SUPPRESSION OF NEOCLASSICAL TEARING MODES IN THE PRESENCE OF SAWTEETH INSTABILITIES BY RADIALLY LOCALIZED OFF-AXIS ELECTRON CYCLOTRON CURRENT DRIVE IN THE DIII–D TOKAMAK

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GENERAL ATOMICS
ORISE

BACKGROUND

- Experiments proposed to stabilize NTMs by radially localized co-ECCD to replace the “missing” bootstrap current
  - ★ C. Hegna and J. Callen, Phys. Plasmas 4, 2940 (1997)
  - ★ H. Zohm, Phys. Plasmas 4, 3433 (1997)
- ASDEX-Upgrade experiment partially successful (reduction seen in 3/2 mode)
  - ★ H. Zohm, *et al.*, Nucl. Fusion 39, 577 (1999)
- ASDEX-Upgrade experiment achieved complete suppression of 3/2 mode
  - ★ G. Gantenbein, *et al.*, PRL 85, 1242 (2000)
    - — Sawteeth went away and did not return after the EC pulse
- JT–60U used ECCD to completely stabilize 3/2 NTM
  - ★ A. Isayama, *et al.*, IAEA 2000
    - — Note no sawteeth present

CO-ECCD RADIALLY LOCALIZED AT ISLAND CAN REPLACE THE "MISSING" BOOTSTRAP CURRENT AND COMPLETELY STABILIZE THE NEOCLASSICAL TEARING MODE

$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta' r + \varepsilon^{1/2}\left(\frac{L_q}{L_p}\right)\beta_\theta\left[\frac{r}{w} - \frac{r w_{pol}^2}{w^3} - \frac{8qr\delta_{ec}}{\pi^2 w^2}\left(\frac{\eta\, j_{ec}}{j_{bs}}\right)\right],\ \eta = \eta_0 e^{-[5\Delta R/3\delta_{ec}]^2} / (1+2\delta_{ec}^2 / w^2)$$

$m/n = 3/2$

$\beta_\theta = 0.9$

$\Delta' r = -3$

$r = 0.36$ m

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

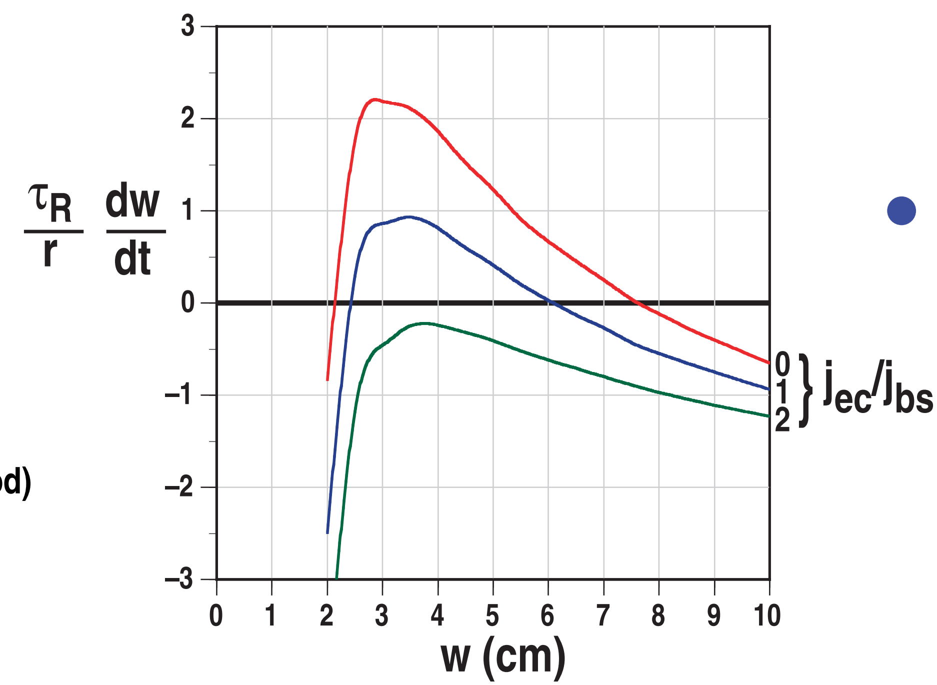
$L_q/L_p = 1.5$

$w_{pol}/r = 0.05$

$\delta_{ec}/r = 0.08$

$\eta_0 = 0.4$ (no mod)

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



- NTM amenable to complete suppression because $\dot{w} < 0$ for $w \lesssim w_{pol}$
- ECCD must lie within island or very near rational surface
  - no effect for $\Delta R \gtrsim \delta_{ec}$

Also see D. Brennan P3.044

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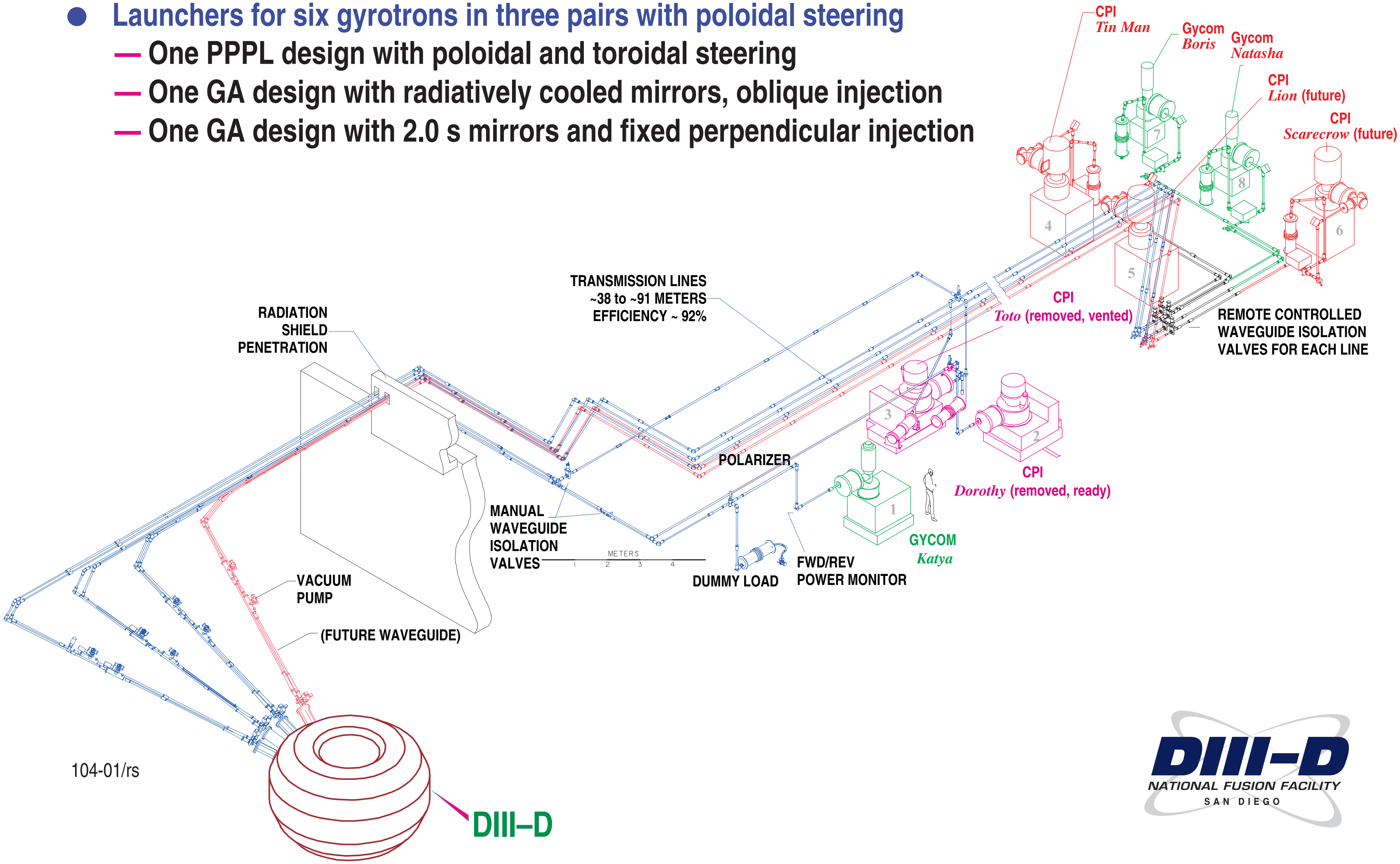
110 GHz SYSTEM ON THE DIII–D TOKAMAK

