Increased Stable Beta in DIII–D by Suppression of a Neoclassical Tearing Mode Using Electron Cyclotron Current Drive and Active Feedback

by
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GENERAL ATOMICS

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STABILIZING NEOCLASSICAL TEARING MODES CAN ALLOW HIGHER BETA IN TOKAMAKS

- **Tearing modes have two significant effects on tokamaks:**
  - Saturated islands reduce the energy confinement and thus the achievable β
    - ★ m/n = 3/2 and/or 2/1 each reduce confinement up to 25%
  - Modes which lock to the wall tend to grow until a major disruption occurs
    - ★ m=2,n=1 modes are the most dangerous in this respect

- **Suppressing the tearing modes by means of electron cyclotron current drive (ECCD) could:**
  - Expand the allowable operating space to higher β (higher fusion power)
  - Enhance reliability of the tokamak

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NTMS CAN BE STABILIZED BY ELECTRON CYCLOTRON CURRENT DRIVE

- **Destabilized by helically perturbed bootstrap current**
  - ★ Seed island $\rightarrow \delta\nabla p \rightarrow \delta j_{bs} \approx \varepsilon^{1/2}\, \delta\nabla p/B_\theta \propto \beta_p/w \rightarrow$ reinforces the island
- **Stabilized by replacing "missing" bootstrap current in O-point of island**
  - ★ Off-axis radially localized co-electron cyclotron current drive (ECCD)
- **Control is to position peak j_{eccd} on island**
  - ★ Developed real-time position control by Plasma Control System (PCS)
    - — "Search and Suppress" in presence of a mode demonstrated
    - — Tracking change of location of q in absence of a mode ready for 2003
- **Complete suppression of both 3/2 and 2/1 NTMs demonstrated**
  - ★ Beta raised 60% (20% above initial 3/2 NTM level)
    - — After 3/2 NTM suppression

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

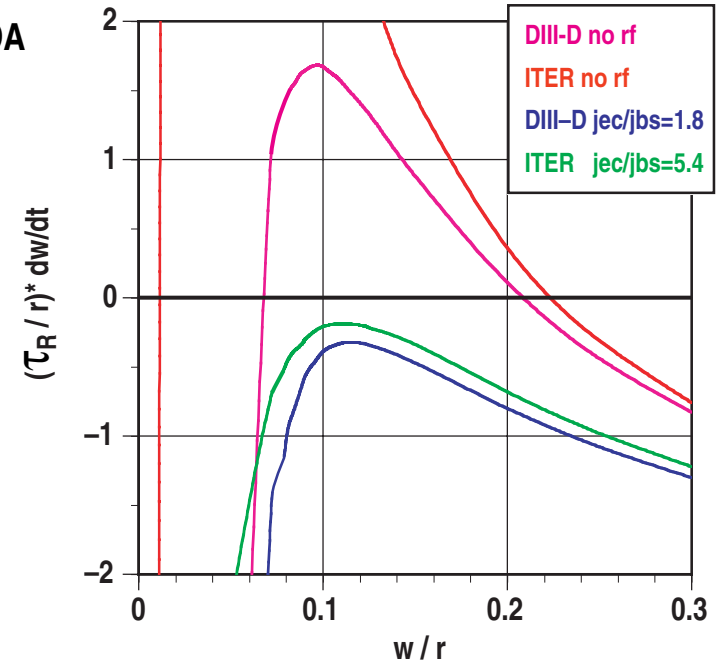
$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta' r + \varepsilon^{1/2}\left(\frac{L_q}{L_p}\right)\beta_\theta\left[\frac{rw}{w^2+w_d^2} - \frac{rw_{pol}^2}{w^3} - \frac{8qr\delta_{ec}}{\pi^2 w^2}\left(\frac{\eta\, j_{ec}}{j_{bs}}\right)\right],$$

(rf over j_{ec})

positioning ⇓ η width ⇓

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

DIII–D	ITER–EDA
m/n = 3/2	same
$\beta_\theta = 0.9$ ($\beta_N = 2.4$)	same
$\Delta' r = -3$	same
$\varepsilon^{1/2} = 0.5$	same
$L_q/L_p = 1.5$	same
$w_{pol}/r = 0.050$	0.007
$w_d/r = 0.025$	0.013
$\delta_{ec}/r = 3/36$	4/169
$\eta_0 = 0.4$ (no mod)	same
$\Delta R/\delta_{ec} = 0$	same



- NTM amenable to complete suppression because of thresholds ($w_{pol}/r \propto \rho_{i*}$ and $w_d/r \propto \rho_{i*}^{1/3}$)
- ITER–EDA vs. DIII–D experimental benchmark
  - $j_{ec}/j_{bs} \times 3$ with $\delta_{ec}/r \times 0.3$ . . . $I_{ec}/I_p \times 0.9$
  - ΔR = 2 cm doubles ECCD needed

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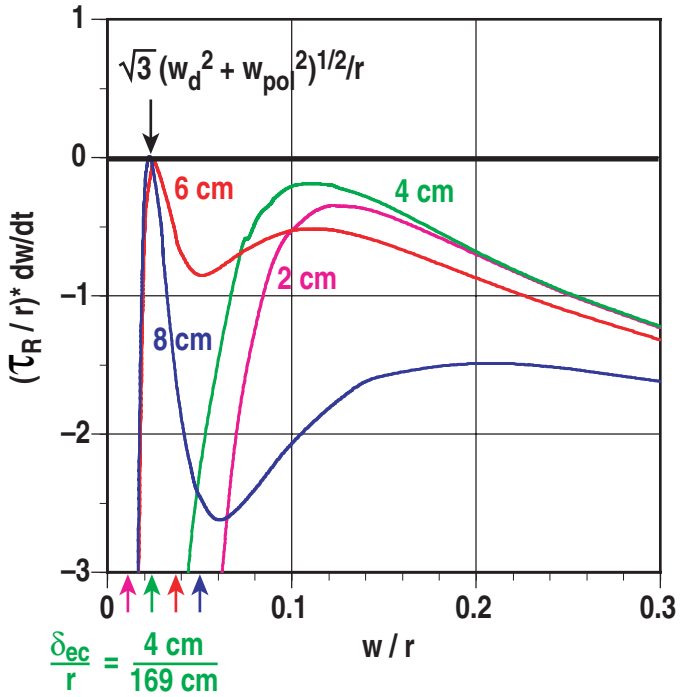
WIDTH OF ECCD FOR ITER IS "OPTIMUM" IF MATCHED TO EFFECTIVE NTM THRESHOLD WIDTH

