Design, Simulation, and Operational Use of Control Algorithms for ECCD Suppression of the m/n=3/2 Neoclassical Tearing Mode

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Abstract

Design, Simulation, and Operational Use of Control Algorithms for ECCD Suppression of the m/n=3/2 Neoclassical Tearing Mode, D.A. Humphreys, R.J. LaHaye, B. Penaflor, M.L. Walker, *General Atomics*,

The 3/2 neoclassical tearing mode (NTM) imposes significant limits on achievable values of normalized plasma beta [1]. Suppression of this mode has been achieved in various tokamaks by preprogrammed application of electron cyclotron current drive (ECCD) fixed at (or swept across) the 3/2 island location to replace lost bootstrap current [2]. We report on the design and development of realtime plasma control algorithms for suppression of the 3/2 NTM by varying the location of the ECCD resonance through modification of either toroidal field or plasma major radial position. Alignment of ECCD resonance and island location is detected solely through measurement and analysis of mode amplitude evolution. These nonlinear "search and suppress" algorithms were designed and developed using computational simulations of modal dynamic response, and were used successfully to completely suppress the 3/2 NTM in the DIII-D tokamak [3].

[1] LaHaye, R.J., et al, Nucl. Fus. **37** (1997) 397

[2] Zohm, H., et al., Phys. Plasmas **8** (2001) 2009

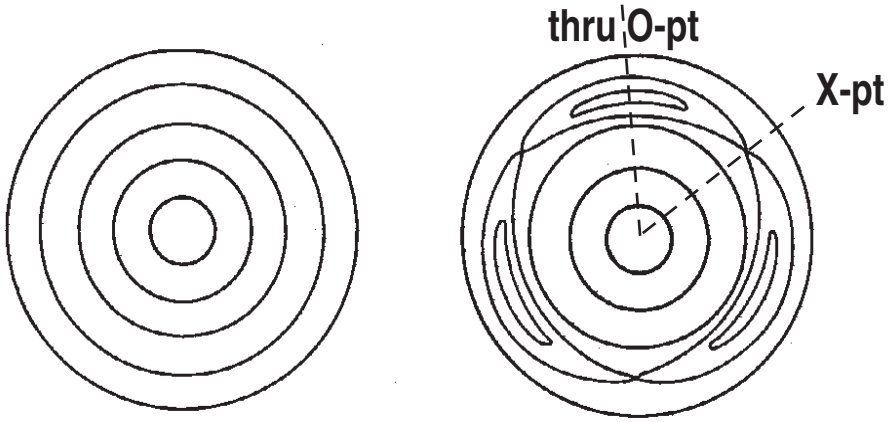
[3] see R.J. LaHaye et al, this conference

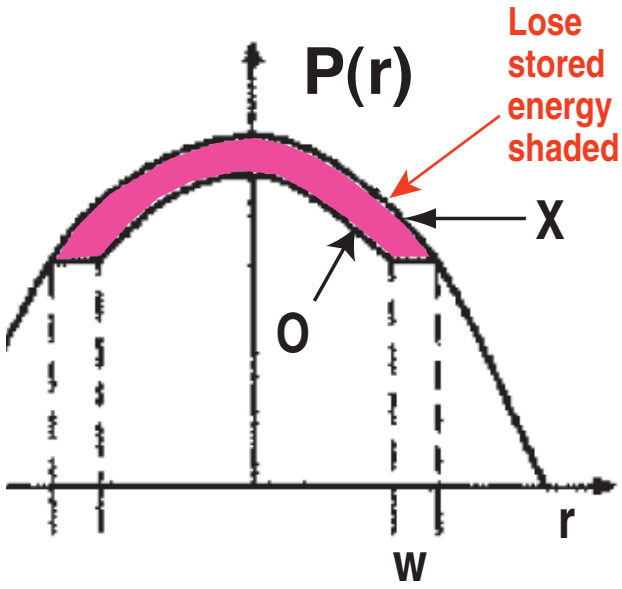
Overview

- Suppression of the m/n=3/2 neoclassical tearing mode (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 a 3/2 NTM and align the ECCD deposition with the island location;
- Simulation of island suppression dynamics and control action was used to develop and improve the control algorithm;
- The DIII-D 2002 campaign will see application of improved realtime control algorithms and testing of new approaches.

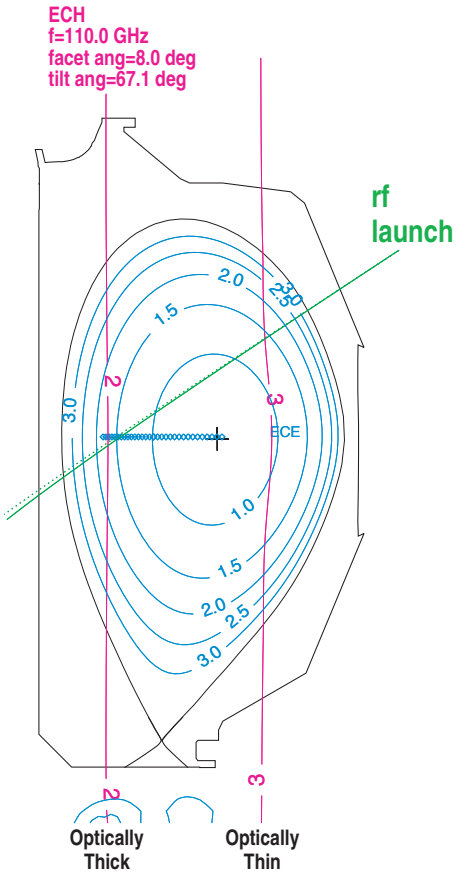
3/2 NTM Typically Limits Confinement but Does Not Cause Disruption

- 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;
- Presence of island degrades confinement.

