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REQUIREMENTS FOR ALIGNMENT OF ELECTRON CYCLOTRON CURRENT DRIVE FOR NEOCLASSICAL TEARING MODE STABILIZATION IN ITER

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ABSTRACT

ITER relies on electron cyclotron stabilization of neoclassical tearing mode islands. The large size and low torque applied in ITER make for slow plasma rotation and susceptibility to island locking by the resistive wall; locking is likely to lead to a loss of the high confinement H-mode, a beta collapse, and possibly disruption. “Front” steering, with narrower electron cyclotron current drive, has resolved the issue in “remote” steering of being too broad and ineffective. However, narrower current drive places demands on alignment of the current drive on the rational surface being stabilized. DIII-D alignment techniques, with and without (preemptive) an island are reviewed. The results are used to check models for the effect of misalignment and are then applied to ITER. Criteria for accuracy of alignment as a function of injected power and for the necessary time response of the controller are presented.

I. INTRODUCTION

A recent change in the electron-cyclotron current drive (ECCD) launcher scheme in ITER from “remote” to “front” steering has narrowed the expected ECCD 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]. However, the narrower ECCD makes the alignment more challenging.

Experiment shows that the marginal island w_{marg} for NTM stabilization is about twice the ion banana width [3], which is only 1–2 cm in ITER. With front steering, the ECCD is still relatively broad, with current deposition full width half maximum $\delta_{eccd} \sim (5/3) w_{marg}$.

DIII-D alignment results [4-7] confirm models for the effect of misalignment on the ECCD effectiveness. Tolerances for misalignment in ITER [8] are presented to establish criteria for both the alignment (by moving mirrors) in the presence of an island, and for the accuracy of real-time ITER magnetohydrodynamic (MHD) equilibrium reconstruction. The time for an $m/n=2/1$ island to lock is contrasted with the rate of decay of an island by using ECCD with different misalignment.

II. MODEL FOR NTM STABILIZATION BY ECCD

The first stabilizing effect is increasing the classical linear stability, i.e., making Δ' more negative. ECCD of peak off-axis current density j_{eccd} changes the total local equilibrium current density j_{tot} [9,10]. In this paper, all current drive widths of an assumed off-axis Gaussian are taken as *full width half-maximum* (FWHM) δ_{eccd}. L_q is the local magnetic shear length, $q/(dq/dr)$. Following the perturbation model of Ref. [9], the change in Δ' is $\delta(\Delta' r) \approx -\left(5\pi^{3/2}/32\right) F\, a_2 \left(L_q/\delta_{eccd}\right)\left(j_{eccd}/j_{tot}\right)$ 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 $q = m/n$). The factor F depends on alignment and duty cycle. $F = 1$ for perfect alignment and duty cycle $\tau = 1$. A radial misalignment $\Delta\rho$ between the ECCD and the $q = m/n$ rational surface of $\left|\Delta\rho/\delta_{eccd} \approx 3/5\right|$ would negate the stabilizing effect [8], i.e. $F \approx 0$.

The other stabilizing effect of ECCD is to replace the "missing" bootstrap current where j_{boot} is the unperturbed bootstrap current [11-14]. The modified Rutherford equation (MRE) for the island growth rate with both effects is

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

where the width of the most unstable (highest dw/dt) island is w_{marg} which arises from small island stabilizing effects [8]; 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]. 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 pre-emptively 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 cycle τ has the advantages of higher effectiveness K_1, particularly for wider ECCD. Disadvantages are a factor τ smaller $\delta(\Delta' r)$.

III. REVIEW OF DIII-D ALIGNMENT TECHNIQUES

DIII-D alignment of peak off-axis electron cyclotron current drive and the $q = m/n$ rational surface being stabilized has used several methods: (1) varying the fixed toroidal field B_{tor} from shot-to-shot to move the ECCD with respect to q and maximize the Mirnov decay rate [4], (2) “search and suppress” in the real-time plasma control system (PCS) to dynamically change either the plasma major radius R_{surf} or B_{tor} in small steps so as to minimize the $n = 2$ or 1 Mirnov amplitude and maximize the decay rate [4], and (3) “active tracking” *without* a mode, in which the PCS uses real-time MHD reconstruction (EFIT) with the motional Stark effect (MSE) diagnostic of internal magnetic pitch angle to accurately locate the q surface [5,7] *and* an algorithm for compensating for refraction of the ECCD from a pre-calculated TORAY-GA code prediction of the ECCD location [7,15]; either R_{surf} or B_{tor} is then adjusted. Methods (1) and (2) stabilize an existing island while method (3) preempts or avoids the island occurring. Existing islands can complicate modeling of stabilization and indeed impede the actual stabilization. Islands can make Δ' a function of w [16,17]. The island can broaden the ECCD reducing the peak j_{eccd} from what it would otherwise be [18,19]. Multiple islands can “mode-lock” and nonlinearly couple [20,21]. Early, preemptive ECCD before a mode would otherwise occur obviates these effects.