- **Four 110 GHz gyrotrons are operational at DIII–D; up to 2.2 MW injected simultaneously**
  — Three Gycom gyrotrons, Katya, Boris and Natasha, with BN windows: 750 kW 2.0 s
  — One CPI gyrotron, Tin Man, with CVD diamond window: 800 kW 2.0 sec
  — Two additional CPI gyrotrons this year, Scarecrow and Lion, with CVD diamond windows: 1 MW 10 s
- **Launchers for six gyrotrons in three pairs with poloidal steering**
  — One PPPL design with poloidal and toroidal steering
  — One GA design with radiatively cooled mirrors, oblique injection
  — One GA design with 2.0 s mirrors and fixed perpendicular injection



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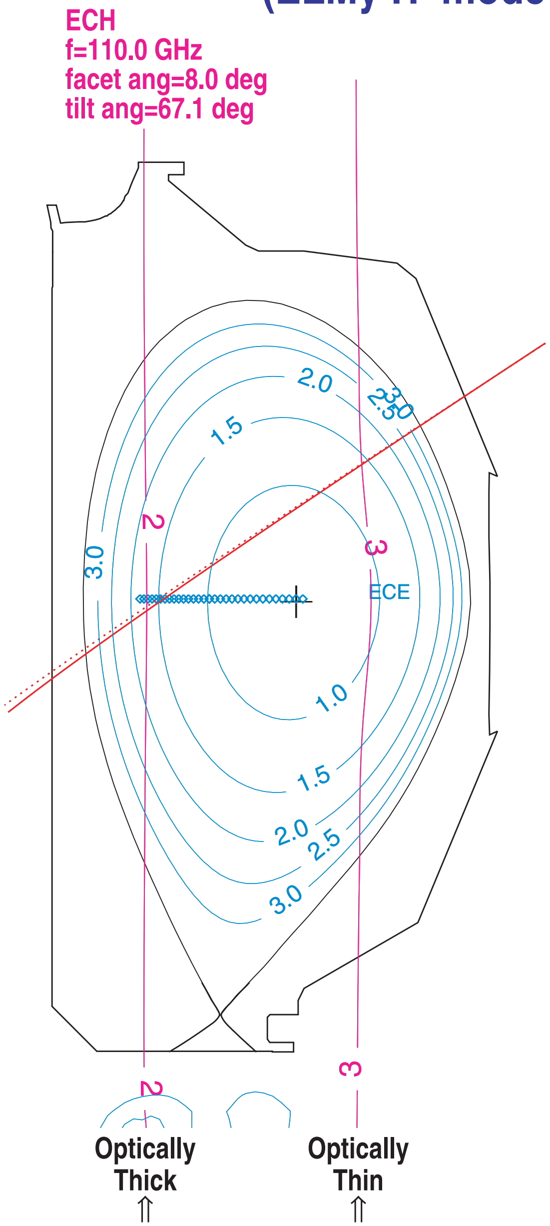
CONFIGURATION FOR OFF-AXIS ECCD

(ELMy H–mode with sawteeth)



Resources:

(1) lower cryopump to improve current drive

(2) 4 gyrotrons injecting up to 2.3 MW for at least 1 s

(3) PPPL & GA steerable launchers

Goal:
Suppress 3/2 NTM

Methods:

(1) Prompt replacing of "missing" bootstrap current in 0–point of island

(2) Slow change of current profile (Δ' more negative)

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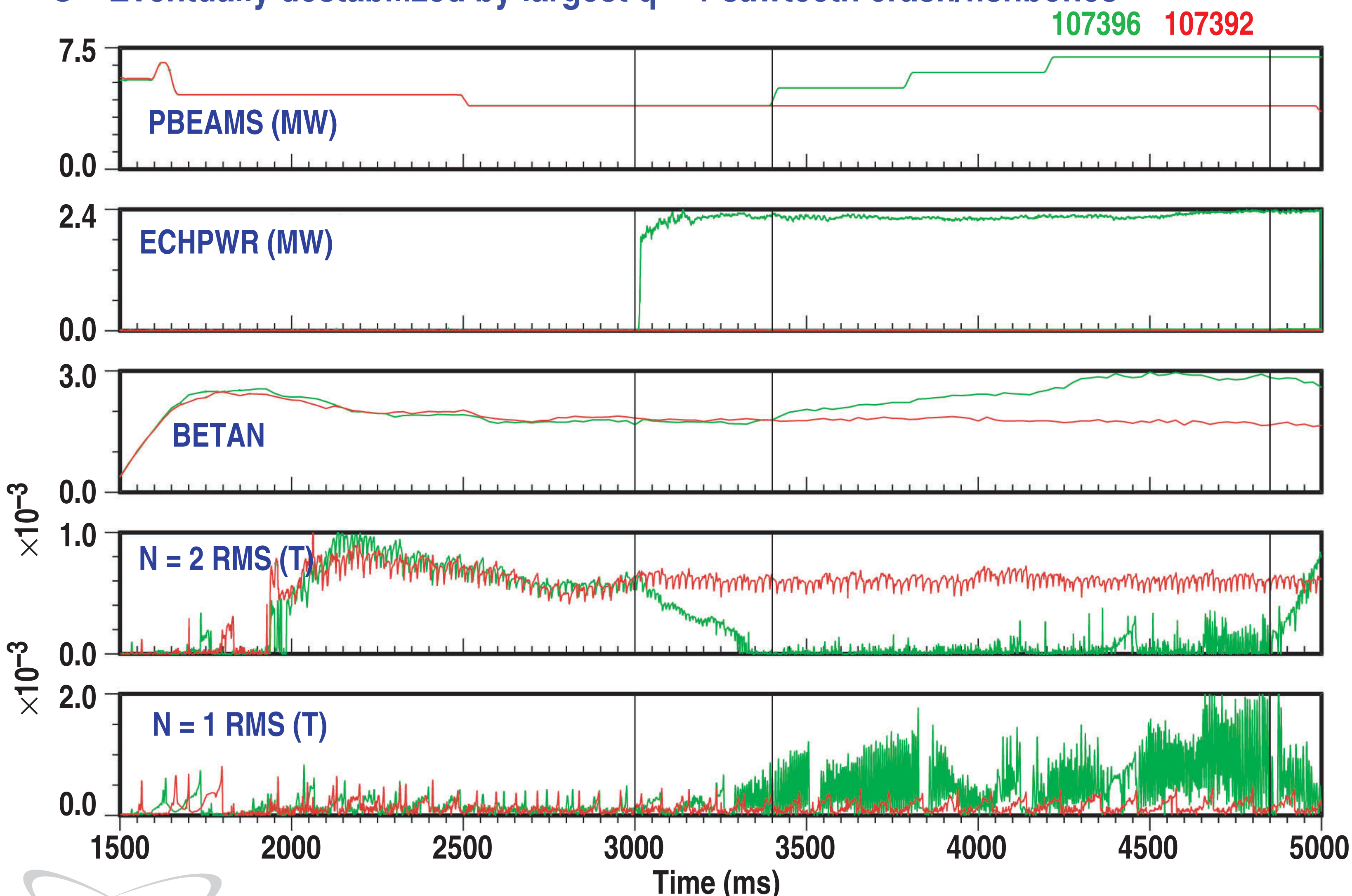
RAISING β_N AFTER ECCD SUPPRESSION OF 3/2 NTM

