Requirements for Alignment of Electron Cyclotron Current Drive for Neoclassical Tearing Mode Stabilization in ITER

by
R.J. La Haye

in collaboration with J.R. Ferron,
D.A. Humphreys, T.C. Luce,
C.C. Petty, R. Prater, E.J. Strait,
and A.S. Welander

12th Workshop on
MHD Stability Control:
Improved MHD Control Configurations

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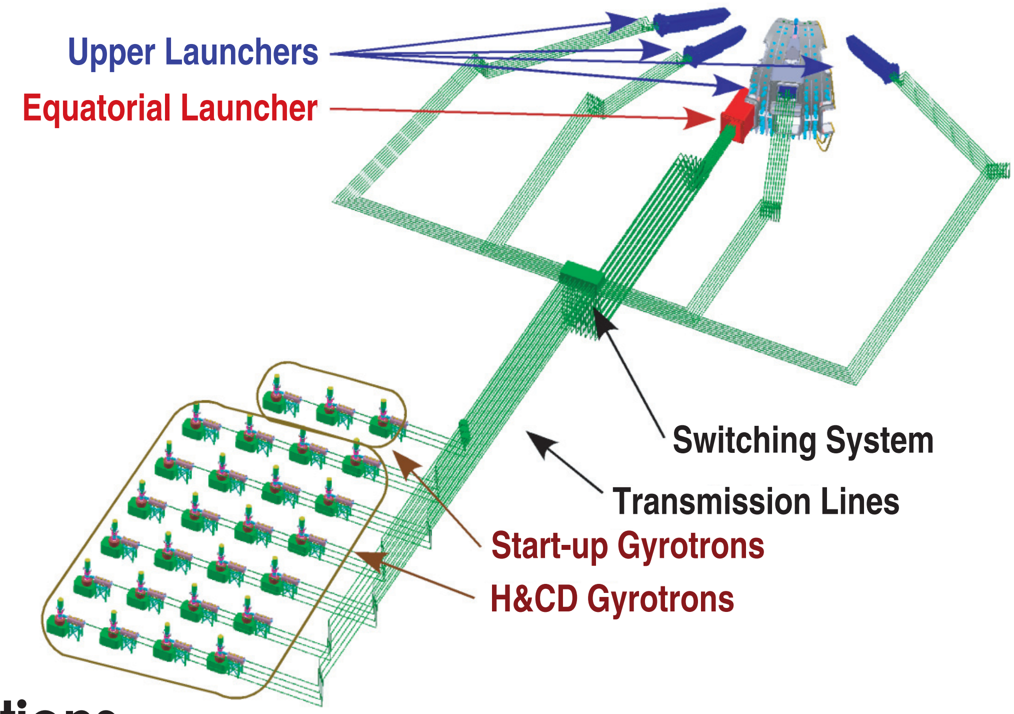


ITER
EC SYSTEM

GENERAL ATOMICS

079-07/RJL/jy

ITER Relies on ECCD Stabilization of NTMs

- **Large size and low torque in ITER makes for**
  - ★ slow plasma rotation
    - … susceptibility to island locking by resistive wall
- **Front steering with narrower ECCD**
  - ★ resolves the issue of too broad and thus ineffective ECCD
- **Narrower ECCD places demands on alignment**

NTMs Can be Stabilized with Electron Cyclotron Co-Current Drive at a Rational Surface

- **Stability given by Modified Rutherford equation for island growth**

$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta_0' r + \delta(\Delta' r) + a_2 \frac{j_{boot}}{j_{tot}} \frac{L_q}{w}\left[1 - \frac{w_{marg}^2}{3w^2} - K_1 \frac{j_{eccd}}{j_{boot}}\right] \quad \text{with } w_{marg} \approx 2\varepsilon^{1/2}\rho_{\theta i}$$

CD makes Δ' more negative

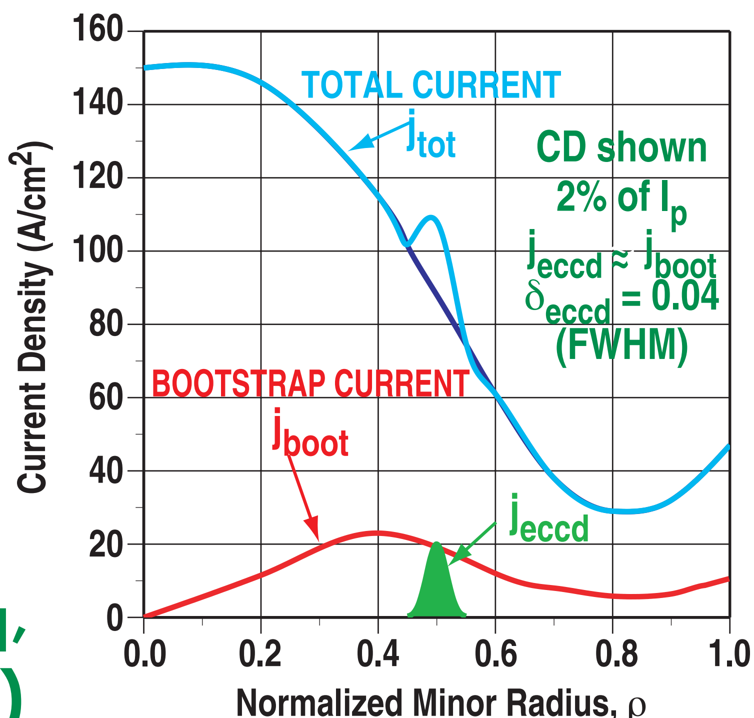
CD replaces "missing" bootstrap current

E. Westerhof 1990, A. Pletzer and F.W. Perkins, 1999

$$\delta(\Delta' r) \approx -\frac{5\pi^{3/2}}{32} a_2 \frac{L_q}{\delta_{eccd}} * \frac{j_{eccd}}{j_{tot}} F$$

