Feedback Control Algorithms Using ECCD for Neoclassical Tearing Mode Suppression

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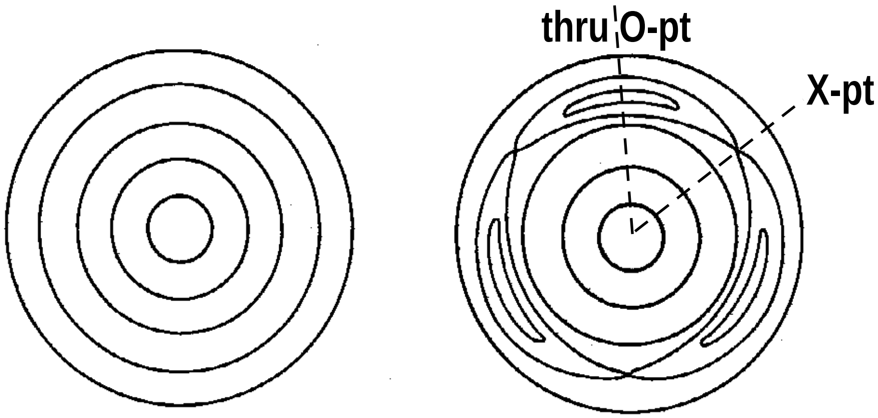
GENERAL ATOMICS

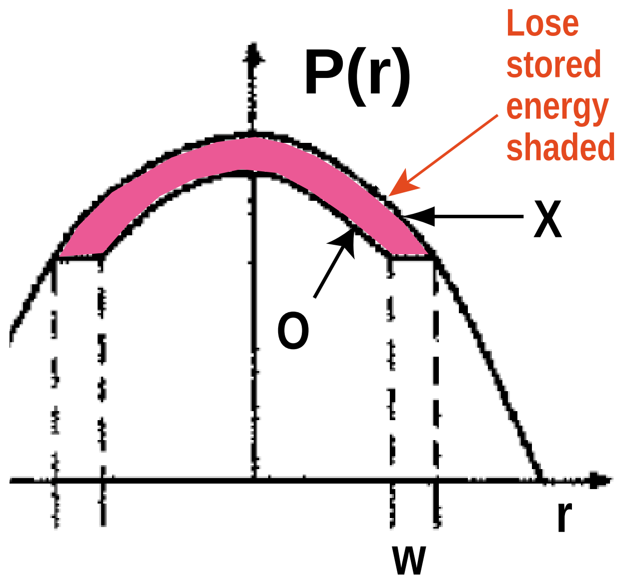
Overview

- Suppression of m/n=3/2 and 2/1 neoclassical tearing modes (NTM) via electron cyclotron current drive (ECCD) has been demonstrated in the DIII-D tokamak;
- Realtime control has been successfully used in DIII-D to detect the presence of 3/2 and 2/1 NTMs and align the ECCD deposition with the island location;
- Simulation of island suppression dynamics and control action are used to develop and improve the control algorithms;
- The DIII-D 2003 campaign will see application of new "Target Lock" algorithm, realtime Shafranov shift compensation, gyrotron control to sustain increased β_N.

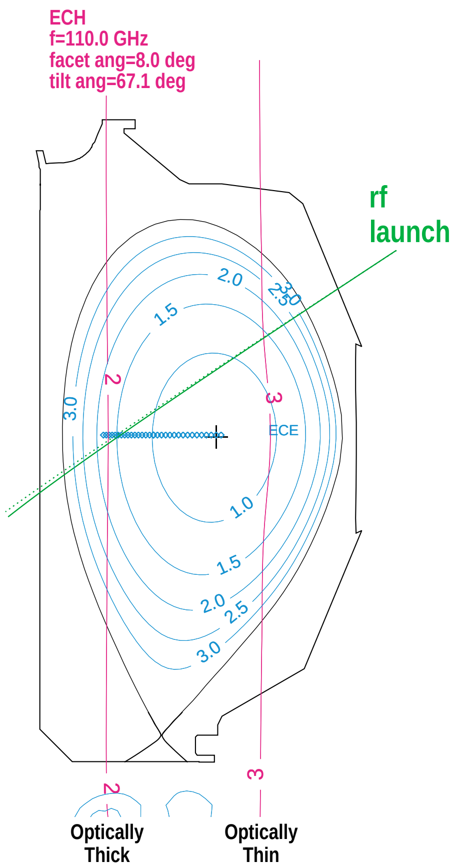
NTM Islands Degrade Confinement and Can Lead to Disruption

- NTM triggered by "seed" island from other MHD;
- Sufficiently high β destabilizes NTM, island grows to saturated size;
- Loss of bootstrap current in O-point ⇒ helically perturbed bootstrap current;
- Pressure flattened inside O-point, not in X-point;
- 3/2 typically degrades confinement, 2/1 often disruptive

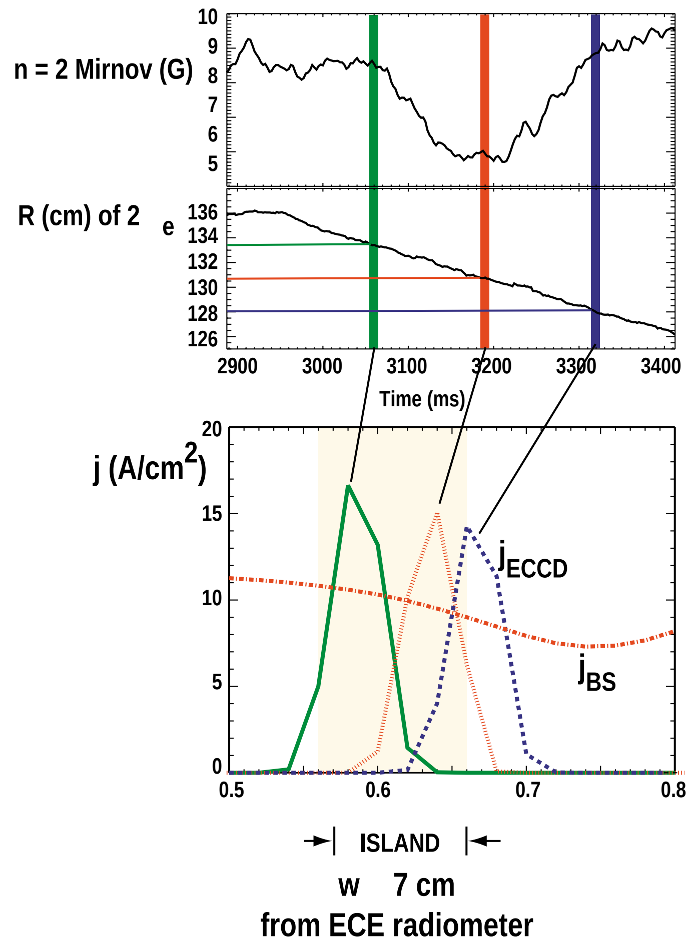




NTM Can Be Suppressed by Replacing Lost Bootstrap Current with ECCD



- Localized deposition of ECCD at island replaces lost bootstrap current
- Resonance layer must be accurately located at q=3/2 surface (with correction for Doppler shift)
- Accuracy required in DIII-D < ~1 cm



