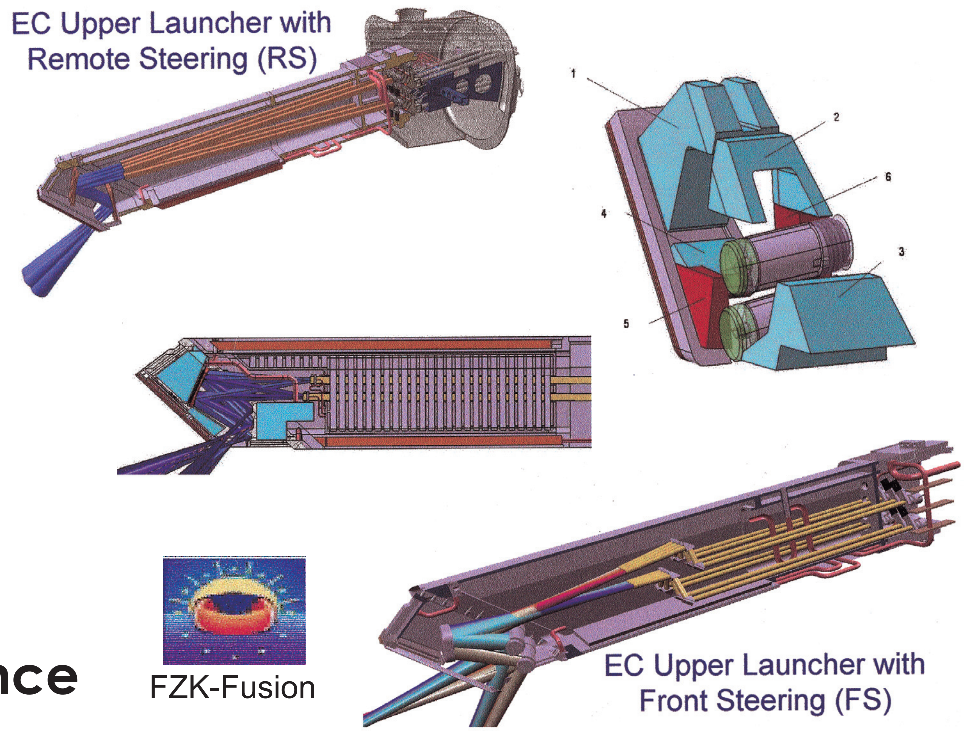
Evaluating Electron Cyclotron Current Drive Stabilization of Neoclassical Tearing Modes in ITER: Implications of Experiments in ASDEX Upgrade, DIII–D, JET and JT-60U

by
R.J. La Haye

for
R.J. Buttery,[*] N. Hayashi,[†] A. Isayama,[†] M. Maraschek,[‡] R. Prater, L. Urso,[‡] H. Zohm,[‡] and the ASDEX Upgrade, DIII–D, JET and JT-60U groups

[*]EURATOM/UKAEA Fusion Assoc., Culham, United Kingdom
[†]Japan Atomic Energy Agency, Naka, Japan
[‡]Max-Planck-Institut für Plasma Physik, Garching, Germany



