m/n=2/1 NEOCLASSICAL TEARING MODE CONTROL WITH ECCD ON DIII–D AND THE REQUIREMENTS FOR ITER

by

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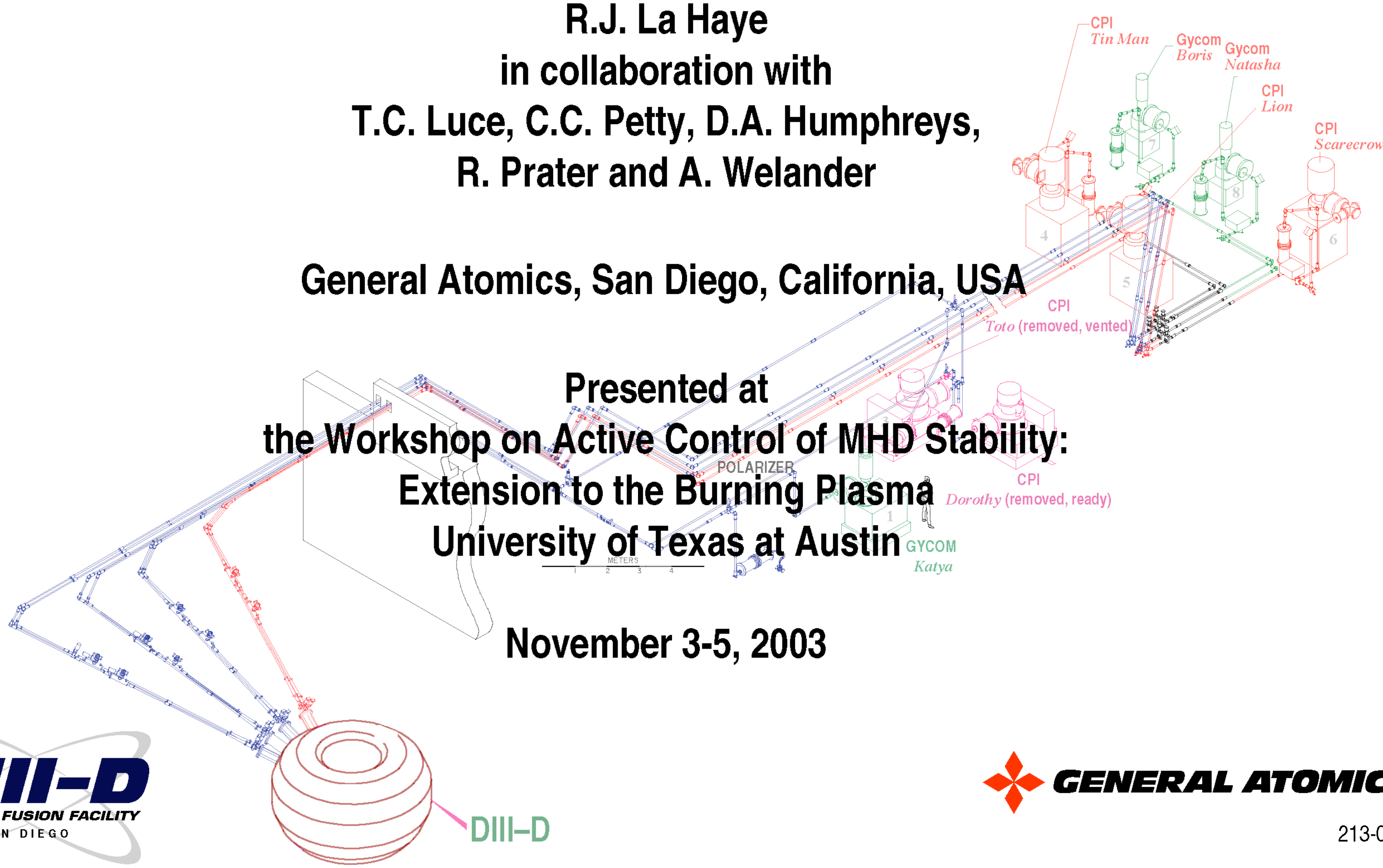