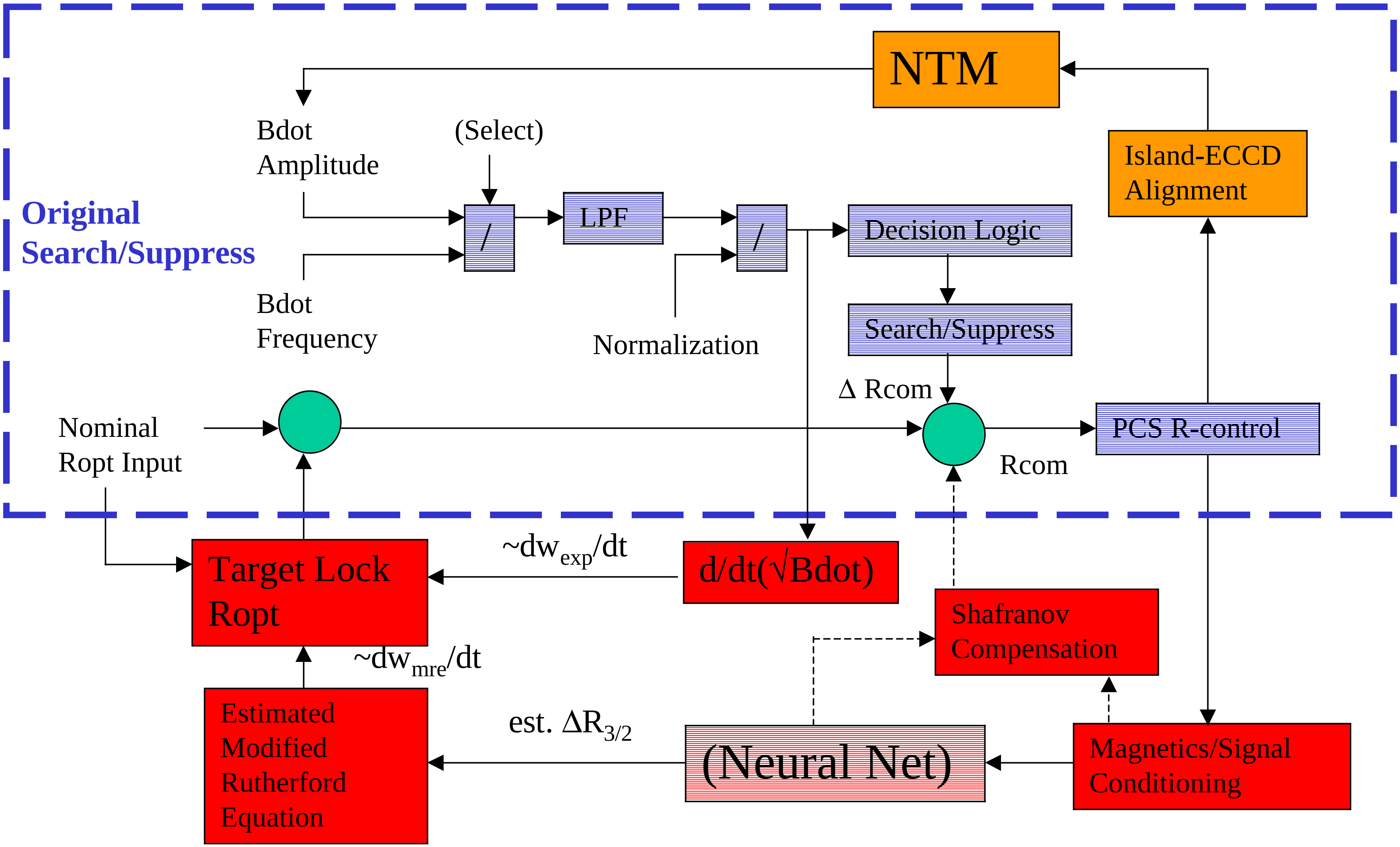
Accuracy Needed for ECCD Suppression of NTM Requires Active Control

- No direct realtime measurement of correct location (q=3/2 surface + Doppler shift correction) for ECCD yet available;
- Measurement of MHD mode amplitude allows indirect inference of proximity to correct deposition location;
- Deposition region and island must be aligned to within ~1 cm for full suppression;
- “Search/Suppress” executed by realtime control system to find best alignment in 1 cm steps: alignment detected by effect on mode amplitude; dwell if sufficient mode decay rate
- DIII-D Plasma Control System provides flexible platform for implementation of complex Search/Suppress logic, digital filters, etc..

NTM Search/Suppress Algorithm Can Now Vary One of Several Quantities to Align ECCD & Island

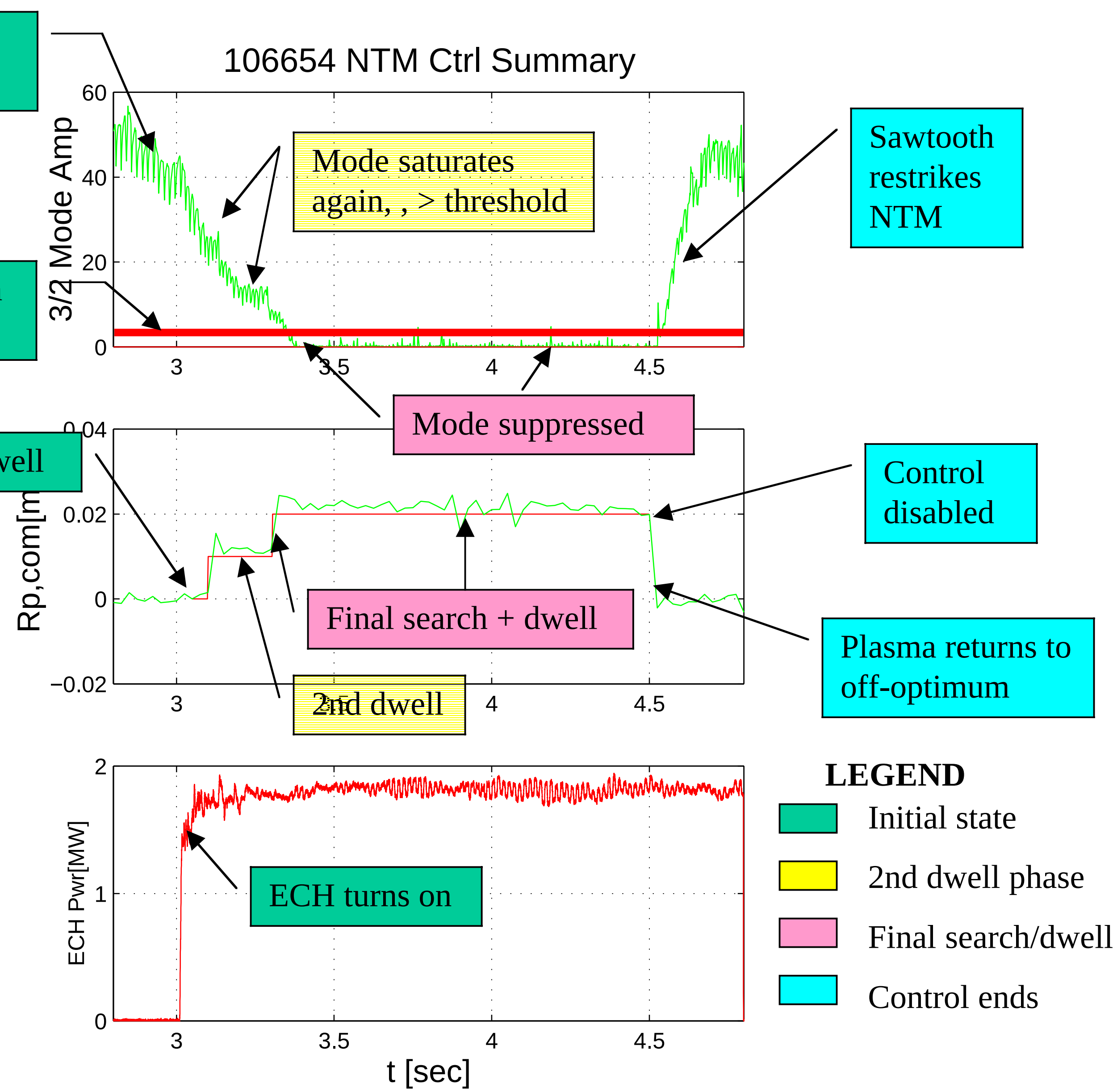
- ΔR = plasma major radius varied with rigid shift (move island itself relative to ECCD deposition) Used successfully for NTM suppression
- ΔBt = toroidal field varied (increase with positive voltage, or decrease with L/R decay) to move location of deposition with island ~fixed Used successfully for NTM suppression
- ΔZ = plasma vertical position with rigid shift (move island relative to ECCD deposition) Basic function tested in piggyback, but not yet used operationally with actual NTM+ECCD

