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# Evaluating Electron Cyclotron Current Drive Stabilization of Neoclassical Tearing Modes in ITER: Implications of Experiments in ASDEX Ugrade, DIII-D, JET, and JT-60U

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**Abstract.** Resistive neoclassical tearing mode (NTM) islands will be the principal limit on stability and performance in the ITER standard scenario as beta is well below the ideal kink limit. NTM island control in ITER is predicted to be challenging both because of the relatively narrower marginal island widths and the relatively broader electron cyclotron current drive (ECCD). Measurements from ASDEX Upgrade, DIII-D, and JET in beta rampdown experiments were used to determine the marginal island size for m/n=3/2 NTM removal. This is compared to data from ASDEX Upgrade, DIII-D and JT-60U with elimination of the m/n=3/2 island by continuous ECCD at near constant beta. The empirical marginal island size is consistent in both sets of removal experiments and found to be about twice the ion banana width. A common methodology is developed for fitting the saturated m/n=3/2 island before (or without) ECCD in all four experimental devices. To this is added (and model tested to experiments) the effect of unmodulated co-ECCD on island stabilization including both replacing the missing bootstrap current and making the classical tearing stability index more negative. The experimentally benchmarked model is then used to evaluate ITER. The ITER ECCD upper launcher with up to 20 MW of injected power is appraised with or without modulation for the m/n=2/1 NTM (which can lock to the resistive wall and induce disruption). An m/n=2/1 rotating island model with drag from eddy current induced in the resistive wall is used to predict the necessary ECCD with "remote" steering to keep the island from locking as a function of the rotation in ITER. This relatively wide ECCD should be capable of regulating the 2/1 island width to avoid mode locking with the anticipated rotation in ITER but there is little margin available for inevitable misalignment and little EC power remaining for 3/2 island control. Narrower ECCD with "front" steering and/or more rotation in ITER would increase confidence in island control and successful operation.

## 1. Introduction

Neoclassical tearing mode (NTM) islands will place the principal limit on stability in ITER in the standard scenario, which is projected to operate well below the ideal kink $\beta$ limit. NTM control in ITER is predicted to be challenging both because the marginal island widths are narrower and the electron cyclotron current drive (ECCD) is broader than in present devices. Existing devices (ASDEX Upgrade, DIII-D, and JT-60U) demonstrate that NTMs can be suppressed or avoided by applying continuous ECCD that is well aligned with the island or rational surface. In addition, an NTM can *potentially* be limited in size (mitigated in effect) by ECCD with less peak power modulated in phase with the island O-point. Benchmarking of the physics of the m/n=3/2 mode in existing devices (including JET) allows better prediction of the ECCD power needed for stabilization in ITER for both this mode and also for the more deleterious m/n=2/1 NTM (for which neither the tearing mode physics nor the stabilization experiments are yet as advanced in standard $q_{95} \gtrsim 3$ sawtoothing plasmas). In this paper, we show that the relatively wide ECCD in ITER should be able to regulate the island widths and avoid mode locking (with the anticipated rotation in ITER) but there is little margin available for inevitable misalignment. Narrower ECCD from front steering in ITER would require less power but reduce the tolerance on misalignment.

## 2. Marginal Island Size and Physics of ECCD Stabilization

The NTM island with poloidal mode number m=3 and toroidal mode number n=2 has received the most experimental study to-date in the areas of: (1) determination of the marginal island size $w_{\text{marg}}$ by beta rampdowns [1], (2) NTM stabilization by continuous electron cyclotron co-current drive of a previously saturated 3/2 NTM island [2-5], and (3) pre-emptive avoidance of NTMs using ECCD [6,7]. The empirical marginal island size is consistent in both sets of removal experiments and found to be about twice the ion banana width [8]. The scaling for the marginal island with ECCD is shown in Fig. 1.