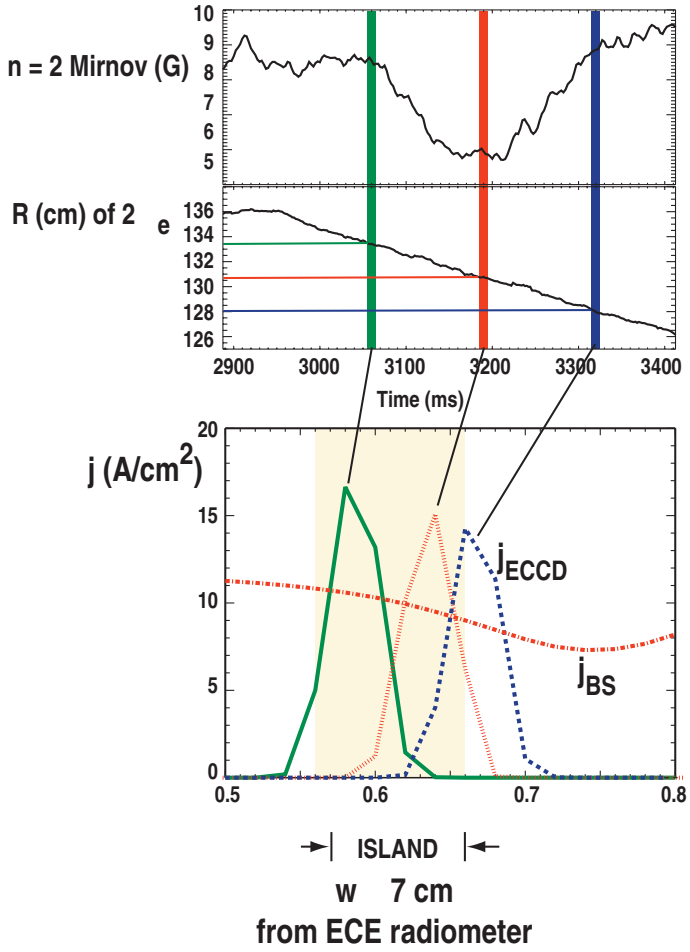




3/2 NTM Can Be Suppressed by Replacing Lost Bootstrap Current with ECCD



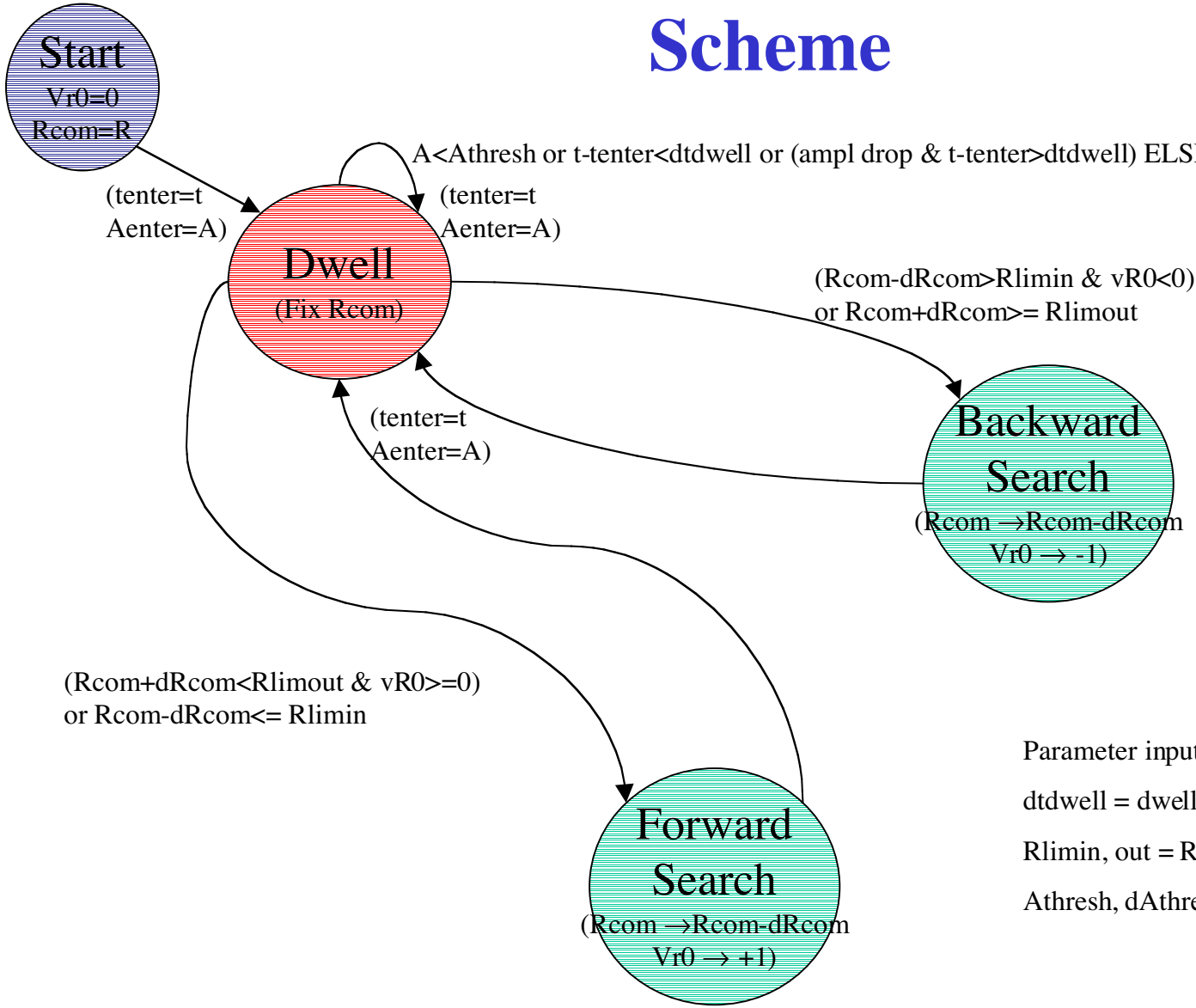
- Localized deposition of ECCD at island replaces lost bootstrap current
- Resonance layer must be accurately located at q=3/2 surface (with correction for Doppler shift)
- Accuracy required in DIII-D < ~1-1.5 cm



Accuracy Needed for ECCD Suppression of NTM Requires Active Control

- No direct realtime measurement available (yet) of correct location (q=3/2 surface + Doppler shift correction) for ECCD;
- Measurement of MHD mode amplitude allows indirect inference of proximity to correct deposition location;
- Deposition region and island must be aligned to within 1-1.5 cm for full suppression;
- "Blind search" 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
- Extremely flexible DIII-D Plasma Control System provides ideal platform for implementation of complex Search/Suppress logic, digital filters, etc..