- 4 gyrotrons, best B_T and R_{surf} optimum position
- β_N 20% higher than peak before 3/2 NTM
- Eventually destabilized by largest q = 1 sawteeth crash/fishbones



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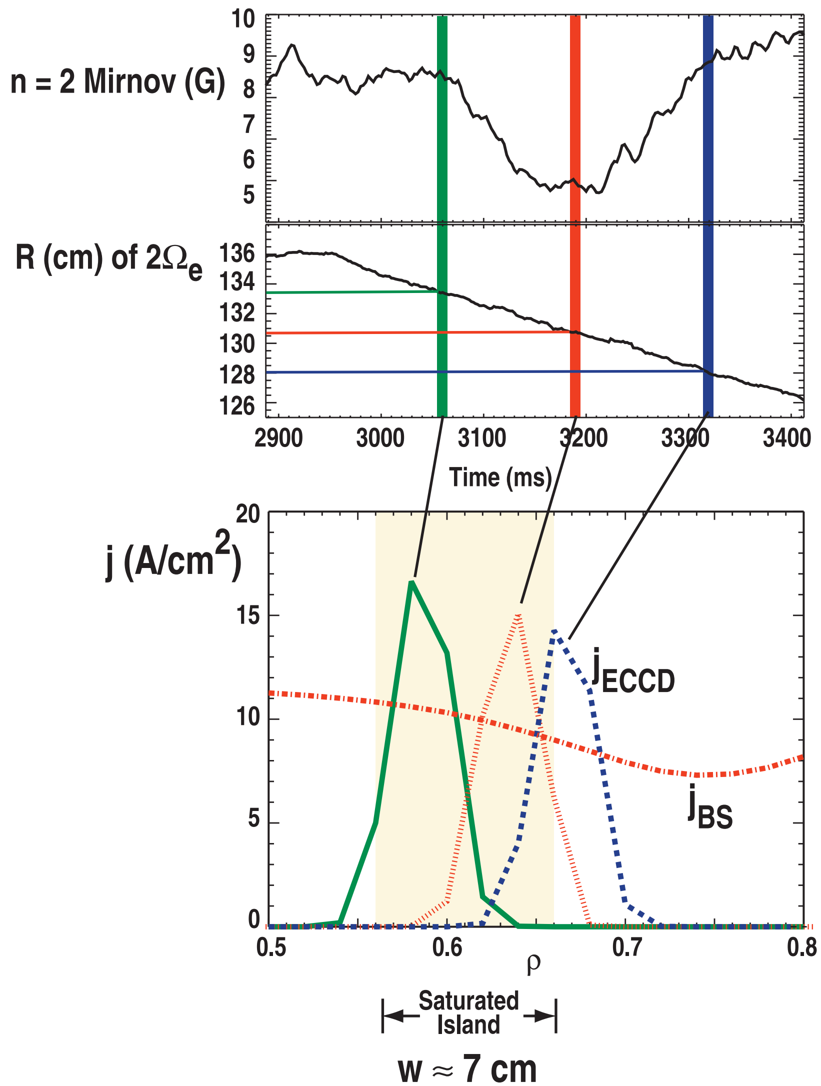
THE LOCATION OF ECCD IS CRITICAL TO FULL STABILIZATION



- Toroidal field was ramped down to scan ECCD past the island
- Alignment within 2 cm is required
- $j_{ECCD} > j_{BS}$ is satisfied (TORAY-GA)
- Sensitivity of effect to location implies that the width of the ECCD is less than the island size, in agreement with ray tracing calculation
- These results show that modeling is accurate even in ELMing H–mode with sawteeth and a tearing mode, at large ρ

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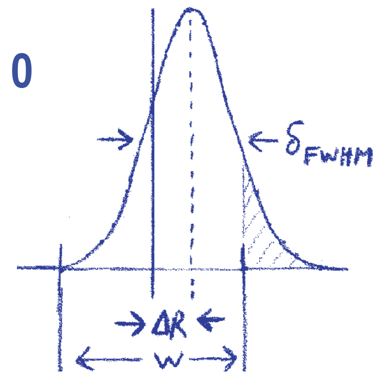
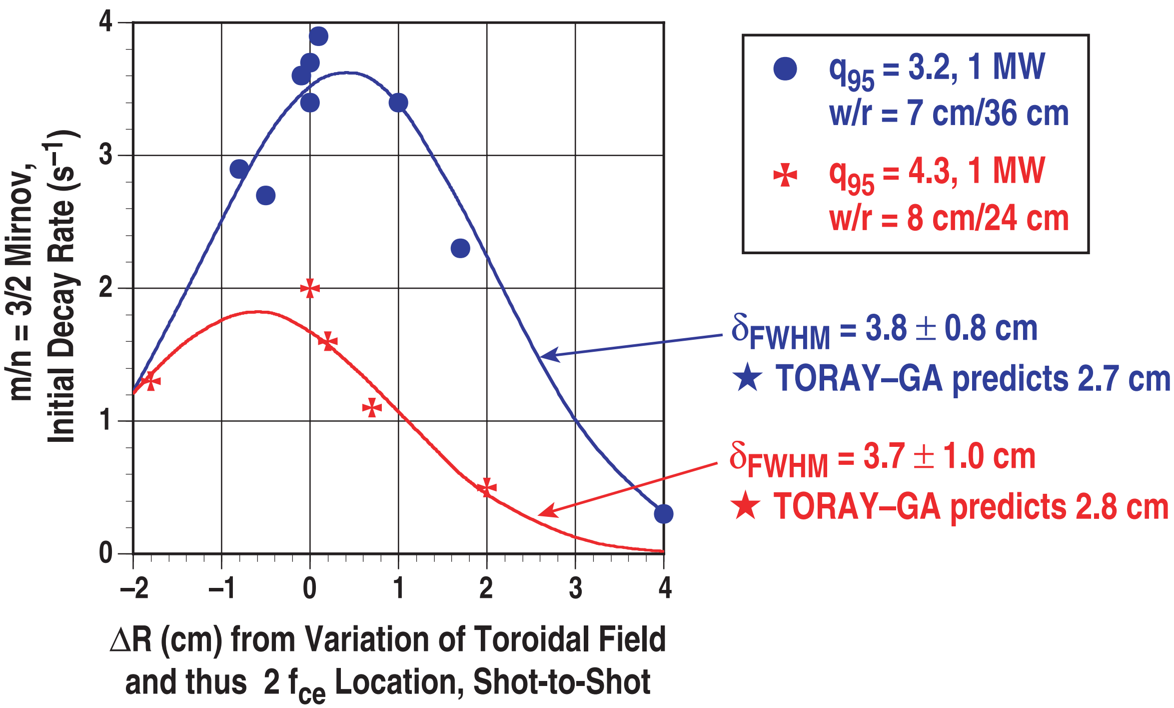
WIDTH OF ECCD CAN BE ESTIMATED FROM INITIAL DECAY RATE OF ISLAND WIDTH VERSUS ΔR

