Prospects for Stabilization of Neoclassical Tearing Modes by Electron Cyclotron Current Drive in ITER

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Abstract. The system planned for electron cyclotron current drive (ECCD) in ITER can mitigate the deleterious effects of neoclassical tearing modes (NTMs) provided that adequate alignment of the ECCD to the rational surface is maintained or too large a misalignment is corrected on a time scale shorter than the plasma response to "large" islands. Resistive neoclassical tearing modes (NTMs) will be the principal limit on stability and performance in the ITER standard scenario as the drag from rotating island induced eddy current in the resistive wall (particularly from the m/n=2/1 mode) can slow the plasma rotation, produce locking to the wall, and cause loss of high-confinement H-mode and disruption. Continuous wave (cw) ECCD at the island rational surface is successful in stabilization and/or preemption of NTMs in ASDEX Upgrade, DIII-D and JT-60U. Modulating the ECCD so that it is absorbed only on the rotating island O-point is proving successful in recovering effectiveness in ASDEX Upgrade when the ECCD is configured for wider deposition as expected in ITER. The models for the effect of misalignment on both the cw and modulated ECCD effectiveness are applied to ITER. Tolerances for misalignment are presented to establish criteria for both the alignment (by moving mirrors in ITER) in the presence of an island, and for the accuracy of real-time ITER MHD equilibrium reconstruction in the absence of an island, i.e. alignment to the mode or to the rational surface in the absence of the mode. The narrower ECCD with front steering makes the alignment more challenging even though the ECCD is still relatively broad, with current density deposition (full width half maximum) almost twice the marginal island width. This places strict requirements on ECCD alignment with the expected ECCD effectiveness dropping to zero for misalignments as small as 1.7 cm for cw. The system response time for islands transiently exceeding the critical value for locking is also provided for the plasma system controller to be developed. Modeling for ITER based on DIII-D mode locking predicts that an m/n=2/1 island 50% larger than critical would take "only" several seconds to lock in ITER. An alignment resolution error of no more than 1 cm and realignment rate of at least 1 cm/s are required.

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 of ECCD with the island a critical issue.

2. Model for NTM Stabilization by ECCD

NTM islands are destabilized by helically perturbed bootstrap current at the rational surface $q=m/n$. The bootstrap current density j_{boot} is approximately proportional to the plasma pressure gradient and increases with β. NTM stabilization uses co-ECCD to drive off-axis current density j_{eccd} parallel to the total equilibrium current density j_{tot}. ECCD has two stabilizing effects.

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 a duty factor of 1.

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

$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta_0' r + \delta(\Delta' r) + a_2\left(j_{boot}/j_{tot}\right)\left(L_q/w\right)\left[1 - \frac{w_{\text{marg}}^2}{3w^2} - K_1\frac{j_{eccd}}{j_{boot}}\right] \quad , \tag{1}$$

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, $w_{\text{marg}} \approx 2\varepsilon^{1/2}\rho_{\theta i}$ [3]. a_2 is typically fitted to experiment for the saturated island without ECCD and an assumed $\Delta' r = -m$ [3]. K_1 is an effectiveness parameter for replacing the missing bootstrap current that 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. However, K_1 is reduced by the stabilizing effect of co-ECCD on the island O-point being partially cancelled by the destabilizing effect of co-ECCD on the island X-point. Modulated current drive (synchronized with the O-point) has the advantage of higher effectiveness K_1, particularly for wider ECCD. Disadvantages are less reduction in Δ' and the need to synchronize the modulation with the phase of the O-point. For a radial misalignment of the ECCD of $|\Delta\rho/\delta_{eccd}| \gtrsim 0.6{\sim}0.9$, stabilization is lost ($F \lesssim 0$ and $K_1 \lesssim 0$) 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 *all* calculations presented here.

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 $\delta_{eccd} \approx 2\varepsilon^{1/2}\rho_{\theta i}$, 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 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]. In general, control techniques and modeling for dealing with the $m/n=3/2$ NTM have been successfully applied to the more deleterious $m/n=2/1$ NTM. 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. 1 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 in such a way as to be absorbed near and just outboard of the cyclotron resonance.