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GENERAL ATOMICS

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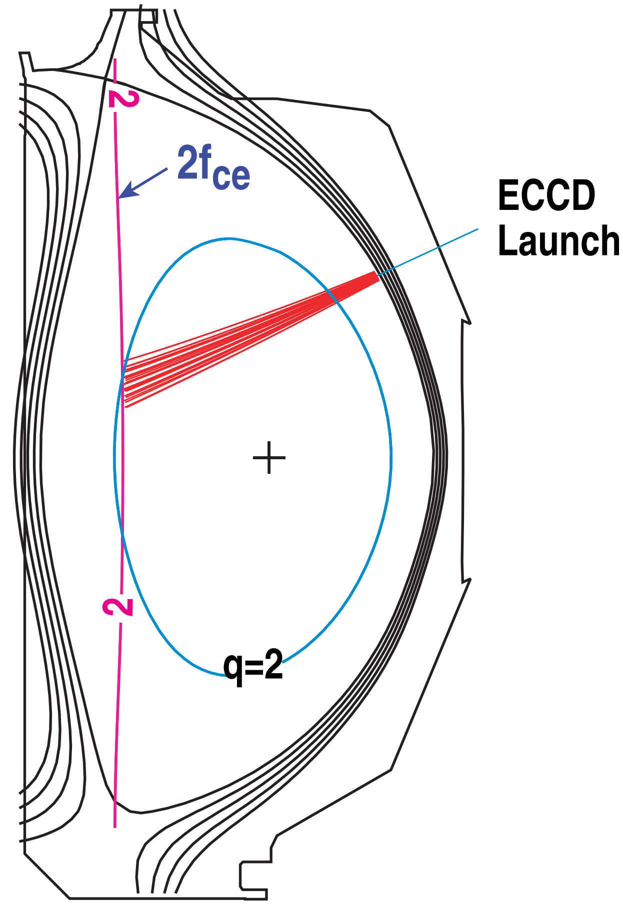
MOTIVATION

- The m=2/n=1 neoclassical tearing mode is dangerous because it often locks to the wall and a major disruption occurs

- Radially localized ECCD can stabilize the m=2/n=1 tearing mode by replacing the “missing” bootstrap current in the island
  - Similar to m=3/n=2 stabilization by ECCD on AUG, JT–60U, and DIII–D

- These experiments on DIII–D use 4 to 5 gyrotrons to inject up to 2.7 MW of ECCD aimed at the q = 2 surface
  - “Search and Suppress” adjusts B_T to automatically position the ECCD on q=2

    . . . equivalent to steering the mirrors (planned for 2004)



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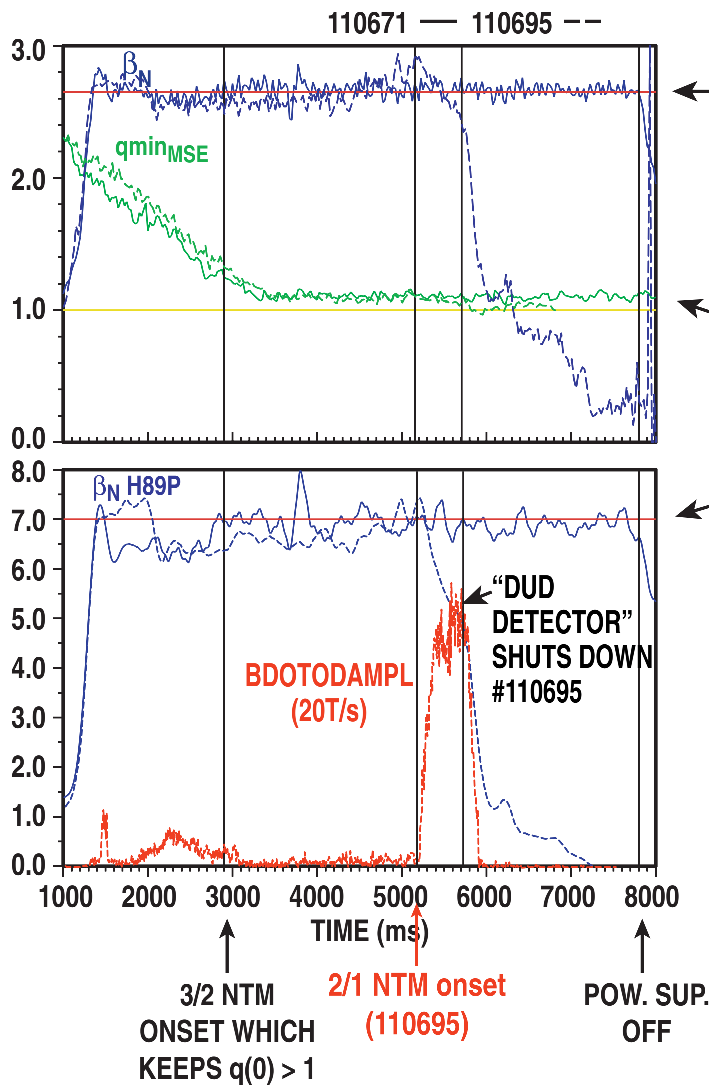
EXPERIMENTS DONE IN A "HYBRID" SCENARIO (IN BETWEEN AN INDUCTIVELY–DRIVEN H–MODE AND AN ADVANCED TOKAMAK WITH HIGH BOOTSTRAP CURRENT)