All alignment techniques developed in DIII-D for the $m/n = 3/2$ mode have been successfully applied to the more deleterious $m/n = 2/1$ NTM [6,7]. Typical misalignments of $\Delta R \approx 1$ cm $\left(|\Delta\rho|/\delta_{eccd} \approx 0.3\right)$ are significant. In general, the theory used in modeling has proved successful in DIII-D experimental design and analysis except where the initial island width is much larger than the calculated current drive width, a situation not expected in ITER. The DIII-D NTM control system is discussed in more technical detail in Ref. [22].

IV. MODELING NTM CONTROL BY ECCD IN ITER

A. Island limit for locking in ITER

The large size and low torque input in ITER make for slow plasma rotation [23] and susceptibility for eddy currents in the vacuum vessel wall induced by rotating islands to exert drag on the island that can stop the plasma rotation [3,24]. The Nave and Wesson resistive wall theory [24] is adapted for shaped tokamaks in Ref. [3] and yields an equation for the island size that locks.

$$\left(\frac{w}{a}\right)^3 \left(1 + C_M \, w/a\right) \geq \frac{m C_W \omega_o{}^2 \, \tau_{Ao}^2}{4} \left(\frac{\tau_w}{\tau_{Eo}}\right) \quad . \tag{2}$$

Parameters are fitted and given in Ref. [3] but key here is ω_o which is the angular plasma rotation frequency at $q = 2$ without an island. For the standard ITER Scenario 2 plasma with $\beta_N = 1.84$, $\omega_o/2\pi = 420$ Hz from ASTRA and $w_{lock} \approx 5$ cm for the $m/n = 2/1$ NTM. The predicted time dependent evolution of the plasma rotation in ITER is shown in Fig. 1; islands of different size are turned on and the time dependent equation for rotation, Eq. (7) in Ref. [3], is solved. At $w = 5$ cm, it takes an essentially infinite time to lock. However for slightly larger islands, the transition to locking (the knee in the curves at ≈ 100 Hz) occurs in several seconds. This sets a limit on the $m/n = 2/1$ island size and a time-scale for the ECCD to align to and suppress the mode.

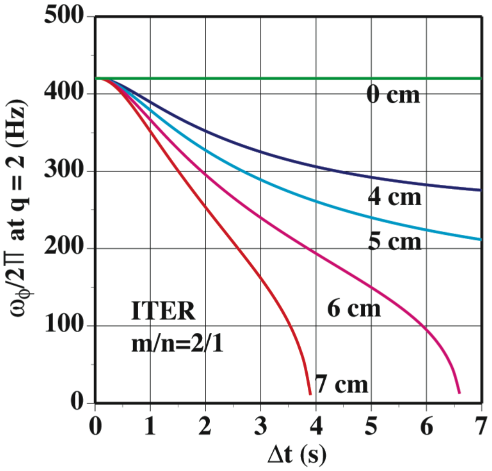

Fig. 1. Calculated effect on rotation of $m/n = 2/1$ islands of different sizes in ITER. Islands larger than 5 cm lead to locking.

B. ECCD suppression of the m/n=21 NTM in ITER

The MRE is evaluated for ITER for the $m/n = 2/1$ mode: (1) without ECCD, (2) with 50/50 modulated ECCD power adjusted to 3 MW to give $dw/dt \lesssim 0$ at all w with no misalignment, and (3) the same cw ECCD power of 3 MW. The parameters are given in Ref. [3] except that the change to front steering with narrower ECCD is used [1,25-27]. Using $\delta_{eccd}/w_{marg} = 1.8$ and $j_{eccd}/j_{boot} = 0.63$ with $\Delta\rho/\delta_{eccd} \equiv 0$, as shown in Fig. 2, the cw and modulated controls are just as effective; there is a trade off of stabilizing effects as the cw with $\tau = 1$ has twice the $\delta(\Delta' r)$ as the modulated with $\tau = 0.5$, while the effectiveness K_1 in replacing the missing bootstrap current is about twice as large with modulation. Increasing the cw EC power to 3.5 MW would make $dw/dt \lesssim 0$ for all w, not shown. Similar calculations are done for the $m/n = 3/2$ NTM in ITER in Ref. [27].

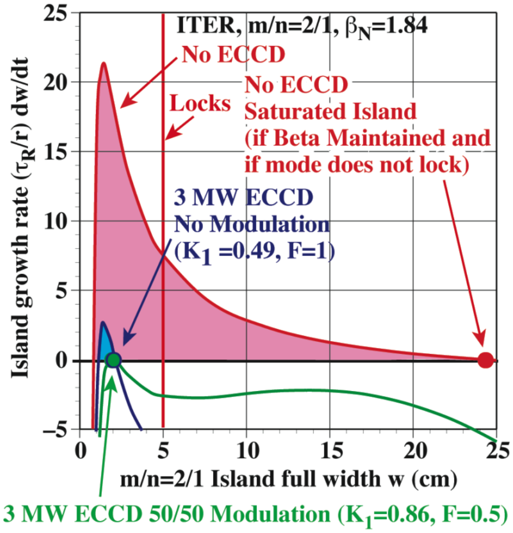

Fig. 2. Evaluation of the MRE for $m/n = 2/1$ NTM in ITER. Locking occurs with $w_{lock} = 5$ cm $<< w_{sat} \approx 24$ cm without ECCD. 3 MW of ECCD without misalignment is equally effective with cw or 50/50 modulation. $(\delta_{eccd}/w_{marg} = 1.8,\ j_{eccd}/j_{boot} = 0.63,\ \Delta\rho/\delta_{eccd}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

Misalignment reduces the NTM control effectiveness and thus more ECCD power is needed as shown in Fig. 3. 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.