Presented at
the 21st IAEA Fusion Energy Conference
Chengdu, China

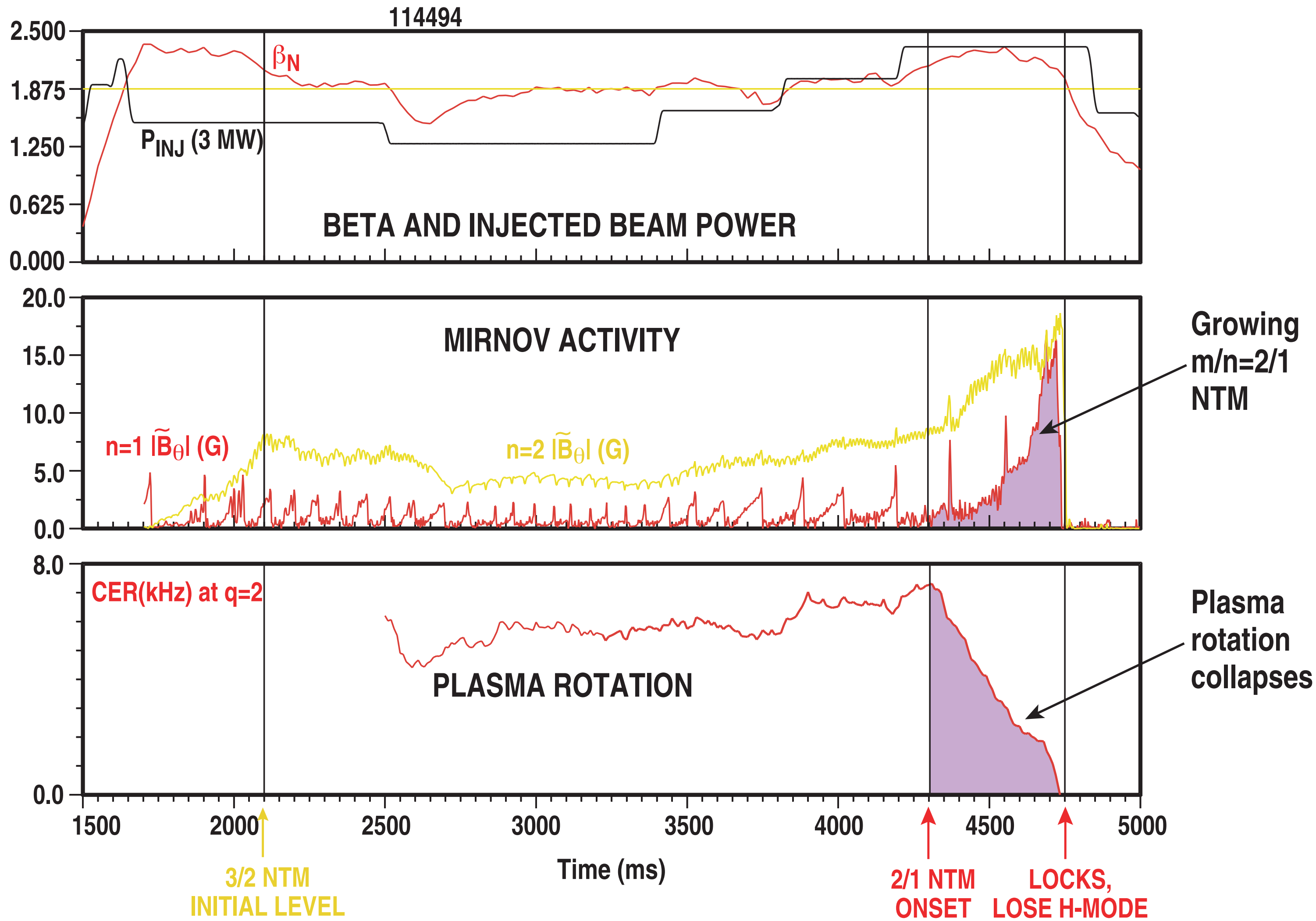
October 16–21, 2006

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 continous 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 high launch system is adequate for the job**
  - front steering (Henderson et al., 2005) narrower than remote steering ... thus requires less EC power
  - but benefits of modulation need to be confirmed

Tearing Modes Degrade Confinement and Rotation

- Plasma can lock, lose H-mode, disrupt with m/n=2/1 NTM

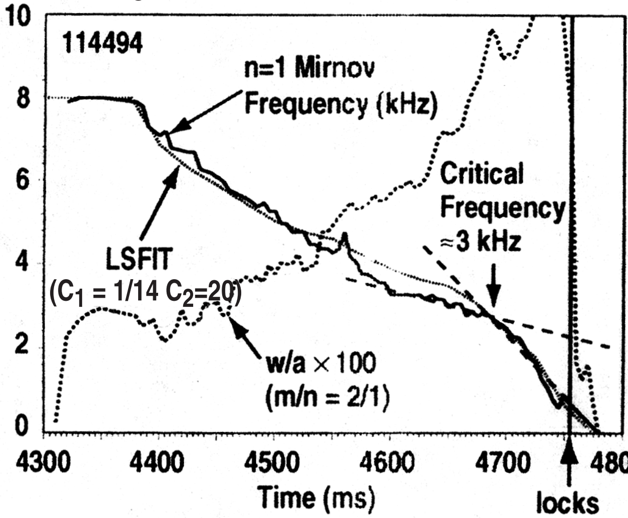


DIII-D NATIONAL FUSION FACILITY

038-05/RJL/jy

Slow Plasma Rotation in ITER Makes Locking Problematic

- **Modeling yields m/n=2/1 critical island of 5 cm in ITER for locking**
  - ★ $\omega_0/2\pi$ = 0.42 kHz at q = 2 (Y. Gribov, ASTRA, 2005)
    ... τ_{A0} = 3.0 μs (Y. Gribov, 2005)
    ... τ_W = 0.188 s (Y. Liu, 2005)
    ... $\tau_{M_0} \equiv \tau_{E0}$ = 3.7 s (J. Cordey 2004)



Mode locking of an m/n = 2/1 mode in DIII–D. The least square fit (LSFIT) is to the Nave-Wesson wall eddy current model and a 'belt' model of the effect of the island on viscosity (La Haye, et al., 2006)

$$\frac{d\omega}{dt} = \frac{\omega_0 (\tau_M/\tau_{M0}) - \omega}{\tau_M} - \frac{C_1}{2\tau^2_{A0}} \frac{(w/a)^3}{\omega\tau_W},$$

$$\tau_M = \tau_{M0}/(1 + C_2 w/a),$$

$$\tau_A^2 = \frac{\mu_0 R_0^2}{B_\theta^2 (r_s)} \left(\frac{r_s}{a}\right) n_e m_i \frac{w}{a} \equiv \tau_{A0}^2 \frac{w}{a},$$

$$\omega = \frac{\omega_0}{2(1 + C_2 w/a)} + \frac{1}{2}\sqrt{\frac{\omega_0^2}{(1 + C_2 w/a)^2} - \frac{2C_1 \tau_{M0} (w/a)^3}{(1 + C_2 w/a)\, \tau_{A0}^2 \tau_W}}$$

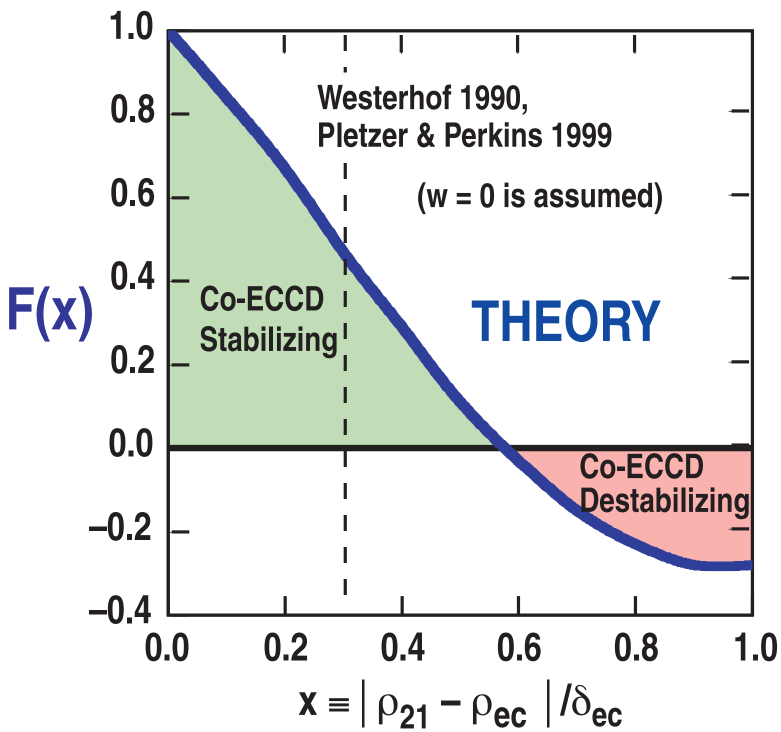
For the $\sqrt{\ }$ equal to zero further drag results in locking. This gives a critical island width

$$\left(\frac{w}{a}\right)^3 (1 + C_2 w/a) = \frac{\omega_0^2 \tau_{A0}^2}{2C_1} \left(\frac{\tau_W}{\tau_{M0}}\right)$$