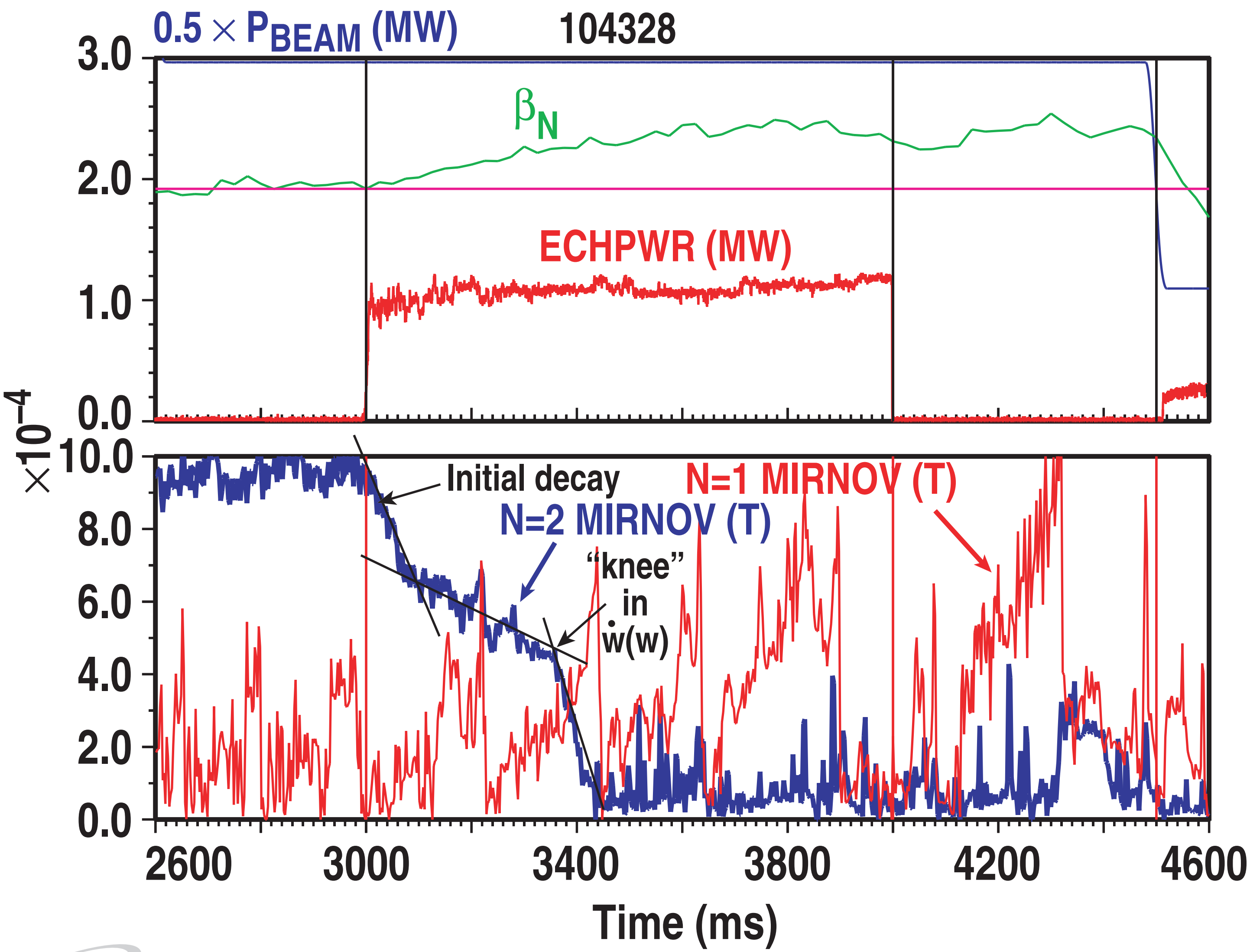
- Before ECCD, γ of Mirnov amplitude $\equiv -|\tilde{B}_{\theta,32}|^{-1}\, d|\tilde{B}_{\theta,32}|/dt \approx 0$
- Upon ECCD, initially $\gamma \propto J_o \exp[-(5\Delta R/3\delta_{ec})^2]$, $\delta_{ec} \equiv \delta_{FWHM}$





- Toray GA predicts narrower deposition, possible reasons include
  - ★ Each of 2 gyrotrons, absorption not at exactly same location
  - ★ Radial diffusion broadens spot size (R. Harvey)
  - ★ NTM model for rf term in modified Rutherford equation (F. Perkins)