- $\beta_N \lesssim \beta_{N,\,nowall}$, $H_{89P} > 2$, $f_{BS} < 0.5$, $q_{95} \gtrsim 4$, $\beta_N\, H_{89P}/q_{95}^2 \approx 0.4$
  - Promise of long-pulse operating regime for physics and materials testing in ITER



β_N maintained constant by NBI feedback of diamagnetic flux (density, not shown, maintained constant by gas puffing and cryopumping)

q(0)=qmin > 1 maintained by 3/2 NTM so no sawteeth or fishbones ($\Delta\tau_E/\tau_E \lesssim -5\%$ due to 3/2 NTM but H_{89P} still $\approx$ 2.7 at $\beta_N \approx$ 2.6)

- Limit on β_N and $\beta_N\, H_{89P}$ is the m/n = 2/1 NTM induced by programming a higher beta

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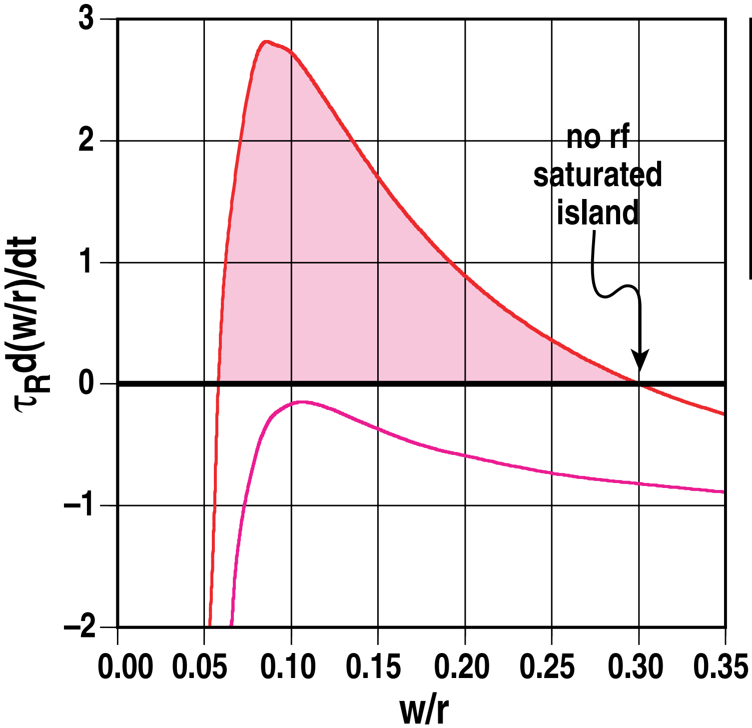
CO-ECCD CAN REPLACE THE "MISSING" BOOTSTRAP CURRENT IN ITER AND STABILIZE THE NEOCLASSICAL TEARING MODE

$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta' r + \varepsilon^{1/2}\left(\frac{L_q}{L_p}\right)\beta_\theta\left[\frac{rw}{w^2+w_d^2} - \frac{rw_{pol}^2}{w^3} - \frac{8qr\delta_{ec}}{\pi^2 w^2}\left(\frac{\eta\, j_{ec}}{j_{bs}}\right)\right]$$, with rf at $q \approx 2$

(rf ⇓ j_{ec})