I. ECCD Can Remove the Metastable Condition by More Negative Δ'

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

- **Co–ECCD can make Δ' more negative**



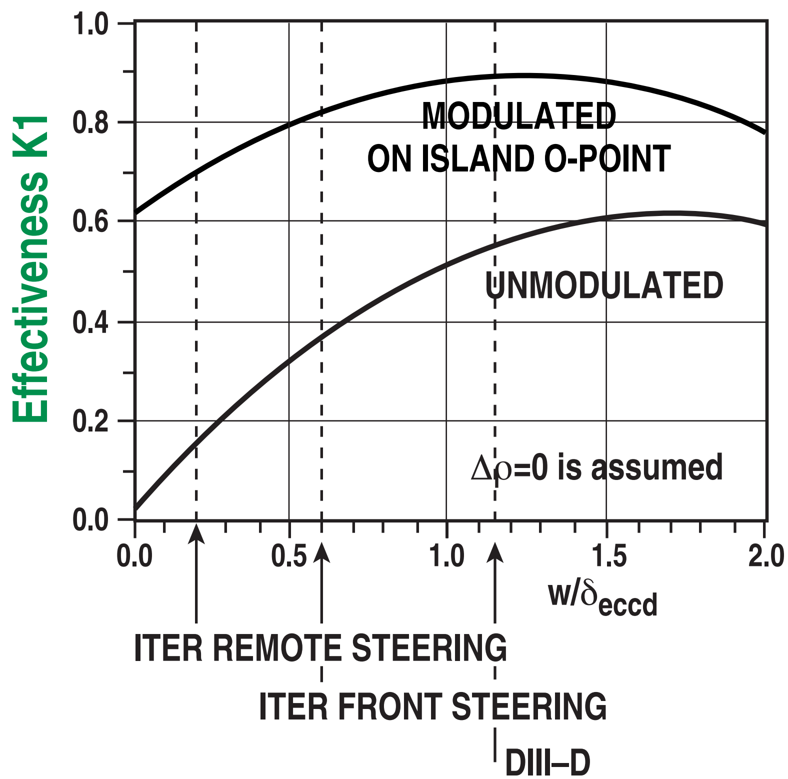
- **alignment must be good**
  - ★ $x = |\delta\rho/\delta_{ec}| < 0.3$
    ... δ_{ec} is FWHM

- $\delta\Delta' r \approx \frac{-5\pi^{3/2}}{32} a_2 \frac{L_q}{\delta_{ec}} F(x) \frac{j_{ec}}{j_{||}}$
  - ★ $\delta\Delta' r \propto \frac{j_{ec}}{\delta_{ec}} \propto \frac{P_{ec}}{\delta_{ec}^2}$
    ... favors narrow ECCD

II. ECCD Can Also Remove the Metastable Condition by Replacing the Missing Bootstrap Current

$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta_0' r + \delta\Delta' r + a_2 \frac{j_{bs}}{j_{\|}} \frac{L_q}{w} \left[1 - \frac{w_{marg}^2}{3\,w^2} - K_1 \frac{j_{ec}}{j_{bs}} \right]$$ **Modified Rutherford Eqn.**