Experiments on ASDEX Upgrade, DIII-D and JT-60U show that all the elements needed for ECCD stabilization of NTMs in ITER are proven. This includes: (1) changing the mirror angle in real-time for placing the ECCD on the island O-point (JT-60U), (2) modulation of the ECCD on the O-point to increase the effectiveness of suppression if the ECCD is relatively broad (ASDEX Upgrade), and (3) pre-empting the onset, i.e. avoiding an NTM, by early application of ECCD without a mode and using accurate real-time MHD equilibrium reconstruction (real-time EFIT) with a motional Stark effect (MSE) diagnostic to determine and adjust the relative locations of the rational surface and the ECCD ("active tracking") in DIII-D. Extensive benchmarking of the physics in Eq. (1) has been done for modeling ECCD control of NTMs in ITER (Refs. 3, 17 for example).

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. The real-time Fourier analysis of the ECE channels gives the mode frequency; the radial profile of the amplitude and phase at this frequency allows identification of the O-point location. The O-point is mapped into the view of the EC wave (Fig. 2) by MHD reconstruction and the mirror tilted for alignment in real-time [16].

ASDEX Upgrade has demonstrated control with modulated ECCD phased on the rotating O-points [18]. 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. 3.

DIII-D shows that with pre-emptive ECCD and real-time MSE EFIT used for alignment ("active tracking") NTMs can be avoided from ever occurring [17,19,20]. This is shown in Fig. 4. The modeling with the MRE of Eq. (1) is quite good in getting the stable region correctly. Note that in the absence of a mode, the complicating effects of an island on Δ'_0, i.e. $\Delta'_0(w)$, and of broadening the ECCD, i.e. $\delta_{eccd}(w)$ and $j_{eccd}(w)$, are absent.

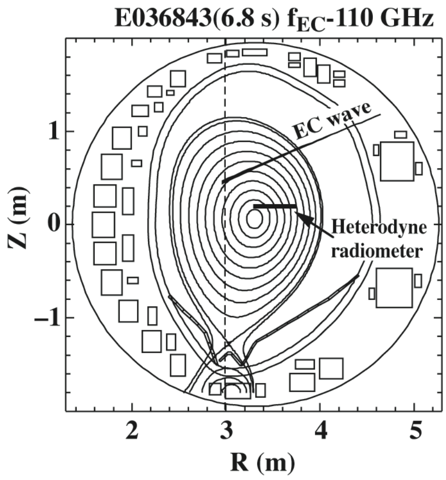

FIG. 1. Shape of the plasma cross section in the JT-60U tearing mode stabilization experiment. Rays of EC wave and measurement range of the heterodyne radiometer are also shown in this figure. [*Reprinted courtesy of IOP, Plasma Phys. and Control. Fusion* ***42****, L37 (2000)*].

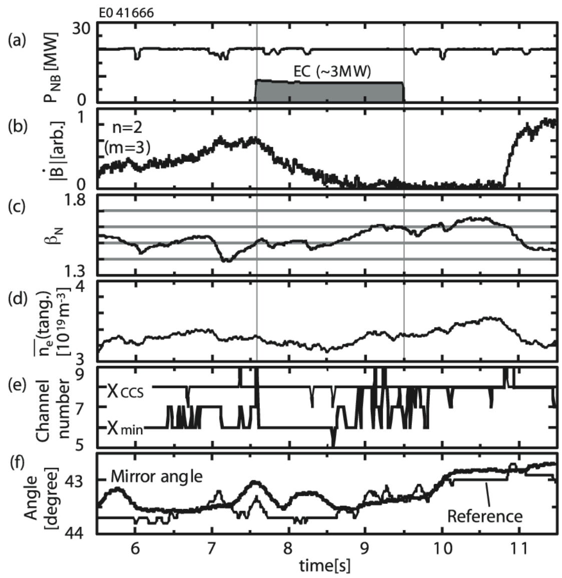

FIG. 2. Typical waveforms of a real-time NTM stabilization experiment in JT-60U: (a) injection power of NBs and EC wave, (b) amplitude of magnetic perturbations with n=2, (c) normalized beta, (d) line-average electron density, (e) channel number of the heterodyne radiometer, (f) mirror angle of the steerable mirror and reference angle. [Reprinted from Ref. 16.]