NTM Control Algorithm in PCS Will Include Many Extensions Beyond Search/Suppress



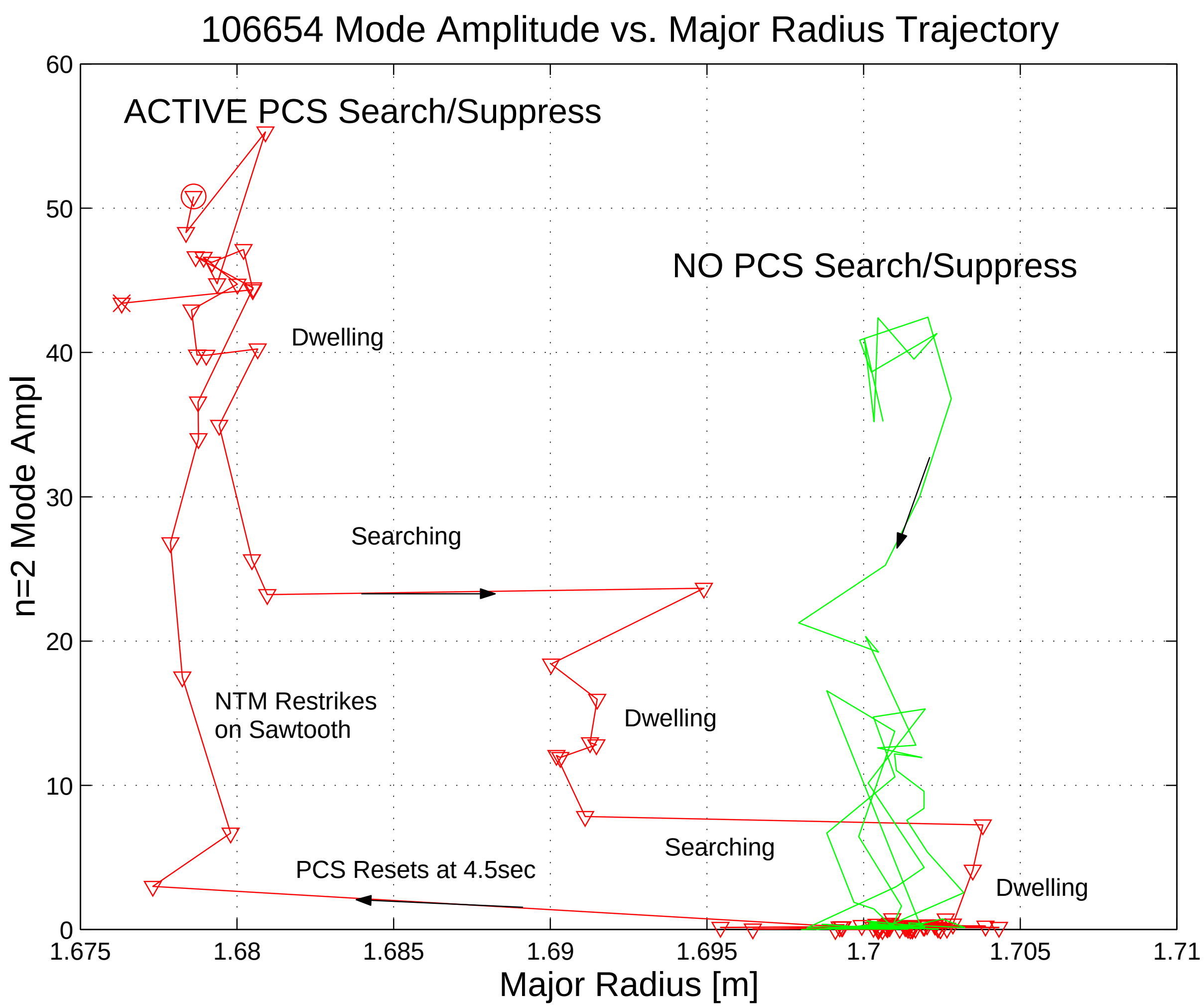
3/2 NTM Suppressed Using ΔR Search Initially Off Optimum

- Control algorithm and ECH enabled @3.0 sec
- Search pattern starts > 1 dwell
- 50 msec dwell, 1 cm step size: 2 searches hit "sweet spot"
- Mode fully suppressed 400 msec after enabling search/suppress

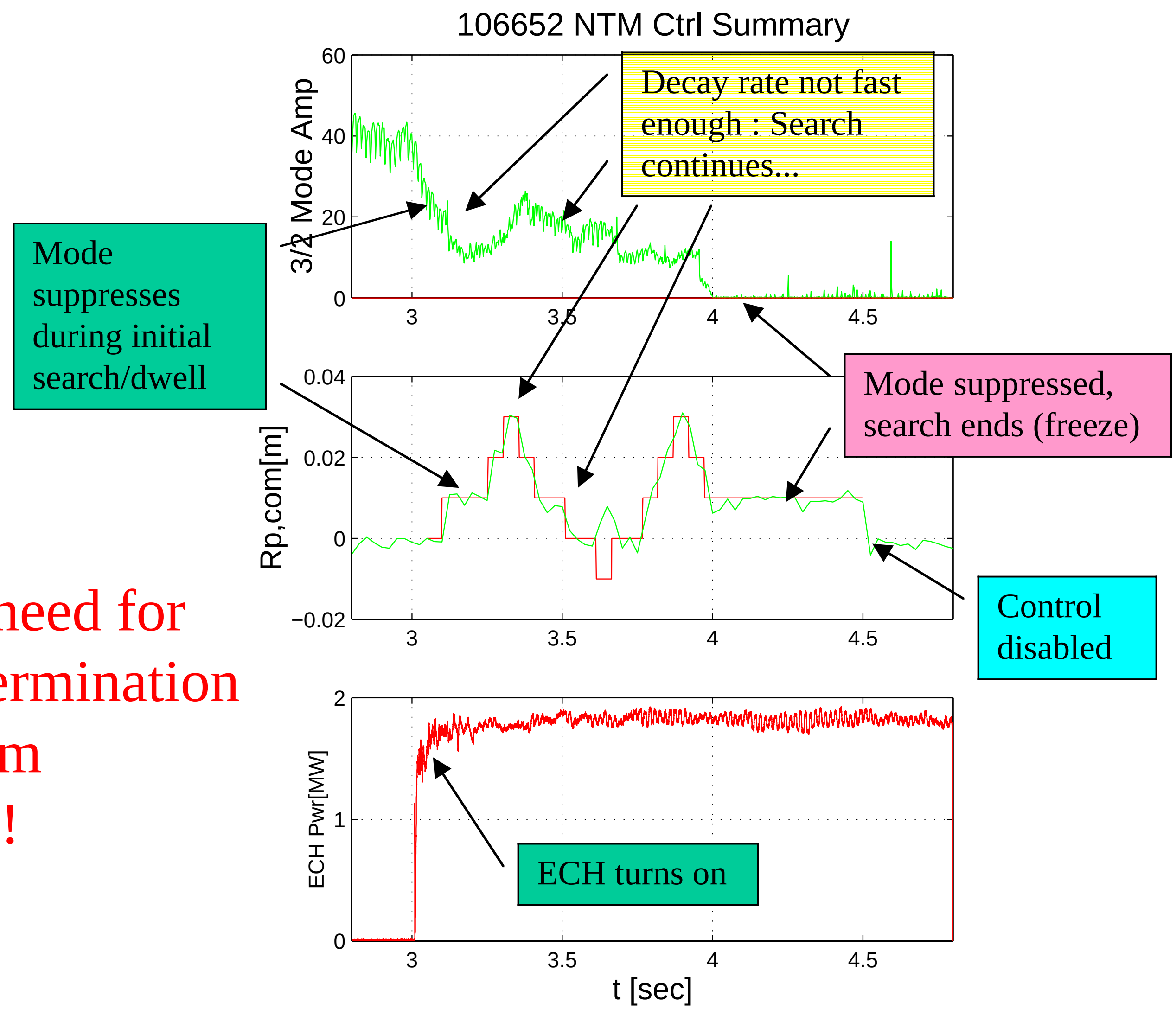


Rp Search/Suppress Finds Same Optimum Location as Preprogrammed ΔR Scan

- Search/Suppress follows several dwell/search steps to reach full suppression
- Suppression point (R~1.7) same for both blind search and preprogrammed scan of ΔR



Search Histories Can Be Very Complex: Wrong Initial Direction, Backtracking…. Eventually Suppressing Mode



