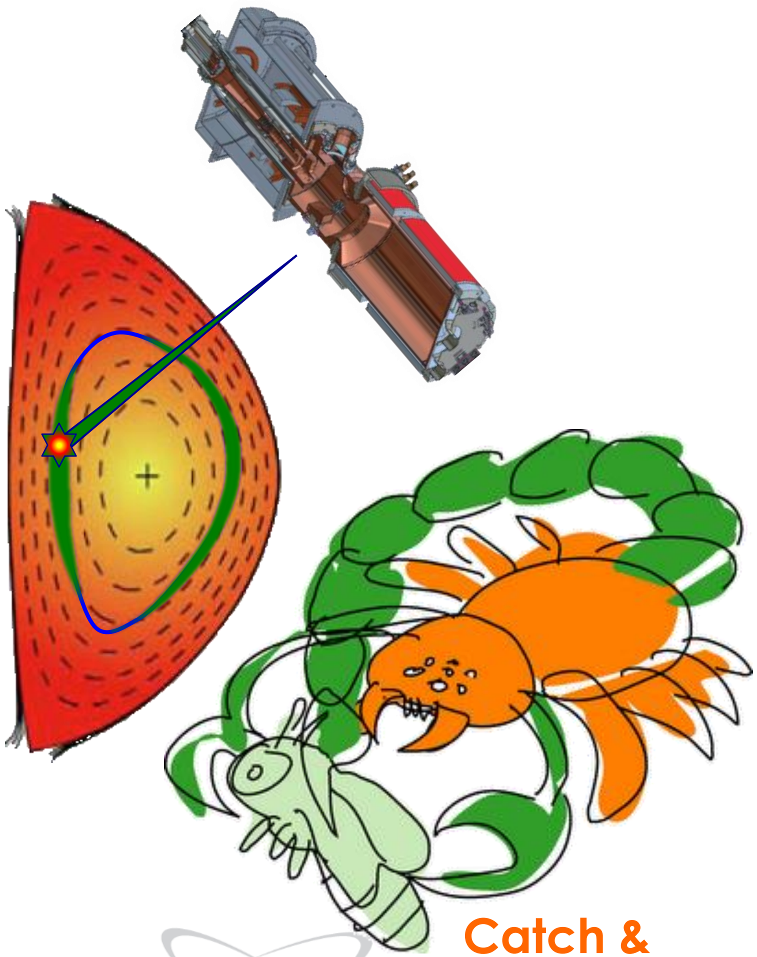
Neoclassical Tearing Mode Control by Electron Cyclotron Current Drive Using Dynamic Alignment to Access Higher Performance



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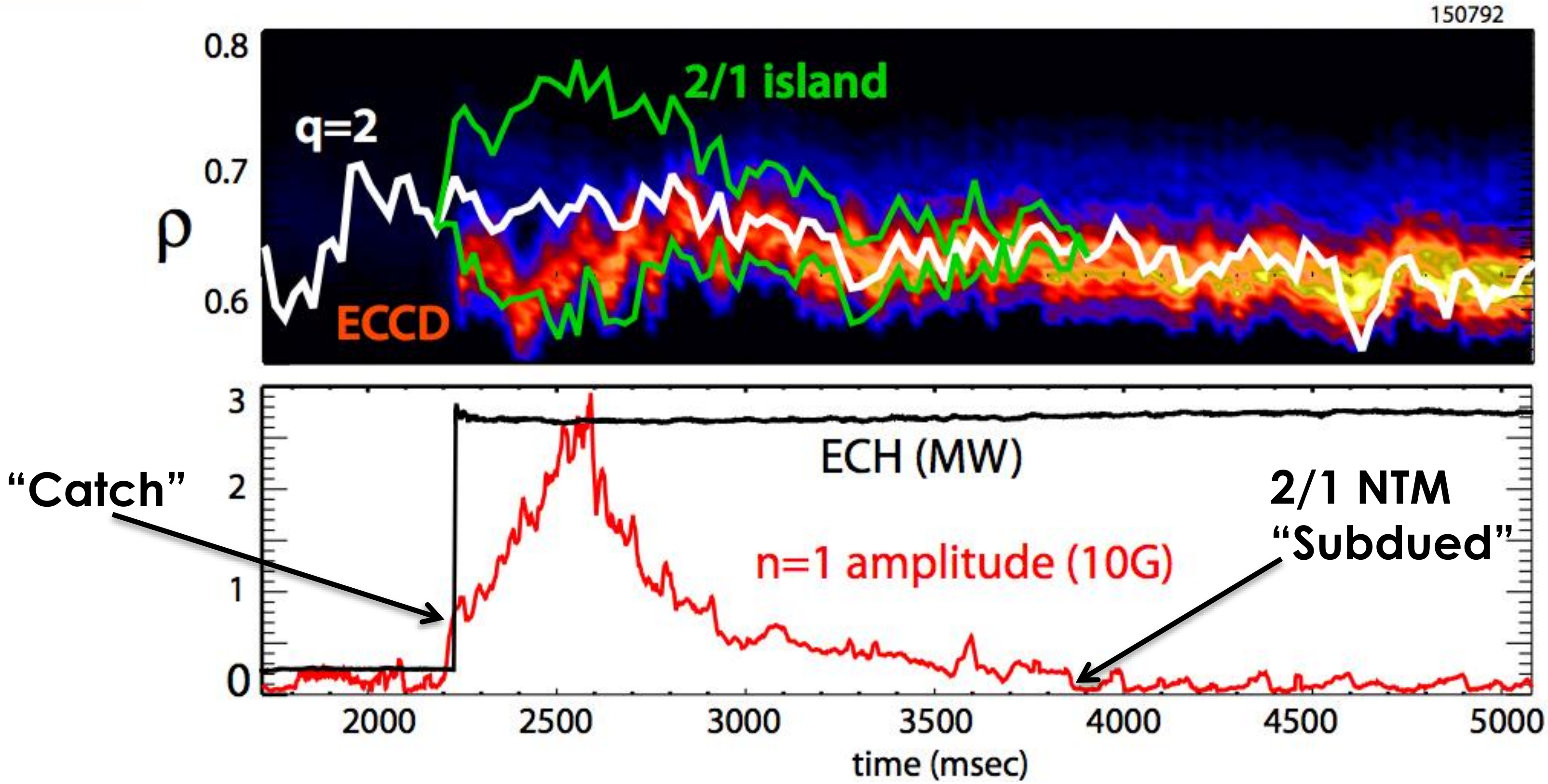
Presented at XX RF Conference, June, 2013

Catch & Subdue

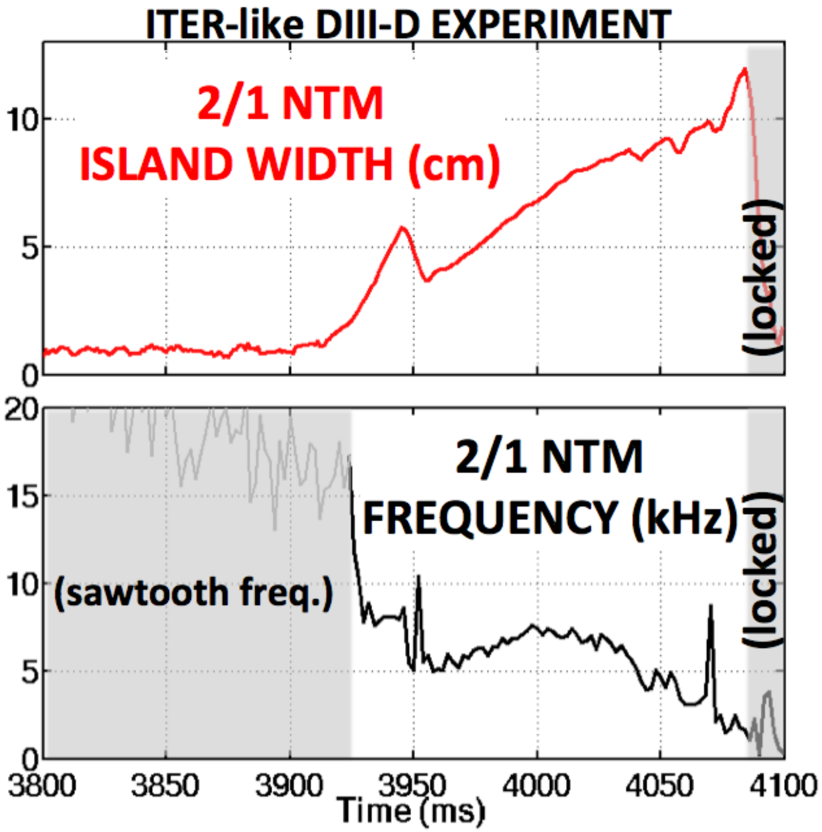
Fully Automatic NTM Control Using Real-Time Mirror Steering Can Suppress the 2/1 Mode



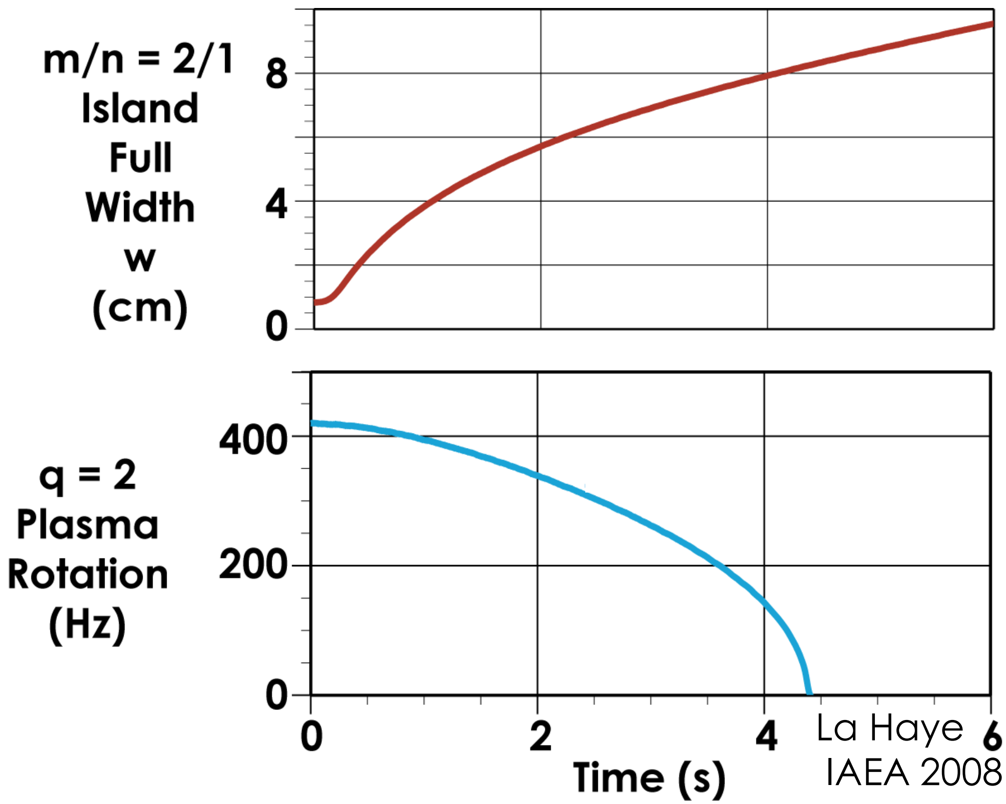
- New fully automatic NTM control system at DIII-D integrates all the Real-Time (RT) components of mode detection, location, suppression.
- New control strategy "*Catch and Subdue*" can reduce the EC power use; lead to higher Q and reduce disruption risk in ITER

