CONTROL OF NEOCLASSICAL TEARING MODES IN DIII–D

by
R.J. LA HAYE

Acknowledgments to
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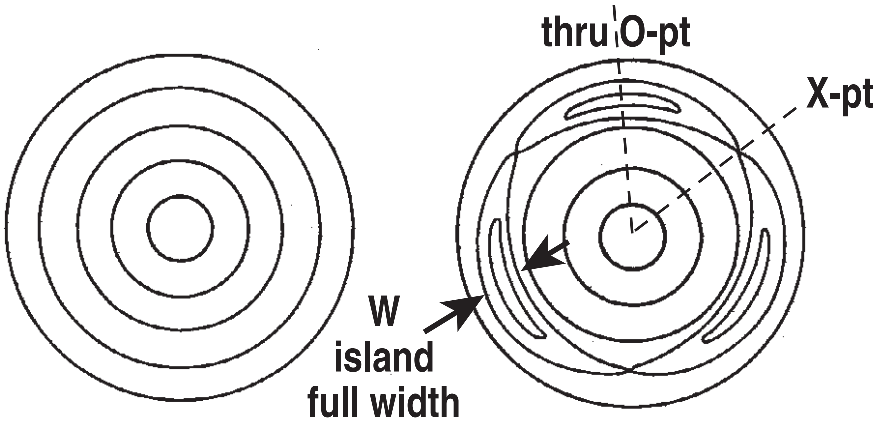
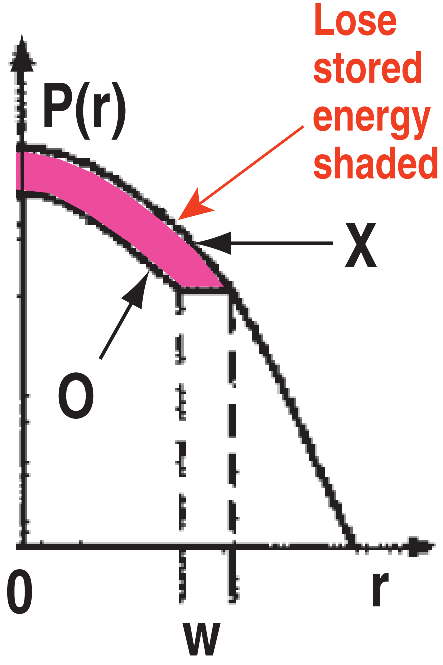
GENERAL ATOMICS

PHYSICS OF NTM DESTABILIZATION

- Comparison of nested surfaces and m=3 (n=2) tearing mode islands





Helically perturbed bootstrap current (Qu and Callen 1985)

★ “Seed” island from another MHD instability

★ Pressure is flattened in island O-point, but not in X-point

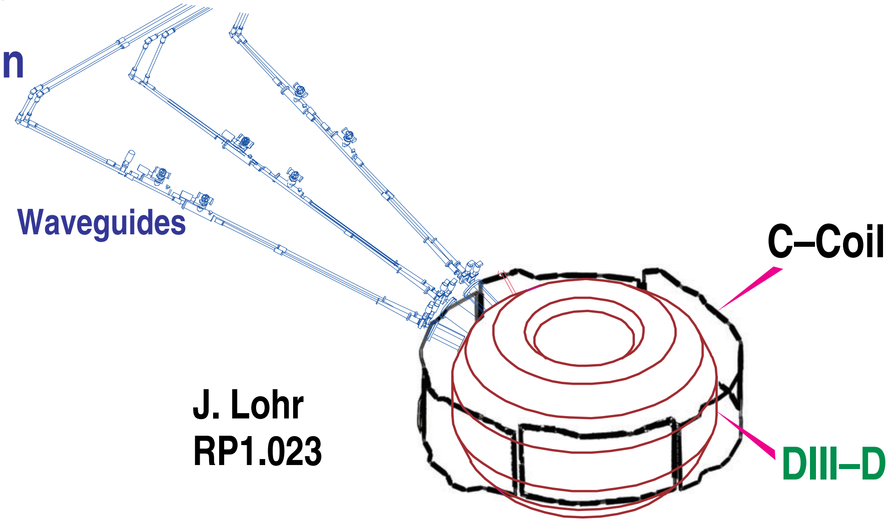
★ O-point and X-point J_{bs} differ; $\delta J_{bs} \approx \varepsilon^{1/2}\, \delta\nabla p/B_\theta \propto \beta_\theta/w$

— Reinforces “seed”, a destabilizing effect at high beta

CONTROL OF NEOCLASSICAL TEARING MODES

- Stabilized by replacing “missing” bootstrap current in O-point of island
  - ★ Off-axis radially localized electron cyclotron current drive (ECCD)

- Control is to position peak j_{eccd} on island
  - ★ real-time feedback of optimum position
  - ★ complete m/n=3/2 NTM suppression
    — in presence of continued sawteeth
  - ★ beta raised after NTM stabilization



J. Lohr
RP1.023

- Inhibited by interfering with the fundamental helical harmonic of perturbed pressure
  - ★ Non-resonant helical field of different helicity

- Control is to apply n = 3 field from C-Coil
  - ★ m/n=3/2 NTM avoided until n=3 field turned off

CO-ECCD CAN REPLACE THE “MISSING” BOOTSTRAP CURRENT AND STABILIZE THE NEOCLASSICAL TEARING MODE

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

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

$m/n = 3/2$

$\beta_\theta = 0.9$

$\Delta' r = -3$

$r = 0.36$ m

$\varepsilon^{1/2} = 0.5$

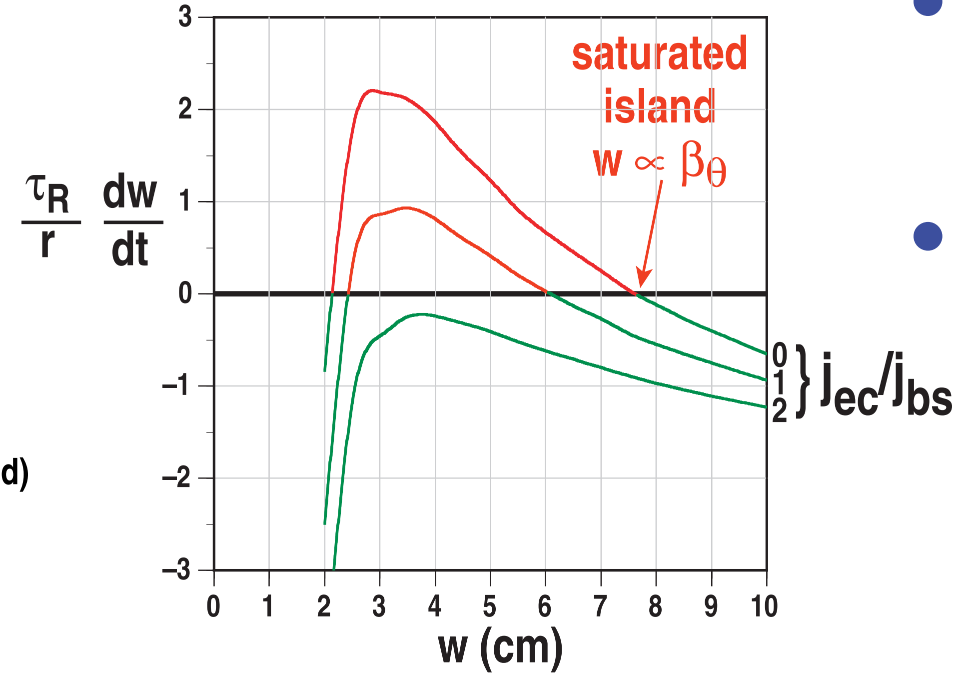
$L_q/L_p = 1.5$

$w_{pol}/r = 0.05$

$\delta_{ec}/r = 0.08$

$\eta_0 = 0.4$ (no mod)