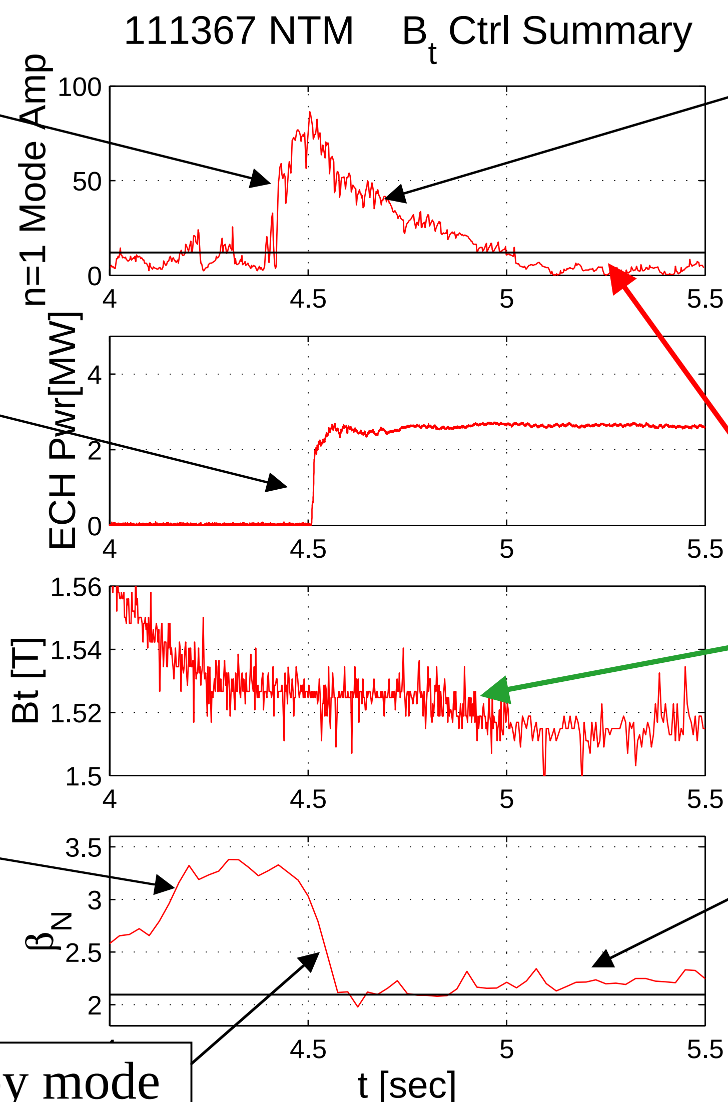
Suggests need for faster determination of optimum alignment!

2/1 NTM Suppressed Using ECCD with Search and Suppress Bt Variation

2/1 NTM triggered after β_N increase

2/1 NTM partially suppressed with initial ECCD

ECCD turned on (preprogrammed)



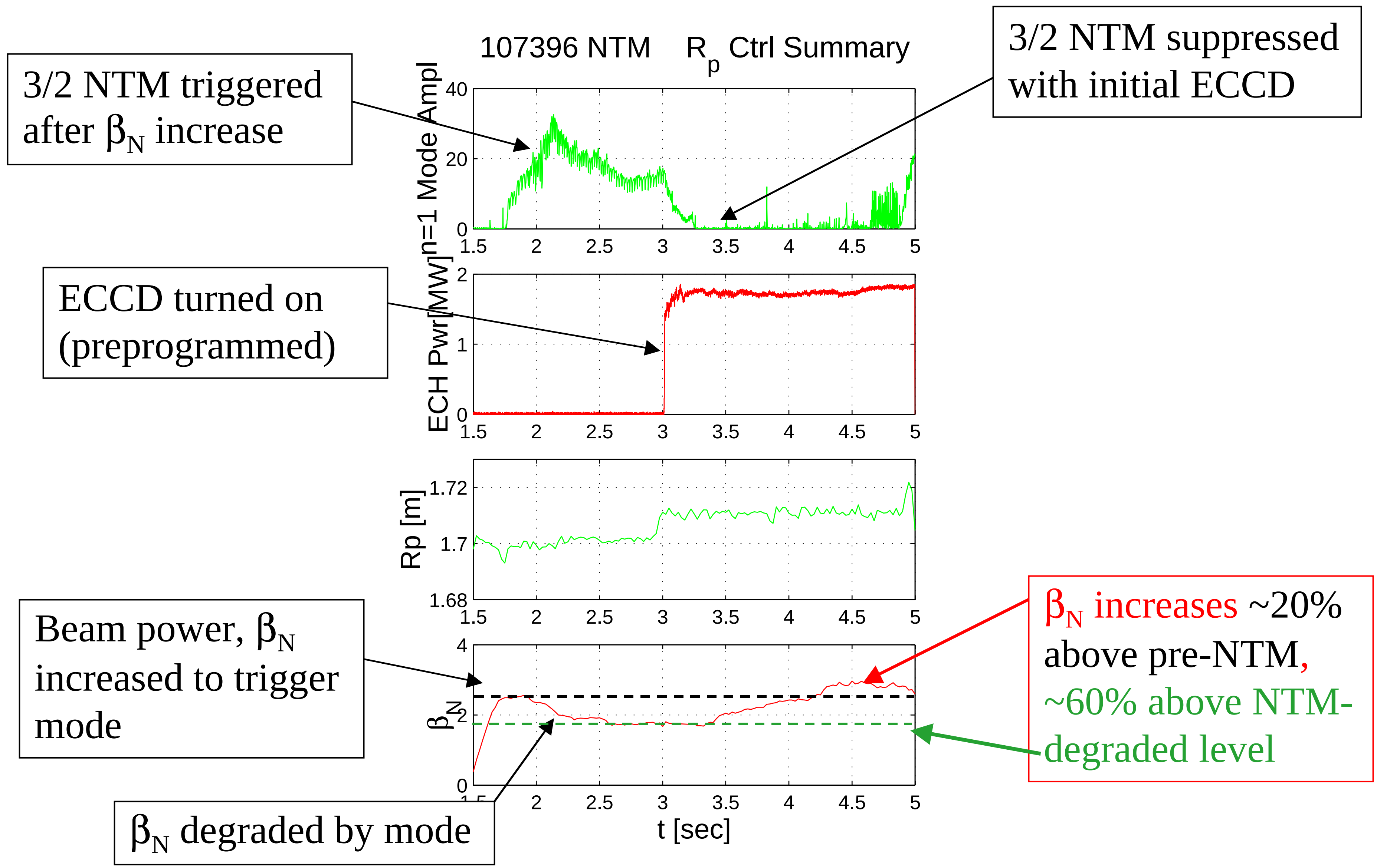
Search/Suppress reduces Bt to align ECCD with island: Mode Suppressed!