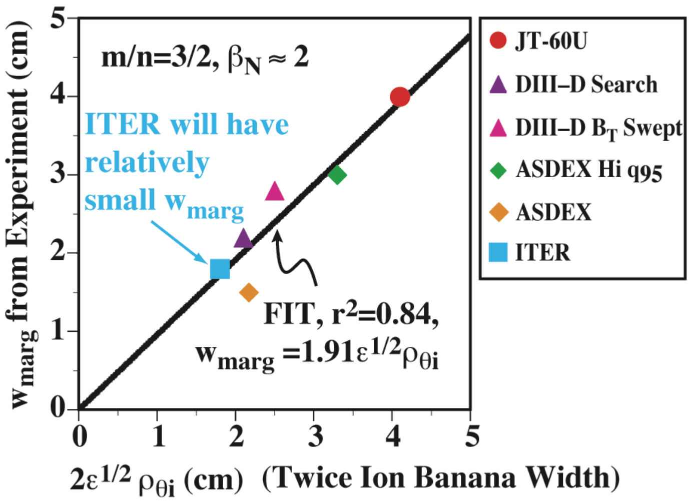


FIG. 1. Marginal island widths (in cm) for ECCD removal in ASDEX Upgrade (both high $q_{95}$ and ITER similar $q_{95}$), DIII-D (both with search and suppress alignment and with toroidal field $B_T$ swept as in ASDEX Upgrade), and JT-60U versus twice the ion banana width. Best linear fit has correlation $r^2 = 0.84$. The ITER value of $2\varepsilon^{1/2}\rho_{\theta i}$ at $q = 3/2$ is shown. [Reprinted courtesy of IOP, Nucl. Fusion **46**, 451 (2006).]

For modeling and benchmarking of both saturated islands without ECCD and of stabilization with ECCD, the modified Rutherford equation is [8] evaluated for mode $q = \text{m/n} = 3/2$,

$$\frac{\tau_R}{r}\left(\frac{dw}{dt}\right) = \Delta'_0 r + \delta\Delta' r + a_2 \frac{j_{bs}}{j_{\parallel}}\left(\frac{L_q}{w}\right)\left(1 - \frac{w_{\text{marg}}^2}{3w^2} - K_1 \frac{j_{ec}}{j_{bs}}\right) \quad , \tag{1}$$

where $\tau_R$ is a resistive time, $r$ is the mode rational surface minor radius, $w$ is the full width of the island, $\Delta'_0 r$ is the classical tearing index in absence of ECCD, $a_2$ is a shaping parameter of order 4 to be fitted, $j_{bs}$is the local bootstrap current, and $j_{\parallel}$ is the local total parallel current density. The parameters $\delta\Delta' r$, $K_1$, and $j_{ec}$ for ECCD will be defined later. A common methodology is developed for fitting the saturated m/n=3/2 island without ECCD in all four experimental devices to the modified Rutherford equation for stability. "Saturated" ($dw/dt = 0$) m/n = 3/2 islands without ECCD are used to fit the quantity $a_2/(-\Delta'_0 r)$ with Eq. (1). Selected quantities and the fitted equation are given in Table I and Fig. 2. Note that the saturated island increases with device size and that there is a region of $dw/dt > 0$ in each case. $a_2/(-\Delta'_0 r) = 0.8$, 1.3, 1.2, and 1.0 respectively for ASDEX Upgrade, DIII-D, JET, and JT-60U, yielding an average of $a_2$ = 3.2 for $\Delta'_0 r \equiv -3$ for ITER modeling.

The effect of unmodulated co-ECCD on island stabilization including both replacing the missing bootstrap current and making the classical tearing stability index more negative can then be evaluated. Details of the model are given in Ref. [8]. Assuming good alignment between the rational $q$ surface and the peak co-current drive density $j_{ec}$, one can consider which effect is more useful and whether modulating the ECCD to be absorbed only on the island O-point has an advantage over continuous current drive. Both effects favor narrower current drive if alignment can be maintained. The change $\delta\Delta' r$ in the classical tearing index is proportional to $-j_{ec}/\delta_{ec}$ where $\delta_{ec}$ is here defined as the full width half maximum in radius. As $j_{ec} \propto P_{ec}/\delta_{ec}$, $\delta\Delta' r \propto P_{ec}/\delta_{ec}^2$ where $P_{ec}$ is the peak rf power. However, a 50% modulation would decrease $\delta\Delta' r$ by a half. The effectiveness $K_1$ in replacing the "missing" bootstrap current is insensitive to width for marginal island widths with $w_{marg}/\delta_{ec} \gtrsim 1$ with continuous current drive but much reduced and nearly linear in $w/\delta_{ec}$ for $w_{marg}/\delta_{ec} \lesssim 0.6$ as expected in ITER with either remote or front steering. However, a 50% modulation is predicted to recover most of this reduced effectiveness at small values of $w_{marg}/\delta_{ec}$. Experimental results in ASDEX Upgrade are confirming this [9].

