CRITERIA FOR CURRENT DRIVE STABILIZATION OF NEOCLASSICAL TEARING MODES

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OUTLINE

- **Backgoround and Physics Approch**
- **Island Evolution Equation — New Terms and Old**
- **Four Criteria**
- **Projections for Reactor-Scale Devices**
- **Conclusions**

PHYSICS OF ISLAND EVOLUTION EQUATION - 1

1. Assume magnetic field which has good helical flux surfaces χ = constant.

$$B = \frac{g}{R}\phi + \frac{q}{q_o}\frac{\phi \times \nabla\psi}{R} + \frac{\phi \times \nabla\chi}{R}$$

$$\chi = \chi\left(\psi, \alpha\right) \qquad\qquad \alpha = \theta - \varphi / q_o$$

2. Assume form for helical flux function χ - Not a complete calculation

$$\Phi = \frac{\chi}{\chi_o(\psi,t)} = \text{nondimensional helical flux function} = \frac{x^2}{w^2} - \left[\frac{1 + \cos(m\alpha)}{2}\right]$$

3. Island width w is really the helical flux function χ

$$w^2 = 2\chi_o r_s (\hat{s} \quad \psi)^{-1}$$

ISLAND EVOLUTION EQUATION - 2

1. Starting point is back emf equation for helical flux

$$\frac{\partial \chi}{\partial t} = \eta \left[j_h - j_{bs} - j_{cd} \right]$$

- **j_h is helical current density; j_{bs}, j_{cd} are emfs**

2. Mechanical equilibrium requires that j_h be a function of helical flux

- Analogous to Grad-Shafranov equation — $\frac{\partial^2 \chi}{\partial x^2} = \mu_o \, j_h(\chi)$

3. Form flux surface average of back-emf equation.

- Only flux surface averages $\langle j_{bs} \rangle$ $\langle j_{cd} \rangle$ **enter**

- Equation is not balanced in detail; only in large-scale properties matter

4. Form α-ψ integral of flux-surface averaged back-emf equation to obtain island evolution equation

ISLAND EVOLUTION EQUATION - 3

1. Island Evolution Equation.

$$\frac{\mu_o}{\eta}\left(\frac{2\,C_1}{\pi}\right)\frac{\partial w}{\partial t} = \Delta'_o + \frac{4\,\mu_o\,Rq\;j_{bs}}{\pi\,w\,\hat{s}\,B}\,C_2\left\{1 - \Lambda\,K_1\left(\tau, x\right)\right\}$$

$\Lambda = j_{cd}/\,j_{bs}$ $\qquad x = w/w_{cd}$ $\qquad w$ = island half-width

w_{cd} = half width of current drive layer $\qquad \tau$ = modulation duty factor

2. Term in C_2 is bootstrap driving term; C_2 = 8/3

- **saturated island width** $\quad w_{sat} = \left(\frac{8\,C_2}{\pi\hat{s}}\right)\left(\frac{j_{bs}\,R\,q\,\mu_o}{2B}\right)\frac{1}{\left(-\Delta_o'\right)}$

- $(-\Delta_o') \approx m/r$

3. Island size comparable to minor radius when $\beta(0) \sim 0.05$.

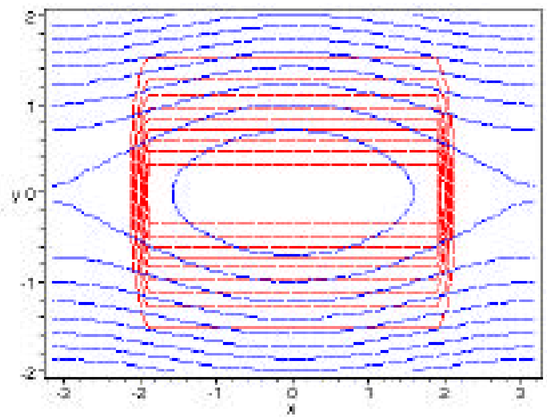
CALCULATION OF STABILIZING TERM $K_1(x, \tau)$

