

Eluding Neoclassical Tearing Modes in DIII-D by Prior Application of Electron Cyclotron Current Drive

by
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in collaboration with
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***Princeton Plasma Physics Laboratory**

**Presented at
Forty-Sixth Annual Meeting
Division of Plasma Physics
Savannah, Georgia**

November 15–19, 2004



282-04/RJL/jy

IMPROVEMENTS IN NTM CONTROL BY ECCD IN 2004 DIII-D CAMPAIGN

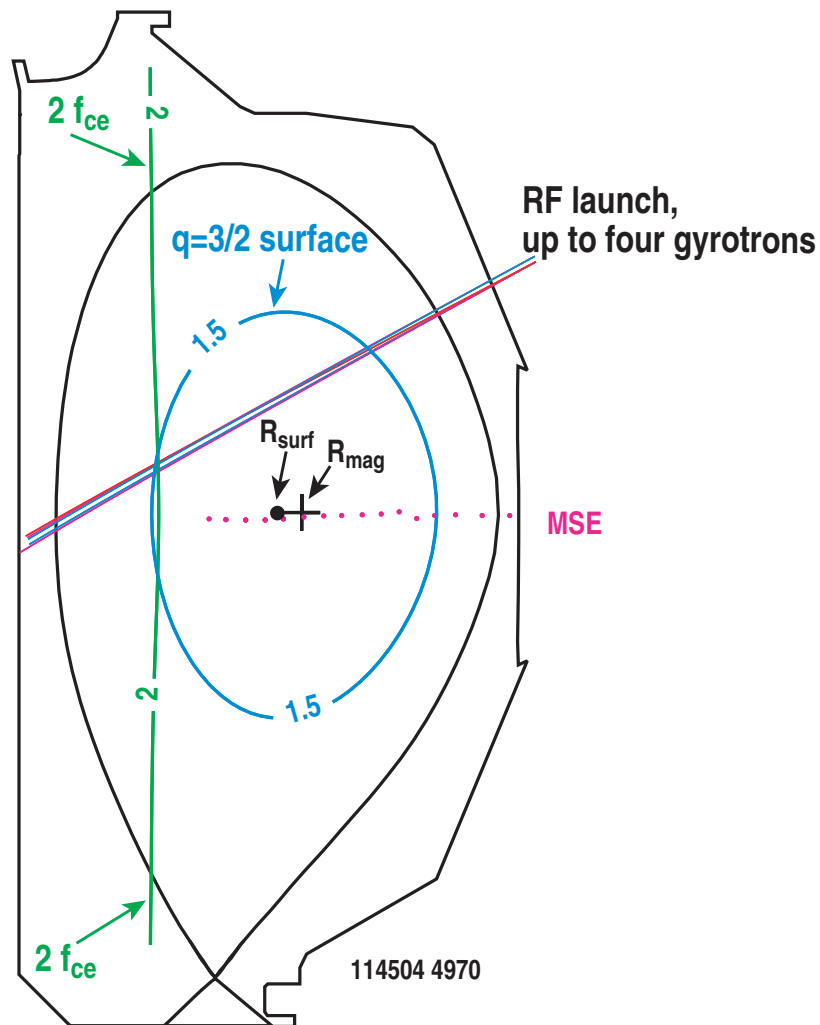
- elude
1. to avoid or escape by speed, cleverness, trickery, etc.
 2. to slip away from

THE RANDOM HOUSE DICTIONARY OF THE ENGLISH LANGUAGE, COLLEGE EDITION

- **Speed**
 - ★ Real-time MSE FITS to locate rational surfaces
... UPDATED EVERY 3 msec
- **Cleverness**
 - ★ Plasma control system (PCS) corrects for changes in location of rational surface with respect to the peak ECCD
- **Trickery (syn.) — Strategem**
 - ★ Apply ECCD early, before $m/n = 3/2$ NTM onset
... Track and adjust alignment
— AVOID THE INSTABILITY EVER OCCURRING

