Stabilization of Neoclassical Tearing Modes by Active Control of Electron Cyclotron Current Drive Alignment in DIII–D

by

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in collaboration with

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OUTLINE AND SUMMARY

- Importance of alignment for effective use of limited rf power for NTM stabilization
- Methods of adjusting alignment previous to 2004
  - ★ with and without an m/n=3/2 NTM
- 2004 campaign improvements
  - ★ REAL-TIME MSE EFITS to locate rational surface
  - ★ EARLY ECCD to avoid initiation of the NTM
    . . . HIGHER STABLE BETA to m/n=3/2 NTM
- Future plans

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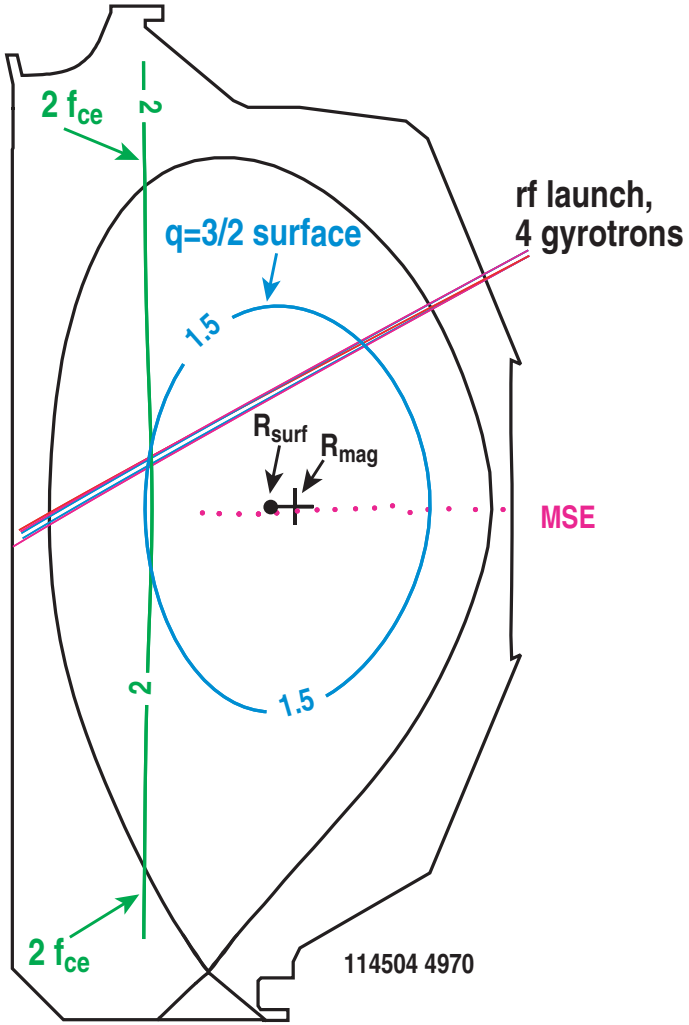
ALIGNMENT OF q=3/2 ON ECCD BY SHIFTING MAJOR RADIUS

- rf directed at $2f_{ce}$ inboard (just above midplane)
- moving plasma horizontally (δR_{surf}) moves q=3/2 wrt $2f_{ce}$
  - ★ peak j_{ec} a little outboard of $2f_{ce}$ due to Doppler effect



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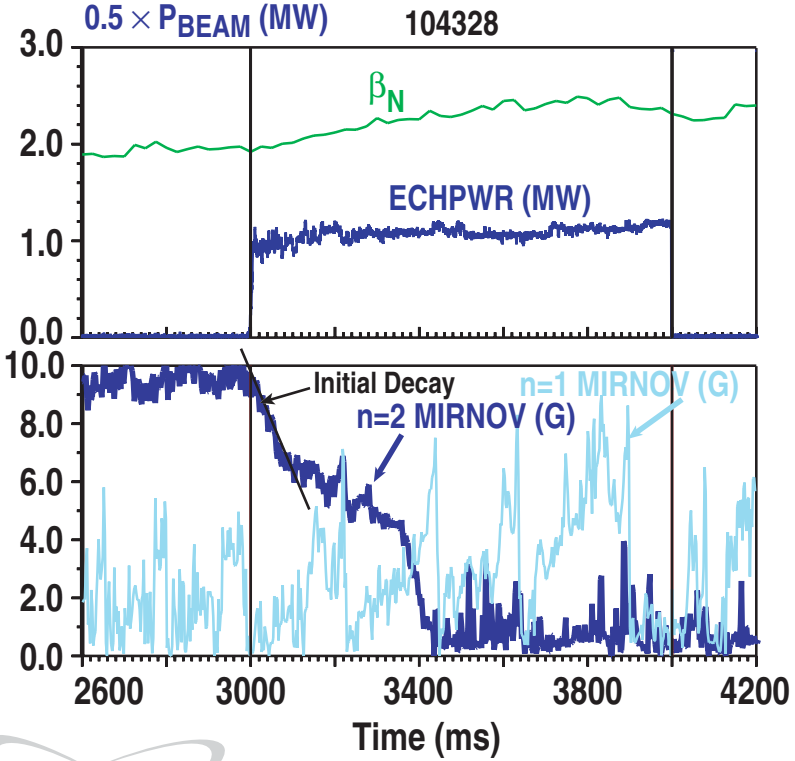
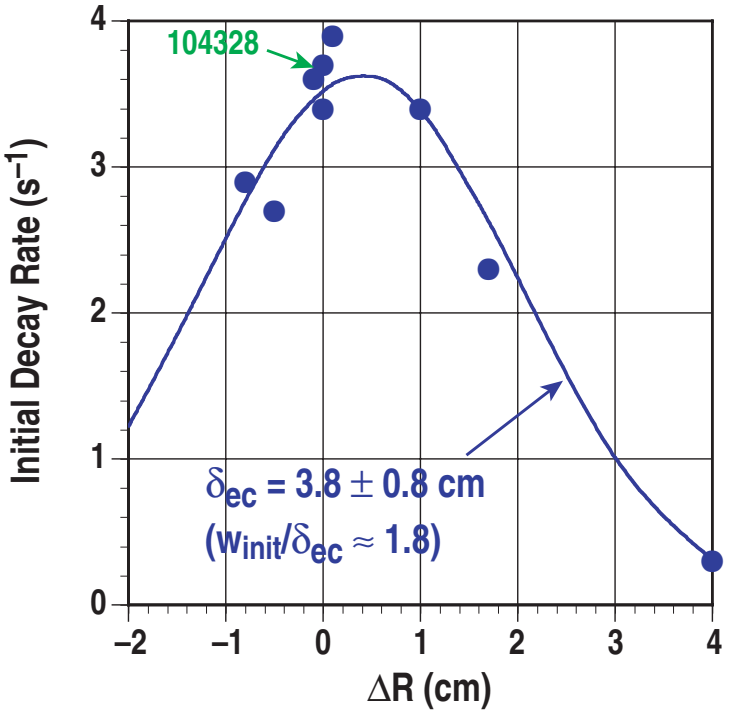
ALIGNMENT OF ECCD IS KEY TO EFFECTIVELY USING RF POWER FOR STABILIZATION OF AN NTM