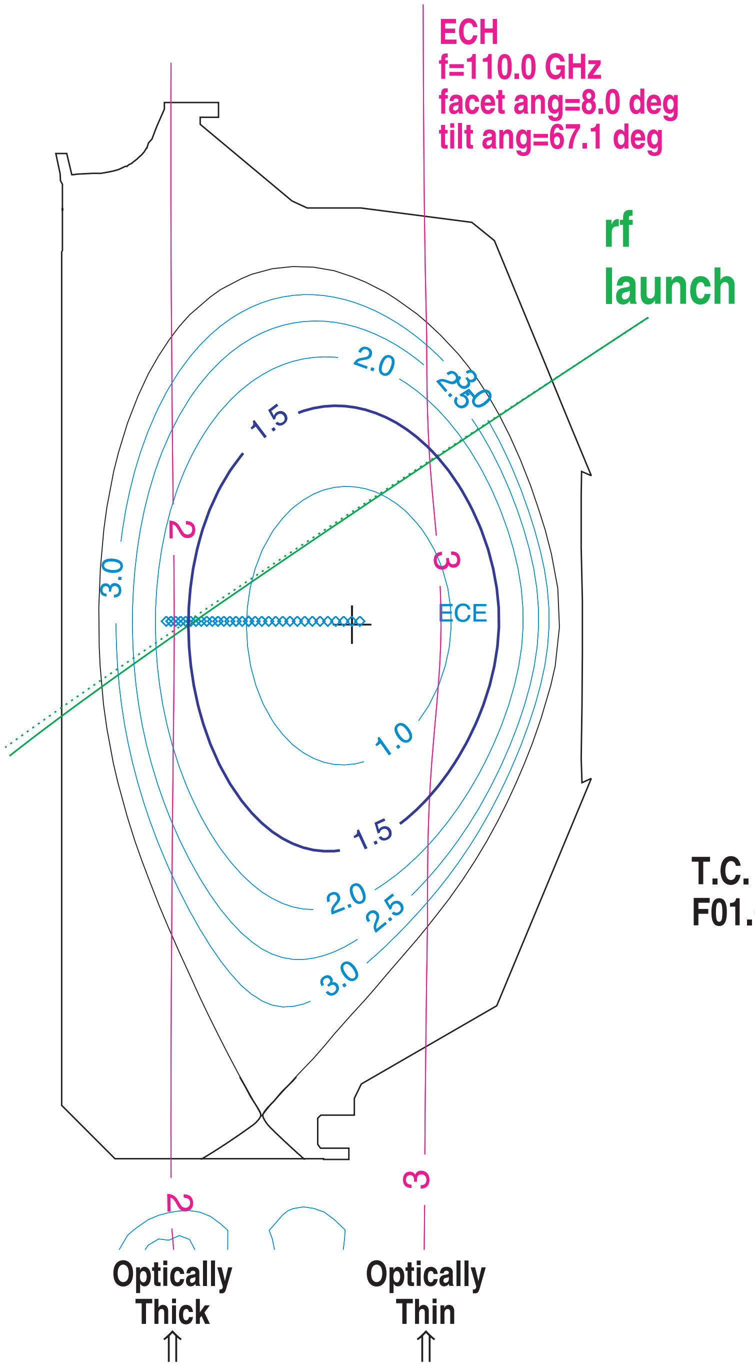
$\Delta R/\delta_{ec} = 0$



- NTM amenable to complete suppression because $\dot{w} < 0$ for $w \lesssim w_{pol}$

- ECCD must be within island
  - – no effect for $\Delta R \gtrsim \delta_{ec}$

SUPPRESSION OF m/n=3/2 NTM BY OFF-AXIS ECCD



(ELMy H–mode with sawteeth)

Resources:

1. (1) lower cryopump to improve current drive
2. (2) up to 4 gyrotrons injecting up to 2.3 MW for 1 to 2 s
3. (3) PPPL & GA co–ECCD steerable launchers

T.C. Luce
F01.005

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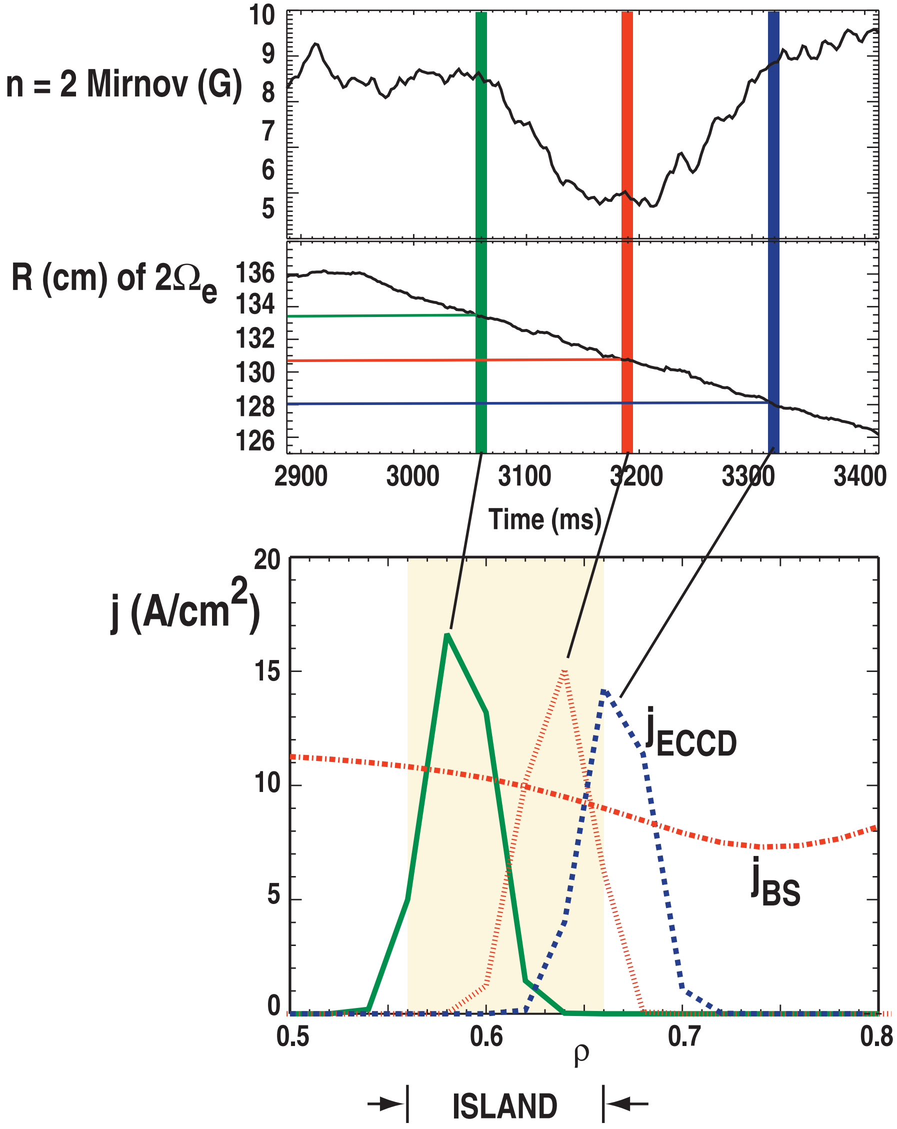
OPTIMUM LOCATION OF ECCD IS FOUND BY SWEEPING TOROIDAL FIELD



w ≈ 7 cm
from ECE radiometer

- Toroidal field was ramped down to scan ECCD past the island
- Alignment within ±1 cm is required
- $j_{ECCD} > j_{BS}$ is satisfied (TORAY-GA)
  - ★ 2 gyrotrons for ≈ 1 MW injected