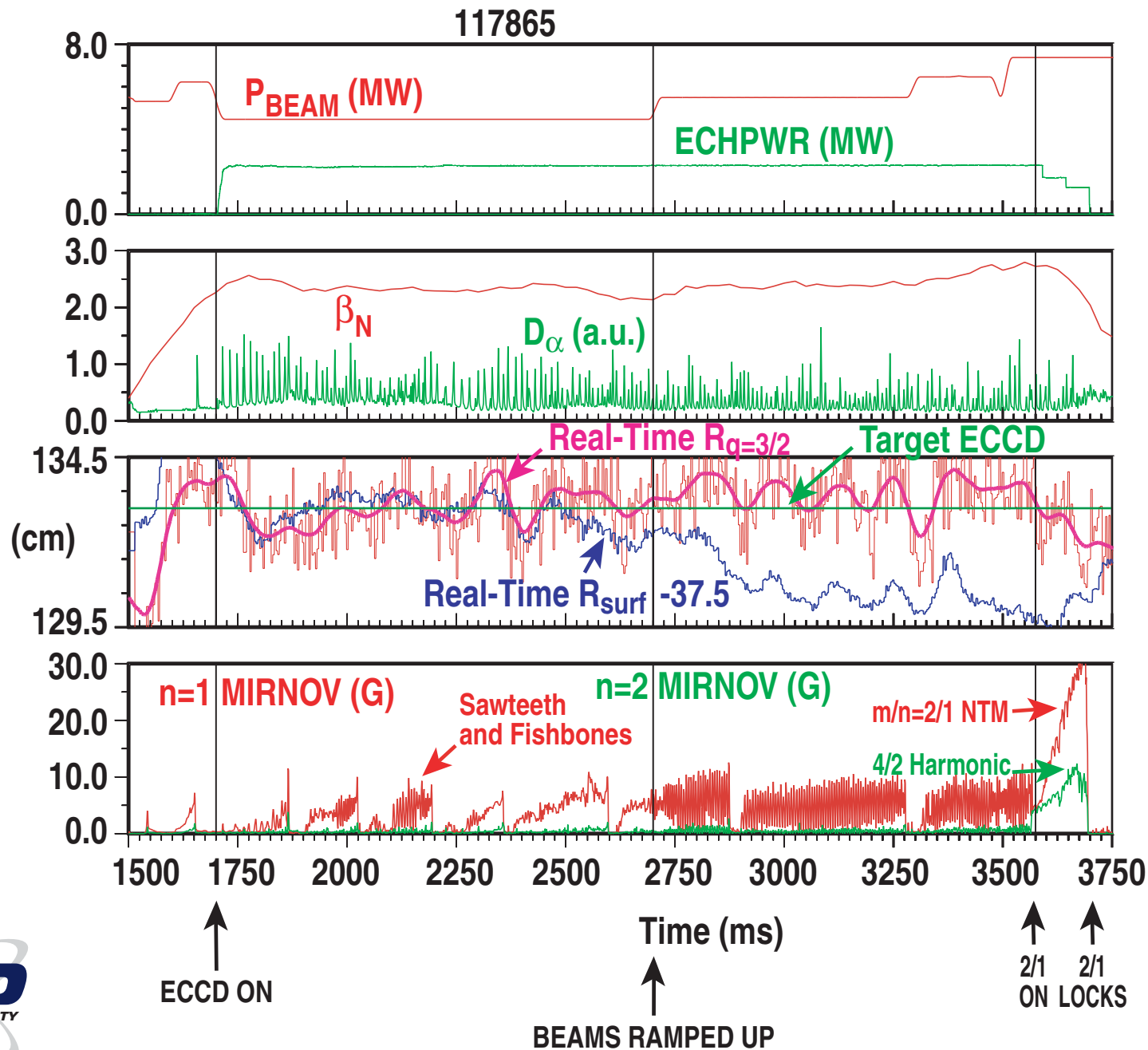
ALIGNMENT OF $q=3/2$ ON ECCD BY SHIFTING MAJOR RADIUS

- RF directed at $2f_{ce}$ inboard
- Moving plasma horizontally (δR_{surf}) moves $q=3/2$