- Before ECCD, $\gamma \equiv -(d|\tilde{B}_\theta|/dt)/|\tilde{B}_\theta| \approx 0$ for a saturated m/n=3/2 NTM
  - ★ Initially with ECCD, only the rf term is "turned on"

    . . . Let $\gamma(\Delta R) \equiv \gamma_{max} \exp[-(5\Delta R/3\delta_{ec})^2]$

    — δ_{ec} is full width half maximum of ECCD, ΔR is misalignment
- Variation of toroidal field, shot-to-shot, scans ΔR
  - ★ a misalignment of only 2 cm reduces the effectiveness a factor of 2





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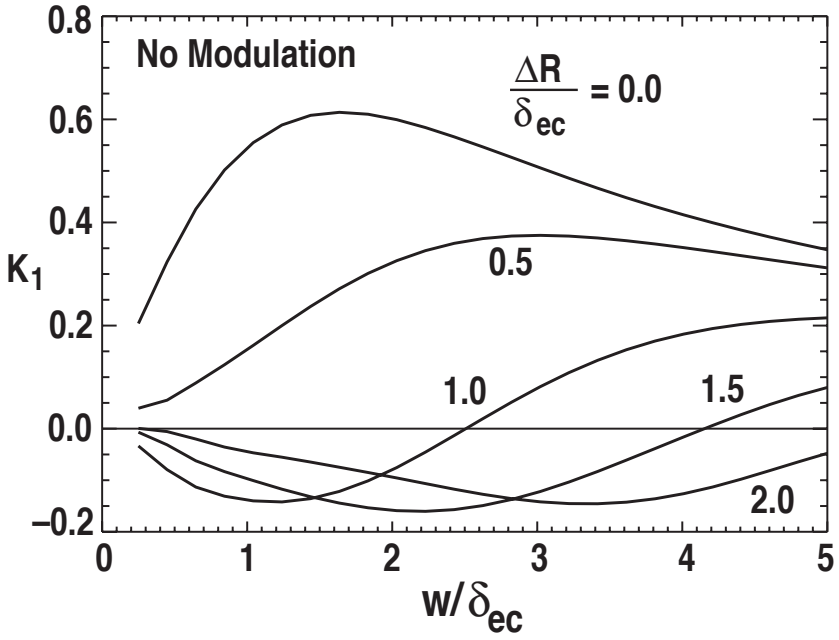
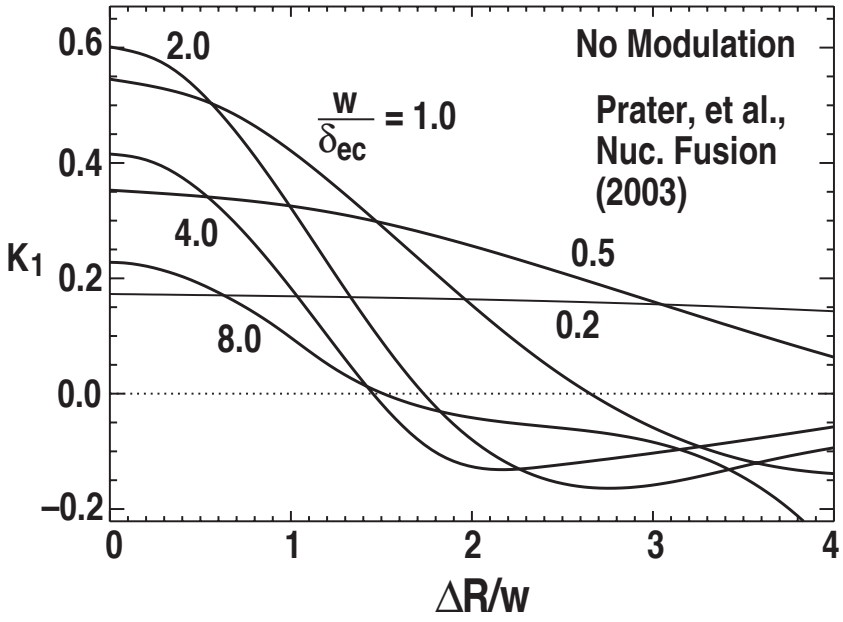
ECCD EFFECTIVENESS "K_1" IS A COUPLED FUNCTION OF MISALIGNMENT AND CURRENT DRIVE WIDTH