Effectiveness

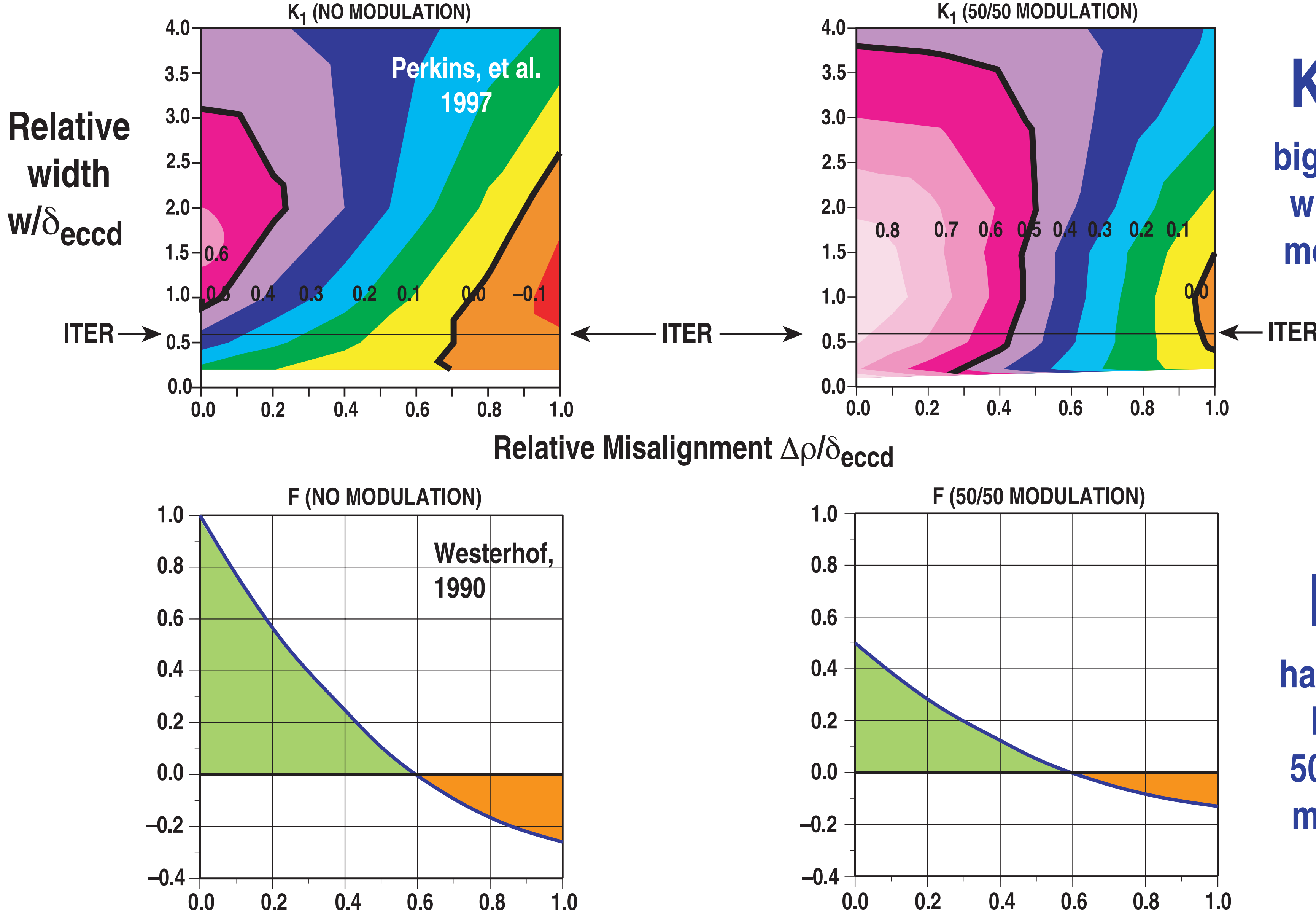
$F(\Delta\rho/\delta_{eccd}$, cw or mod)



C.C. Hegna and J.D. Callen 1997, H. Zohm 1997, F.W. Perkins et al., 1997

Effectiveness K_1 is a function of
... $\Delta\rho/\delta_{eccd}$
... w/δ_{eccd}
... cw or modulated

Both K_1 and F Effectivity Decrease with Misalignment

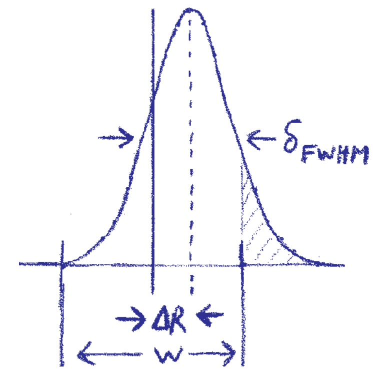


K_1 bigger with mod.

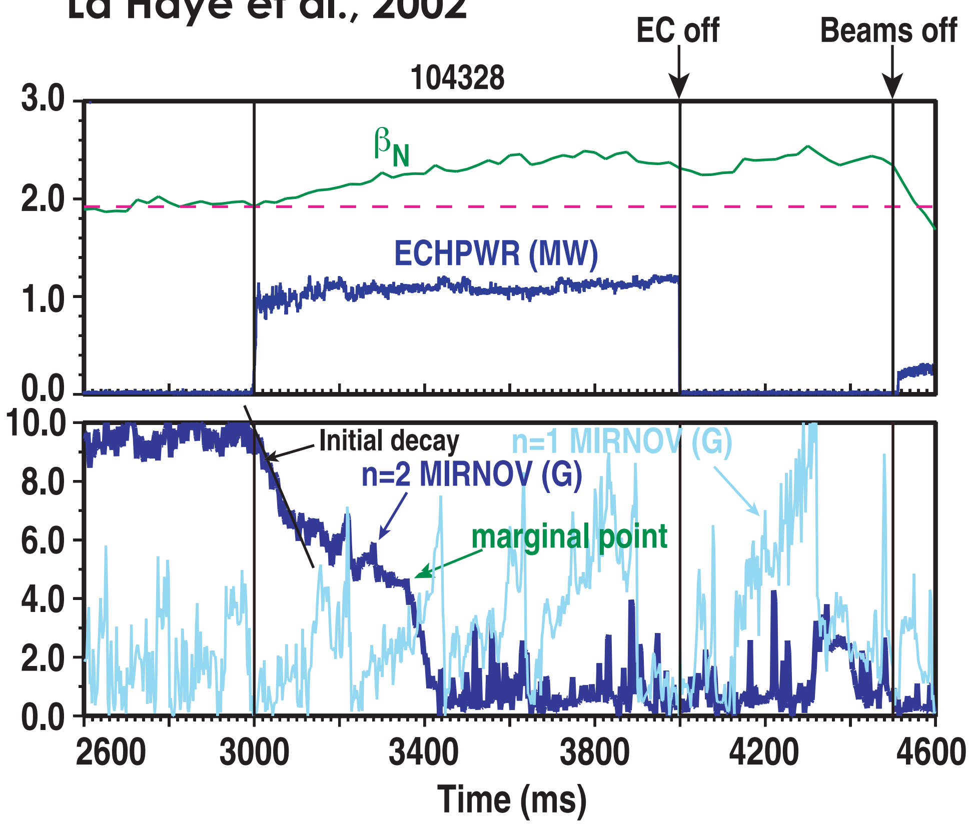
F halved by 50/50 mod.

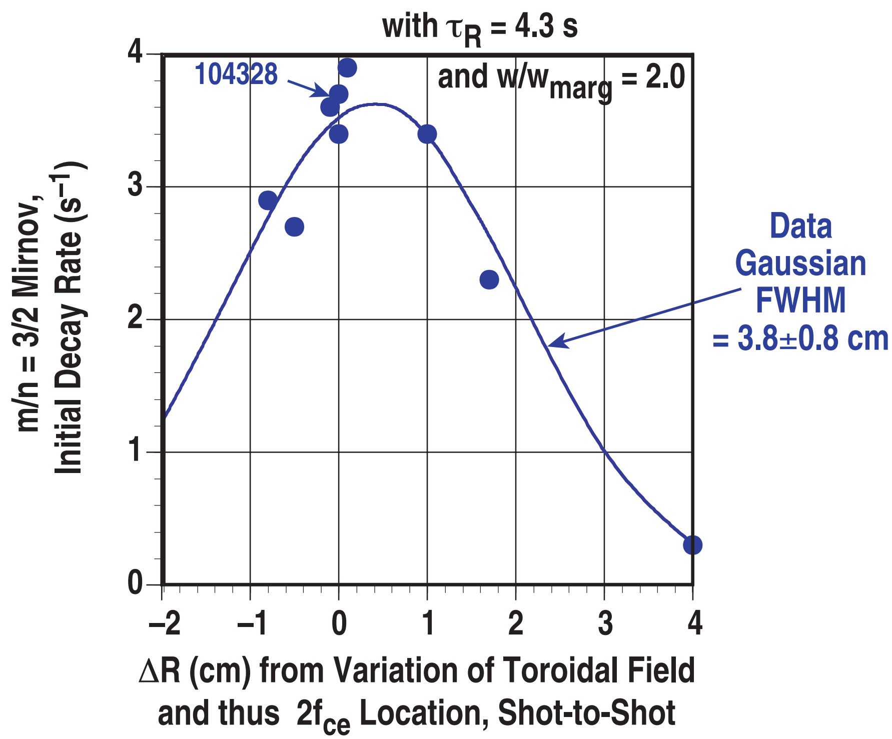
Optimum in DIII–D Can be Found with Shot-to-Shot Toroidal Field Adjustment and Initial Decay Rate