- No rf critical β_θ is a minimum for
  - ★ $w_{min} \approx \sqrt{3}\,(w_d^2 + w_{pol}^2)^{1/2}$
- Required j_{ec}/j_{bs} and I_{ec}/I_p are minimized for
  - ★ $\delta_{ec} \equiv \delta_{FWHM} \approx w_{min}$
    . . . too narrow, j_{ec}/j_{bs} is big
    . . . too wide, I_{ec}/I_p is big



2 cm, jec/jbs=10.8, Iec/Ip=1.7%

4 cm, jec/jbs= 5.4, Iec/Ip=1.7%

6 cm, jec/jbs= 4.4, Iec/Ip=2.1%

8 cm, jec/jbs= 5.3, Iec/Ip=3.7%

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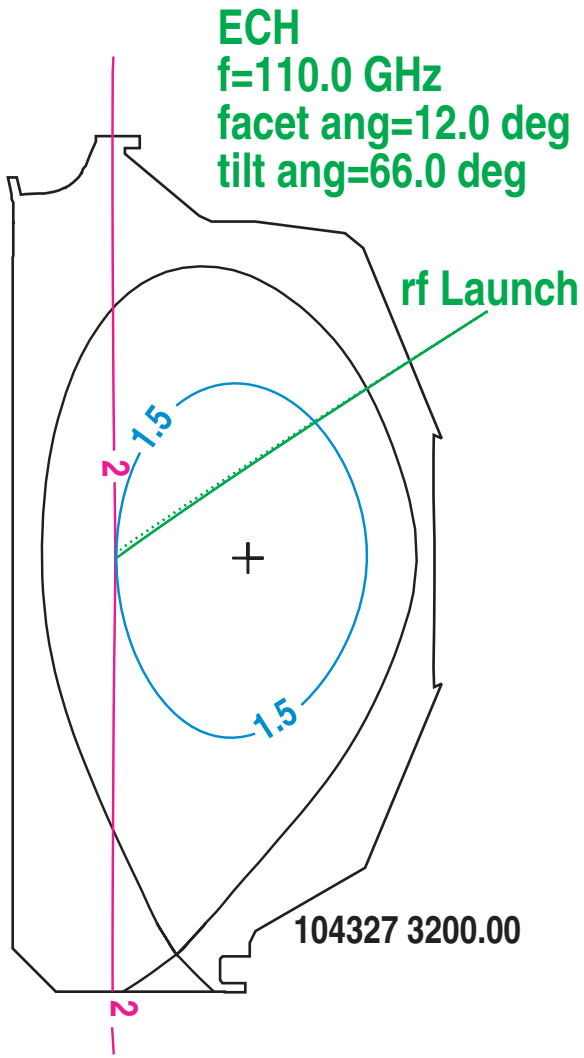
DIII–D USES OFF-AXIS CO-ECCD TO SUPPRESS m/n=3/2 NTM



(ELMy H–mode with sawteeth)

Resources:

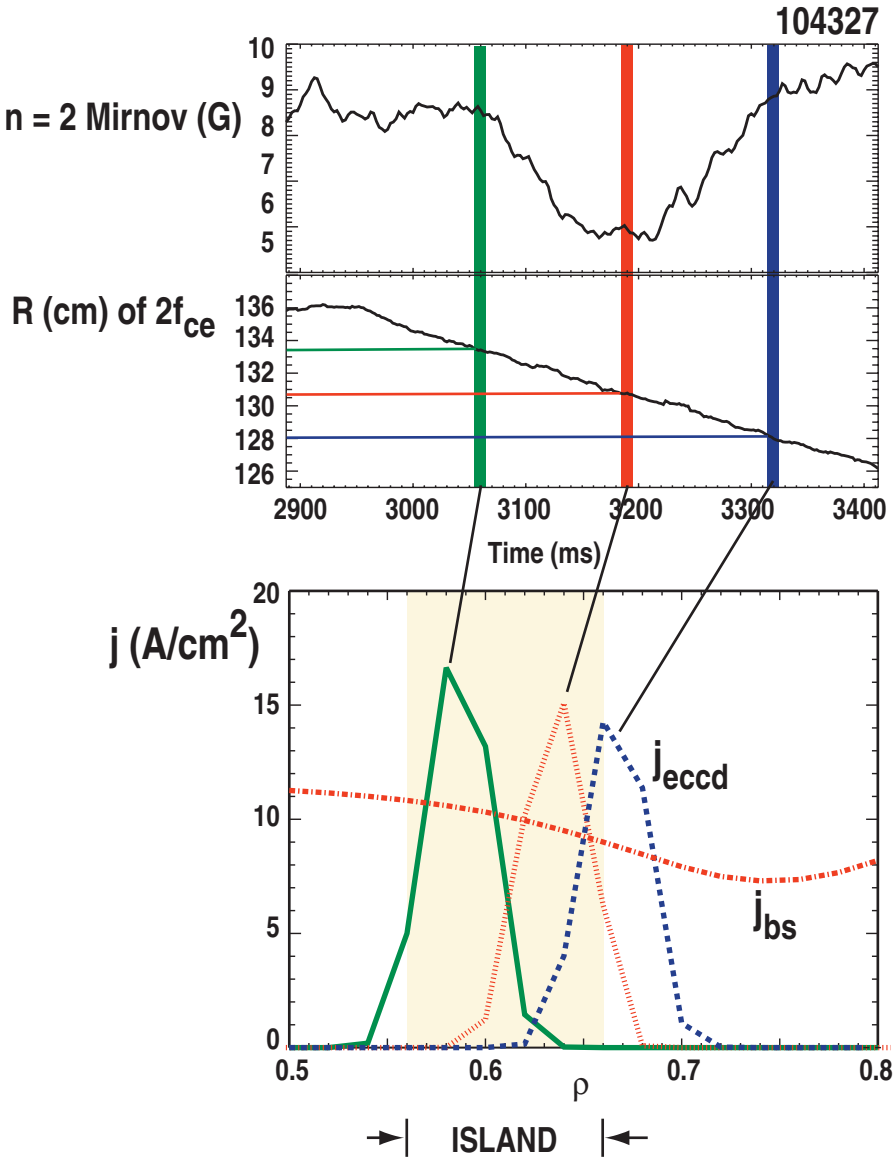
(1) inboard midplane resonance and lower cryopump to improve current drive