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

- $\Delta' r$ by PESTIII, j_{bs} from ONETWO, $j_{||}$ and L_q from EFIT, j_{ec} from TORAY–GA
- $a_2 = \vartheta(1)$ fitted to w_{sat} (no rf) $\approx a_2 (j_{bs}/j_{||})\, L_q/(-\Delta' r)$; $w_{marg} \approx 2\varepsilon^{1/2}\rho_{\theta i}$
- K_1 peaks at $\approx 1/\sqrt{3}$ at $w/\delta_{ec} \approx \sqrt{3}$ for $\Delta R/\delta_{ec} \approx 0$ with δ_{ec} FWHM





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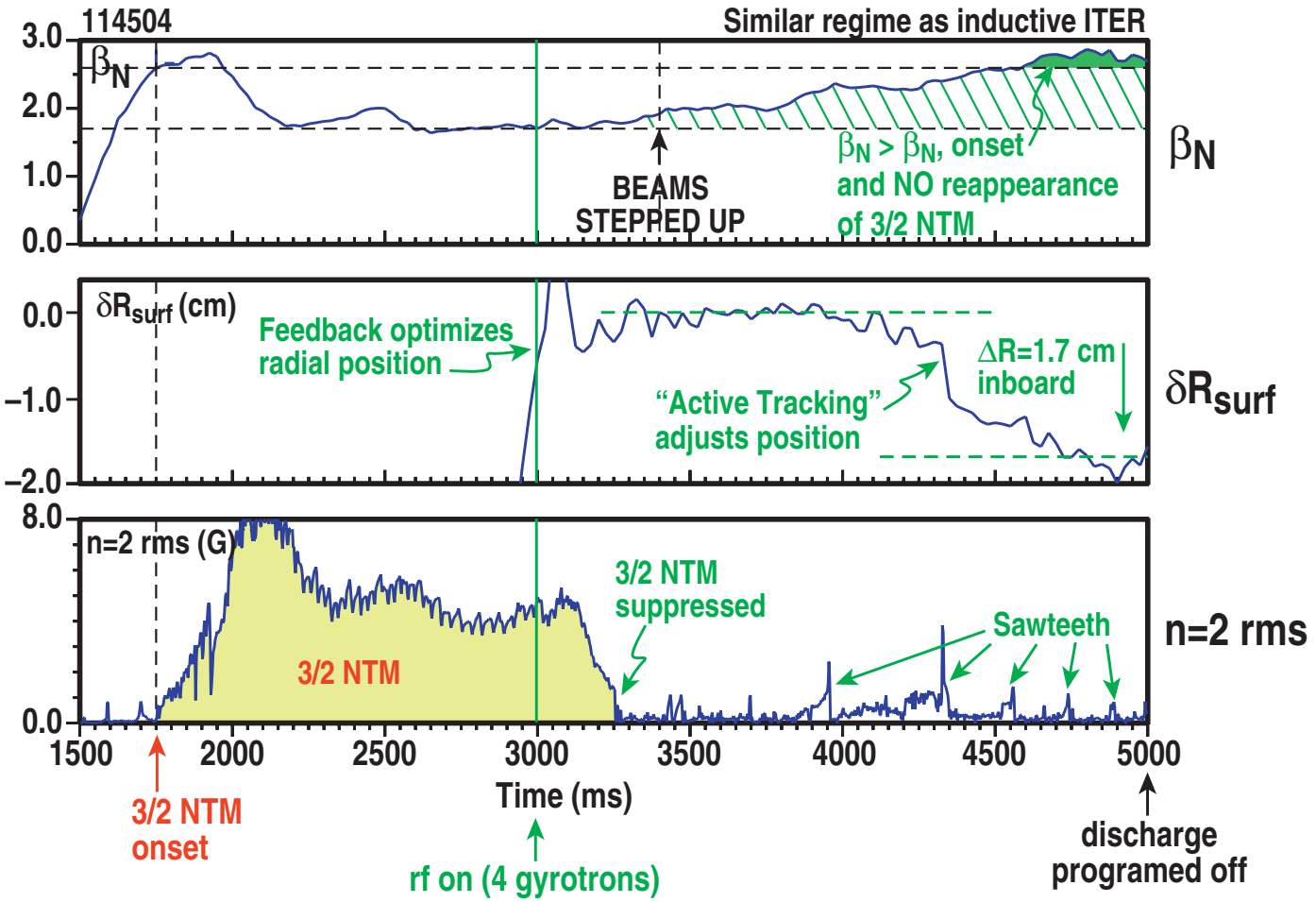
2003 DIII–D CAMPAIGN ALIGNMENT TECHNIQUES