C. Petty
FO1.002

R. Prater
RP1.022

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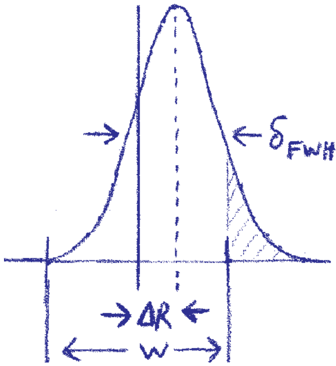
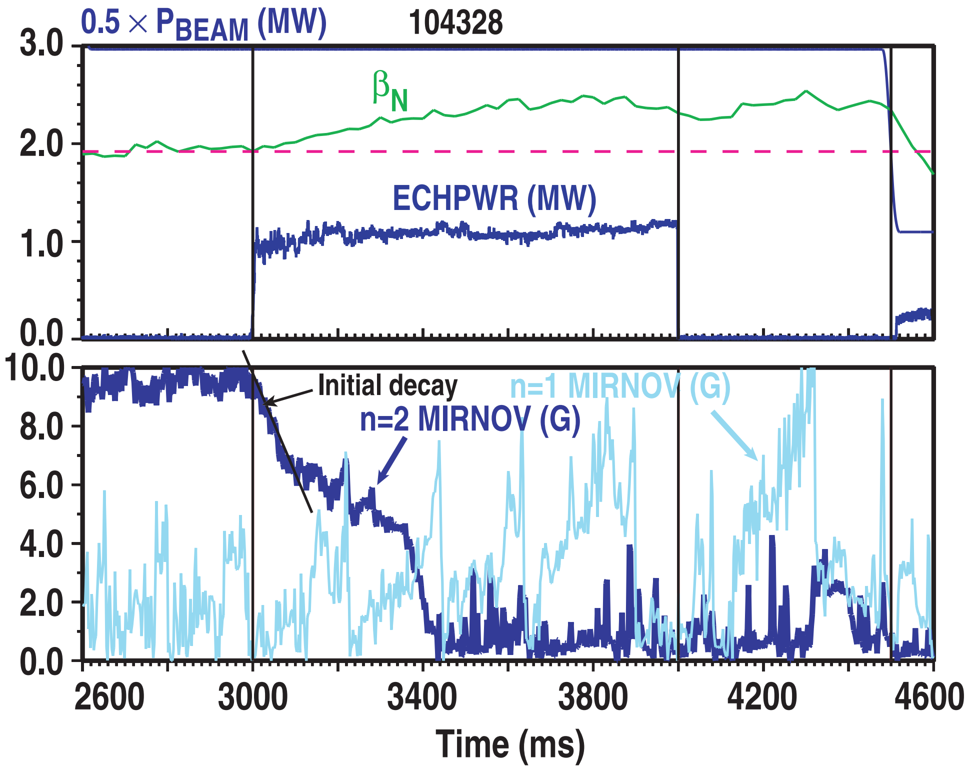
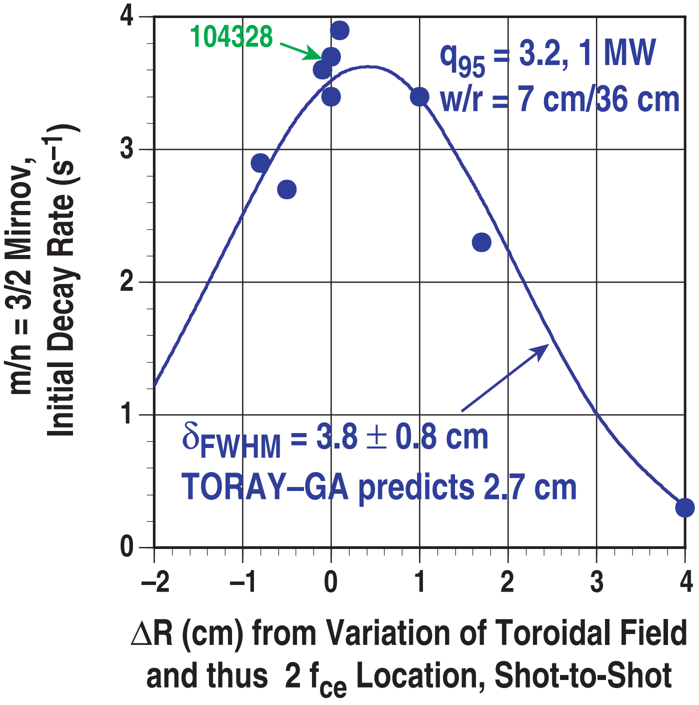
OPTIMUM CAN ALSO BE FOUND WITH FLATTOP TOROIDAL FIELD ADJUSTMENT

- Before ECCD, $\gamma \equiv -|\tilde{B}_{\theta,32}|^{-1}\, d|\tilde{B}_{\theta,32}|/dt \approx 0$
- Upon ECCD, initially $\gamma \propto J_o \exp[-(5\Delta R/3\delta_{ec})^2]$, $\delta_{ec} \equiv \delta_{FWHM}$







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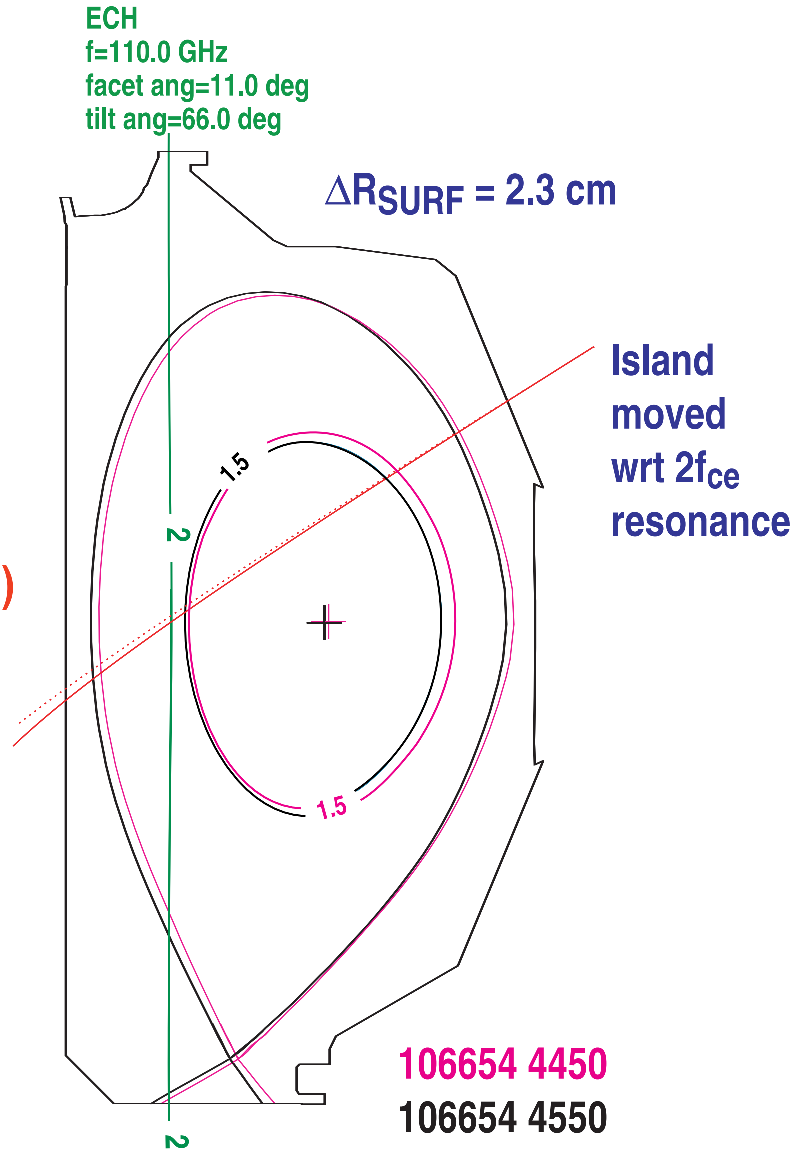
PLASMA CONTROL SYSTEM REAL-TIME FEEDBACK
NTM CONTROL VARIES MAJOR RADIUS IN RESPONSE TO MODE AMPLITUDE

