# Tearing Mode Control for ITER


## Egemen Kolemen

**Mechanical & Aerospace Engineering**

**Jointly appointed with the Andlinger Center for Energy and the Environment**

**and the Plasma Physics Laboratory (PPPL)**

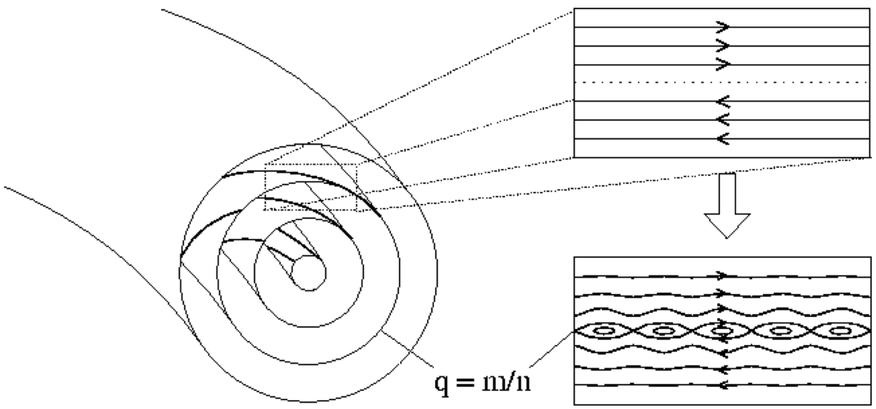


**Special Thanks to**

**Rob La Haye, Carlos Paz-Soldan, Ryan Sweeney, John Ferron**

1. Tearing Mode Intro
2. Need for TM Control
3. TM Avoidance
4. ECCD TM Control Development
    a. Physics MRE with ECCD
    b. Control Technique
    c. D3D results
5. Projection to ITER ECCD TM Control
6. Issues, Future Work

# Classic Tearing Mode and Magnetic Reconnection



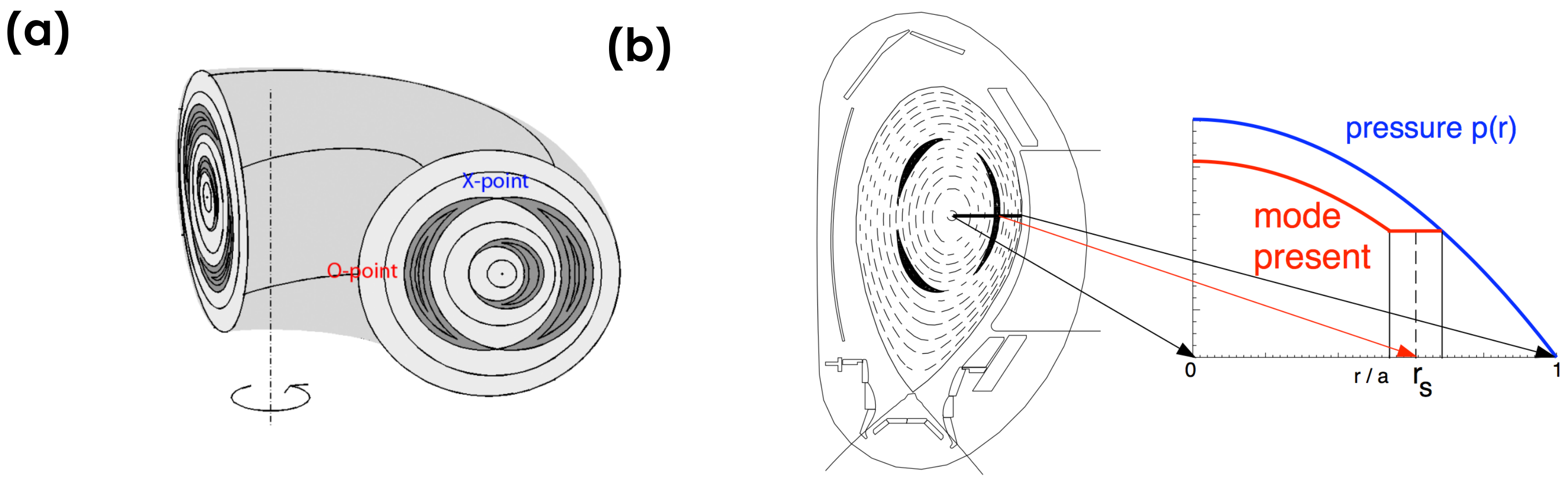

Tearing and reconnection

$$\frac{\tau_R}{r^2}\frac{dw}{dt} = \Delta'$$

Rutherford Equation

- Finite plasma resistivity allows toroidally non-axisymmetric helical currents to tear magnetic field lines at rational surfaces where the safety factor q = m/n
- Leading to reconnection of the flux surfaces and the formation of the magnetic islands
- In the classical tearing mode formulation, the perturbation current leading to island growth is due to unfavorable equilibrium current profile which is parametrized by $\Delta'$ [Rutherford, 1973]

# Pressure Flattening and Toroidal Effects

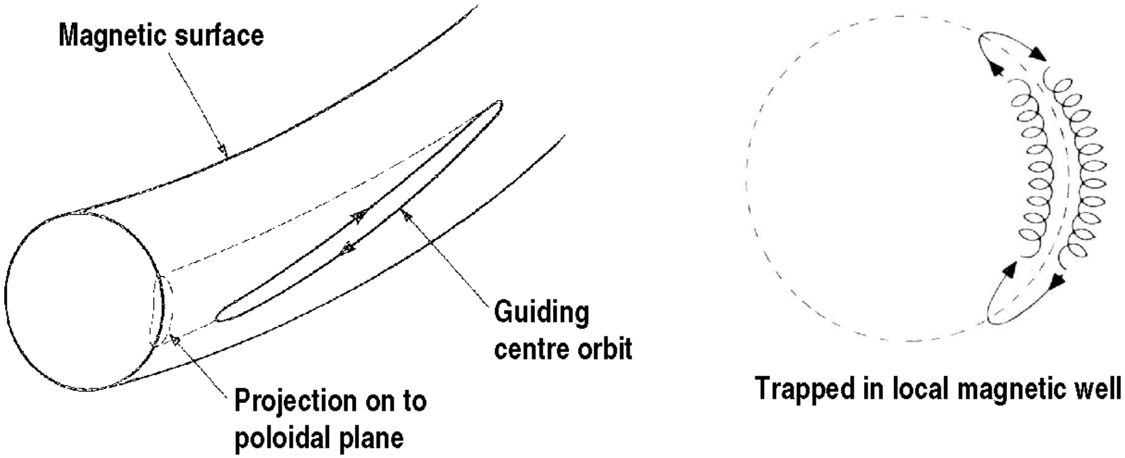



Tearing Mode island mode structure: (a) 3D, (b) Pressure Flatting (Orso 2009)

- **Due to reconnection ➔ Rapid energy transport**
- **Flattened pressure profile across the island ➔ Reduced confinement**
- **In tokamak, *toroidal effects* produce a pressure gradient driven bootstrap current $j_{bs} \sim - \varepsilon^{1/2}/B_\theta \, dp/dr$**
- **Thus the island which reduces the gradient near the rational surface produces a helically perturbed bootstrap current**

# Neoclassical Tearing Mode (NTM) Islands Arise from Toroidal Effects that Produce a Pressure Gradient Driven "Bootstrap" Current

- **Toroidal effects add drift to ion gyrations**
  - **fraction of ions are trapped in ion "banana" orbits**




J. Wesson, "Tokamaks", third edition, 2003

- **$(r/R_0)^{1/2}$ of ions are trapped in drift orbits**

- **Bootstrap current carried by circulating electrons** $j_{bootstrap} \sim -\frac{\varepsilon^{1/2}}{B_\theta}\frac{dp}{dr} \approx \mathcal{O}(20\%)\,\langle j_{\parallel} \rangle$ **[ITER, DIII-D IBS]**
  - **island flattens pressure → hole in bootstrap current → destabilizing**

$$\frac{\tau_R}{r^2}\frac{dw}{dt} = \Delta' + 2\,\frac{j_{bootstrap}}{B_\theta}\,\frac{L_q}{w}$$

**with $L_q = q/(dq/dr)$, the magnetic shear length**

**classical tearing index**

**destabilizing effect of perturbed bootstrap current**

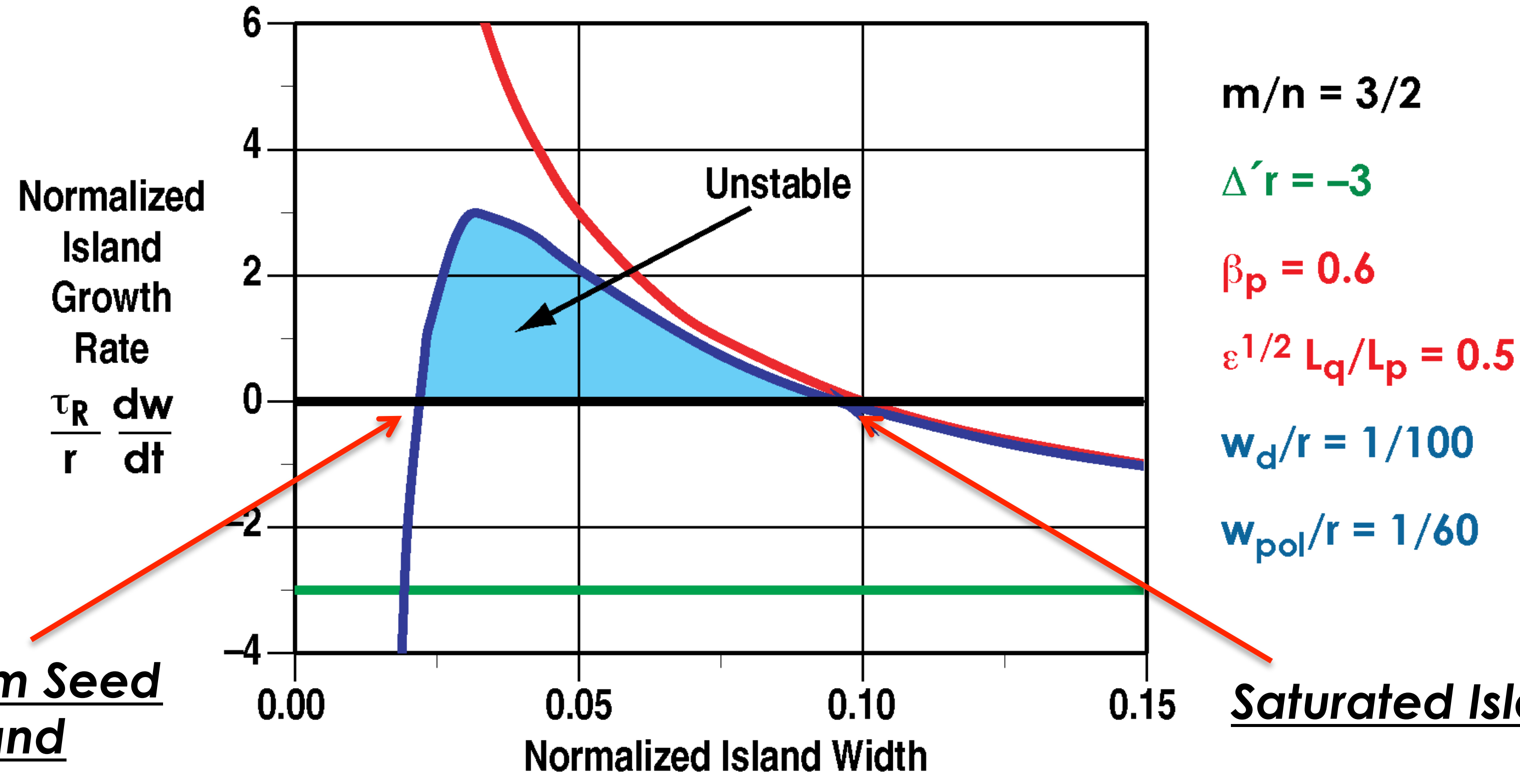
# Threshold Physics Makes an NTM Linearly Stable and Non-Linearly Unstable

**Modified Rutherford Equation**

$$\frac{\tau_R}{r^2}\frac{dw}{dt} = \Delta' + \varepsilon^{1/2}\frac{L_q}{L_p}\beta_p\left[\frac{w}{w^2 + w_d^2} - \frac{w_{pol}^2}{w^3}\right]$$

transport threshold

polarization threshold




***Minimum Seed Island***

***Saturated Island***

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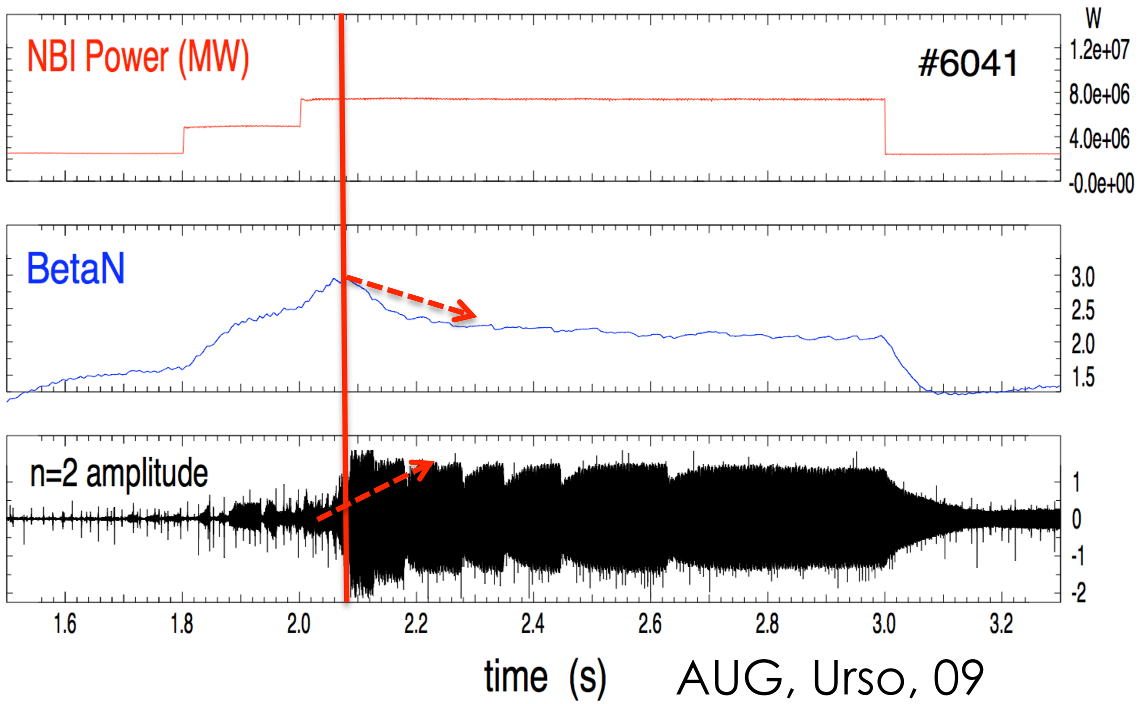
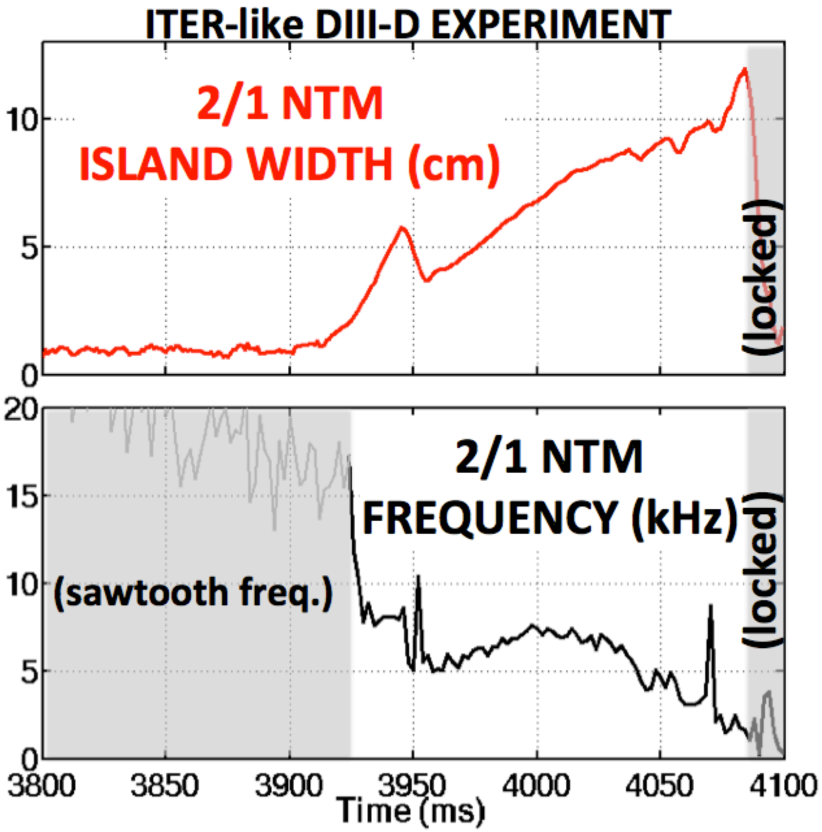
# NTM Reduces BetaN



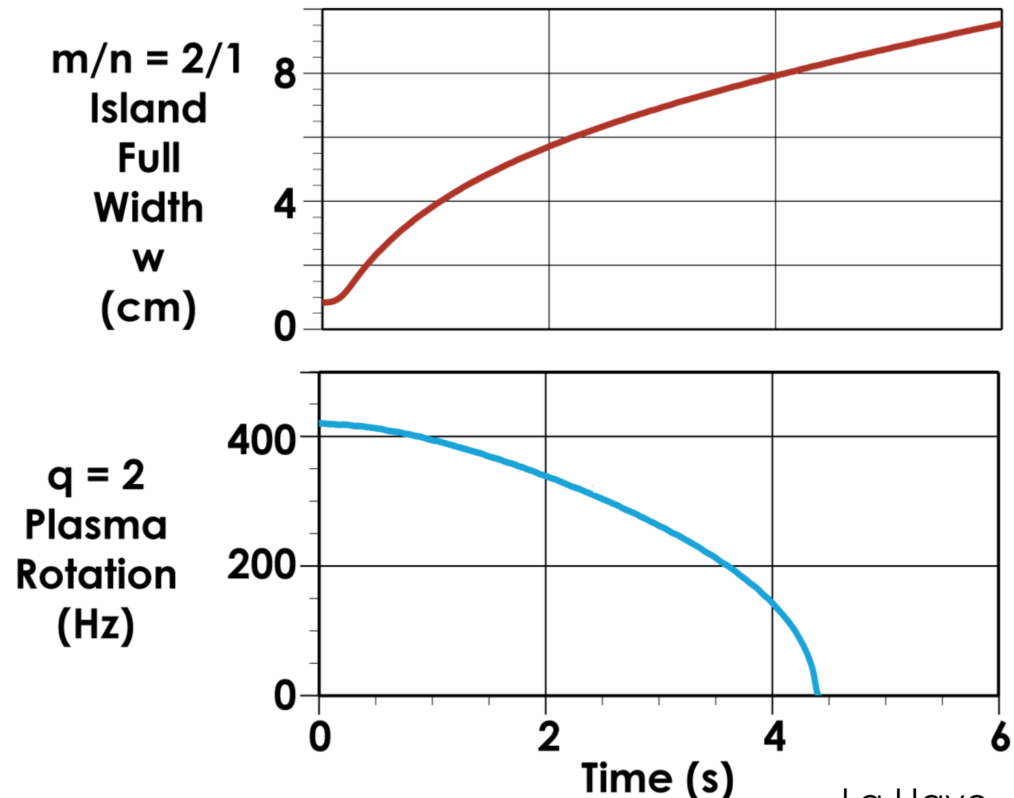

AUG, Urso, 09

# In ITER, without Control, NTM Islands Can Grow and Cause Disruptions

**DIII-D experiment**




**ITER Simulation**




La Haye 2008

- **Loss of H-mode and disruption is expected after locking (~5 cm)**
- **Need robust and efficient NTM control strategies**