positioning ⇓ width ⇓

$$\eta = \eta_0 e^{-[5\Delta R/3\delta_{ec}]^2} / (1+2\delta_{ec}^2 / w^2)$$



- DIII–D: jec=0
- DIII–D: jec=27A/cm^2

β_N = 2.6 fixed

β_θ = 1.2 fixed

$\Delta' r$ = –1.3

δ_{ec} = 4 cm

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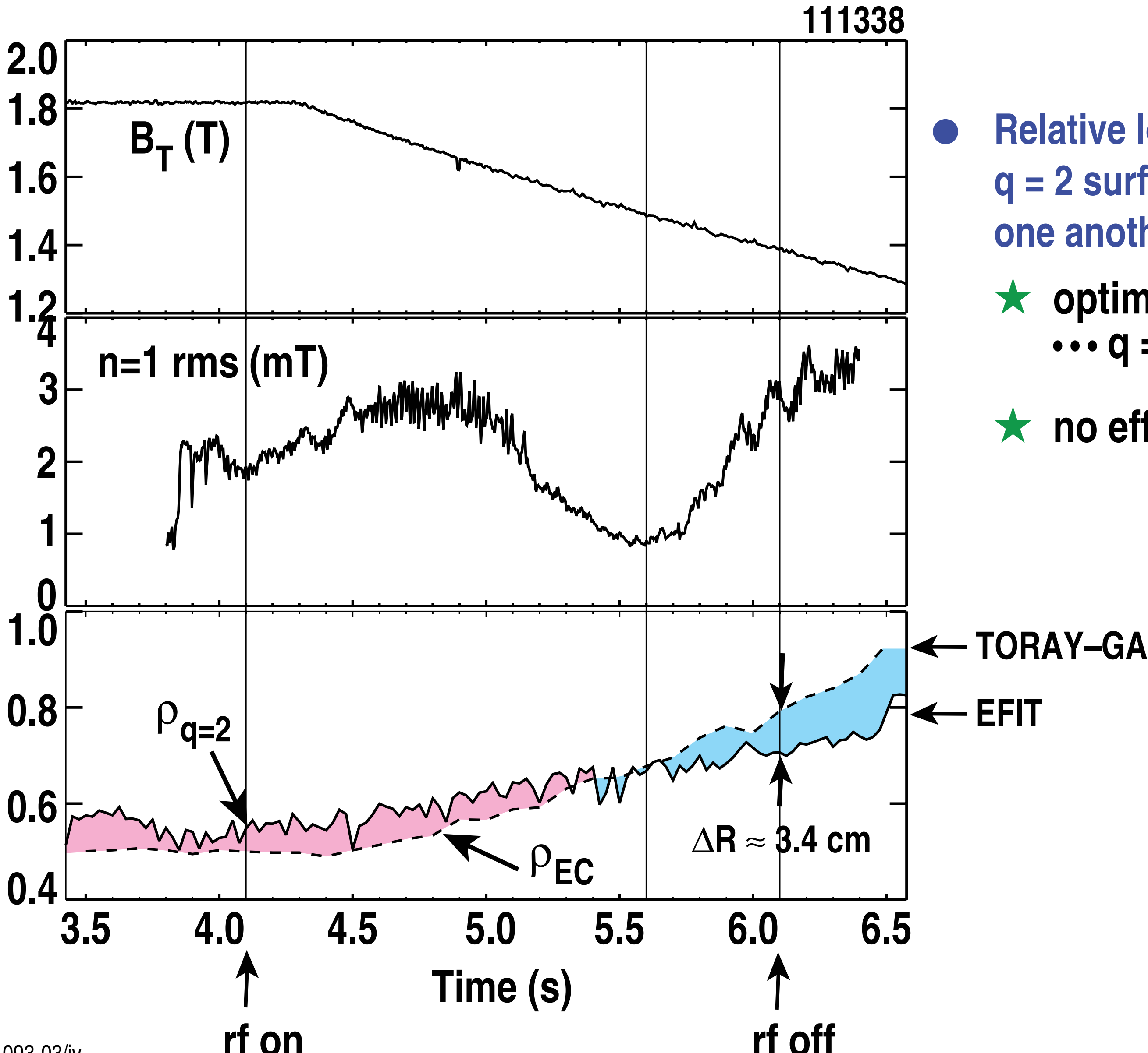
OPTIMAL SUPPRESSION OF m = 2/n = 1 ISLAND OCCURS WHEN ECCD IS ALIGNED WITH q = 2 SURFACE



- Relative locations of ECCD and $q = 2$ surface are scanned past one another using B_T ramp down
  - ★ optimum is far off-axis ••• $q = 2$ at $\rho \approx 0.66$
  - ★ no effect for $\Delta R \gtrsim 3.4$ cm