- ΔR "Blind Search" when mode (3/2 island) amplitude exceeds threshold
- Move plasma major radius (and island) "rigidly" (ΔR_{step} = 1 cm)
- Detect alignment of ECCD current deposition with island ("sweet spot") by sufficient change in mode amplitude over the "dwell" time (100 ms)
- If mode decays at > threshold rate, continue to dwell. If not, continue search (or "jitter" . . .)

D.A. Humphreys
RP1.010



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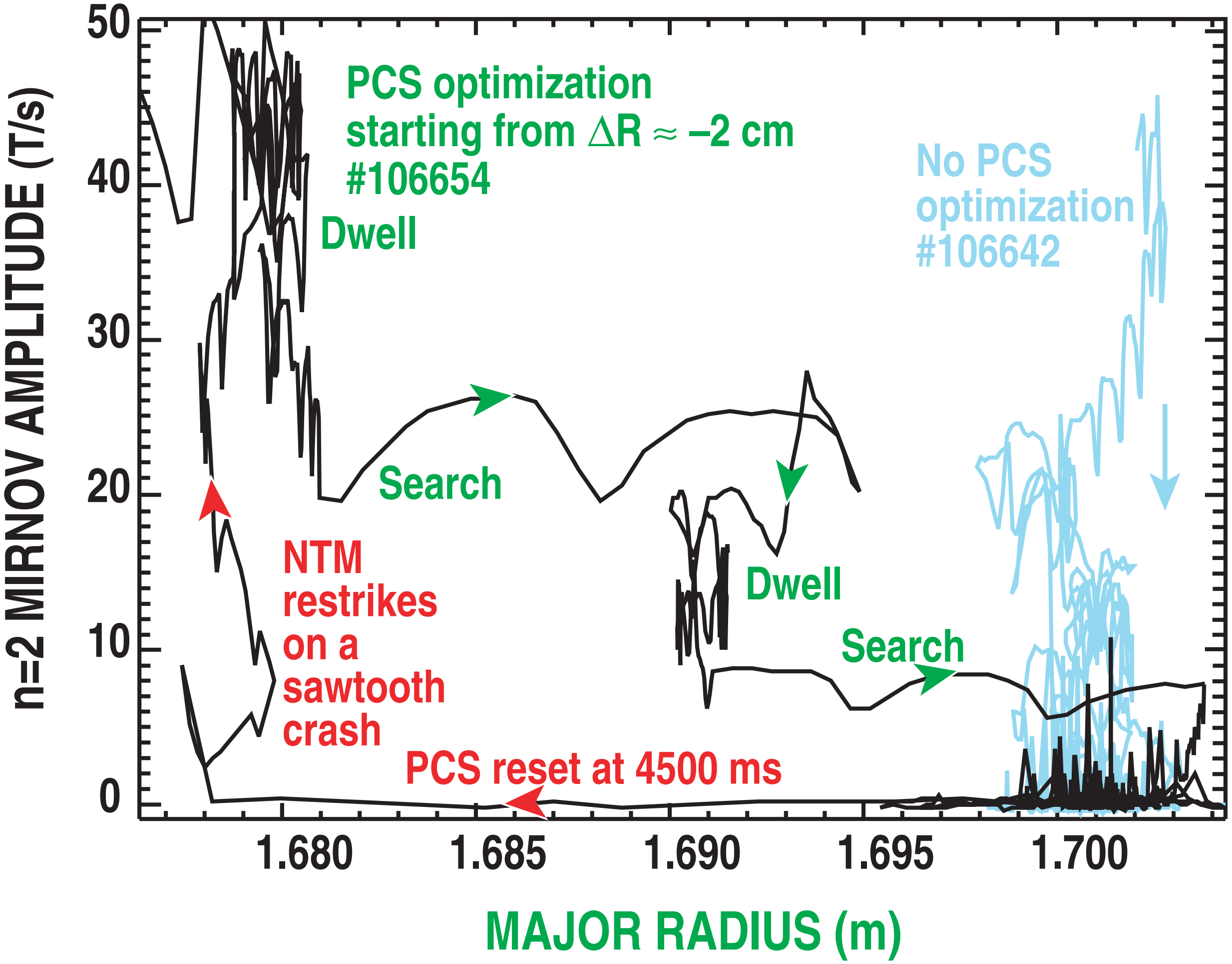
REAL-TIME CONTROL OF MAJOR RADIUS FOR ECCD SUPPRESSION
(m/n = 3/2 NTM, 3 GYROTRONS, 1.5 MW, 3000 TO 4800 ms)



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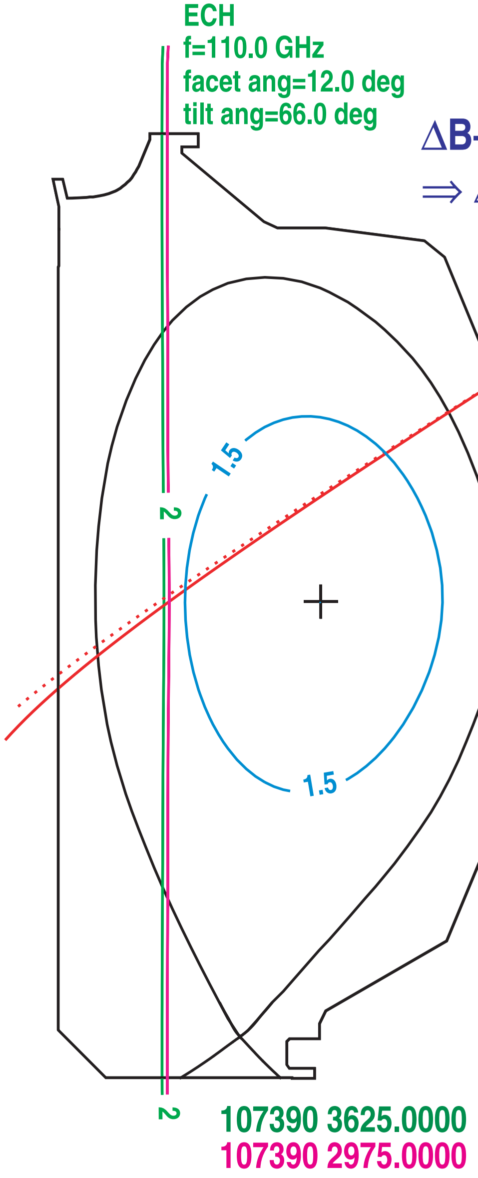
PLASMA CONTROL SYSTEM REAL-TIME FEEDBACK NTM CONTROL VARIES TOROIDAL FIELD IN RESPONSE TO MODE AMPLITUDE

- ΔB_T "Blind Search" when mode (3/2 island) amplitude exceeds threshold
- Adjust toroidal field and location of $2f_{ce}$ ($\Delta B_T = 0.01$ T $\Rightarrow \Delta R \approx 0.9$ cm)
- Detect alignment of ECCD current deposition with island ("sweet spot") by sufficient change in mode amplitude over the "dwell" time (100 ms)
- If mode decays at > threshold rate, continue to dwell. If not, continue search (or "jitter" . . .)