COMPLETE SUPPRESSION OF AN m/n=3/2 NTM BY ECCD IN PRESENCE OF PERIODIC SAWTEETH



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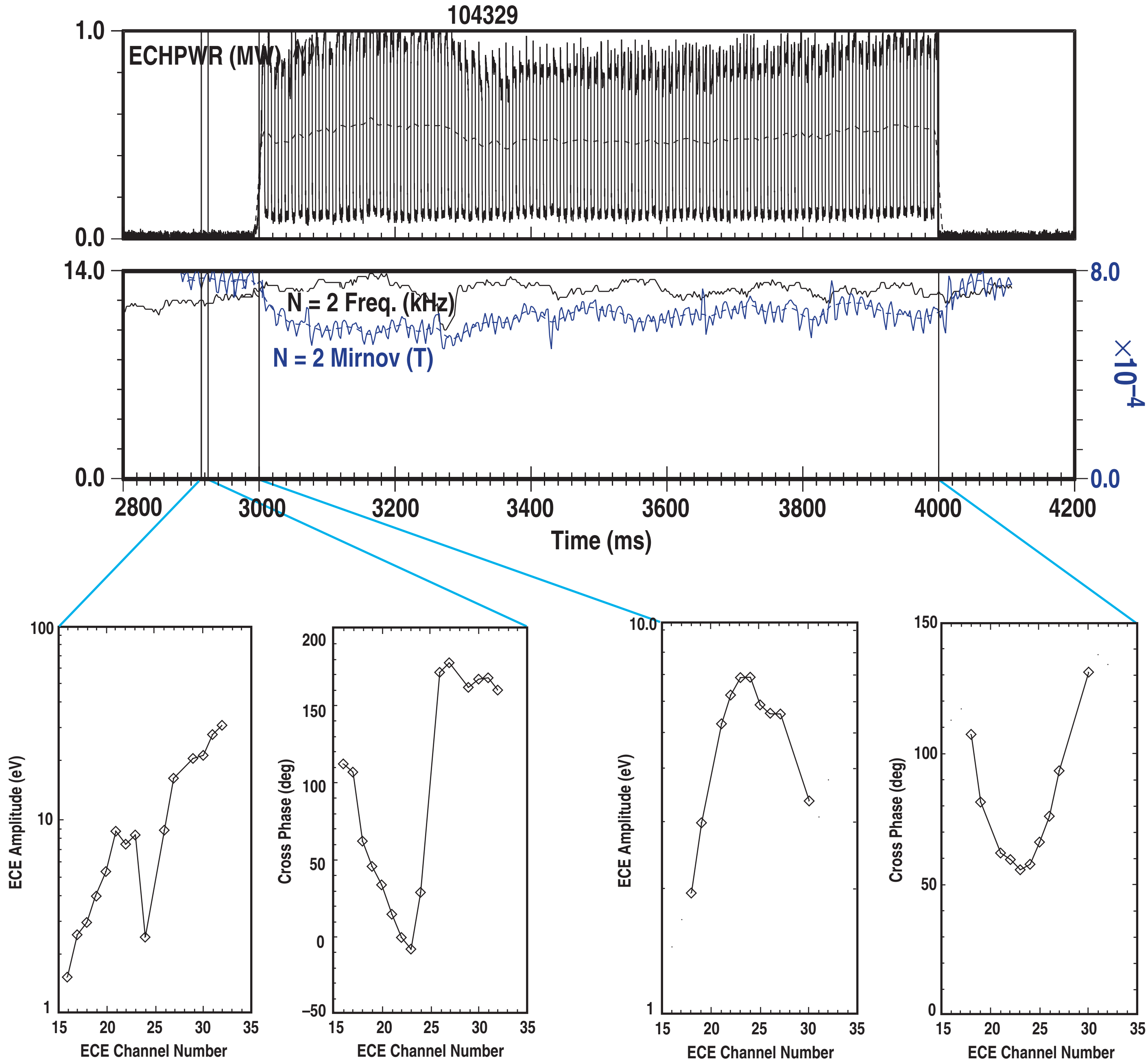
ECE RADIOMETER CONFIRMS OPTIMUM TUNING IS AT ISLAND



12.1 kHz ampl. null and π phase jump indicate 3/2 island O point between channels 23 and 24

100 Hz modulation shows peak response between channels 23 and 24

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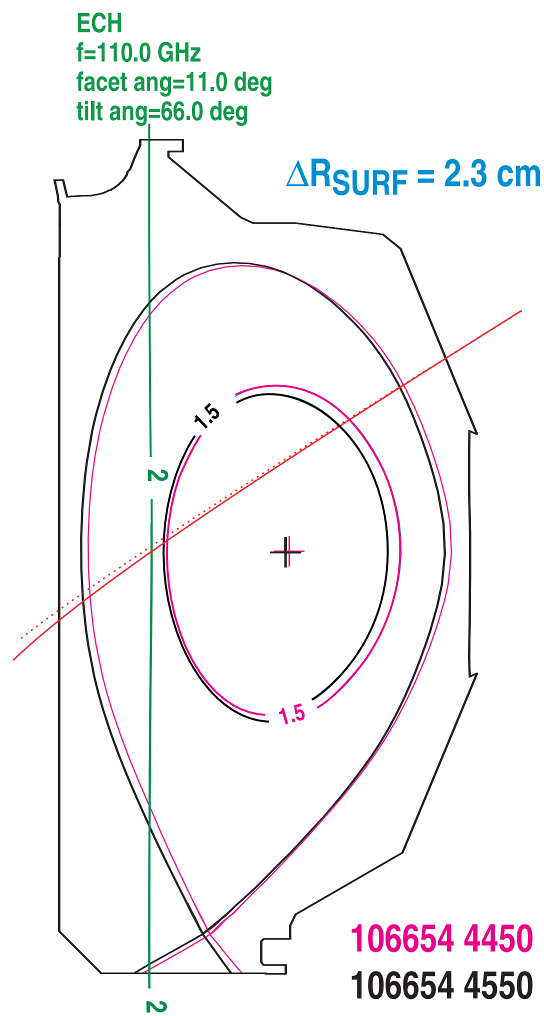
PLASMA CONTROL SYSTEM REAL-TIME FEEDBACK NTM CONTROL VARIES MAJOR RADIUS IN RESPONSE TO MODE AMPLITUDE

- Execute ΔR "Blind Search" pattern 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 specified "dwell" time (100 ms)
- If mode decays at > threshold rate, continue to dwell. If not, continue search (or "jitter" . . .)



