Evaluating ECCD Stabilization of Neoclassical Tearing Modes in ITER

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Presented at
the 10th MHD Control Workshop
University of Wisconsin, Madison

October 31 to November 2, 2005

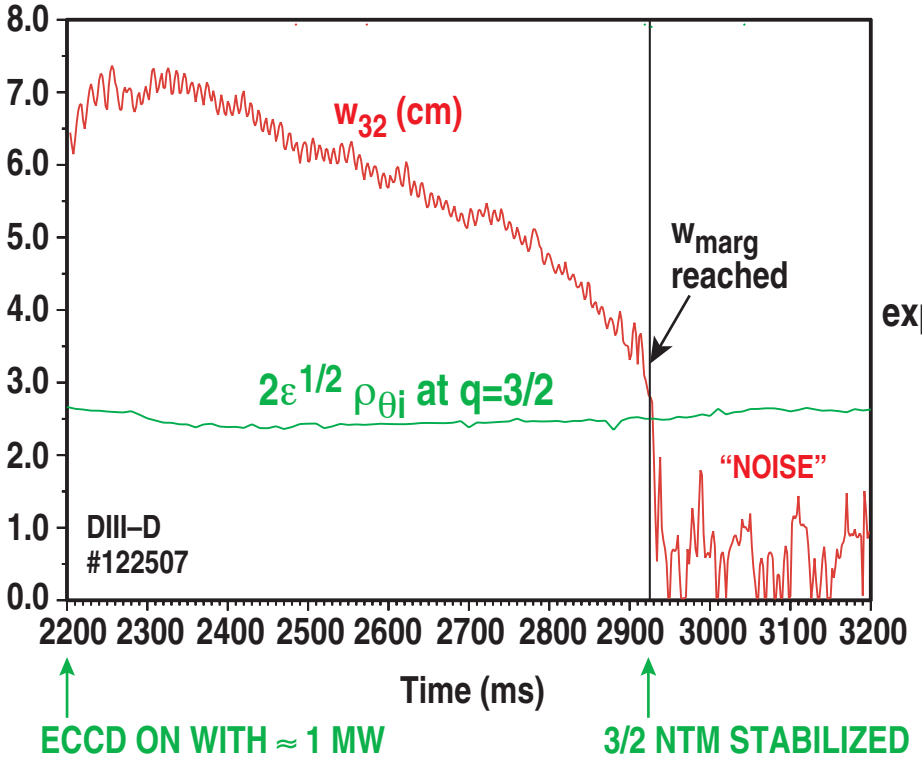
GENERAL ATOMICS

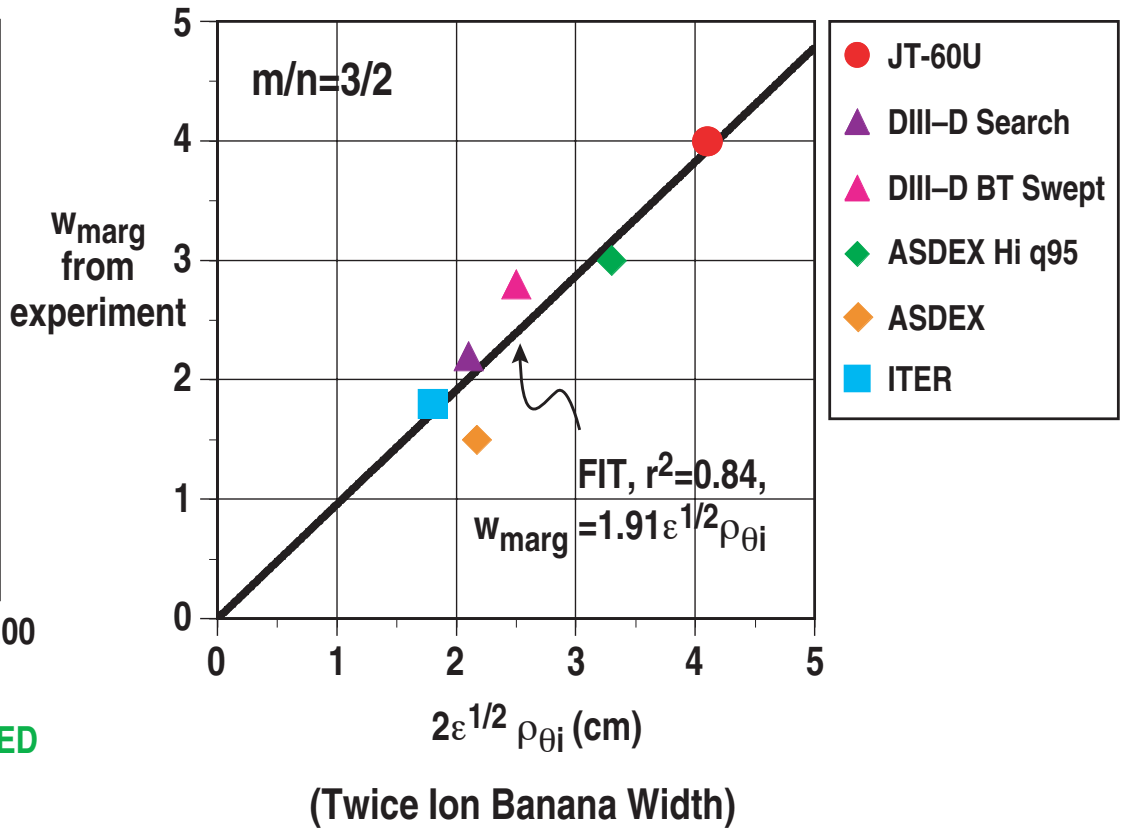
Outline

- **NTMs will be the principal limit to performance in ITER with operation well below the ideal kink beta limit**
- **An NTM can be avoided by removing the "metastable" condition with continuous well-aligned ECCD**
  - or an NTM can potentially be limited in size by ECCD modulated in phase with the island O-point
- **Existing devices (ASDEX Upgrade, DIII–D, JET, JT-60U) can be used to:**
  - benchmark the NTM physics
  - model the ECCD power requirement for stabilization
- **The ITER ECCD top launch system is adequate for the job**
  - but benefits of modulation need to be confirmed (TO BE DONE)

Experimental Case Studies of ECCD Stabilization of m/n = 3/2 Mode Yield the Marginal Condition

- All "suddenly" stabilize when $w \approx 2\varepsilon^{1/2}\rho_{\theta i}$, "marginal" island width





(Twice Ion Banana Width)