$\Delta B_T = 0.018$ T
$\Rightarrow \Delta R \approx 1.6$ cm

$2\ f_{ce}$ resonance moved wrt island

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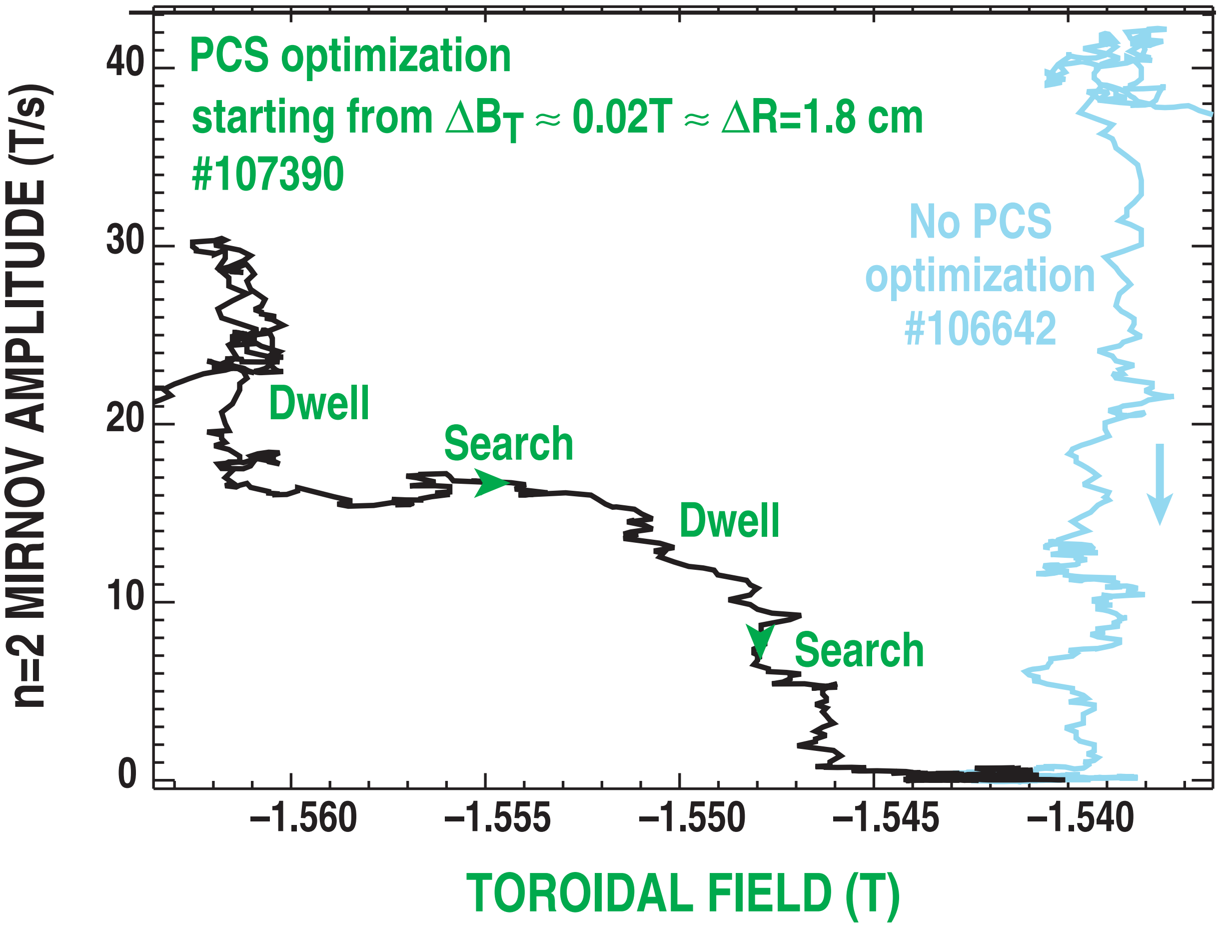
REAL-TIME CONTROL OF TOROIDAL FIELD FOR ECCD SUPPRESSION
(m/n = 3/2 NTM, 3 GYROTRONS, 1.5 MW, 3000 TO 4000 ms)



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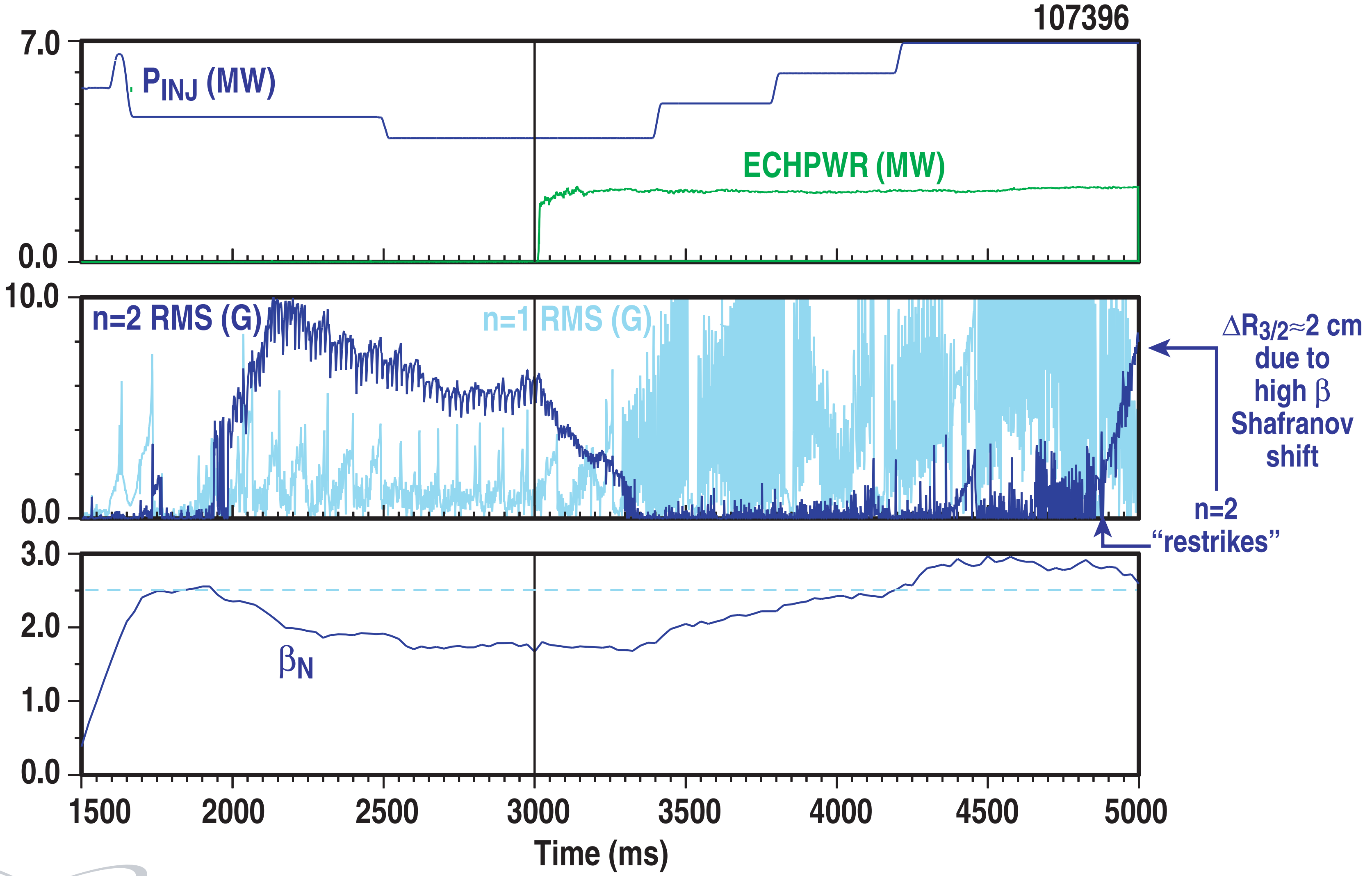
RAISING β_N AFTER ECCD SUPPRESSION OF m/n = 3/2 NTM