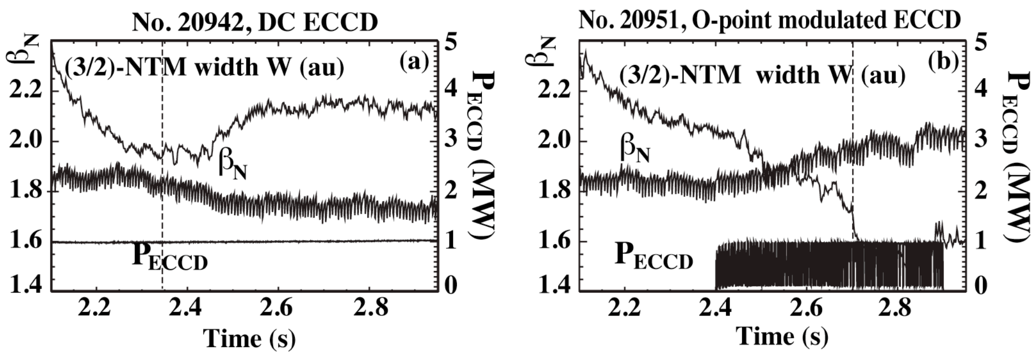

FIG. 3. Comparison between nearly identical discharges in ASDEX Upgrade with unmodulated (a) and modulated (b) broad ECCD. Only the B_T ramp has been slightly adapted to match the resonance condition between ECCD and the mode. The vertical dashed lines indicate the time when the resonance is reached and the minimum island size W_{min} is taken. [*Reprinted courtesy of AIP, Phys. Rev. Lett.* ***98****, 205009 (2007).*]

4. Background on ECCD Stabilization of *m/n=2/1* NTMs on ITER

ECCD is the primary tool planned for NTM control in ITER [22,23]. 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. [24]. Partial stabilization and controlling NTMs at small size in burning plasmas are considered in Ref. [25].

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 with the anticipated plasma rotation of 420 Hz at $q=2$.

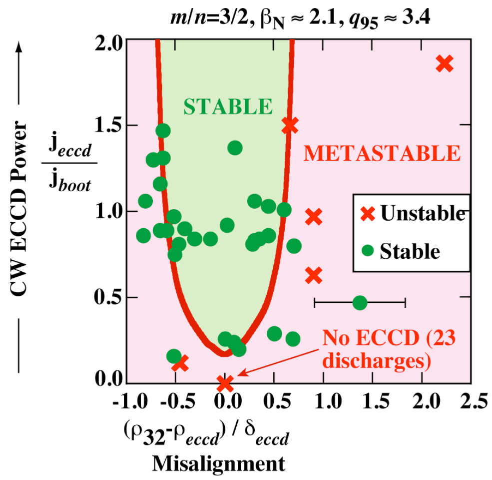

FIG. 4. Pre-emptive ECCD in DIII-D avoids m/n=3/2 NTM ever occurring. $\delta_{eccd}/2\varepsilon^{1/2}\rho_{\theta i} \approx$ 1.2. Green solid circle points are stable at potentially seeding sawteeth crashes. Red X points are 3/2 NTM destabilized. The red curve is the boundary dw/dt=0 at $w=w_{marg}$ from the MRE. [Reprinted from Ref. 19.]