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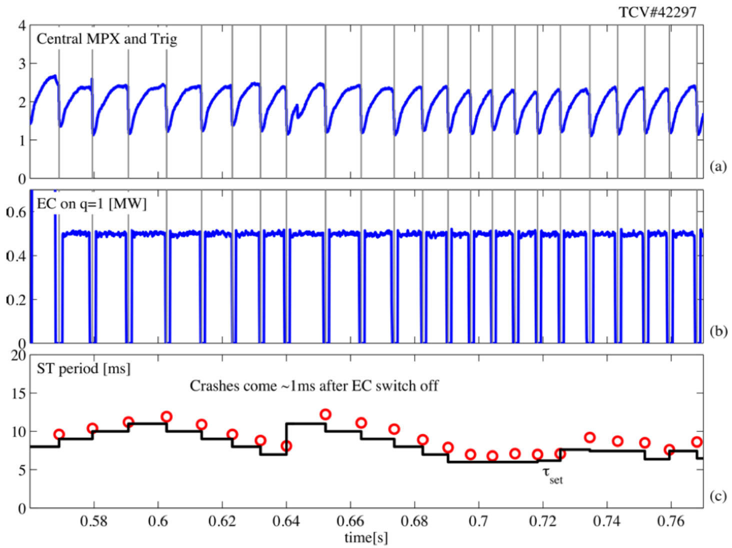
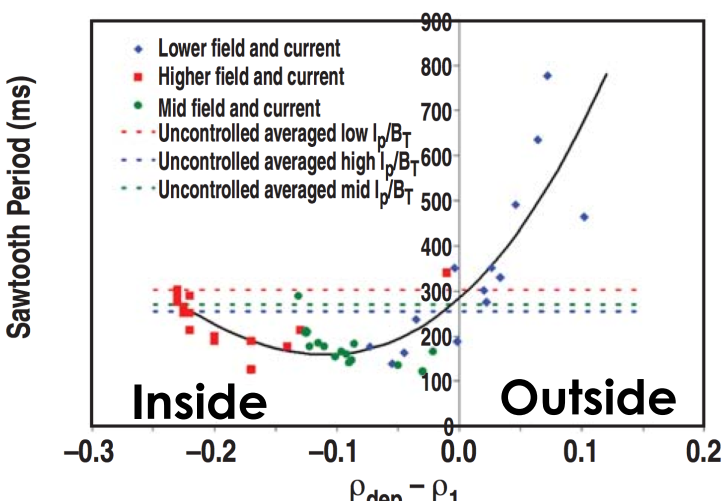
# Sawtooth Control with ECCD for NTM Seeding Avoidance



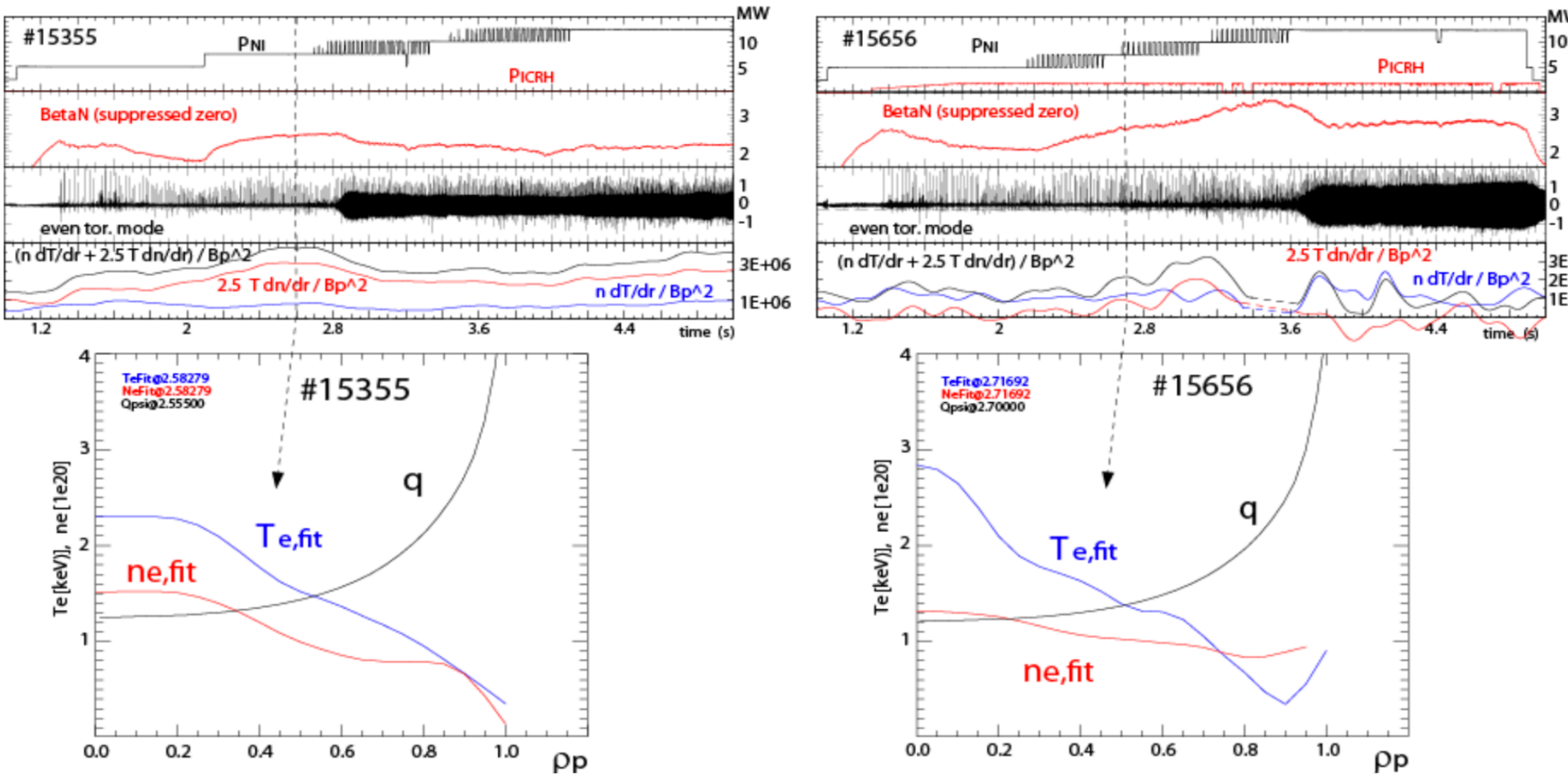

**Sawtooth pacing TCV**
**[Goodman 11, PRL]**




**DIII-D** **Chapman 2012**

- DIII-D analyses show that most of the NTMs are induced by sawtooth crashes
- Smaller crashes lead to less disturbance and can stop island seeding for NTM
- ITER to avoid disruptive “monster sawteeth”
- ITER would benefit from two methods:
  - *Sawtooth pacing with ECCD frequency locking*
  - *ECCD inside the q=1*

# Central Heating to Reduce $dn_e/dr$




- **Flatten the $n_e$ profile by central heating (AUG ICRH example)**
- ***Reduce $j_{BS}$***
- **Delay the onset of the tearing mode**
- **Increase BetaN**

**Stober, PPCF 2001**
**Maraschek MHD Cnt. Wrk. 2008**

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# Accurate Alignment of Electron Cyclotron Current Drive (ECCD) to Resonant Surface Suppresses NTM

$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta'_0 r + \delta(\Delta' r) - (q^2-1)\frac{L_q^2\beta}{L_p w} + a_2 \frac{j_{boot}}{j_{tot}}\frac{L_q}{w}\left[1 - \frac{w_{small}^2}{3\,w^2} - K_1 \frac{j_{eccd}}{j_{boot}}\right],\ K_1\left(\frac{\Delta\rho}{\delta_{eccd}}, \frac{w}{\delta_{eccd}}\right)$$

Classical Tearing Stability Index

CD makes $\Delta'$ more negative

Stabilizing Curvature

Destabilizing Helically Perturbed Bootstrap Current

Small Island Stabilizing Effect

CD replaces "missing" bootstrap current

E. Westerhof 1990,
A. Pletzer and
F.W. Perkins, 1999

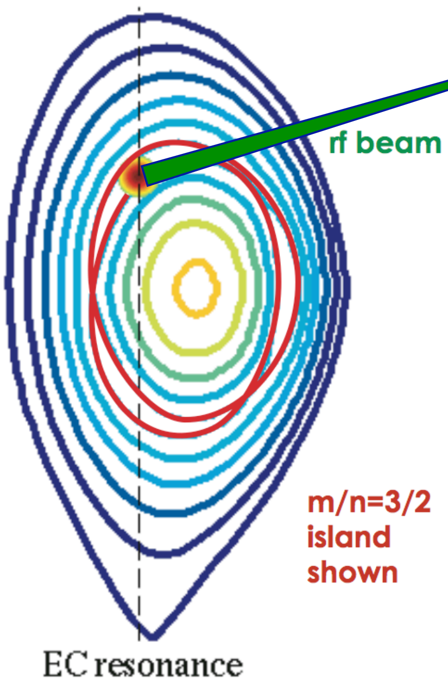
C.C. Hegna and J.D. Callen 1997,
H. Zohm 1997, F.W. Perkins et al., 1997

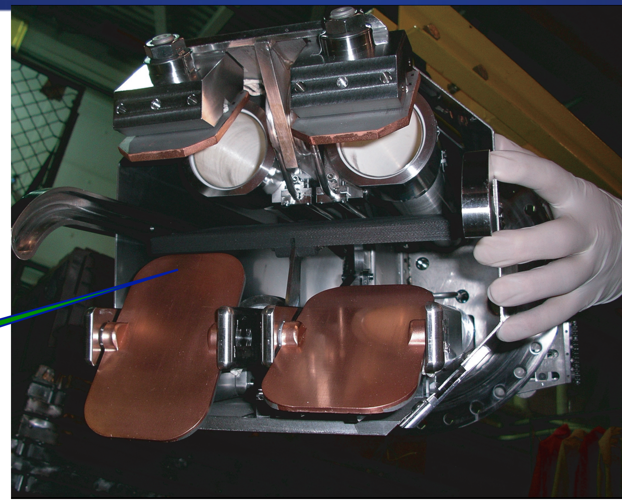
- Modified Rutherford Equation (MRE) with stabilizing current terms
- ECCD can stabilize NTMs mainly by replacing the "missing" bootstrap current, giving the rule of thumb requirement $j_{ECCD} > 1.2\, j_{Bootstrap}$
- This is the primary method that will be used at ITER
- K1 is a function of alignment, and the relative size of the island size versus ECCD size



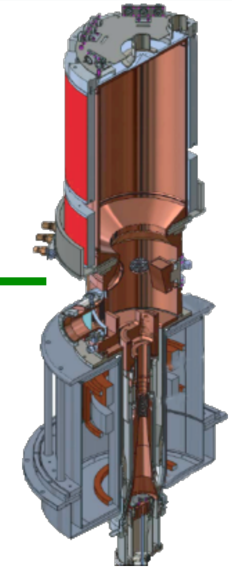
La Haye, NF, 2009

# Accurate Alignment of Electron Cyclotron Current Drive (ECCD) to Resonant Surface Suppresses NTM



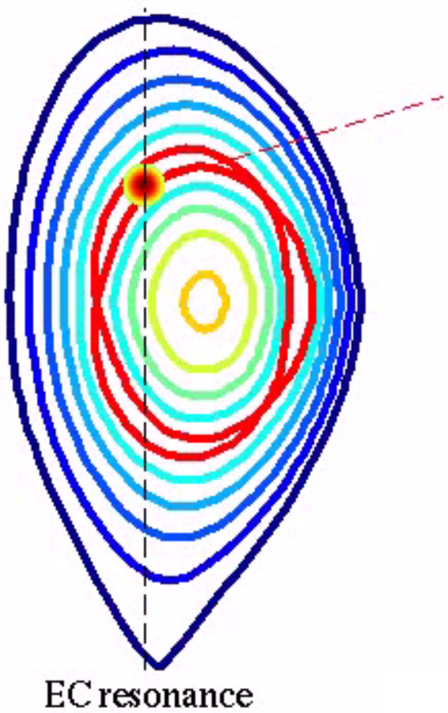
**Steerable Launcher Mirror**

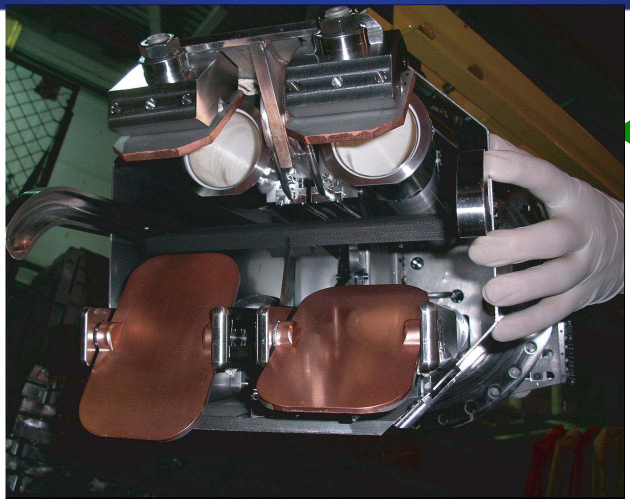


**5 Gyrotrons**
**(~2.8 MW injected)**

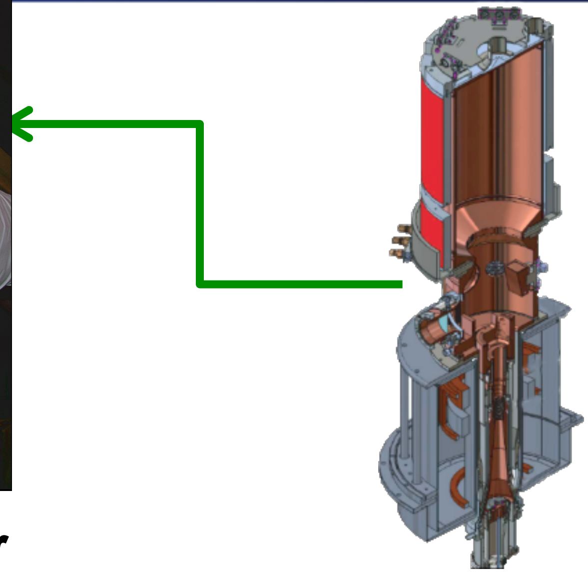
- The ECCD is obtained by finite parallel refractive index, $n_{||}$, by oblique injection to the magnetic field
- Align the ECCD deposition with the NTM island for suppression
- Mirrors steered to move the beam vertically along the EC resonance for best alignment

