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ITER BASELINE SCENARIO DISCHARGES**

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# 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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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.

### 3. $\Delta'$ 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  $\Delta'$  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.

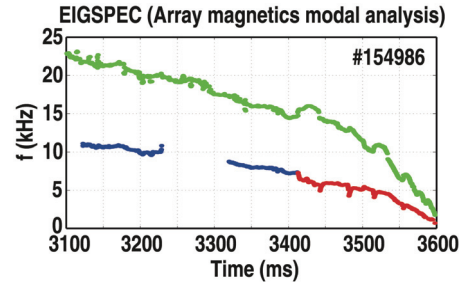


Fig. 2. Mirnov magnetics modal array analysis to determine precise time when the  $2/1$  mode starts to grow. Blue is  $1/1$ , red is  $2/1$  and green is  $3/2$ .

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

If  $\Delta' > 0$ , and  $w \ll w_{\text{sat}}$  initially  
 $w = w_0 + (\eta \Delta' / \mu_0) \delta t$

If  $|\Delta'| \ll w_{\text{nc}} w / w_d^2$  and  $w^2 \ll w_d^2$  initially  
 $w = w_0 \exp[\eta / \mu_0 (w_{\text{nc}} / w_d^2) \delta t]$

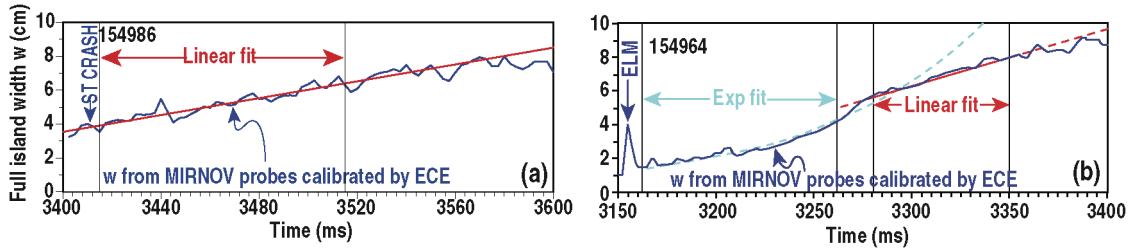


Fig. 3. (a) An  $m/n=2/1$  tearing mode “seeded” by a sawtooth crash initially grows linearly with time. (b)  $m/n=2/1$  tearing mode “seeded” by an ELM, initially grows exponentially, then linearly with time. In general, larger initial island sizes from either a sawtooth crash or an ELM start in the 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  $Z_{\text{eff}}$ . The mean  $\tau_R = 1.9 \pm 0.6$  s with mean trapping correction  $f(\epsilon) = 0.27 \pm 0.01$  and  $Z_{\text{eff}} = 2.4 \pm 0.3$ . 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  $w_{\text{small}}$  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).

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

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

$\Delta'r$  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  $\Delta'r=1.1\pm 0.3$  is *destabilizing*. The other fitted parameters are  $a_{bs}=0.48\pm 0.25$ ,  $a_{GGJ}/a_{bs}=0.35\pm 0.38$  and  $w_{small}/w_{ib}=3.0\pm 0.4$ . 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  $a_{GGJ}/(w/3w_{ib})=0.15$ ].

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

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  $w_{init}\sim 1.5w_{ib}$  (where again  $w_{ib}$  is the ion banana width) and to be  $\sim 1$  for  $w_{init}\sim 3w_{ib}$ . 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.

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  $\rho_i$  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  $\pm 0.4$  uncertainty of the data fit) makes the necessary power slightly lower as shown in Fig. 6. The

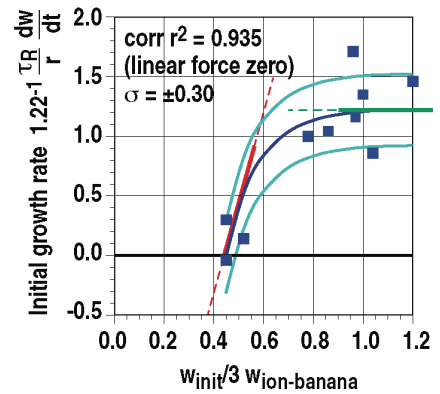


Fig. 4. Fit of the database of initial island growth rate versus island size finds a positive (destabilizing) classical tearing index (with stabilizing curvature included). The fit (blue,  $\sigma$  cyan) is in accord with the different initial variation functional forms of the island growth. Red is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

increased marginal island width also makes the match of the ITER front-launched ECCD width better.

## 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 initial 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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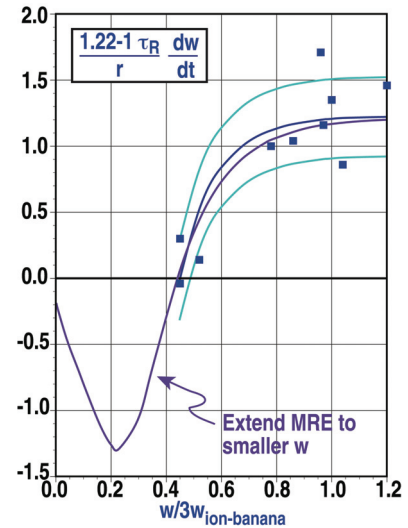


Fig. 5. Same as (4) but including the turn off at very small island widths of all neoclassical effects as well as keeping the minimum island at which the curvature effect is operational (and no longer  $\sim w^{-1}$ ).

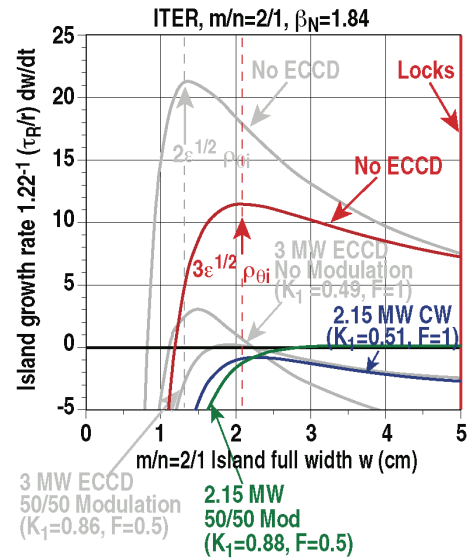


Fig. 6. Updated assumptions (from those in Ref. [7]) for ITER modeling of minimum well-aligned ECCD power for  $2/1$  NTM stabilization. Normalized growth rate versus real island full width in cm. Grayed out is from previous assumptions in Ref. [7]. Locking limit at 5 cm unchanged.  $K_1$  and  $F$  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.