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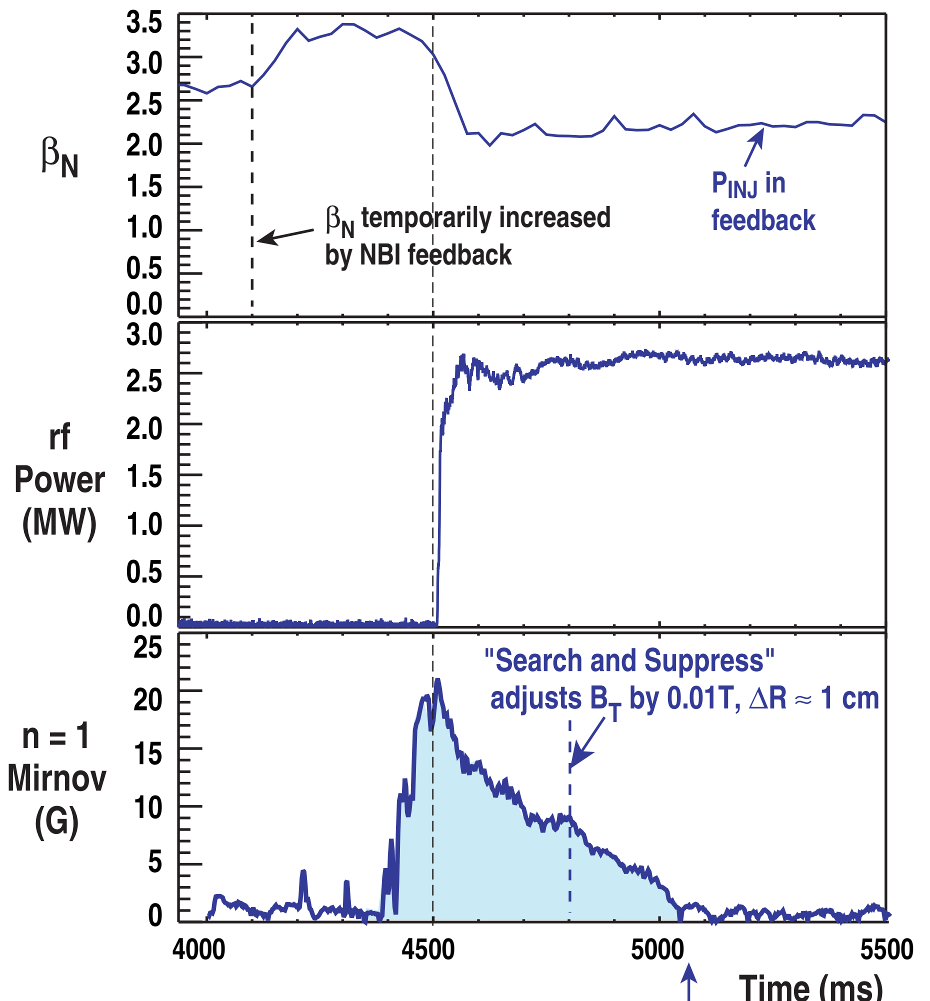
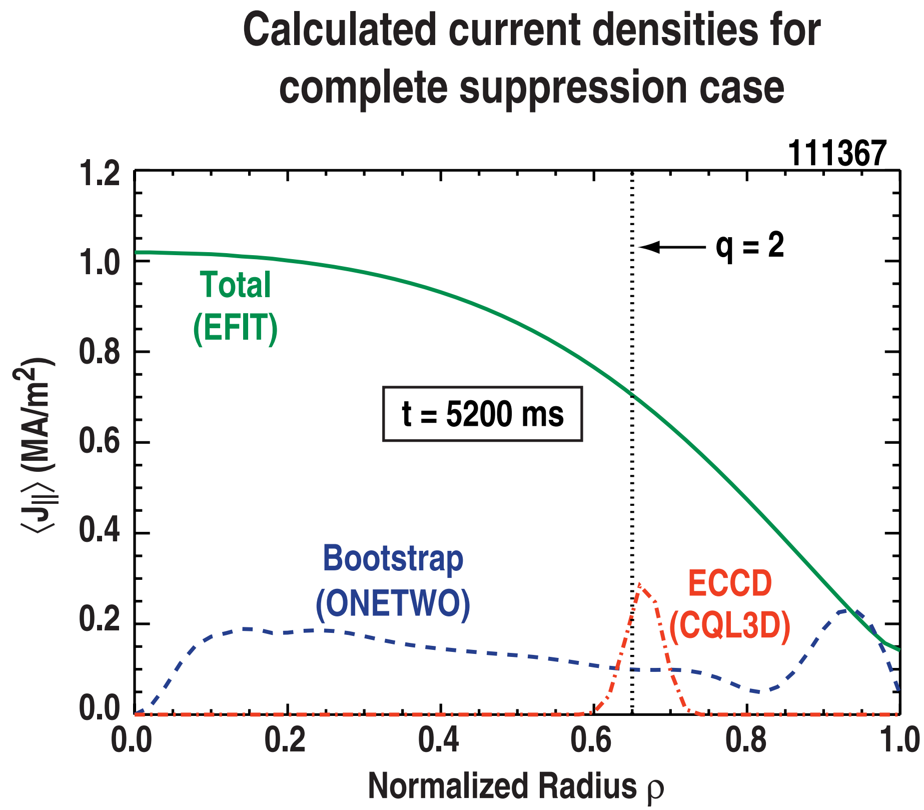
DEMONSTRATED COMPLETE SUPPRESSION OF THE m/n = 2/1 TEARING MODE BY RADIALLY LOCALIZED ECCD

- β_N is feedback controlled to <u>temporarily</u> rise to excite the mode
- Location of ECCD optimized (#111367) by toroidal field PCS "Search and Suppress"