# Accurate Alignment of Electron Cyclotron Current Drive (ECCD) to Resonant Surface Suppresses NTM



**Steerable Launcher Mirror**



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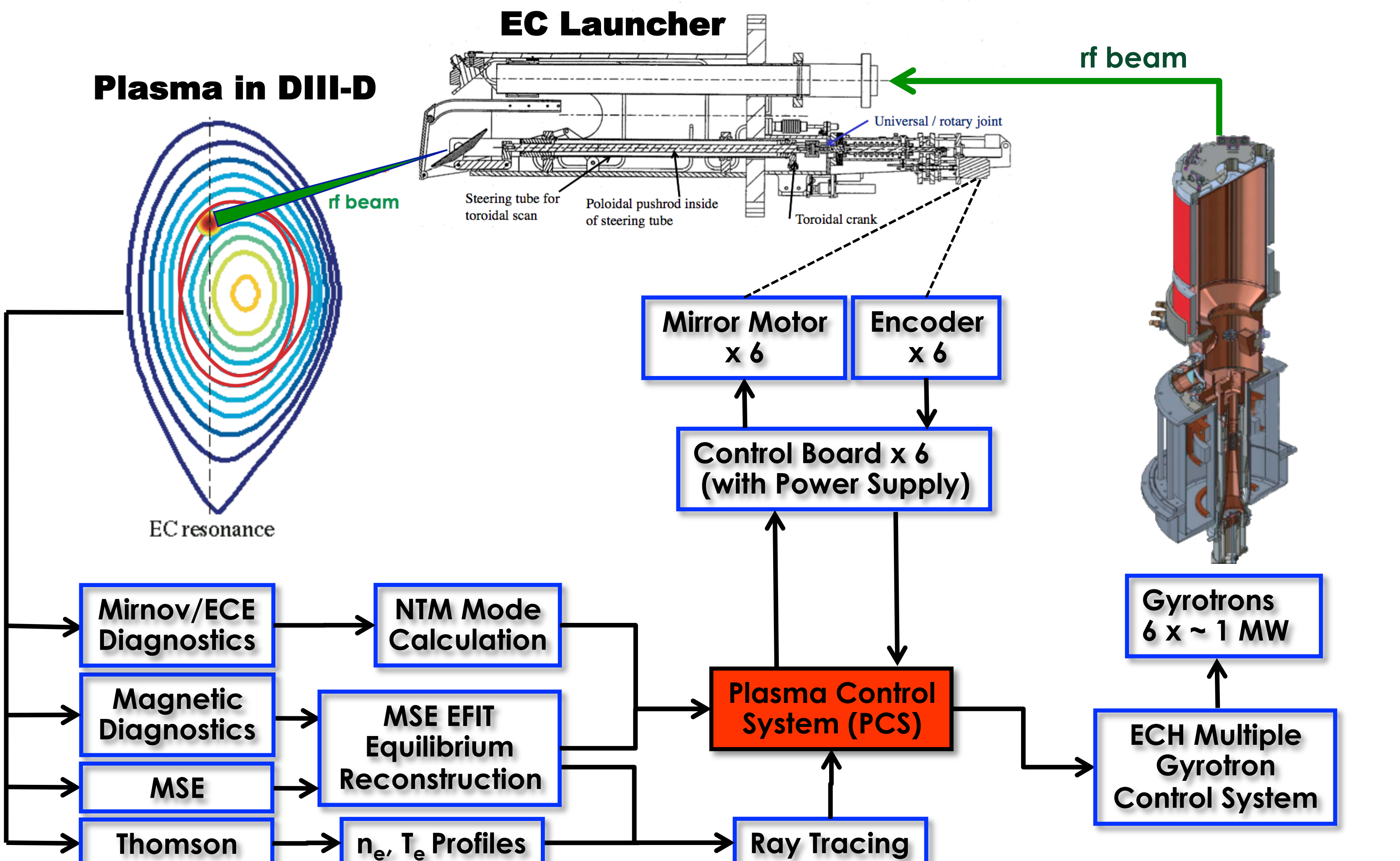
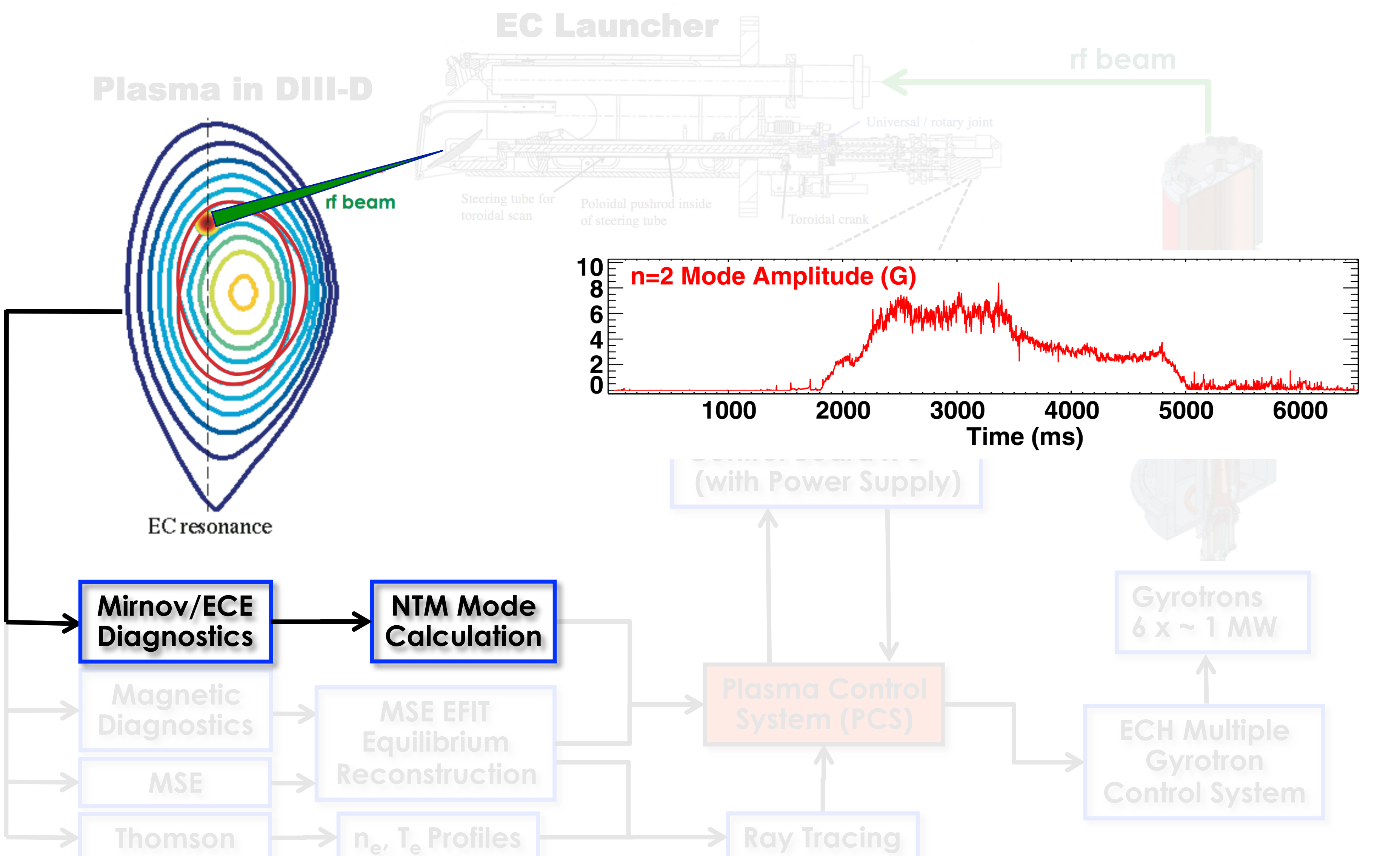
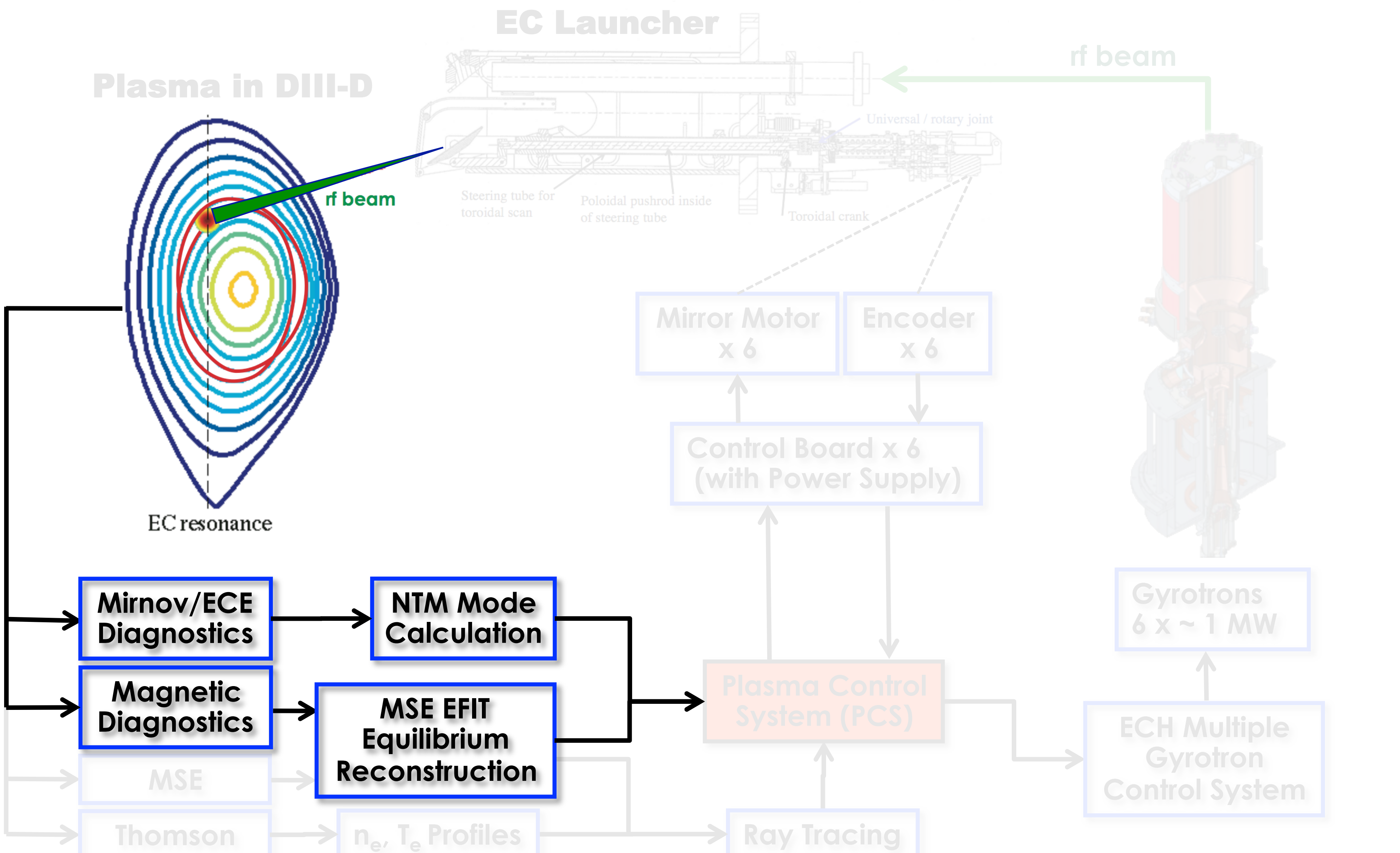
# DIII-D NTM Control System Overview



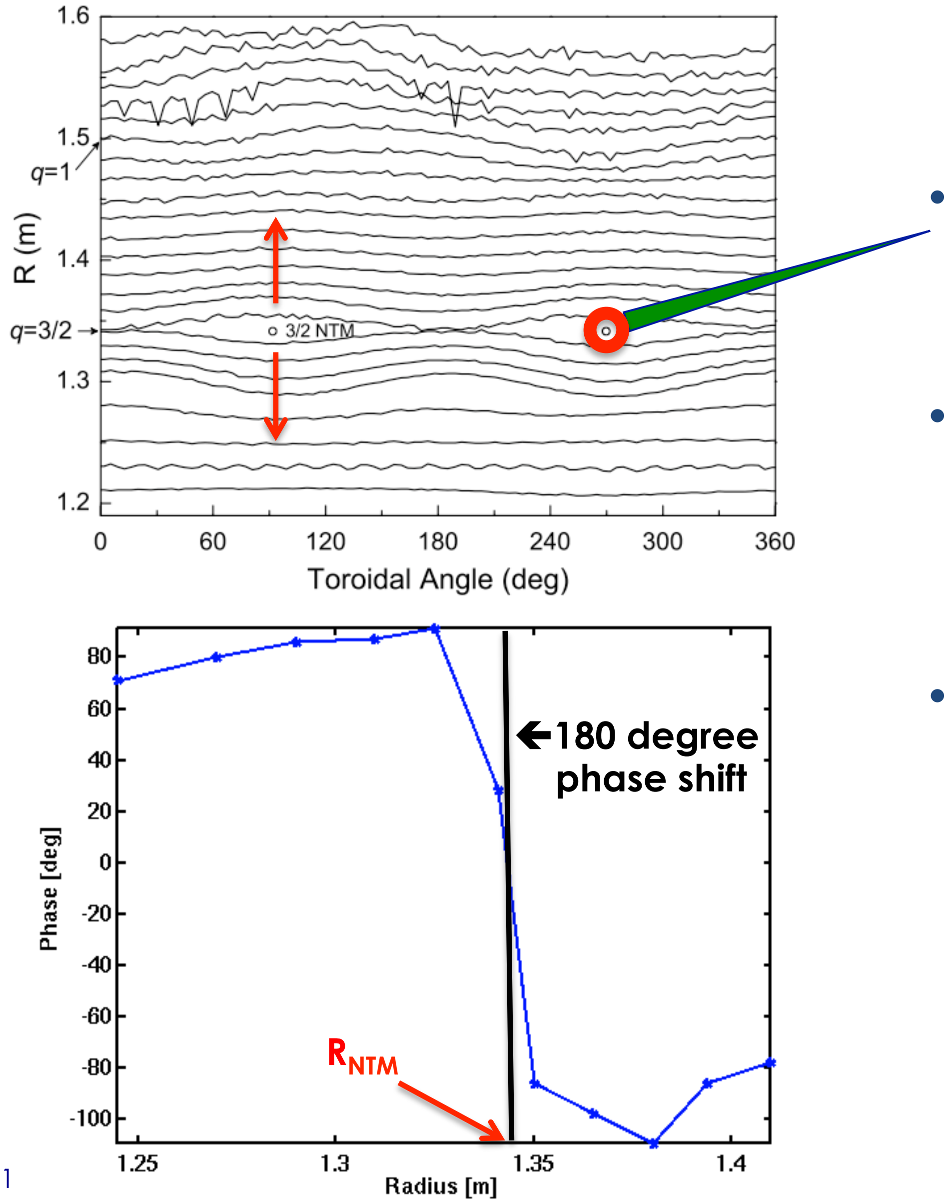
# 1. NTM Detection



# 2. NTM Location



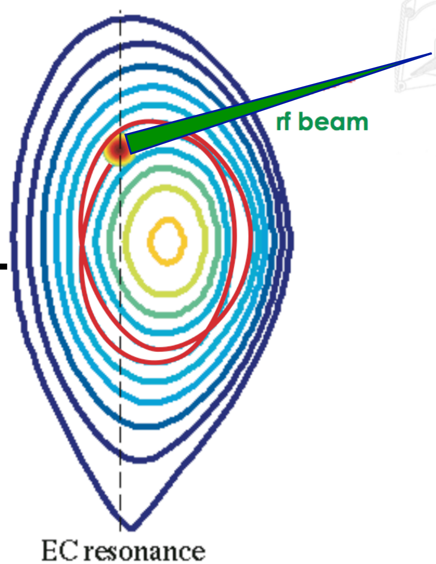
# ECE-Based NTM Location Calculation

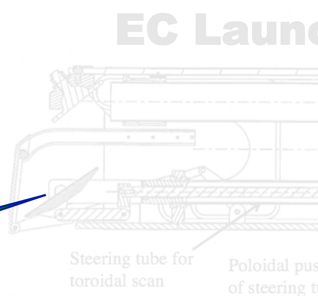


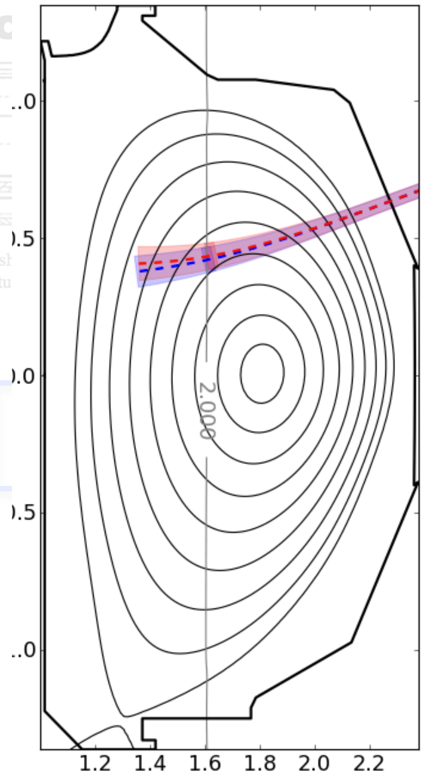

- **NTM displaces the flux surfaces**
- **180 degree phase shift in the ECE temperature fluctuation data across the island**
- **Use this condition to find the island location**

# 3. ECCD Location via Ray Tracing

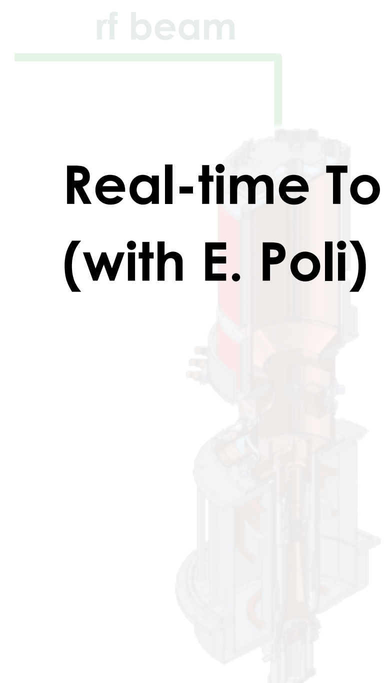
**Plasma in DIII-D**




**Real-time Torbeam (with E. Poli)**



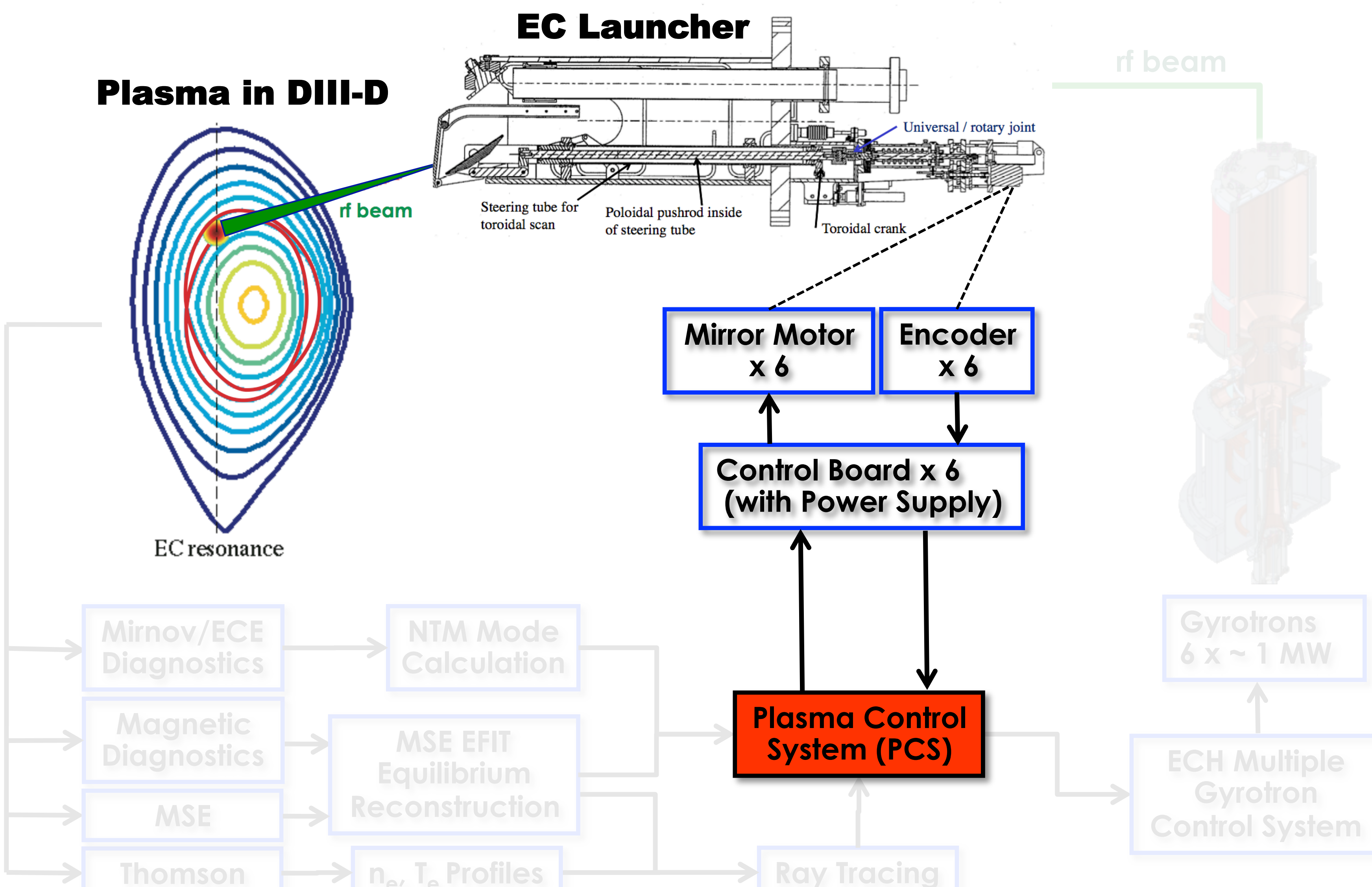

Mirnov/ECE Diagnostics → NTM Mode Calculation → Plasma Control System (PCS) → ECH Multiple Gyrotron Control System → Gyrotrons 6 x ~ 1 MW

**Magnetic Diagnostics** → **MSE EFIT Equilibrium Reconstruction** → **Ray Tracing**

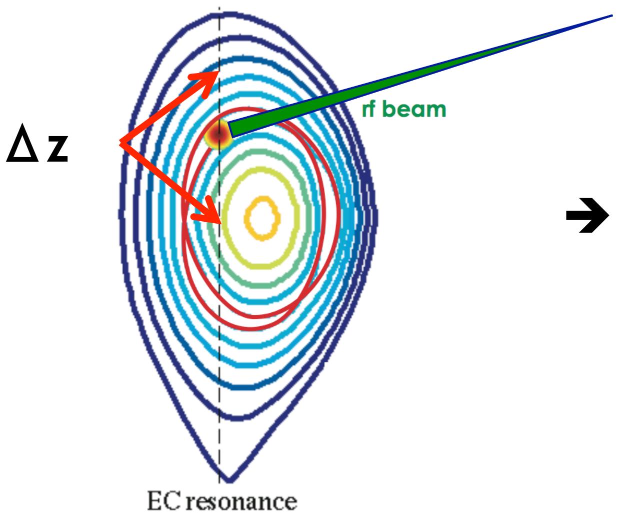
**MSE** → **MSE EFIT Equilibrium Reconstruction**