Beam power, β_N increased to trigger mode

β_N increases slightly after mode suppressed…

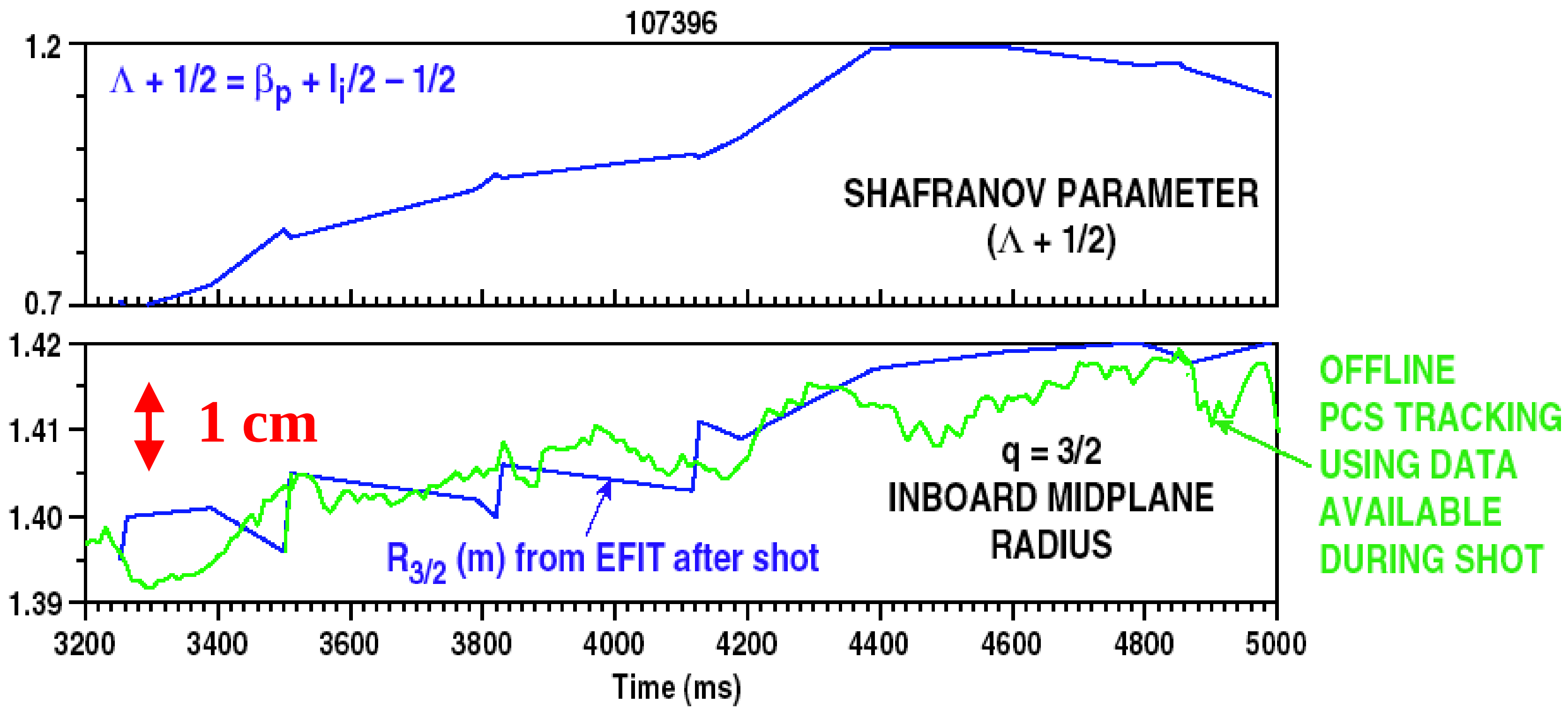
β_N degraded by mode

Suppression of 3/2 NTM Allows β_N to Increase



Detuning from Shafranov Shift Will be Corrected by Realtime Tracking

- Raised β produces (Shafranov) shift in island R
- Realtime compensation for Shafranov shift after island suppression will maintain alignment



Target Lock Algorithm Developed for Fast Acquisition of Optimum Plasma Position

- The Target Lock algorithm compares variations in measured NTM growth rate with those predicted due to radial displacements of the plasma
- Predicted variations are calculated using an approximation to the Modified Rutherford Equation with multiple choices of optimum plasma position:

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

ECCD stabilizing term

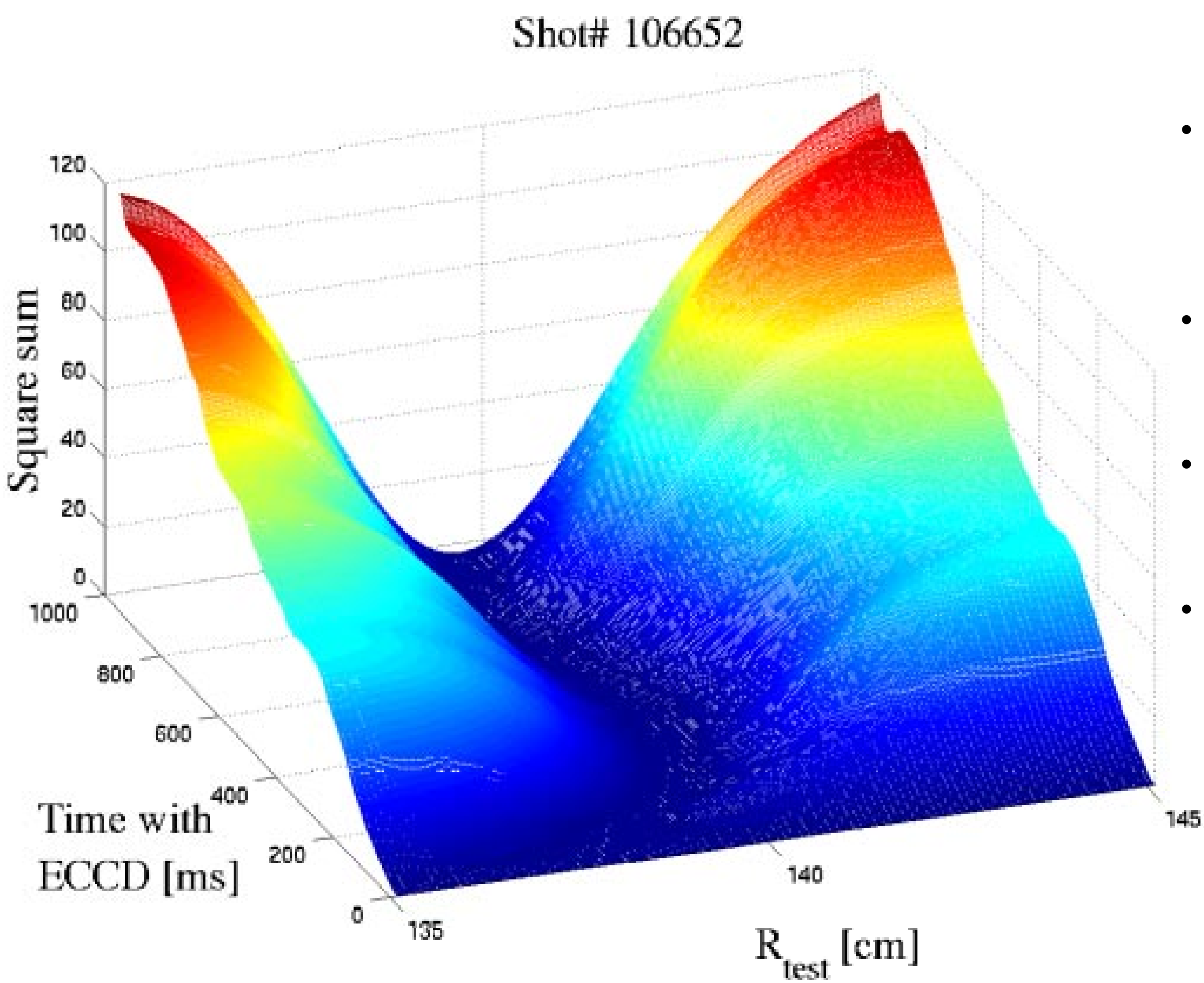
$$\eta = \eta_0\left(1 + 2\delta_{ec}^2 / w^2\right)^{-1}\exp\left[-\left(5\Delta R / 3\delta_{ec}\right)^2\right]$$

Alignment error

$\Rightarrow$ While island present, MRE provides estimate of $\partial\dot{w}/\partial R$

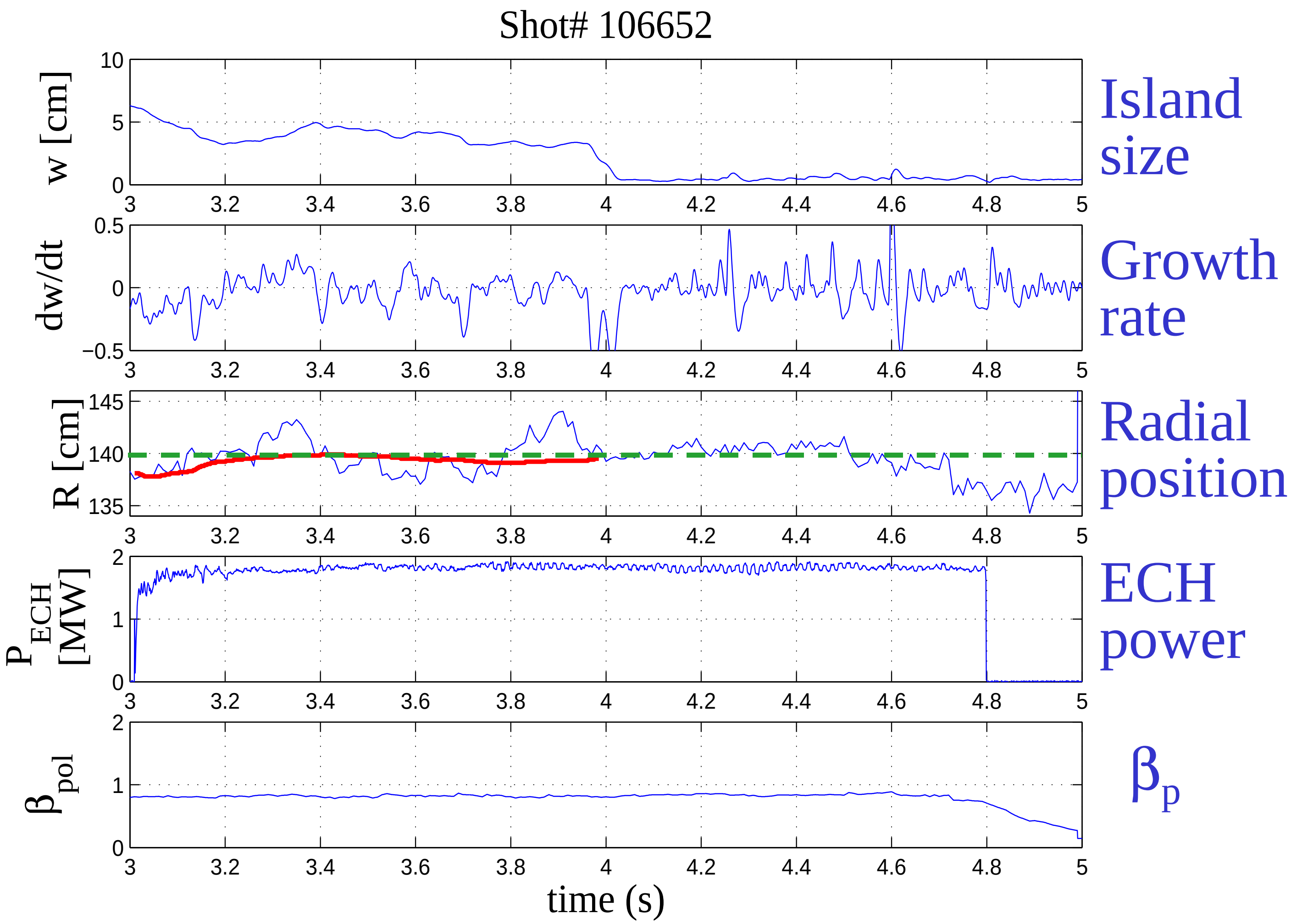
$\Rightarrow$ Optimum is least-squares min of estimated-measured difference