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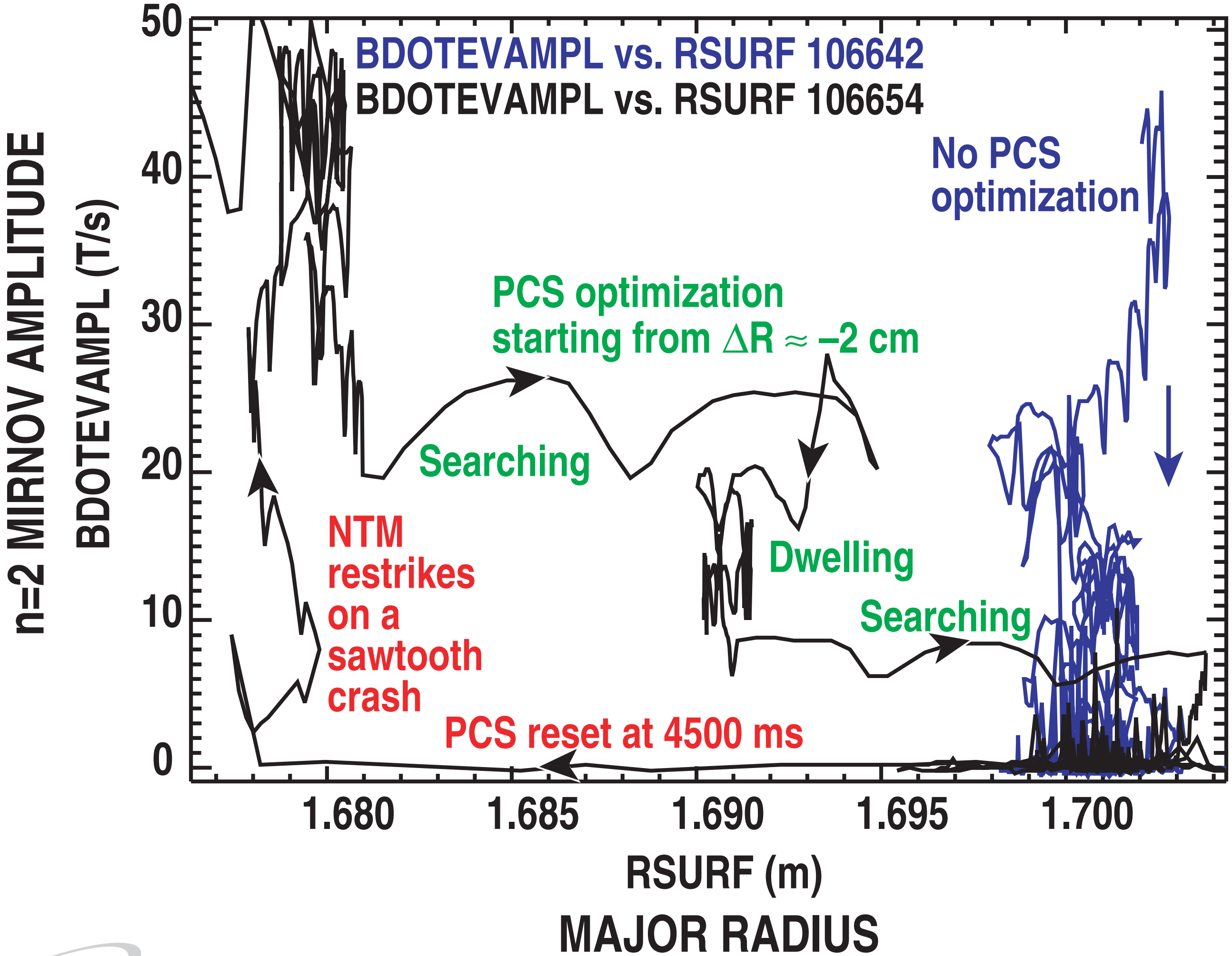
WITH AND WITHOUT PCS REAL-TIME CONTROL OF OPTIMUM RIGID PLASMA POSITION FOR ECCD SUPPRESSION (m/n = 3/2 NTM, ECCD WITH 3 GYROTRONS, 1.5 MW, 3000 TO 4800 ms, q_{95} = 3.6 COUPLED SAWTOOTH CASE)



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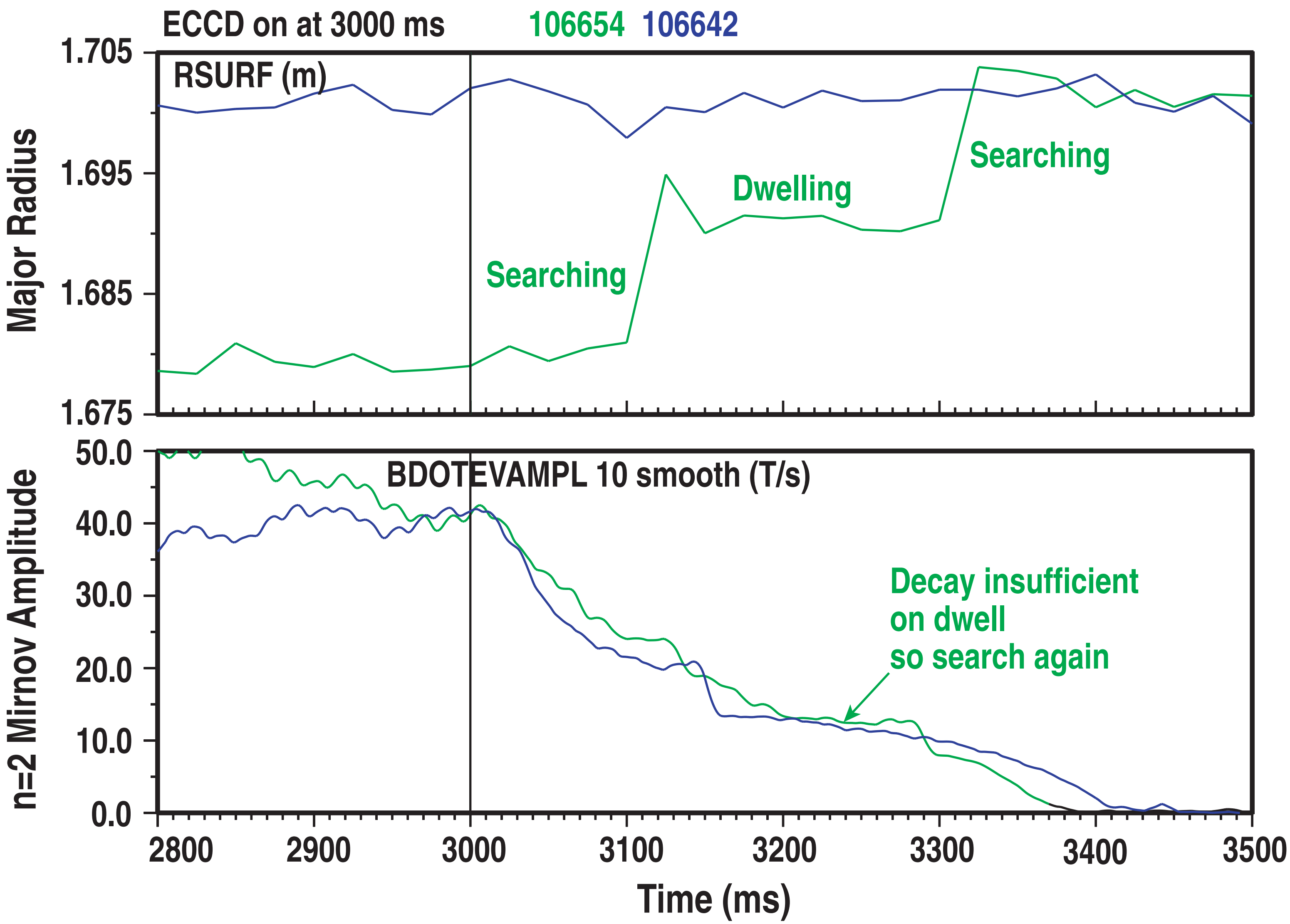