In ITER, without ECCD, 2/1 Islands Can Grow, Lock and Cause Disruptions

DIII-D experiment

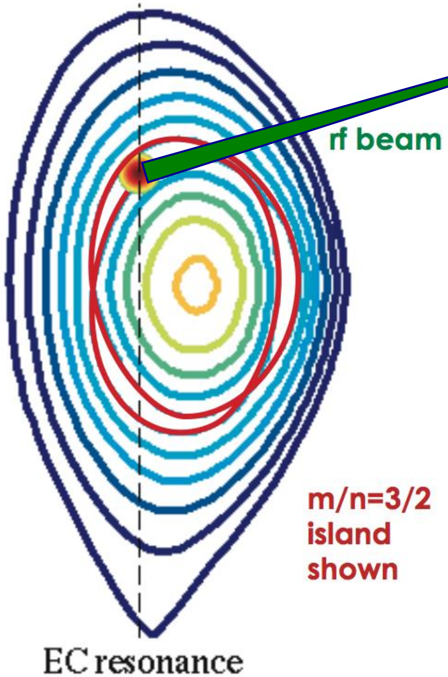


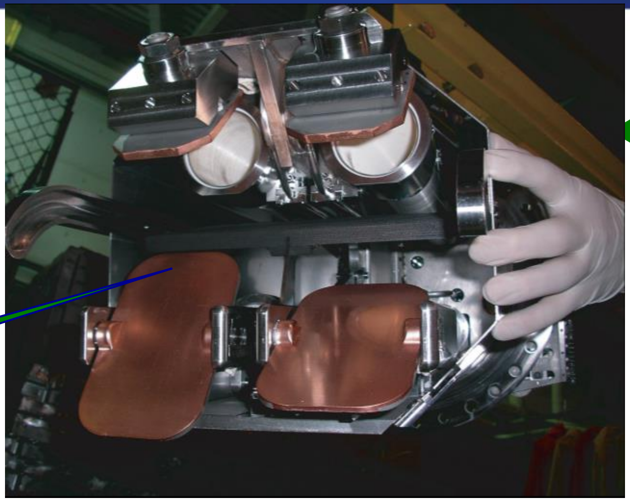
ITER Simulation



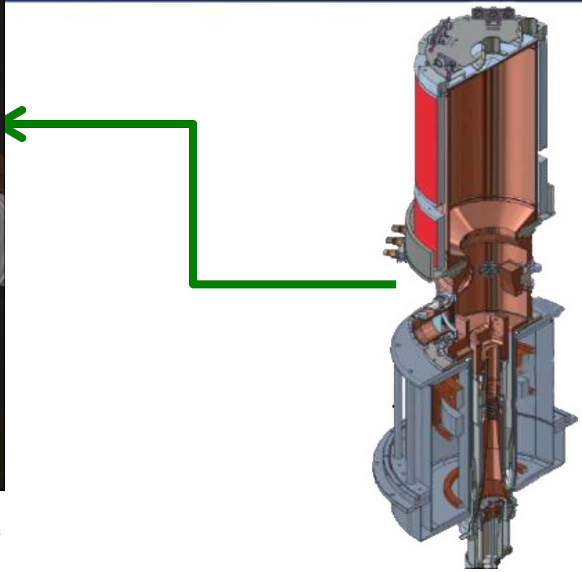
- **Loss of H-mode and disruption is expected after locking**
- **Need robust and efficient NTM control strategies**

Accurate Alignment of ECCD to Resonant Surface Suppresses Neoclassical Tearing Mode





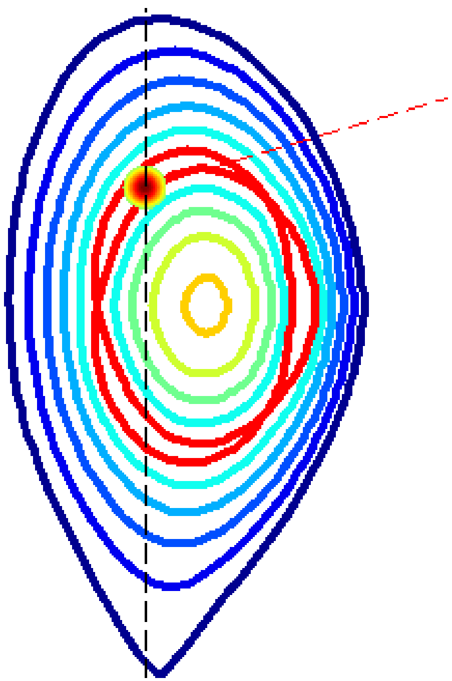
Steerable Launcher Mirror

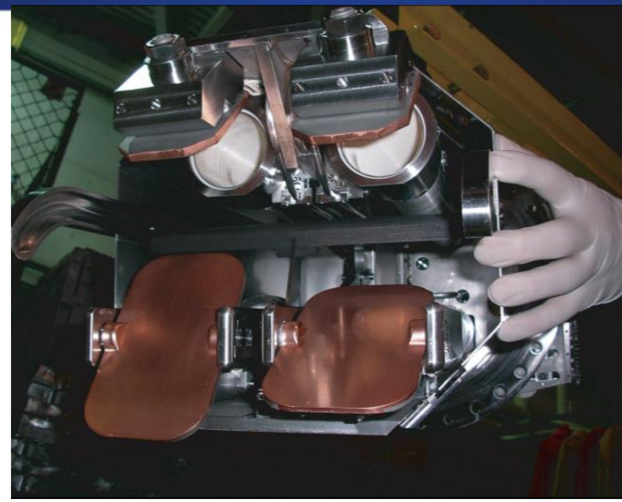


5 Gyrotrons
(~2.8 MW injected)

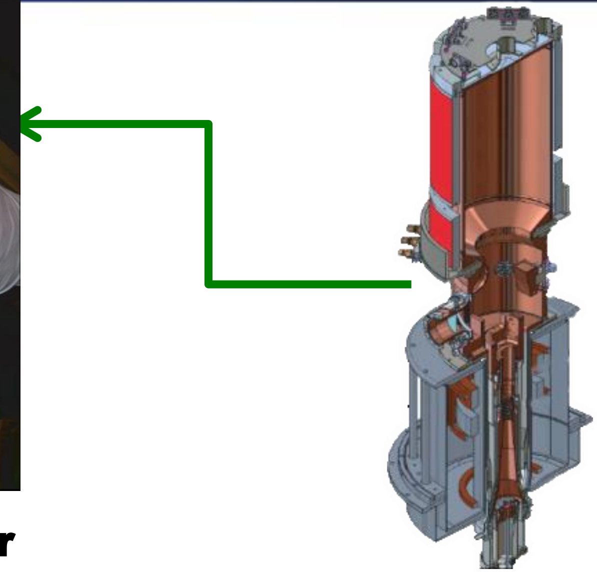
- Align the Electron Cyclotron Current Drive deposition with the Neoclassical Tearing Mode (NTM) island for suppression
- Mirrors steered to move the beam vertically along the EC resonance for best alignment

Accurate Alignment of ECCD to Resonant Surface Suppresses Neoclassical Tearing Mode





Steerable Launcher Mirror



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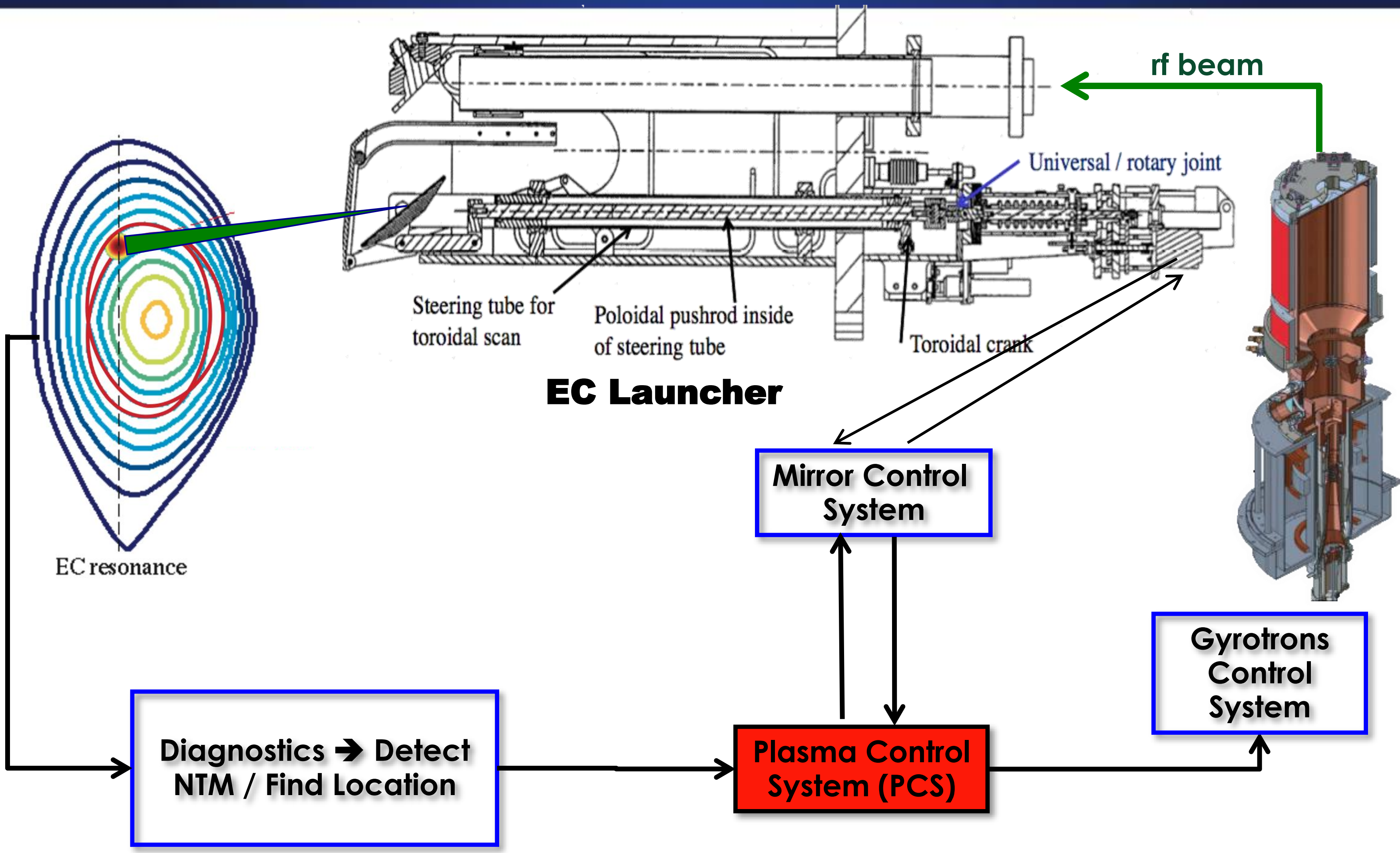
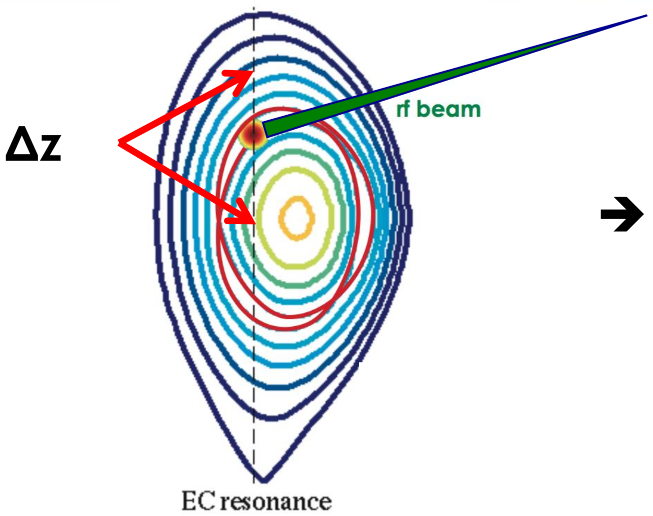
DIII-D NTM Control System Overview