- **Co–ECCD can replace the "missing" bootstrap current in island**

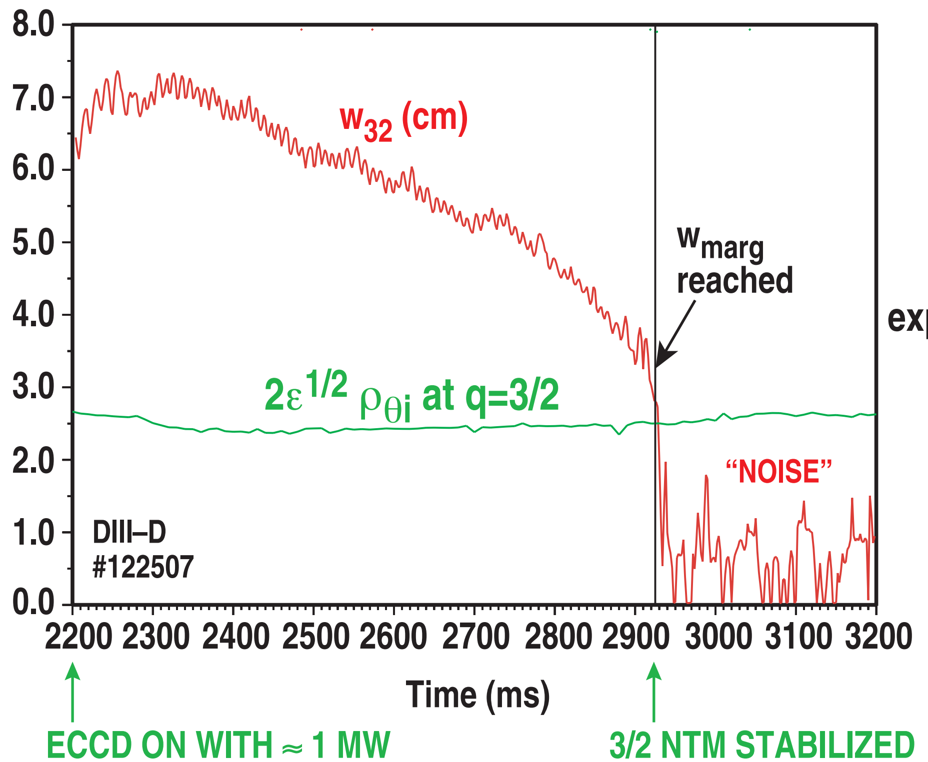


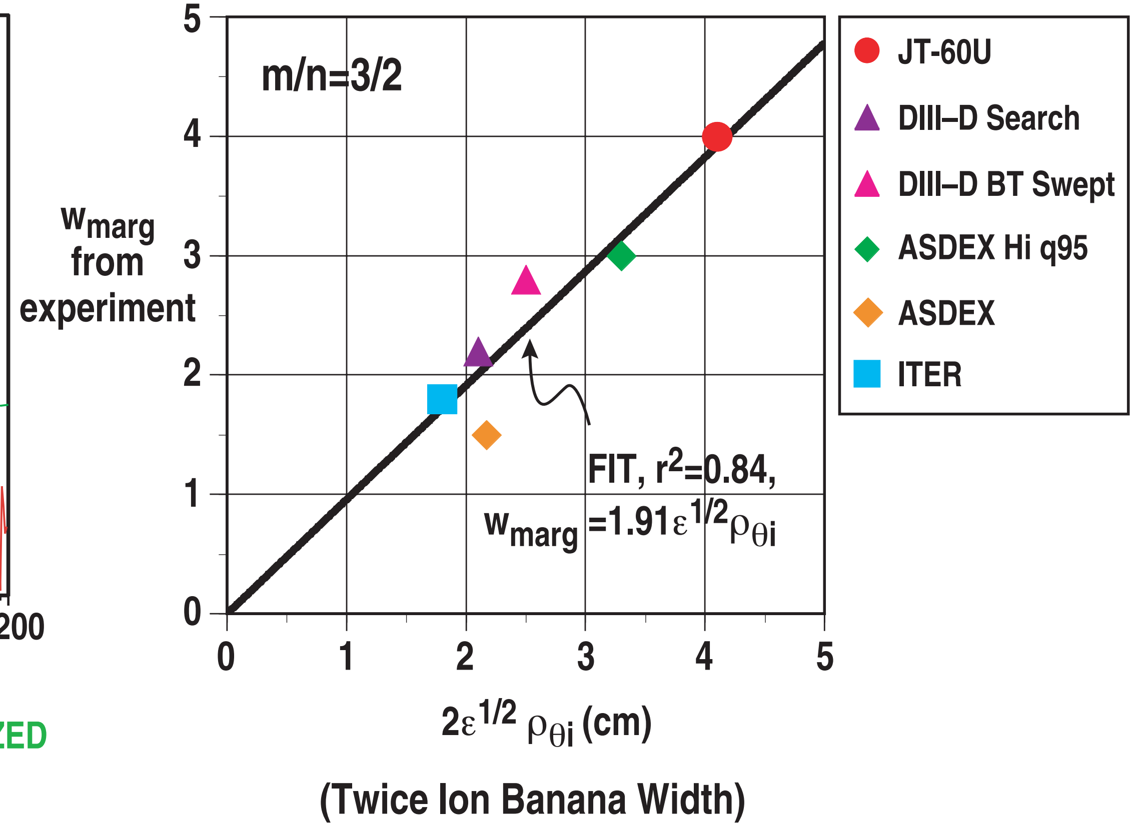
- **for w/δ_{ec} <<1, modulation is desirable**
  - ★ existing devices have $w/\delta_{ec} \gtrsim 1$
  - ★ ITER has relatively small w/δ_{ec} ... front steering advantageous
- **modulation has drawbacks**
  - ★ $\delta\Delta' r$ halved
  - ★ need to operate at $w \gtrsim w_{marg}$

(Hegna & Callen 97, Zohm 97, Perkins et al, 97)

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**
  - ★ w_{marg}/r is relatively smaller in ITER





DIII-D NATIONAL FUSION FACILITY SAN DIEGO

ASDEX Upgrade

JAEA

210-06/RJL/jy

Benchmarking m/n=3/2 NTM Suppression by ECCD Experiments Checks Model for m/n = 2/1 Control in ITER

- **Saturated island before/without ECCD**

  ★ $$\frac{a_2}{-\Delta_o' r} = \frac{(w_{sat}/L_q)}{(j_{bs}/j_{//})}\left[\frac{1}{1-(w^2_{marg}/3w_{sat}{}^2)}\right]$$

  . . . AUG, DIII–D, JET, JT-60U = 0.8, 1.3, 1.2, 1.0

  — $\langle a_2 \rangle \approx 3.2$ for $\Delta_o' r \approx -3$

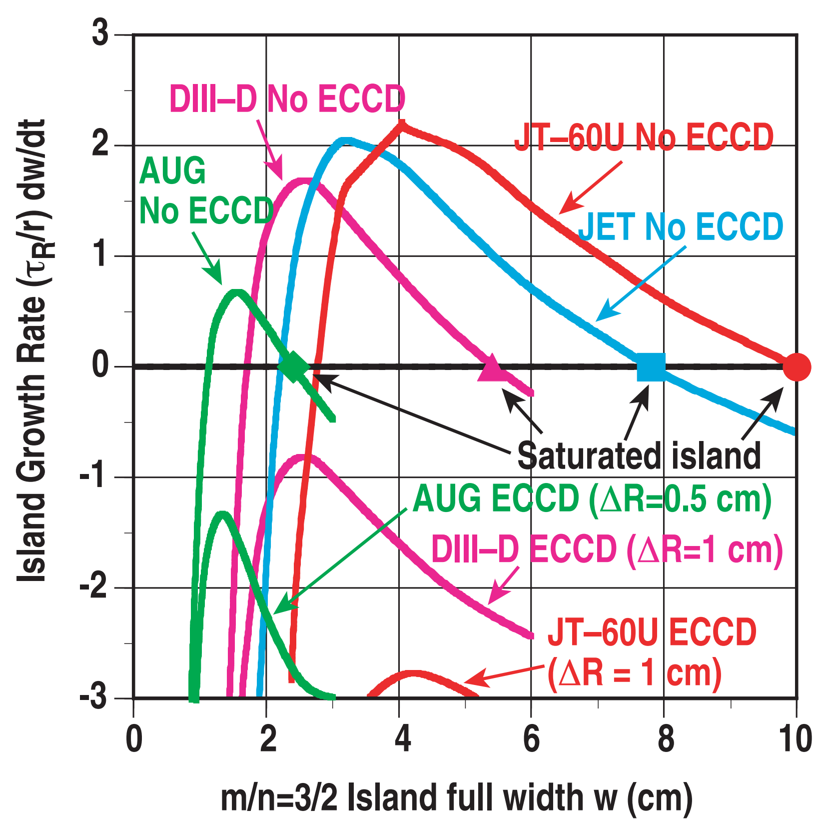
Device	Shot #	β_N	q_{95}	j_{ec}/j_{bs}	j_{bs}/j_{II}
AUG	19713	2.7	3.85	3.1	0.21
DIII–D	122507	1.9	3.5	0.9	0.15
JET	47276	1.9	3.4	—	0.14
JT-60U	E41666	1.5	3.8	1.2	0.19