- "Search and suppress" adjusts R_{surf} to minimize mode amplitude
- "Active tracking" keeps ECCD alignment unchanged in the absence of the mode



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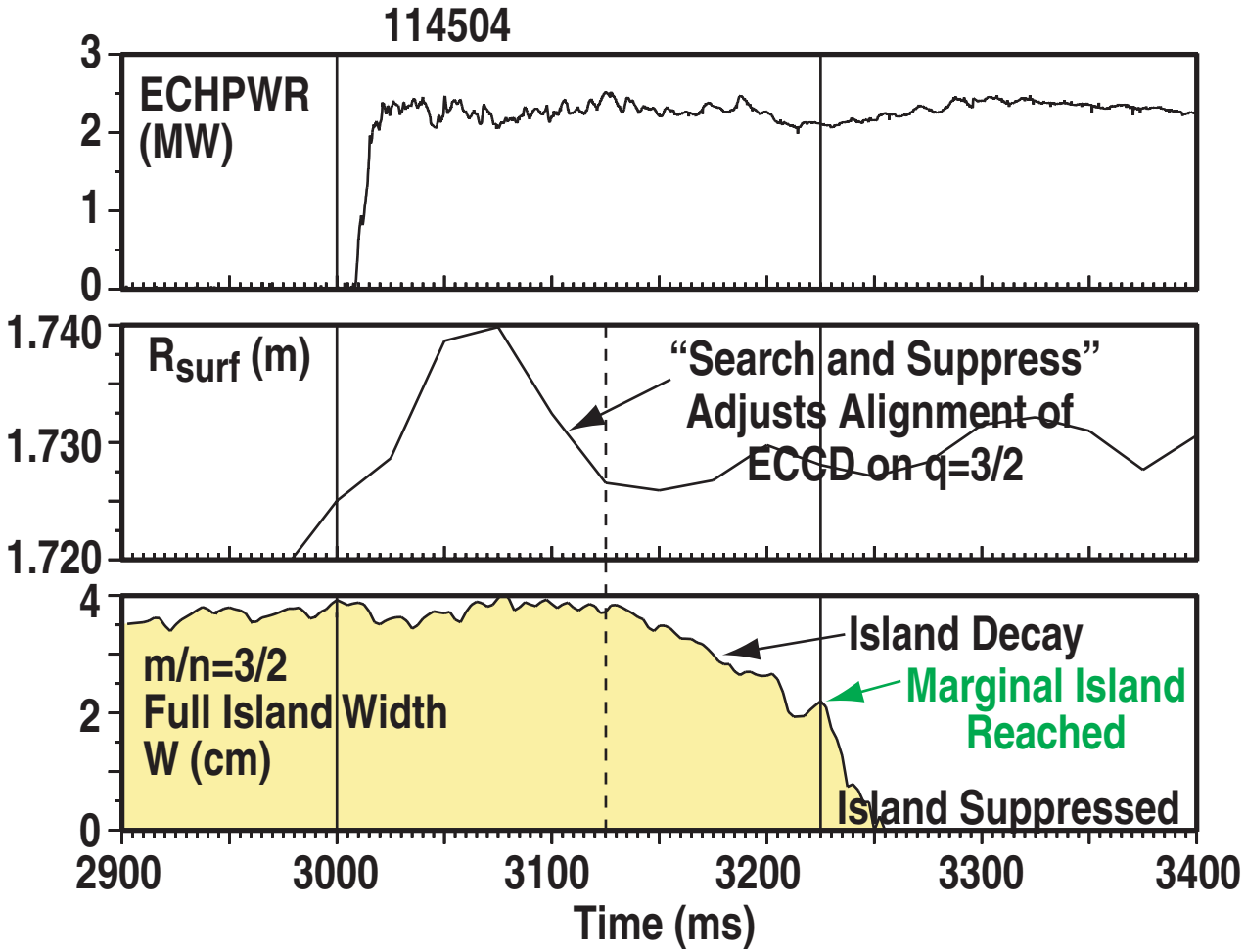
WITH 3/2 NTM, SEARCH AND SUPPRESS ADJUSTS ALIGNMENT OF ECCD