- Before ECCD, all terms in MRE balance to zero
- Upon ECCD, initially only rf effects are present
  - ★ 2 cm misalignment decreases effectiveness by a factor of 2



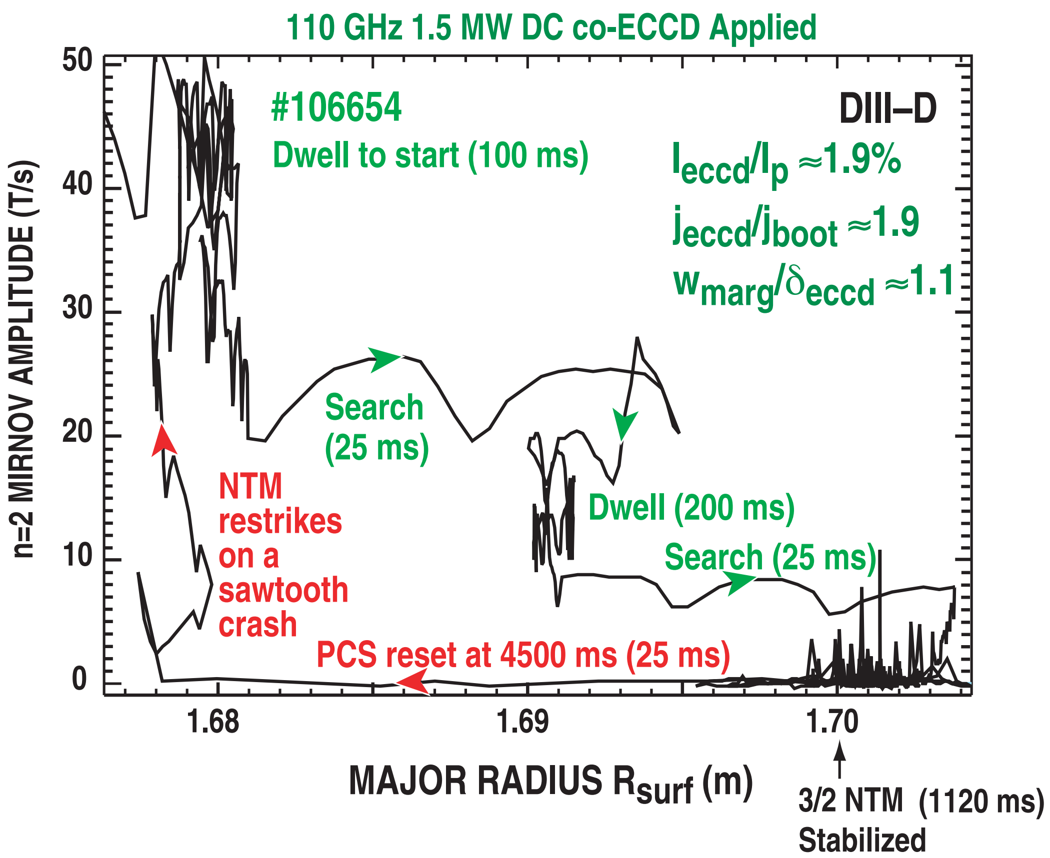
La Haye et al., 2002

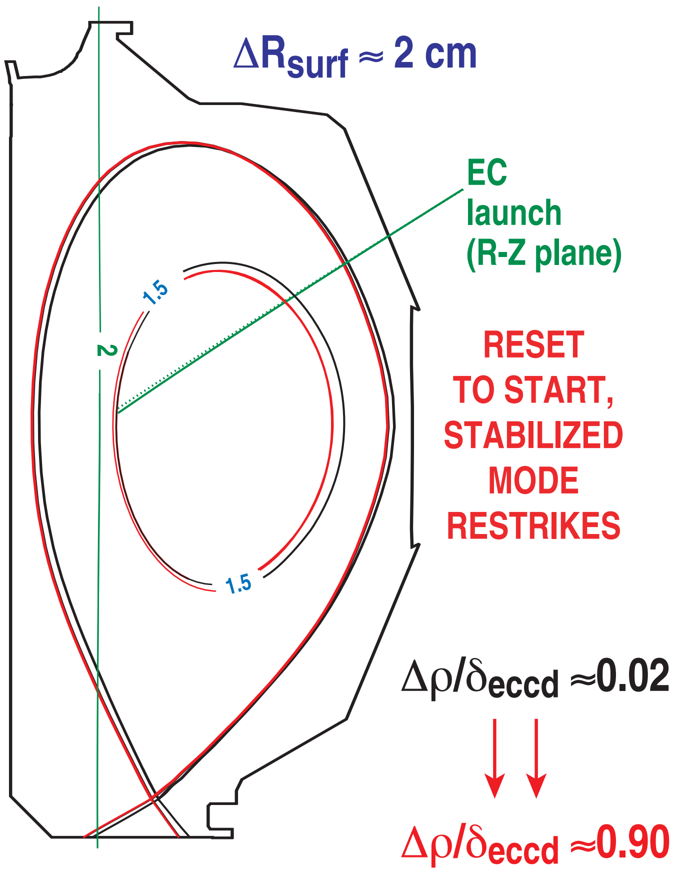




DIII–D Uses Real-Time Control of Plasma Major Radius to Put the Rational Surface on the ECCD

- "Search and Suppress" locks onto optimum alignment changing R_{surf}
  - ★ ΔR=1 cm misalignment is significant

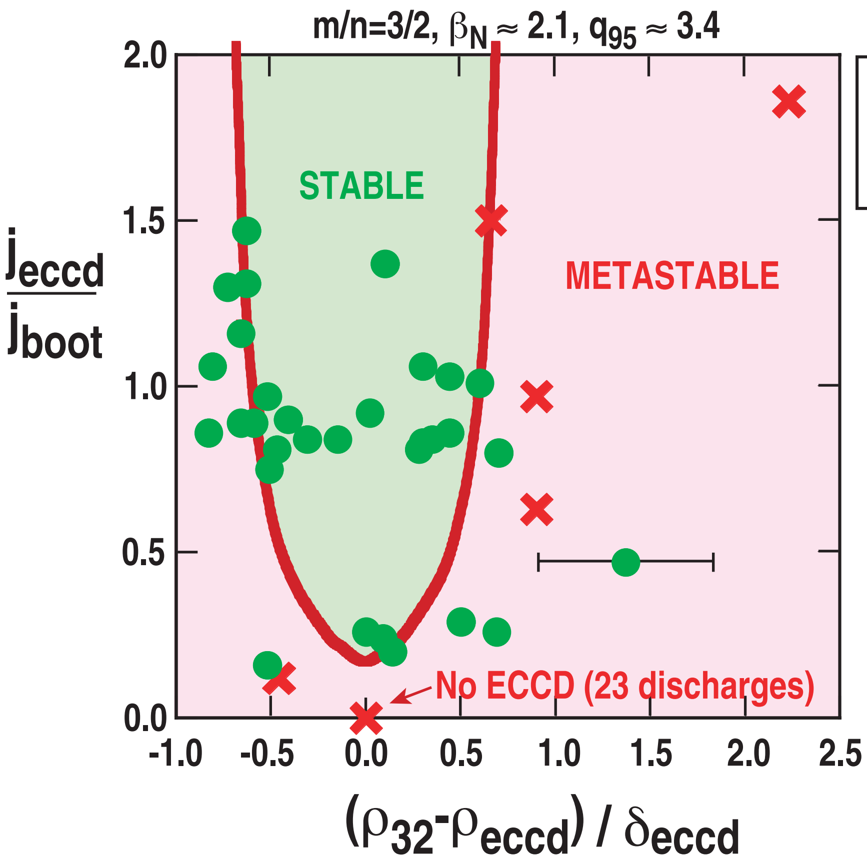




(R.J. La Haye, 2002, R. Prater, 2003 R.J. La Haye, 2005)