ELMing H-mode
Sawteeth
 $q_{95} = 3.4$
 $\beta_N = 2.1$
 $\rho (q=3/2) = 0.60$

PREEMPTIVE ECCD AND REAL-TIME MSE EFIT TRACKING AVOID $m/n=3/2$ NTM



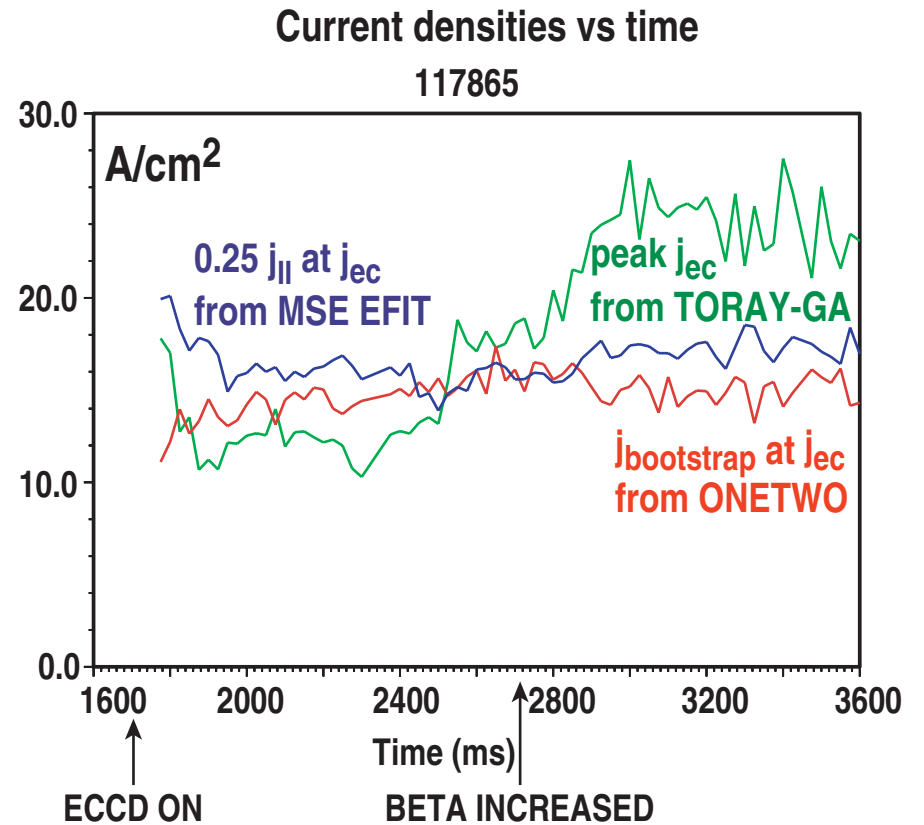
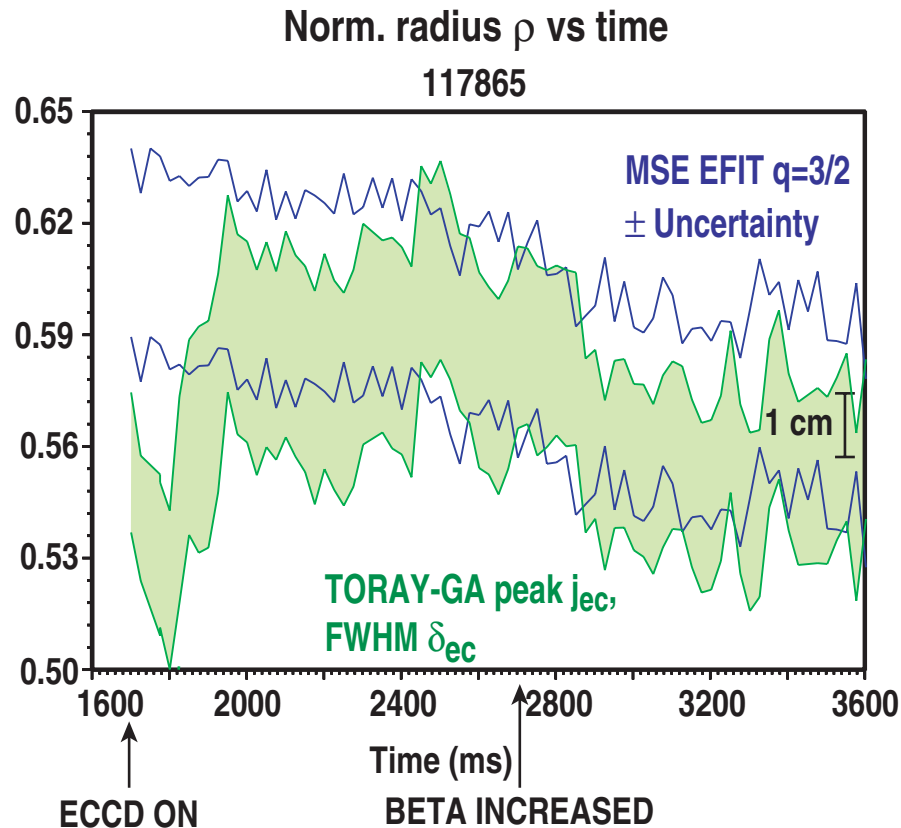
OFF-LINE ANALYSIS OF REAL-TIME EFIT ALIGNMENT ON ECCD

- Alignment is good (within uncertainties)

★ EFIT uncertainty $\approx \pm 1.7$ cm ($\pm 5\%$ in q)