- Alignment is made "good enough" for complete stabilization



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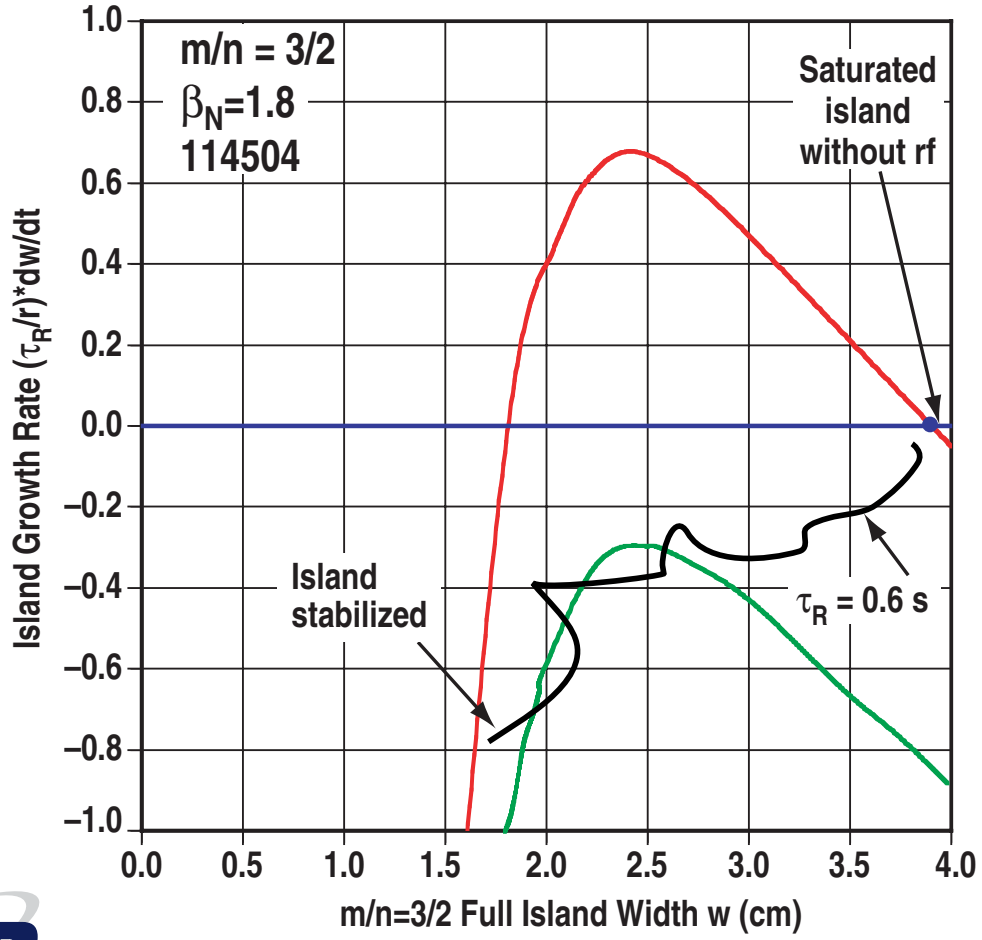
BENCHMARKING SEARCH AND SUPPRESS TO MODIFIED RUTHERFORD EQUATION

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

- a misalignment of ≈ 2 cm was "good enough" for stabilization with $j_{ec}/j_{bs} \approx 2$



$\Delta' r = -2.7$
$j_{bs}/j_{||} = 0.22$
$L_q = 21$ cm
$w_{marg} = 2.3$ cm
$a_2 = 2.5$

$j_{ec}/j_{bs} = 1.9$
$\delta_{ec} = 2.7$ cm
$\Delta R = 2$ cm
$\Delta R/\delta_{ec} = 3/4$

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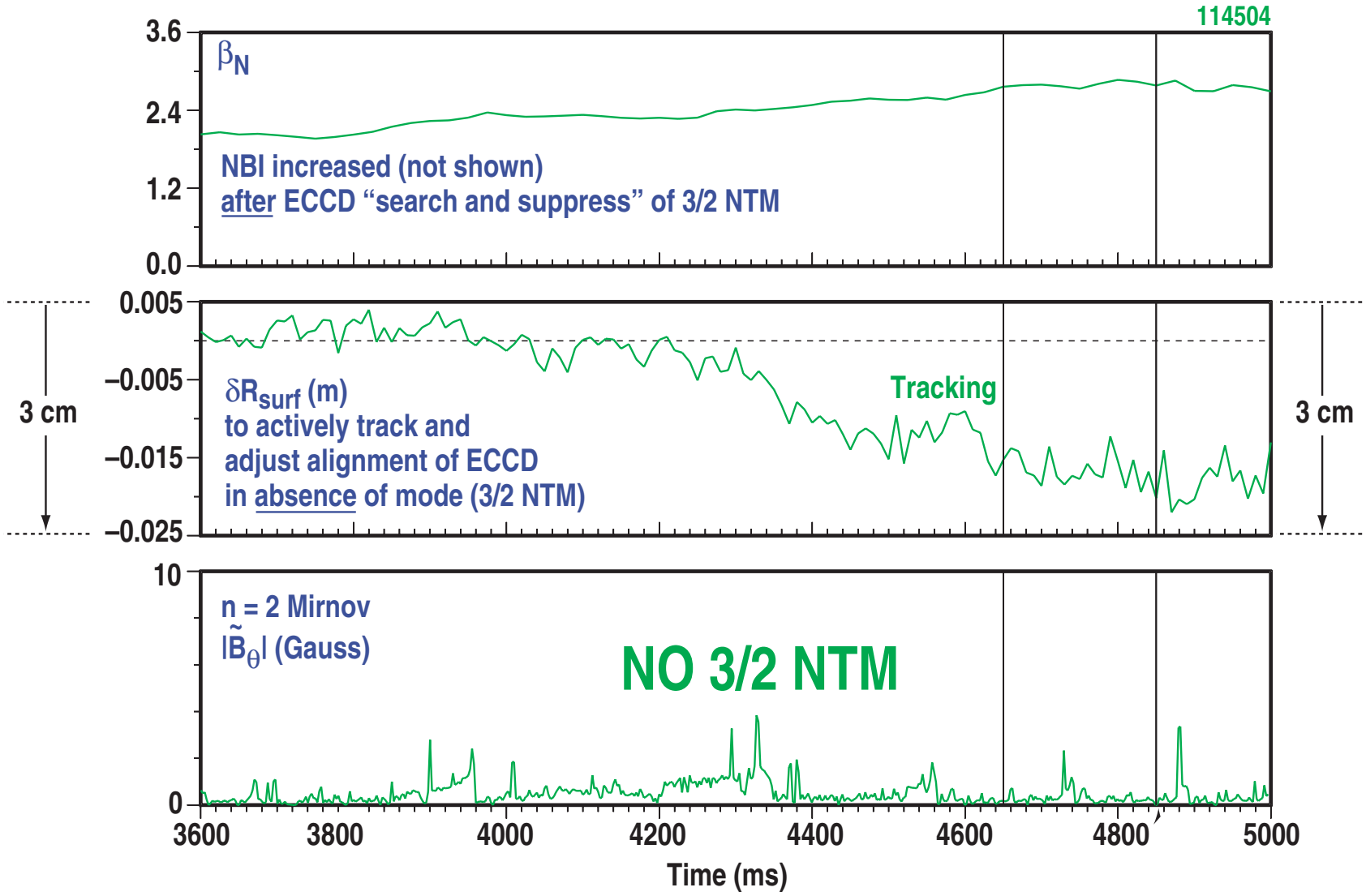
SUCCESSFUL SEARCH AND SUPPRESS OF 3/2 NTM HANDS OFF TO ACTIVE TRACKING