- **Model for driven current layer**

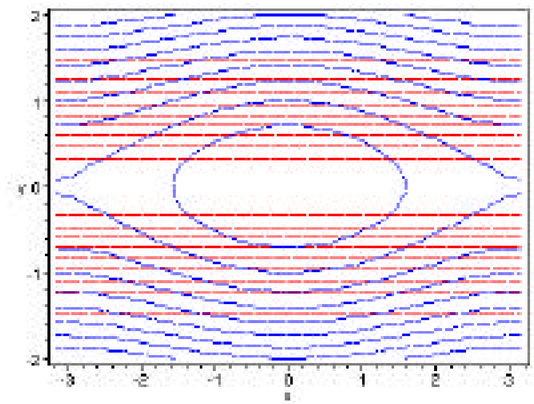
$$j_{cd} = j_{cd} \exp\left\{ -\frac{(r - r_s)^2}{w_{cd}^{\;2}} \right\} M(\tau) \qquad\qquad j_{cd} = \frac{I_{cd}}{2\,\pi^{3/2}\, r_s\, w_{cd}}$$

- **First, average current density over helical flux surface**

- **Second, evaluate weighted integral over helical flux**



τ = 0.64



τ = 1.0

Do this as a function of island width and τ .

FOUR STABILITY CRITRIA

1. Stabilization of arbitrarily small islands ($w << w_{cd}$)

2. Limitation of growing island size to $w \approx w_{cd}$.

a) Δ' independent of current drive

b) Current drive layer changes Δ'

3. Reduction of already-established saturated islands to $w \approx w_{cd}$

- $w_{sat} >> w_{cd}$ **assumed**

STABILZATION OF SMALL ISLANDS

1. Results for $K_1(x, \tau)$ show that it has a finite value for $x \rightarrow 0$, assuming a modulated source.

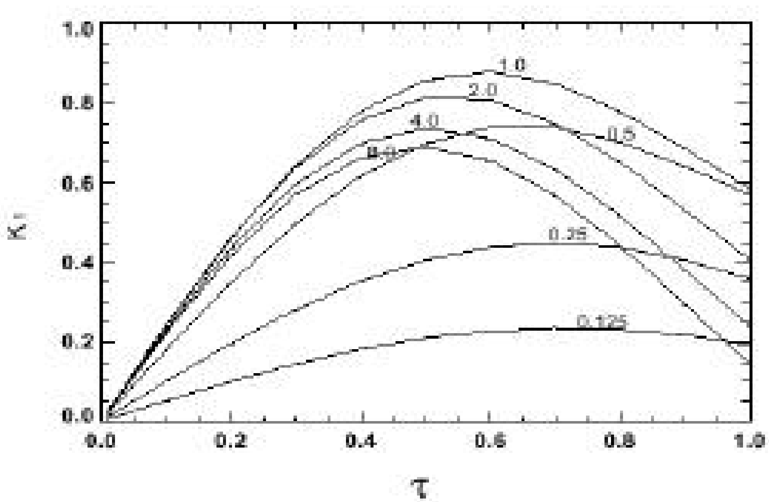


Fig. 4. K1 versus "on"-time τ for the various island widths w_{cd}/w marked on the diagram.

• **Maximum value of $K_1(0,\tau)$ is $K_1 = 0.65$ with 50% "on" 50% "off"**

• **Stabilization will occur when $\Lambda = j_{cd}/ j_{bs} > 1.6$**

LIMITATION OF ISLAND GROWTH - NO MODULATION

- **Evaluate $K_1(x,1)$ with no modulation and represent by analytic fit.**

$$K_1(x,1) = \frac{x}{1+\left(\frac{2}{3}\right)x^2}$$

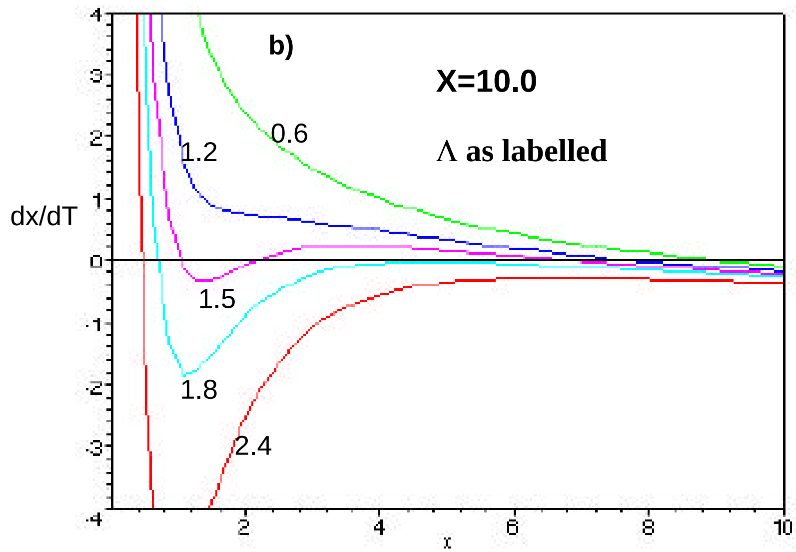
- **Non dimensional island evolution equation with $X = (w_{sat}/w_{cd}) >> 1$.**

$$\frac{dx}{dT} = -1 + X\left(\frac{1}{x} - \frac{\Lambda}{1+\left(\frac{2}{3}\right)x^2}\right) \qquad x = \frac{3}{4}\left(\Lambda \pm \sqrt{\Lambda^2 - (8/3)}\right)$$