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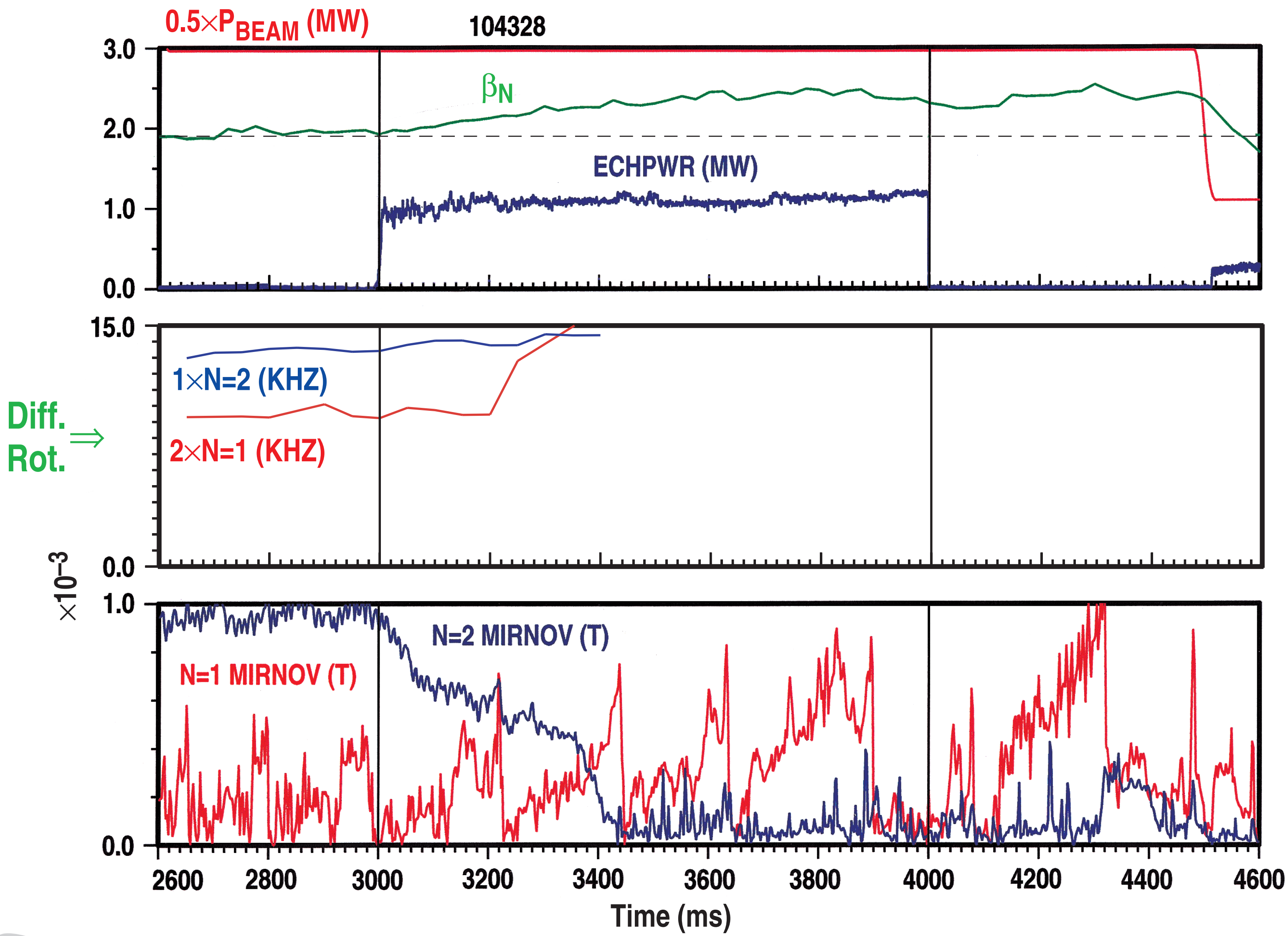
COMPLETE SUPPRESSION OF 3/2 NTM ACHIEVED WITH N=1 NOT FREQ. COUPLED (BEST BT TUNING)



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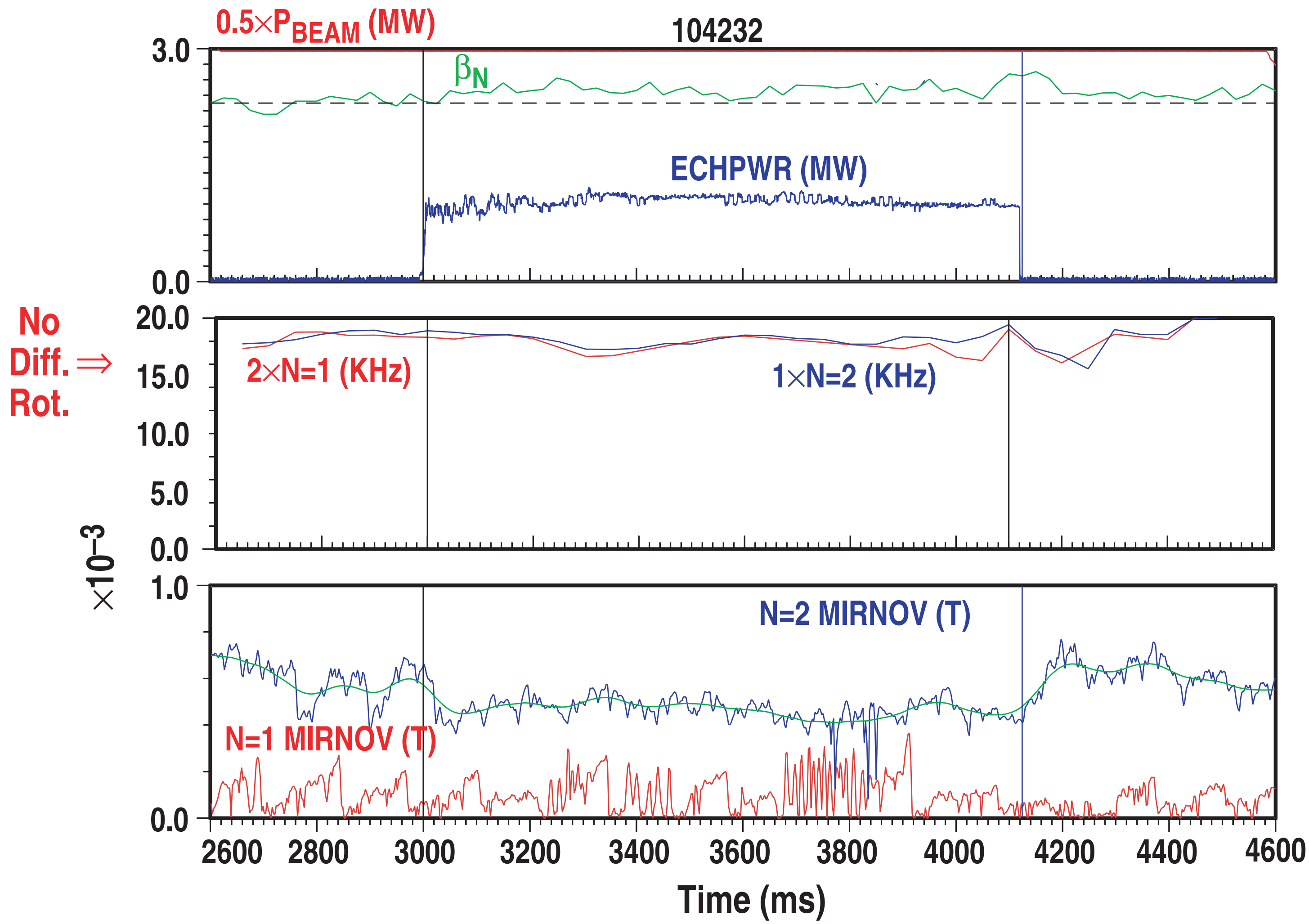
DIFFERENT LOWER I_p/HIGHER BT/HIGHER q_{95} TARGET PLASMA (SAME BEAMS, SAME ECHPWR) N=1 FREQ. COUPLED TO 3/2 NTM, NO COMPLETE SUPPRESSION (BEST BT TUNING)