**Thomson** → **$n_e$, $T_e$ Profiles** → **Ray Tracing** → Plasma Control System (PCS)

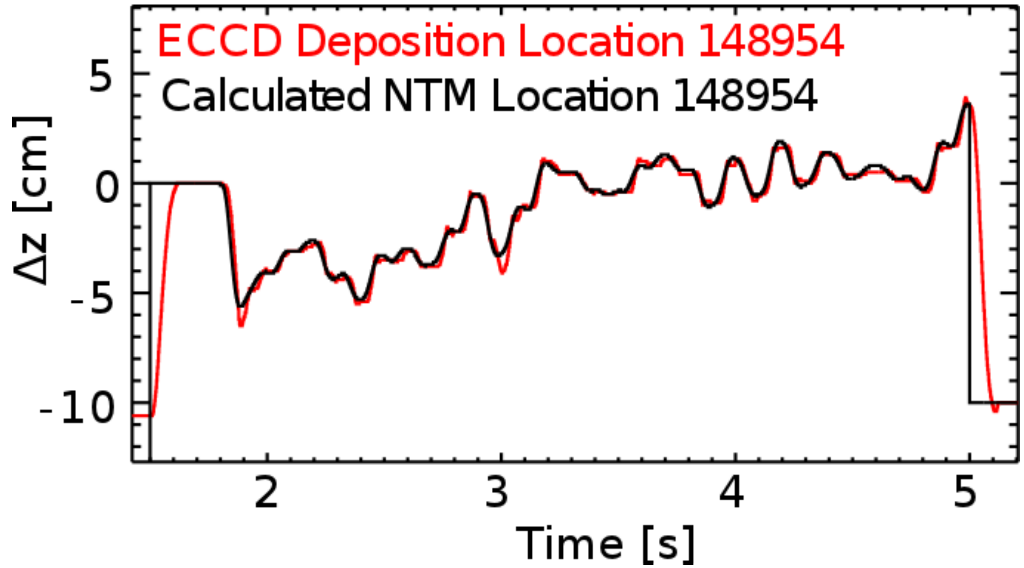
# 4. Alignment of NTM and ECCD



# Alignment is Achieved by Real-time Ray Tracing and Precise Tracking of Resonant Surface

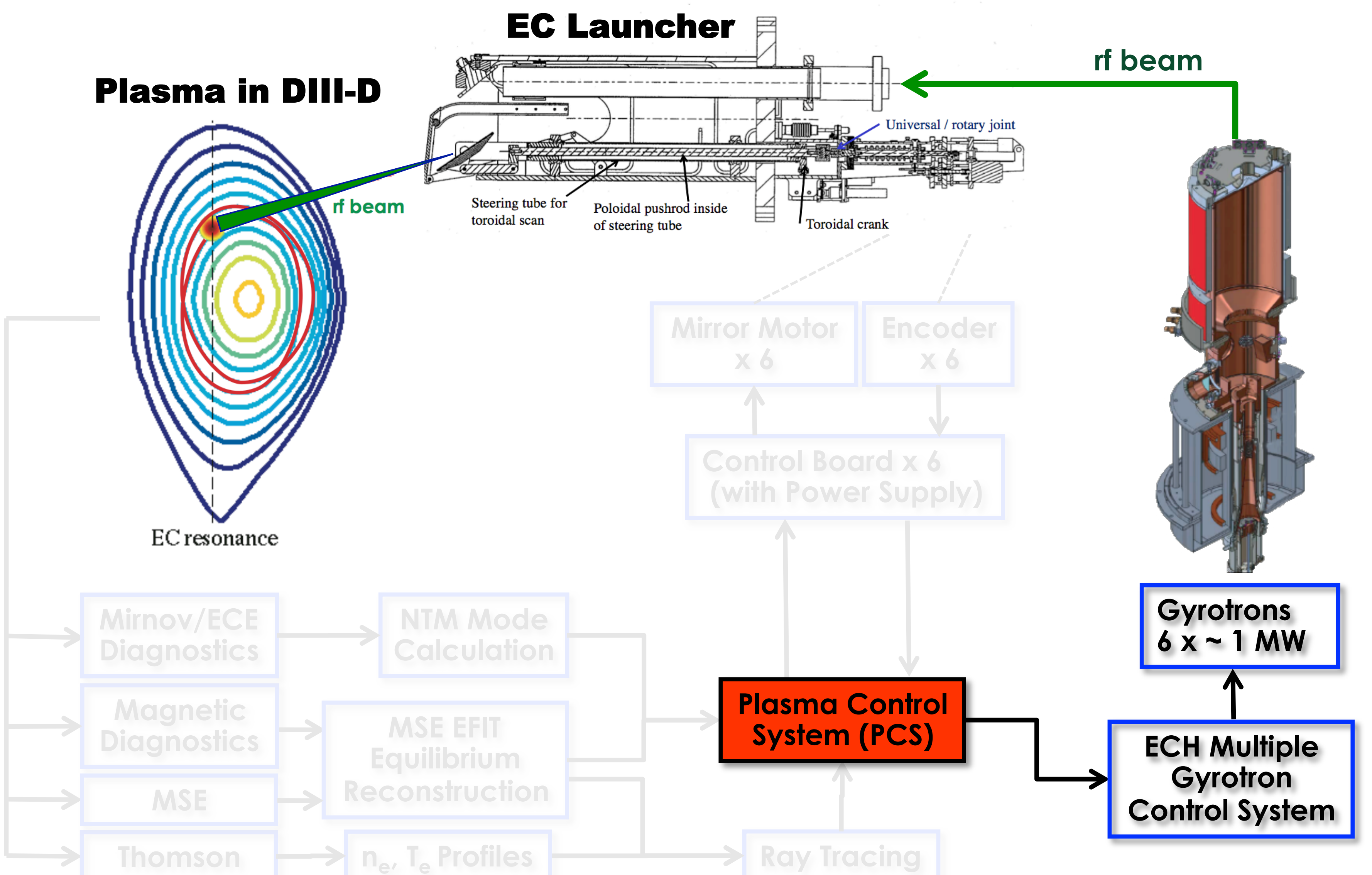



➔




- **Calculate:**
  - ECCD Location
  - NTM Location
- **Move the mirrors to align the ECCD with NTM**
- **Tracking performance with minimal overshoot and <1 cm error**

# 5. Gyrotron Power Control



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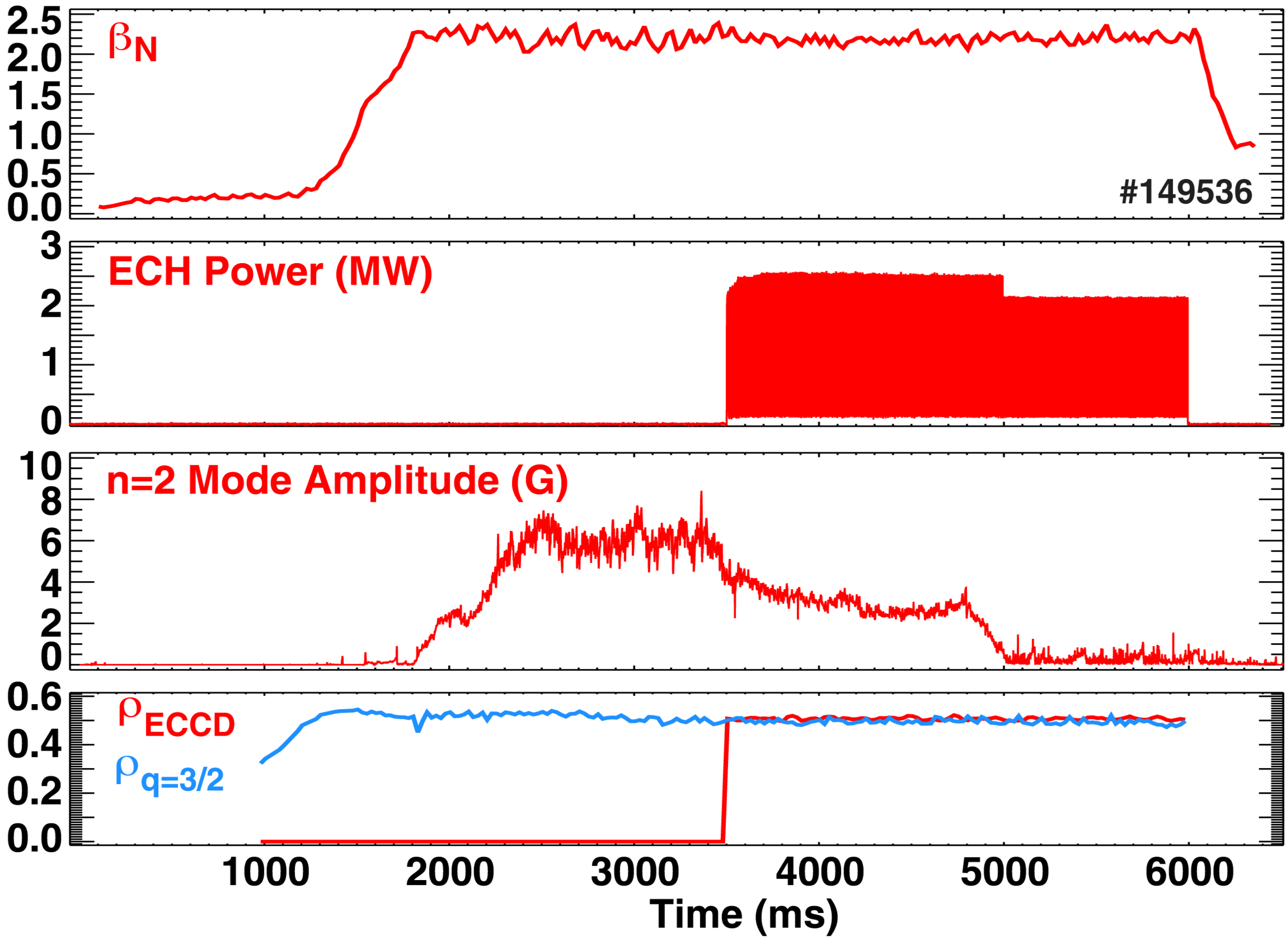
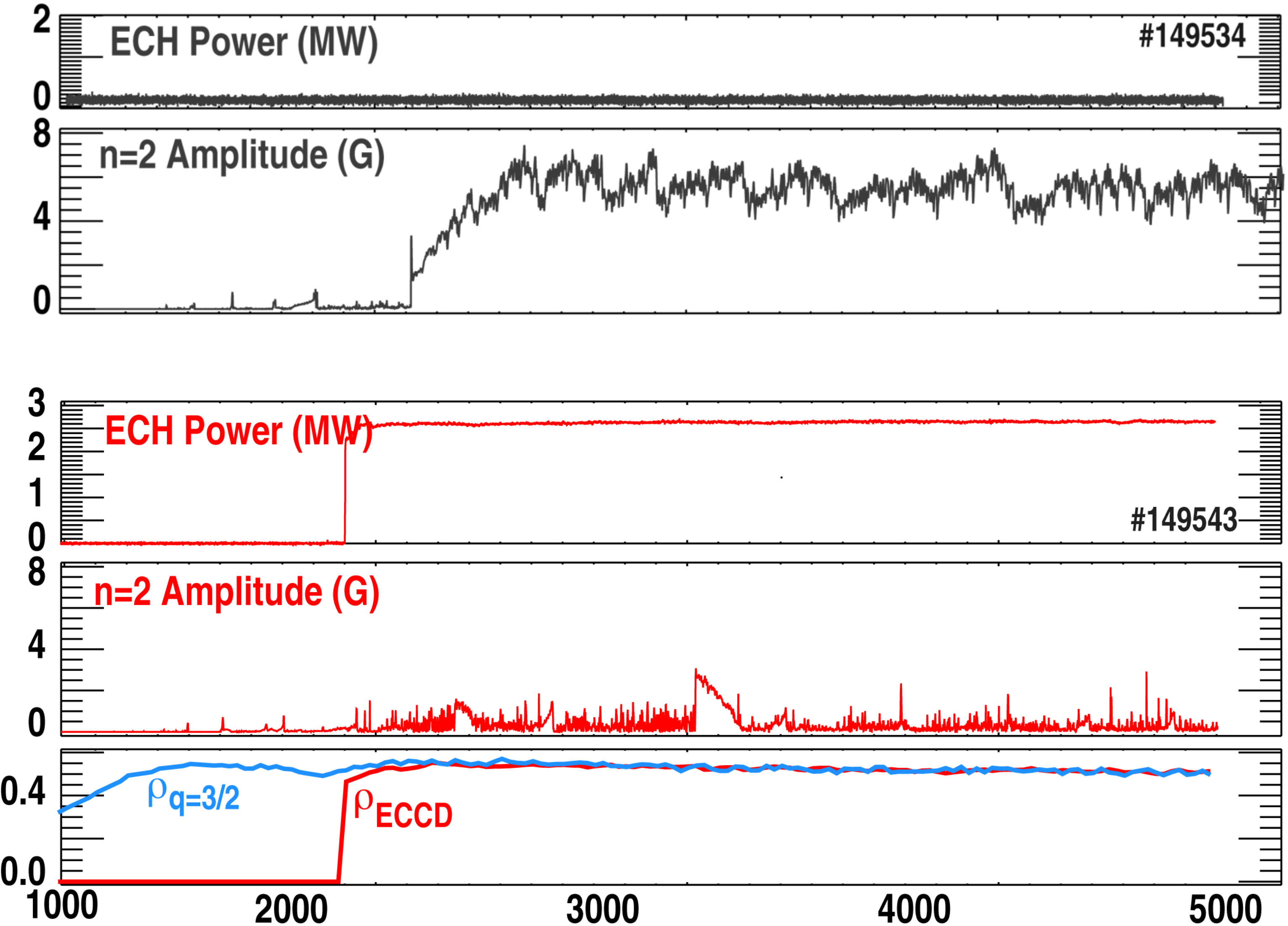
# Application to the 3/2 NTM:

– Head room to develop the technique

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



# NTM Control Methods: Preemptive NTM Suppression Achieved

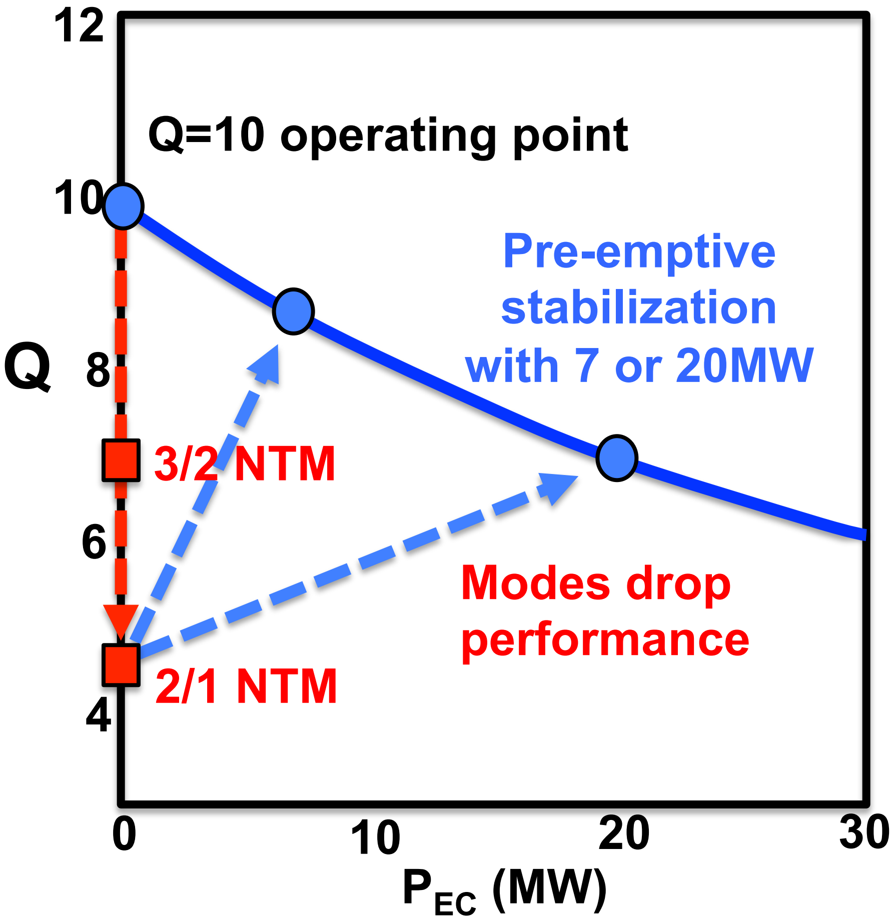



**Without ECCD, 3/2 NTM develops**

**NTM Preemption with ECCD**

# Need to Catch Mode Early to Minimize EC Power Use for High Fusion Gain Q

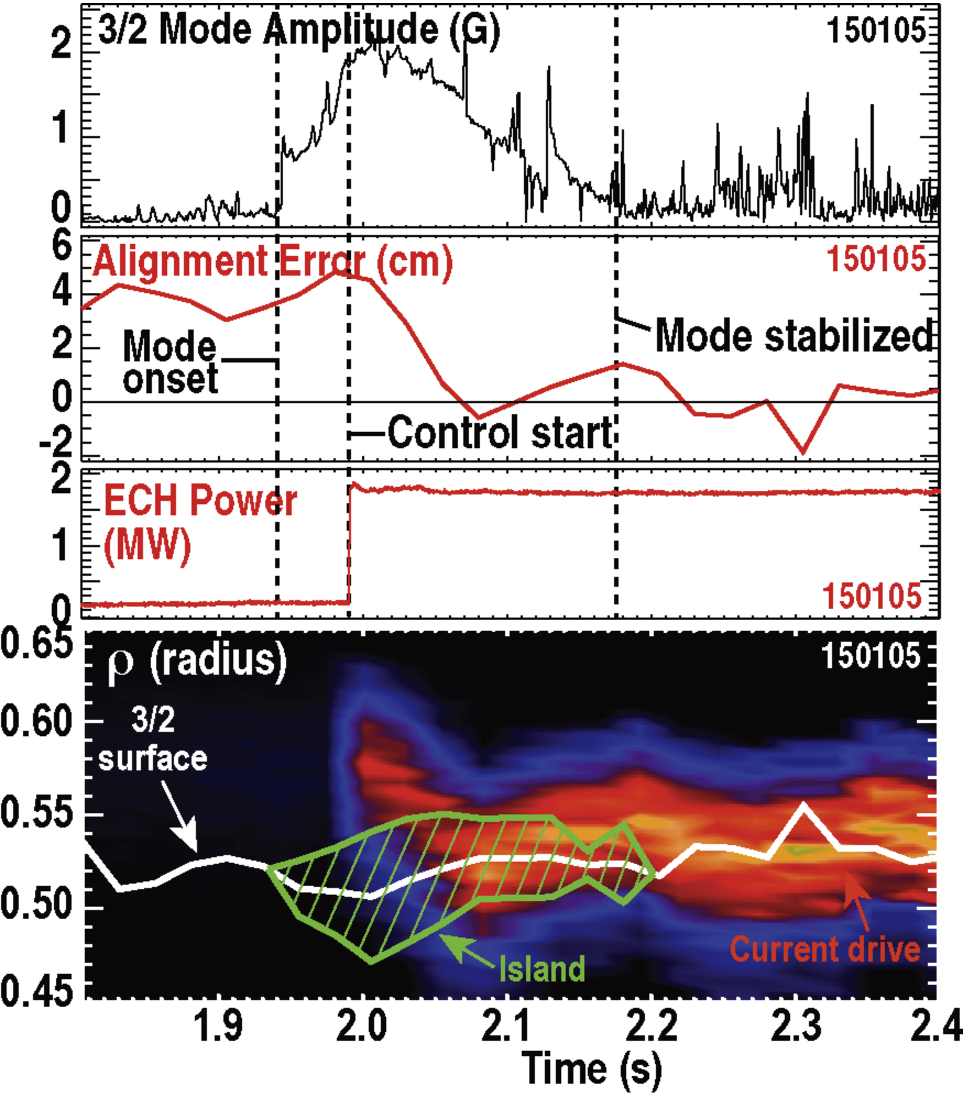
Pre-emptive suppression




[Souter, 2010; Zohm, Princeton 2006]