TABLE I. Parameters for the m/n = 3/2 NTM used in the cross-machine benchmarking.

| Device | Shot No. | $\beta_N$ | $q_{95}$ | $j_{bs}/j_{\parallel}$ | $2\varepsilon^{1/2}\rho_{\theta i}/r$ |
|---|---|---|---|---|---|
| AUG | 19713 | 2.7 | 3.85 | 0.21 | 0.079 |
| DIII-D | 122507 | 1.9 | 3.5 | 0.15 | 0.068 |
| JET | 47276 | 1.9 | 3.4 | 0.14 | 0.060 |
| JT-60U | E41666 | 1.5 | 3.8 | 0.19 | 0.128 |
| ITER | Scenario 2 | 1.84 | 3.1 | 0.16 | 0.014 |

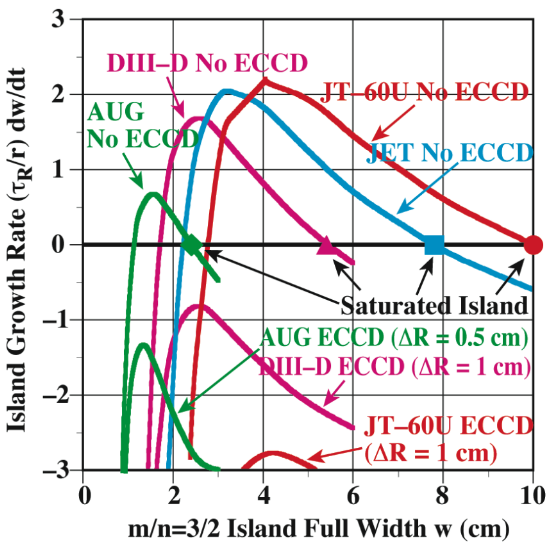


FIG. 2. Common form of the modified Rutherford equation evaluated for all four devices for the m/n = 3/2 saturated island and for ECCD stabilization (except JET). Selected parameters along with ITER values are in Table I. [Reprinted courtesy of IOP, Nucl. Fusion **46**, 451 (2006)].

Applying unmodulated ECCD, using different alignment schemes, produced complete stabilization of the previously saturated m/n = 3/2 island in ASDEX Upgrade, DIII-D, and

JT-60U. Evaluation is shown in Fig. 2 using estimated misalignments which reduce $\delta\Delta' r$ and $K_1$. Selected parameters are given in Table II. The forms used for modeling both $K_1$ and $\delta\Delta' r$ as functions of $w/\delta_{ec}$ and $\Delta R/\delta_{ec}$ are given in Ref. [8] in Figs. 4 and 5 and Eqs (4) and (5). The model has no adjustable parameters except, arguably, $\Delta R$. Note that each case is "overstabilized" as $dw/dt < 0$ for all $w$ by substantial margins. The model used, from Ref. [8], has only one free parameter fitted to experiment, $a_2/(-\Delta'_0 r)$ and $\Delta'_0 r \equiv -$m. An alternate fit in Refs. [10,11] uses a second parameter $C_j$ in front of the current drive terms, i.e., $\delta\Delta' \to C_j \delta\Delta'$ and $K_1 \to C_j K_1$, to additionally account for shaping effects. While a misalignment $\Delta R$ can be minimized by a control system, $C_j < 1$ cannot and would decrease the stabilization in ITER. One should also note that the presence of the island can introduce additional effects that make ECCD stabilization more difficult. $\Delta'_0 r$ can be a function of $w$, typically of form $\Delta'_0 r =$ -m - $c_w w$ where $c_w$ is the effect of the island on the local equilibrium current density profile [12]. If $\Delta'_0 r$ becomes less negative as $w$ is reduced, the stabilization is more difficult. The island can also nonlinearly couple to other islands, m/n = 3/2 to the m/n = 2/2 harmonic of sawteeth precursors for example. This makes for an additional destabilizing term in Eq. (1) not usually accounted for [4,13]. The existence of the island can also potentially broaden the ECCD, lowering $j_{ec}$, and thus making stabilization less effective [14,15]. This could contribute to $C_j < 1$. Preemptive ECCD, i.e. applying ECCD before the island appears, obviates these effects and seems to give a better estimate of the minimum ECCD needed [7] with the model of Ref. [8].