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

(3) PPPL & GA co–ECCD steerable launchers (toroidal and poloidal)

Also see C.C. Petty EX/W–4

APPROXIMATE LOCATION OF THE ECCD IS FOUND BY B_T SWEEP



- 3/2 NTM allowed to saturate
  - ★ rf power applied
- Toroidal field ramped down to scan ECCD past the island
- Alignment within ± 1 cm is required
  - ★ No effect for $\Delta R \approx \pm 2.5$ cm
- $j_{eccd} > j_{bs}$ is satisfied (TORAY-GA)
  - ★ 2 gyrotrons for ≈ 1 MW injected

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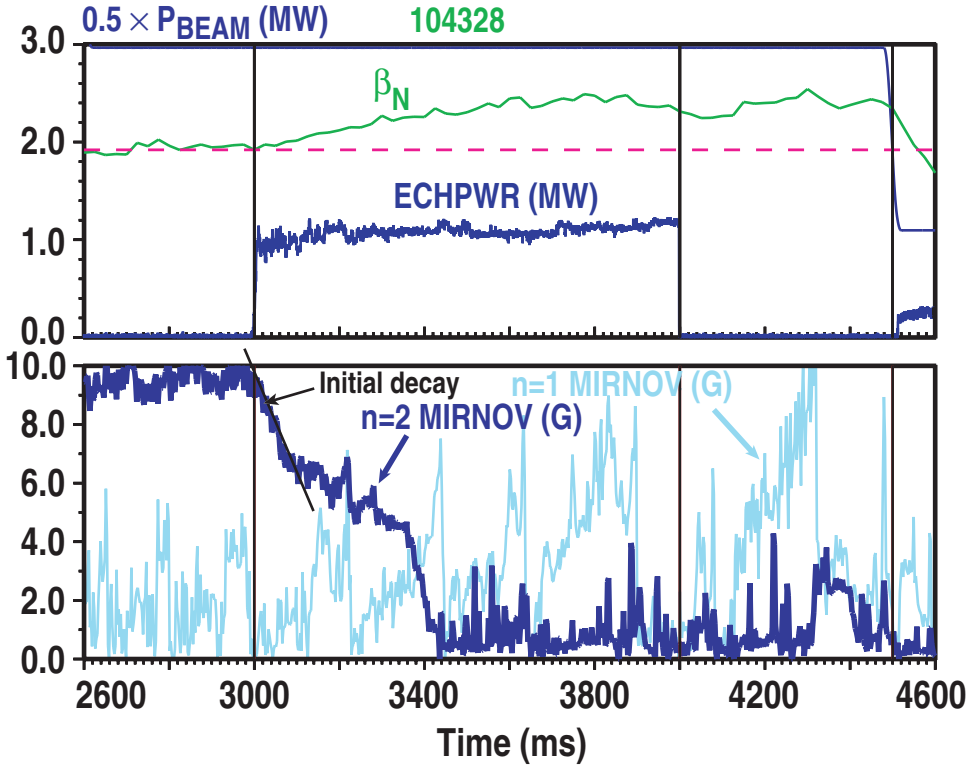
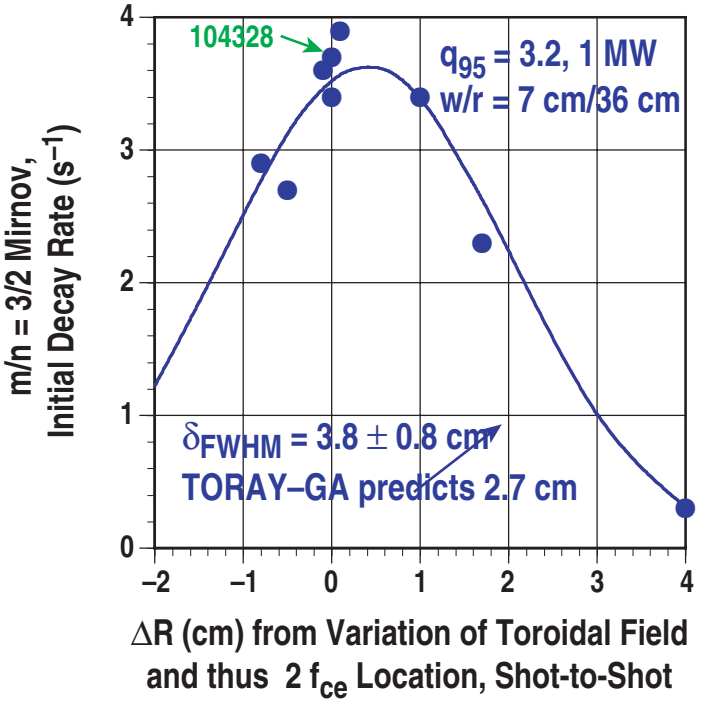
DEMONSTRATED COMPLETE SUPPRESSION OF THE m/n = 3/2 TEARING MODE BY RADIALLY LOCALIZED ECCD

- B_T constant
  - ★ At value of dip in B_T sweep
- Confinement increases by 25%
- Initial decay rate vs. ΔR
  - ★ Used to design PCS active control
    - — "Search and Suppress"