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ASDEX Upgrade

JAERI

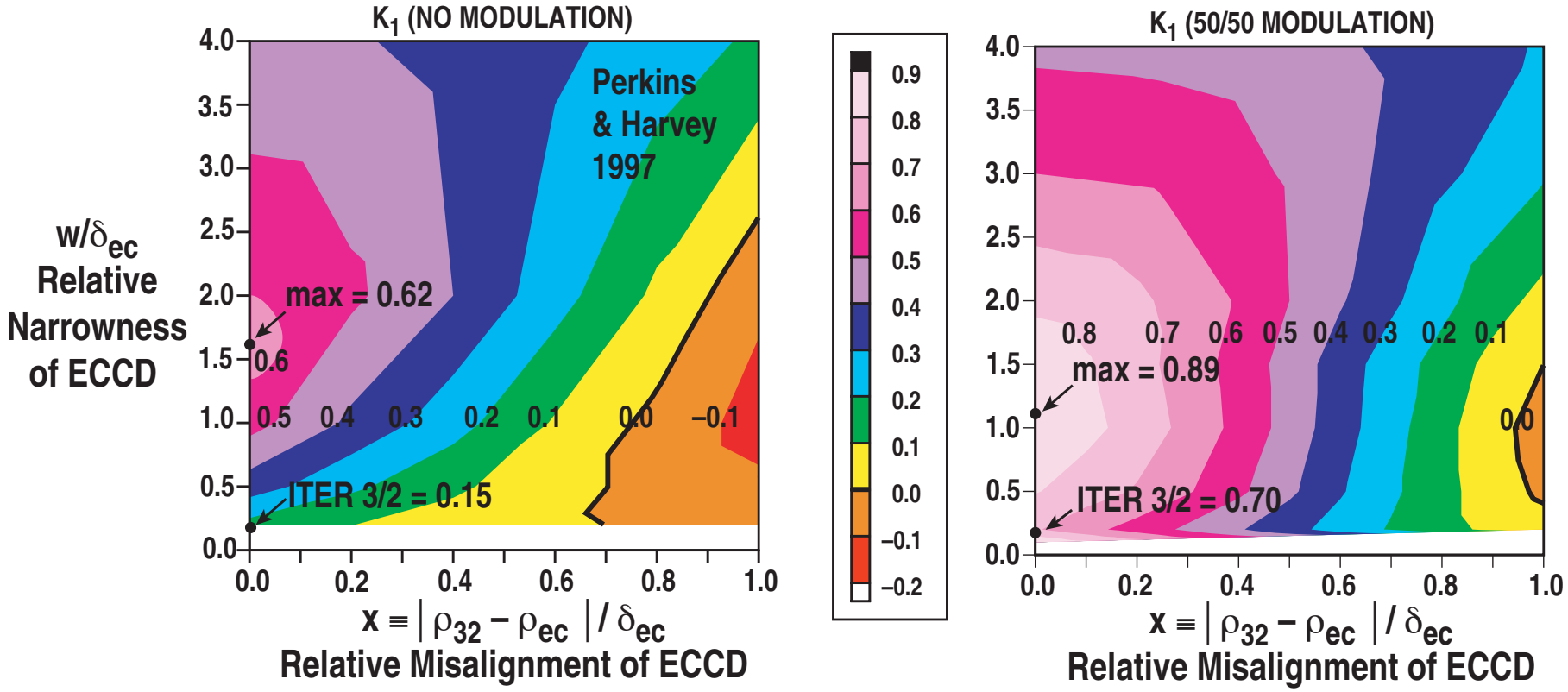
156-05/RJL/rs

ECCD Can Remove the Metastable Condition by Replacing The Missing Bootstrap Current

$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta'_0 r + \delta\Delta' r + a_2 \frac{j_{bs}}{j_{||}}\frac{L_q}{w}\left[1 - \frac{w^2_{marg} - K_1}{3\,w^2}\frac{j_{ec}}{j_{bs}}\right]$$

Modified Rutherford Eqn.