TABLE II. Parameters for the experimental full suppression of the m/n = 3/2 NTM using unmodulated co-ECCD. The ITER case, for comparison, assumes 15 MW with remote steering, i.e., wide ECCD.

| Device | Shot No. | Injected Power (MW) | $j_{ec}/j_{bs}$ | $\delta\Delta' r$ | $2\varepsilon^{1/2}$x $\rho_{\theta i}/\delta_{ec}$ | $\Delta R/\delta_{ec}$ |
|---|---|---|---|---|---|---|
| AUG | 19713 | 1 | 3.1 | 0.1 | 2.4 | 0.6 |
| DIII-D | 122507 | 1 | 0.9 | -2.3 | 1.1 | 0.5 |
| JT-60U | E41666 | 3 | 1.2 | -1.1 | 0.43 | 0.1 |
| ITER | Scenario 2 | 15 | 0.75 | -2.2 | 0.16 | 0.0 |

## 3. NTM Stabilization by ECCD in ITER

The geometry for the ITER ECCD launch configuration is shown in Fig. 3. Neutron shielding requires use of high ports with a resulting oblique angle between the rays and the cyclotron resonance. The original "remote" launch led to relatively wide current drive as a result. This is described in Ref. [8] in which previous calculations of ECCD power requirements with this configuration are also reviewed. Even assuming perfect alignment and the benefits of modulation, it is calculated [8] to take 15 MW and 12 MW respectively to reduce the m/n = 3/2 and 2/1 islands to marginal size. The total required to stabilize both modes exceeds the planned 20 MW total injected power from 24 gyrotrons of 1 MW output.

A new design using "front" steering from the same ports reduces the width of the ECCD in ITER Scenario 2 in both the $q = 3/2$ and 2/1 cases [16]. The peak $j_{ec}$ at $q = 3/2$ increases by about 2.6 times and at $q = 2/1$ by about 2.9 times. The performance of the different options was analyzed in terms of NTM stabiliation efficiency $j_{ec}/j_{bs}$ for both modes in Ref. [17]; it was indeed found that in terms of the figure of merit, the narrow ECCD from front steering is preferred.

### 3.1 m/n = 2/1 Control Contrasting Remote and Front Steering

The m/n = 2/1 NTM is more deleterious than the 3/2 mode since it is further out on the radial profile. The resulting loss of stored energy is larger for the same width of island due to a larger volume ($\propto wrR$). The slower plasma rotation and closer proximity to the resistive wall allows easier locking to the wall with subsequent loss of H-mode and disruption. The working model of 2/1 mode wall locking in Ref. [8] predicts a full width m/n = 2/1 island of $w_{\rm lock}$ = 5 cm radial width (at the $q = 2$ outboard midplane) will lock compared to a marginal island width at $q = 2$ of 1.4 cm.