- $j_{ec} \geq j_{bootstrap}$ at $q = 3/2$

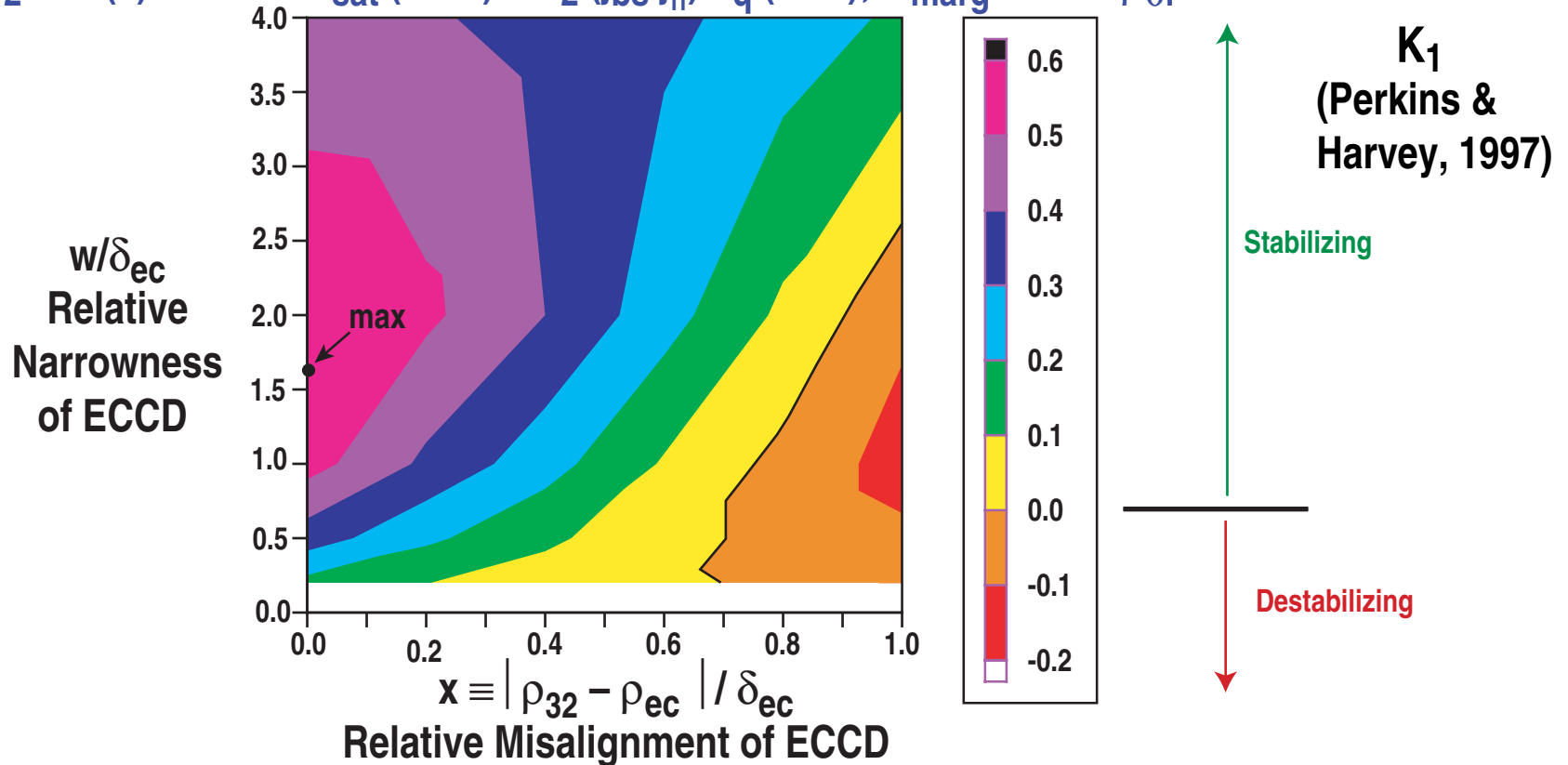
★ j_{ec} increases with cryopumping



I. ECCD CAN STABILIZE AN NTM BY REPLACING “MISSING” BOOTSTRAP CURRENT

$$\frac{\tau_R}{r} \frac{dw}{dt} = \Delta'_0 r + \delta \Delta' r + a_2 \frac{j_{bs}}{j_{||}} \frac{L_q}{w} \left[1 - \frac{w_{marg}^2}{3w^2} - K_1 \frac{j_{ec}}{j_{bs}} \right] \quad \text{Mod. Rutherford Eqn.}$$

- $\Delta'_0 r$ 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) $\approx a_2 (j_{bs}/j_{||}) L_q / (-\Delta' r)$; $w_{marg} \approx 2\epsilon^{1/2} \rho_{\theta i}$



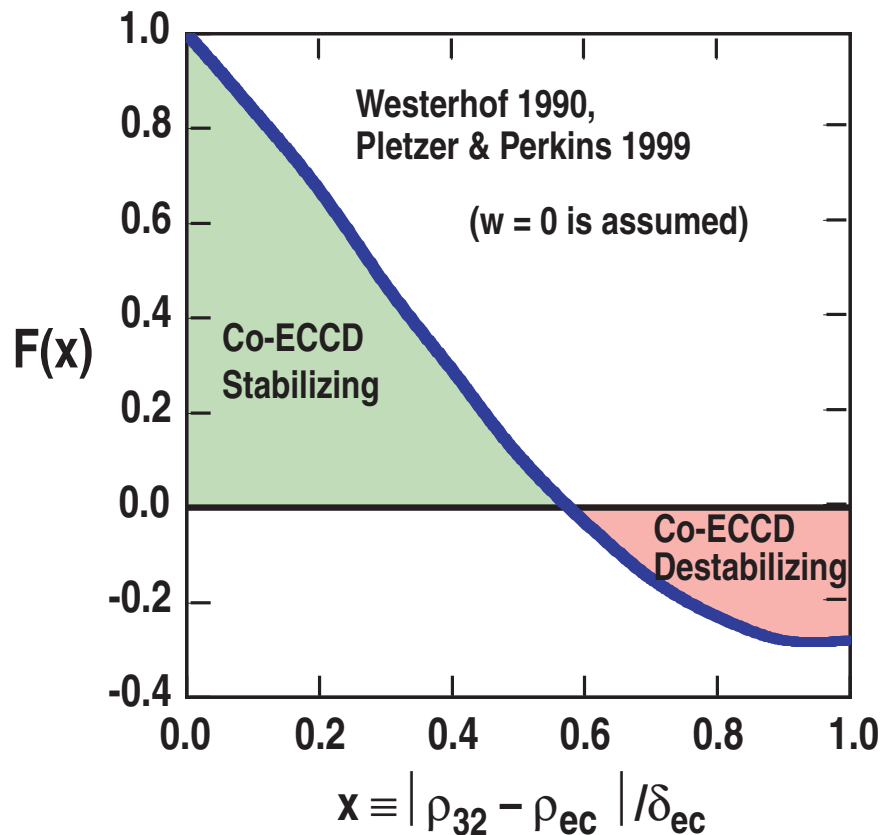
- ECCD “effectiveness” K_1

★ Requires good alignment ($w_{marg}/\delta_{ec} = 0.6$, $x \leq 0.3$ for $K_1(x)/K_1(0) \gtrsim 0.5$, $\Delta R \lesssim 1.1$ cm)