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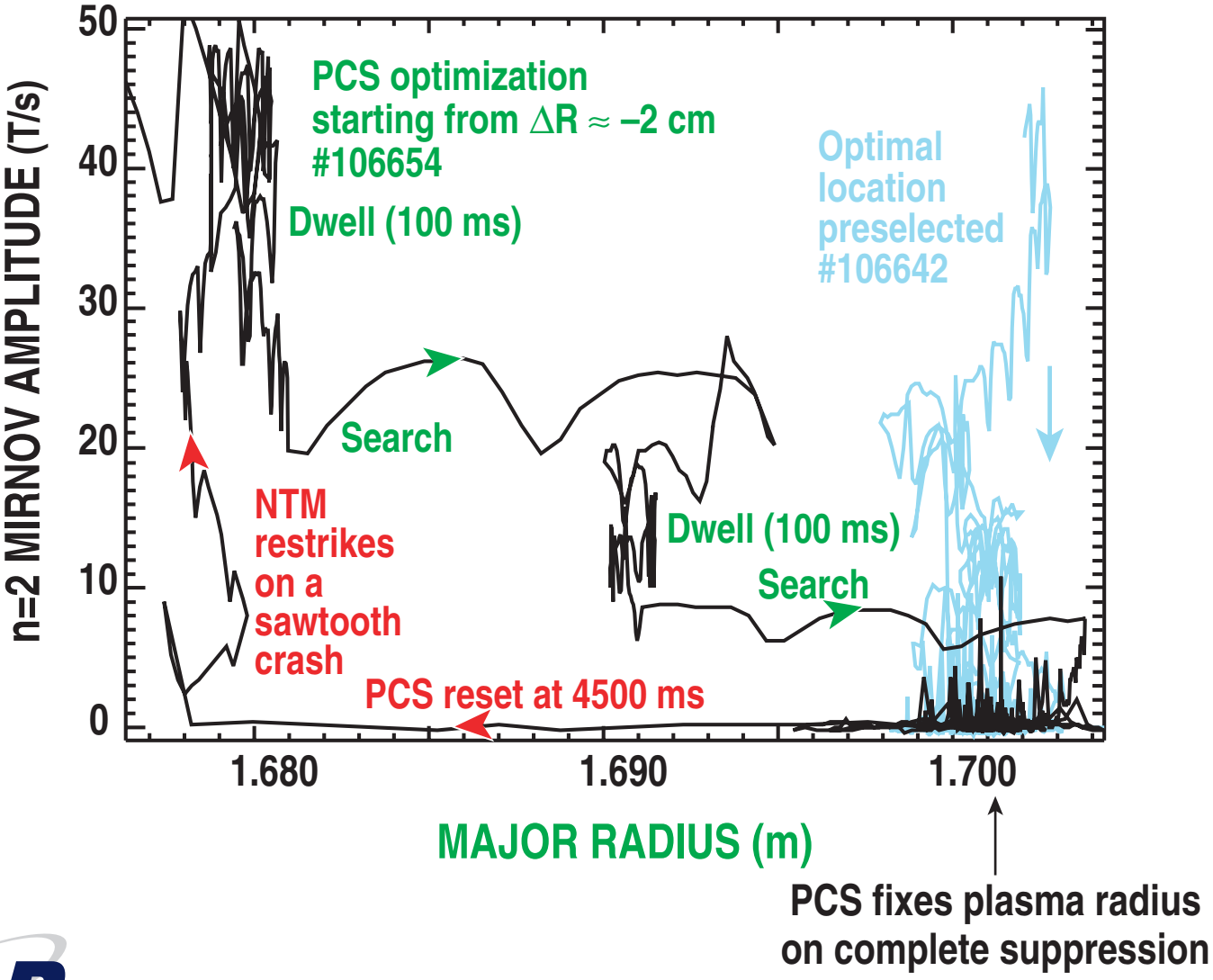
PLASMA CONTROL SYSTEM "SEARCH AND SUPPRESS" IS REAL-TIME CONTROL OF MAJOR RADIUS FOR ECCD SUPPRESSION (m/n = 3/2 NTM, 3 GYROTRONS, 1.5 MW, 3000 TO 4800 ms)