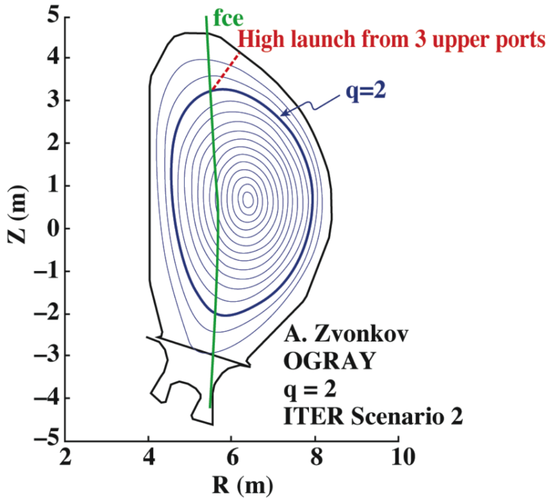


FIG. 3. Cross-section of ITER Scenario 2. Shown are the launch from three high upper ports, the $q = 2$ surface, and the first harmonic surface at 170 GHz.

For "remote" steering with FWHM $\delta_{\rm ec}$ = 7.5 cm, i.e. wide current drive, 12 MW is needed with perfect alignment for modulated ECCD to reduce $w$ to $w_{\rm marg}$ as shown in Fig. 4(a) [8]. The same unmodulated power is not as effective and $w \lesssim w_{\rm lock}$.

For "front" steering with $\delta_{\rm ec}$ = 2.6 cm (both smaller $\delta_{\rm ec}$ and larger $j_{\rm ec}$ by factors of 2.9 are taken based on Ref. [16]), i.e. narrow current drive for ITER, only 3 MW is needed with perfect alignment for modulated ECCD to reduce $w$ to $w_{\rm marg}$ as shown in Fig. 4(b). The same unmodulated power is almost as effective and $w < w_{\rm lock}$ with considerable margin.

By contrast, 15 MW and 4.3 MW are needed for modulated control of the m/n = 3/2 mode with remote and front steering respectively. This assumes a factor of 2.6 narrower ECCD at $q$ = 3/2 with front steering [16]. The figures of merit, $j_{ec}/j_{bs}$, are 0.75 and 0.56. The total power needed for simultaneous control of both the 3/2 and 2/1 modes is 27 and 7.3 MW for remote and front steering respectively, with the remote steering case exceeding the available 20 MW of injected power [8].