ECCD Replaces "Missing" Bootstrap Current

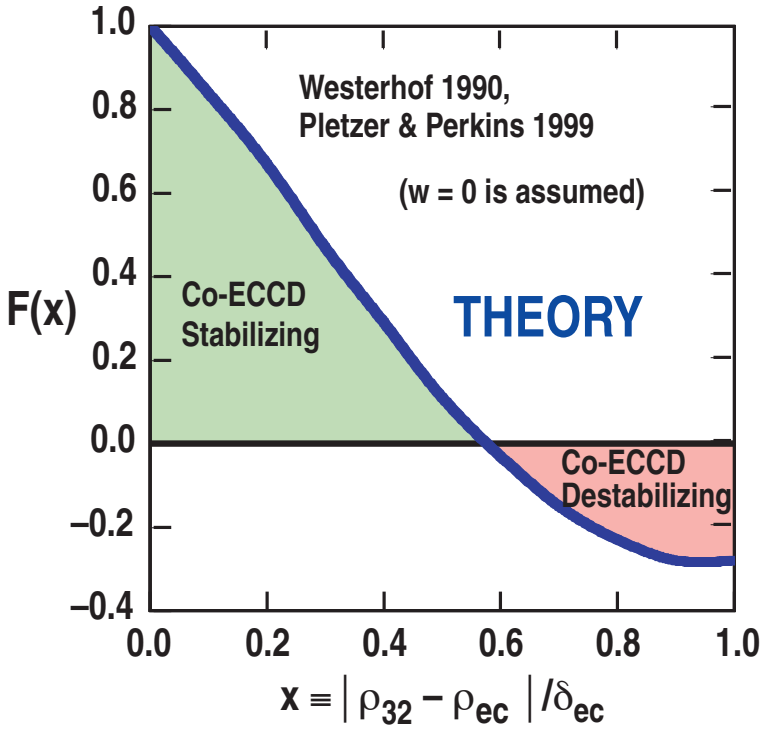


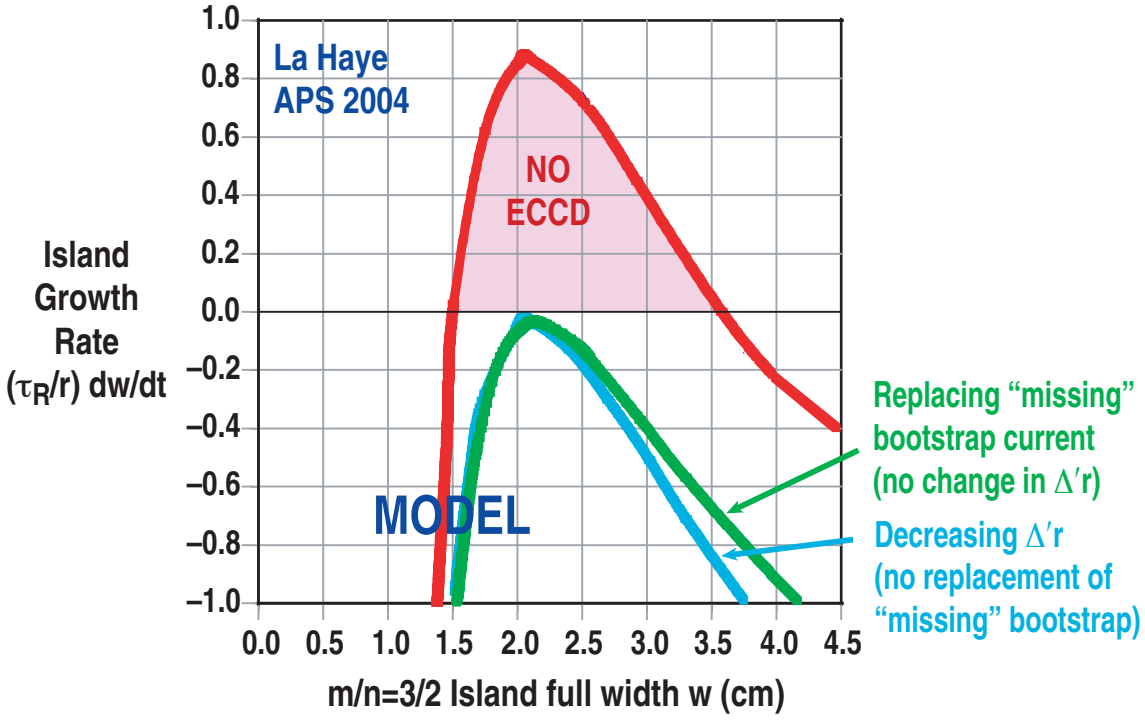
- ECCD "Effectiveness" should be larger and broader with 50/50 modulation on the O-point

ECCD Can Remove the Metastable Condition by More Negative Δ'

$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta'_0 r + \underbrace{\delta\Delta' r}_{\text{ECCD Change}} + a_2 \frac{j_{bs}}{j_{||}}\frac{L_q}{w}\left[1 - \frac{w^2_{marg}}{3\,w^2} - K_1 \frac{j_{ec}}{j_{bs}}\right]$$ **Modified Rutherford Eqn.**

- **Co–ECCD can make Δ' more negative,** $\delta\Delta' r \approx \frac{-5\pi^{3/2}}{32} a_2 \frac{L_q}{\delta_{ec}} F(x) \frac{j_{ec}}{j_{||}}$





Benchmarking m/n=3/2 NTM Suppression by ECCD Experiments Checks Model for ITER

- **Saturated island before/without ECCD**
  - ★ $\frac{a_2}{-\Delta_o' r} = \frac{(w_{sat}/L_q)}{(j_{bs}/j_{//})} \left[\frac{1}{1-(w^2_{marg}/3w^2_{sat})}\right]$