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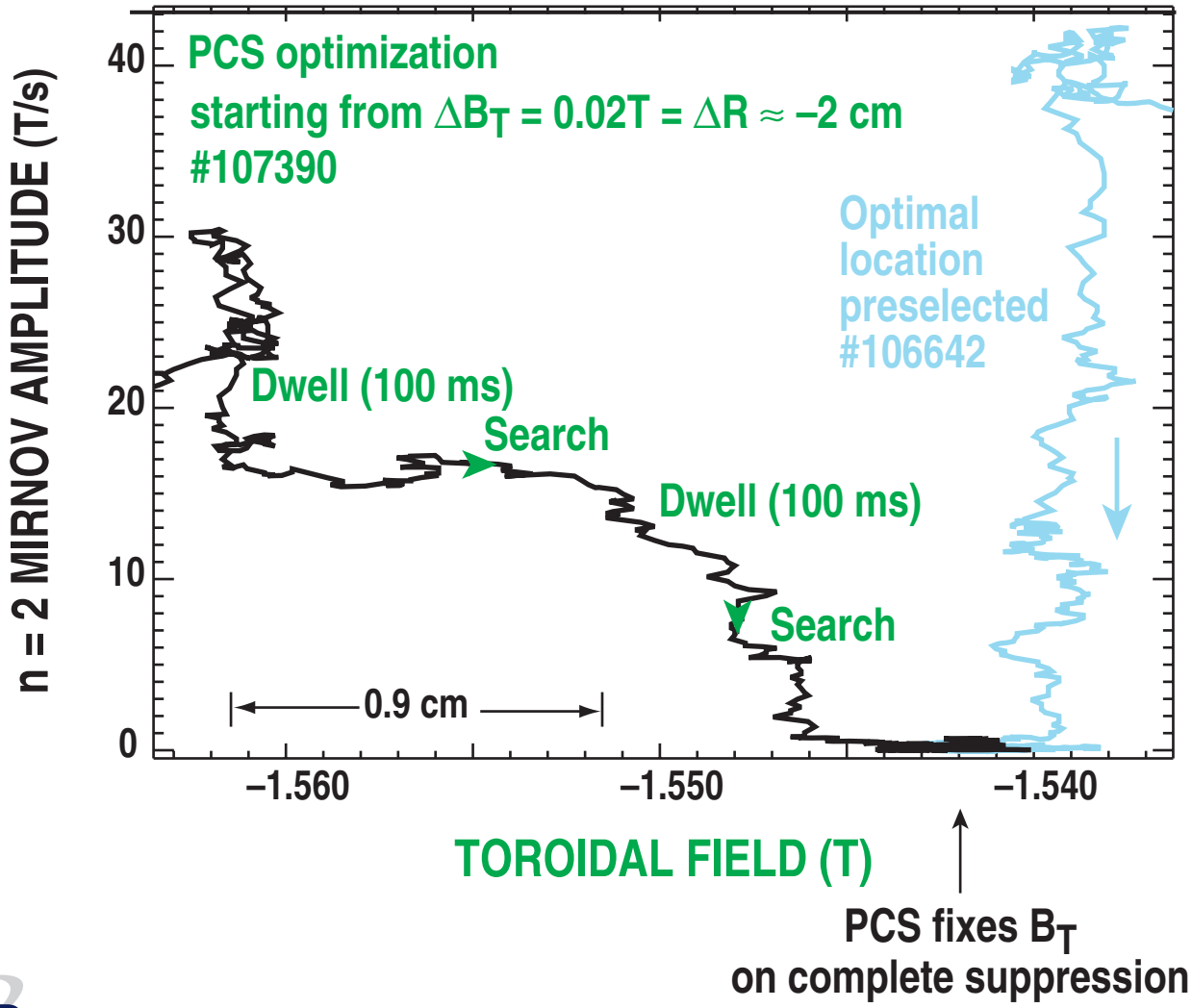
PLASMA CONTROL SYSTEM "SEARCH AND SUPPRESS" ALTERNATIVELY CONTROLS TOROIDAL FIELD FOR ECCD SUPPRESSION (m/n = 3/2 NTM, 3 GYROTRONS, 1.5 MW, 3000 TO 4000 ms)



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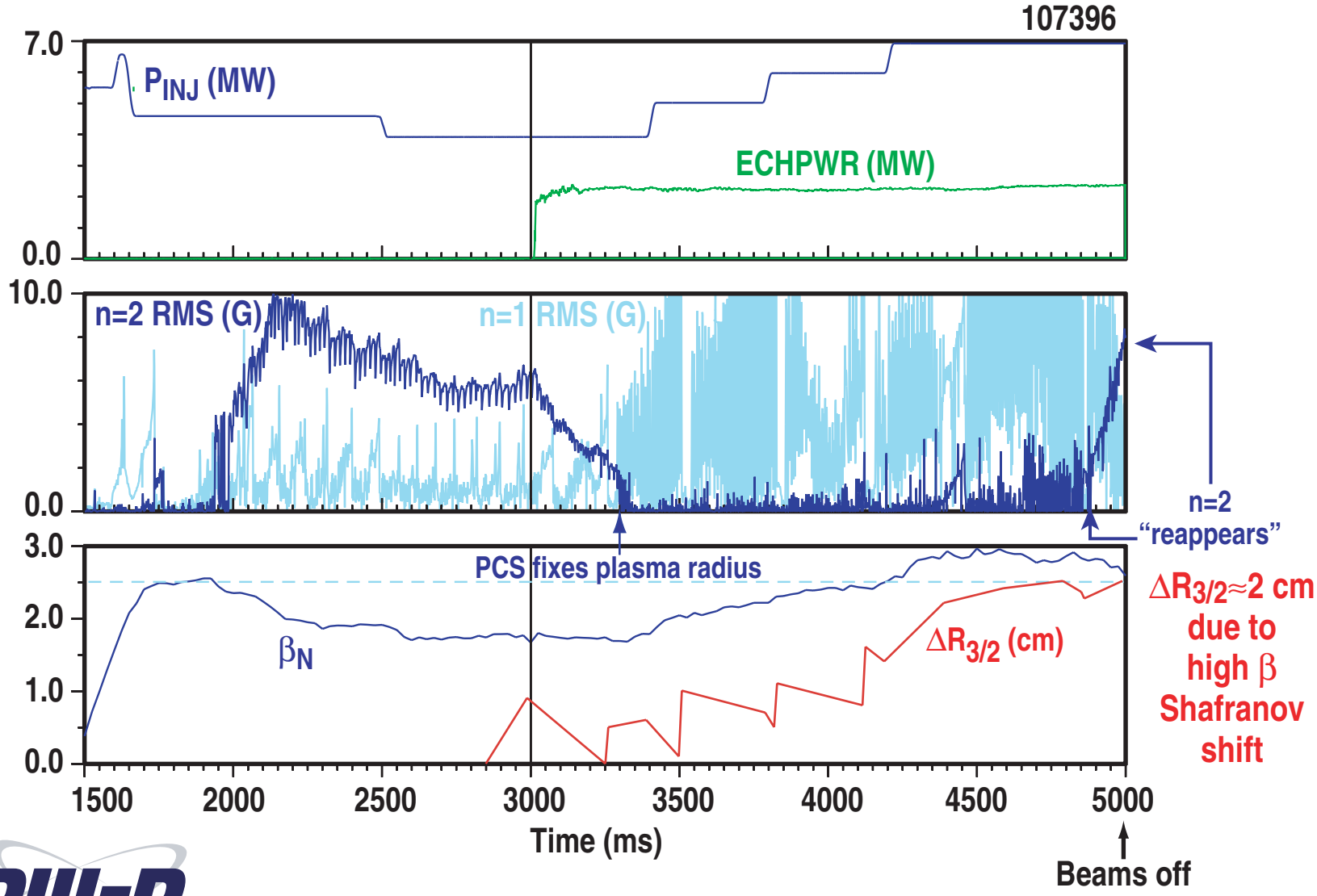
BETA CAN BE RAISED AFTER ECCD SUPPRESSION OF m/n = 3/2 NTM