II. ECCD CAN STABILIZE AN NTM BY MAKING Δ' MORE NEGATIVE

$$\frac{\tau_R}{r} \frac{dw}{dt} = \Delta'_0 r + \delta\Delta' r + a_2 \frac{j_{bs}}{j_{||}} \frac{L_q}{w} \left[1 - \frac{w_{marg}^2}{3w^2} - K_1 \frac{j_{ec}}{j_{bs}} \right] \quad \text{Mod. Rutherford Eqn.}$$

- $\Delta'_0 r$ by PESTIII, j_{bs} from ONETWO, $j_{||}$ and L_q from EFIT, j_{ec} from TORAY-GA
- $a_2 = \mathfrak{D}(1)$ fitted to w_{sat} (no rf) $\approx a_2 (j_{bs}/j_{||}) L_q / (-\Delta' r)$; $w_{marg} \approx 2\varepsilon^{1/2} \rho_{\theta i}$

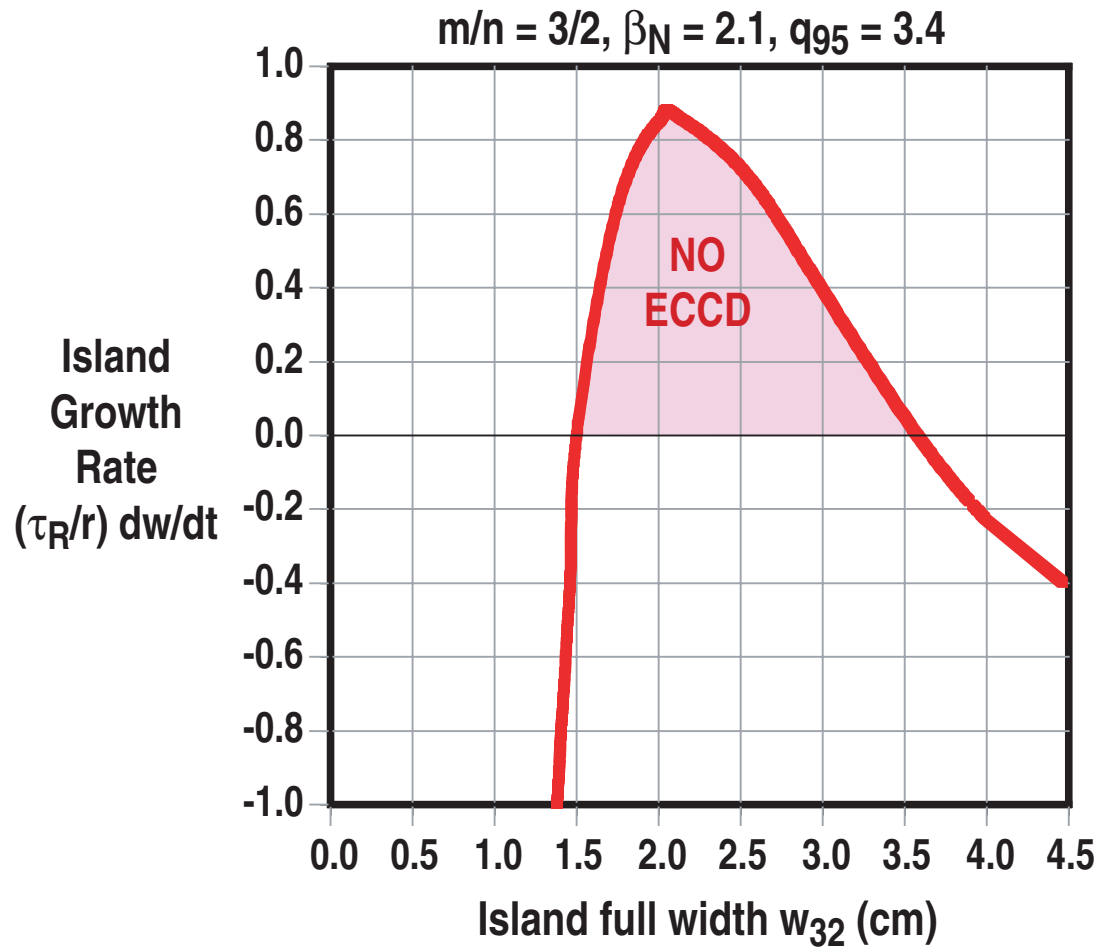


- CO-ECCD can make Δ'
 - ★ more negative

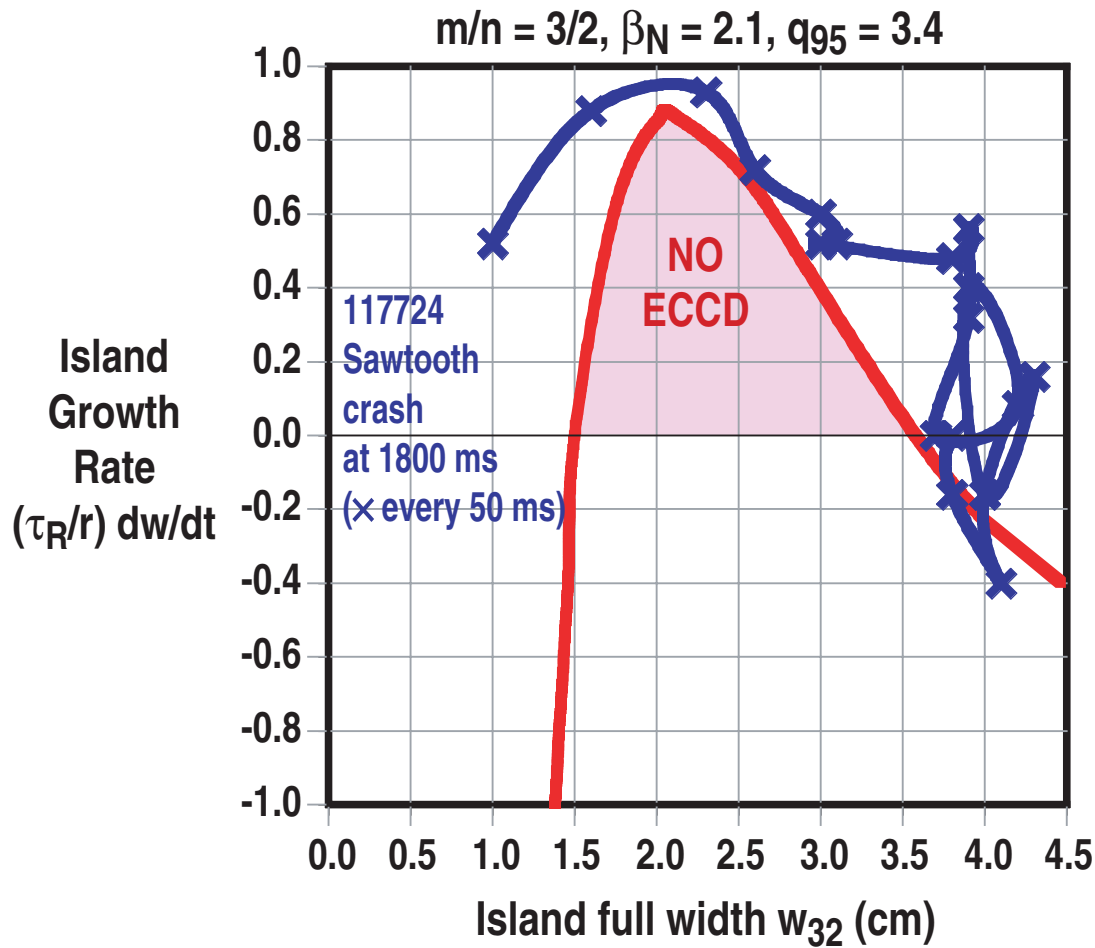
$$\dots \delta\Delta' r \approx \frac{-5\pi^{3/2}}{32} a_2 \frac{L_q}{\delta_{ec}} F(x) \frac{j_{ec}}{j_{||}}$$
 - ★ requires good alignment