- **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



See also R. Prater EX/4-2 for m/n=2/1 NTM stabilization in DIII–D

DIII–D NATIONAL FUSION FACILITY SAN DIEGO

ASDEX Upgrade

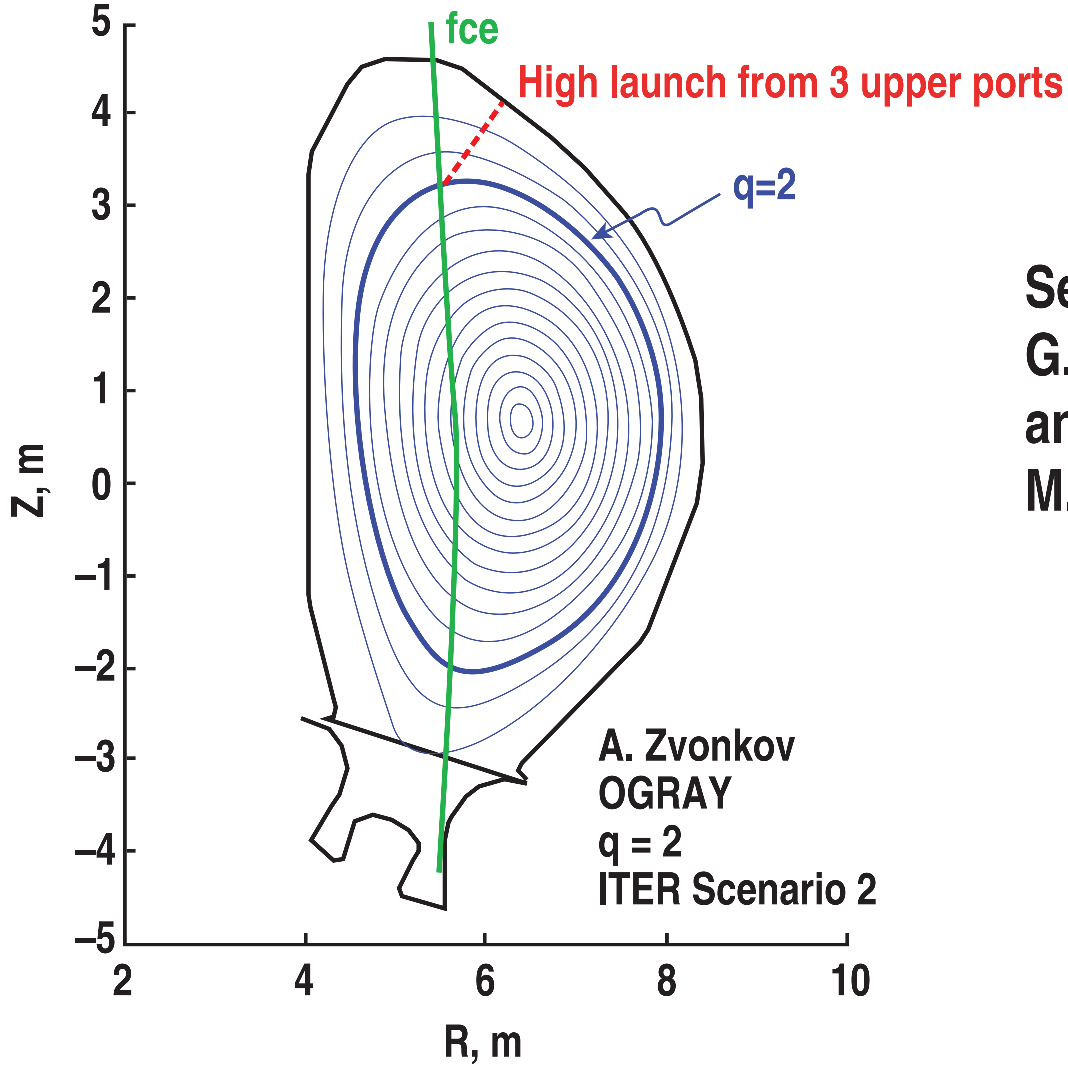
EFDA JET

JAEA

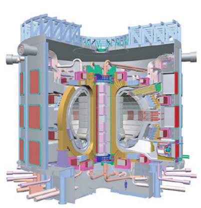
210-06/RJL/jy

ITER rf Launching Point is Constrained by Shielding

- **"High" launch is not best for narrow current drive**
  - ★ ITER has $\delta_{ec}/2\varepsilon^{1/2}\rho_{\theta i} \approx 5.4 >> 1$ (remote steering) or ≈ 1.8 (front steering)
    - – AUG, DIII–D, JT-60U experiments have 0.4~2



See also
G. Saibene, IT/P2-14
and
M. Henderson, IT/P2-15



GENERAL ATOMICS

156-05/RJL/rs

Minimum Necessary Peak ECCD Should Occur by Matching ECCD Width to "Marginal" Island

- **ECCD effectiveness K_1 ($\Delta\rho/\delta_{ec} \equiv 0$)**

  ★ peaks at $K_1 \approx 1/\sqrt{3}$ at $w/\delta_{ec} \approx \sqrt{3}$ without modulation
  . . . too wide δ_{ec} makes only partial use of rf current