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



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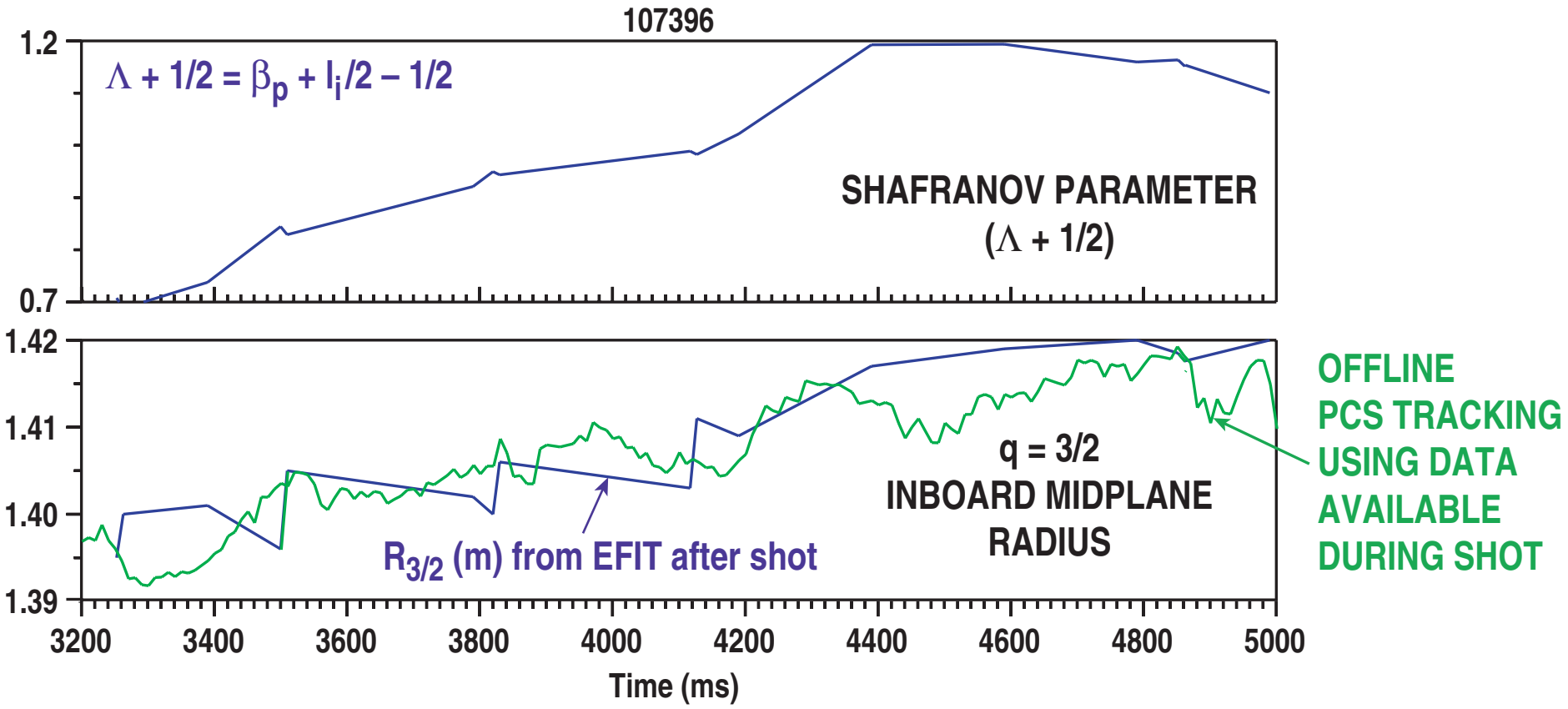
DIII–D PCS CAN TRACK AND COMPENSATE FOR VARIATION OF q-SURFACE LOCATION WITH β_p, ℓ_i

- ECCD-island alignment detuned as q=m/n surface moves with Shafranov shift
- PCS algorithm can now track/compensate for shift of selected q-surface:
  - ★ Ready for 2003 DIII–D campaign