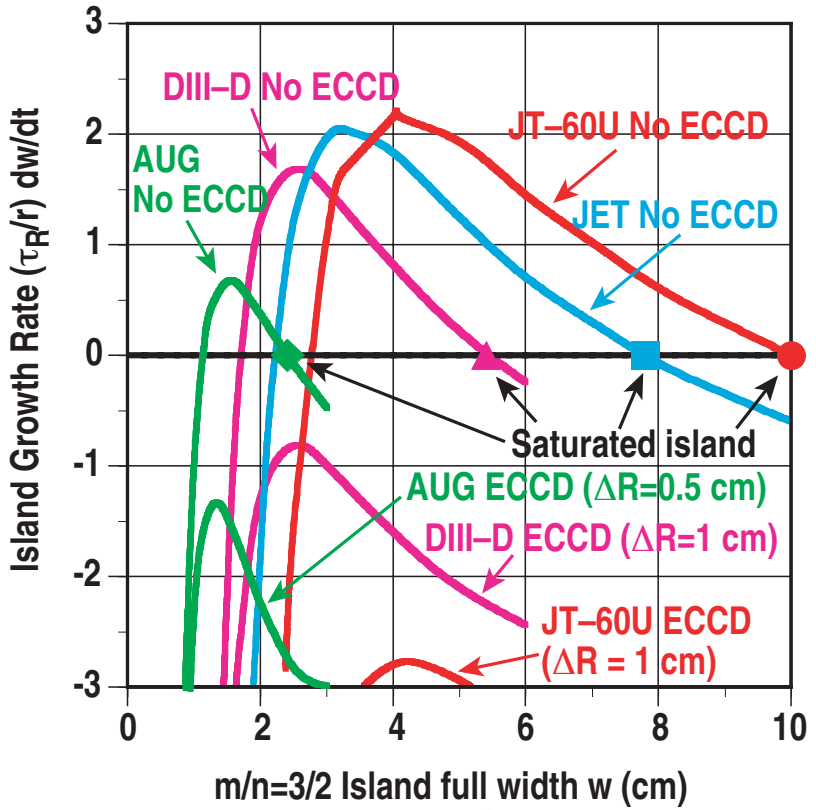
    . . . AUG, DIII–D, JET, JT-60U = 0.8, 1.3, 1.2, 1.0
    — $\langle a_2 \rangle \approx 3.2$ for $\Delta_o' r \approx -3$

Device	Shot #	β_N	q_{95}	j_{ec}/j_{bs}	j_{bs}/j_{II}
AUG	19713	2.7	3.85	3.1	0.21
DIII–D	122507	1.9	3.5	0.9	0.15
JET	47276	1.9	3.4	——	0.14
JT-60U	E41666	1.5	3.8	1.2	0.19