  ★ peaks at $K_1 \approx 7/8$ at $w/\delta_{ec} \approx 5/4$ with modulation
  . . . insensitive to width δ_{ec}

- **NTM has (<u>with no rf</u>) largest dw/dt at $w_{marg} \approx 2\varepsilon^{1/2}\rho_{\theta i}$**

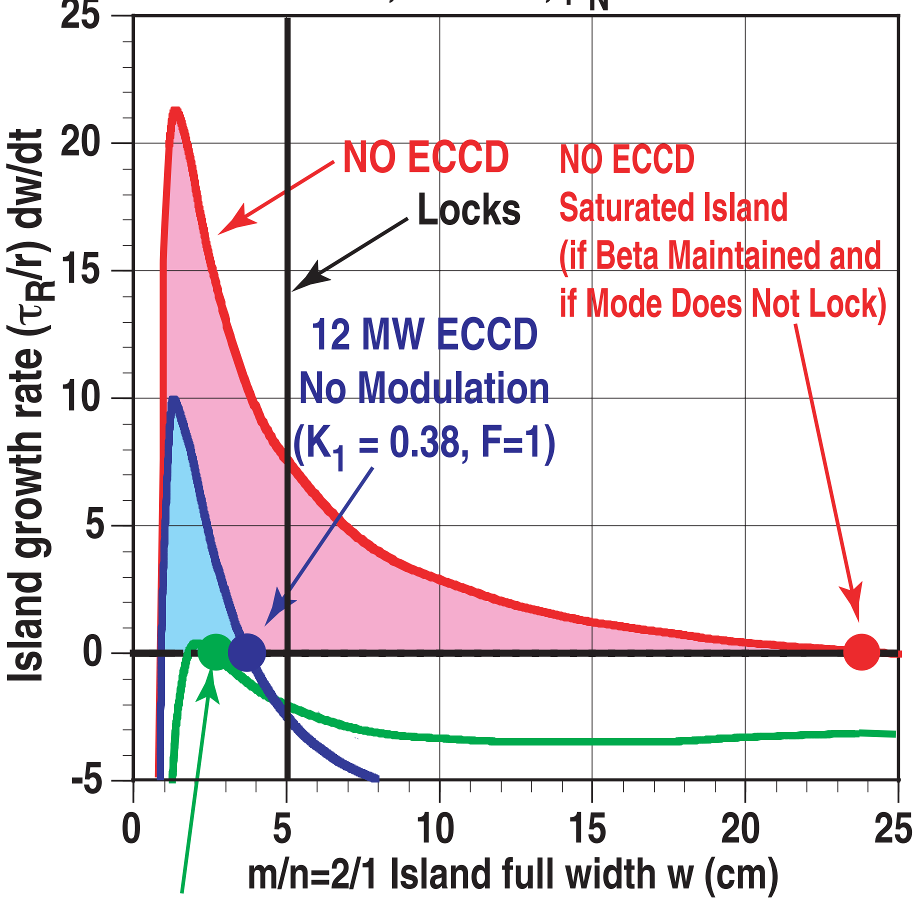
- **Taken together, $\dot{w} \equiv 0$ and $\partial\dot{w}/\partial w \equiv 0$ for stabilization**

  ★ ⇒ min j_{ec} required at $\delta_{ec} \approx 1/\sqrt{3} \sim 4/5$ of w_{marg}
  . . . should design rf launcher accordingly to minimize rf power

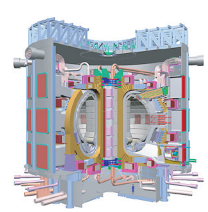
  – favors front steering in ITER over remote steering

Remote Steering ECCD in ITER Can Mitigate the 2/1 NTM

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



- **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} (no misalignment)
    - – for $w_{sat} \gtrsim 2\varepsilon^{1/2} \rho_{\theta i}$ need 12 MW
      ...$\delta\Delta' r = -2.6$ for $\Delta' r = -4.6$
  - ★ Unmodulated less effective
    - – but within locking limit