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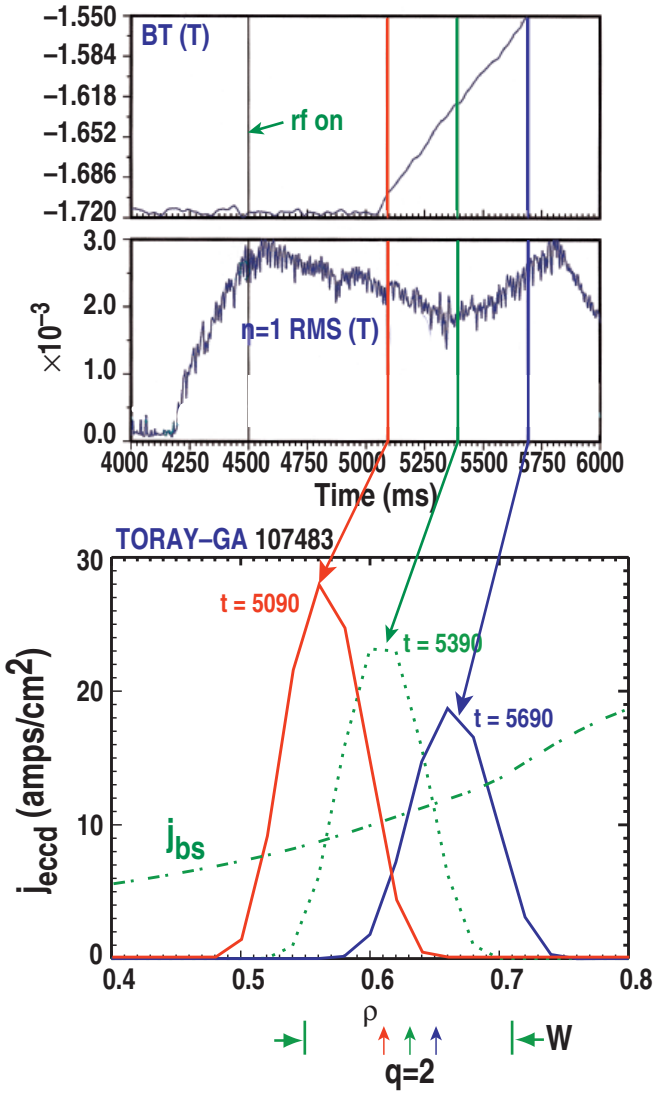
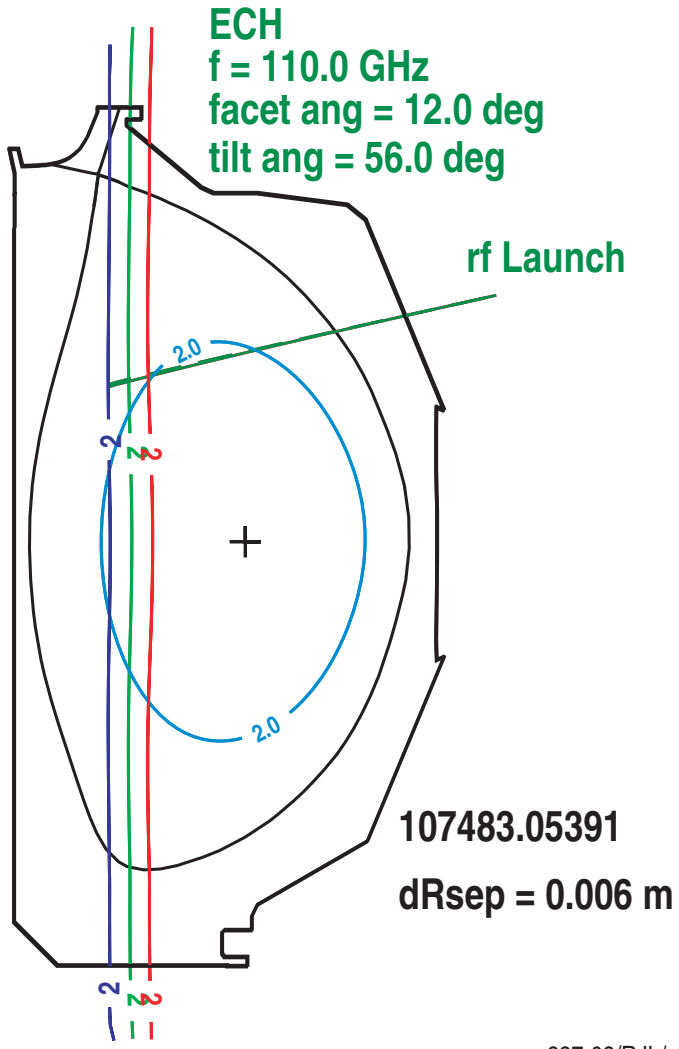
SUPPRESSION TOOLS DEVELOPED ALSO APPLY TO m/n=2/1 NTM



- Sweeping B_T moves j_{eccd} past q=2 island
  - ★ $j_{eccd} > j_{bs}$ is satisfied (TORAY-GA)
  - — 4 gyrotrons for ≈ 2 MW injected



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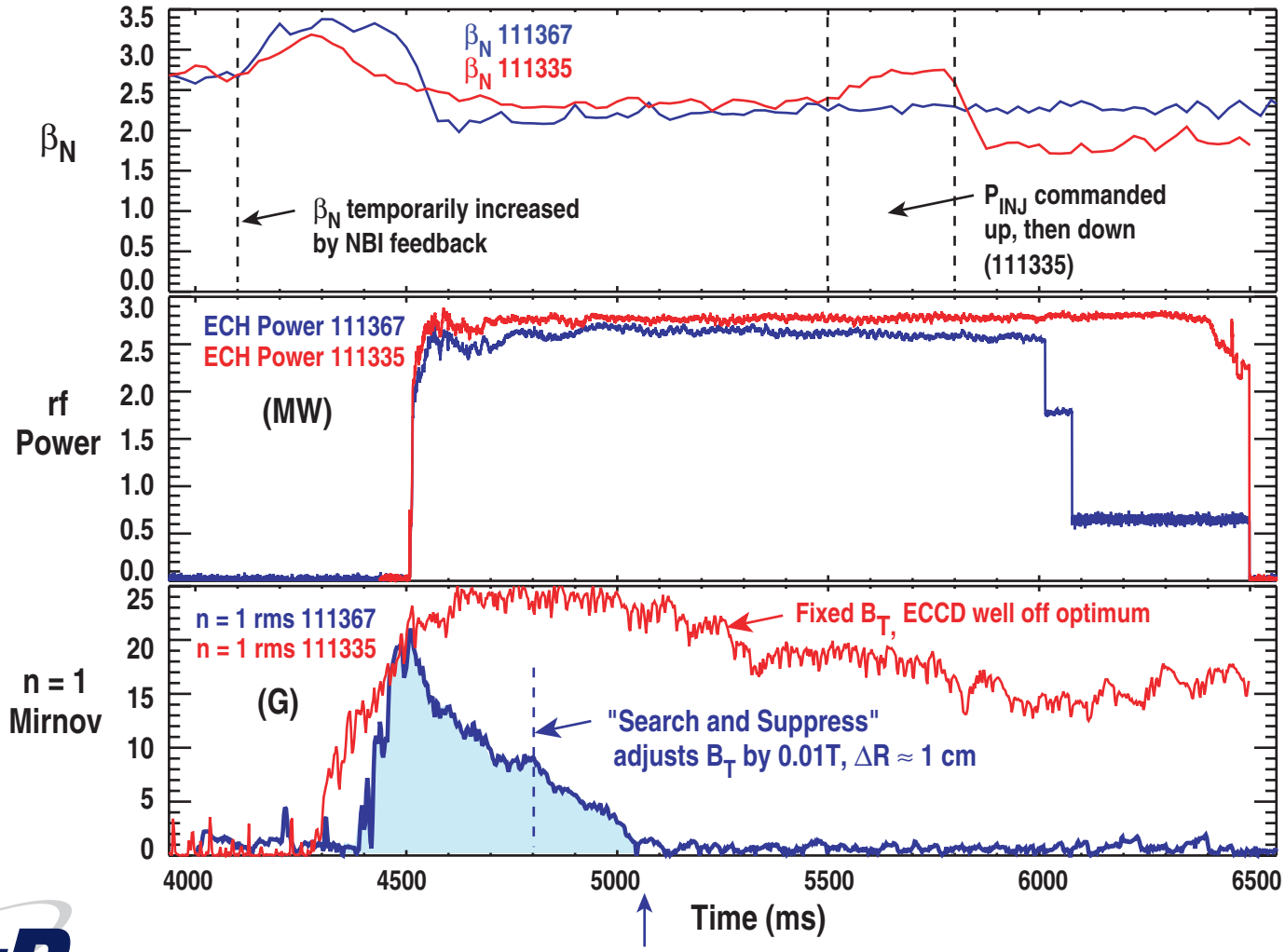
DEMONSTRATED COMPLETE SUPPRESSION OF THE m/n = 2/1 TEARING MODE BY RADIALLY LOCALIZED ECCD