- 40 kA of ECCD is ≈ 3% of total current
  - ★ 2.7 MW rf power injected

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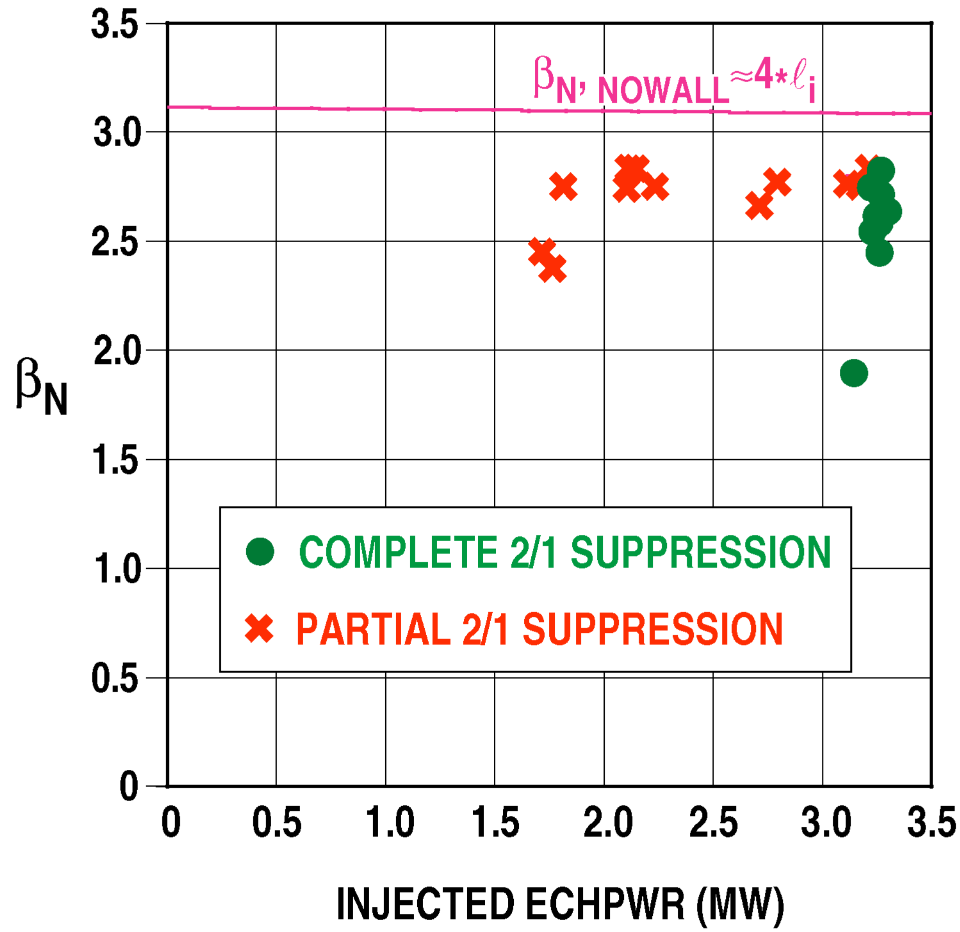
m/n = 2/1 NTM EXPERIMENTS IN 2003 DIII–D CAMPAIGN

- Done in Hybrid scenario H–mode without sawteeth (Wade GO1.008)
- Increased rf injected power to ≈ 3 MW
- New q = 2 Search & Suppress with "TARGET LOCK" (B_T jitter) and Active Tracking
- Raised β_N with complete suppression
  - ★ to > 90% of n = 1 ideal kink no wall beta limit . . . (β_N up to 2.9, 4 $\ell_i \approx$ 3.1)



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DIII–D HYBRID SCENARIO EXTRAPOLATED TO ITER

- Same q_{95} = 4.3, shape, profiles, D2
- R_0 = 1.7 m → 5.7 m
- B_T = 1.7 T → 5.3 T and I_p = 1.2 MA → 12.4 MA
- $\bar{n}/n_{GW}$ = 0.34 → 1.02
- T_i/T_e at q = 2 = 1.65 → 1.00 and T_i = 3.50 → 9.85 keV
- ρ_{i*} (10^{-3}) at q = 2 = 11.9 → 1.9 and $\nu \equiv \nu_{ii}/\varepsilon\omega_{e*}$ = 0.012 → 0.005
  - ★ w_{pol} ($\propto\rho_{i*}$) = 2.0 cm → 1.1 cm and w_d ($\propto\rho_{i*}^{1/3}$) = 1.0 cm → 1.8 cm are NTM thresholds

    . . . $w_{th} = \sqrt{3}\,(w_{pol}^2 + w_d^2)^{1/2}$ = 3.9 cm → 3.7 cm about same effective threshold