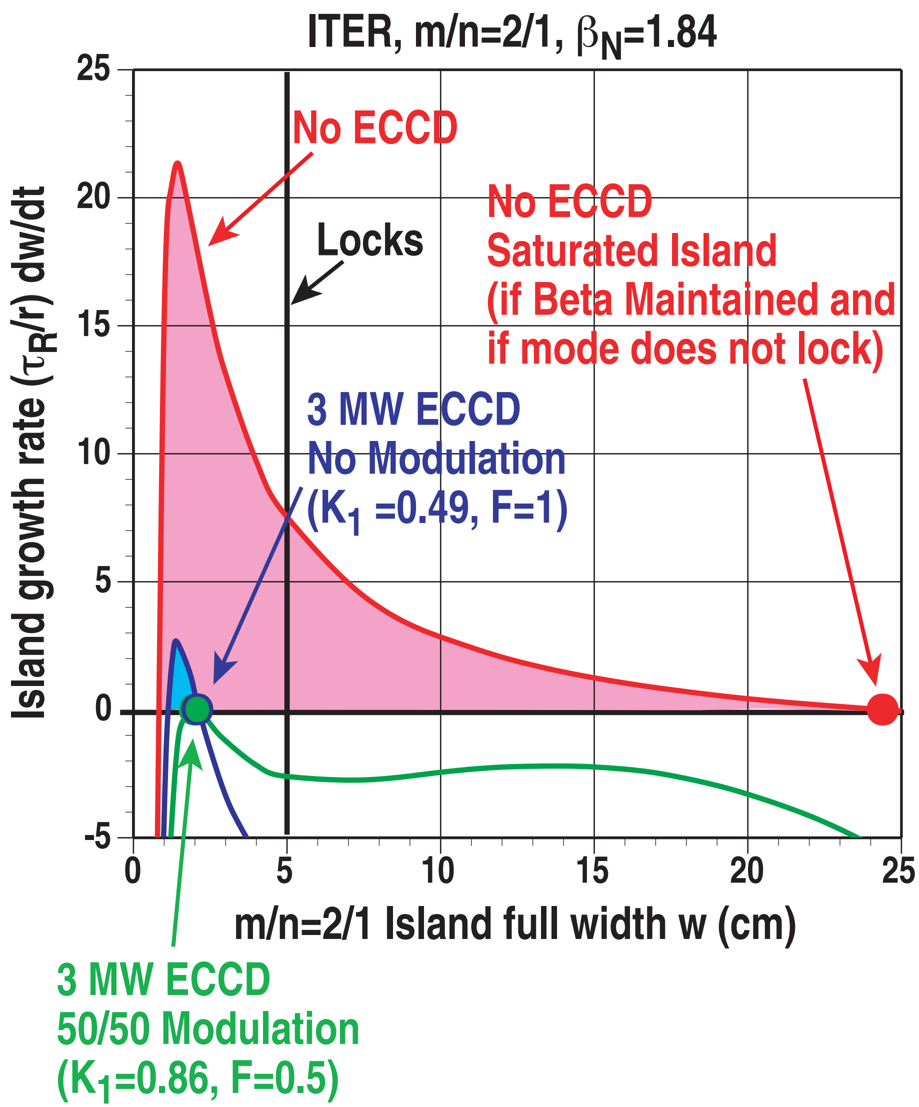


GENERAL ATOMICS

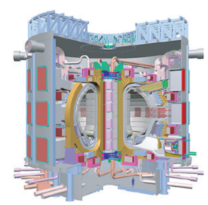
210-06/RJL/jy

Front Steering ECCD in ITER Requires Less Power

- **Again assume no misalignment**
  - ★ as in remote steering



- **With ECCD directed at q = 2**
  - ★ Narrow current drive
    - – δ_{ec} = 2.6 cm
      … $\delta_{ec}/2\varepsilon^{1/2}\ \rho_{\theta i}$ = 1.8 $\gtrsim$ 1
  - ★ Adjust modulated j_{ec} (no misalignments)
    - – for $w_{sat} \gtrsim 2\varepsilon^{1/2}\ \rho_{\theta i}$ need 3 MW
      … $\delta\Delta'r$ = –5.3 for $\Delta'r$ = –7.3
  - ★ Unmodulated as effective
    - – more margin from 5 cm locking
      … than remote steering

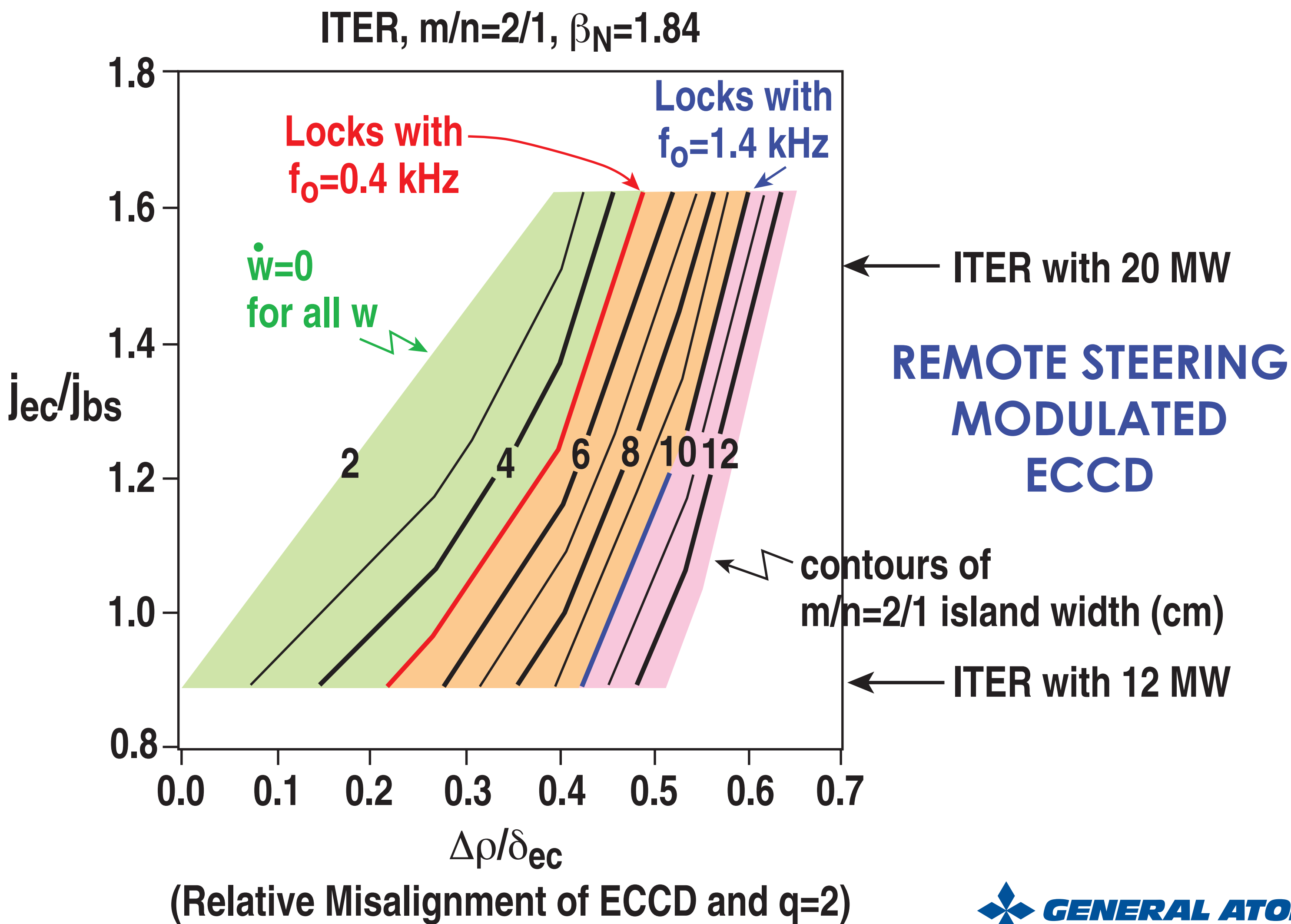


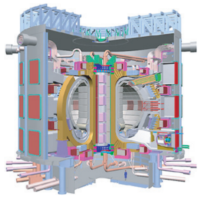
GENERAL ATOMICS

210-06/RJL/jy

Well-aligned Remote ECCD Can Avoid m/n=2/1 Mode Locking in ITER

- $|\Delta\rho/\delta_{ec}| \lesssim 0.2$, ($|\Delta R| \lesssim 1.5$ cm), is necessary with 12 MW
  - ★ tolerance increases with more EC power and/or more plasma rotation ... little "extra" power for m/n = 3/2 NTM control