- **Criterion for two roots is** $\Lambda > \sqrt{8/3}$

LIMITATION ON ISLAND GROWTH

- **No Modulation**
- **No current drive effect on Δ′**



- **Reduction of Saturated Island Size**

$$x = 0.5 \{ X \pm (X^2 - 6 \Lambda X)^{1/2} \}$$

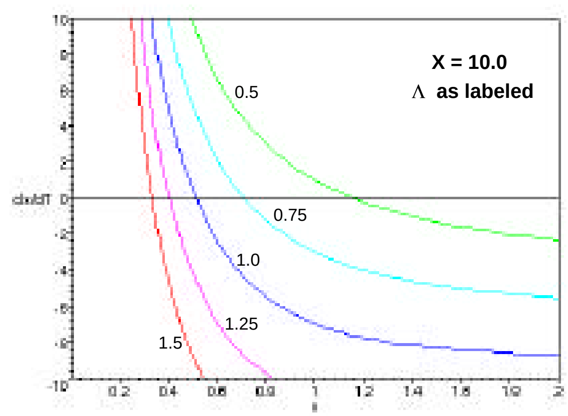
- **Criterion for elimination of saturated islands $\Lambda > X/6$; $I_{cd} > 0.23\ I_{bs}$**

EFFECT OF CURRENT DRIVE LAYER ON Δ'

• **Current Drive Layer centered on rational surface**

$$(-\Delta')_{cd} = (-\Delta'_o)\, X\, \Lambda \qquad\qquad \frac{dx}{dT} = -1 + X\left\{\frac{1}{x} - \Lambda\,\frac{2 + \left(\frac{2}{3}\right)x^2}{1 + \left(\frac{2}{3}\right)x^2}\right\}$$

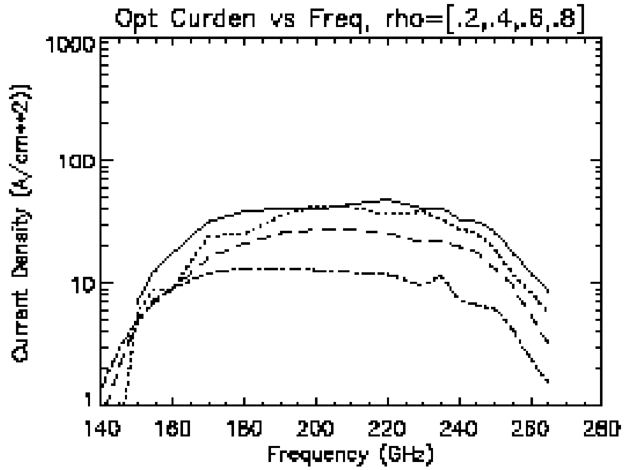
• **Only one real root; growth to saturated level is prohibited**



• **Island size limited to** $w < w_{cd}$ **when** $\Lambda > 0.6$ **.**

APPLICATION TO ITER FEAT

- ECCD maximized by off-axis launch location
- For ITER FEAT with 30 MW ECCD; $j_{bs} \approx 0.07$ MA/m^2 $j_{cd} = 0.1$ MA/m^2
- Wide range of gyrotron frequencies work; above midplane lauch location



- For FIRE, experiments may have to be done at reduced B_T because of gyrotron availability

  - Key goal will be to establish β-limit for inductive and Advanced discharges in a reactor like environment

CONCLUSIONS

1. **Correct Figure-of-Merit for ECCD stabilization of Neoclassical Tearing Modes is $\Lambda = j_{cd} / j_{bs}$**

    - **$\Lambda > 0.6$ reduces island size to driven current layer thickness**
    - **$\Lambda > 1.6$ (with modulation) completely stabilizes modes**

2. **Most effective physics is changing Δ' by thin , unmodulated current drive layer centered on rational surface**

3. **Technical and wave propagation requirements can be met for ITER-FEAT**

    - **FIRE experiments at reduced field can establish experimental basis for design of an ECCD/NTM capability for Integrating Inductive or Advanced tokamak**