- Uses an adaptive learning network predictor based on previous experiments



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2004 DIII–D CAMPAIGN ALIGNMENT IMPROVEMENTS

- Use real-time MSE EFITS to locate q=3/2 (UPDATED EVERY $3\frac{1}{4}$ ms)
  - ★ does not need training to specific discharges
  - ★ does not propagate misalignments on hand-off from search and suppress

- Apply ECCD early, before 3/2 NTM onset
  - ★ track and avoid the instability ever occuring
    . . . increase beta to highest level without 3/2 NTM
    - — subject to 2/1 NTM onset, not yet being controlled simultaneously

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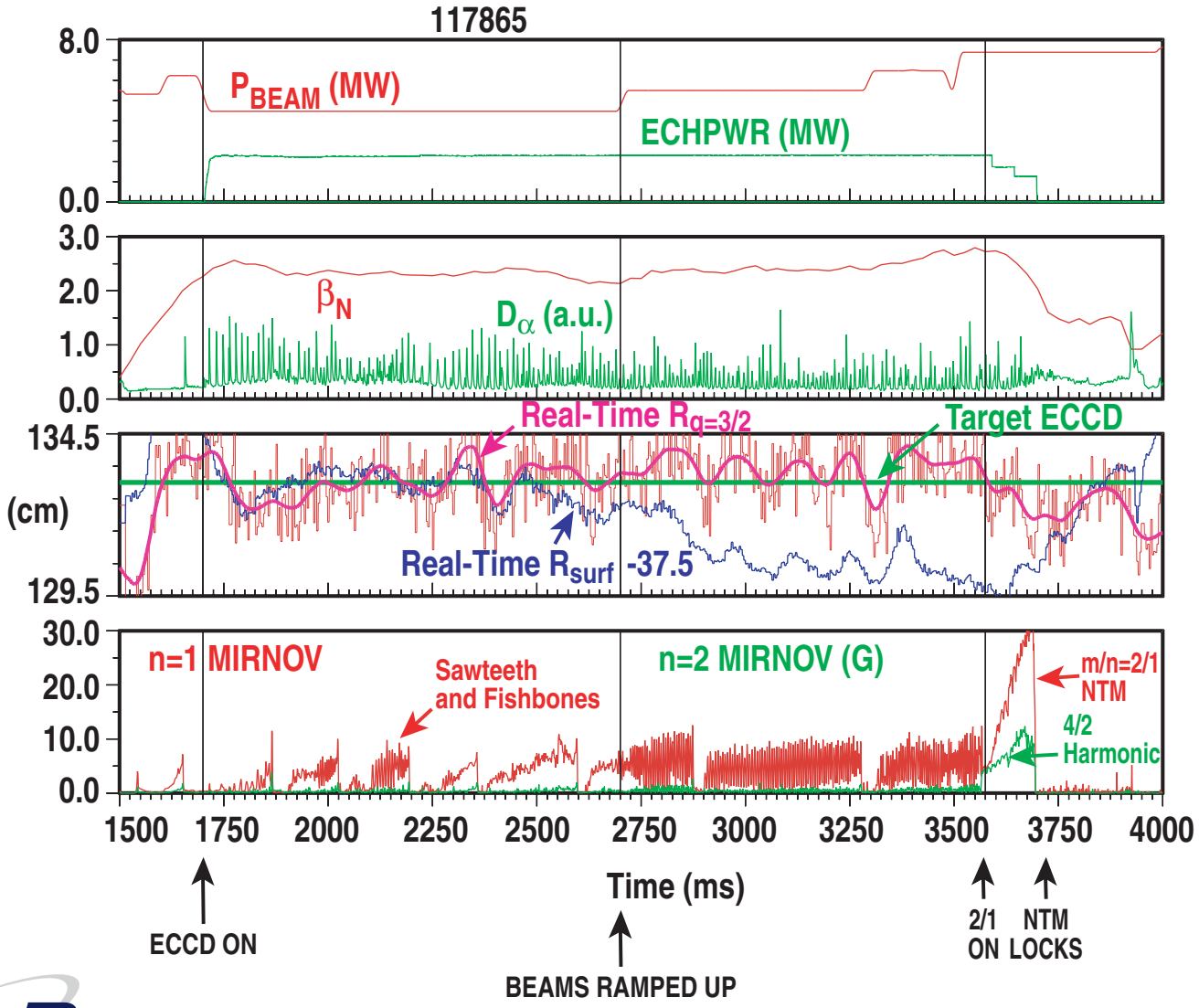
EARLY ECCD AND REAL-TIME MSE EFITS ALLOW AVOIDING m/n=3/2 NTM