State-Flow Structure for Search/Suppress Scheme



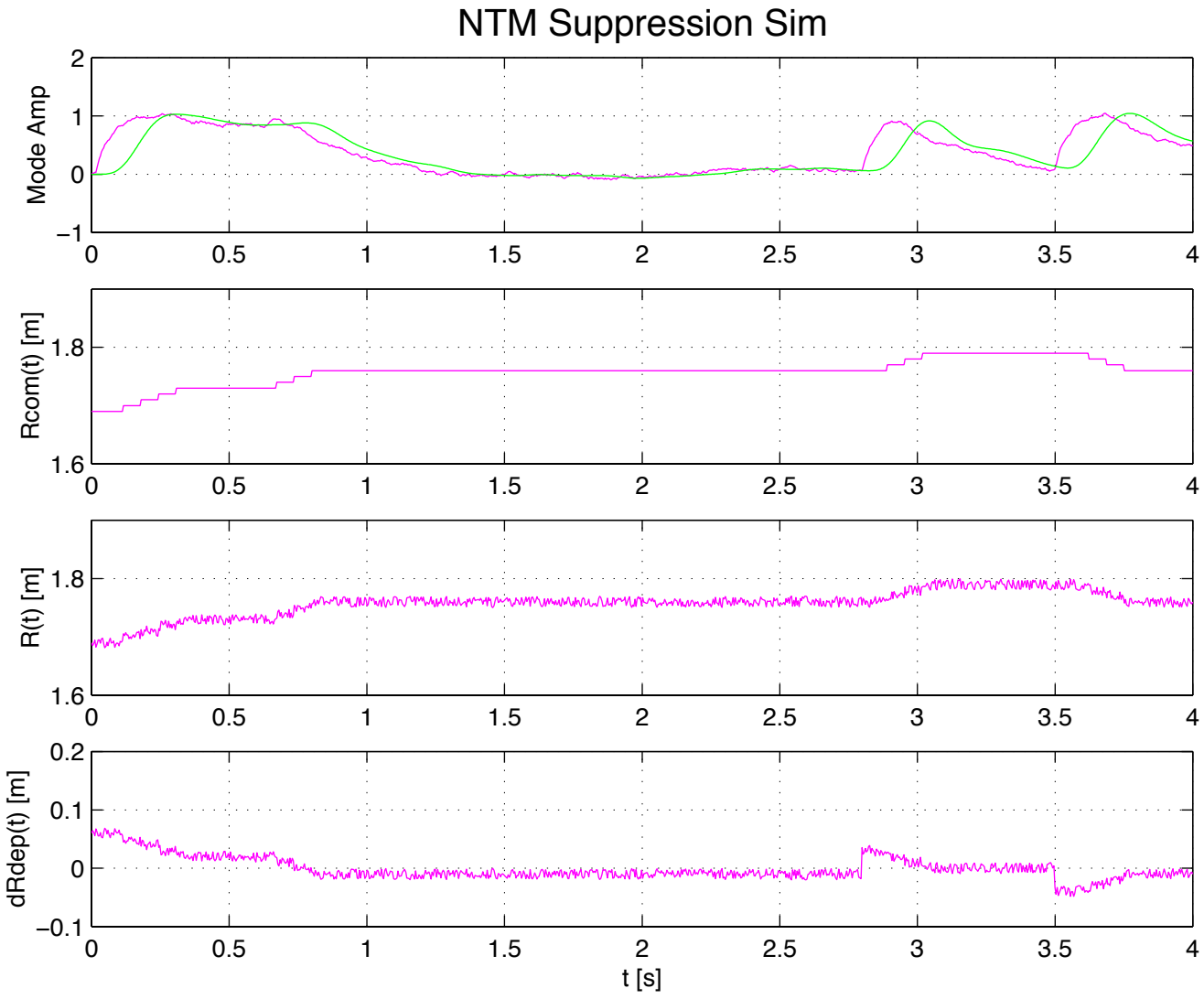
Parameter inputs:

dtdwell = dwell time interval

Rlimin, out = R limits

Athresh, dAthresh = Ampl. thresholds

Simulations Allow Selection of Control Parameters and Improvement of Algorithm



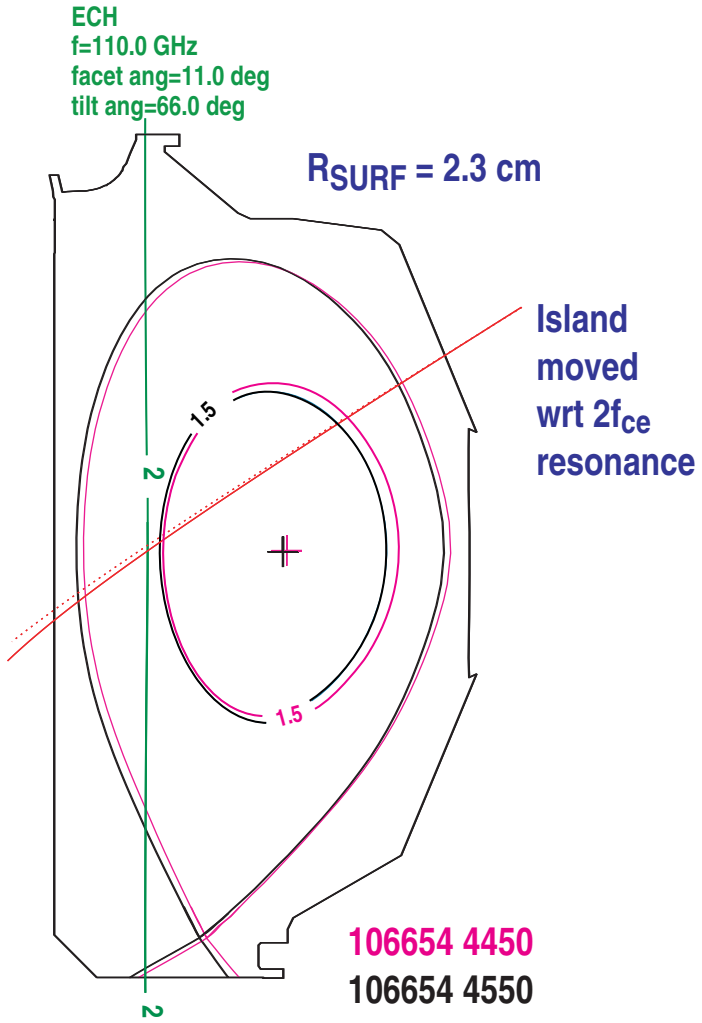
- Mode growth starts @ 20 ms
- Search pattern starts when mode ampl > threshold
- Mode suppressed by 1.5 sec
- Real timescales..
- Simulation yields effective dwell time 50 ms, threshold amplitude 0.1-0.2