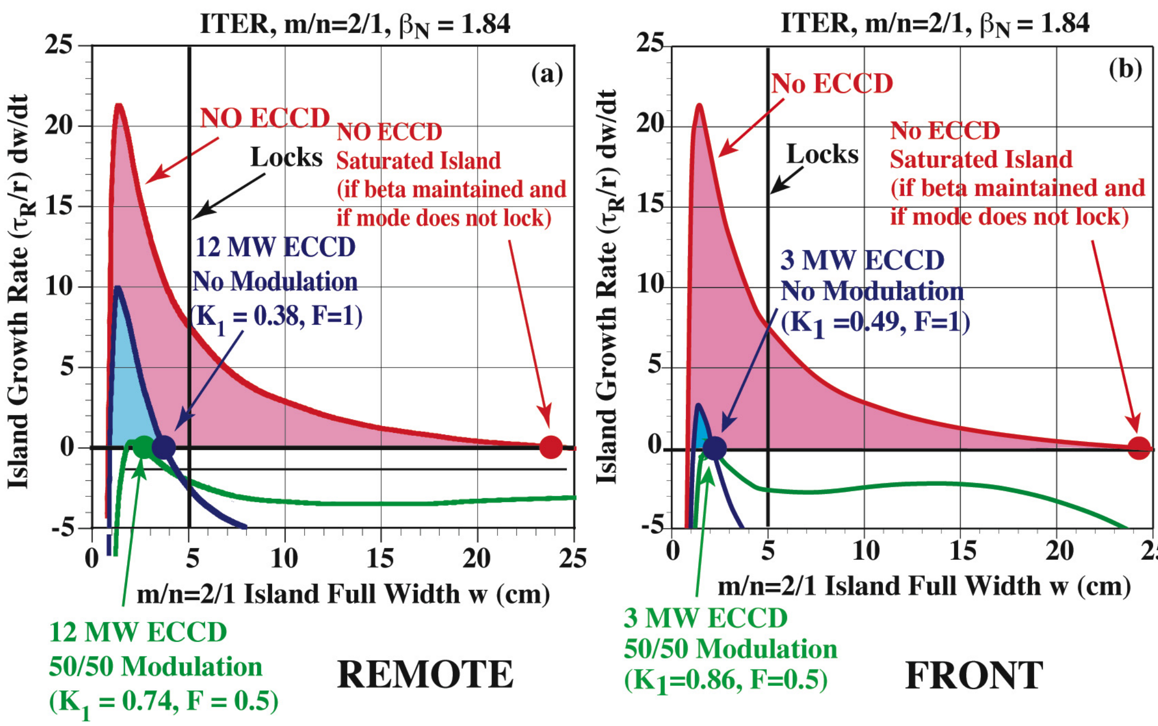


FIG. 4. Evaluation of the modified Rutherford equation for stability of (a) m/n = 2/1 NTM with remote steering and (b) m/n = 2/1 with front steering in ITER, each with perfect alignment. The plasma without ECCD has a saturated island that well exceeds the critical island for locking. The 50/50 modulated well-aligned co-ECCD of 12 MW in (a) and 3 MW in (b) 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 in each case.

Table III has a comparison of the parameters for remote and front steering for the m/n=2/1 or 3/2 modes. All cases have a figure of merit, $j_{ec}/j_{bs}$, of the order of one. Of course, using a $\Delta R/\delta_{ec}$ of the order of present day experiments (equivalent to keeping $C_j < 1$) will increase the requirements. This is discussed in 3.2.

TABLE III. Parameters for the control of the m/n = 2/1 or 3/2 NTMs in ITER using modulated ECCD and assuming perfect alignment.

| Launch | Mode | $\delta_{ec}/2\varepsilon^{1/2}\rho_{\theta i}$ | $P_{ec}$ (MW) | $j_{ec}/j_{bs}$ |
|---|---|---|---|---|
| Remote | 2/1 | 5.4 | 12 | 0.86 |
| Front | 2/1 | 1.8 | 3 | 0.63 |
| Remote | 3/2 | 6.2 | 15 | 0.75 |
| Front | 3/2 | 2.4 | 4 | 0.56 |

### 3.2 Effect of Misalignment on m/n = 2/1 Control With Different Steering

ECCD control of NTMs is a precision tool requiring accurate placement of the peak co-current drive on the rational surface in question. Without a mode, DIII-D uses "$q$-tracking" with real-time MHD reconstruction (RTEFIT) using the multi-channel MSE pitch angle profile diagnostic to locate $q$ and a real-time algorithm to account for refraction due to density profile changes in the absorption of the ECCD, trained by the code TORAY-GA [7].

Off-line analysis yields an accuracy in alignment of ±1 cm corresponding to ±1.7% of minor radius $a$. This is equivalent to approximately ±3 cm in ITER. JT-60U, with a mode, uses the real-time multi-channel electron cyclotron emission (ECE) diagnostic to locate the island O-point [5,18]. Alignment with a steerable mirror is good to $\lesssim 1$ cm or $\lesssim 1.3\%$ of $a$. It, of course, cannot be determined at this date if the ITER alignment system will be good to the absolute $\Delta R \approx 1$ cm or the relative $\Delta R$ of about 1.5% of $a$, i.e. to ≈3 cm. This difference has consequences for ECCD NTM control in ITER with $\delta_{ec}$ = 2.6 or 7.5 cm depending on the launch configuration.

While well-aligned remote launch ECCD can avoid m/n = 2/1 mode locking in ITER, misalignment hinders the stabilization as shown in Fig. 5(a). With modulation, $\Delta\rho/\delta_{ec} \approx 0.2$ ($\Delta R \approx$ 1.5 cm) at 12 MW for $j_{ec}/j_{bs} = 0.9$ allows an island almost big enough to lock, i.e., $w \approx$ 5 cm. Increasing initial plasma rotation from 0.4 to 1.4 kHz doubles the tolerance for misalignment [8]. Increasing injected EC power to increase the figure of merit $j_{ec}/j_{bs}$ also increases the misalignment tolerance; 20 MW for $j_{ec}/j_{bs}$ = 1.5 allows $\Delta\rho/\delta_{ec} \approx 0.4$ ($\Delta R \approx$ 3 cm) at the expected "initial" (no island) rotation in ITER.