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

# Starting from a Misalignment of ECCD to the q Surface, "Catch and Subdue" is Effective in NTM Suppression

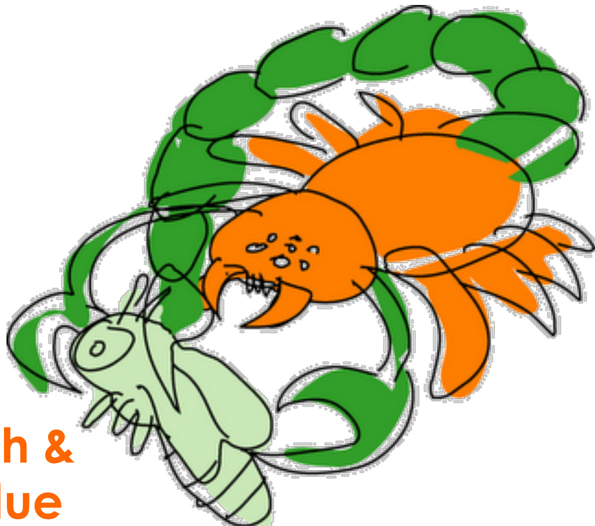



**Experiment:**

- Initial misalignment ~4 cm

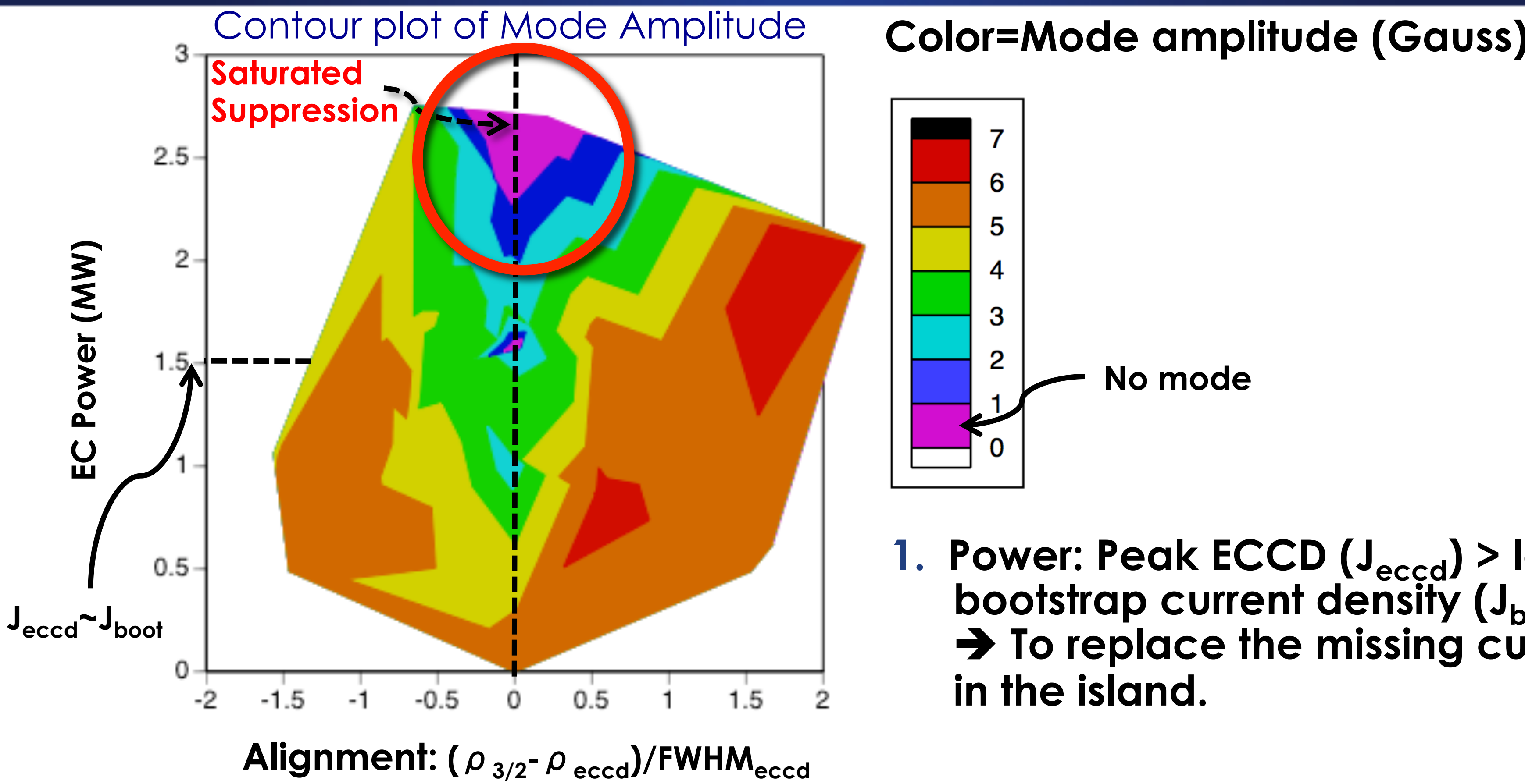
**Result:**

- System rapidly corrects deposition location
- Fast suppression: complete suppression takes ~250 ms
- Reduced EC power with Catch and Subdue [Post-deadline IAEA'12]



Catch & Subdue

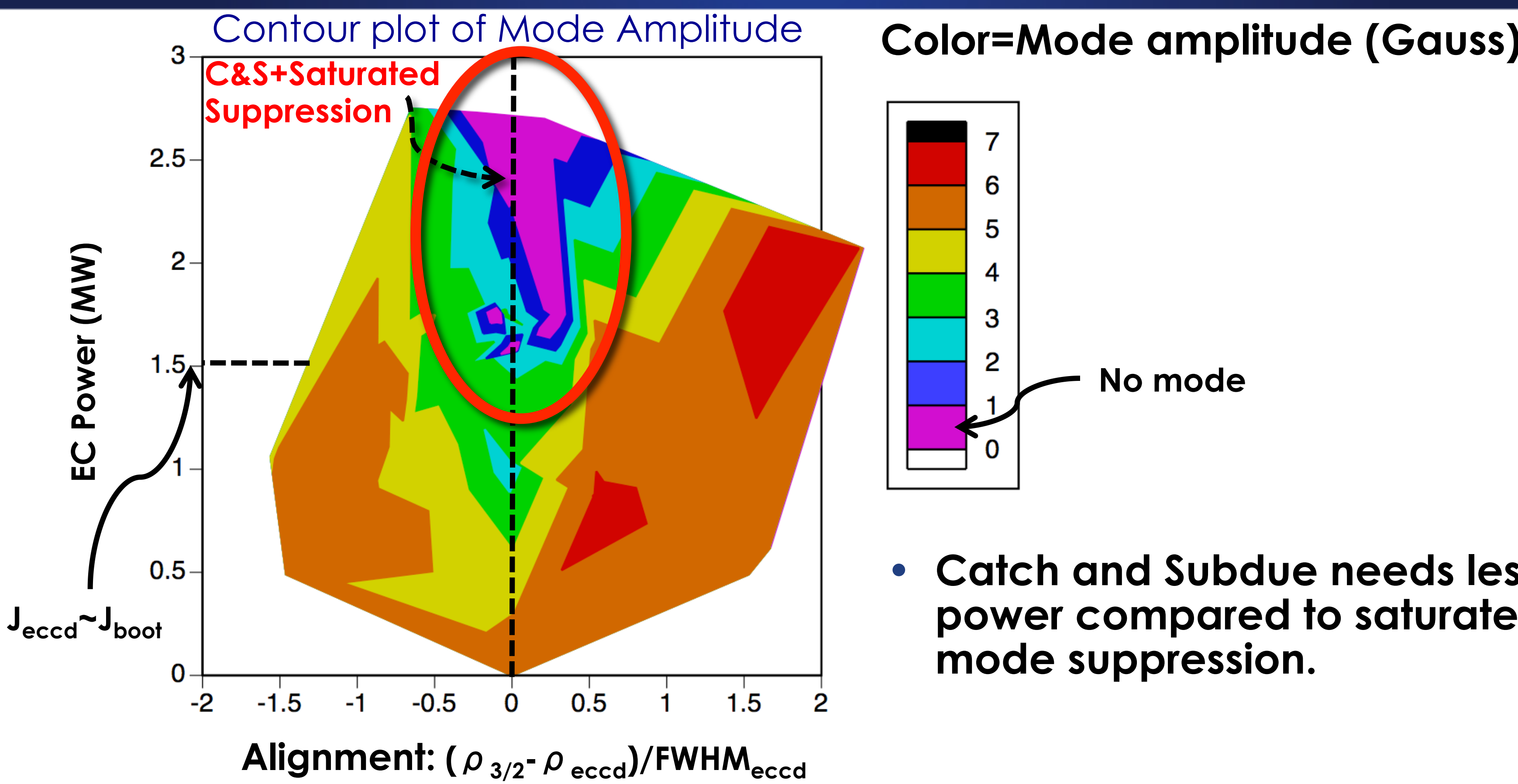
# Saturated Mode Suppression of 3/2 NTM Requires Good Alignment & $J_{eccd}>J_{boot}$




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

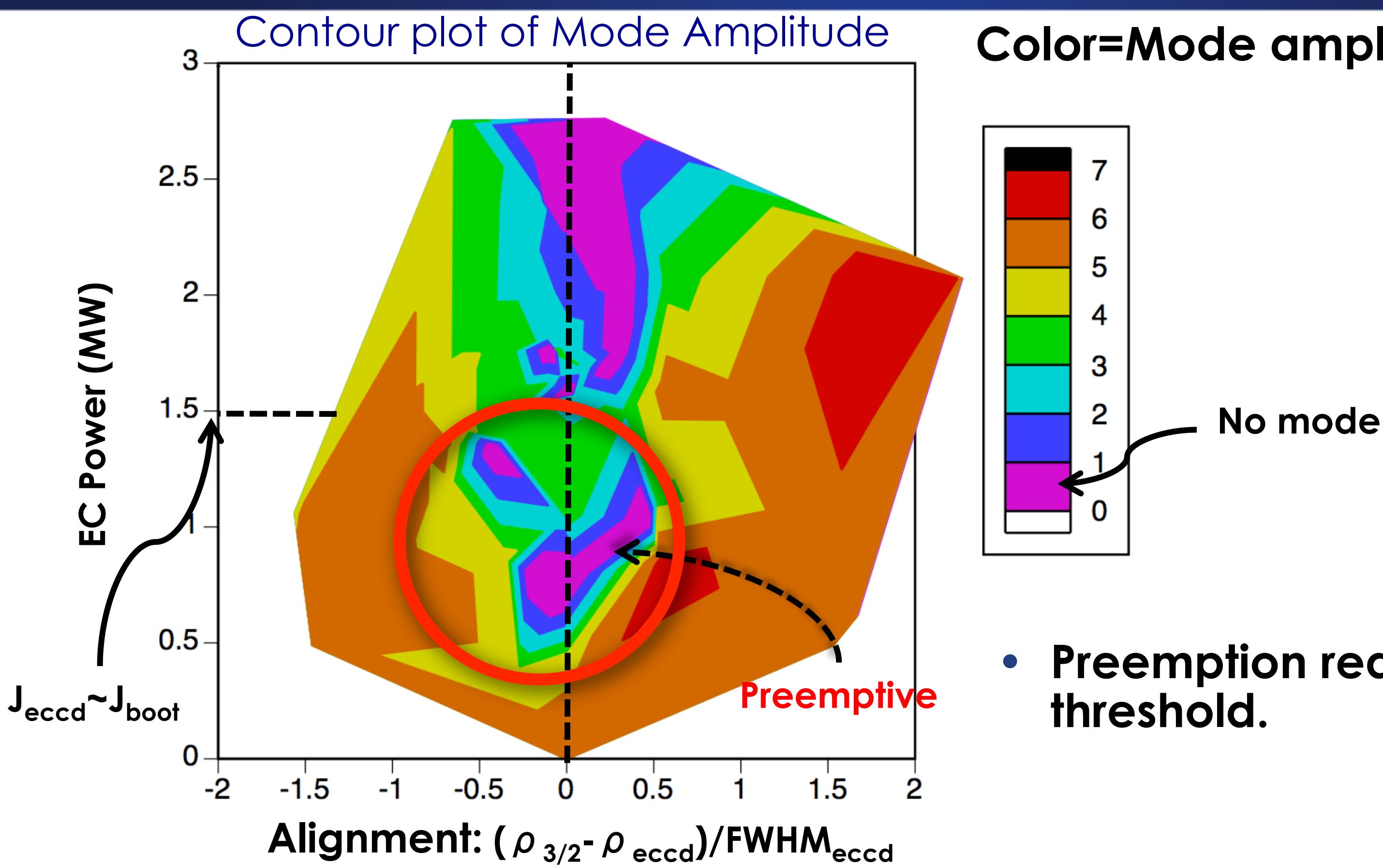
2. **Alignment: ECCD aligned with the 3/2 island within the half width of the ECCD profile**

# Catch and Subdue Needs Less Power



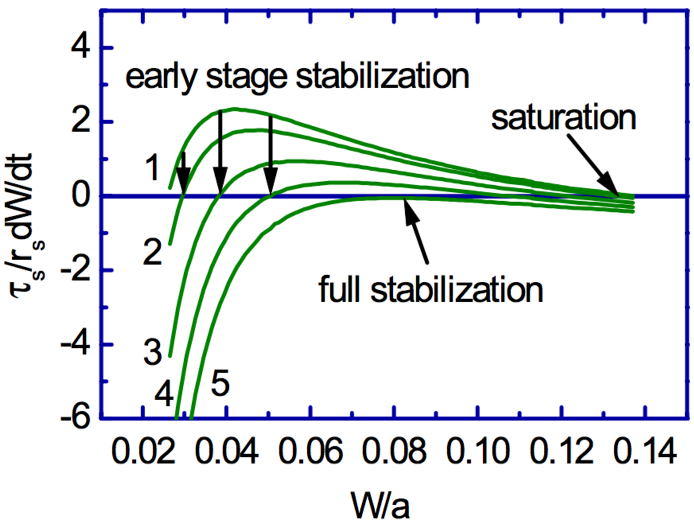

- Catch and Subdue needs less power compared to saturated mode suppression.

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

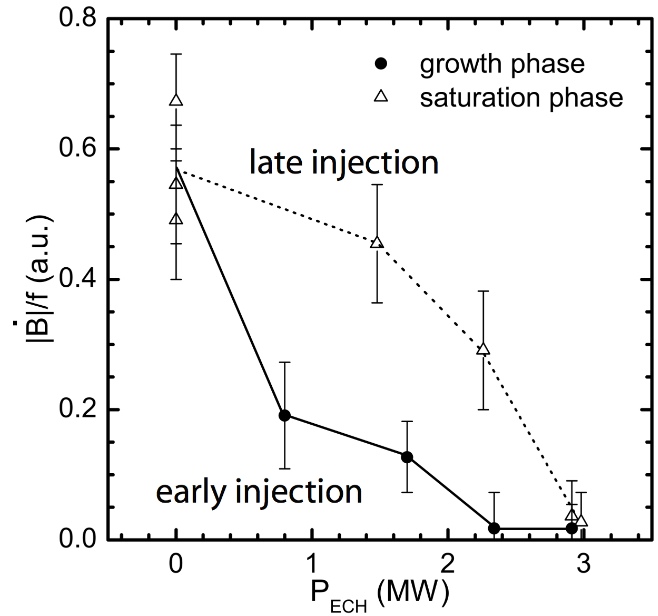



- Preemption reduces the power threshold.

# Early Mode Detection is Key for Rapid NTM Suppression



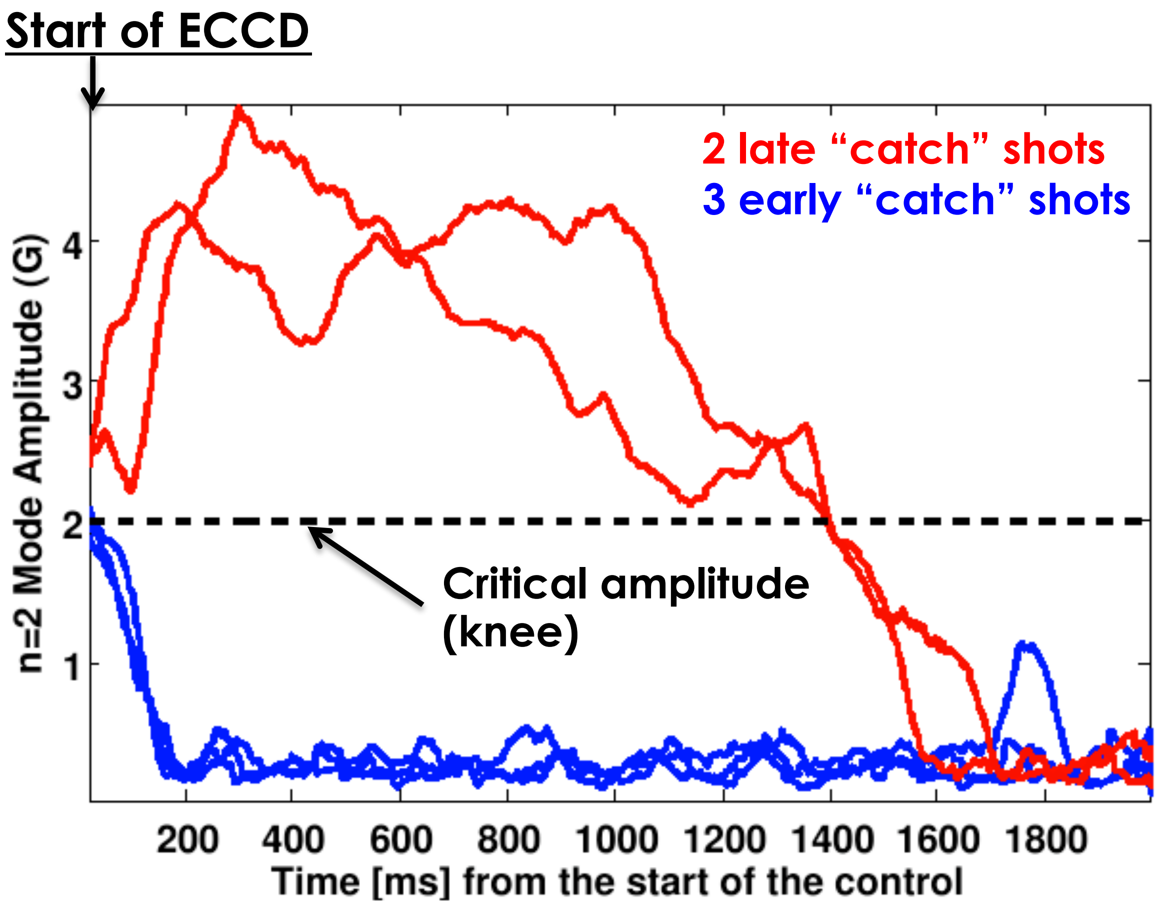

$P_5 > P_4 > P_3 > P_2 > P_1 = 0$




**ITER Simulation: Early detection reduces EC Power requirement [Pustovito, ITERP/07]**

**JT-60U Experiment: Early ECCD x2 smaller island size for same EC Power [Marasheck, NF, 12]**

# Early Mode Detection is Key for Rapid NTM Suppression



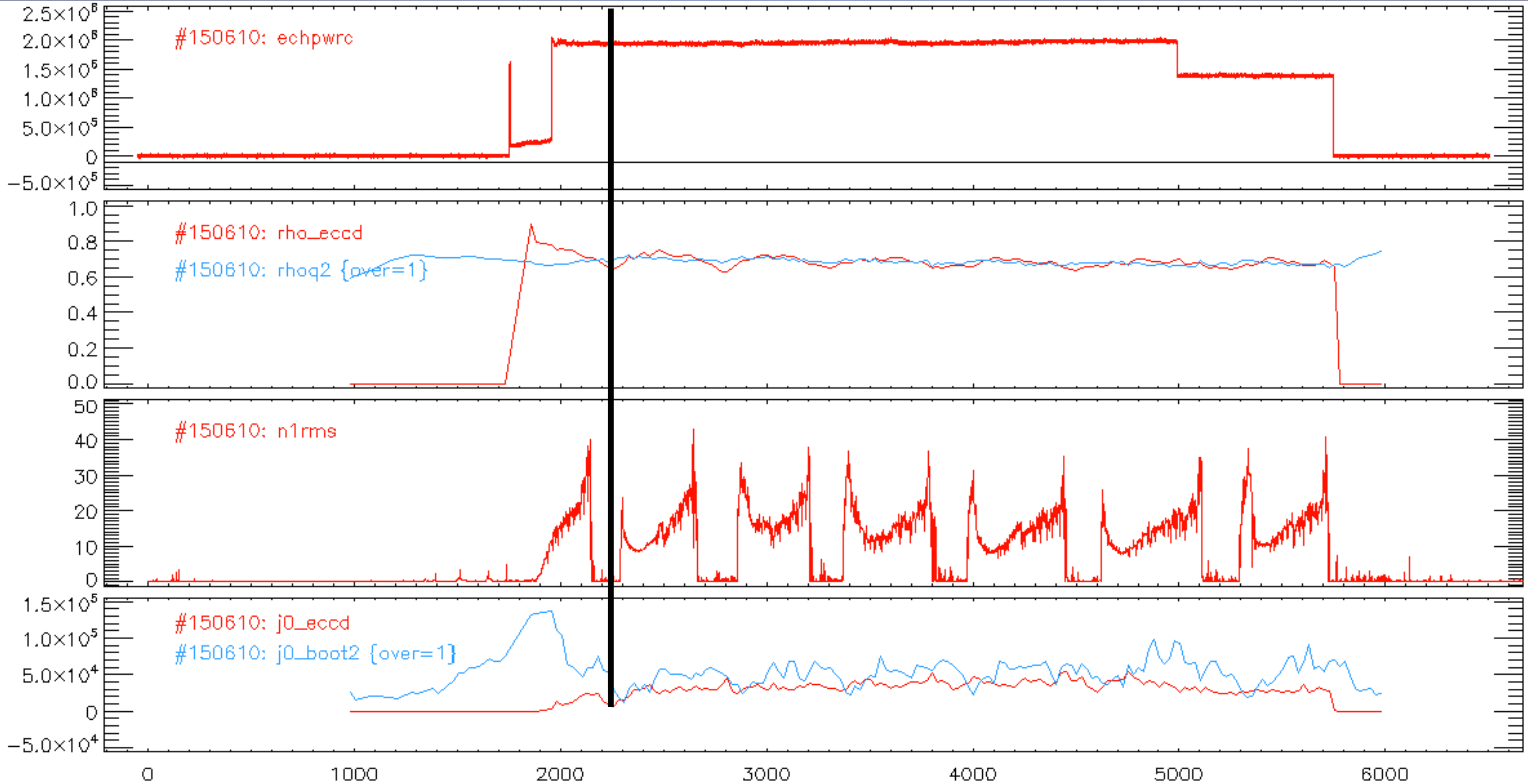

- **Below the critical amplitude** *small island effect takes over which enables fast suppression*
- **Above the critical amplitude** *the mode saturates and suppression takes more than a second or becomes unachievable*