Target Lock Finds Unique Value for Optimum Plasma Position



- Smaller square sums signify better fits between predicted and measured growth rates
- In every time slice there is only one minimum in the square sum
- The Target Lock algorithm infers R_{opt} from this minimum
- With more time and hence more information the minimum becomes clearer

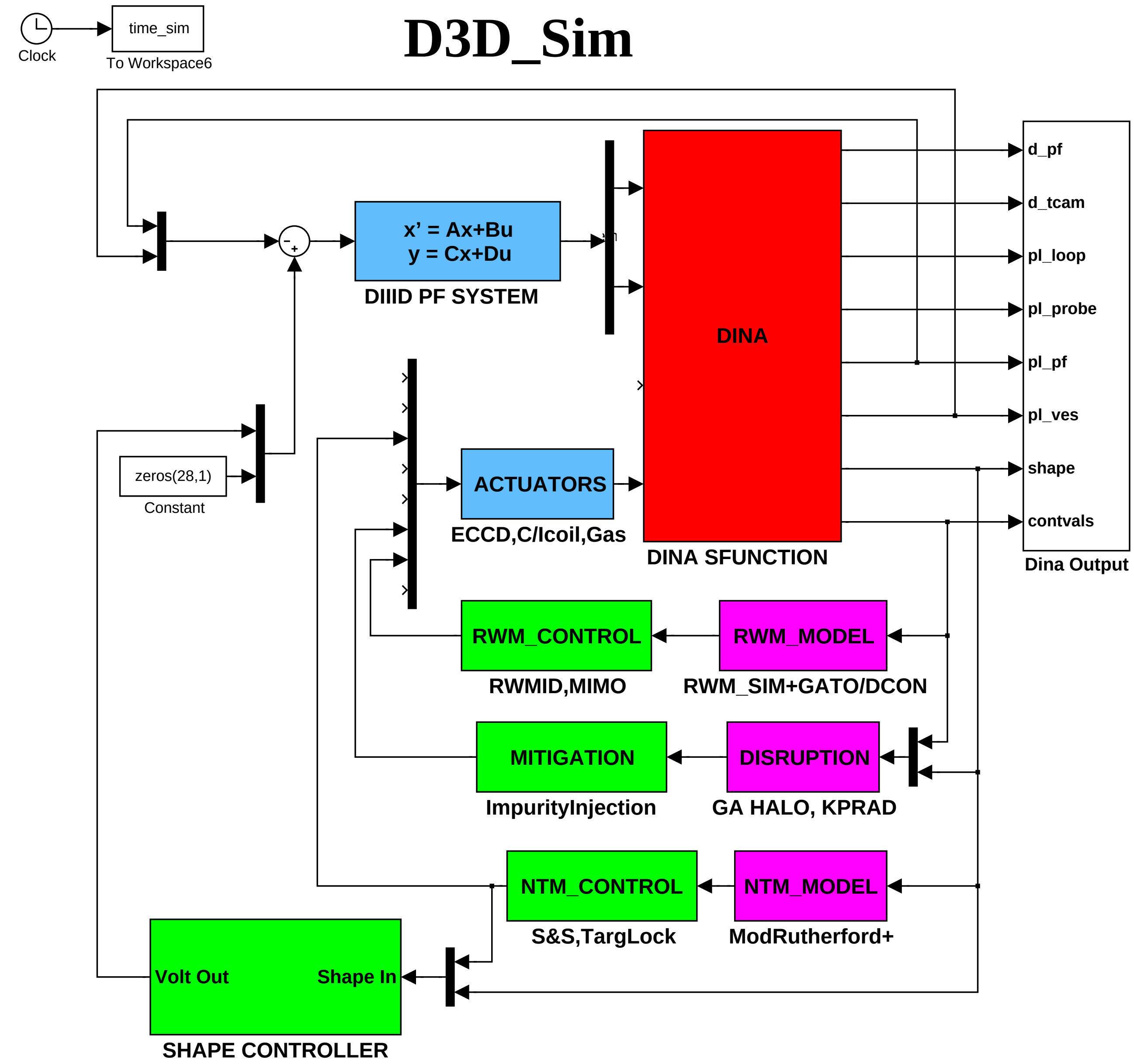
Target Lock Algorithm Performs Well in Simulation from Experimental Data



- A magnetic island has grown to its saturated size
- ECCD turned on 3 s into discharge
- The Target Lock algorithm finds R close to optimum instantaneously
- Minor adjustments occur during first 150 ms

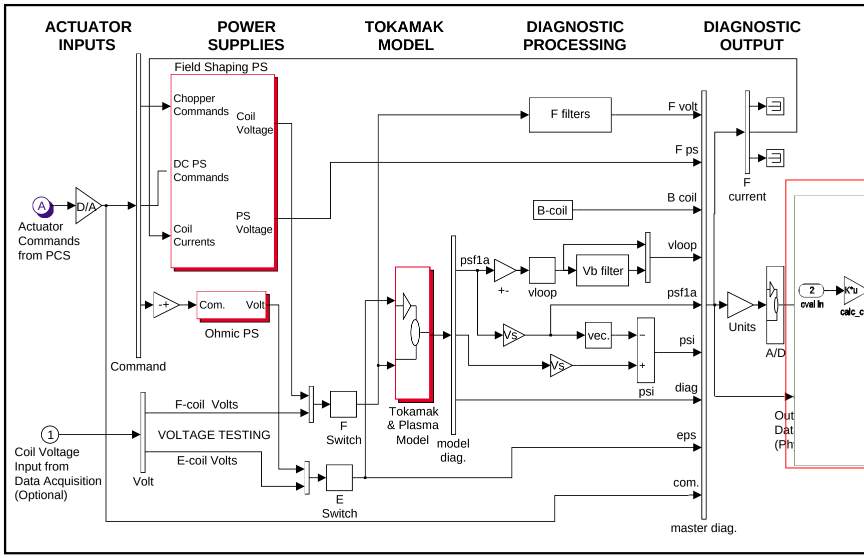
High Performance MHD Control Design Benefits from Detailed Simulation of Integrated Systems