Real time MSE Equilibria Enable Precise Tracking of Resonant Surface



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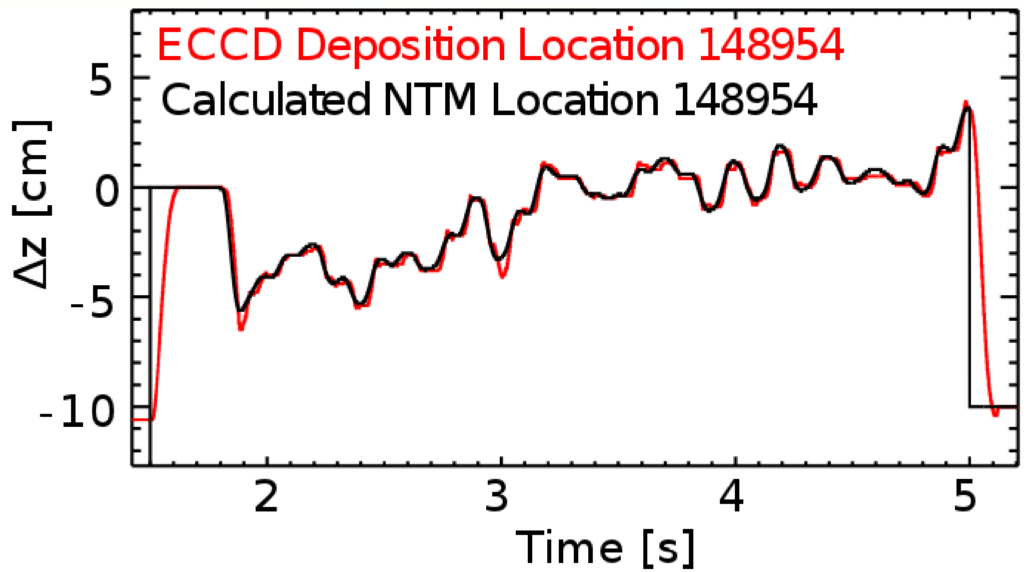
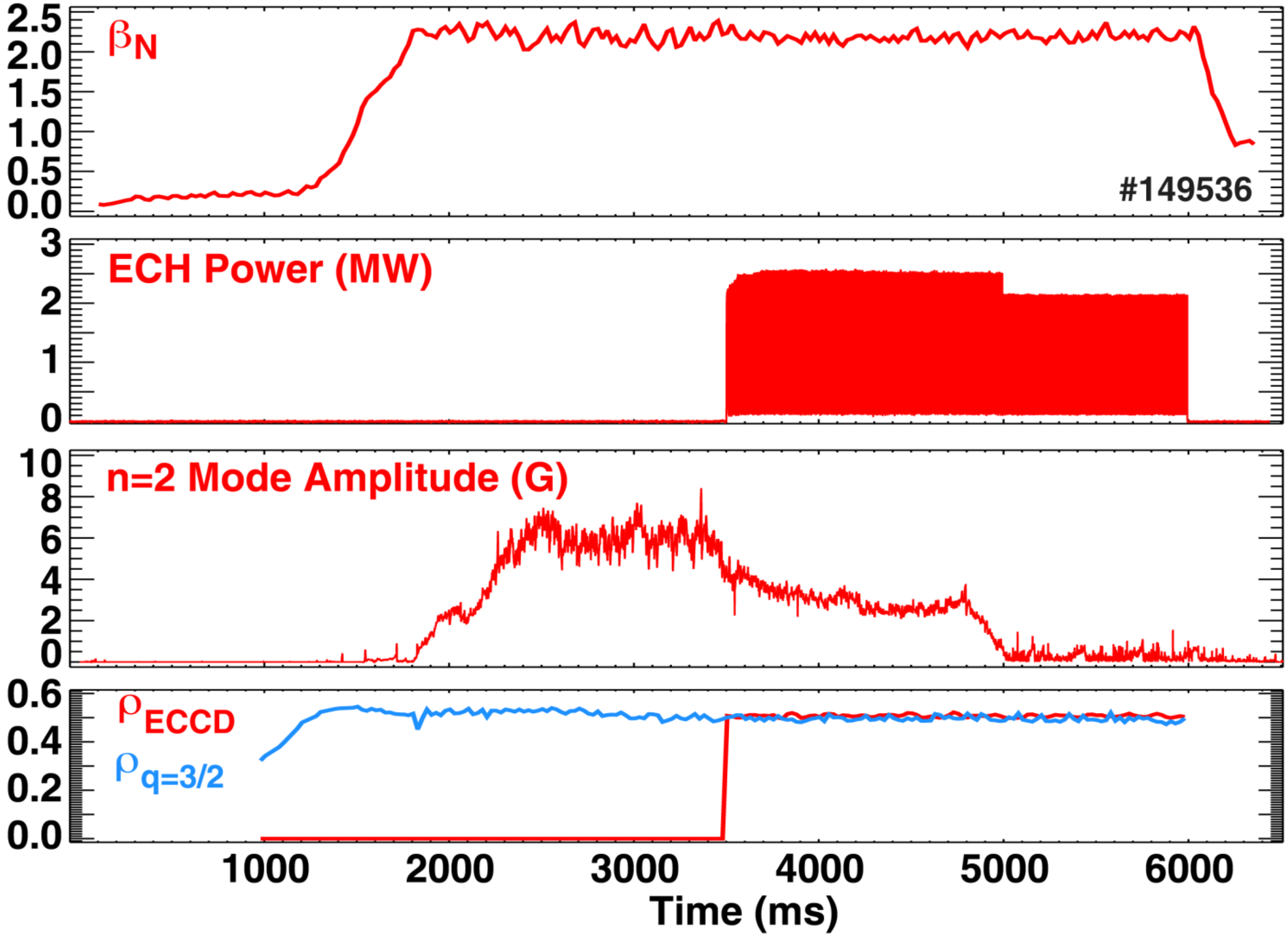


- **Real time MSE tracks q=3/2 or 2**
- **Calculate intersection point of the q surface with $2f_{ce}$**
- **Move the mirrors to align the ECCD with NTM**
- **Tracking performance with minimal overshoot and <1 cm error.**
- **Calibration:**
  - ***ECCD deposition:* *with 100 Hz ECCD modulation***
  - ***NTM location:* *with ECE based calculation & Sweeps across NTM***
  - ***Mapping of angle in mirror to position in plasma:* *Ray tracing***

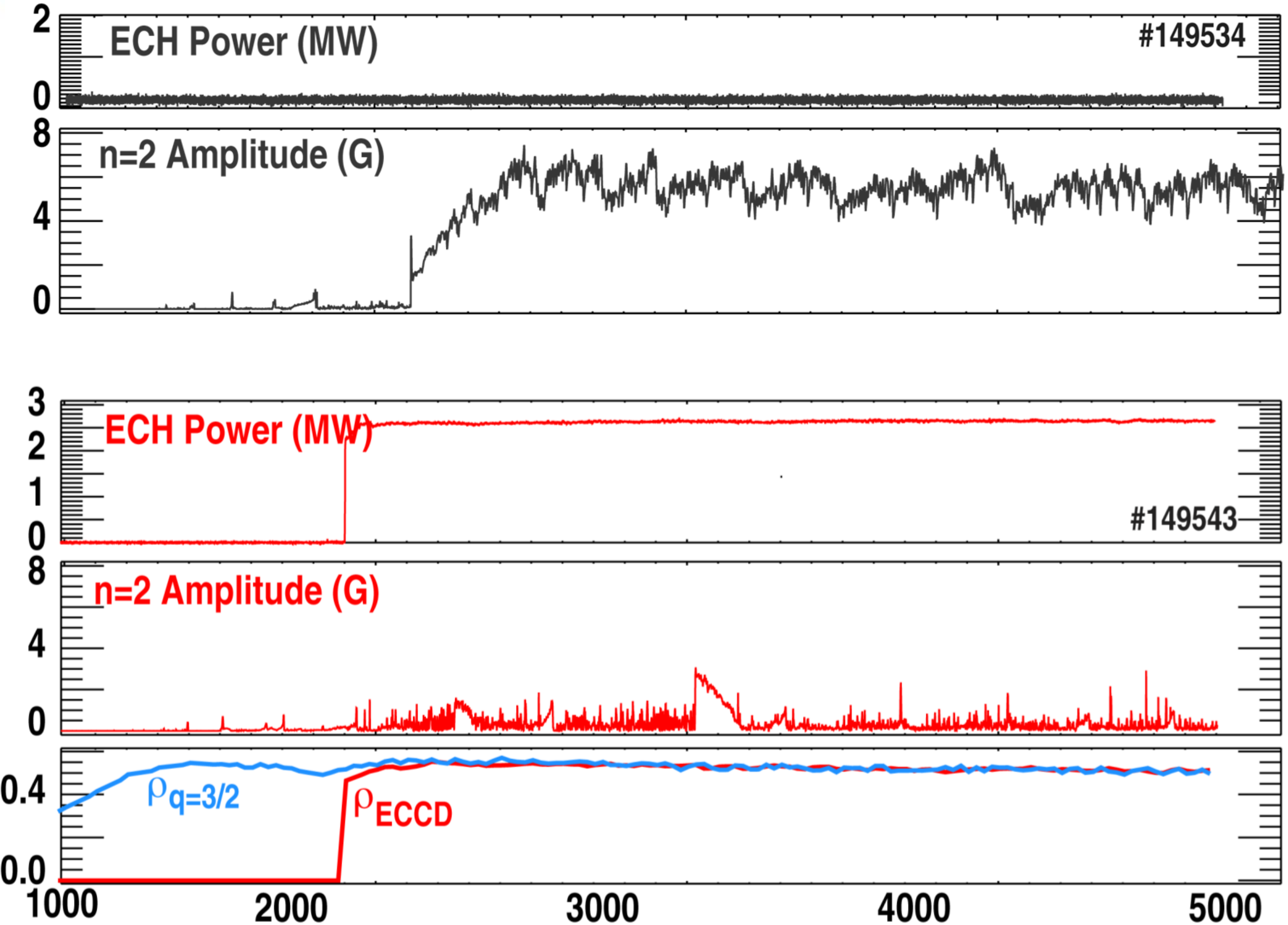
Application to the 3/2 NTM:

- Head room to develop the technique

NTM Control Methods: Successful 3/2 NTM Suppression After Mode Saturation



NTM Control Methods: Preemptive NTM Suppression Achieved

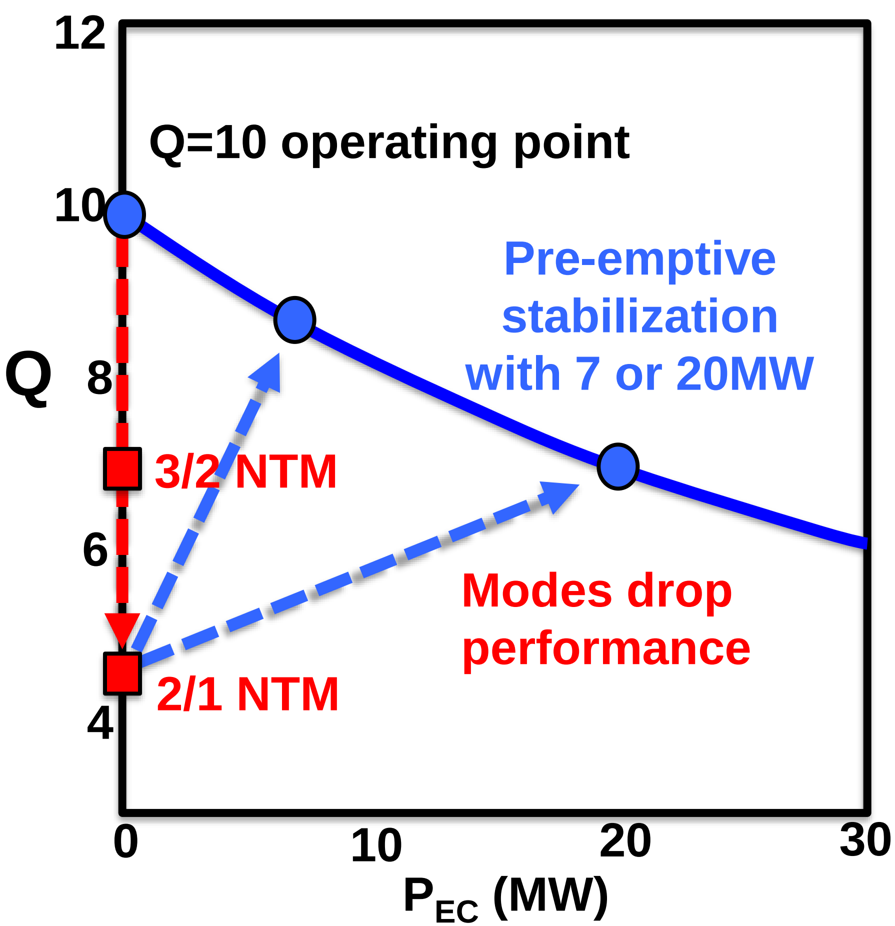


Without ECCD, 3/2 NTM develops

NTM Preemption with ECCD

Minimize EC Use for Higher Q Operation

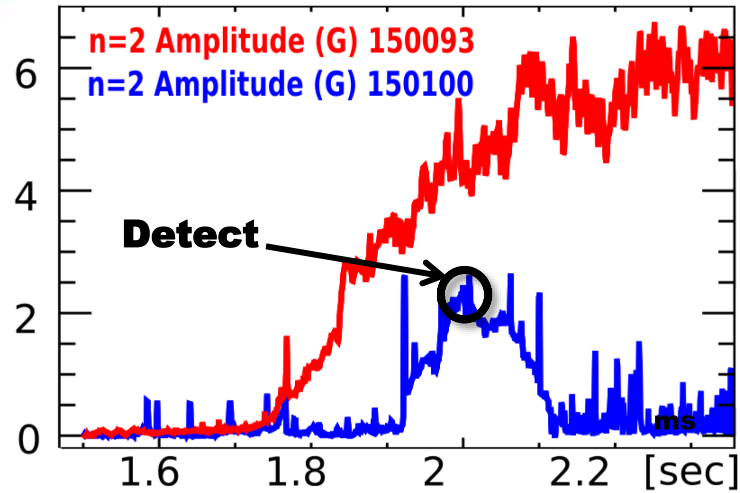
Pre-emptive suppression



[Zohm, IAEA 2006]

- **ITER strategies:**
  - **Preemptive suppression:** ***uses continuous power, decreases Q***
  - **Suppression after saturation:** ***requires large power and long time, risking disruptions***
  - **Preferable to intercept mode while still small**

New "Catch and Subdue" Technique is More Efficient



Example of 3/2 Catch&Subdue

- **Continuous q-surface Following**
  - Constantly calculate q-surface in plasma
  - Track w/ mirrors and be ready to suppress
- **Detect that island is forming (2/1 or 3/2)**
  - Real-time Fourier analysis of Mirnov diagnostics
- **Turn Gyrotrons ON when the mode is detected**
- **Result: Catch the island before it saturates**
  - Island saturation for 2/1 mode ~100-150 ms, 3/2 mode ~200ms

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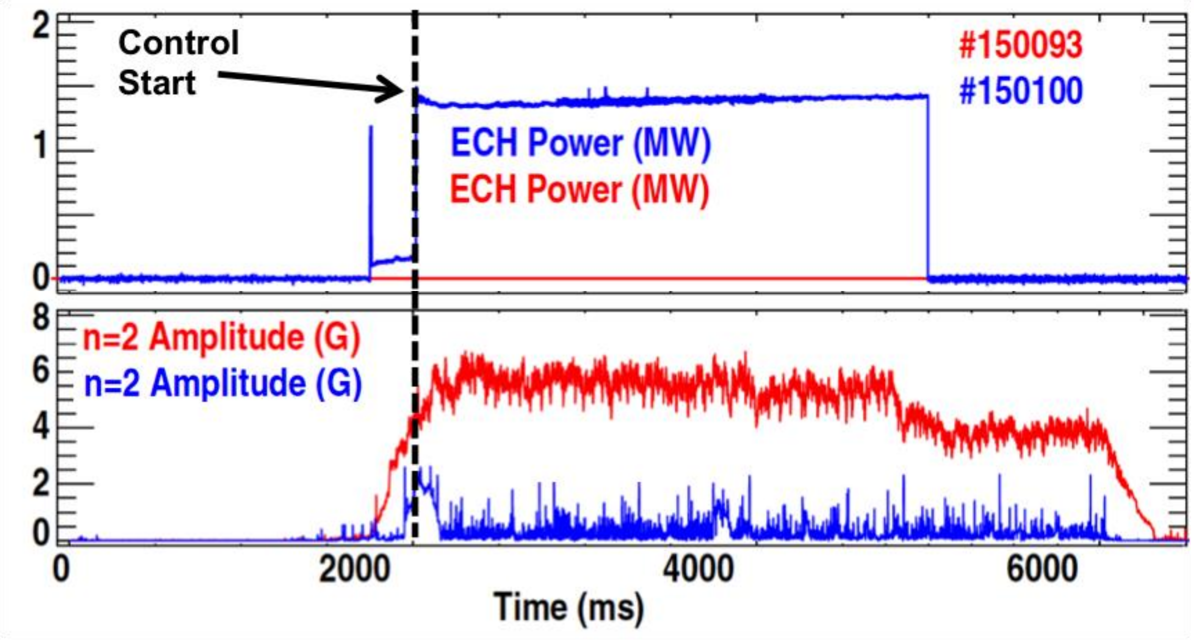
Catch and Subdue Technique Enables Much Faster Suppression and Reduced ECCD Power



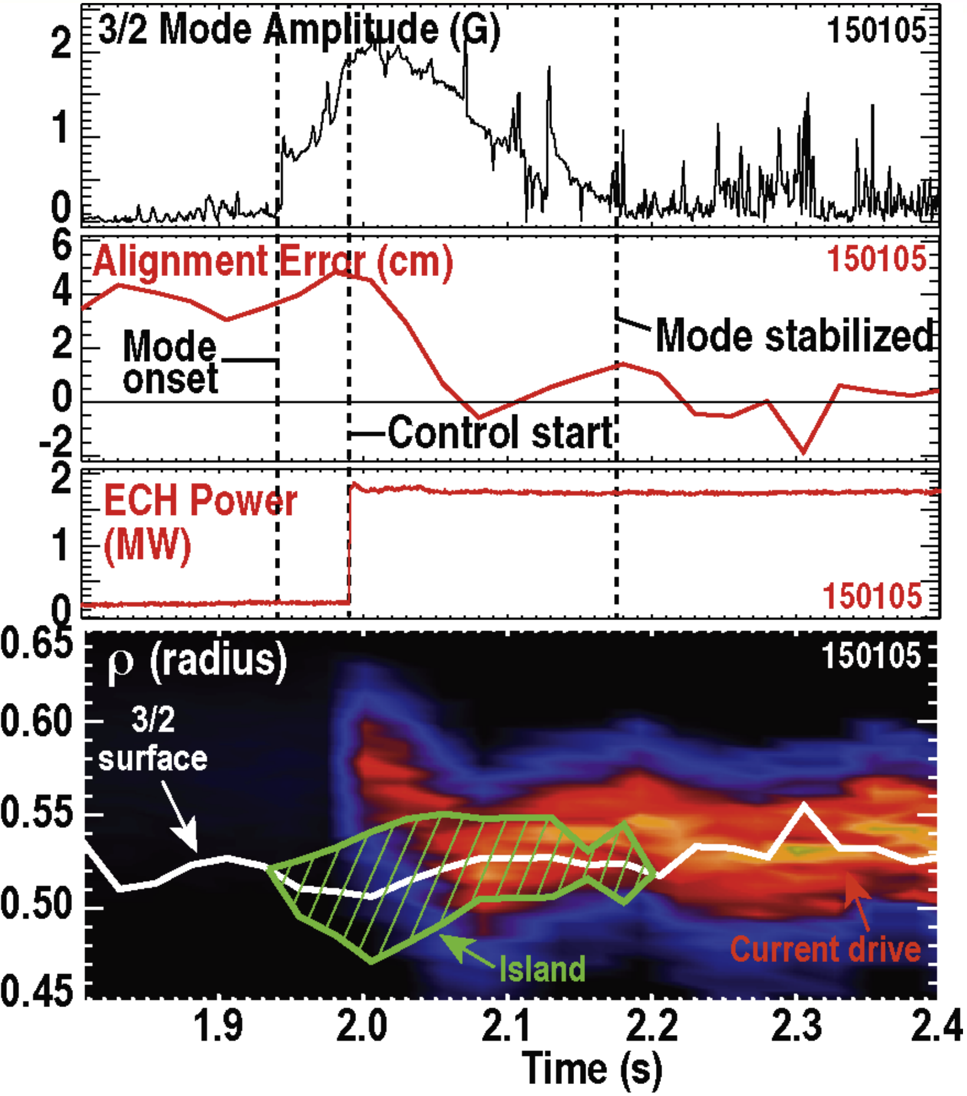
150093: No ECCD
(Beam drops after 5 sec)

150100: Catch and Subdue
(Many more examples)

Results:

- *Less power needed*: Suppression with 3 gyrotrons instead of 5 for fully saturated modes
- *Faster suppression* (~140 ms after the gyrotrons turn on)
- *Avoids continuous power* deposition of the preemptive approach

Catch and Subdue Even Works Well Starting from Intentional Misalignment of ECCD and q Surface