For perfect alignment of the ECCD on $q=2$, 3 MW of peak modulated ECCD removes the unstable parameter space as shown in Fig. 5 [3,17]. The same 3 MW of cw ECCD is almost as good; the reduced effectiveness in replacing the missing bootstrap current is compensated by being twice as effective in reducing Δ'. The $\lesssim$2 cm resulting islands would be less than the predicted 5 cm island that locks and very much less than the "saturated" island of 24 cm. 3.5 MW is needed with perfect alignment for cw ECCD to reduce w to w_{marg} as shown in Fig. 6. The figure of merit, j_{eccd}/j_{boot}, is 0.73. Thus the 2/1 NTM would be linearly and nonlinearly stable. Misalignment reduces the NTM control effectiveness and thus more ECCD power is needed as shown in Fig. 6 for the cw case. With $|\Delta\rho|/\delta_{eccd} \gtrsim$ 0.6 and thus $|\Delta R| \gtrsim$ 1.5 cm misalignment in major radius, no amount of ECCD power will suppress the 2/1 mode below the 5 cm locking limit.

While the presence of an $m/n=2/1$ island can reduce the energy confinement τ_E, the drag on the rotation from eddy currents in the vessel wall can slow the island rotation enough to bring it to a stop; H-mode is then usually lost as a result of the island growing yet larger. The size of the island that locks scales as the two thirds power of the initial island rotation [3]. A conservative estimate is that ω_o is given by the plasma rotation anticipated at $q=2$ but this is itself based on assumptions that ITER energy and momentum transport are equal and that the frame of zero island rotation is that of the plasma rotation, not necessarily true at "low" rotation [26]. Integrating the MRE dw/dt of Fig. 5 *without ECCD* one gets $w(t)$ as shown in Fig. 7. Initial island rotations of 420 and 1400 Hz are contrasted with the rotation decreasing until zero by solving Eq. (7) of Ref. 3 for the anticipated ITER parameters. While the critical island widths for locking are 5 and 10 cm respectively, the dynamic locking occurs at about 8 and 12 cm in about 4 and 11 s respectively. More initial rotation with more torque allows the island size and time to lock to be larger, but locking still occurs.

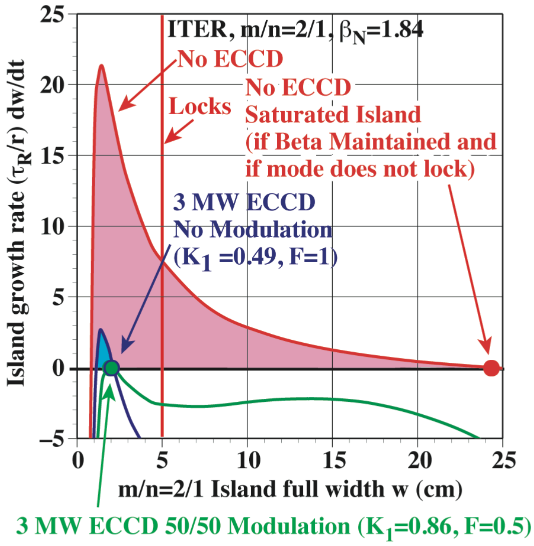

FIG. 5. Evaluation of the MRE for m/n=2/1 NTM in ITER. Locking occurs with an island of size w_{lock} = 5 cm << w_{sat} ≈ 24 cm, the expected saturated island width without ECCD. 3 MW of ECCD without misalignment is equally effective with cw or 50/50 modulation ($\delta_{eccd}/w_{\text{marg}}$ = 1.8, j_{eccd}/j_{boot} = 0.63, $\Delta\rho/\delta_{eccd}$ = 0).