Preemptive ECCD Control in DIII–D with Active Tracking Avoids an NTM Occurring by Keeping |ΔR| to ~1 cm

- Real-time MSE EFIT to locate q=3/2 accurately
  - ★ R_{surf} adjusted to keep aligned with ECCD



La Haye, et al., 2005

"ACTIVE TRACKING"
MODELING WITH MRE
AND BOTH K1 & F
WORKS WELL

- All early ECCD discharges evaluated at every potentially destabilizing ("seeding") sawtooth crash
- For $\dot{w} \equiv 0$ at least stable $w_{marg} \approx 0.8\, \delta_{eccd}$

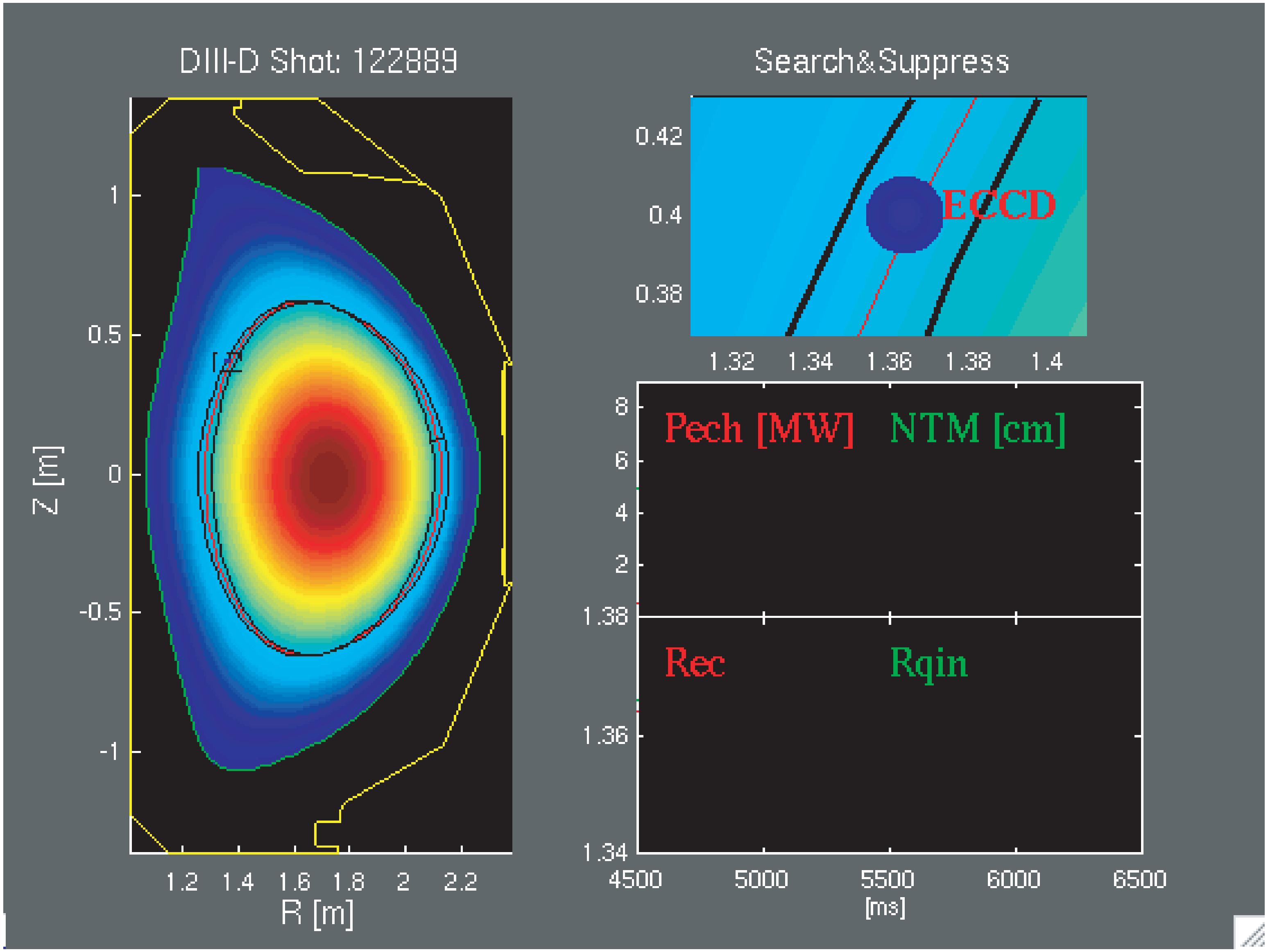
$$\left.\frac{j_{eccd}}{j_{boot}}\right|_{min} = \frac{\Delta_0' r + \frac{2}{3} a_2 \frac{L_q}{w_{marg}} \frac{j_{boot}}{j_{tot}}}{a_2 \frac{L_q}{w_{marg}} \frac{j_{boot}}{j_{tot}} K_1 + \frac{5\pi^{3/2}}{32} a_2 \frac{L_q}{\delta_{ec}} \frac{j_{boot}}{j_{tot}} F}$$

with $K_1\ (w, \delta_{eccd}, \Delta\rho)$ and $F\ (\Delta\rho/\delta_{eccd})$

Multiple Alignment Methods Implemented in DIII–D in the Control System and Used in Experiments

DIII–D
Shot:
122889

m/n=2/1
cw
ECCD
with
B_{tor}
adjusted
for
alignment



Petty, et al., 2004
Prater, et al., 2007

Marginal time,

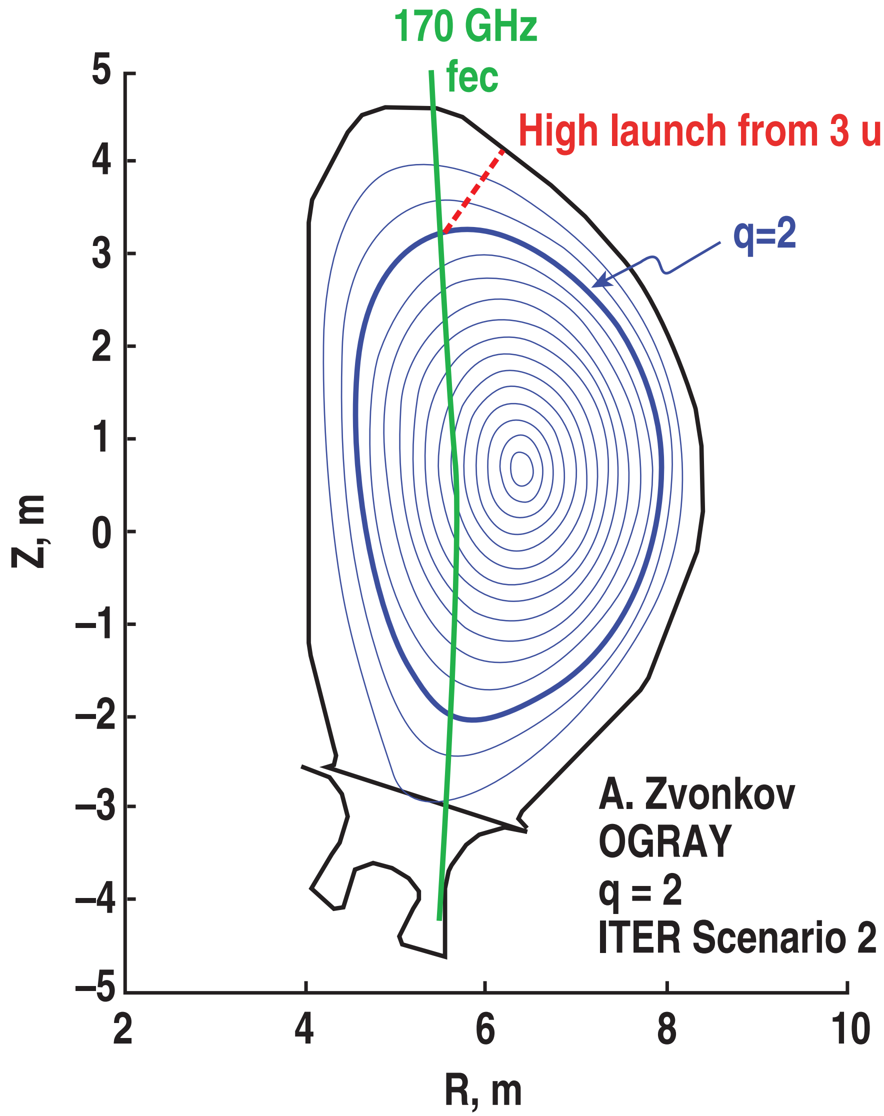
$$\frac{j_{eccd}}{j_{boot}} \approx 1.6$$