- 23 of 25 discharges without early ECCD have 3/2 NTM, 2 of 25 early 2/1 NTM instead
- stable beta can be raised up to onset of m/n=2/1 NTM [not (yet) being controlled]



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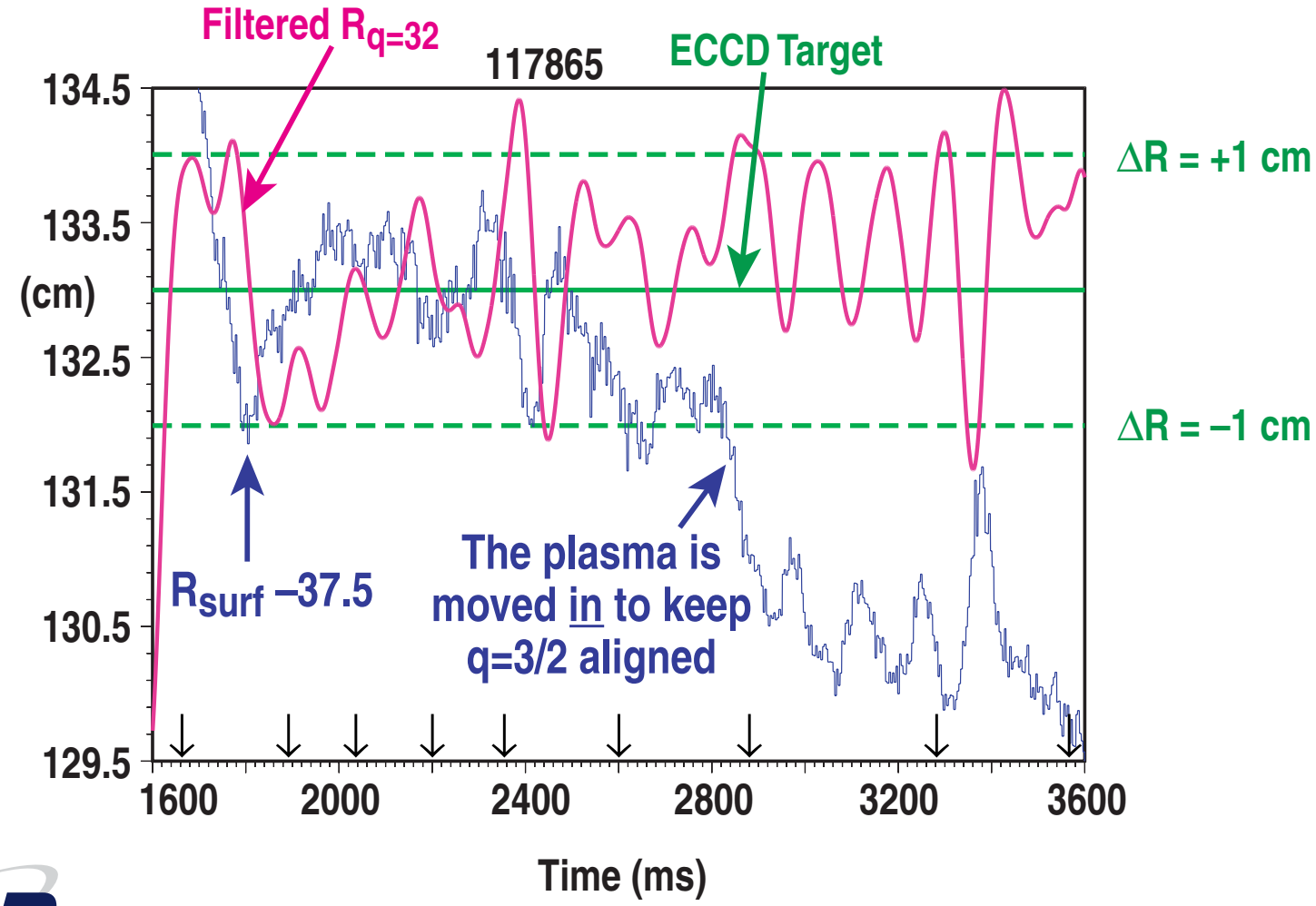
REAL-TIME EFIT ALIGNMENT OF q=3/2 ON ECCD IS DONE BY MOVING THE PLASMA