5. Active Control of m/n=2/1 NTM by ECCD in ITER

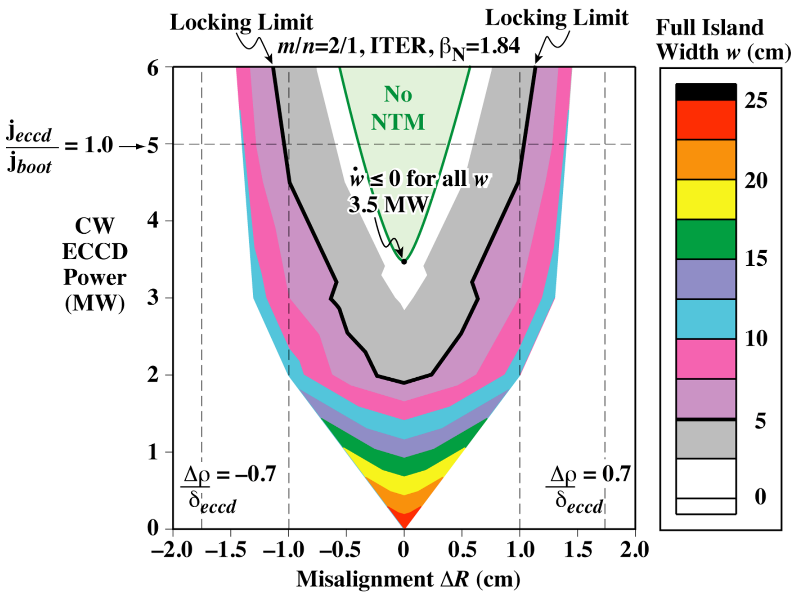

FIG. 6. Variation of m/n=2/1 island width in ITER with cw power and misalignment. For ΔR=0, 3.5 MW, (j_{eccd}/j_{boot}=0.73) is needed for complete stability. Above the green curve, $\dot{w}$ < 0 for all w and the NTM is stable. The 5 cm island locking is highlighted (solid black line) and occurs about $|\Delta R|$ = 1 cm for 5 MW.

The plasma control system (PCS) in ITER must either actively track the rational surface without the mode to better than 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. Good alignment is key for prompt suppression of an existing island and avoiding mode locking. The full 2/1 island width $w(t)$ is shown in Fig. 8 for no ECCD and for 5 MW of cw ECCD (j_{eccd}/j_{boot} ≈ 1 at $q=2$) applied at the peak growth rate time of 0.26 s (w = 1.43 cm) vs misalignment ΔR. Prompt suppression occurs for perfect alignment. For less than perfect alignment, the island size is limited unless |Δ*R*| ≳ 2 cm. Avoiding mode locking requires |Δ*R*| ≲1 cm at *f*(0) = 420 Hz.

Alignment of the ECCD on the island with an *m*/*n*=*2*/*1* mode present needs to be done "dynamically" by the ITER plasma control system (PCS) at small amplitude to avoid locking. Detection of a growing mode will have to be done by real-time Fourier analysis of arrays of external Mirnov probes (to discriminate at least the toroidal *n* number if not also the poloidal *m* number) as the planned ITER ECE system may not be able to discriminate the mode number *n*. ECE on ITER will also be unable to accurately locate the O-point, unlike what is done on JT-60U, as the radial resolution of Δ*R* ≈ 5 cm is too large [27] for resolving small islands. As $w \propto |\tilde{B}_\theta|^{1/2}$, the *n=1* Mirnov amplitude is a good quantity for control, provided the "noise" from periodic *m*/*n*=*1*/*1* sawteeth (at higher frequency than *m*/*n*=*2*/*1*) and ELMs (broad *n* including *n*=*1*) can be discriminated.

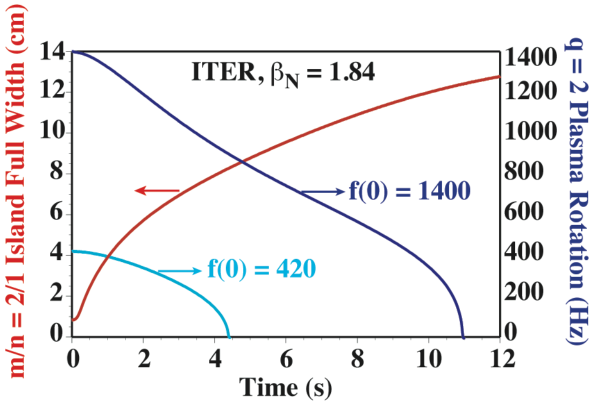

FIG. 7. Without ECCD, an *m*/*n*=*2*/*1* island grows from a minimum initial level in ITER as found by integrating the MRE of Fig. 5 (τ_R/r = 4.4 s/cm). Also shown is the plasma rotation at *q*=2 for initial rotations of 420 and 1400 Hz found from the Nave-Wesson wall drag model elaborated on in Ref. 3.