$$\frac{\delta_{eccd}}{2\varepsilon^{1/2}\rho_{\theta i}} \approx 0.6$$

$\Delta R \approx 0.5\text{cm}$

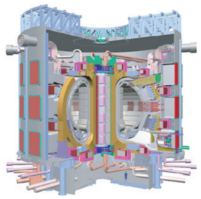
ITER rf Launching Point is Constrained by Shielding

- **“High” launch is not best for narrow current drive**
  - ★ ITER has relatively wide ECCD $\delta_{eccd}/2\varepsilon^{1/2}\rho_{\theta i} \approx 1.8$ (front steering) $\gtrsim 1$



See also IAEA 2006
G. Saibene, IT/P2-14
and
M. Henderson, IT/P2-15

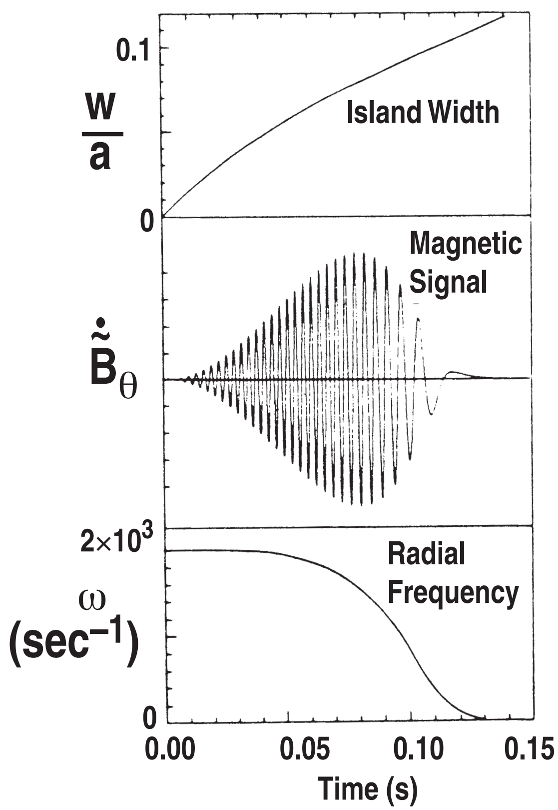
20 MW AVAILABLE



039-07/RJL/jy

Large Size and Low Torque in ITER Make for Slow Plasma Rotation and Susceptibility to Island Locking

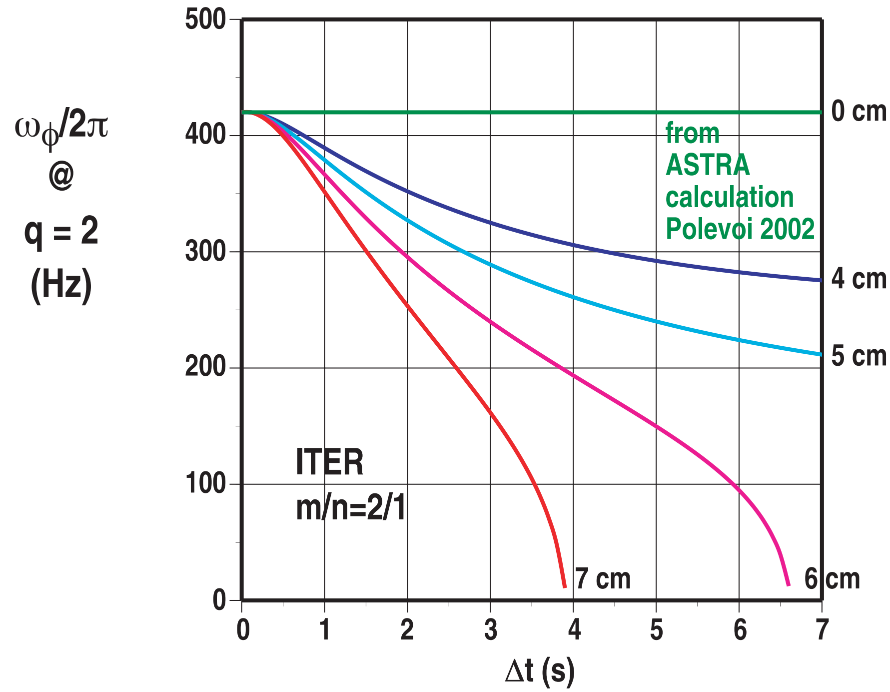
- **Eddy currents induced in vacuum vessel wall**
  - ★ exert drag at island surface
    - – can stop plasma rotation
      - . . . "locks", loss of H-mode (disruption?)



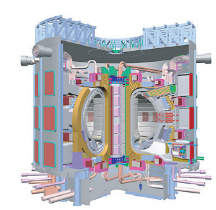
M.F.F. Nave and J.A. Wesson 1990

Resistive Wall Theory

- **islands turned on with e-folding time 0.3 s**
  - ★ larger than w = 5 cm full width
    - – locks to wall
      - . . . larger islands lock sooner



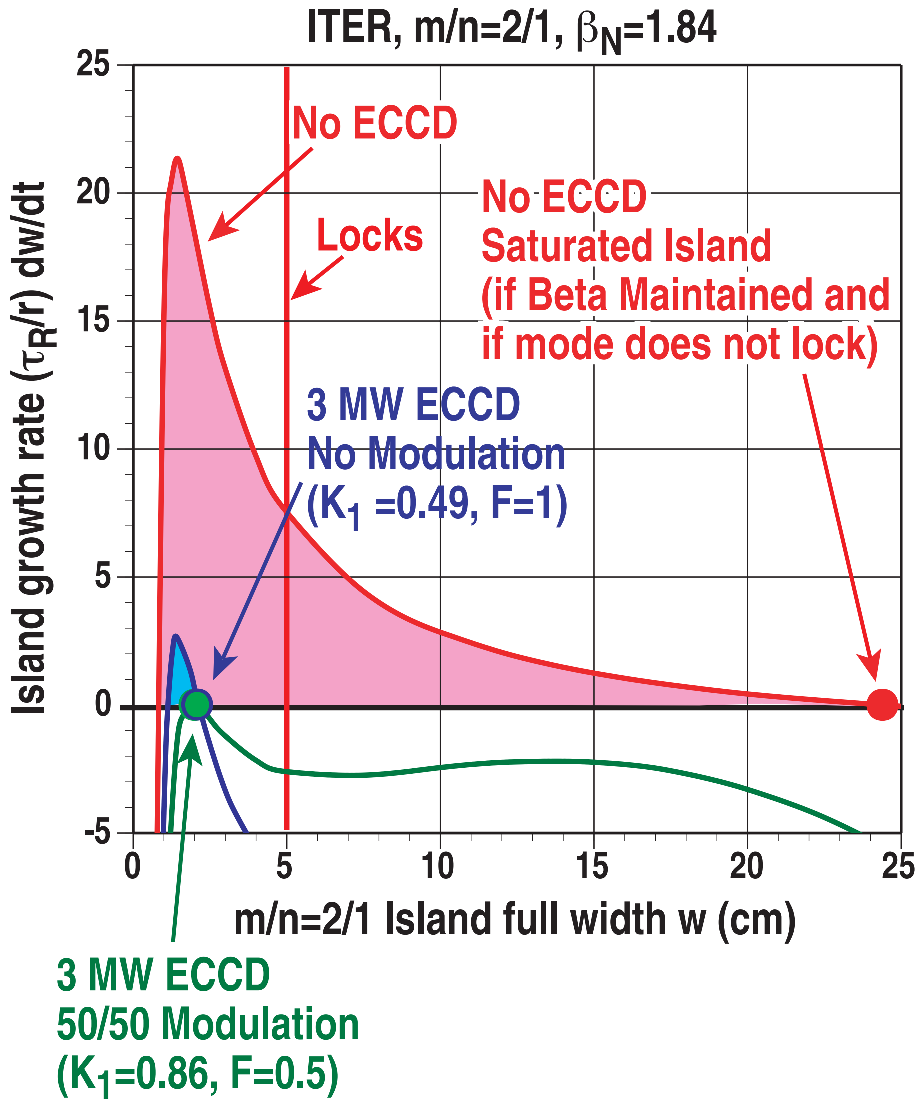
Parameters given in Section 7. of R.J. La Haye, et al., NUCLEAR FUSION 46 (2006) 451.