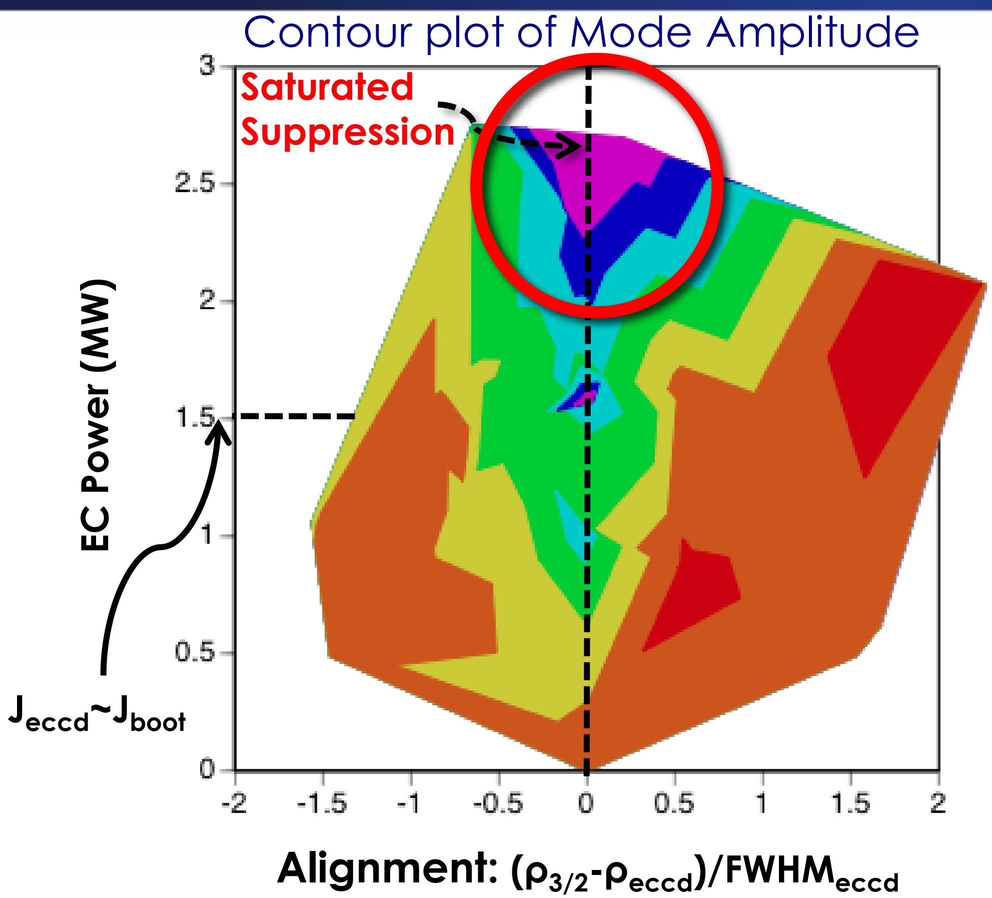
Experiment:

- Intentional mirror misalignment ~4 cm

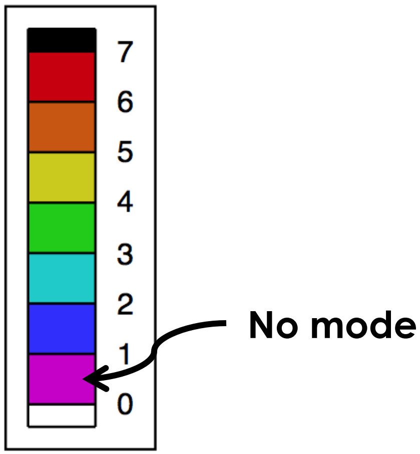
Result:

- System rapidly corrects deposition location
- Fast suppression: complete suppression takes ~40 ms longer than aligned case

Saturated Mode Suppression of 3/2 NTM Requires Good Alignment & $J_{eccd}>J_{boot}$



Color=Mode amplitude (Gauss)



1. **Power: Peak ECCD (J_{eccd}) > local bootstrap current density (J_{boot}) ➔ To replace the missing current in the island.**

2. **Alignment: ECCD aligned with the 3/2 island within the half width of the ECCD profile**

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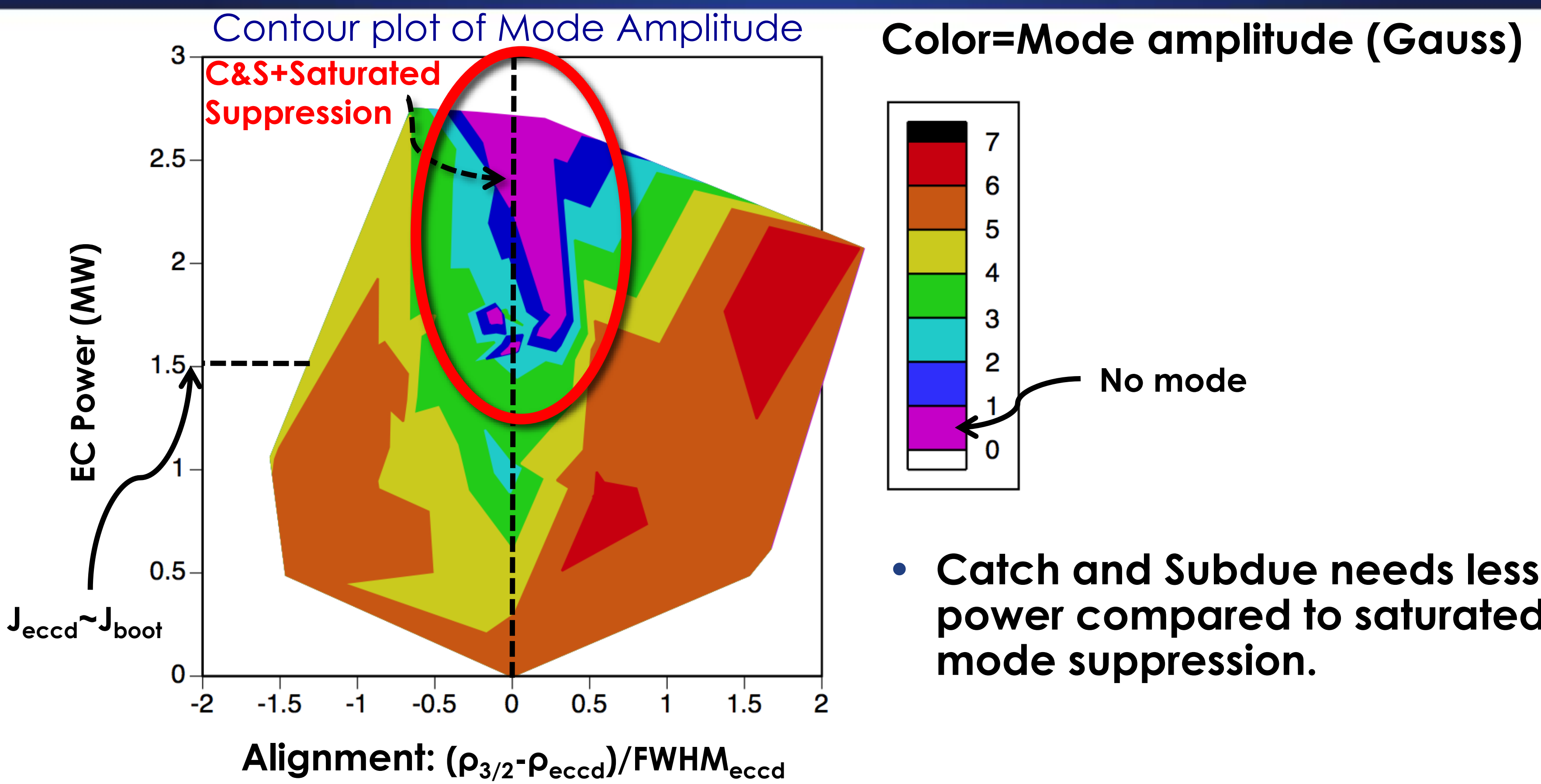
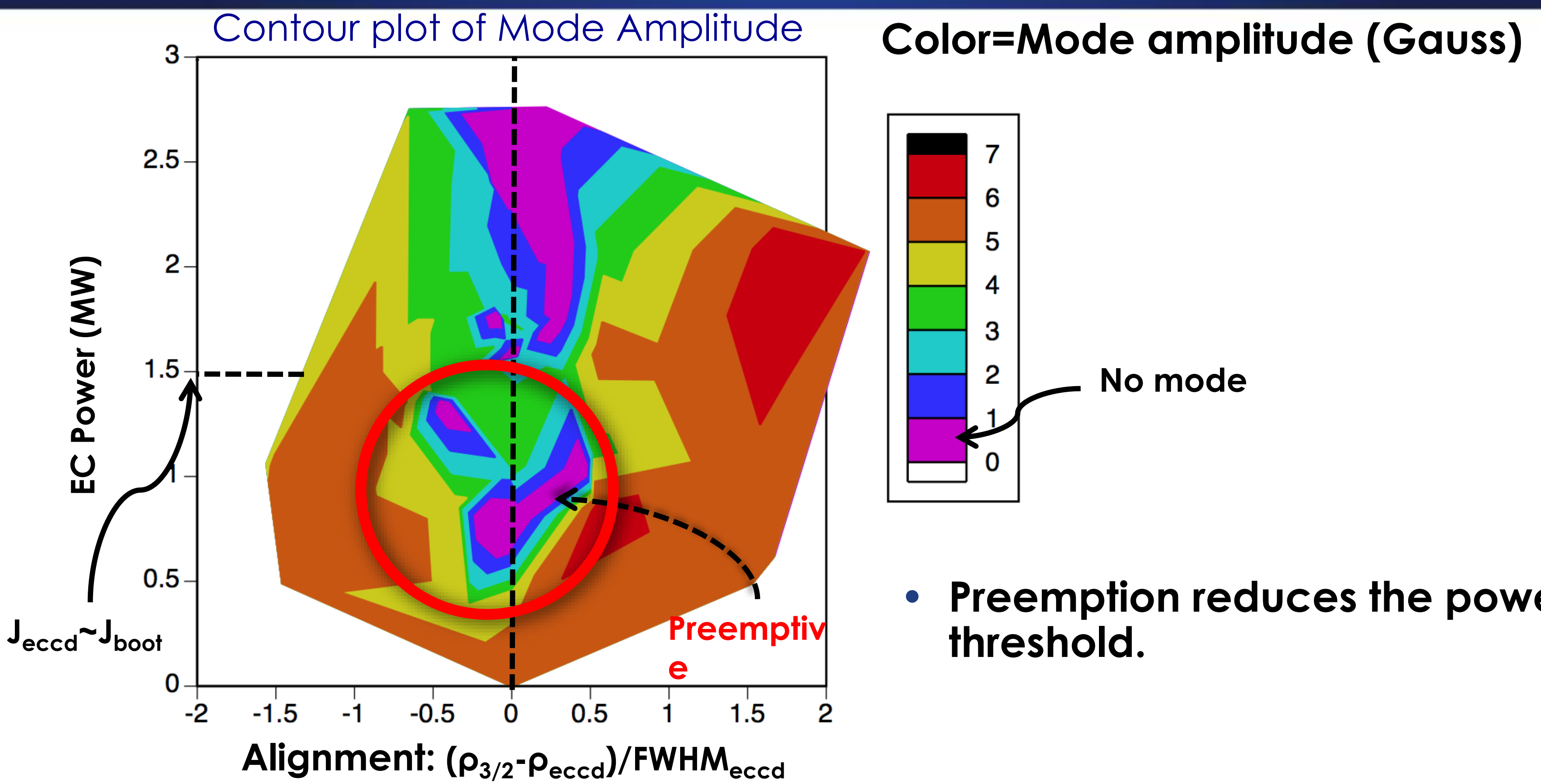
Catch and Subdue Needs Less Power