    — w_{th}/r = 0.093 → 0.029 is 3X smaller relative threshold

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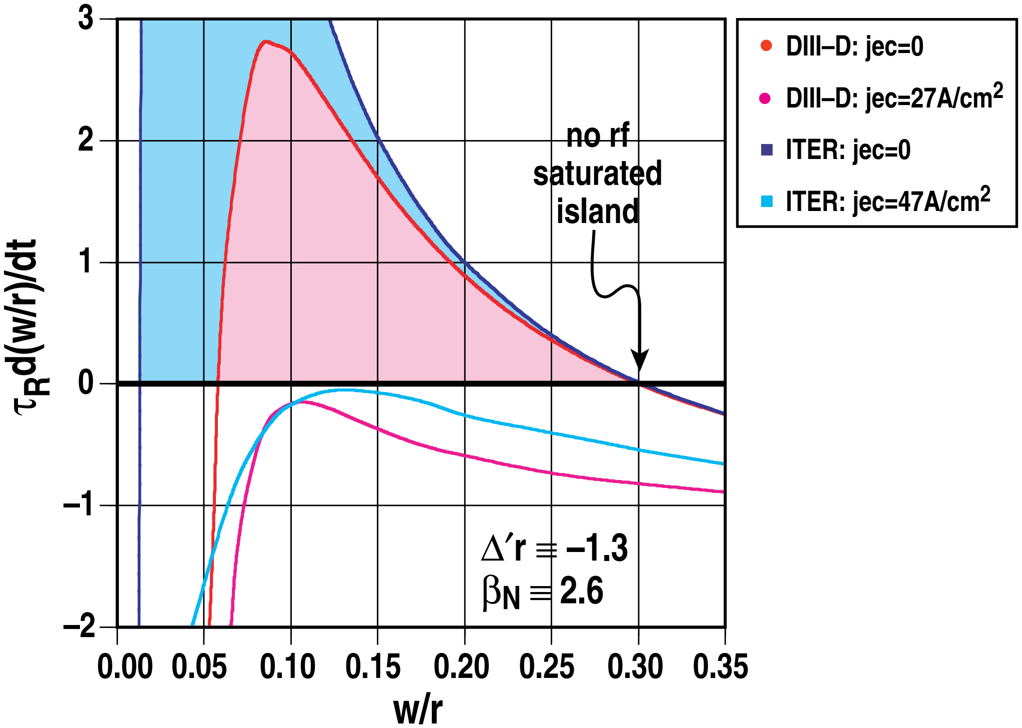
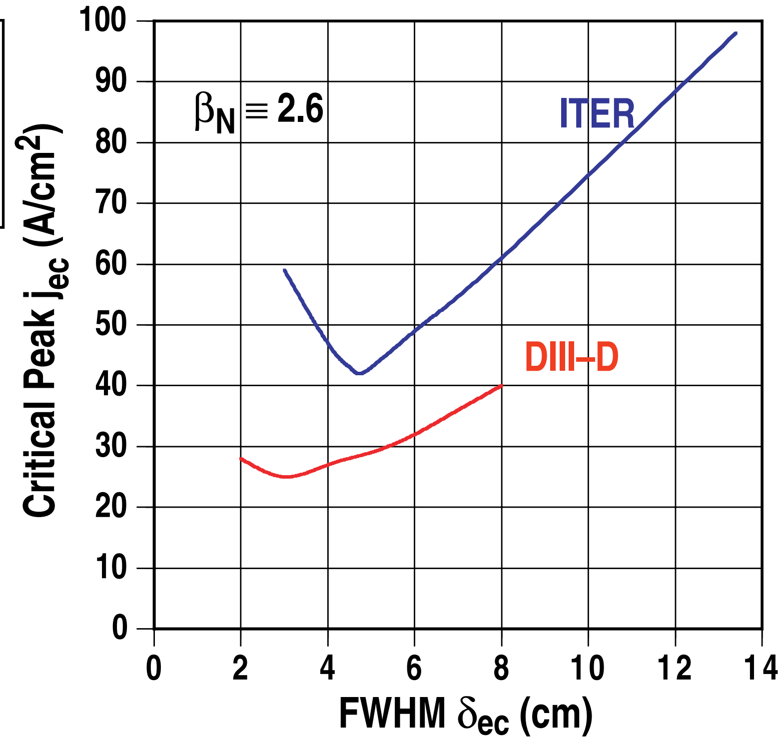
REQUIREMENT FOR j_{ec} IS MINIMIZED FOR FWHM $\delta_{ec} \approx$ NTM THRESHOLD ISLAND WIDTH w_{th}

- **Modeling assumes...**
  - ★ alignment is good
  - ★ $w_{th} \approx \sqrt{3}\,(w_{pol}^2 + w_d^2)^{1/2}$