212-07/RJL/jy

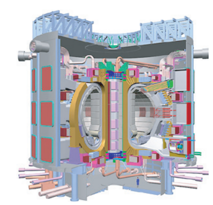
Front Steering ECCD in ITER Can Limit the 2/1 NTM

- Island must be kept less than $w \approx 5$ cm to avoid locking



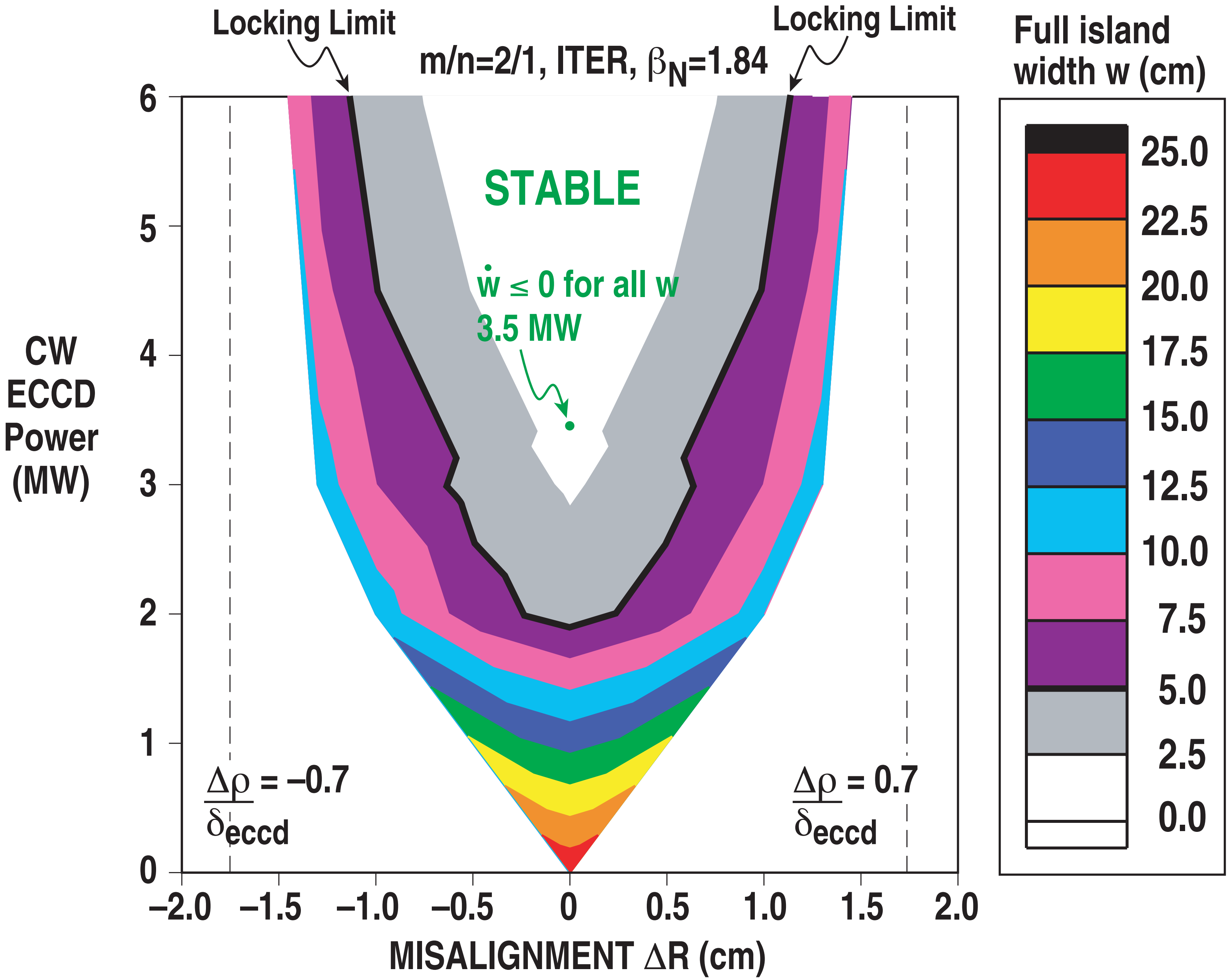
- With ECCD directed at q = 2
  - ★ $\delta_{eccd}/2\varepsilon^{1/2}\rho_{\theta i} = 1.8 \gtrsim 1$
  - ★ Adjust modulated j_{eccd} (assume no misalignments)
    - – for $w \gtrsim 2\varepsilon^{1/2}\rho_{\theta i}$ need 3 MW
  - ★ cw just as effective as modulated
    - – trade off of stabilizing effects
      - ... cw twice the $\delta\Delta' r$
      - ... modulated about twice as effective in replacing the missing bootsrap current
        - – but small island remains

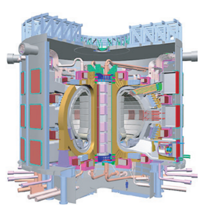
3 MW WITH NO MISALIGNMENT



079-07/RJL/jy

Necessary ECCD Power Larger with Increasing Misalignment (Too Large Misalignment and m/n=2/1 NTM Locks)