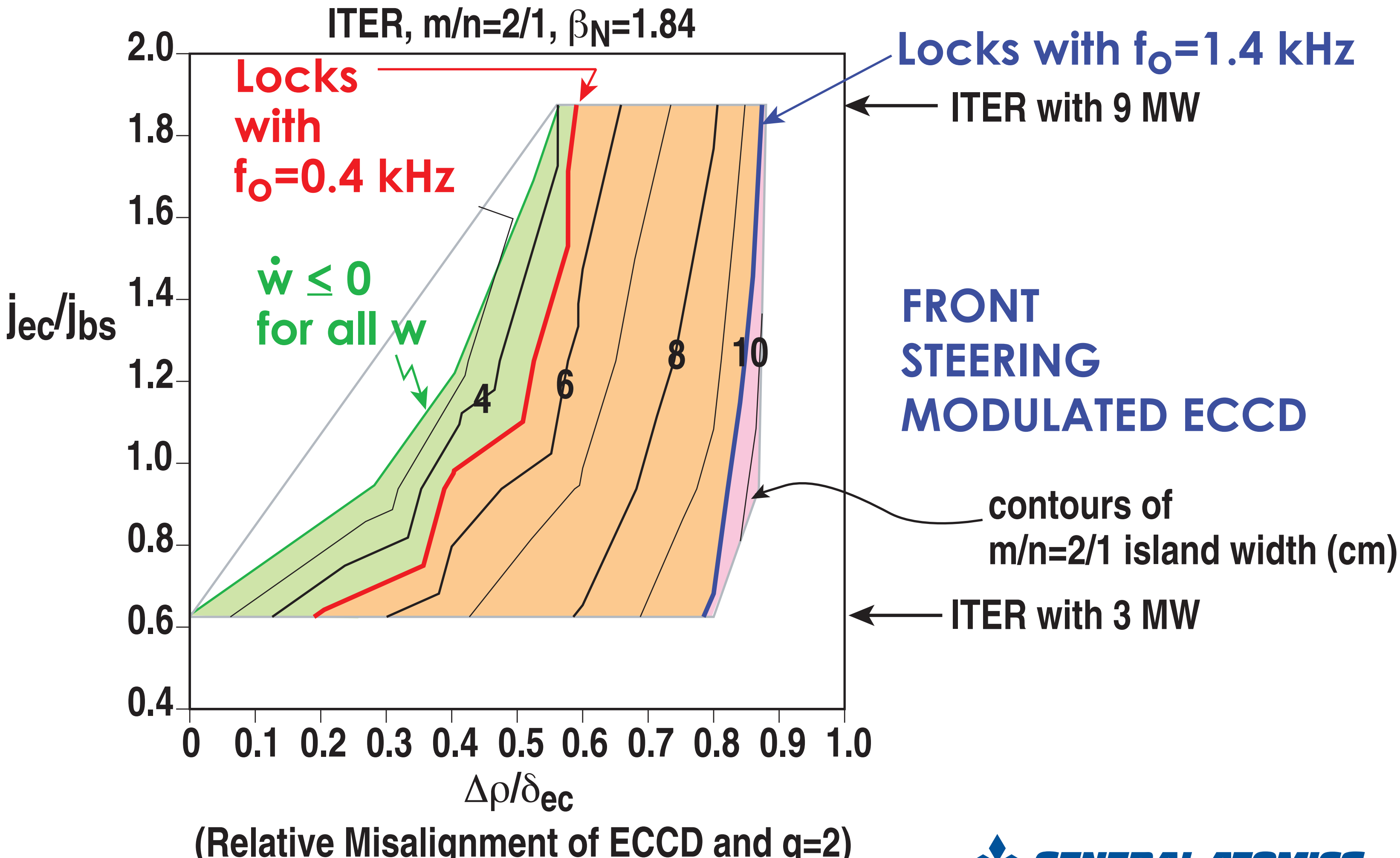


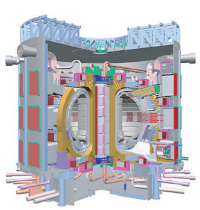
GENERAL ATOMICS

210-06/RJL/jy

Front Steering ECCD Requires Less Power for Avoiding m/n=2/1 Mode Locking in ITER

- **But $|\Delta\rho/\delta_{ec}| \lesssim 0.2$ is a very difficult $|\Delta R| \lesssim 0.5$ cm with 3 MW**
  - ★ tolerance increases to $|\Delta R| \lesssim 1.5$ cm with $\approx$ 7 MW
    ... leaving 20-7 $\approx$ 13 MW for m/n=3/2 NTM control

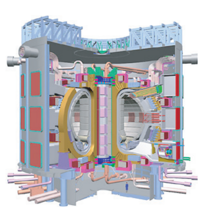




GENERAL ATOMICS

Conclusions for ITER NTM Stabilization by ECCD

- **Proposed 20 MW injected, 170 GHz, "high launch" system**
  - ★ adequate to avoid mode locking of the 2/1 NTM
    ... front steering favored as narrower, needs less EC power
      — but tolerance on misalignment is tighter
- **More plasma rotation would expand the stable operational space**
- **Existing devices need to confirm the advantage of modulation**
  - ★ ASDEX Upgrade (this conference) and DIII–D (2007 planned)
    ... see also A. Isayama to rapp. H. Zohm, EX/4–1Rb



GENERAL ATOMICS