- **Catch and Subdue needs less power compared to saturated mode suppression.**

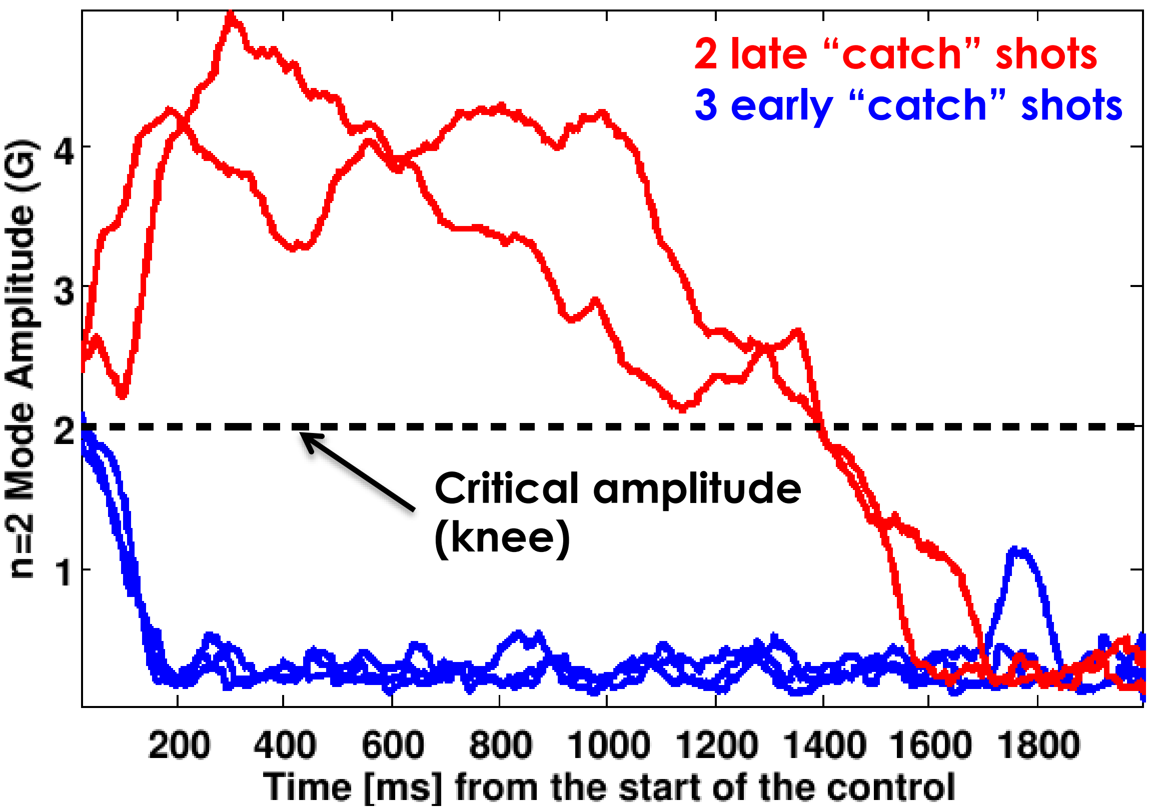
DIII-D NATIONAL FUSION FACILITY

Preemptive ECCD Reduces Power Requirement for 3/2 Suppression by Over 50%



- **Preemption reduces the power threshold.**

Early Mode Detection is Key for Rapid NTM Suppression



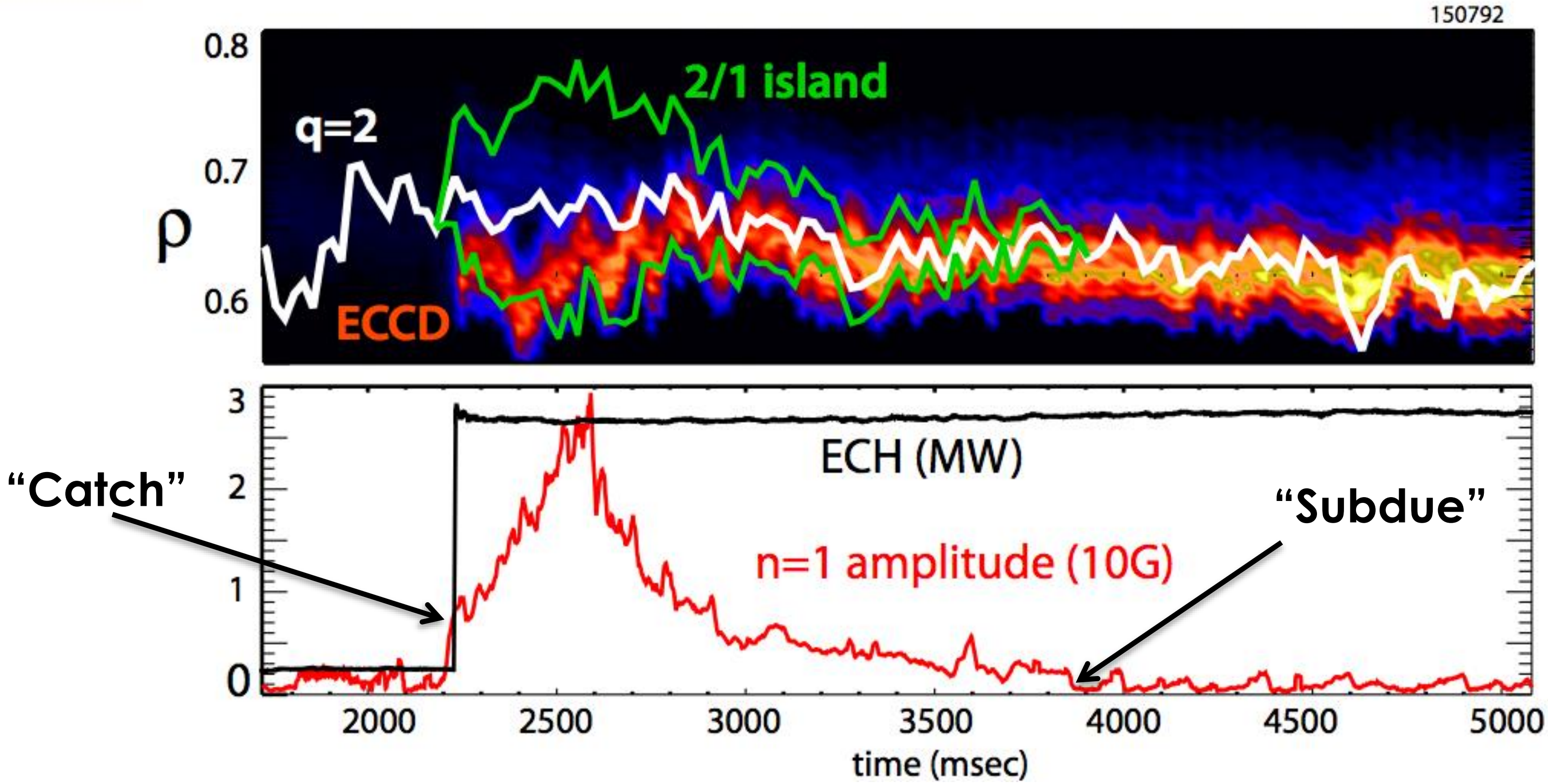
- **Below the critical amplitude** *small island effect takes over which enable fast suppression*
- **Above the critical amplitude** *the mode saturates and suppression takes more than a second or becomes unachievable*

***All shots with same β_N and ECCD is actively aligned with a power of 1.5±0.2 MW at the island location.**

Application to the 2/1 NTM:

– Most challenging and important case

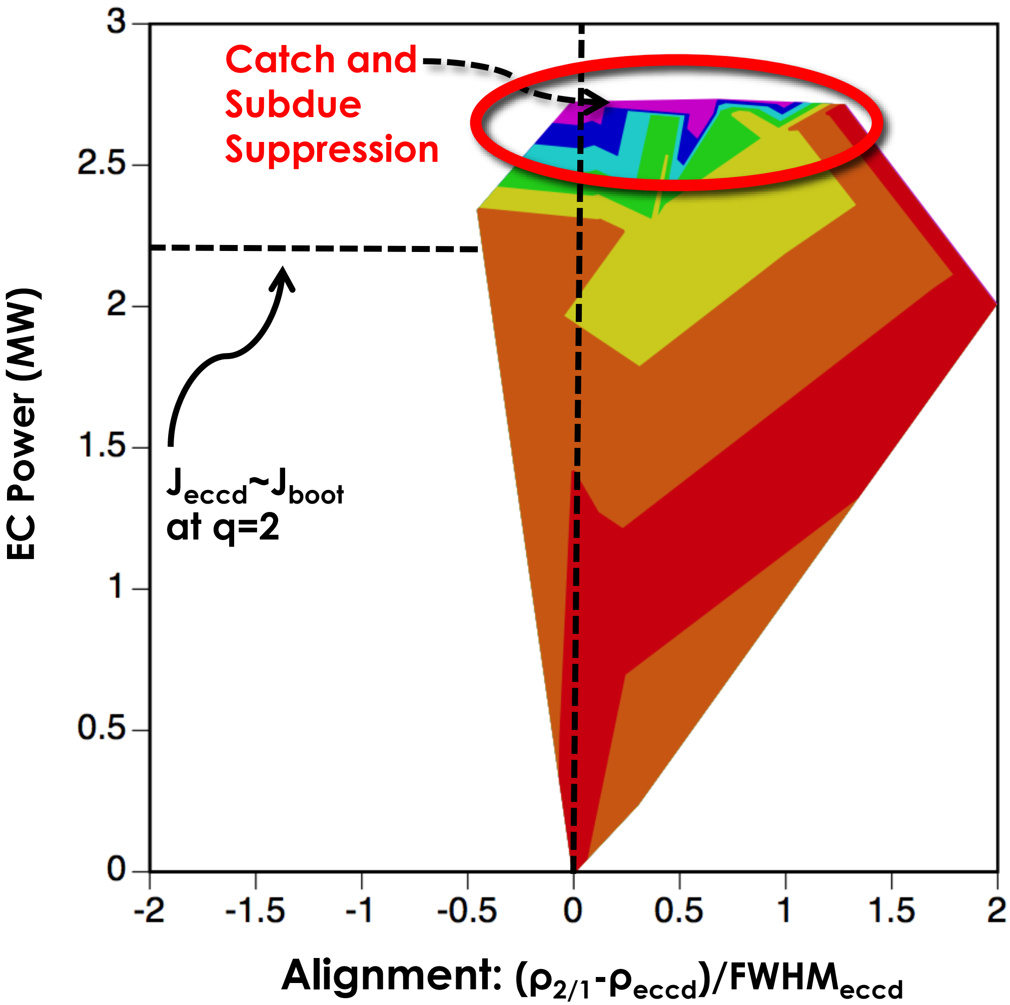
Successful 2/1 NTM Catch and Subdue Demonstrated



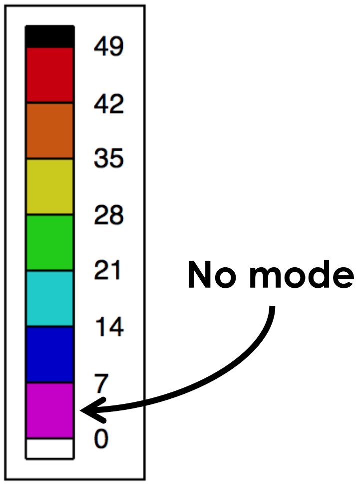
- Peak mode amplitude is reduced; without ECCD, mode reaches ~40 G and locks with loss of H-mode
- The mode is brought to full suppression