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

# Application to the 2/1 NTM:

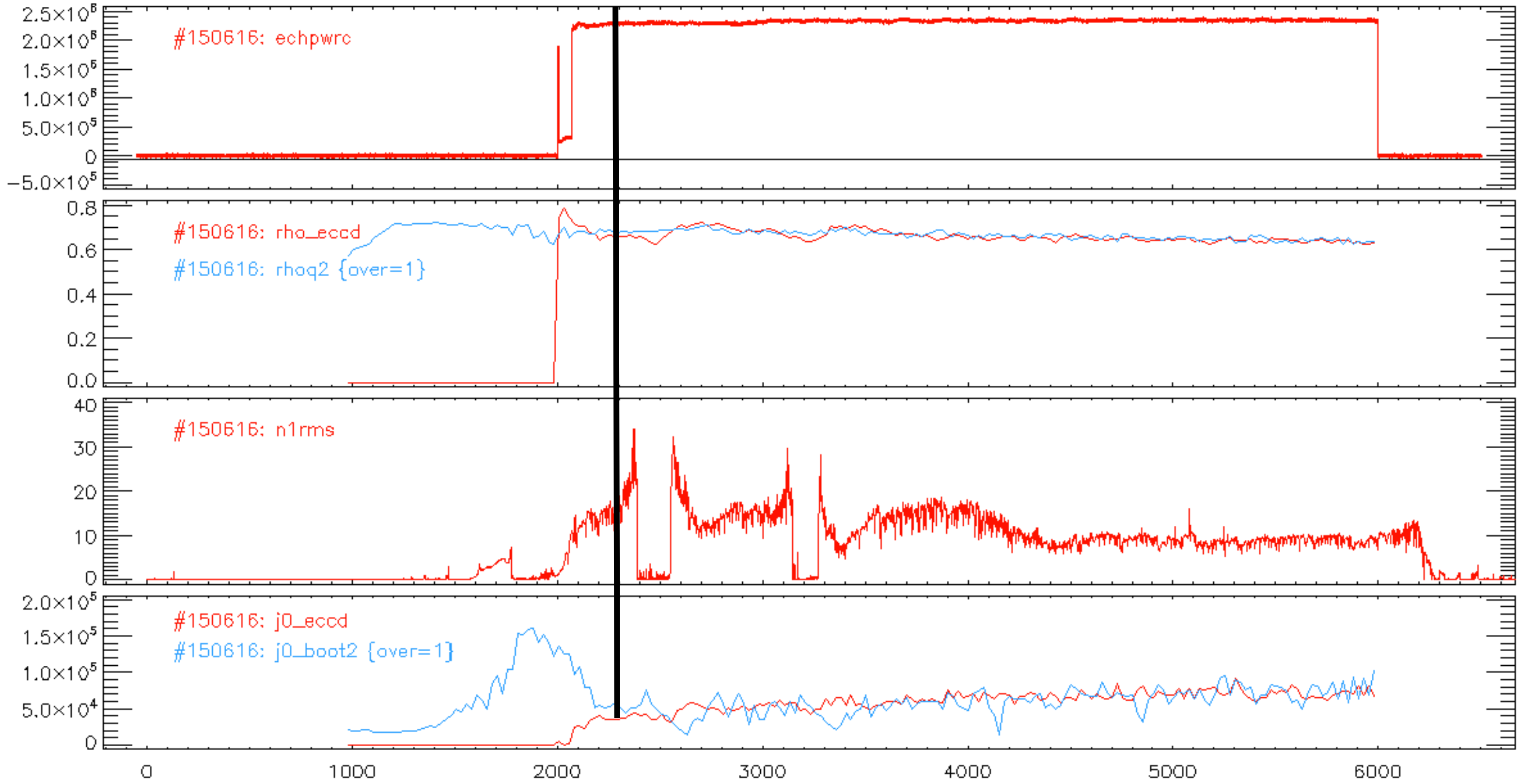
- Most challenging and important case

# 2/1 NTM Catch and Subdue: 1.9 MW Not Enough



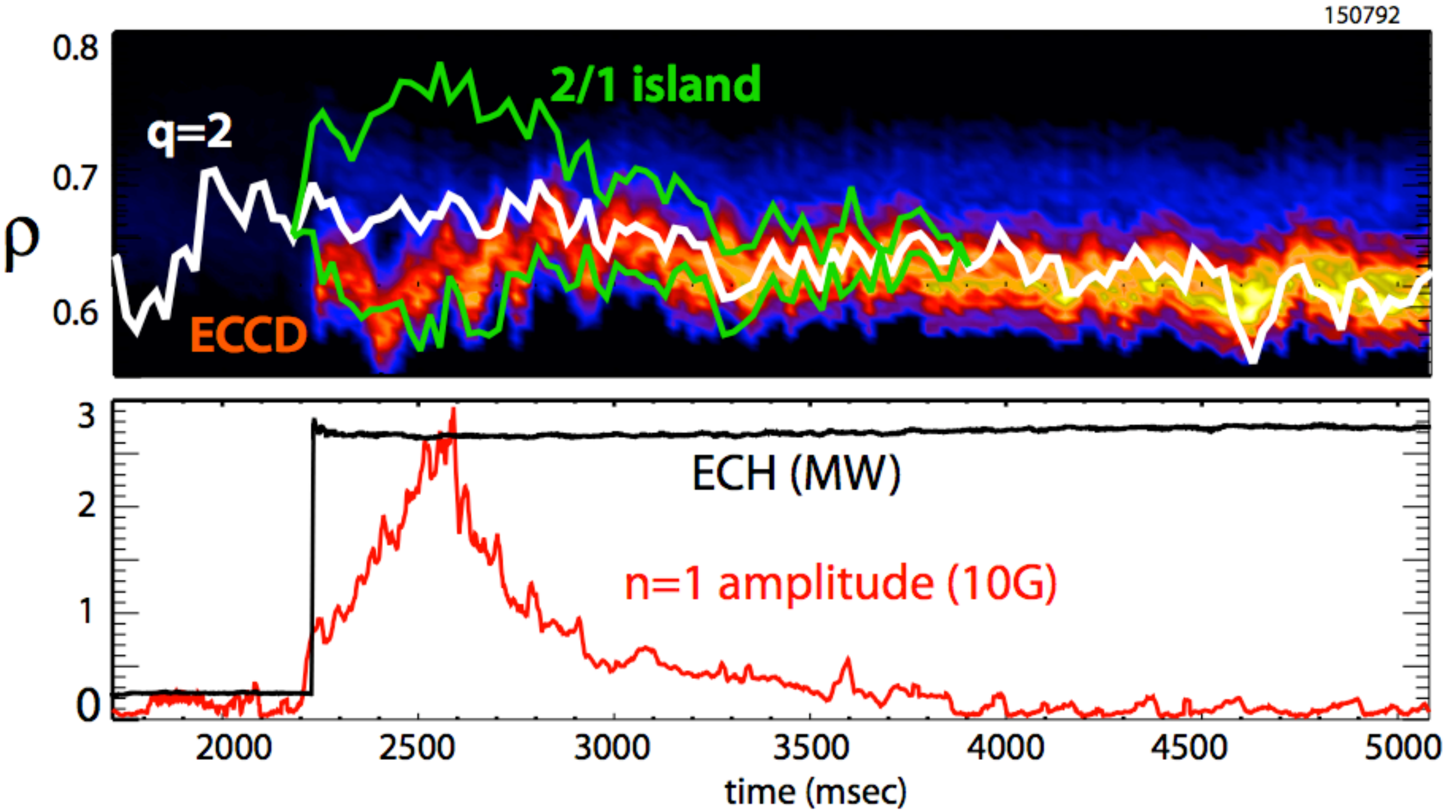

- **ECH Power of 1.9 MW slowed the 2/1 mode but was not able to suppress.**
- **ECCD driven current was lower than the bootstrap current.**

# 2/1 NTM Catch and Subdue: 2.3 MW ECCD Marginal




- ECH Power is only 2.3 MW marginal $j_{ECCD} \sim j_{Bootstrap}$
- Either increase power
- Or reduce density (increase temperature to increase current drive)

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

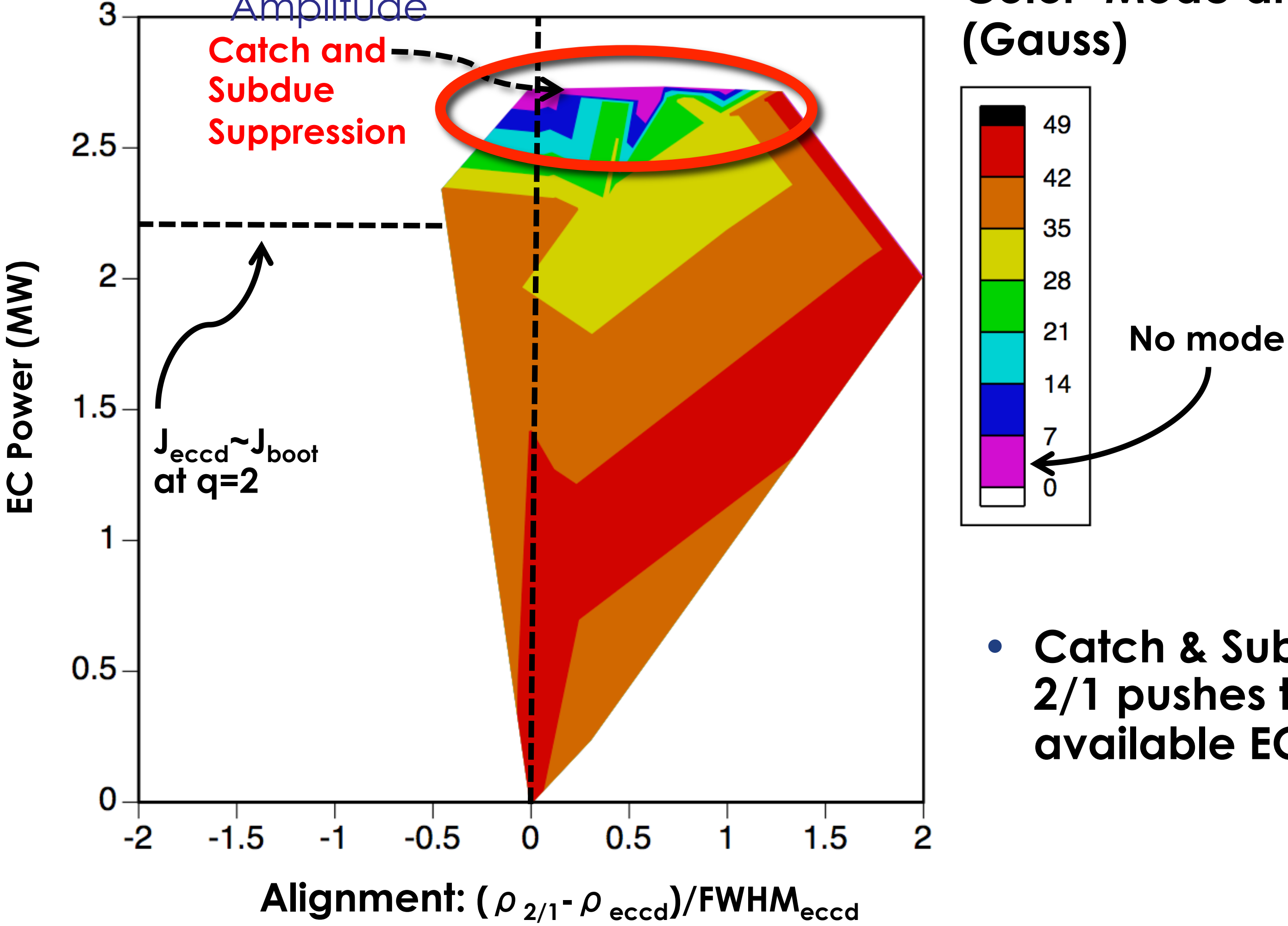



- New fully automatic NTM control system at DIII-D integrates all the Real-Time (RT) components of mode detection, location, suppression
- New control strategy reduces the EC power use; leads to higher Q and reduces disruption risk in ITER

# 2/1 Mode Suppression Requires

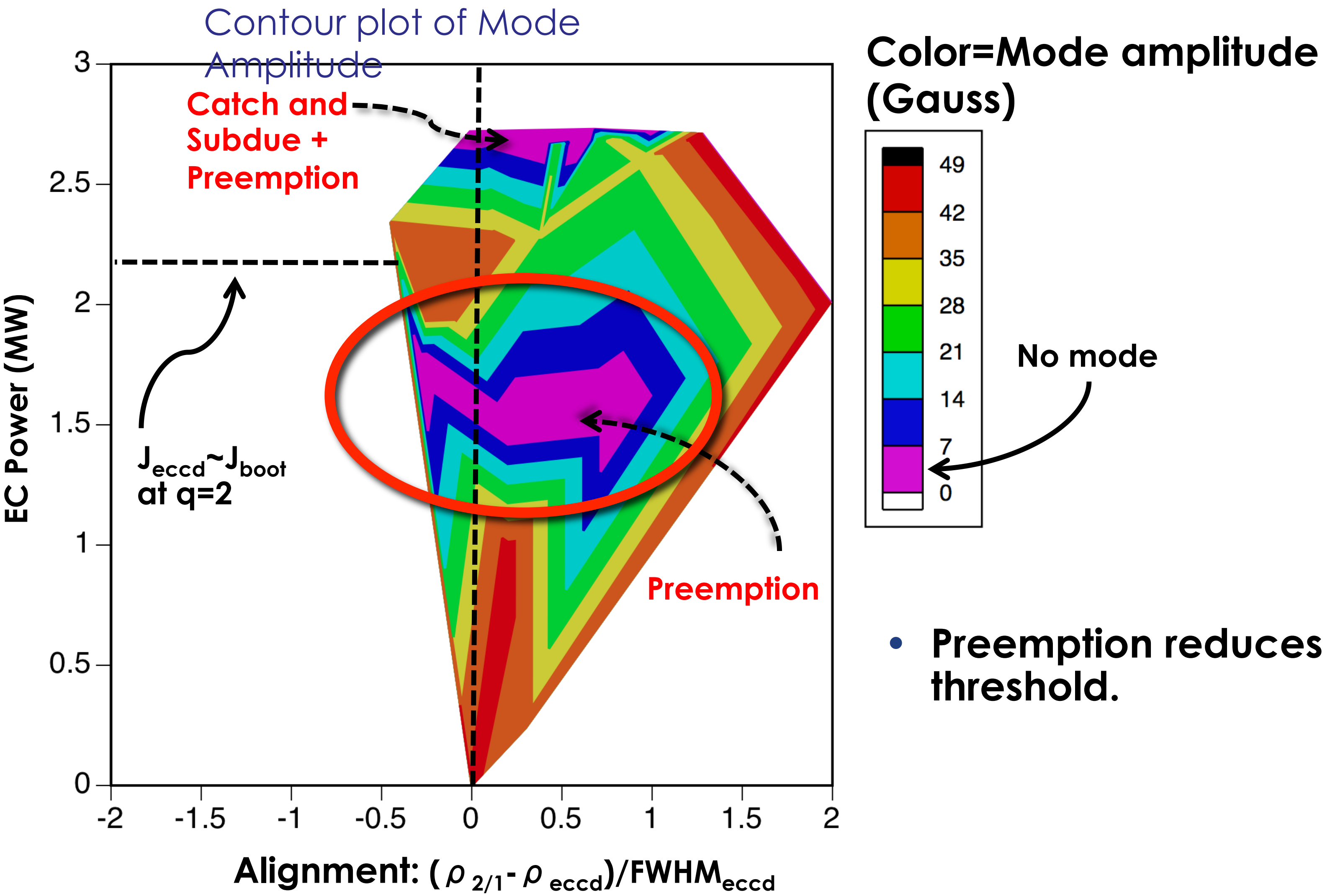
Contour plot of Mode Amplitude

Color=Mode amplitude (Gauss)