NTM Control 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 3/2 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 3/2 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 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" while keeping resonance fixed
- Detect alignment of ECCD current deposition with island ("sweet spot") by sufficient change in mode amplitude over the specified "dwell" time
- Continue to dwell if mode decays at > threshold rate. Freeze if mode < threshold. If not, continue search (or "jitter"…)

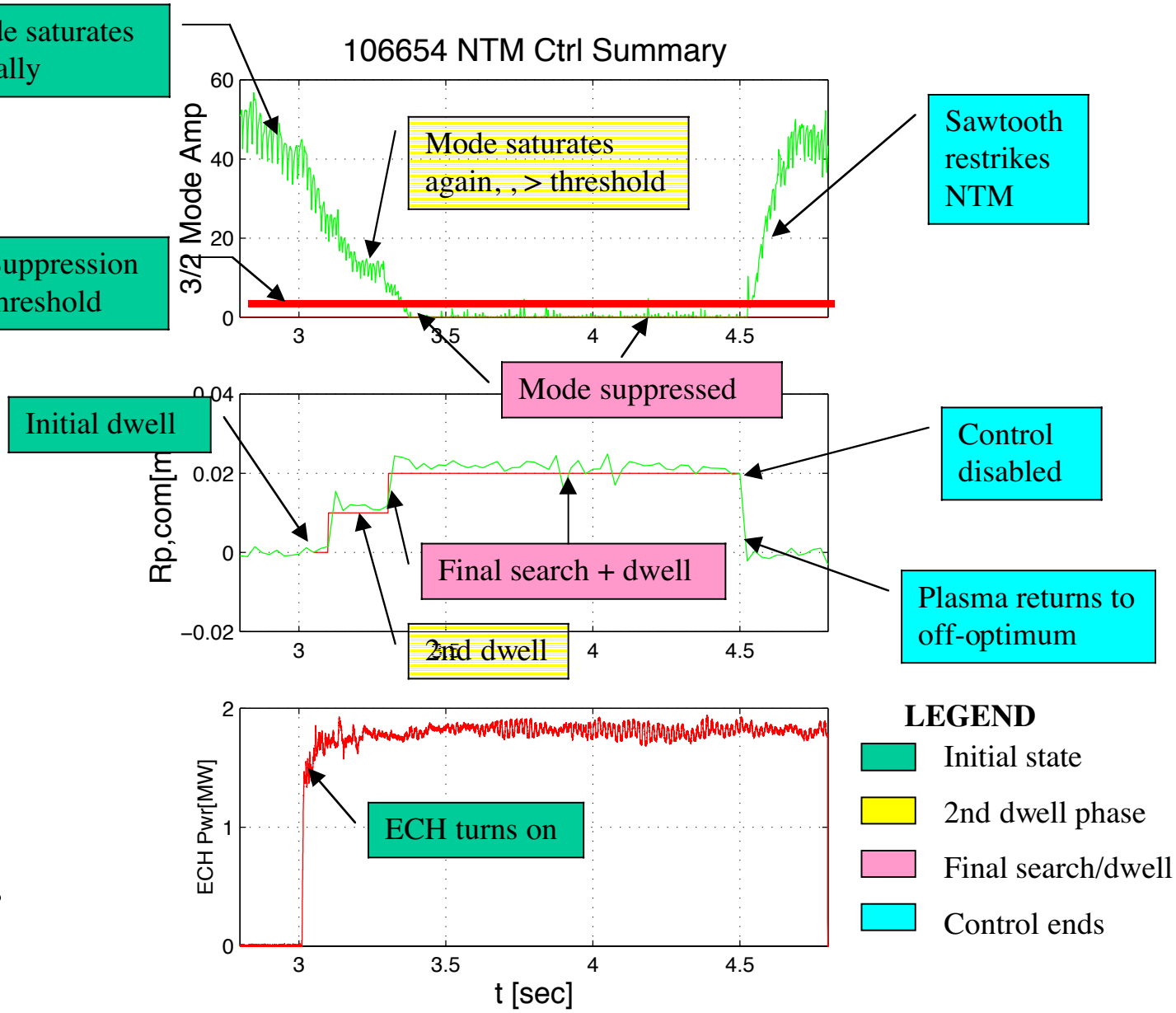


106654: Discharge with ECCD Initially ~2cm Off Previously Determined Sweet Spot

- Dwell time = 50 ms, ΔRstep=1cm, Mode threshold = 10%, ΔMode threshold=5%,
- NTM control enabled at t=3000, PCS dwells for two dwell times (100 ms)
- Mode partially suppressed initially, but saturates: PCS thinks not suppressing, continues search...
- Eventually hits ideal location, suppresses completely. Turnoff of NTM control restores plasma to original (non-sweet spot) location, mode returns to full unsuppressed saturated amplitude.