$$\dots F(0.25) = 0.5, \Delta R \approx 0.9 \text{ cm}$$

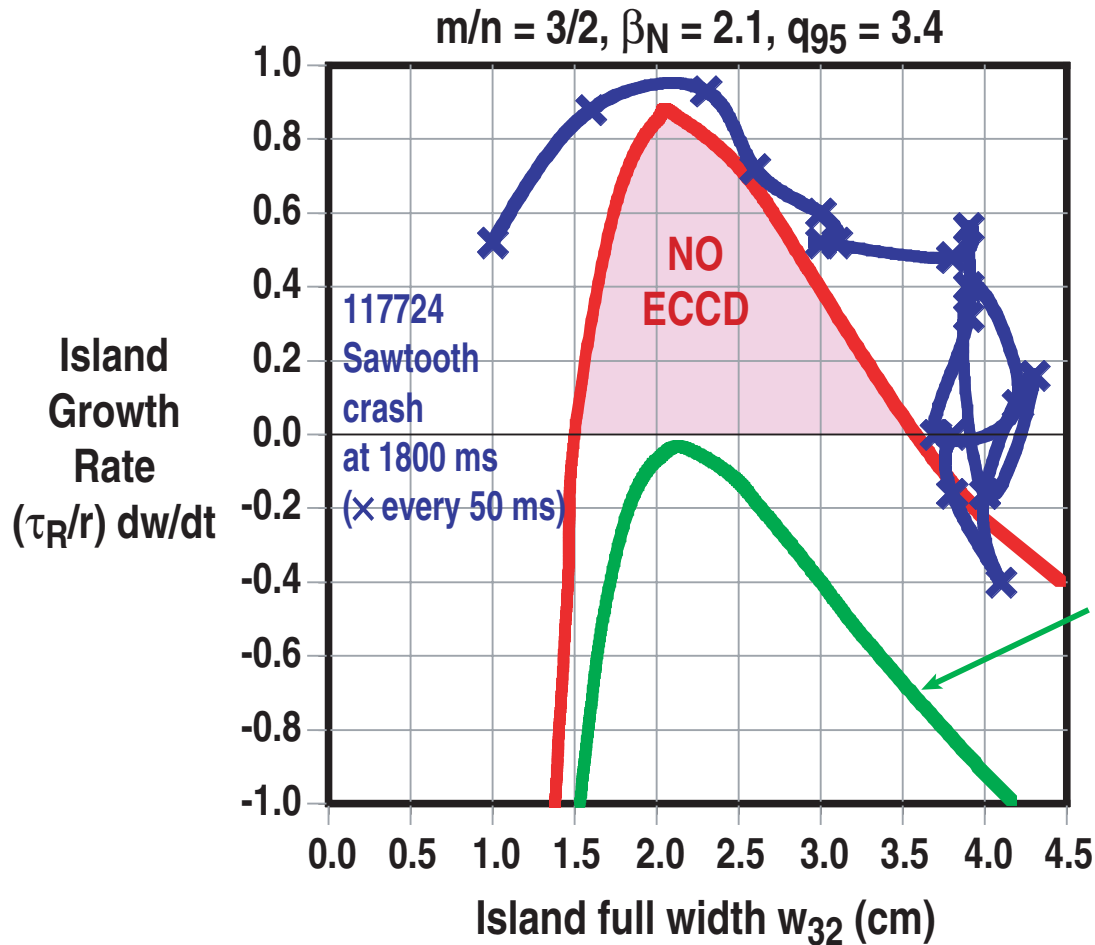
III. NTM STABILITY CAN BE ASSURED BY ELIMINATING THE METASTABLE REGION



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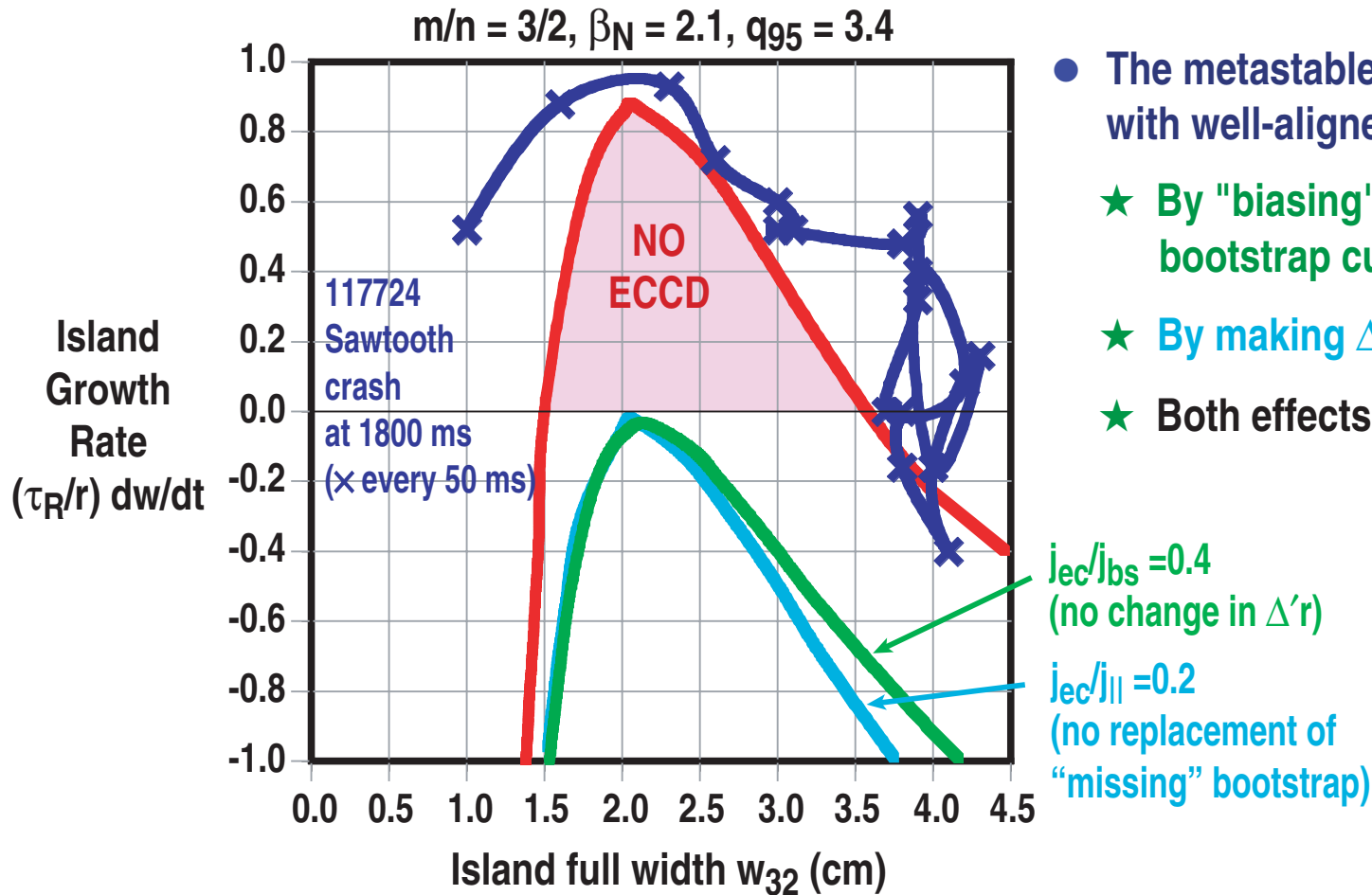
III. NTM STABILITY CAN BE ASSURED BY ELIMINATING THE METASTABLE REGION



