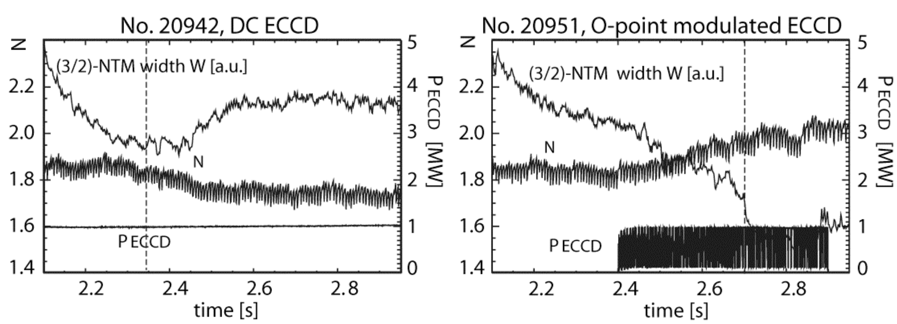

FIGURE 8. Comparison between 2 nearly identical discharges with unmodulated (a) and modulated (b) broad ECCD deposition. Only the B_T ramp has been slightly adapted to match the resonance condition between ECCD and the mode. The vertical dashed lines indicate the time when the resonance is reached and the minimum island size W_{min} is taken. [*Reprinted courtesy of AIP, Phys. Rev. Lett.* ***98****, 205009 (2007).*]

ECCD STABILIZATION OF NTMs ON ITER

ECCD is the primary tool planned for NTM control in ITER [24,25]. Up to 20 MW of rf power at 170 GHz will be injected from upper outer ports. Real-time alignment by aiming the launcher mirrors is planned. A new design using “front” steering reduces the width of the ECCD in the ITER standard scenario [26]. The performance of the different options was analyzed in terms of NTM stabilization efficiency $j_{\rm eccd}/j_{\rm bs}$ in Ref. [27].

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 [17] predicts locking with a full width m/n = 2/1 island of $w_{\rm lock}$ = 5 cm. For “front” steering only 3 MW is needed with perfect alignment for modulated ECCD to reduce w to $w_{\rm marg}$ as shown in Fig. 9. The figure of merit, $j_{\rm eccd}/j_{\rm bs}$, is 0.63 and $\delta_{\rm eccd}/w_{\rm marg}$ = 1.9. The same unmodulated power is as effective [28]. By contrast, 4.3 MW is needed for modulated control of the m/n = 3/2 mode with front steering. The figure of merit, $j_{eccd}/j_{\rm bs}$, is 0.56 and $\delta_{\rm eccd}/w_{\rm marg}$ = 2.4. The total power needed for simultaneous modulated control of both the 3/2 and 2/1 modes is 7.3 MW [28], assuming perfect alignment. Front steering ECCD is narrower, with larger $j_{\rm eccd}$ per MW injected but is thus less tolerant to misalignment. As shown in Fig. 10, 3 MW for $j_{\rm eccd}/j_{\rm bs} = 0.63$ would lead to locking with only $\Delta\rho/\delta_{\rm eccd} \approx$ 0.2. Increasing injected power to 7 MW for $j_{\rm eccd}/j_{\rm bs} = 1.5$ would allow a larger misalignment. In principle, more plasma rotation is desirable to allow yet more tolerance for misalignment.

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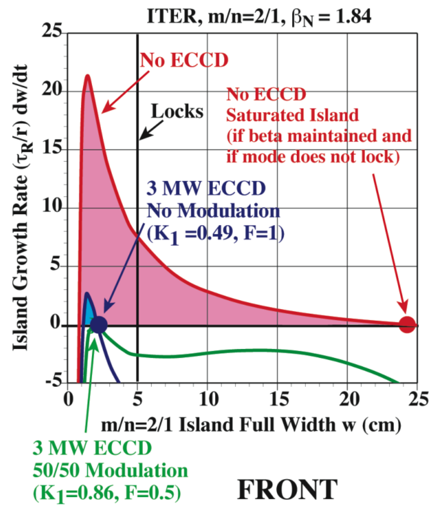

FIGURE 9. Evaluation of the modified Rutherford equation for stability of *m/n*=2/1 with front steering in ITER, with perfect alignment. Plasma without ECCD has a saturated island that well exceeds the critical island for locking. The 50/50 modulated well-aligned co-ECCD of 3 MW injected power has been adjusted to drive the island down in size to just above the marginal island width. For contrast, the predicted effect of the same power without modulation is also shown. *[Reprinted courtesy of IOP, Proc. 21st IAEA Fusion Energy Conf., Chengdu, 2006, EX/P8-12.]*

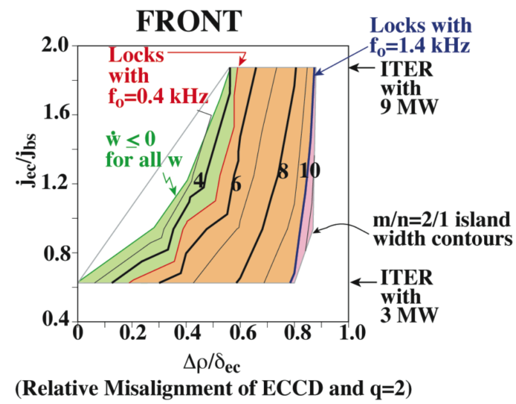

FIGURE 10. Necessary modulated peak ECCD with font steering at *q*=2, normalized to the local bootstrap current density, calculated to regulate *m/n*=2/1 island widths (labeled 2 to 12 cm) vs misalignment with the *q*=2 surface. Here δ_{ec} is the full width half maximum of the ECCD. The predicted island widths for locking with the initial *q*=2 plasma rotations of 0.4 and 1.4 kHz respectively are noted. *[Reprinted courtesy of IOP, Proc. 21st IAEA Fusion Energy Conf., Chengdu, 2006, EX/P8-12.]*

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