- β_N raised 60% (20% above onset level)
  - ★ mode restrikes as q=3/2 moves radially by 2 cm off ECCD



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EXTERNAL HELICAL FIELD OF DIFFERENT HELICITY CAN DECREASE NTM PRESSURE PERTURBATION

- $$\frac{\tau_R}{r^2}\frac{dw}{dt} = \Delta' + \frac{\varepsilon^{1/2} L_q}{L_p}\left(\frac{\beta_\theta}{w}\right)\left[\frac{w^2}{w^2+w_d^2} - \frac{w_{pol}^2}{w^2}\right]$$

with $w_d \approx \left(\frac{L_s}{k_\theta}\right)^{1/2}\left(\frac{\chi_\perp}{\chi_{||}}\right)^{1/4}$

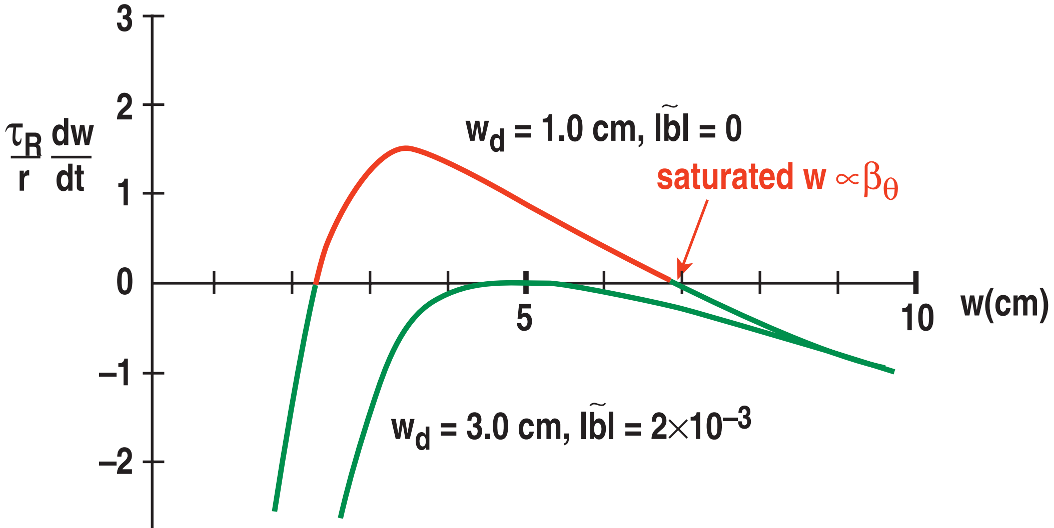
effect of cross-field transport "washing out" helically perturbed bootstrap current

— if $w^2 < w_d^2$

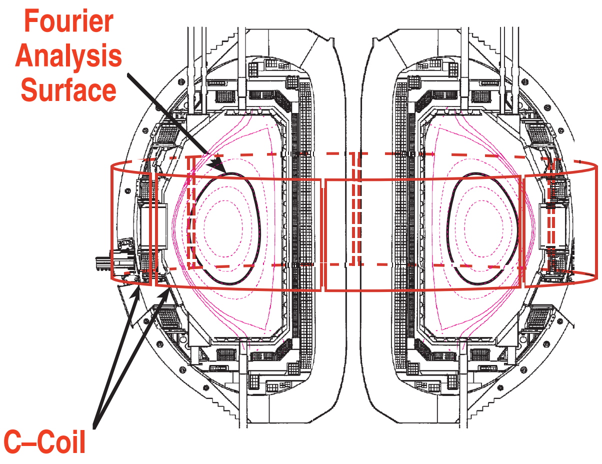
- Non-resonant, static, n = 3 helical field
  - ★ $|\tilde{b}| \equiv |B_{rmn}|/B_{To}$ can be up to 2×10^{-3} from C–Coil
- $|\tilde{b}|$ interferes with helical ∇p of NTM
  - ★ acts similar to increasing cross-field "washing out"
    - $$w_d \rightarrow w_{do} * \left(1 + \frac{|\tilde{b}|^2}{4\,\chi_\perp/\chi_{||}}\right)^{1/4}$$

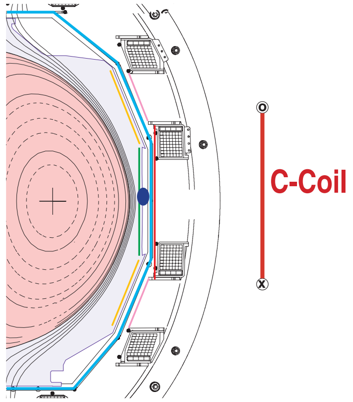
Q. Yu et al PRL (2001)

m/n = 3/2
r = 36 cm
w_{pol} = 1.8 cm
$\Delta' r = -3$
$\varepsilon^{1/2}\frac{L_q\beta_\theta}{L_p} = 0.675$
$\chi_\perp/\chi_{||} = 2\times10^{-8}$