- **Unmodulated ECCD applied**
  - ★ 3/2 mode stabilized experimentally

    . . . model has no adjustable constants, given a_2 and $\Delta_o' r$

    – Consistency check for yes/no



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ASDEX Upgrade

EFDA JET

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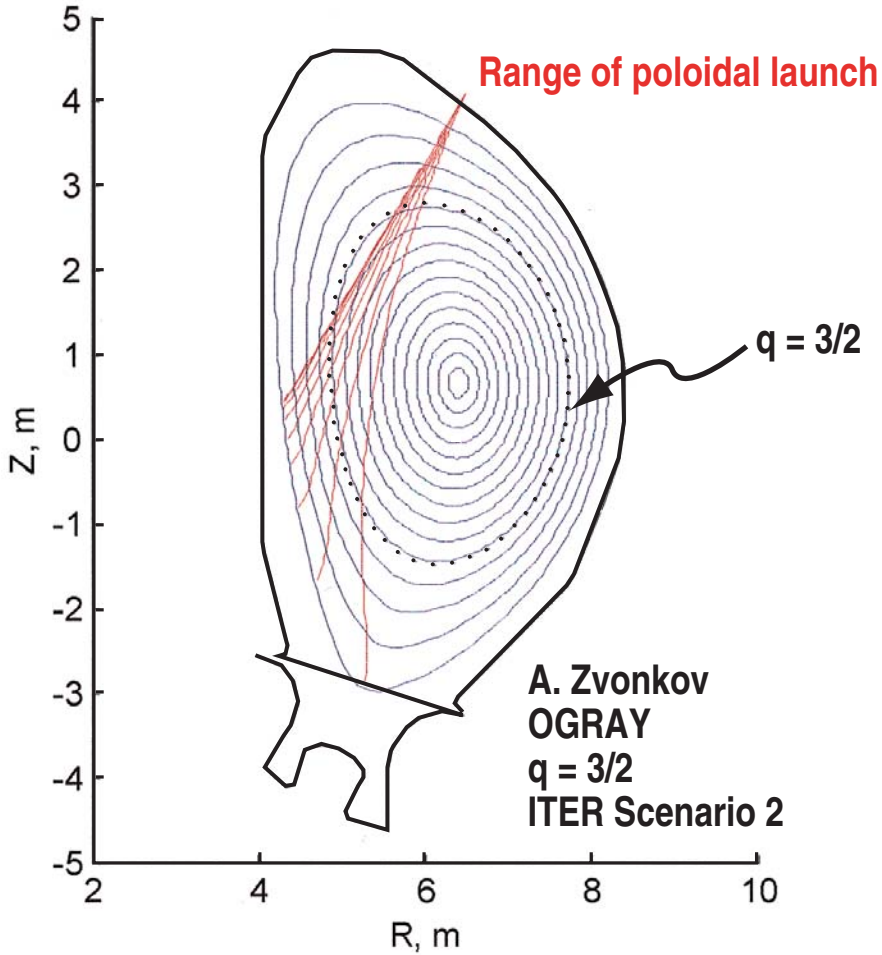
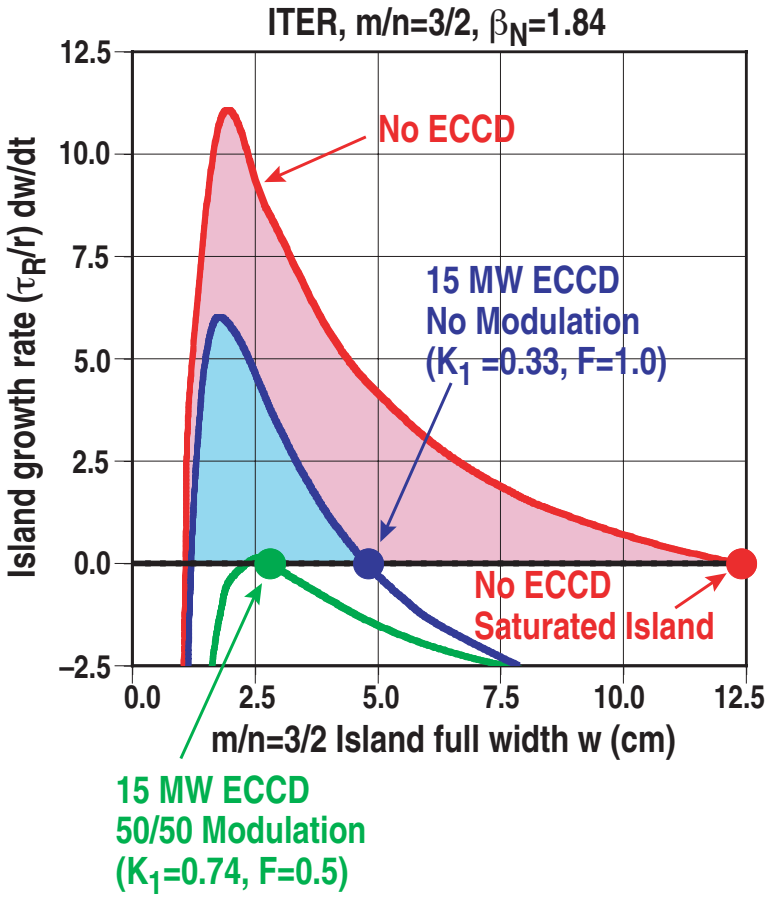
ITER rf Launching Point is Constrained by Shielding

- **Not best for narrow current drive**
  - ★ ITER has $\delta_{ec}/2\varepsilon^{1/2}\rho_{\theta i} \approx 6 >> 1$
    - – AUG, DIII–D, JT-60U experiments have 0.4~2



Modulated ECCD in ITER Can Mitigate the m/n=3/2 NTM

- **No ECCD**
  - ★ j_{bs}, $j_{||}$, r, L_q from equilibrium
    - – assume $\Delta'_o r = -3$
    - – $a_2 = 3.2$ from benchmarking