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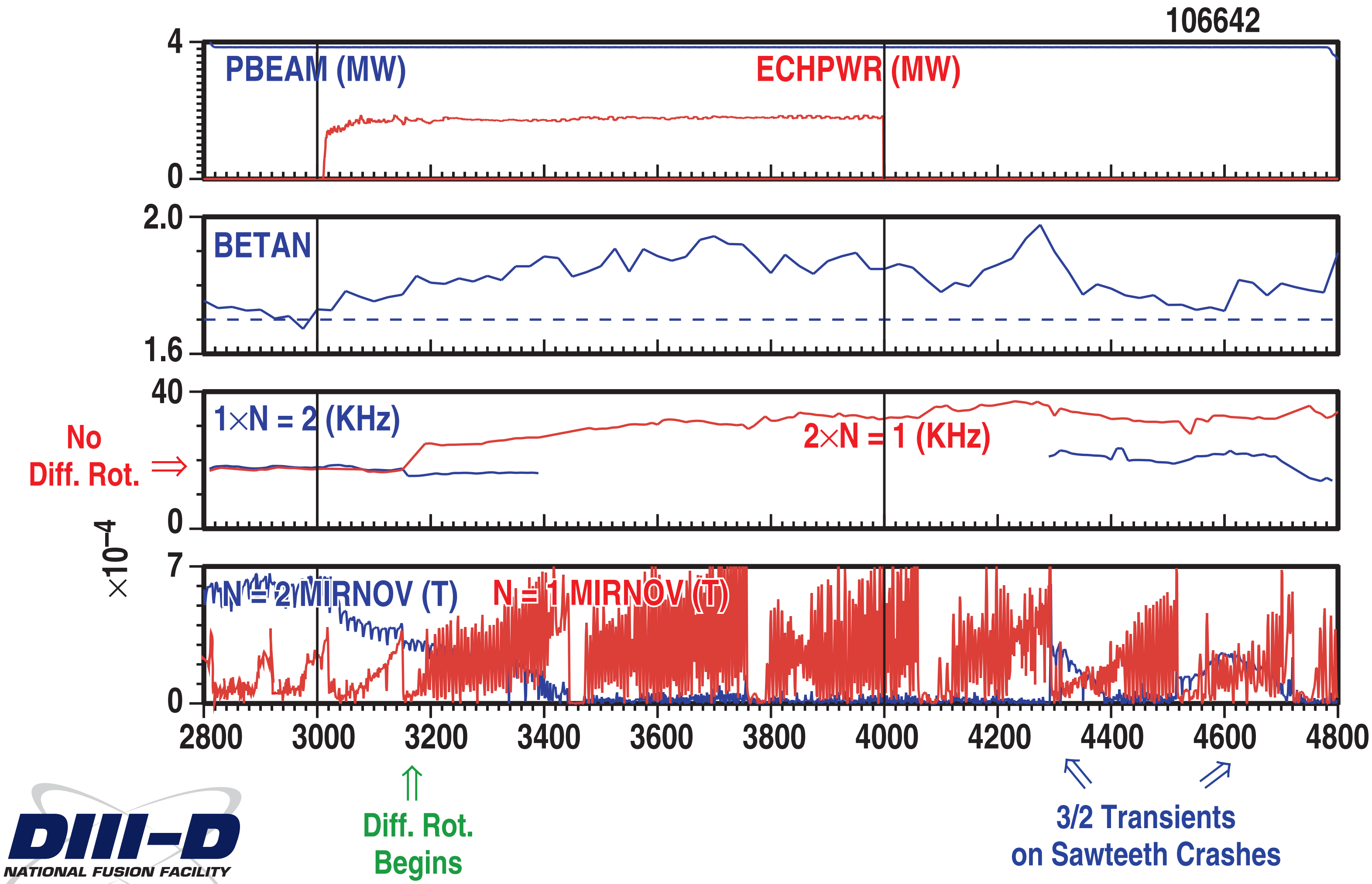
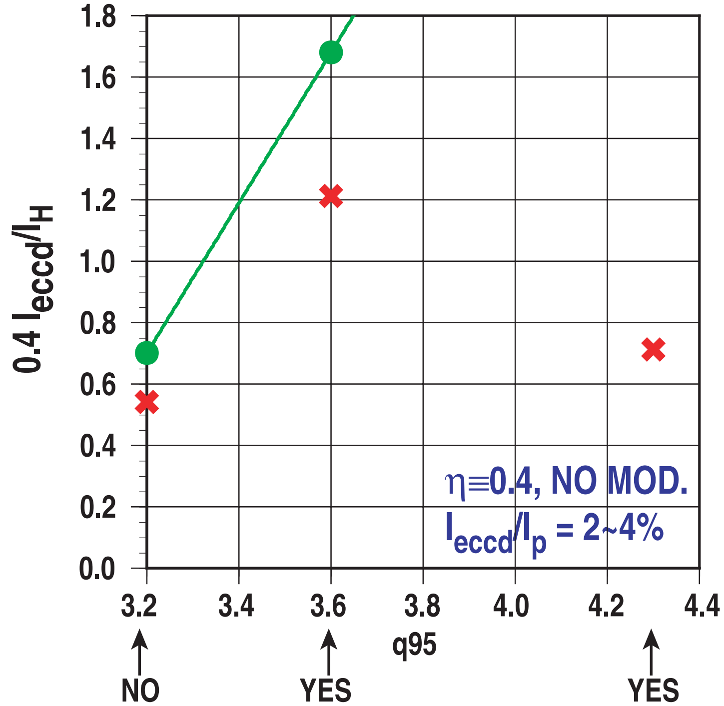
COMPLETE SUPPRESSION OF M/N = 3/2 NTM BY ECCD IN PRESENCE OF COUPLED q = 1 SAWTEETH (q_{95} = 3.6 CASE WITH 3 GYROTRONS INJECTING 1.5 MW)

- Note sudden decoupling as 3/2 Mirnov amplitude decreases
- “Fishbones” then appear



ECCD REQUIRED FOR 3/2 NTM SUPPRESSION (BEST ALIGNMENT IN EACH CASE)

- I_{eccd} from TORAY–GA
- I_H at $r=r_s$ from n=2 rms Mirnov $|\tilde{B}_\theta|$ at wall $r=r_w$
  - ★ $I_H = \pm m I_h = \frac{\sqrt{2}|\tilde{B}_\theta| r_w}{\mu_0} \left[\frac{1}{k r_s I'_m(k r_s) K_m(k r_w)} \right]$, $k = n/R_o$



q=1 sawteeth coupled?

● Complete suppression

✖ Partial suppression

See also A.M. Popov P3.049

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SUMMARY

- ECCD suppression of the 3/2 mode is demonstrated for the first time in sawtoothing plasmas
- Active real-time feedback optimization using position control has been demonstrated
- Basic features of the theory are consistent with the experimental observations:
  - Stabilization effect only when deposition is within the island
  - $J_{EC}/J_{BS} > 1$ from modeling (direct measurements not possible)
- Modes coupled to sawteeth precursors are more difficult to suppress

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