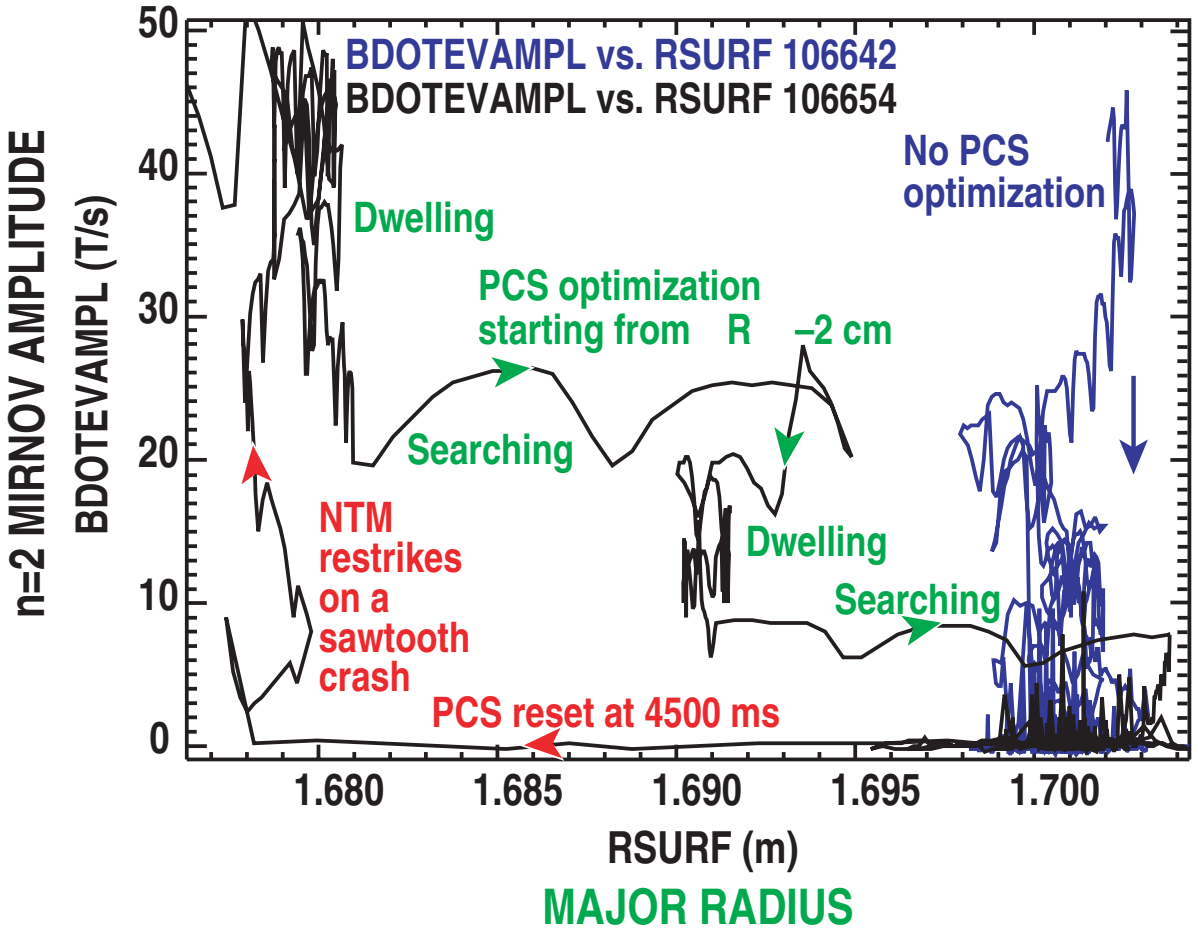
3/2 NTM Suppressed Using ΔR Search Initially Off Optimum

