Insights Into m/n=2/1 Tearing Mode Stability Based on Initial Island Growth Rate in DIII-D ITER Baseline Scenario Discharges

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1. Introduction

Deleterious *m*/*n*=2/1 tearing modes appear in some slowly evolving (internal inductance ℓ_i decreasing, β nearly constant) ITER baseline scenario DIII-D discharges [1,2]. These modes tend to lock to the resistive wall, cause loss of high confinement H-mode and produce a disruption. Understanding the nature of the destabilization is important for both extrapolating to ITER and for learning what must be done to avoid or stabilize them. The destabilization is here interpreted as due to an initially positive (destabilizing) classical tearing index balanced only in part by curvature and the small island stabilization effects of neoclassical tearing modes. As in a true neoclassical tearing mode (NTM) with negative stabilizing classical tearing index, the instability must be seeded by something else. By evaluating the mode growth rate at the onset, the classical tearing stability index Δ' is appraised before the island grows to large size and the plasma equilibrium has time to change.

2. DIII-D ITER Baseline Scenario Discharges

Examples of *m*/*n*=2/1 tearing occurring after at least 3 seconds into discharges (ELMing H-mode at 2 seconds, global resistive diffusion time τ_R~1 s) are analyzed with "seeding" by either sawteeth or edge localized modes (ELMs). Discharges are taken from the 2013 campaign with: 1) no electron cyclotron current drive (ECCD), 2) no off-axis neutral beam injection (NBI), 3) no gas-puffing which would modify the edge current density and 4) no impurity injection (which would modify the current profile and thus stability). These criteria allow for natural relaxation of the current and safety factor (q) profiles. Torque is however varied within this set and the resulting initial 2/1 tearing frequency varies as shown in Fig. 1. The mean q_{95}=3.28±0.10, β_N=1.90±0.12 and l_i=0.90±0.03. Island width evolution is evaluated by the Mirnov magnetic probe arrays using the motional Stark effect EFIT equilibrium reconstructions and calibrated by the electron cyclotron emission (ECE) diagnostic. The magnetics analysis code EIGSPEC [3] uses so-called subspace methods (instead of FFT methods) to estimate peaks in the array magnetics power spectrum to discriminate multiple modes and determine the precise point at which the *m*/*n*=2/1 mode begins to grow. An

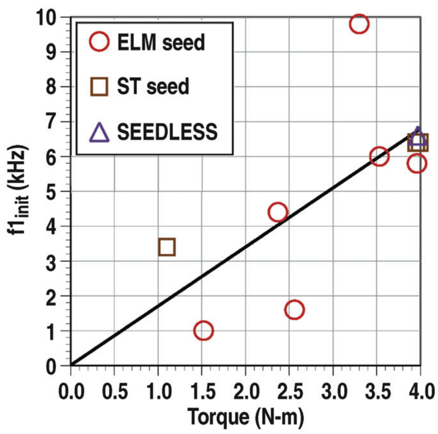

Fig. 1. DIII-D ITER baseline scenario discharges evaluated at onset of *m*/*n*=2/1 tearing mode. The initial rotation frequency is plotted versus applied torque. Onsets are from ELMs, sawteeth or possibly seedless.

example of EIGSPEC for a sawtooth m/n=1/1 mode seeding the 2/1 mode (in presence of a previously “saturated” 3/2 mode) is shown in Fig. 2.

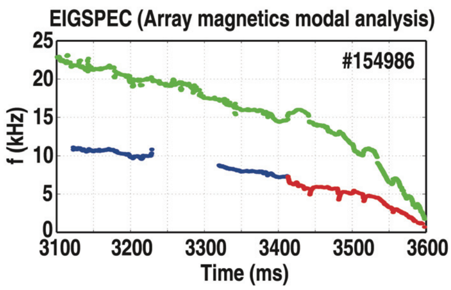

Fig. 2. Mirnov magnetics modal array analysis to determine precise time when the 2/1 mode starts to grow. Blue is 1/1, red is 2/1 and green is 3/2.