D3D_Sim

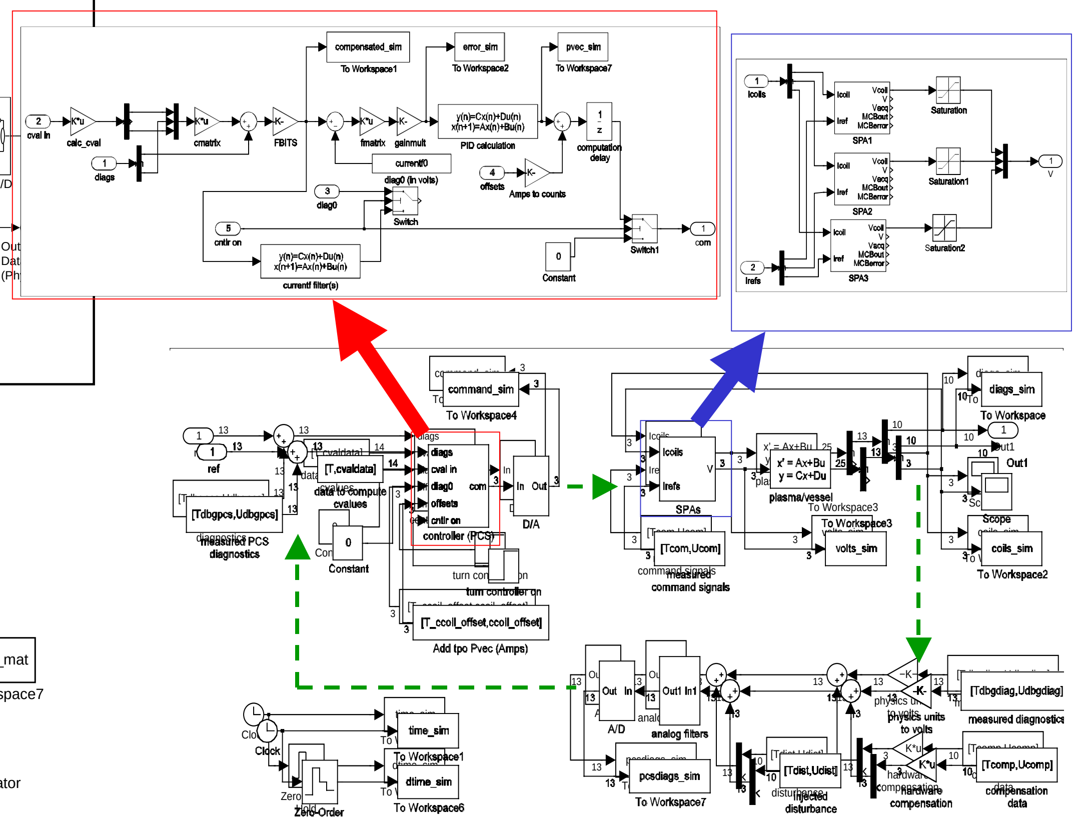


Individual Blocks Can be Very Complex

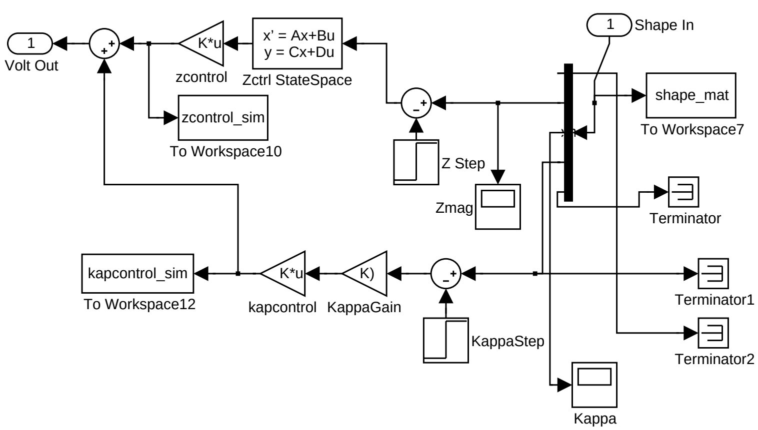
PF System



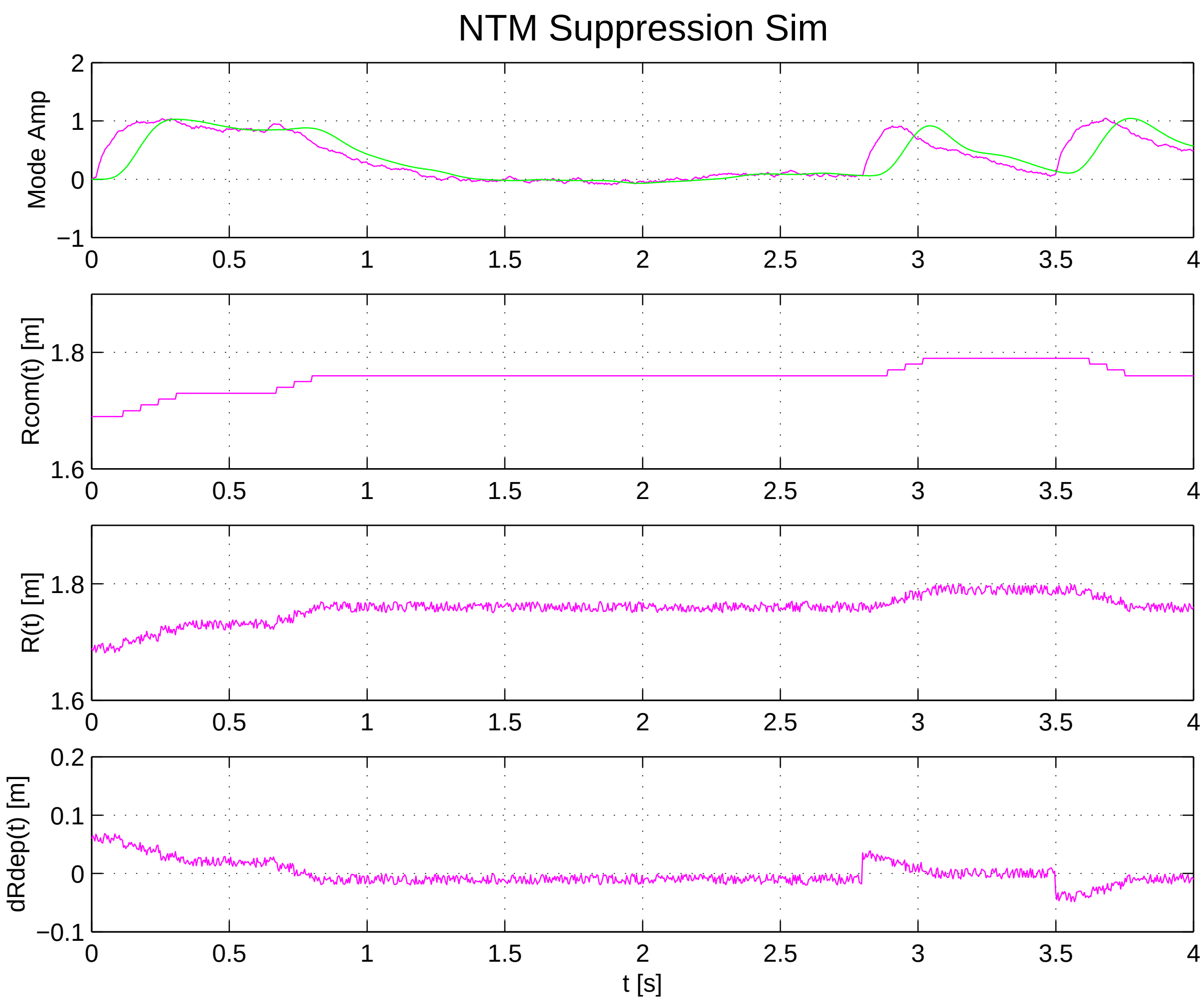
RWM Model



Shape Controllers

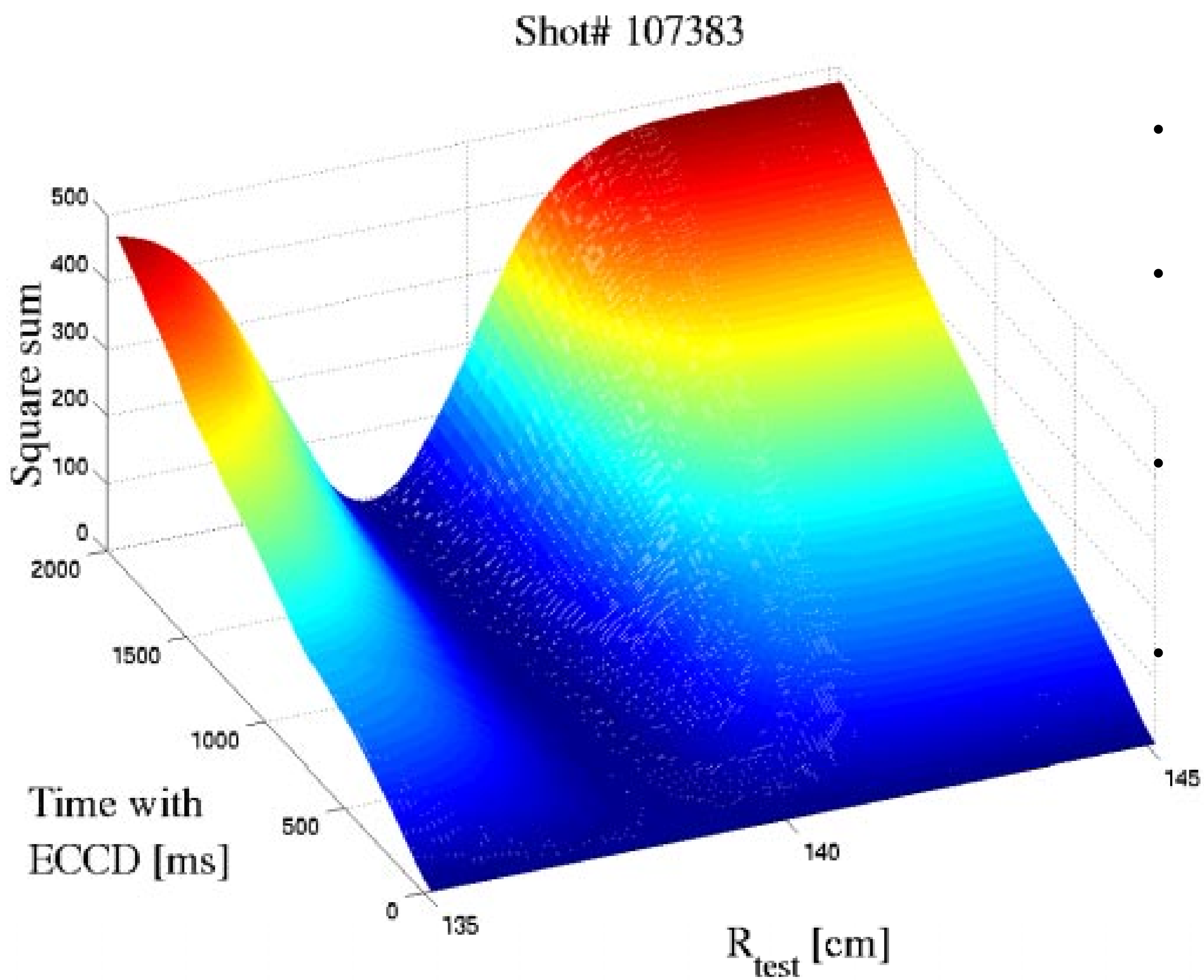


Simulations Allowed Design/Optimization of Search/Suppress for Robust First-Time Performance



- Mode suppressed in < 1.5 sec
- Realistic timescales..
- Simulation yielded effective dwell time 50 ms, step size 1 cm, threshold amplitude 0.1-0.2
- Search/Suppress was successful in first-time experimental use!

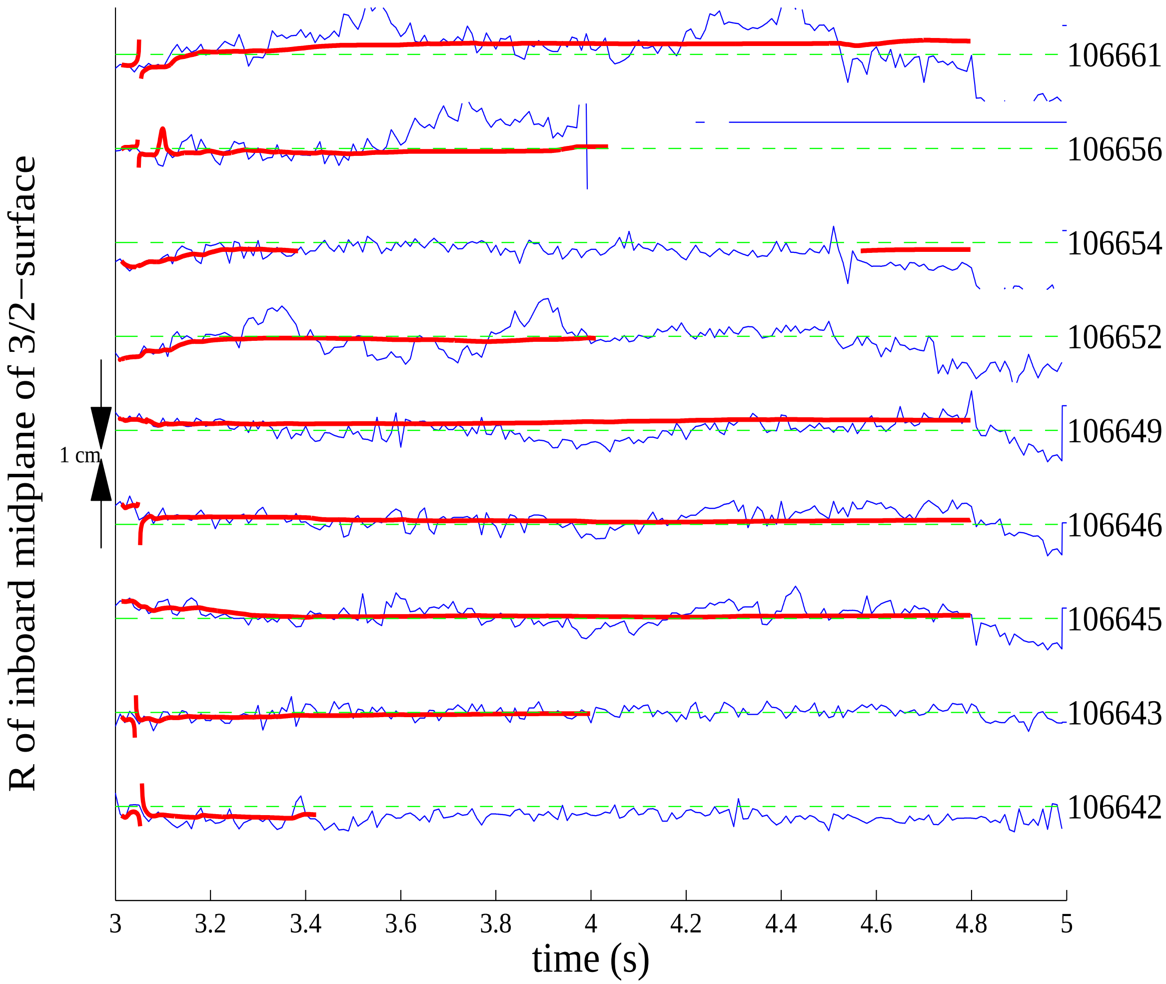
Simulations Show Target Lock Accuracy can be improved by jitter in the plasma position



- This discharge displays a higher fluctuation in plasma position
- As a consequence the Target Lock algorithm has more information on how suppression depends on R
- This makes the solution for optimum plasma position clearer (the minimum or trench in the graph)
- Improved accuracy in R_{opt} is obtained by a jitter of the plasma

Fast Target Lock in All Simulated Cases

Plasma position R, Target Lock value R_{opt},
and best guess of sweet spot (--)



- ECCD turned on at 3 s with a 3/2 NTM mode present in all of these shots.
- R_{opt} is calculated at all times when both the mode and ECCD is present
- Target lock in ~50-100 ms

Summary

- Use of ECCD with realtime NTM "Search and Suppress" control was successful in suppressing 3/2 and 2/1 NTM using major radial and toroidal field regulation (separately)
- Plasma β_N increased through active (3/2) NTM suppression
- Simulation of NTM suppression scenarios is used extensively to test and optimize control schemes prior to experimental execution

NTM Suppression Plans for 2003 Campaign

- Sustained increased β_N through 3/2, 2/1 NTM control
- Improvements to algorithm:
  - Shafranov shift compensation (primarily due to βp change)
  - Target Lock algorithm to accelerate search
- Realtime gyrotron (power) control
- Direct feedback on R(q=3/2) error in concert with reduced-displacement Search&Suppress+Target Lock+Shafranov Compensation algorithms