- 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



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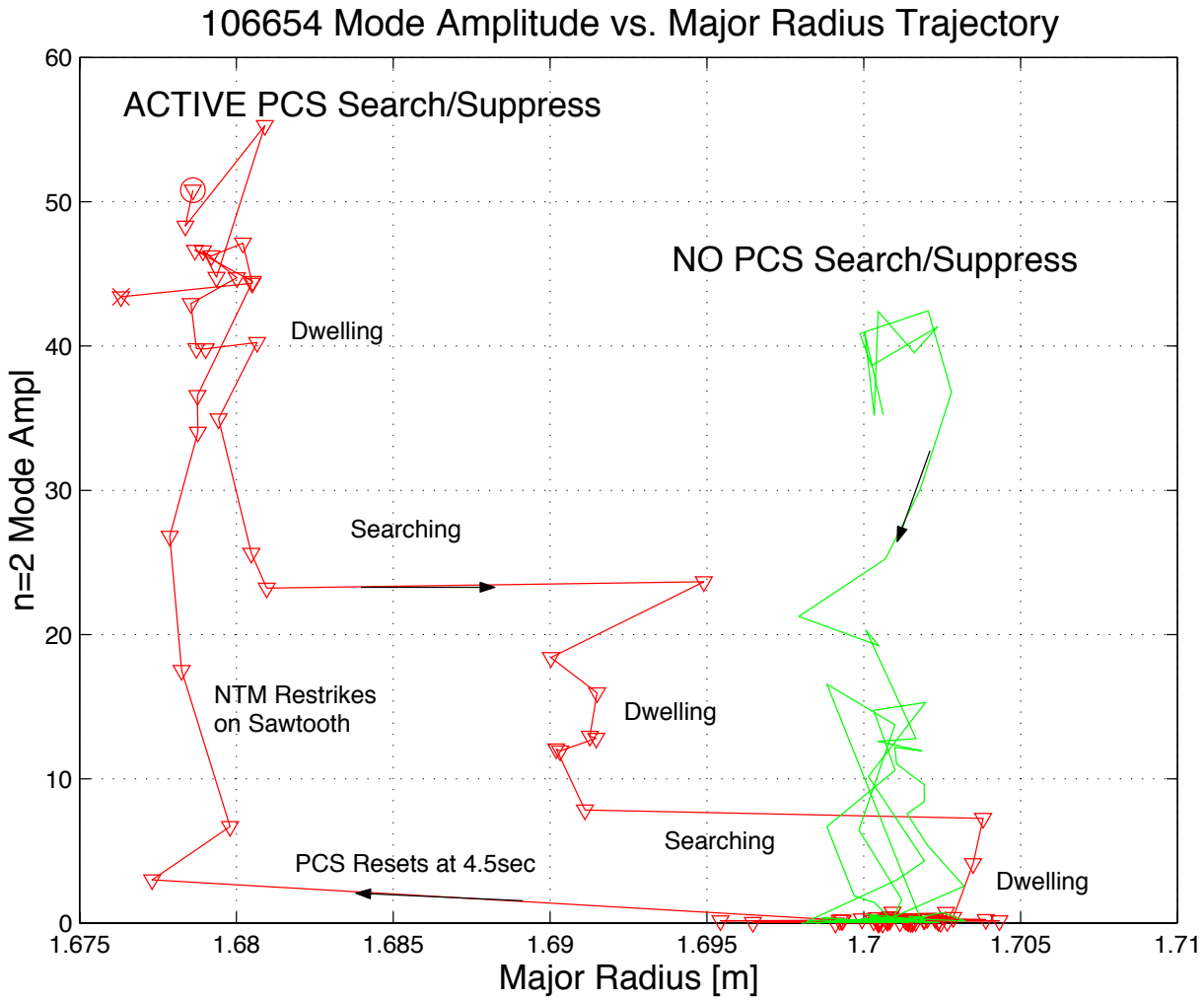
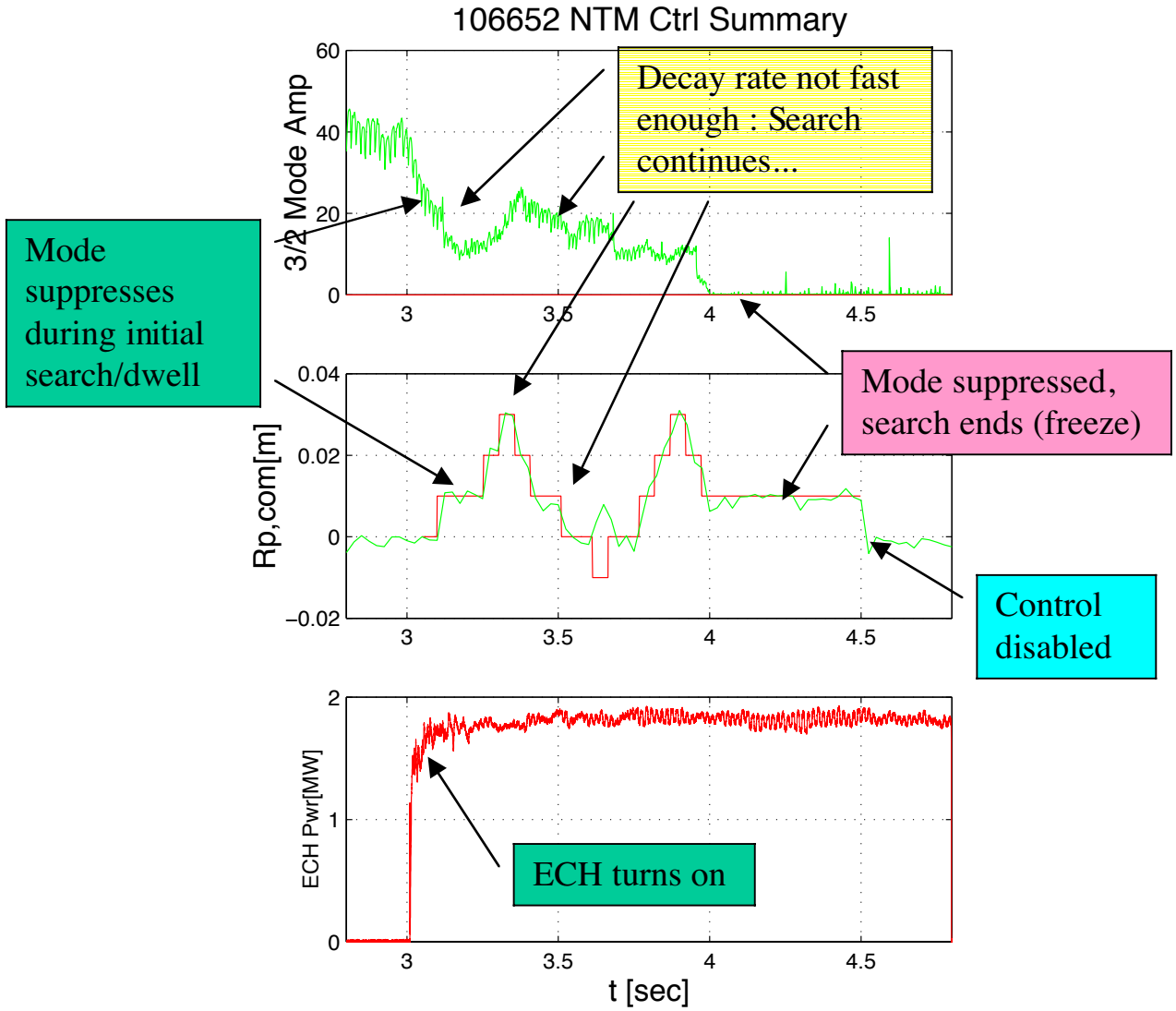


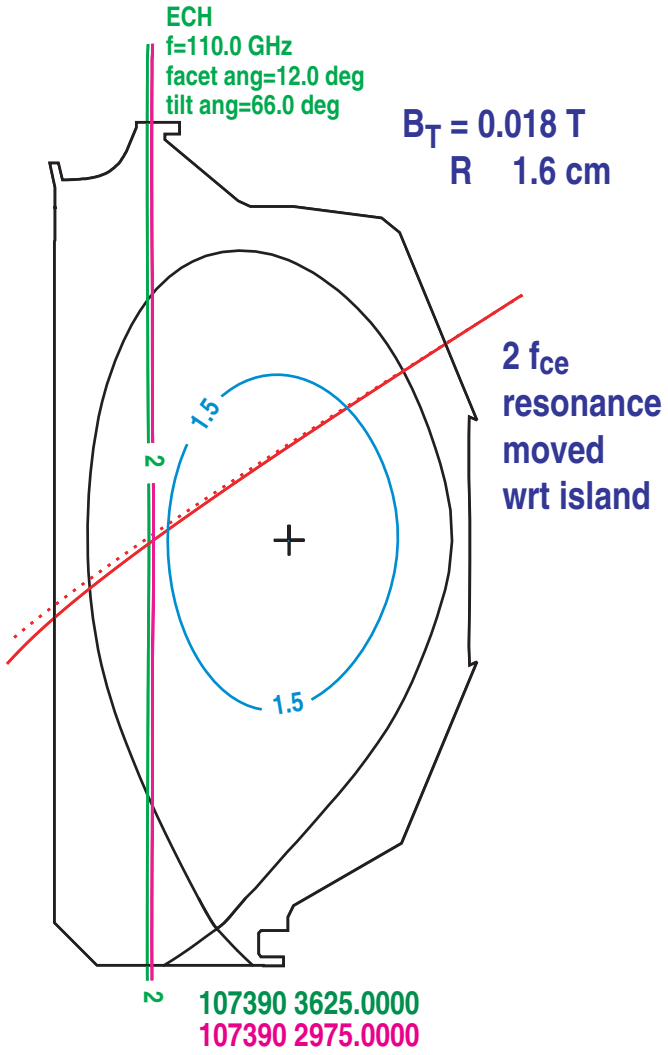
Search Histories Can Be Very Complex: Wrong Initial Direction, Backtracking…. Eventually Suppressing Mode