3. Δ′ and the Growth Rate of a Tearing Mode

Absent the curvature and neoclassical effects, an initially “small” island unstable tearing mode will grow linearly with time in proportion to Δ′ and the plasma resistivity [4], Eq. (1a). If neoclassically perturbed bootstrap current effects at small island size are included and dominate the $\Delta' r$ term, the tearing mode will initially grow exponentially [4], Eq. (1b). Both behaviors are observed as seen in Fig. 3.

$$\text{(a)}\quad \frac{dw}{dt} = \frac{\eta}{\mu_0}\Delta'\left(1-\frac{w}{w_{sat}}\right) \qquad \text{(b)}\quad \frac{dw}{dt} = \frac{\eta}{\mu_0}\left(\Delta' + \frac{w_{nc}w}{w^2+w_d^2}\right) \tag{1}$$

If $\Delta'>0$, and $w \ll w_{sat}$ initially

$w = w_0 + (\eta\Delta'/\mu_0)\delta t$

If $|\Delta'| \ll w_{nc}w/w_d^2$ and $w^2 \ll w_d^2$ initially

$w = w_0 \exp[\eta/\mu_0\,(w_{nc}/w_d^2)\delta t]$

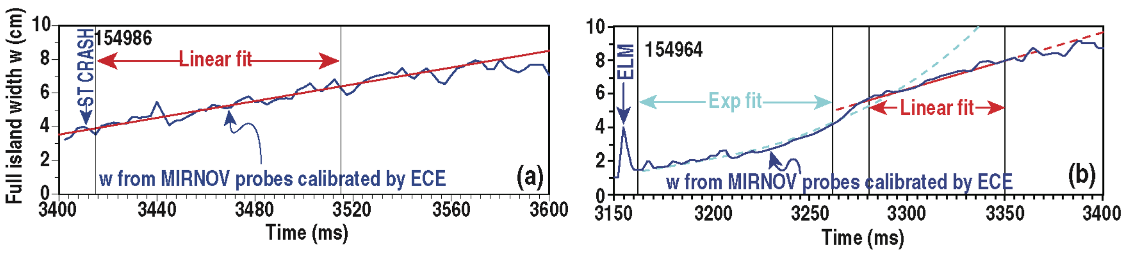

Fig. 3. (a) An m/n=2/1 tearing mode “seeded” by a sawtooth crash initially grows linearly with time. (b) m/n=2/1 tearing mode “seeded” by an ELM, initially grows exponentially, then linearly with time. In general, larger initial island sizes from either a sawtooth crash or an ELM start in the linear phase.

The full Modified Rutherford Equation (MRE) used in Eq. (2a) is taken from Ref. [5] with a local q=2 resistive time that includes both Sauter electron trapping corrections to Spitzer resistivity and the measured Z_{eff}. The mean τ_R=1.9±0.6 s with mean trapping correction $f(\varepsilon)$=0.27±0.01 and Z_{eff} = 2.4±0.3. In Eq. (2a), the second term is the stabilizing effect of good average magnetic field curvature (“GGJ” after Glasser, Green, and Johnson), and the third term is the destabilizing helically perturbed bootstrap current effect (empirically obviated at very small islands with a form suggested by the “ion polarization current” effect). Results in Ref. [5] and references therein explain how each term was arrived at based on experiments. In particular, the effective parameter w_{small} measured at q_{95}=4 and 7 scales to about 3 times the ion banana width at ITER q_{95}=3.2 (to be discussed).