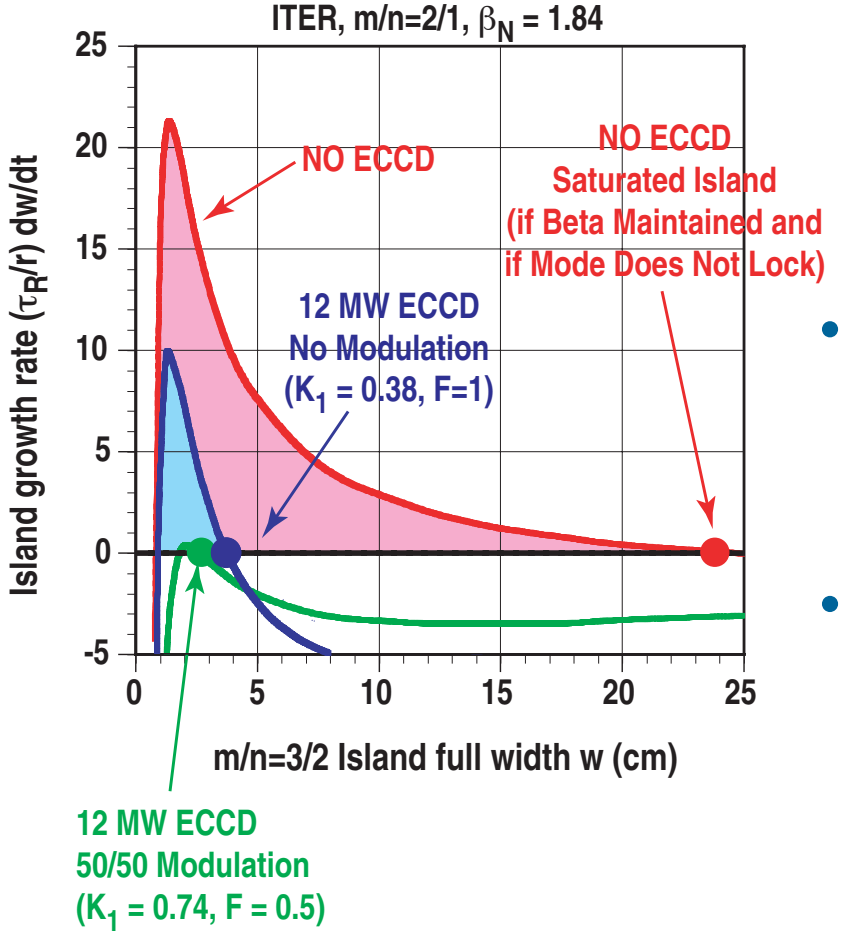
- **with ECCD directed at q = 3/2**
  - ★ Wide current drive
    - – δ_{ec} = 11.1 cm
      - ...$\delta_{ec}/2\varepsilon^{1/2}\,\rho_{\theta i} = 6.3 >> 1$
  - ★ Adjust modulated j_{ec}
    - – for $w_{sat} \gtrsim 2\varepsilon^{1/2}\,\rho_{\theta i}$
      - ...$\delta\Delta' r = -1.1$ for $\Delta' r = -4.1$

- **15 MW modulated reduces island**
  - ★ Factor of 5
    - – energy loss becomes negligible

- **15 MW unmodulated less effective**

Modulated ECCD in ITER Can Mitigate the m/n=2/1 NTM

- **No ECCD**
  - ★ j_{bs}, $j_{||}$, r, L_q from equilibrium
    - – assume $\Delta'_o r = -2$
    - – $a_2 = 2.8$ from benchmarking



- **with ECCD directed at q = 2**
  - ★ Wide current drive
    - – δ_{ec} = 7.5 cm
      - ...$\delta_{ec}/2\varepsilon^{1/2}\,\rho_{\theta i} = 5.4 >> 1$
  - ★ Adjust modulated j_{ec}
    - – for $w_{sat} \gtrsim 2\varepsilon^{1/2}\,\rho_{\theta i}$
      - ...$\delta\Delta' r = -2.6$ for $\Delta' r = -4.6$
- **12 MW modulated reduces island**
  - ★ Factor of 11
    - – wall rotation drag greatly reduced
- **12 MW unmodulated less effective**

Conclusions for ITER NTM Stabilization by ECCD

- **Proposed 20 MW, 170 GHz, "high launch" system**
  - ★ adequate to mitigate either or both the 3/2 and 2/1 NTMs
    - – good alignment and modulation should keep both islands small
  - ★ removing the metastable condition with unmodulated ECCD is problematic
    - – as $\delta_{ec}/2\varepsilon^{1/2}\,\rho_{\theta i} \approx 6 >> 1$
- **Existing devices need to confirm the advantage of modulation**
  - ★ ASDEX Upgrade and DIII–D (2006 planned)