ITER front steering mirrors are proven to be steerable ±6° in 2 s with a precision of ±0.025° [28]. This is equivalent to |δ*R*/δ*t*| ≲ 1.7 cm/0.1 s at *q*=*2* with a precision of ±0.07 cm. The steering uncertainty is small (i.e. good) compared to the alignment requirement of |Δ*R*| ≲ 0.5 cm, and the sweep time is short (i.e. good) compared to the locking time provided that the PCS can actively and precisely command the position of the mirrors.

In existing devices, an initially "saturated" mode with *dw*/*dt*≈0 is allowed to form, a lower power ECCD is applied with a known large misalignment to one side, and a slow sweep is made of the alignment to find the optimum alignment without complete suppression. With higher power ECCD, the mode is stabilized with the optimum alignment. In DIII-D, upon stabilization, active tracking with the real-time MSE EFIT can monitor changes in both the location of *q* and of the ECCD and adjust to maintain alignment [29]; note that *q* can change location due to periodic *m*/*n*=*1*/*1* sawteeth [and thus variation in *q*(0)] and/or variation in beta poloidal, and the ECCD can change location due to different refraction from changes in the line-averaged density and/or density profile [20].

The ITER PCS must find and lock onto the optimum alignment with a small and initially growing mode and hand over to active tracking without the mode to maintain stabilization with ECCD. A fast controller in DIII-D uses the "target lock" method [30] in which the toroidal field is given a small sweep up and down and back (to move

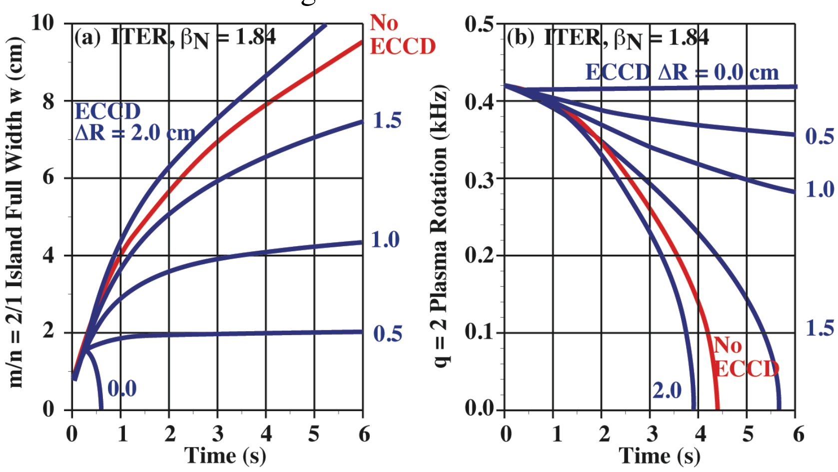

FIG. 8. (a) Island growth with time for no ECCD or with cw ECCD of 5 MW (j_{eccd}/j_{boot} = 1.0 at *q*=2) for different misalignments Δ*R* (δ_{eccd}/w_{marg} = 2.5/1.4 in cm). (b) *q*=2 island rotation with time for f_o = 0.42 kHz using drag from islands of (a).