$$1.22^{-1}\frac{\tau_R}{r}\frac{dw}{dt} = \Delta' r + -(q^2-1)\frac{L_q^2\beta}{L_p w} + \varepsilon^{1/2}\frac{rL_q}{L_{pe}}\beta_{\theta e}\left(\frac{1}{w} - \frac{w_{small}^2}{3w^3}\right) \tag{2a}$$

$$\tau_R \equiv \mu_0 r^2/\eta \quad , \quad \eta^{-1} = 1258\, T_e^{3/2}\,(\text{eV})\, f(\varepsilon)/Z_{eff} \quad . \tag{2b}$$

$\Delta' r$ for classical stability (where r is the minor radius) is determined from Eq. (2a) by taking the helically perturbed bootstrap components (including both curvature and small island effects) and subtracting from the initial normalized island growth rate. The fitted form is Eq. (3) based on Eq. (2). The data are well described (using the MRE fitted in Fig. 4) by the imbalance of the sum of the destabilizing classical tearing and the helically perturbed bootstrap current terms with the sum of the stabilizing curvature and "ion polarization" effects. In particular $\Delta' r$=1.1±0.3 is *destabilizing*. The other fitted parameters are a_{bs}=0.48±0.25, a_{GGJ}/a_{bs}=0.35±0.38 and w_{small}/w_{ib}=3.0±0.4. The fitted parameters correspond well to values from measured profiles [using Eq. (2) for 154986 for example of Fig. 3(a) $a_{bs}/(w/3w_{ib})$=0.45 and $a_{GGJ}/(w/3w_{ib})$=0.15].

$$1.22^{-1}\frac{\tau_R}{r}\frac{dw}{dt} = \Delta' r + \frac{\left(a_{bs} - a_{GGJ}\right)}{w/3w_{ib}} - \frac{a_{bs}\left(w_{small}/3w_{ib}\right)^2}{3\left(w/3w_{ib}\right)^3} \quad . \tag{3}$$

The islands have slower beginning growth rates at smaller initial island size (w_{init}). ($\tau_R/1.22r$)dw/dt is found to be just >0 for initial island width w_{init}~1.5w_{ib} (where again w_{ib} is the ion banana width) and to be ~1 for w_{init}~3w_{ib}. The form of the early evolution of w(t) tends to be an exponential if the island is small [Fig. 3(b)] and linear [Fig. 3(a)] if large. The fit to Eq. (3) is in accord with the different initial time variation functional forms of the island growth as shown in Fig. 4. For small w_{init} (in red), the initial dw/dt is linear in w which produces an exponential w(t) at first. For larger w_{init} (in green), the initial dw/dt is independent of w which produces a constant dw/dt at first.

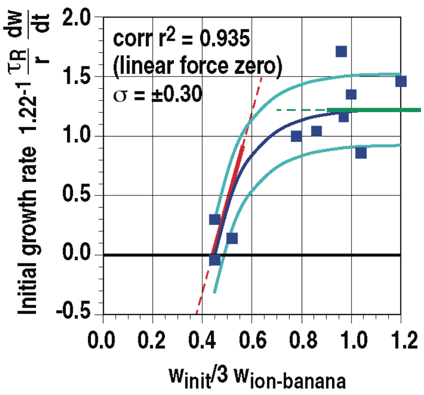

Fig. 4. Fit of the database of initial island growth rate versus island size finds a positive (destabilizing) classical tearing index (with stabilizing curvature included). The fit (blue, σ cyan) is in accord with the different initial variation functional forms of the island growth. Red is small island fit which gives an exponential growth. Green is large island fit which gives a linear growth.

At very small island widths (w goes to zero) where neoclassical effects are gone ($w^2 \ll w_{ib}^2$) and the curvature effect is no longer $\sim w^{-1}$ ($w^2 \ll \rho_i^2$ with ρ_i the ion gyroradius), the stability with positive $\Delta' r$ is maintained by the finite curvature. This is shown in Fig. 5. Including these effects does not affect the fits to data. Despite a destabilizing positive $\Delta' r$, the neoclassical and curvature effects make the 2/1 tearing mode destabilization appear as an NTM which needs seeding. (Although one case may be seedless as occurs with a delay after an ELM.)