- The metastable region can be eliminated with well-aligned co-ECCD

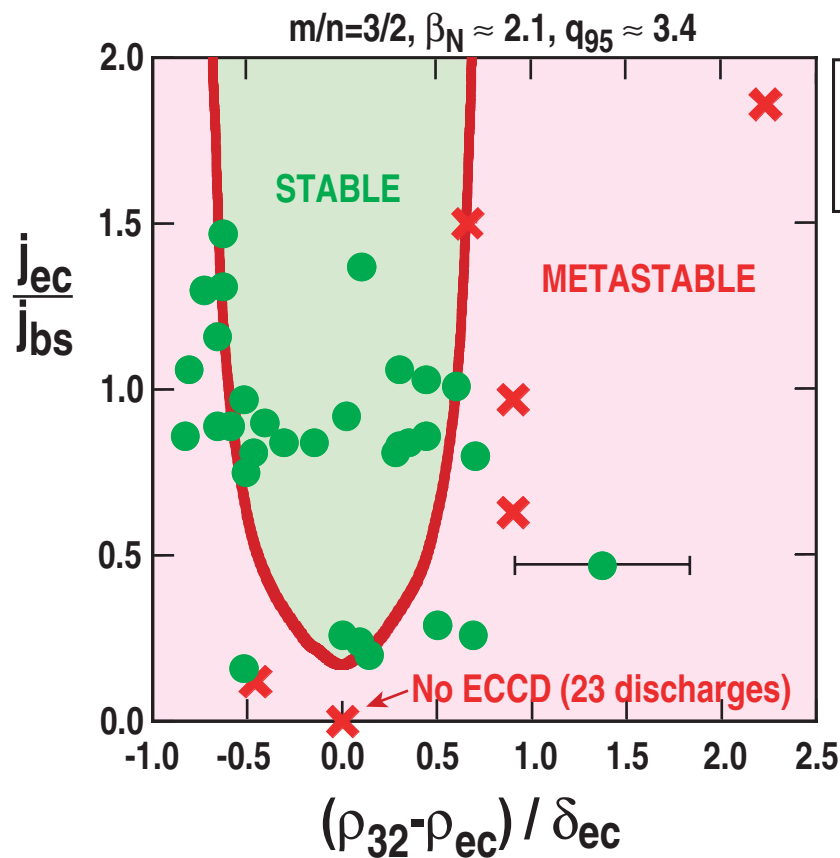
- ★ By "biasing" to replace the "missing" bootstrap current

III. NTM STABILITY CAN BE ASSURED BY ELIMINATING THE METASTABLE REGION



- The metastable region can be eliminated with well-aligned co-ECCD
- ★ By "biasing" to replace the "missing" bootstrap current
- ★ By making $\Delta'r$ more negative
- ★ Both effects occur together

THE MODIFIED RUTHERFORD EQUATION SUCCESSFULLY PREDICTS THE PARAMETER SPACE IN WHICH THE PLASMA IS **NOT** METASTABLE



- All early ECCD discharges evaluated at every potentially destabilizing (“seeding”) sawtooth crash
- For $\dot{w} \equiv 0$ at least stable w_{marg}

$$\left. \frac{j_{ec}}{j_{bs}} \right|_{\min} = \frac{\Delta'_0 r + \frac{2}{3} a_2 \frac{L_q}{w_{marg}} \frac{j_{bs}}{j_{||}}}{a_2 \frac{L_q}{w_{marg}} \frac{j_{bs}}{j_{||}} K_1 + \frac{5\pi^{3/2}}{32} a_2 \frac{L_q}{\delta_{ec}} \frac{j_{bs}}{j_{||}} F}$$

- ECCD must be aligned to $|\Delta\rho|/\delta_{ec} < 1$
 - Minimum $j_{ec}/j_{bootstrap}$ of ≈ 0.2 includes $\delta\Delta'r \approx -0.6$ to $\Delta'r \approx -3.6$

CONCLUSIONS

- Operation at high beta is possible without ever having an $m/n = 3/2$ NTM despite sawteeth
 - ★ with preemptive ECCD and real-time MSE EFIT tracking

FUTURE WORK

- Implement real-time TORAY-GA
 - ★ To track any changes in location of peak ECCD
 - ... A higher order effect than change in q-location
- Apply early ECCD to $m/n=2/1$ NTM control

"Is there any point to which you would wish to draw my attention," asked Watson.

"To the curious incident of the dog in the night-time," said Holmes.

"The dog did nothing in the night-time," exclaimed Watson.

"That was the curious incident," remarked Holmes.

Silver Blaze, *Memoirs of Sherlock Holmes,* Sir Arthur Conan Doyle