- j_{ec} **for $\dot{w} \lesssim 0$ for all w**
  - ★ i.e., 2/1 NTM stabilized



- **FWHM $\delta_{ec} \equiv$ 4 cm**
  - ★ evaluated at outboard midplane

- w_{th} = 3.9 cm DIII–D, 3.7 cm ITER
  - ★ w_{th}/r = 0.093 DIII–D, 0.029 ITER

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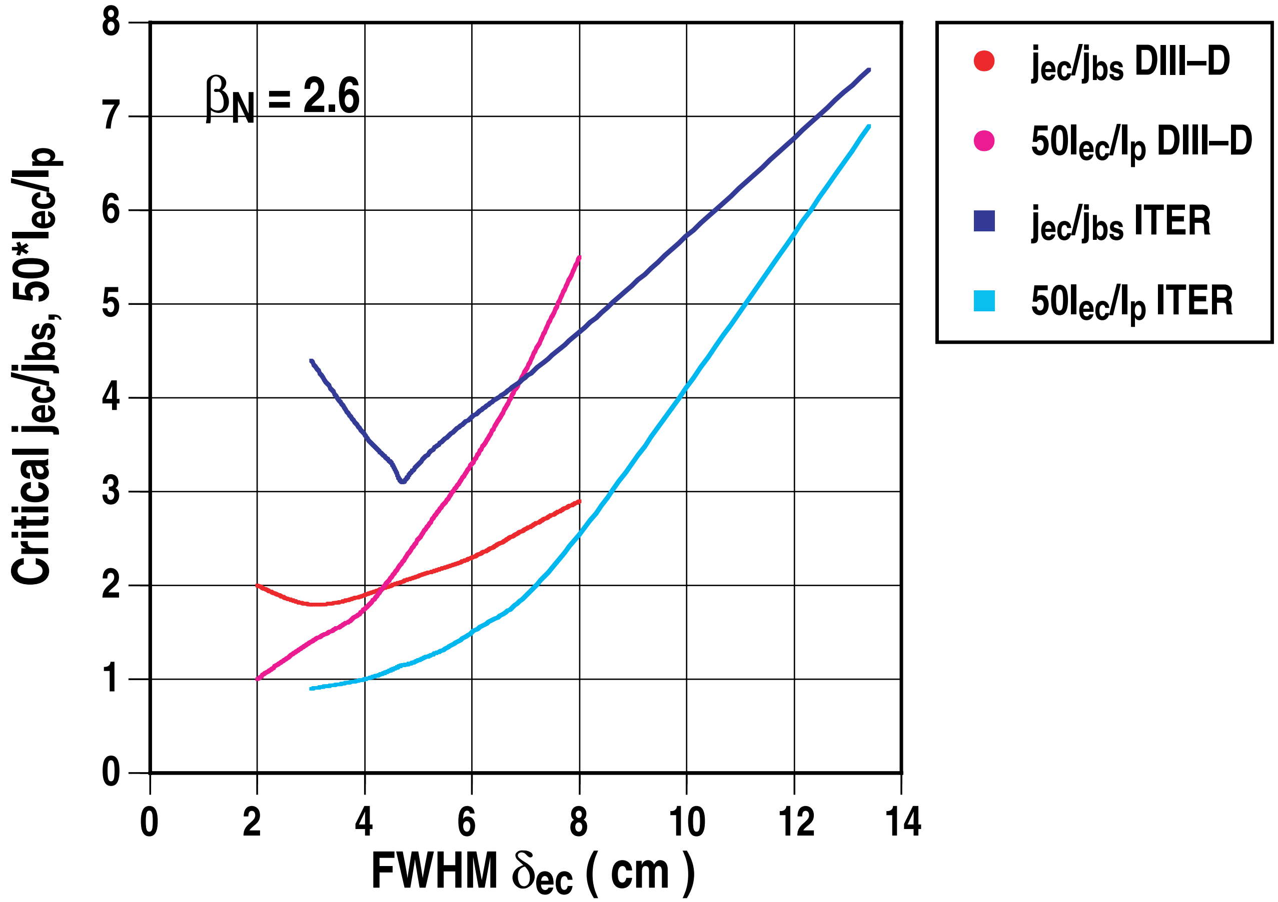
WIDTH OF ECCD DETERMINES BOTH j_{ec} AND I_{ec} NEEDED

- too narrow, j_{ec}/j_{bs} is large
- too wide, I_{ec}/I_p is large



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CONCLUSIONS FOR ITER

- The m/n = 2/1 NTM is dangerous and must be avoided
- Lower ρ_{i*} in ITER makes 2/1 NTM expected at lower β_N
  - ★ however, at same β_N as DIII–D, island size will be similar
- Radially localized ECCD can supress or avoid 2/1 NTM as in DIII–D
  - ★ optimum is for FWHM $\delta_{ec}/r \approx 0.035$
    - — $j_{ec} \approx 40$ A/cm^2, $j_{ec}/j_{bs} \approx 3$, $I_{ec} \approx 250$ kA, $I_{ec}/I_p \approx 0.02$
      (Assuming no modulation, i.e. $\eta_0 \equiv 0.4$)
      - • • • DIII–D experiments proposed to examine effect of δ_{ec}
    - — Assuming modulation, i.e. $\eta_0 \equiv 1.0$, $\rightarrow$ 17 A/cm^2, 1.2, 100 kA, 0.008
      - • • • modulation with island O–point needs to be demonstrated in existing devices

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