Front steering ECCD is narrower, with larger $j_{ec}$ per MW injected but is thus less tolerant to misalignment. As shown in Fig. 5(b), 3 MW for $j_{ec}/j_{bs} = 0.63$ would allow locking at $w$ = 5 cm with $\Delta\rho/\delta_{ec} \approx 0.2$ and a challenging $\Delta R \approx$ 0.5 cm. Increasing injected power to 7 MW for $j_{ec}/j_{bs} = 1.5$ allows a misalignment of up to 1.5 cm. Increasing initial rotation to 1.4 kHz (from 0.4 kHz) would allow $\Delta R \approx$ 2 cm at 3 MW. In principle, more plasma rotation is desirable to allow more tolerance for misalignment for either launching scheme.

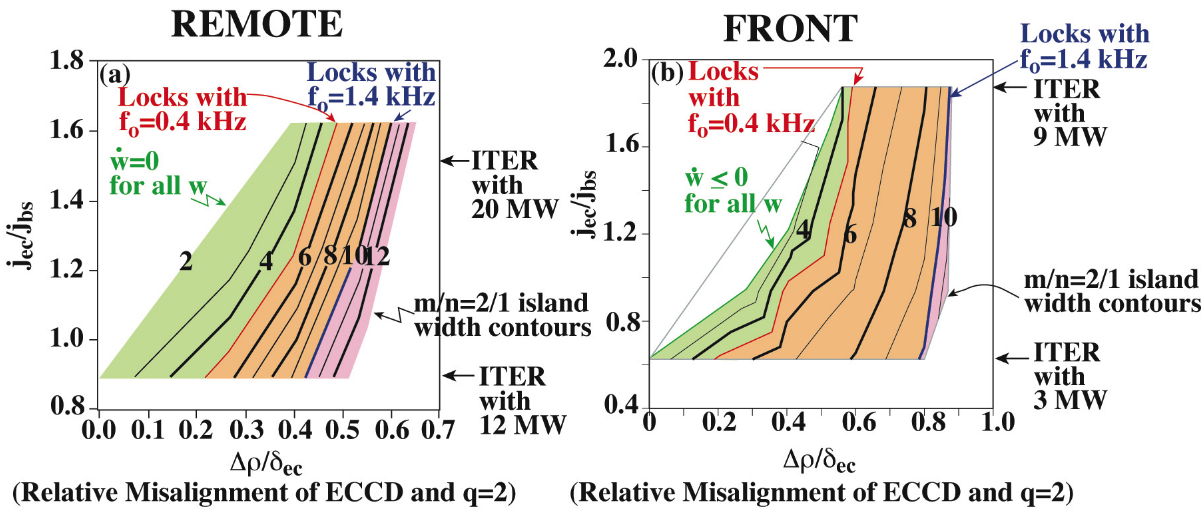


FIG. 5. Necessary modulated peak ECCD with (a) remote steering, i.e. wide current drive, and (b) front steering, i.e. narrower current drive, at $q = 2$, normalized to the local bootstrap current density, calculated to regulate m/n = 2/1 island widths (labeled 2 to 12 cm) vs misalignment with the $q = 2$ surface. Here $\delta_{ec}$ 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.

## 4. Summary

The proposed 20 MW injected, 170 GHz, “high launch” system in ITER is adequate to avoid mode locking the m/n = 2/1 NTM with the anticipated initial rotation in ITER. Front steering is favored as providing narrower current drive, needing less EC power and leaving “unused” power for control of the m/n = 3/2 mode, but tolerance on misalignment is tighter. More plasma rotation would expand the stable operational space. Existing devices need to continue to confirm the advantage of modulation. Experiments are also needed to find the power for marginal stabilization to distinguish between $C_j < 1$ and $\Delta R > 0$. The successful use of the ECCD stabilization will need care in designing alignment control both with or without the presence of islands.

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