- Search/suppress follows several dwell/search steps to reach full suppression
- Final suppression point ~same for both blind search and preprogrammed scan of ΔR



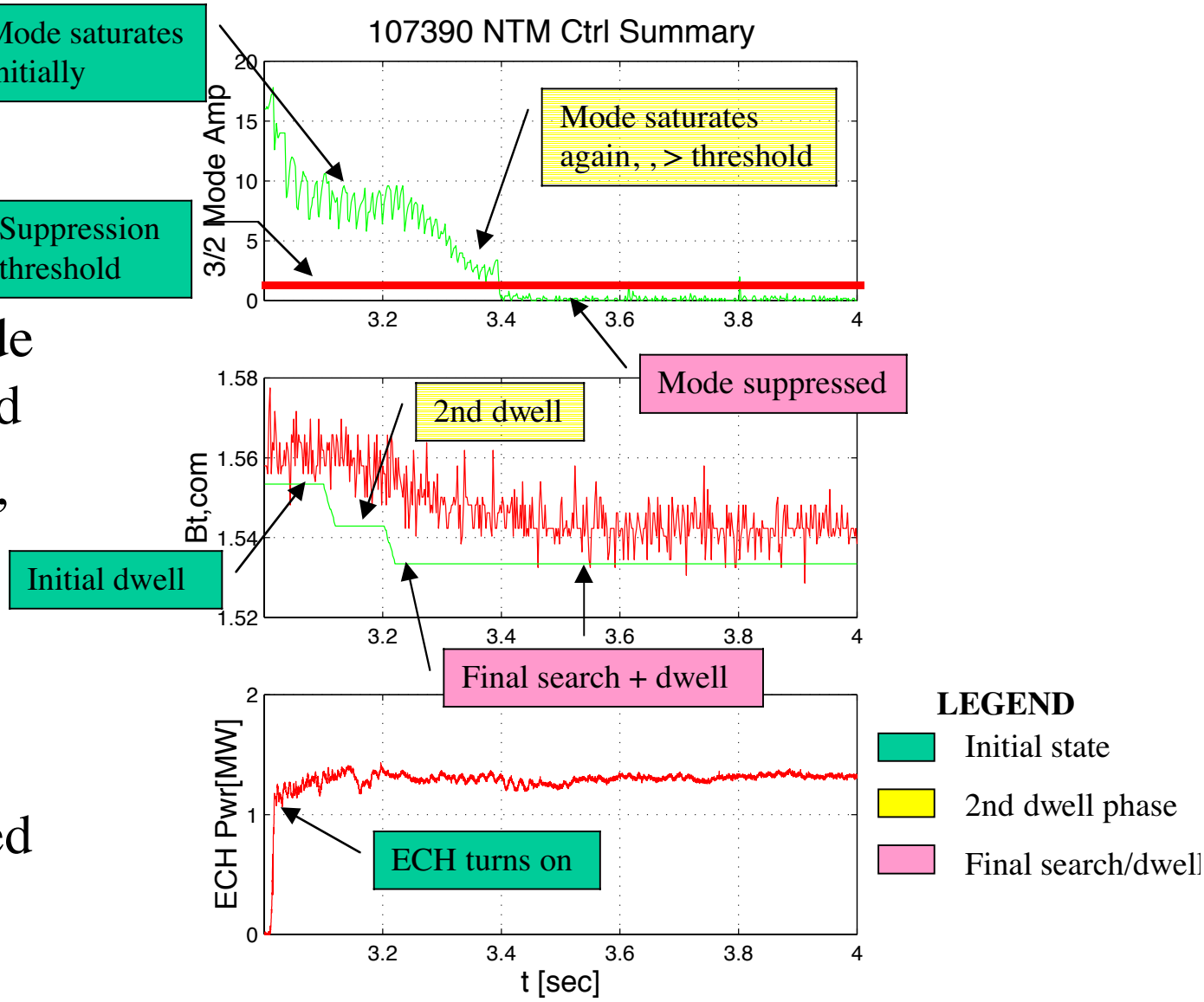
NTM Control Can Also Vary Toroidal Field in Response to Mode Amplitude

- Execute ΔBt "Blind Search" pattern when mode (3/2 island) amplitude exceeds threshold
- Vary toroidal field (and thus resonance location) keeping island location fixed
- ΔBt advantages: preserves plasma shape, maintains pumping
- Successfully used in 2001 Campaign to suppress 3/2 NTM
- Refined versions of algorithm will be applied in 2002 Campaign.