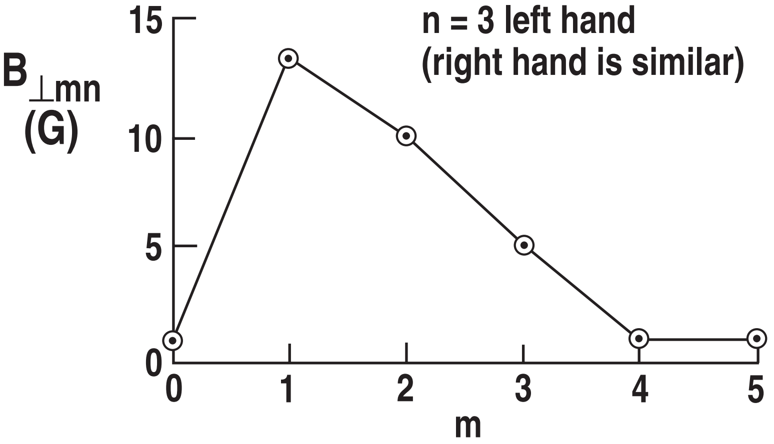
n = 3 FIELD FROM C–COIL

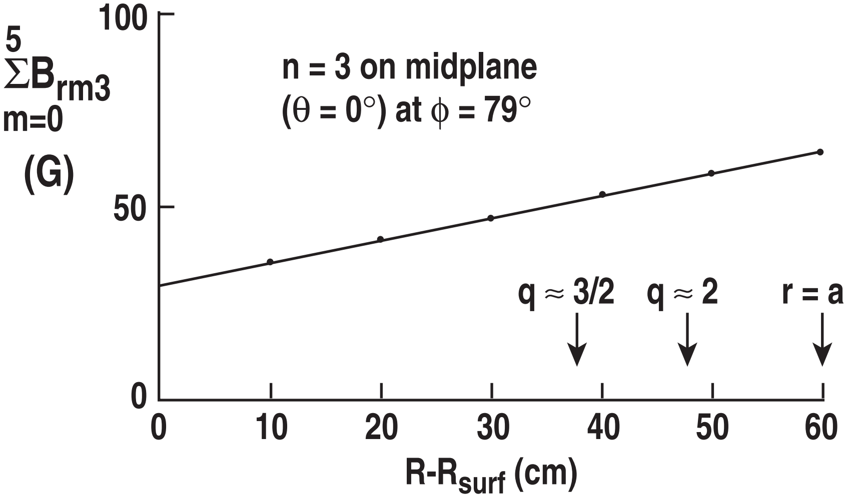




- n = 3 helical field is predominantly non-resonant ($m/n \le q_o \approx 1$)
  - ★ Fourier analysis on hi-lited surface . . . 4 turn coils, + 5000, –5000, + 5000, amps etc.

- n = 3 radial field “ripple” fall-off with minor radius is gradual
  - ★ $\sum_{m=0}^{5} B_{rm3}$ vs $R\text{-}R_{surf}$



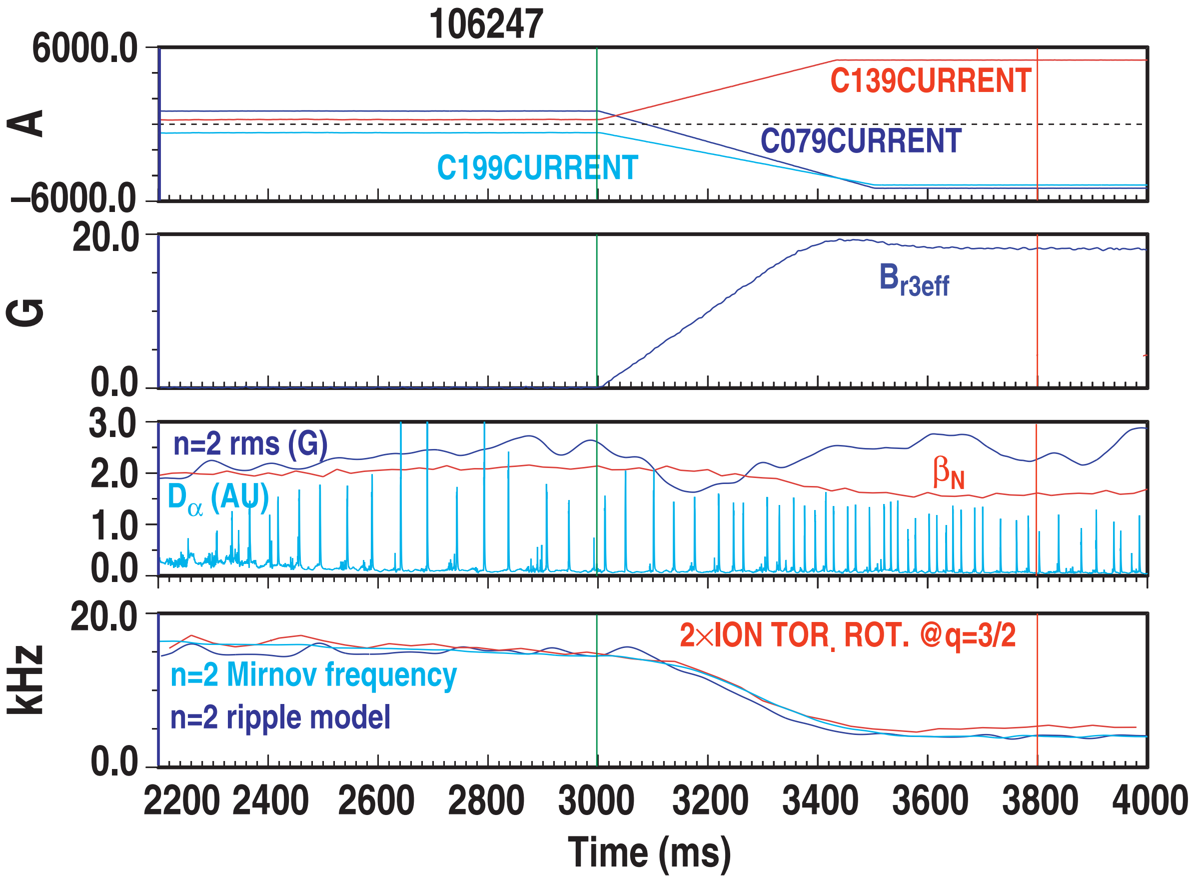


n = 3 NON-RESONANT HELICAL FIELDS APPLIED TO m/n = 3/2 NTM

- **NTM not suppressed**
  - ★ $|\tilde{b}| = B_{r3eff}/B_{To} \approx 1.6\times10^{-3}$