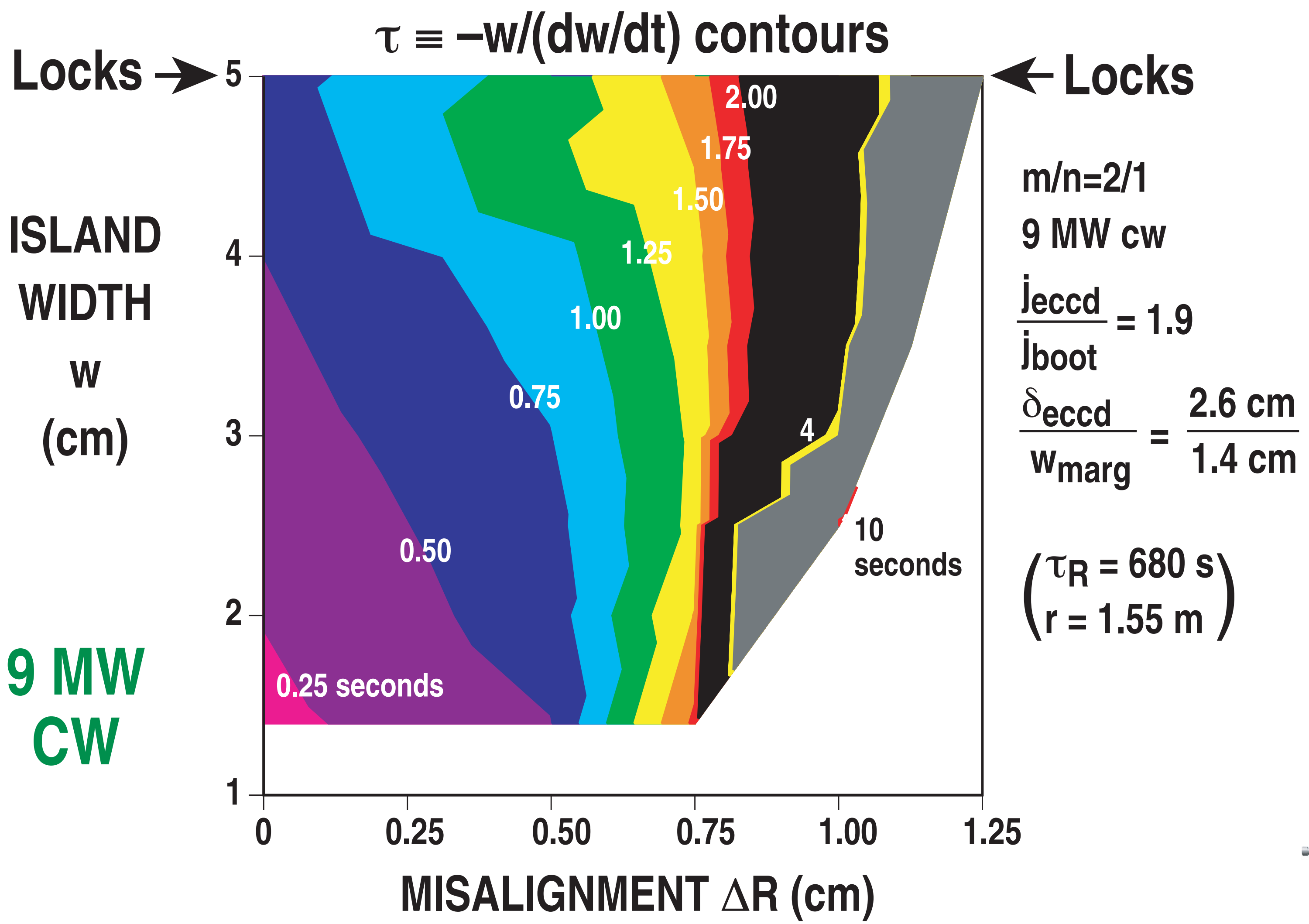


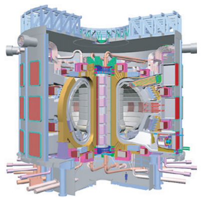


212-07/RJL/jy

Alignment Controller Must Respond "Quickly" to Govern the m/n=2/1 Island in ITER

- smaller, better aligned islands respond faster



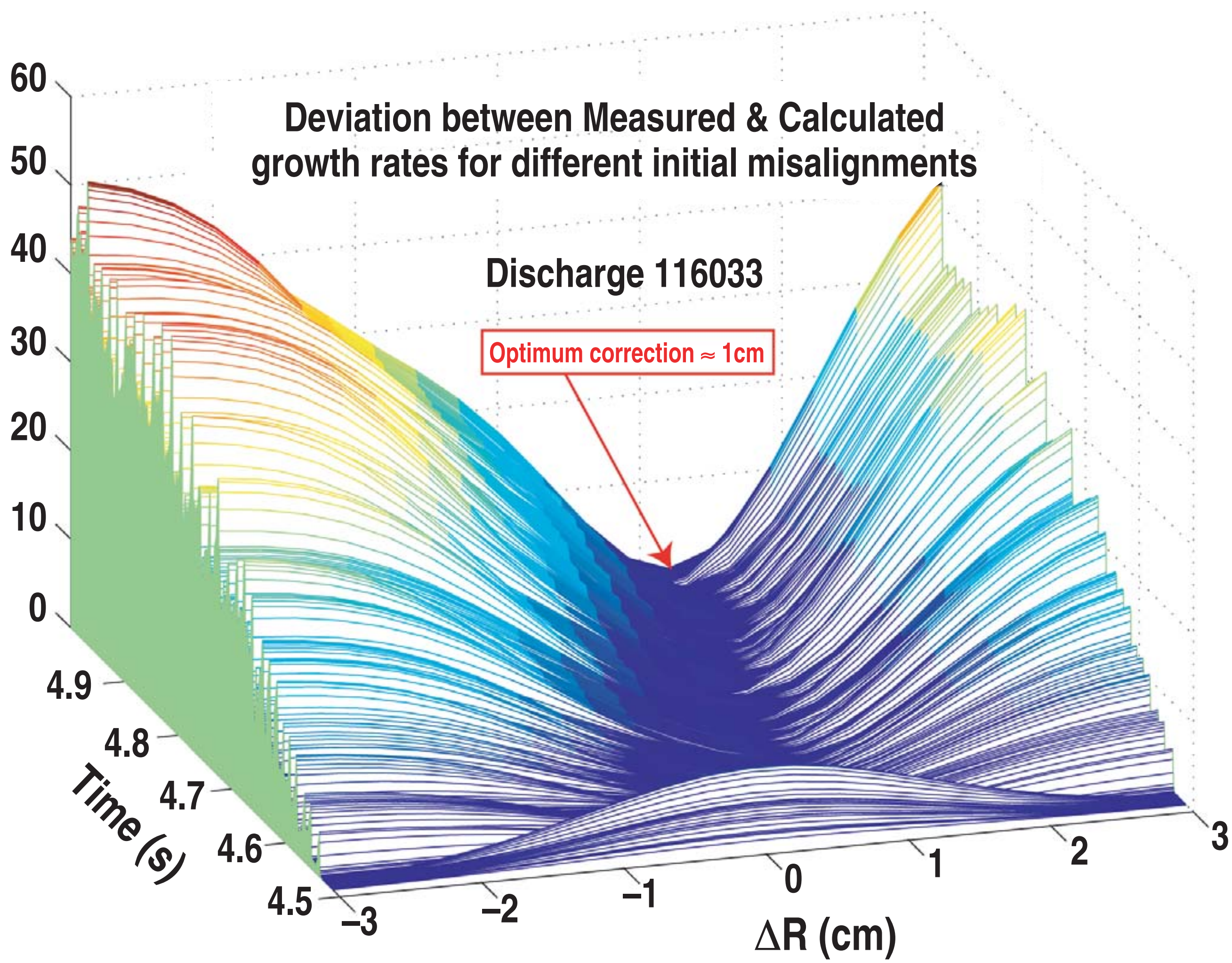


212-07/RJL/jy

Conclusions

- **With or without an m/n = 2/1 island in ITER**
  - ★ ECCD stabilization requires alignment to ~ 1cm
    . . . comparable to smaller size DIII–D
- **ITER alignment controller has "only" several seconds to optimize control**
  - ★ time to lock is comparable to island decay time
    . . . at ΔR ~ 1cm
  - ★ fast controller in DIII–D is "target lock"
    (variant of "search and suppress", Welander 2003)
    . . . sweep B_{tor} up, back down, and back (mirror in ITER)
    – analyze dynamic response of the mode
    – train algorithm