- β_N is feedback controlled to temporarily rise to excite the mode
- Location of ECCD optimized (#111367) by toroidal field PCS "Search and Suppress"
  - ★ #111335 has fixed B_T with EC resonance detuned well off optimum ($\Delta R \approx 10$ cm)



m/n = 2/1 MODE ELIMINATED

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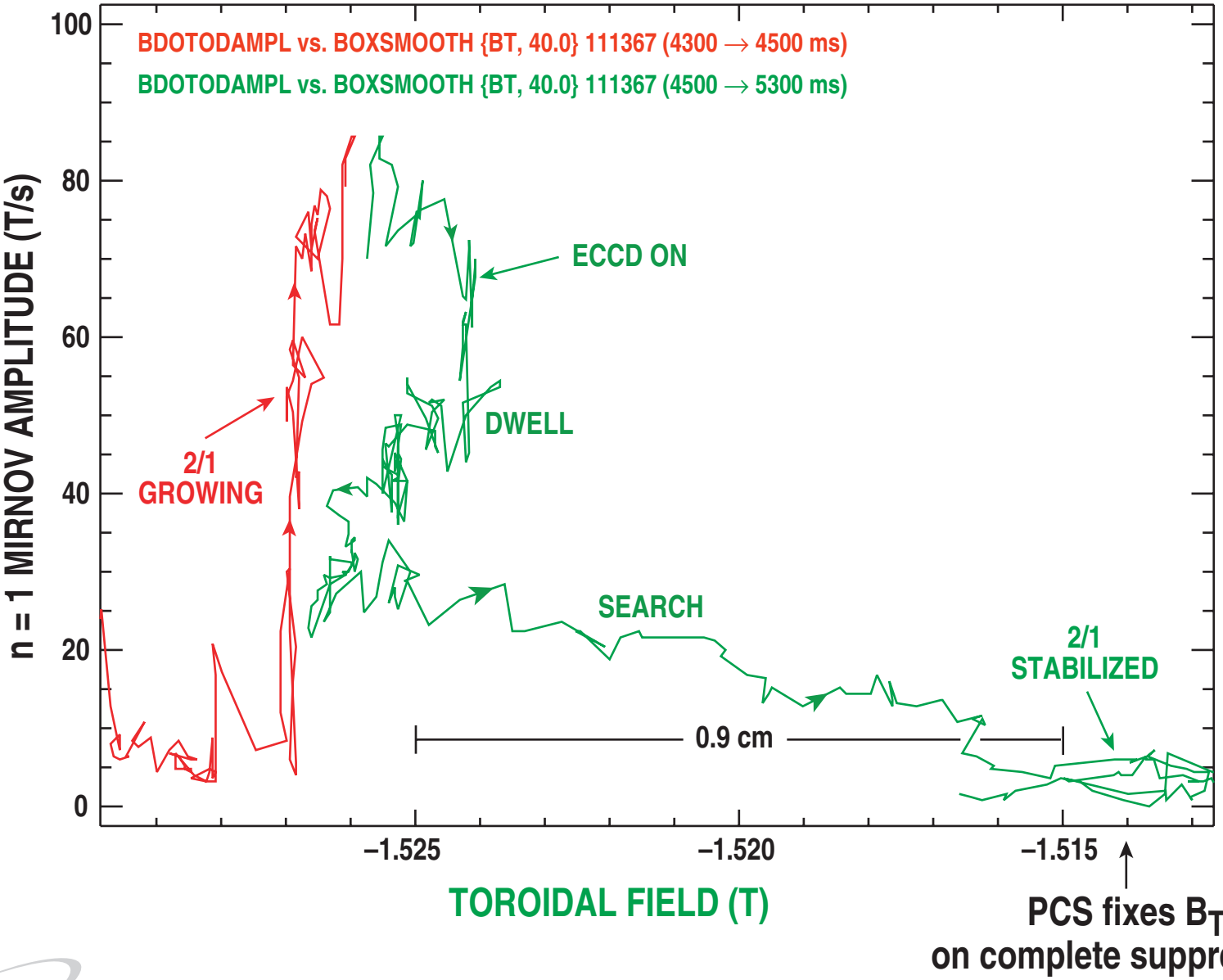
PCS "SEARCH AND SUPPRESS" IS ALSO EFFECTIVE FOR ECCD STABILIZATION OF 2/1 NTM



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CONCLUSIONS AND FUTURE WORK

- **Real-time ECCD position control demonstrated**
  - ★ "Search and Suppress" in presence of 3/2 or 2/1 mode
    - — Tracking change of location of q in absence of mode ready for 2003
- **Complete 3/2 NTM suppression demonstrated**
  - ★ Beta raised 60% (20% above the initial 3/2 NTM onset level)
- **Complete 2/1 NTM suppression demonstrated**
- **Future goal is simultaneous control of 3/2 and 2/1 NTMs for stable high beta**
  - ★ With 8 gyrotrons on 4 launchers

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