The plasma control system in ITER must either actively track without the mode to better than 1 cm accuracy, or in the presence of a growing mode, identify it, optimize the alignment, and rapidly suppress it. Smaller, better-aligned islands should respond faster to the ECCD as shown in Fig. 4 for 9 MW cw ECCD with $j_{eccd}/j_{boot} = 1.9$. Comparison of Figs. 1 (the "problem") and 4 (the "solution") give time scales for the controller. Clearly if ΔR is too big the controller response is too slow to avoid locking for $w > 5$ cm. Figures 3 and 4 suggest using a variation of search and suppress called "target lock" [28]. The mirrors could be given small "fast" oscillations, the response on the Mirnov or electron cyclotron emission diagnostics determined, and the alignment adjusted on a "slower" time scale. As in DIII-D, if the mode were stabilized or went below a preset level, active tracking would take over to maintain alignment.

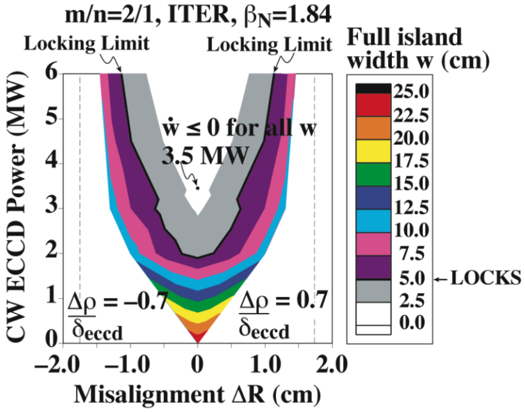

Fig. 3. Variation of $m/n = 2/1$ island width in ITER with cw ECCD power and misalignment. For $\Delta R \equiv 0$ and 3.5 MW, $j_{eccd}/j_{boot} = 0.73$ and all w have $dw/dt \lesssim 0$. The 5 cm locking limit is highlighted.

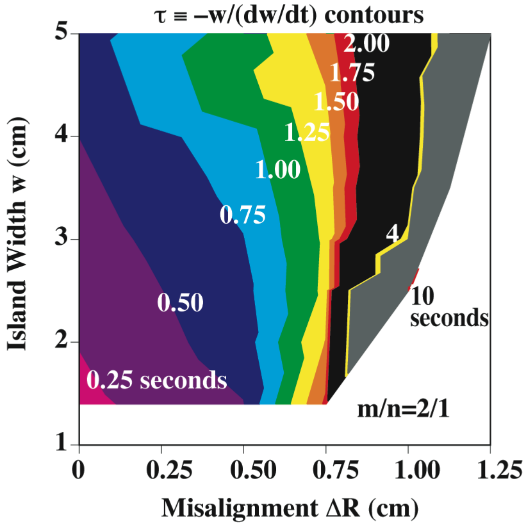

Fig. 4. Contours of the characteristic decay time of islands, vs island width and misalignment. (9 MW cw, $j_{eccd}/j_{boot} = 1.9$, $\delta_{eccd}/w_{marg} = 1.9$, $\tau_R/r = 440$ s/m.)

V. CONCLUSIONS

The narrower front steering has reduced the necessary power for ECCD control of NTMs in ITER. For no misalignment and cw ECCD, for example, the $m/n = 2/1$ NTM has $dw/dt < 0$ for all w for 3.5 MW at $j_{eccd}/j_{boot} = 0.73$. (For the similar analysis of the $m/n = 3/2$ mode, 6.1 MW is necessary at $j_{eccd}/j_{boot} = 0.78$). A total injected power of 10 MW out of 20 available is necessary for complete stabilization of both modes, *with no misalignment*.

Locking of the $m/n = 2/1$ mode is predicted to occur at island sizes of only 5 cm, much smaller than the otherwise saturated island of 24 cm. Increasing the cw ECCD power directed at $q = 2$ to 9 MW, would allow misalignments up to $|\Delta R| \approx 1.5$ cm $\left(|\Delta\rho|/\delta_{eccd} \approx 0.6\right)$ at the locking condition. However, the time response of the ECCD control would be slow compared to the time for islands to lock. A fast controller in DIII-D is “target lock” [28] in which the toroidal field is given a small sweep, the Mirnov signal response is noted, and the search and suppress is then adjusted for best alignment. For preemptive control without an island, the real-time equilibrium reconstruction in ITER will have to do at least as well as the 1 cm uncertainty in DIII-D, if not better.

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