2/1 Mode Suppression Requires Good Alignment & $J_{eccd} > J_{boot}$

Contour plot of Mode Amplitude

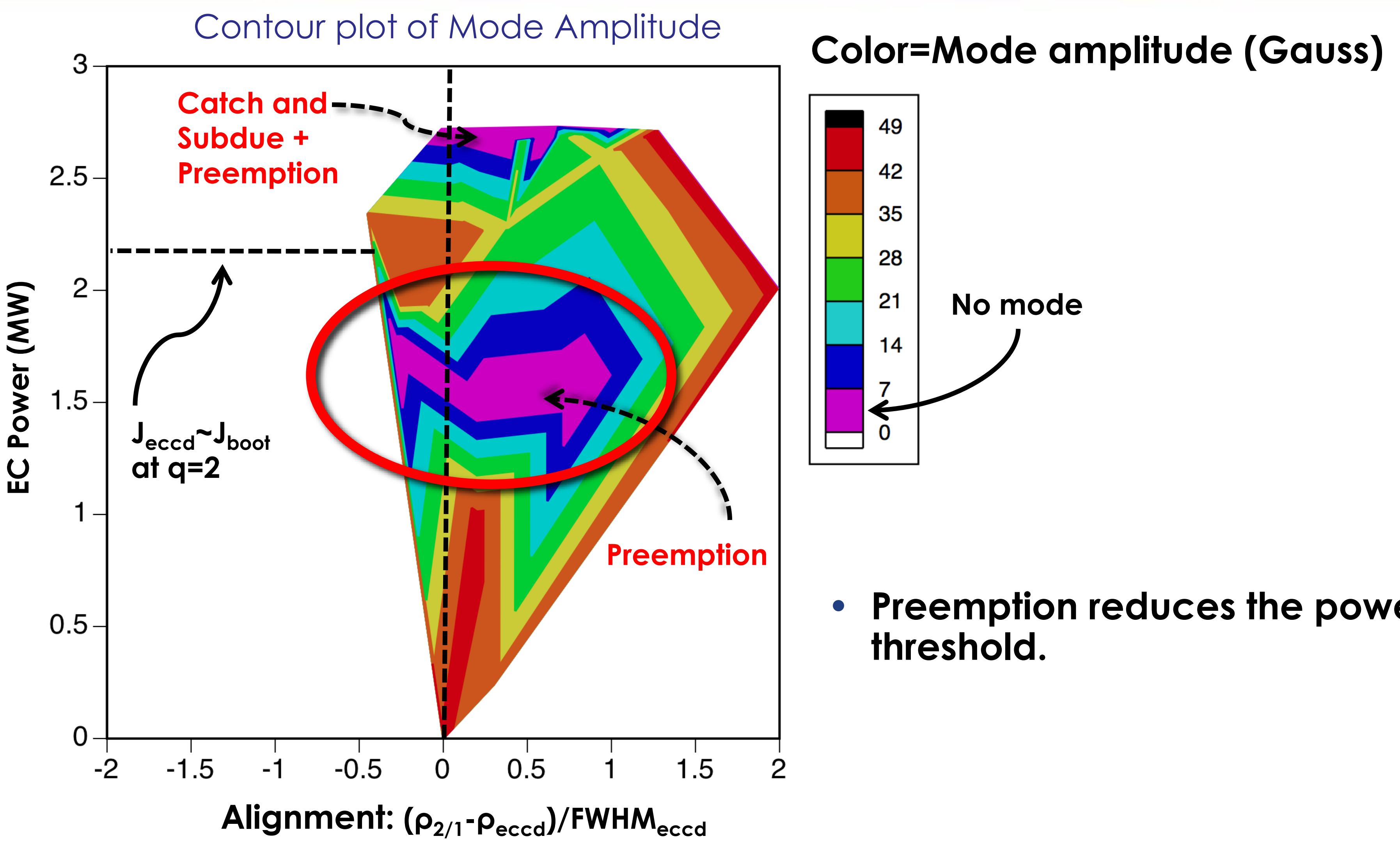


Color=Mode amplitude (Gauss)



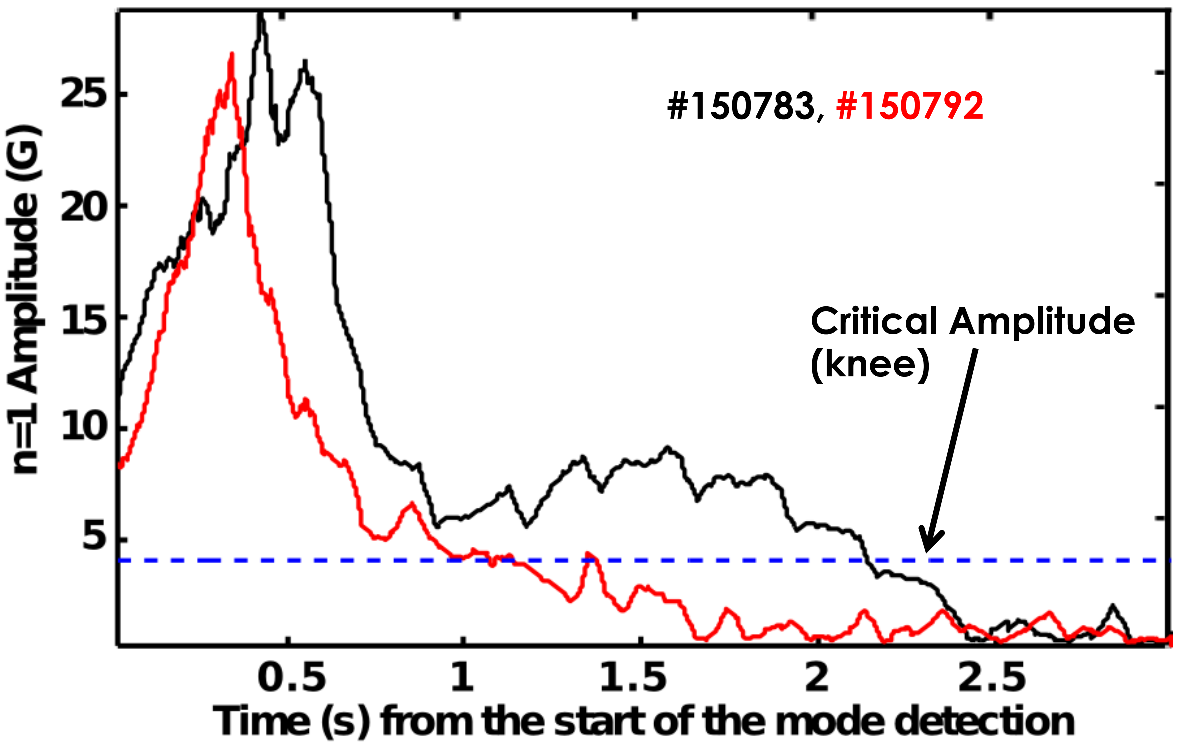
- No cases of Saturated Supression
- Catch & Subdue suppression of 2/1 pushes the limit of the available EC power

Preemptive ECCD Reduces Power Requirement for 2/1 Suppression by 40%



- **Preemption reduces the power threshold.**

Faster Suppression Needs Early Mode Detection for "Catch and Subdue"

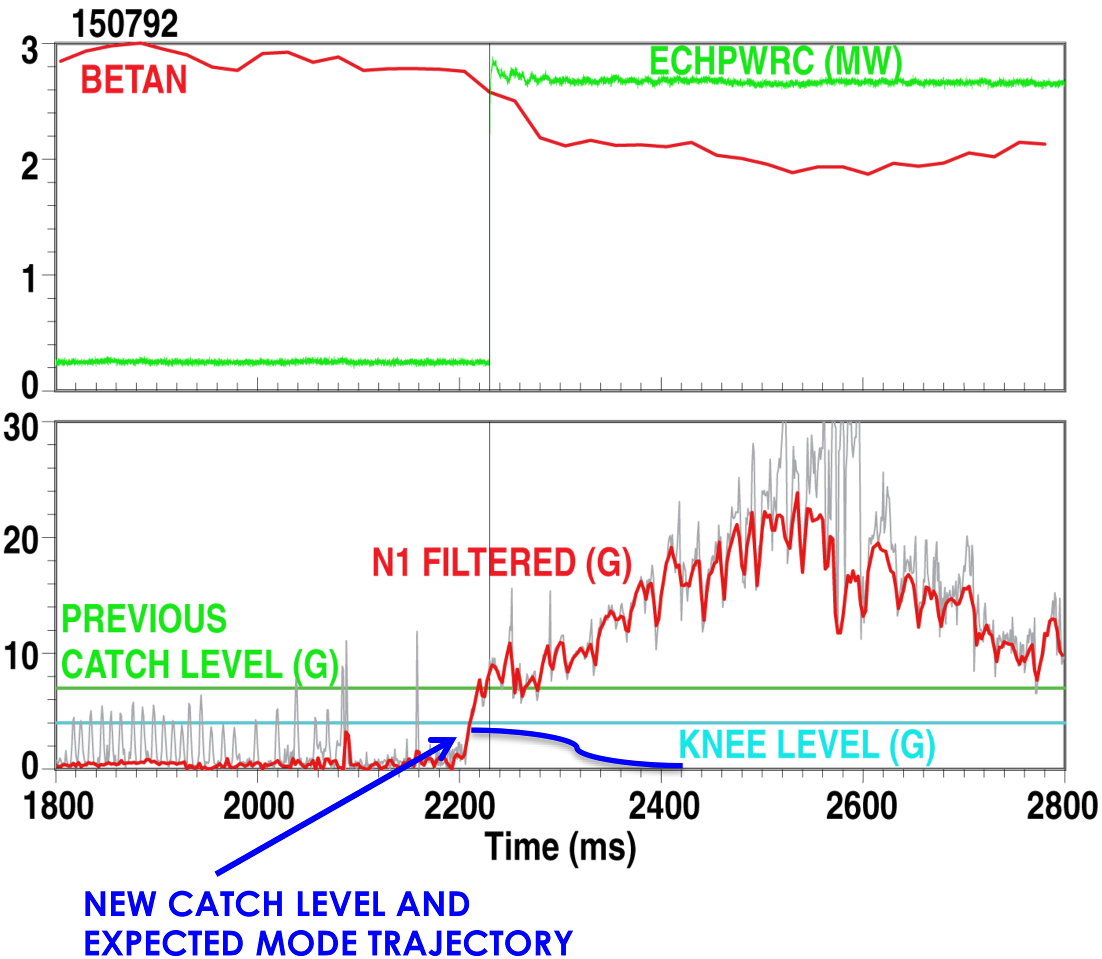


- **Islands caught bigger than the critical amplitude takes much longer to suppress**
- **Noise from sawteeth, fishbones and ELMs are hindrance for small island detection**
  - Also important for ITER
- **Detection below the critical amplitude would reduce the energy even lower**

New Capabilities for 2013:

– Improvements to the Catch Subdue

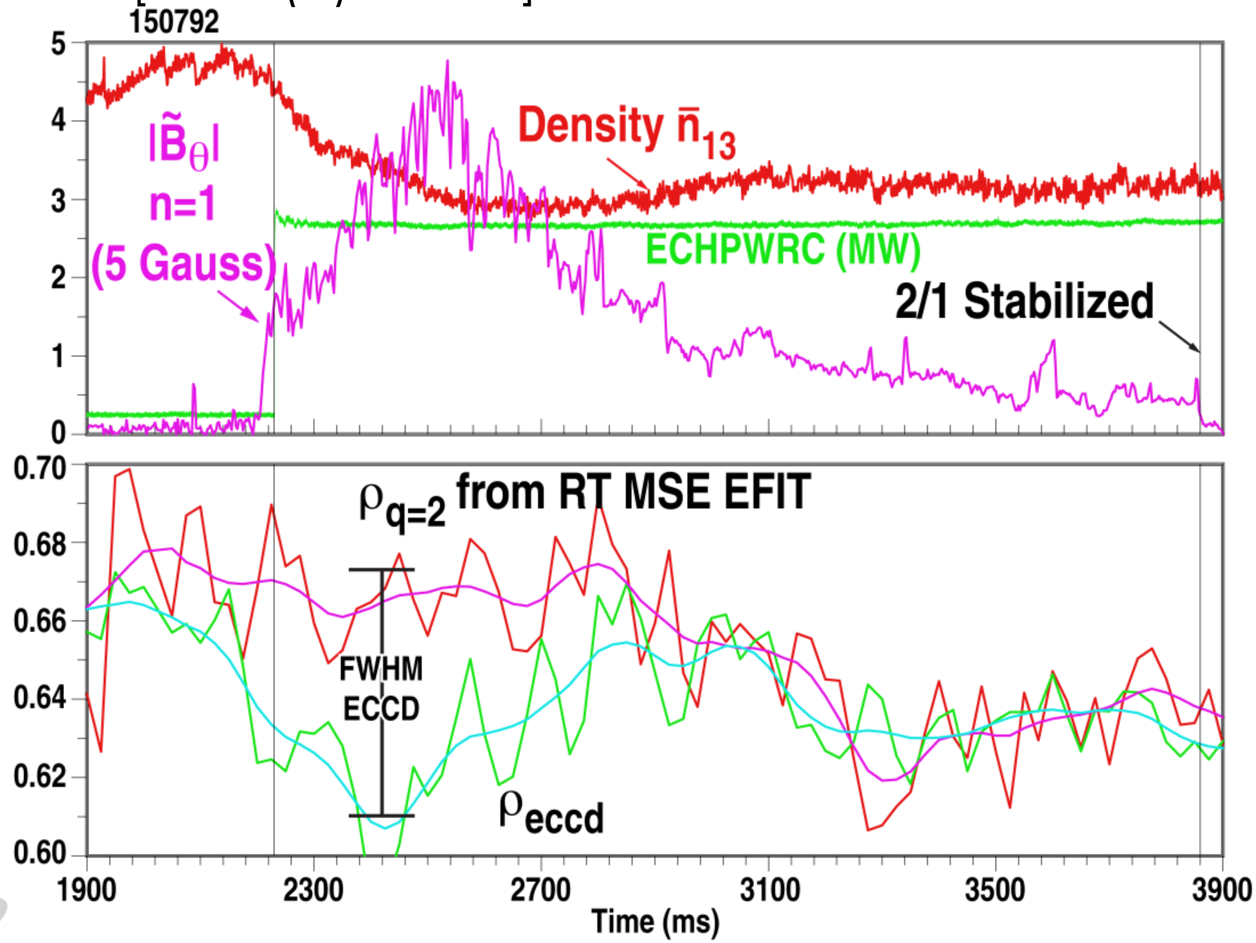
Better Mode Detection Enable Early Catch



- Improved band-pass filtering for mode detection
- Reduce catch level from > 7 Gauss below critical “knee” level of ≈4 Gauss for “help” from small island effects
- Faster mode suppression with reduced peak amplitude and shorter time to stabilize

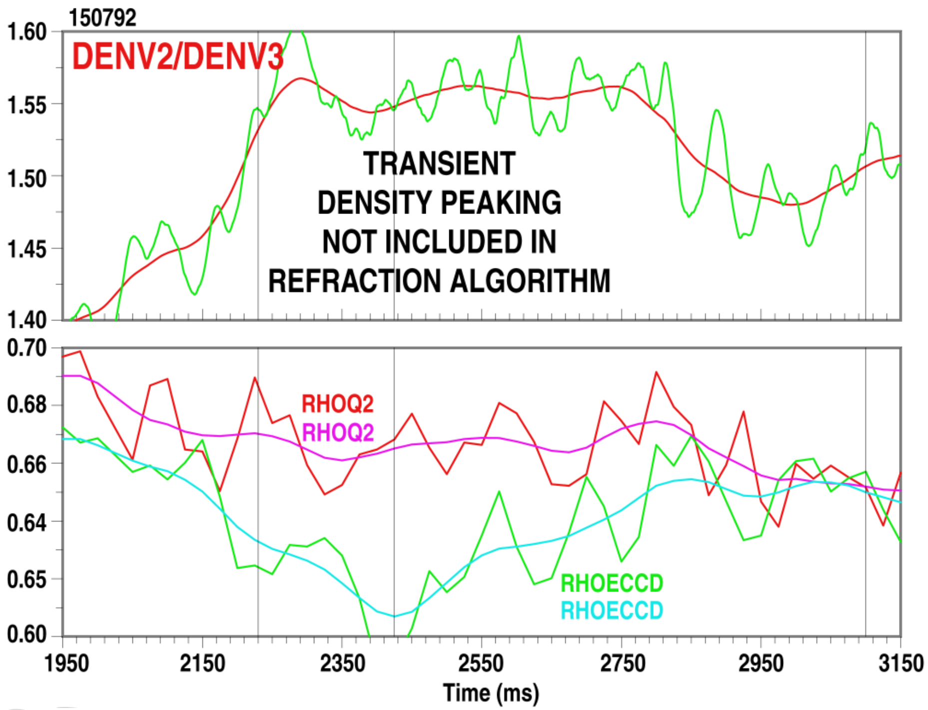
Need for Improved Refraction Algorithm: When EC Turned On, Density Drops, Refraction Changes

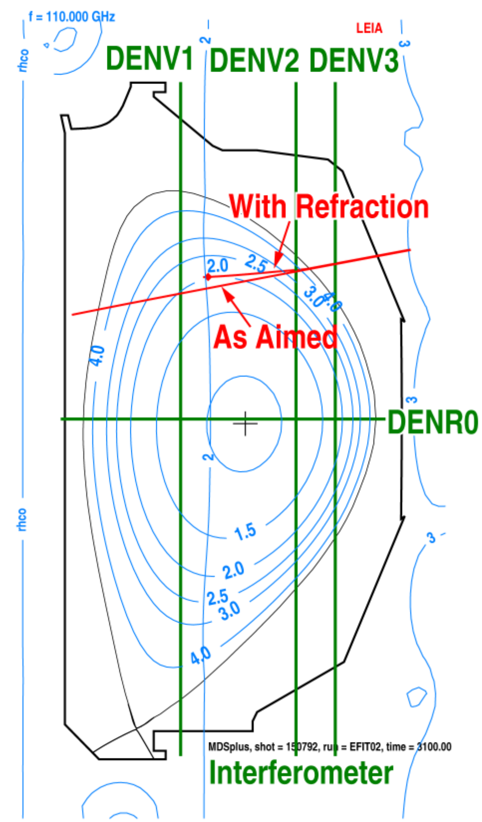
- **2012: A simple linear algorithm with n used to redirect mirrors alignment off initially due to *transient density profile change***
  - $dz_{eccd}=0.4273*[denr0(V)-0.3599]$ meters



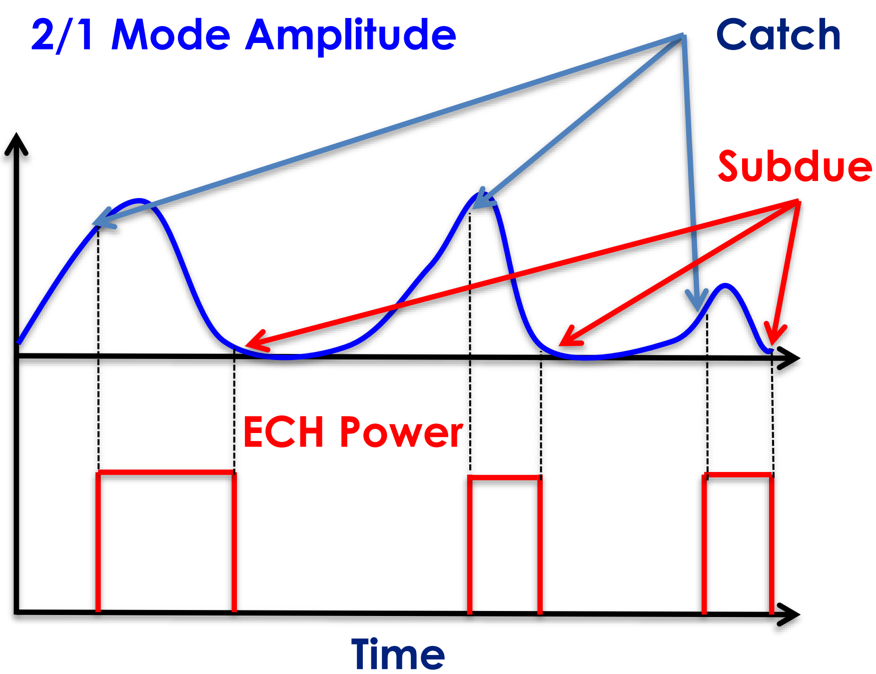
Improved Refraction Algorithm Enables Better Alignment

- **2013:**
  - **Real-time Thomson (42 chan.) density profile calc. implemented**
  - **Real-time Torbeam and a Snell's Law based code being tested**
  - **Mirrors will be given better directions for tracking**





Multiple Catch & Subdue Suppress Cycles with Improved PCS



- **Aim:**
  - Reduce the Average EC Power
  - Study the reappearance time scales
- **Method:**
  - Turn on the ECCD when the mode is detected
  - Turn off the ECCD when the mode is suppressed
  - Wait for another mode to appear

Additional Improvements to be Made in 2013 Campaign

- **Increased number of gyrotrons and thus EC power**
  - 5 in 2012→ 6 in 2013 (2.85MW→3.5MW injected)
- **More robust mirror operations (hardware/software upgrade)**
  - New mirror motors(~3x faster), encoders control boards
  - 100-200 ms to move the mirrors from center to q=2
  - Enable multiple mode suppression and central heating while suppressing NTMs.
- **Real-time ECE diagnostic for better identification of location of q=2 surface of island to be used to augment real-time MSE EFIT which was used in 2012 and is basis for active tracking without mode**

Integration of NTM Control Elements Is Demonstrating the Ability to Efficiently Control NTMs in ITER

- **Advanced integrated control:**
  - Mode detection with Fourier analysis of the Mirnov diagnostics
  - Real-time high accuracy equilibrium reconstruction with MSE
  - Fast EC steerable mirrors
  - Fully automatic control algorithm “catch and subdue” that fuses all the ingredients.

- **Provides an efficient approach for ITER**
  - Reduces power requirements for NTM control
  - Reduces time to suppress modes
  - Decreases adverse effects on confinement & disruption
  - Enables higher Q in ITER

- **New capabilities enhances the operations for 2013 campaign**

Catch & Subdue