DIII–D Target Lock Calculation



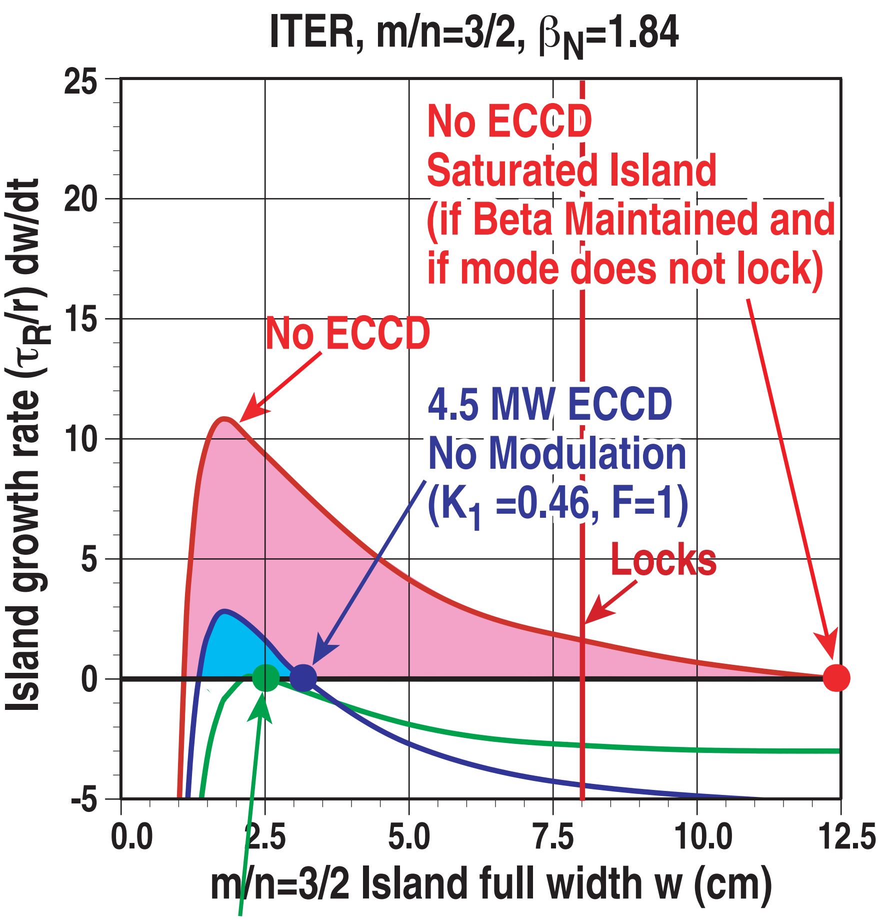
- Smaller square sums signify better fits between calculated and measured growth rates
- When enough data has been collected at time 4.55s there is only one minimum in the square sum
- The Target Lock infers the adjustment to make from the corresponding DR
- With more time and more information the minimum gets clearer

Issues

- **Resolution of real-time EFIT q location?**
- **No experimental demonstration yet of simultaneous stabilization of both 3/2 and 2/1 modes**
- **If both are stabilized on ITER...**
  - ★ m/n=4/3 becomes unstable?
    ... likely tolerable as nearer to axis
  - ★ but would m/n=5/2 and/or 3/1 modes appear?
    ... numerous modes will be metastable in ITER?
- **More plasma rotation gives margin for avoiding locking**

Front Steering ECCD in ITER Can Limit the 3/2 NTM

- **Island must be kept less than w≈8 cm to avoid locking**



- **With ECCD directed at q = 3/2**
  - ★ $\delta_{eccd}/2\varepsilon^{1/2}\rho_{\theta i} = 2.4 \gtrsim 1$
  - ★ Adjust modulated j_{eccd} (assume no misalignments)
    - – for $w \gtrsim 2\varepsilon^{1/2}\rho_{\theta i}$ need 4.5 MW
  - ★ cw nearly as effective as modulated
    - – trade off of stabilizing effects
      - ... cw twice the $\delta\Delta' r$
      - ... modulated about twice as effective in replacing the missing bootsrap current
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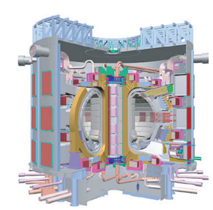

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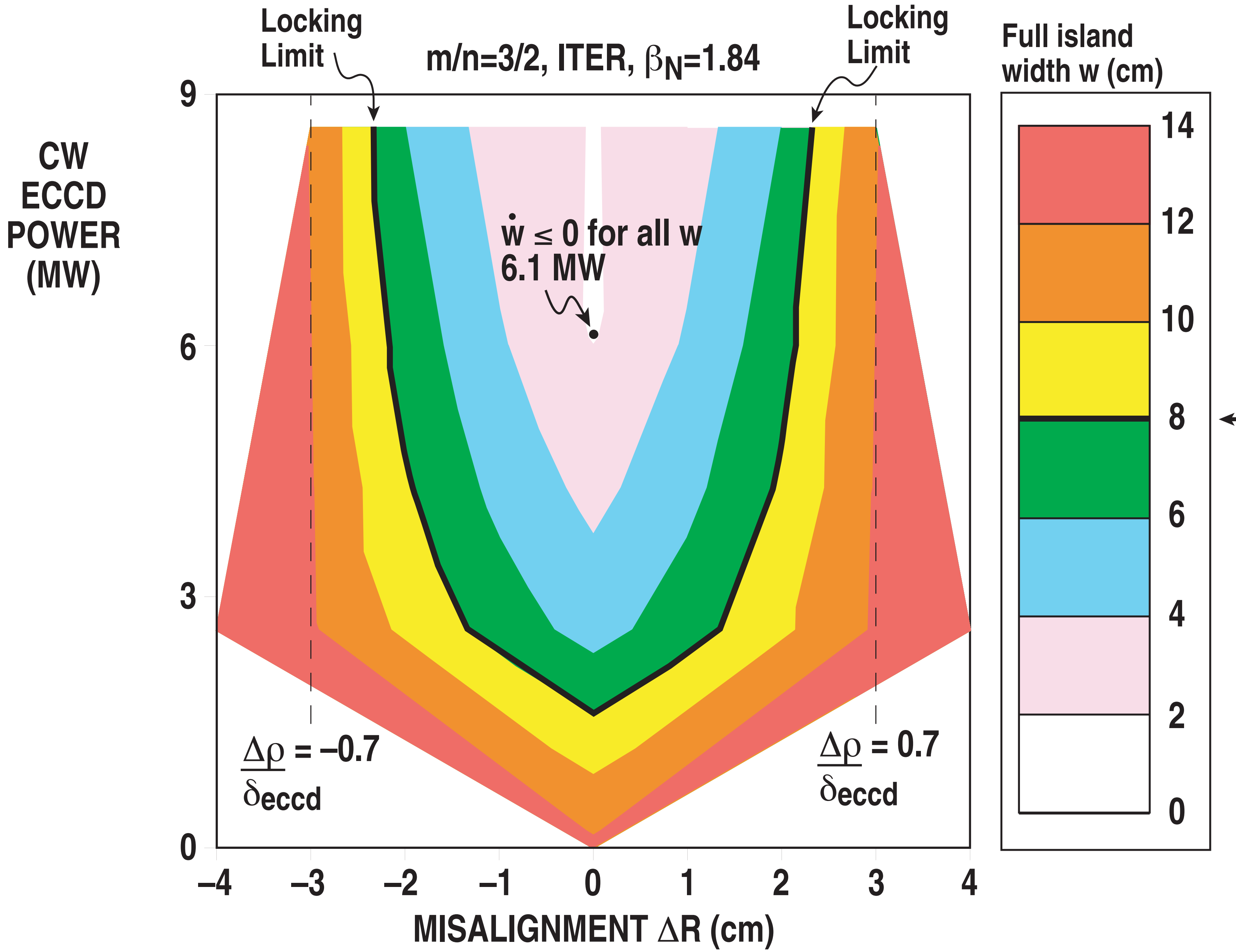

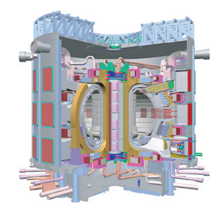

079-07/RJL/jy