the ECCD in the presence of a mode), the Mirnov signal response is noted, and the toroidal field is then adjusted for best alignment. This would be done by sweeping the mirror in ITER. A control scenario for ITER is shown in Fig. 9 assuming an initial ("large") misalignment of $\Delta R = -2$ cm and the PCS, while not knowing what this value is, knows on which side it is as is done for the B_T sweep in ASDEX Upgrade for example. Figure 9(a) shows the different stages of control: (1) a mode grows without ECCD, (2) ECCD is applied with a short dwell in mirror tilt to evaluate if the ECCD is stabilizing (it is not), (3) the PCS orders the mirrors to sweep $\delta R = +4$ cm at the achievable rate of 1.7 cm/0.1 s, i.e. +4 cm in 0.24 s, (4) the PCS monitors the small dip and the large change in the time variation in the *n=1* Mirnov amplitude to determine the optimum δR (which is here $\delta R = +2$ cm to compensate for the initially unknown $\Delta R = -2$ cm), (5) the PCS orders the mirrors to tilt back to this optimum by $\delta R = -2$ cm in 0.12 s (at the fastest rate) and holds this alignment which should with $\Delta R \approx 0$ yield complete stabilization, and finally (6) the PCS hands over to active tracking when the *n=1* Mirnov amplitude goes below a preset minimum level just above the resolvable noise amplitude of the array.

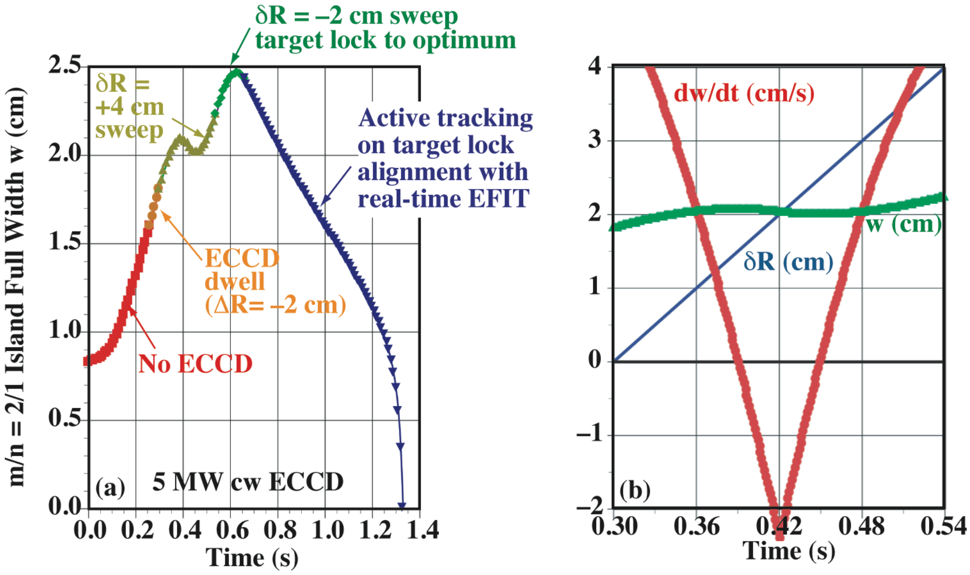

FIG. 9. Scenario for the ITER PCS to find and "target lock" on the optimum alignment for *m/n=2/1* stabilization assuming an initial misalignment of $\Delta R = -2$ cm. (a) All the steps in the alignment and stabilization, (b) details of the sweep to find the optimum mirror tilt.

6. Conclusions

The prospects are good for stabilizing both the *m/n=2/1* NTM in ITER by ECCD and the other principal mode of concern, *m/n=3/2*, not discussed here but generally of less consequence and easier to deal with. The front steering launch has narrow enough ECCD to reach the figure of merit of $j_{eccd}/j_{boot} \approx 1$ at $q=2$ in the ITER standard scenario 2 with only 5 MW of the 20 MW available for injection; this leaves power available for the *m/n=3/2* mode and the 4/3 and 5/4 control if deemed necessary (which are of even less consequence on energy confinement). Issues are: (1) can the radial resolution of the ITER ECE be improved enough to be useful for accurate location of small islands, (2) can the real-time Fourier analysis of Mirnov amplitude be made accurate and discriminatory enough to properly find the minimum in the rate of change of the n=1 Mirnov amplitude on a mirror sweep, and (3) can the real-time equilibrium reconstruction determine q location to $\lesssim 1$ cm which is comparable to existing devices but three times relatively smaller? Modulated ECCD may be beneficial in the presence of a mode in having both reduced average power and somewhat less sensitivity to misalignment.

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