- Time markers (↓) indicate sawteeth crashes



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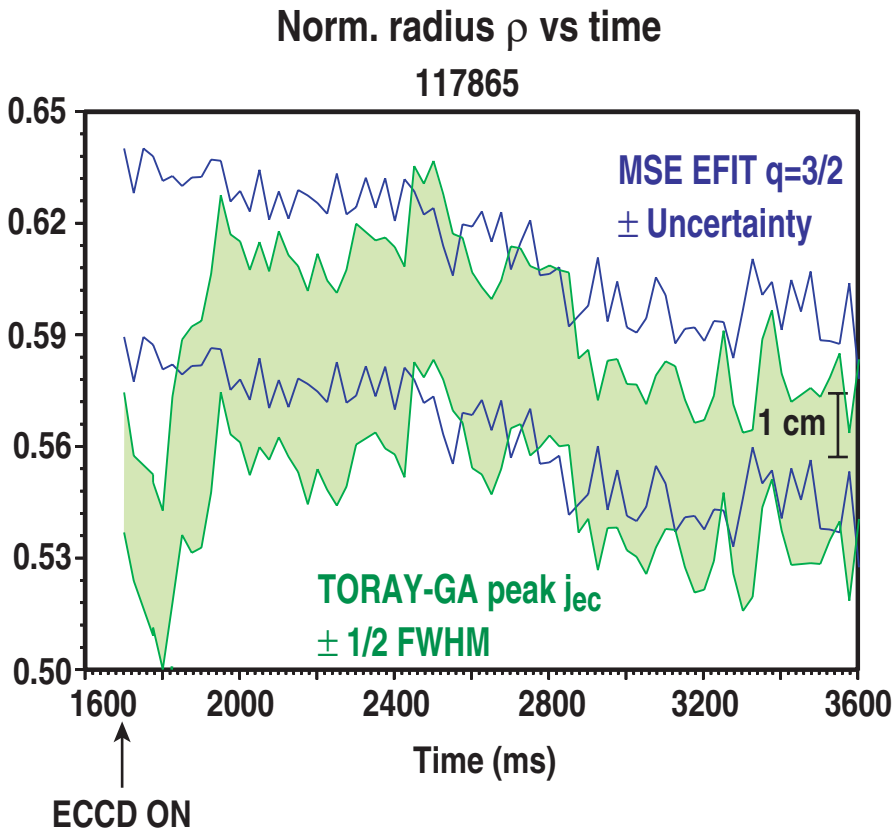
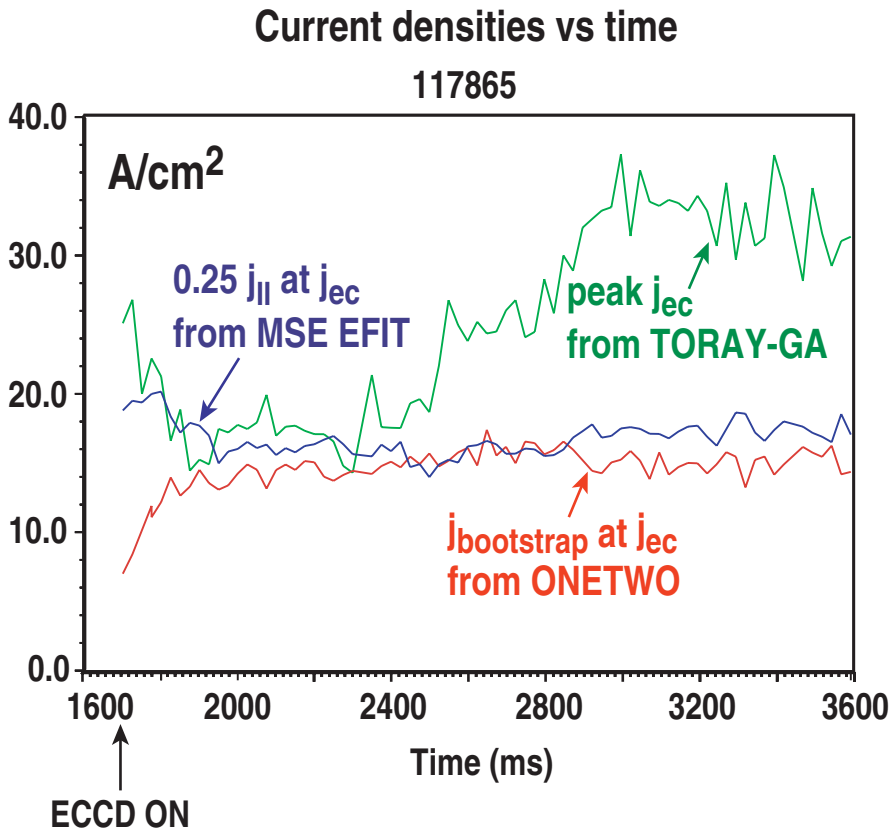
OFF-LINE ANALYSIS OF REAL-TIME EFIT ALIGNMENT ON ECCD

- Alignment is good (within uncertainties)
  - ★ EFIT uncertainty ≈ ±1.7 cm (±5% in q)
- $j_{ec} \gtrsim j_{bootstrap}$ at q = 3/2
  - ★ j_{ec} increases with cryopumping





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FUTURE WORK

- **Implement real-time TORAY-GA (or faster equivalent)**
  - ★ to track location of peak ECCD
    . . . a higher order effect than change in q-location
- **Implement real-time mirror steering**
  - ★ avoids small shape changes currently used
- **Apply early ECCD (6 gyrotrons) to m/n=2/1 NTM avoidance**
  - ★ eventually control both 3/2 and 2/1 NTMs simultaneously
    . . . with up to 6 MW injected

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