4. Effect of Updated Assumptions for ITER Modeling of ECCD 2/1 NTM Stabilization

ITER relies upon well-aligned localized electron cyclotron current drive (ECCD) at q=2 to stabilize or suppress (limit to small amplitude transients) m/n=2/1 neoclassical tearing modes [7]. The effectiveness and power requirements of ECCD in ITER were previously predicated on an "educated guess" of the classical stability index ($\Delta' r \approx$-m). At first thought, the DIII-D results suggest that there will be classical instability ($\Delta' r$ >0) in ITER and thus more ECCD power needed for stabilization than previously estimated. However, it is found that also including the curvature stabilization, and in particular, the increased small island stabilization (w_{small}/w_{ib} was 2 and is updated as 3, the difference being more than the ±0.4 uncertainty of the data fit) makes the necessary power slightly lower as shown in Fig. 6. The increased marginal island width also makes the match of the ITER front-launched ECCD width better.

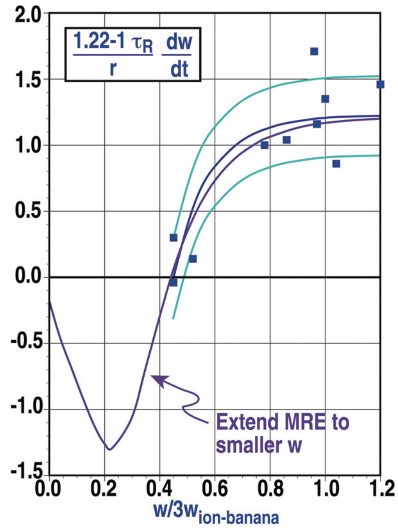

Fig. 5. Same as (4) but including the turn off at very small island widths of all neoclassical effects as well as keeping the minimum island at which the curvature effect is operational (and no longer $\sim w^{-1}$).

5. Conclusions

DIII-D ITER baseline scenario discharges tend to evolve to where "seeding" by sawteeth or ELMs destabilize deleterious *m*/*n*=2/1 tearing modes. This is interpreted as due to a classically unstable tearing index at intial island growth; but with the behavior of a neoclassical tearing mode. Stabilizing curvature and small island effects balance destabilizing $\Delta' r$ and the helically perturbed bootstrap current unless seeds are large enough. The consequences found of similar $\Delta' r$ in ITER are minimal on required EC power when all effects are updated from Ref. [7]. Furthermore, stabilization of sawteeth by ECCD [8] and of ELMs [9] in ITER would reduce seeding and be of help.

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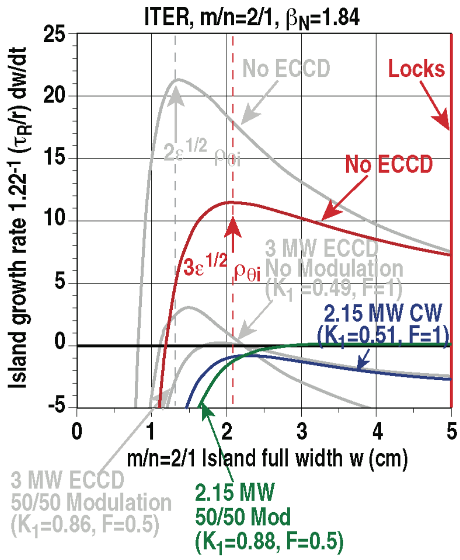

Fig. 6. Updated assumptions (from those in Ref. [7]) for ITER modeling of minimum well-aligned ECCD power for 2/1 NTM stabilization. Normalized growth rate versus real island full width in cm. Grayed out is from previous assumptions in Ref. [7]. Locking limit at 5 cm unchanged. K1 and F are the ECCD effectiveness parameters. Note with no ECCD, maximum growth rate is smaller and shifts to larger island width with updated assumptions based on this paper.

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