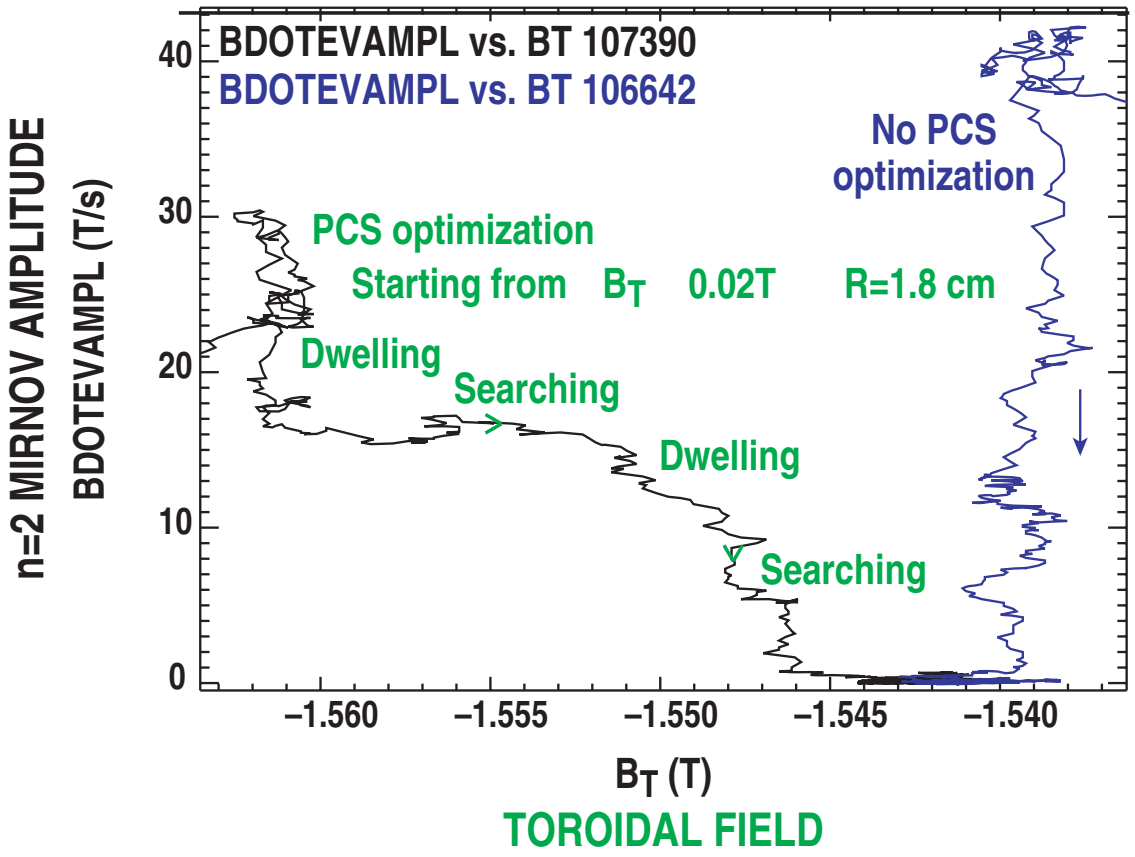
3/2 NTM Suppressed Using Bt Search Initially Off Optimum

- Control algorithm and ECH enabled @3.0 sec
- Search pattern starts when mode ampl > threshold
- 100 msec dwell, 0.01 T step size (ΔR~1 cm): 2 searches hit "sweet spot"
- Mode suppressed in 400 msec



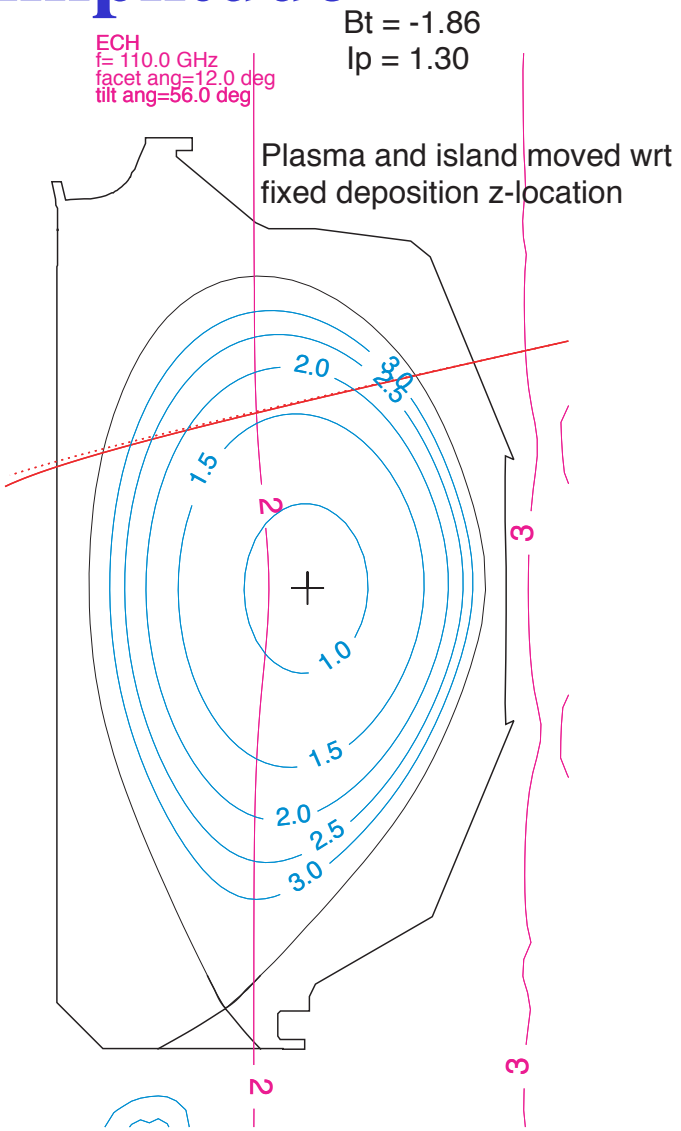
Bt Search/Suppress Finds Same Optimum Location as Preprogrammed ΔBt Scan

- Search/suppress follows several dwell/search steps to reach full suppression
- Suppression point (Bt~-1.54) same for both blind search and preprogrammed scan of ΔBt



NTM Control Can Vary Vertical Position in Response to Mode Amplitude

- Execute ΔZ "Blind Search" pattern when mode (3/2 island) amplitude exceeds threshold
- Move plasma vertical position (and island) "rigidly" while keeping resonance fixed
- ΔZ advantages: island is larger on top (less alignment accuracy required), allows higher field, Shafranov shift orthogonal to vertical motion, best for use of realtime launcher steering
- Piggyback tests of algorithm successfully executed with NTM present but without ECCD (not yet tested with both)
- Plan to use in 2002 Campaign experiments



Summary

- Use of realtime NTM "Search and Suppress" control was successful in suppressing 3/2 NTM using major radial and toroidal field regulation (separately)
- Vertical motion regulation for island/ECCD alignment has been implemented but not used operationally yet
- Simulation of NTM suppression scenarios with blind search algorithm was used to determine control parameters prior to experimental execution
- 2002 campaign will make use of realtime q=3/2 identification, compensation for Shafranov shift effects, realtime control of gyrotrons

NTM Suppression Plans for 2002 Campaign

- Regulation of vertical position (with plasma-top ECCD deposition) for realtime Search/Suppress of 3/2 NTM
- Higher order corrections to algorithm:
  - Shafranov shift (due to β_p change)
  - Doppler shift (moves actual resonance outboard)
- Direct feedback on R(q=3/2) error in concert with small-displacement Search/Suppress algorithm
- Realtime gyrotron control
- 2/1 NTM suppression