S. Günter
F01.006

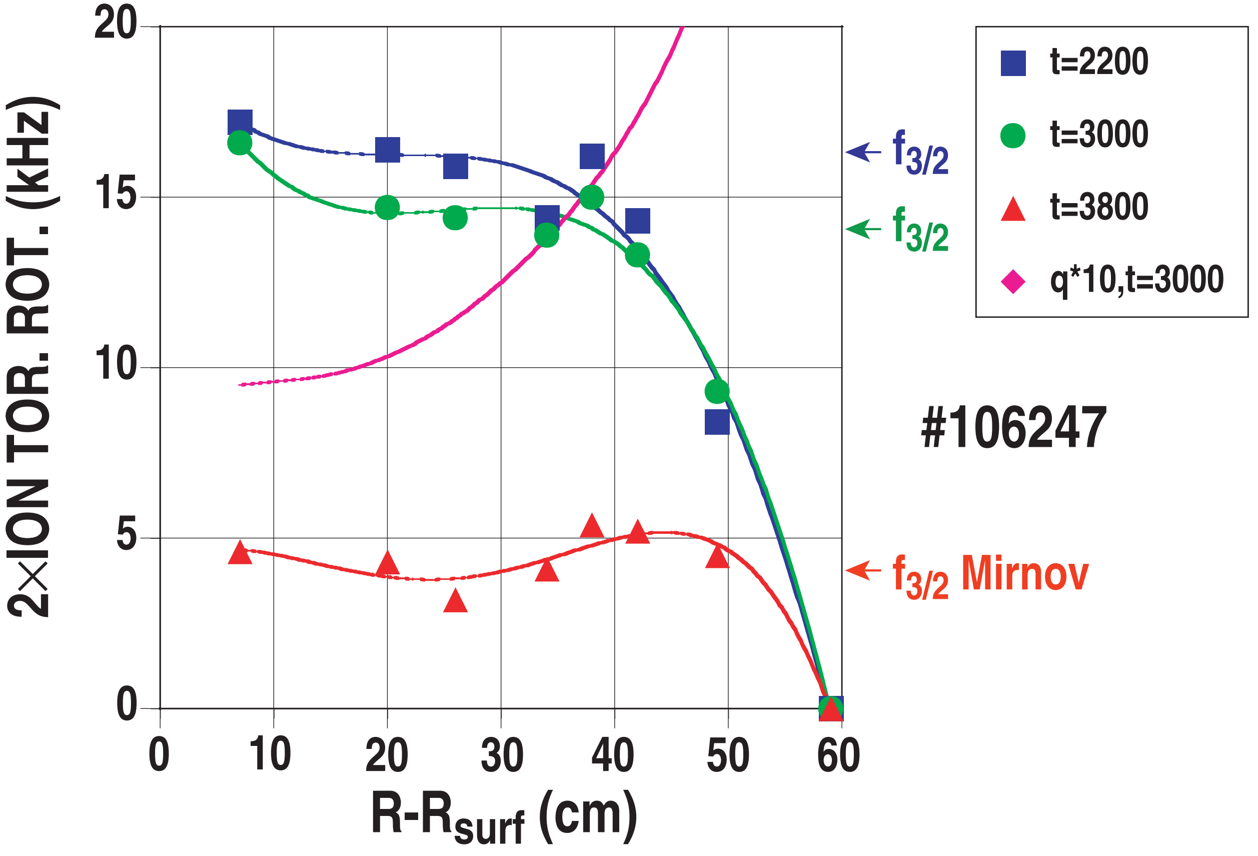
- **Plasma rotation slowed**



PLASMA TOROIDAL ROTATION SLOWED ACROSS PROFILE

- Consistent with n=3 ripple drag like TTMP

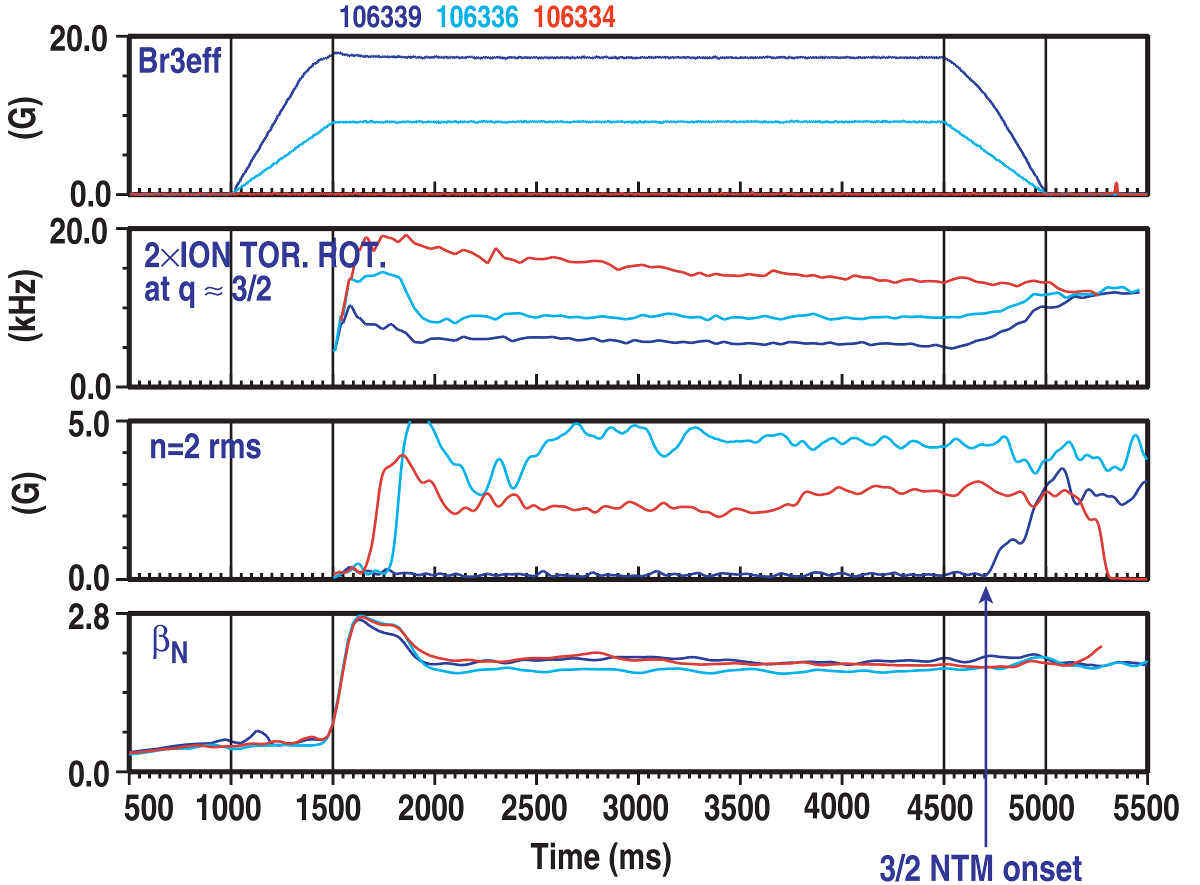
★ $f_{model} = (f_O - \dot{f}\tau_M) / (1 + C_3 B^2_{r3eff})$



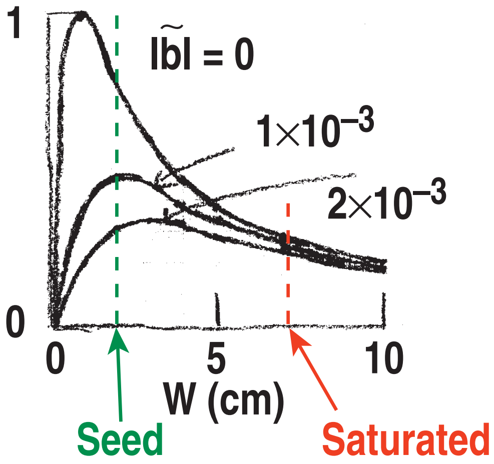
n = 3 NON-RESONANT HELICAL FIELDS APPLIED BEFORE m/n = 3/2 NTM

- **NTM inhibited**
  - ★ $|\tilde{b}| = B_{r3eff}/B_{To} \approx 1.6\times10^{-3}$
  - ★ Hysteresis makes $|\tilde{b}|$ more effective for small seed islands

$$\delta J_{bs} \propto \frac{\beta_\theta}{w} \frac{w^2}{w^2+w_d^2}$$



3/2 NTM onset
as n = 3 field ramped off



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CONCLUSIONS ON CONTROL OF NTMS IN DIII–D

- Precise location of off-axis ECCD is needed for effective suppression
  - ★ achieved by either ΔR or ΔB_T real-time control “search and suppress”
    - in presence of continued sawteeth
    - control requires pre-existing mode
  - ★ Beta can be raised above the initial NTM onset level
    - Shafranov shift moves $q = 3/2$ radially off the optimum
    - future work is real-time PCS alignment of j_{ec} on $q = 3/2$ in absence of NTM
- Large $n = 3$ helical fields can inhibit NTM onset
  - ★ large island suppression ineffective
  - ★ plasma rotation strongly damped

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