- 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.**

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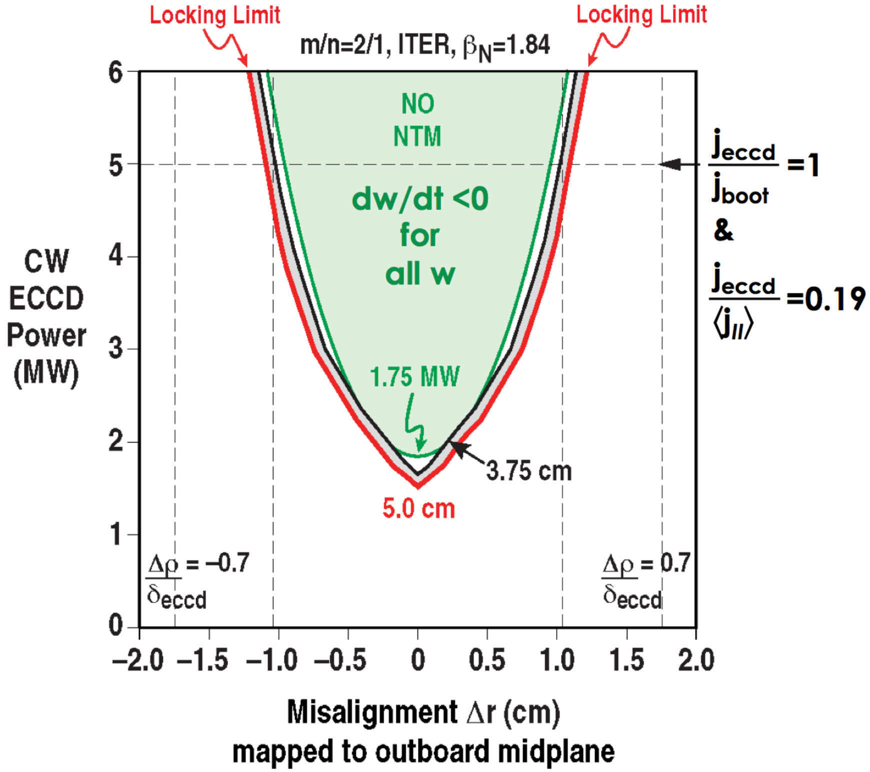
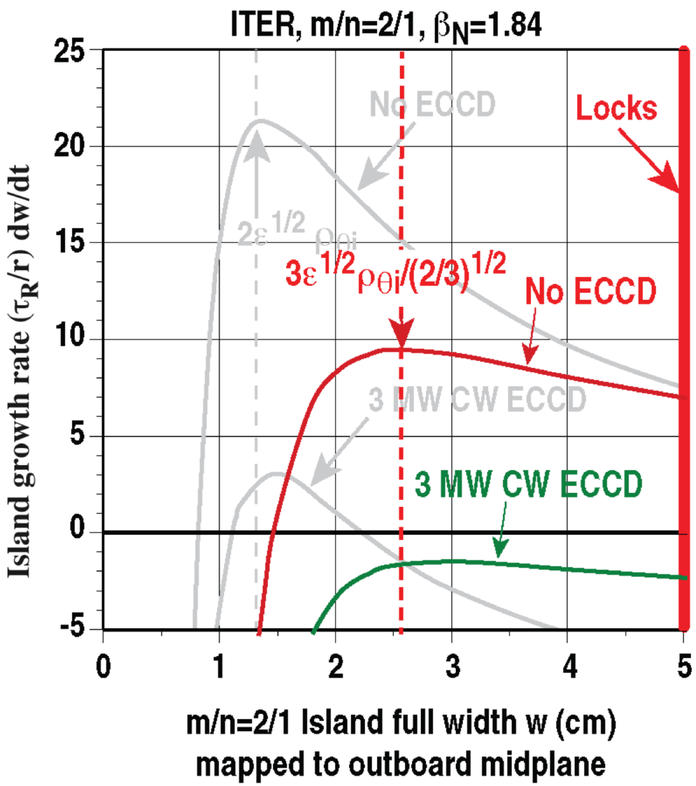
6. Issues, Future Work

# ECCD NTM Control Projections to ITER

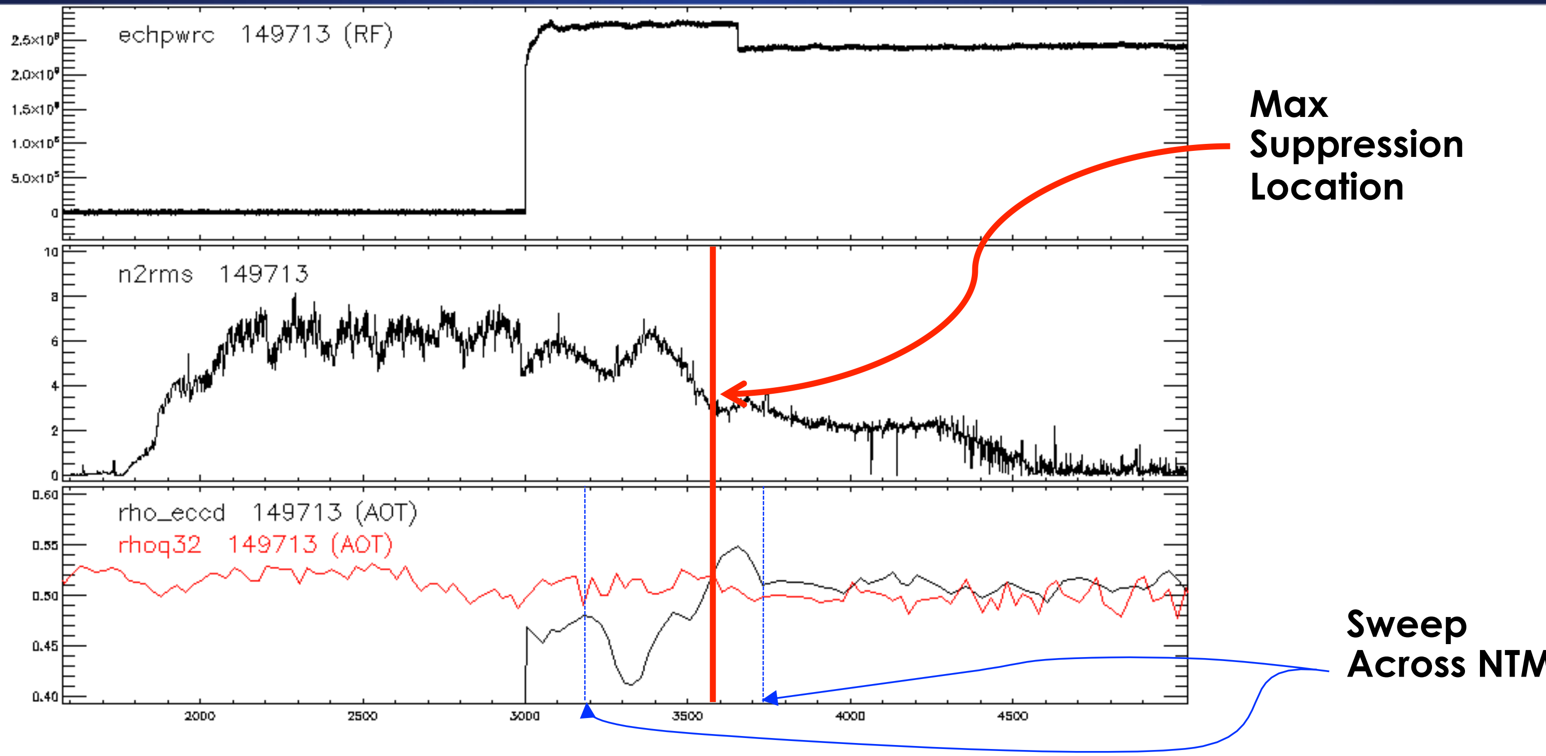



- **Island < 5cm to avoid locking**
- **It maybe possible with good alignment to achieve 2/1 NTM Suppresion with ~2 MW**
- **However, 6 MW is needed for 1.2 cm misalignment**

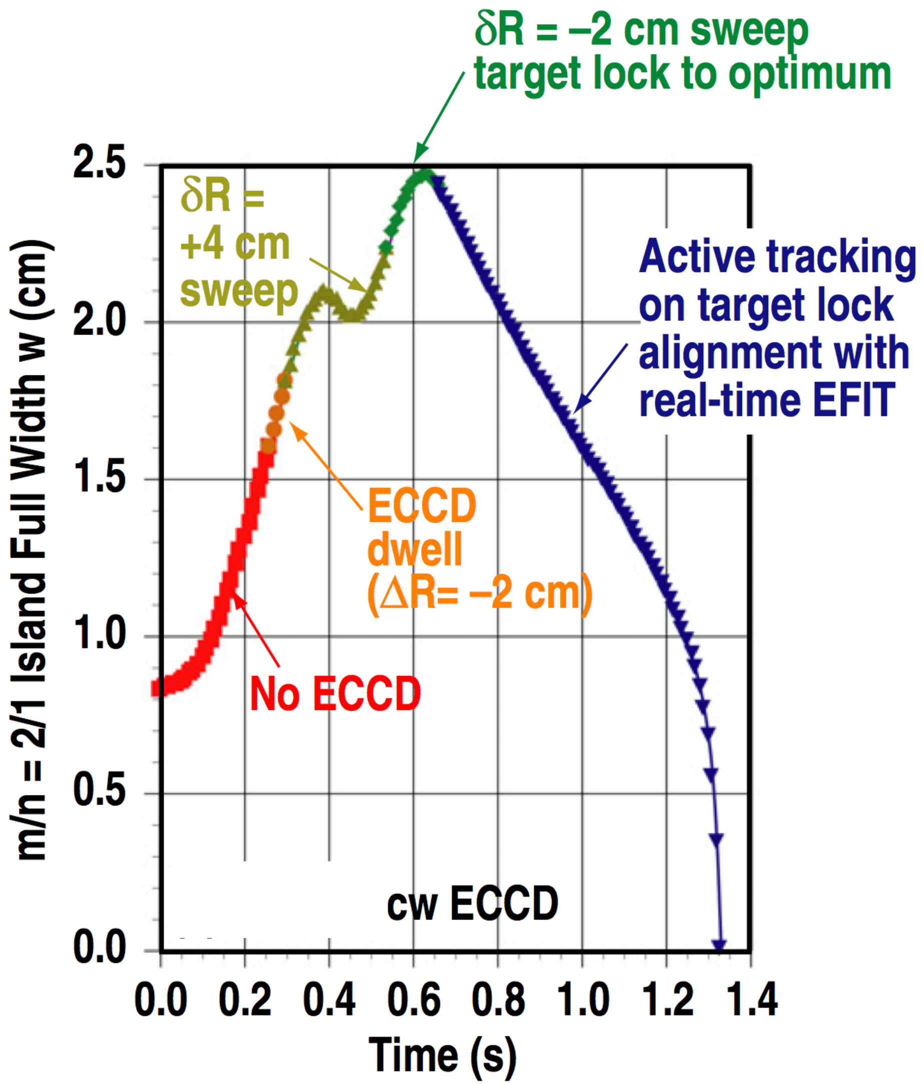
La Haye, Top. Conf. on RF Power in Plasmas,2015

# NTM Suppression: Search and Suppress



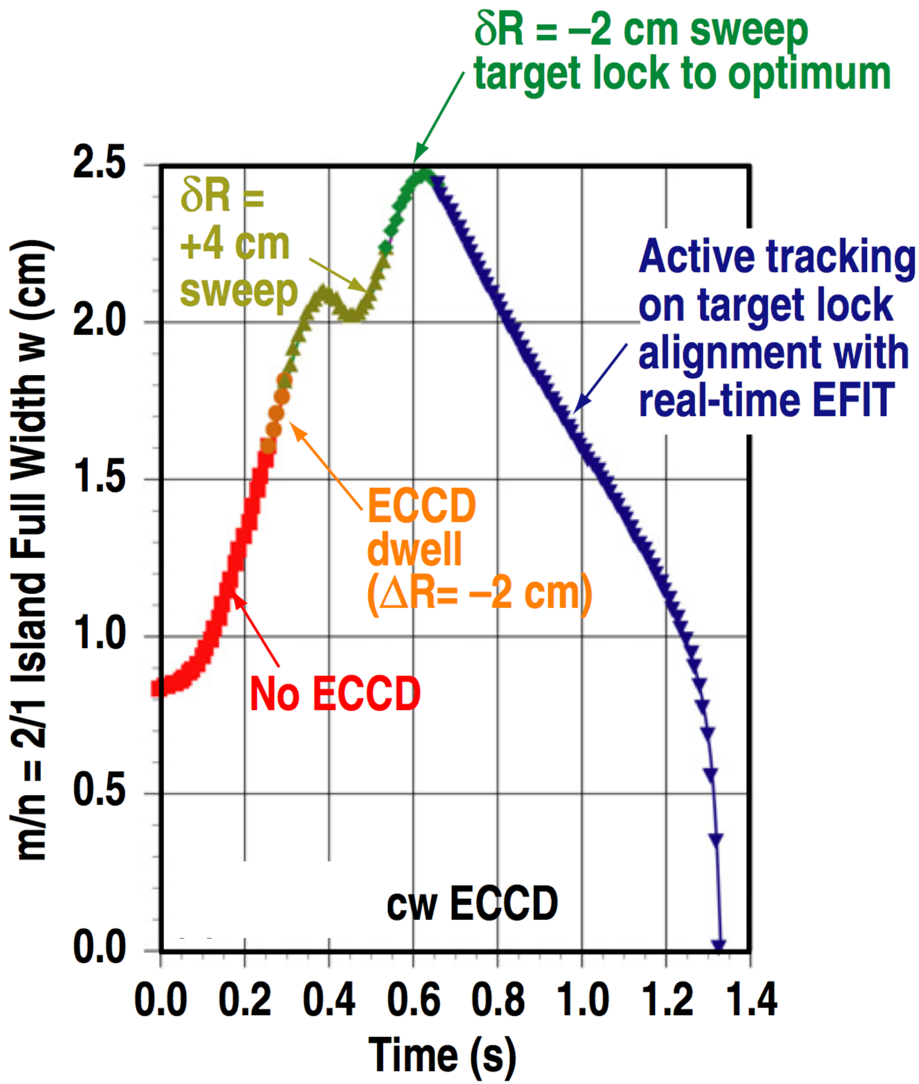

- **Mirnov based Feedback Control**
  - Sweep around the NTM, look at the Mirnov amplitude to find the sweet spot.
  - Go to the sweet spot and stay there.
- **Example Shot where full suppression is achieved is shown above.**

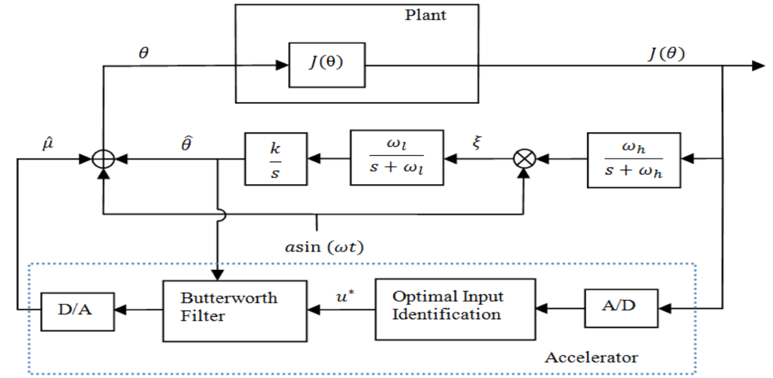
# ITER 2/1 NTM Target Lock Simulation




- **Move the ECCD over the island and optimize alignment**

# ITER 2/1 NTM Target Lock Simulation

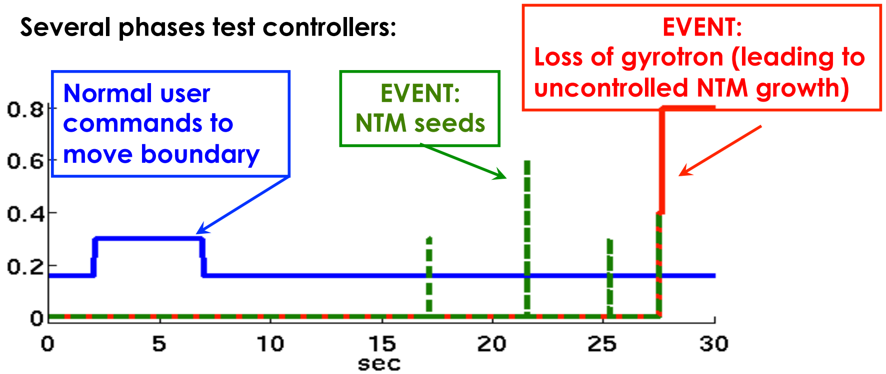


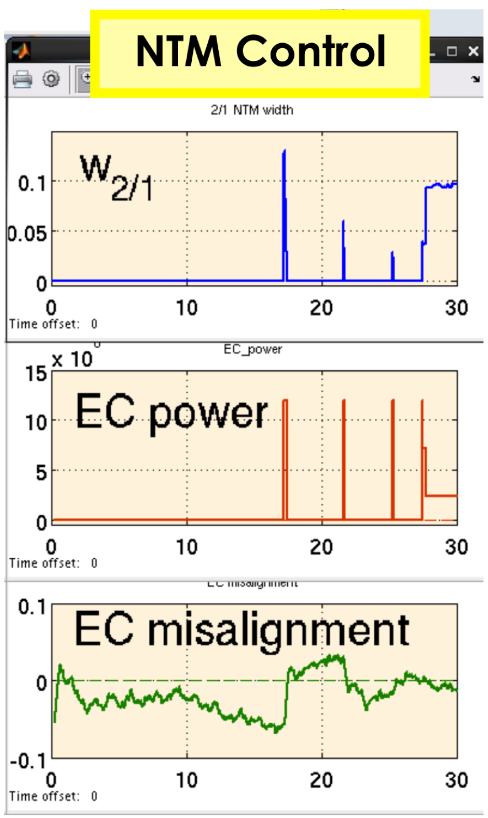



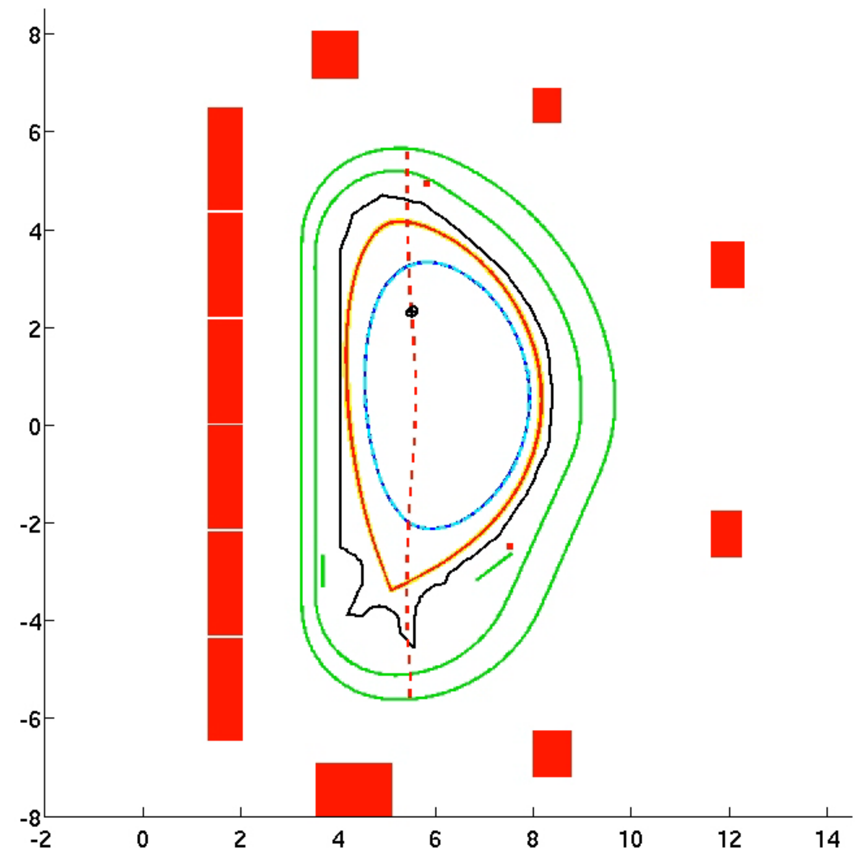

- Theoretically possible to increase the speed of suppression and maximum island size by using a more sophisticated control algorithm [Extremum-Seeking, Schuter, 09]
- However, the ITER ECH launcher system probably will not be responsive enough

# NTM Control Demonstration with Exception Handling

- Several phases test controllers:



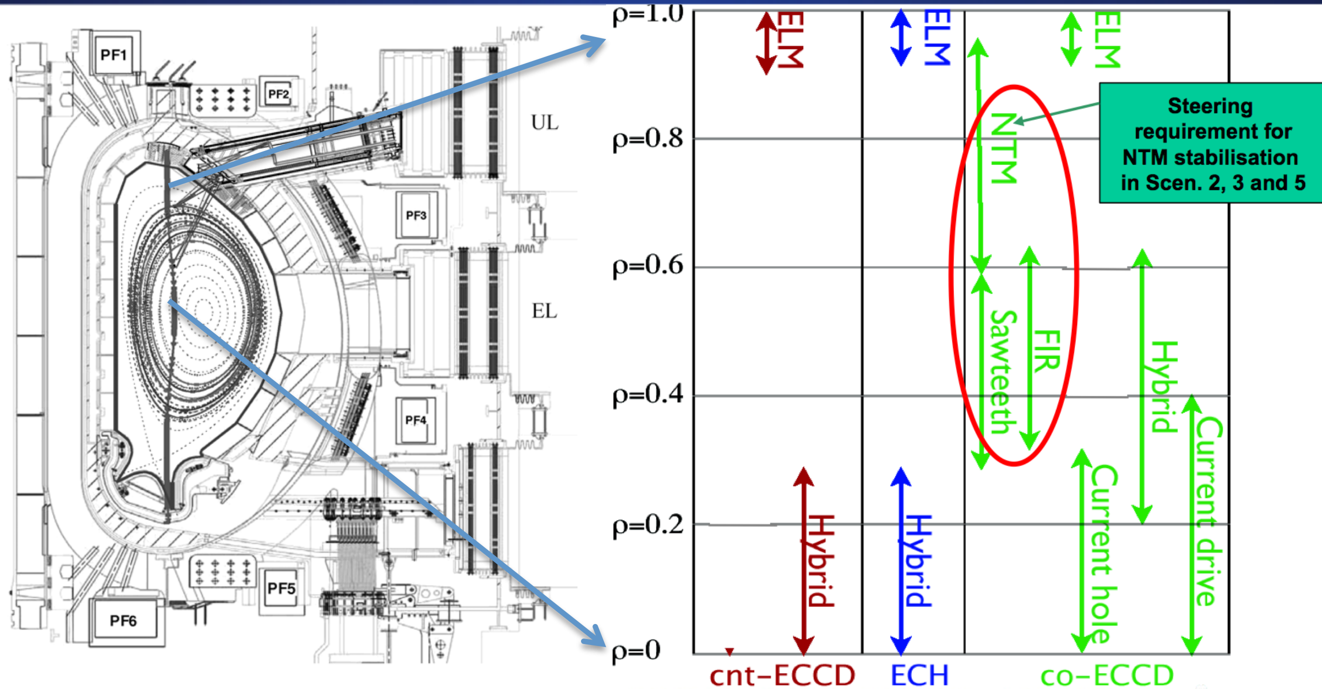



# ITER SPECS for NTM Control System

| *Actuator* | *Plasma parameter controlled* | *Actuator output controlled* | *Category (MP, BC, AC)* | *Range* | *Response time* | *Total Latency* |
|---|---|---|---|---|---|---|
| ECCD | m=2,n=1 Mirnov amplitude | Mirror poloidal position | BC | plus or minus three degrees | six degrees per sec | no more than 10 msec (0.04 sweep time) |
| ECCD | m=2,n=1 Mirnov amplitude | EC power | BC | 3-6 MW | no more than 10 msec (0.04 sweep time) | no more than 10 msec (0.04 sweep time) |
| ECCD | Alignment of ECCD on q=2 | Mirror poloidal position | BC | plus or minus 0.1875 degrees | six degrees per sec | no more than 20 msec (time to 1.4 cm wo ECCD) |
| ECCD | Alignment of ECCD on q=2 | EC power | BC | >3.5 MW | CW | ________ |

**Based on Extrapolation and Simulations [ITER PCS Physics Requirement 2012]**

# ITER NTM Control Hardware

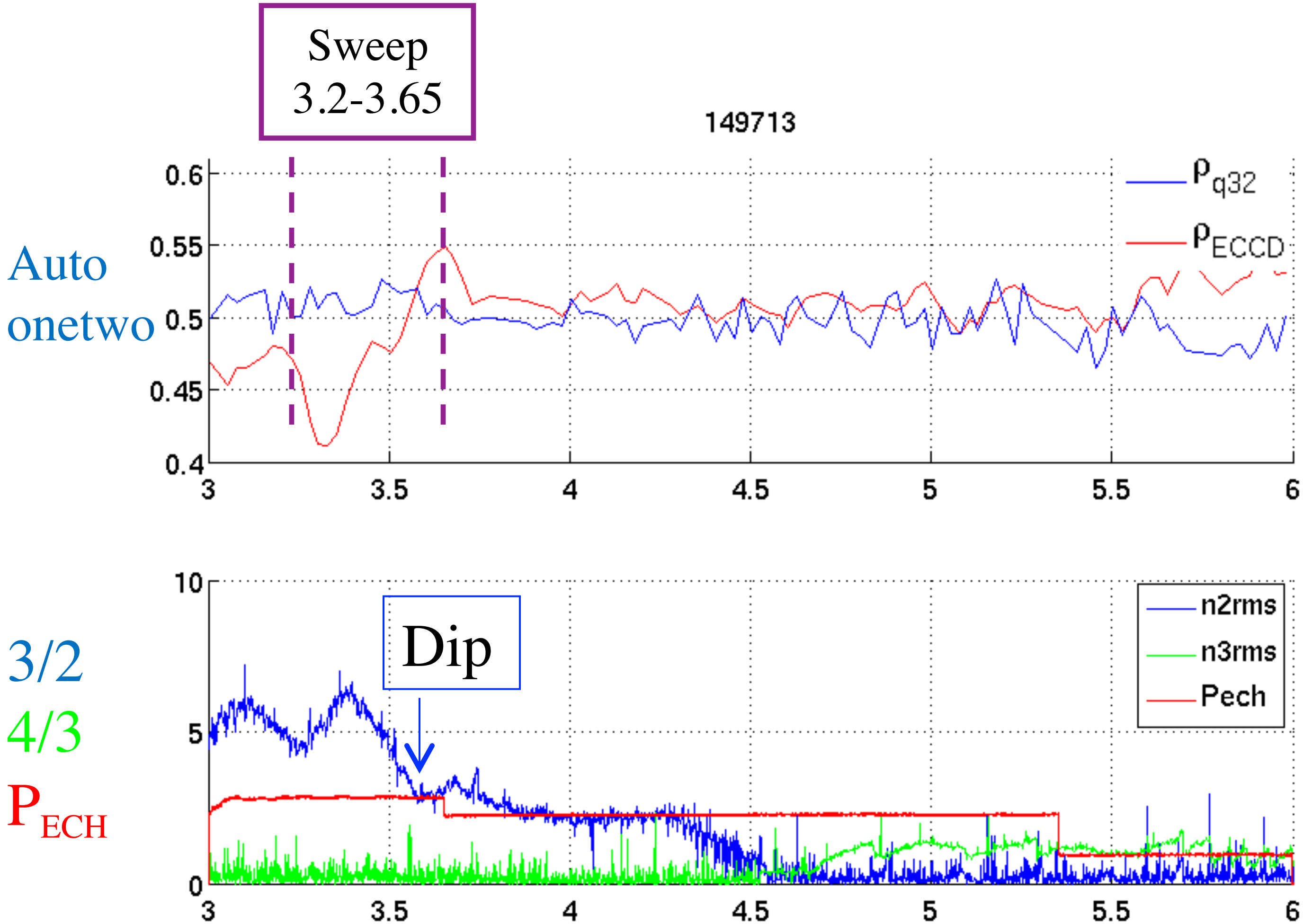



- The upper launcher system designed for mainly for NTM suppression along with other tasks
- Due to neutrons, no moving part (remote steering is studied)
- The systems are already in testing:
  - They will have the 0.1 degree accuracy in steering
  - Speed of 2 seconds to move for the ~+/-7 degree range of the mirror

Henderson NF 2008

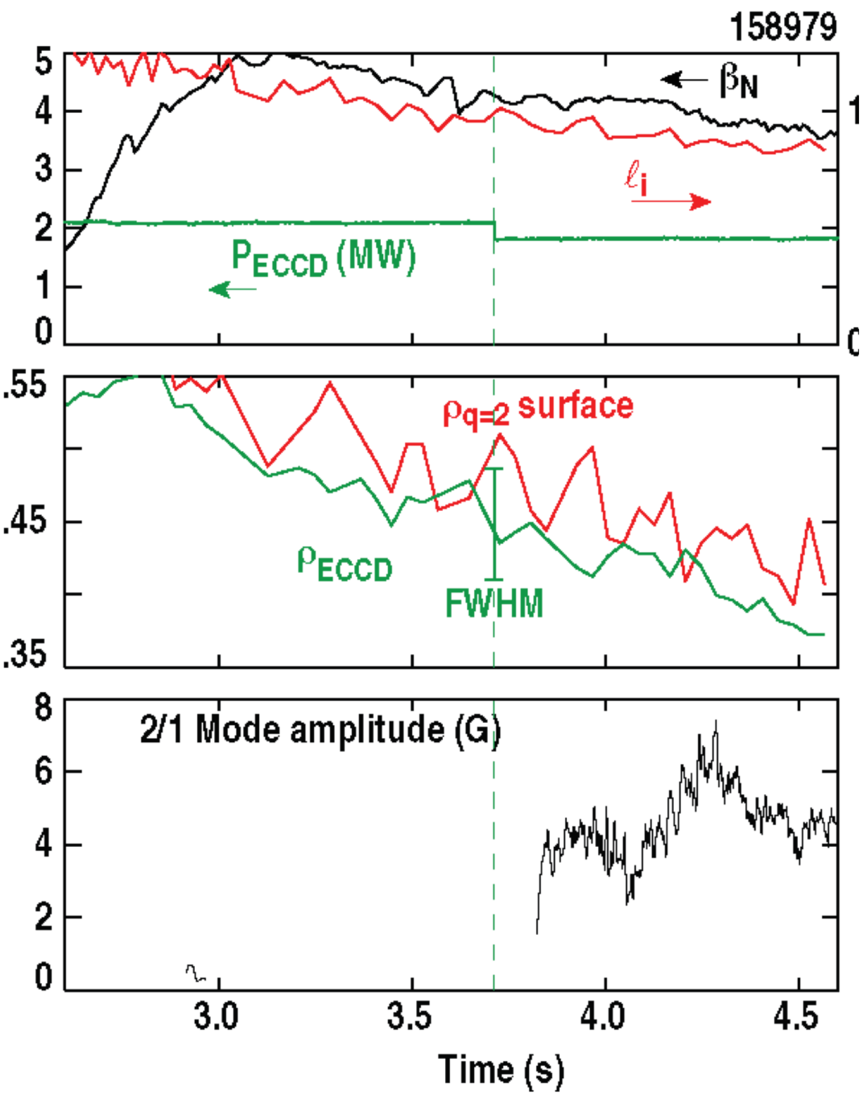
1. Tearing Mode Intro
2. Need for TM Control
3. TM Avoidance
4. ECCD TM Control Development
    a. Physics MRE with ECCD
    b. Control Technique
    c. D3D results
5. Projection to ITER ECCD TM Control
6. **Issues, Future Work**

# Target Lock Suppresses 3/2 NTM but 4/3 NTM Replaces It




**4/3 NTM triggered shortly after suppression of the 3/2**

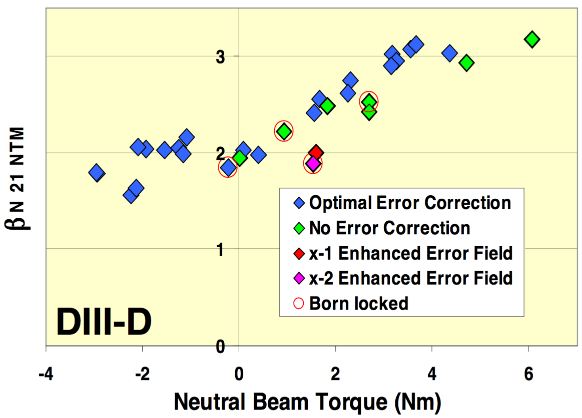
# 2/1 Suppression Leads to 3/1 Island

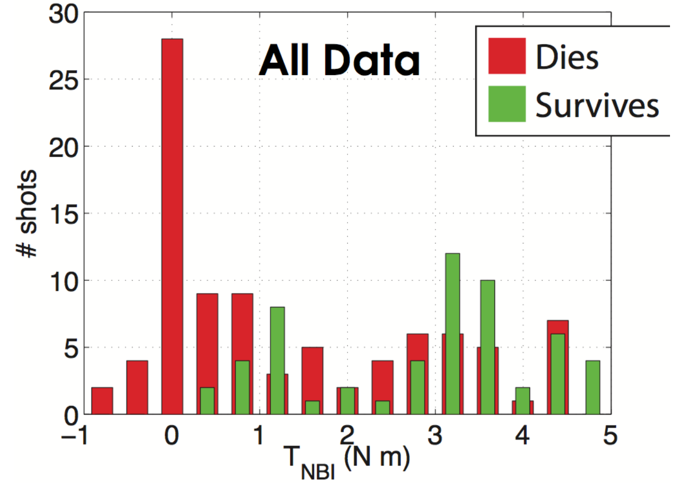


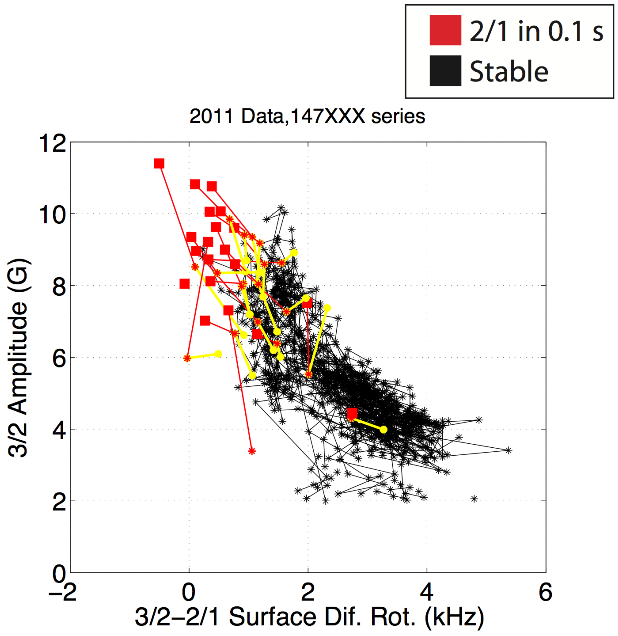

Ferron, NF, 2015

- **Suppression 2/1 leads to formation of other NTMs such as 3/2 or 3/1**
- **When the ECCD is turned off 2/1 NTM comes back**
- ***Also in high qmin (>2) avoids the 2/1 but gets 3/1 NTM that lock***
- **I.e. if the plasma is fundamentally unstable to tearing modes, ECCD can only serve as a Band-Aid**

# NTM Avoidance/Control via Rotation Profile Control?



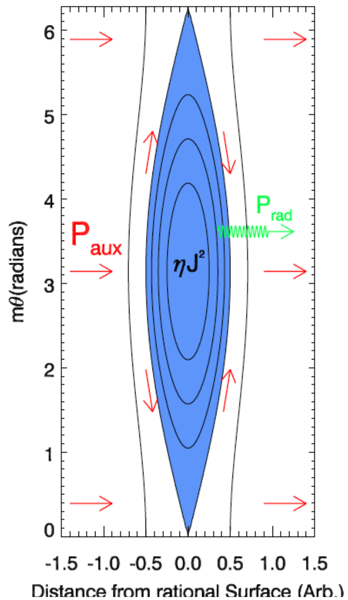



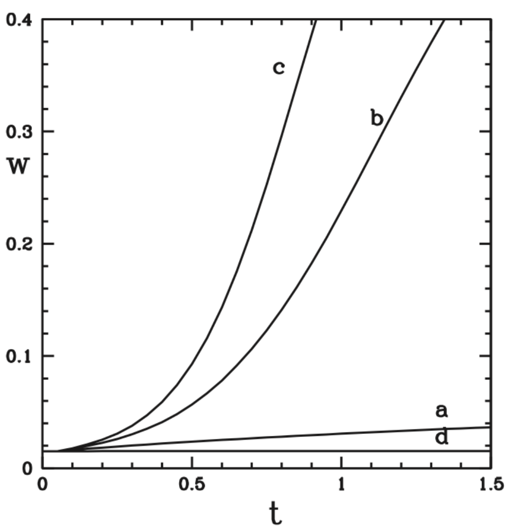

- **2/1 NTM becomes less stable at low torque**
- **DIII-D ITER Baseline experiments show this may be a major issue for ITER**
- **There is not enough actuator to increase the rotation at ITER**
- **However, differential rotation which maybe playing an important role in NTM disruption is a reasonable target for control (intrinsic rotation profile control?)**



Paz-Soldan, Science Seminar, 2015
Buttery, EPS 2007

# Radiative Island Growth and Control for ITER



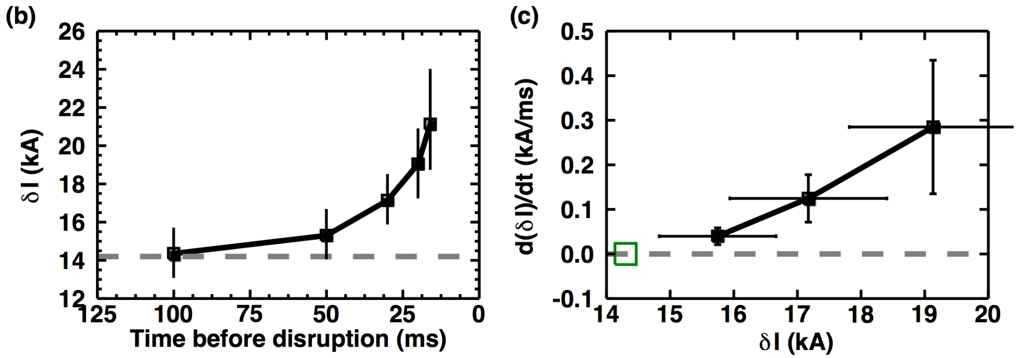




- Island is isolated
- Inside an island impurities radiate
- ➔ cools the island
- ➔ leads to increased resistivity
- ➔ enhances the helical current perturbation
- ➔ The island grows causing process continue
- Model, MRFE:

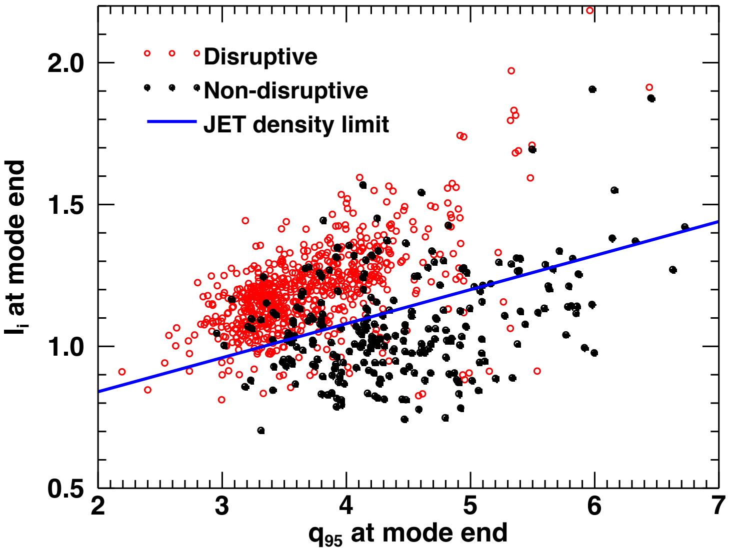
$$\frac{dw}{dt} = \Delta' r_s + \ldots + 3\left(r_s/s\right)\left(\delta P/\left[n_e \chi_\perp T_e\right]\right) w$$

- Even a few percent change causes an exponential growth [White PoP 2015]
- In Figure, b, c at $T_O < T_X$ by a small percent

# DIII-D Disruption Database In Agreement with Radiative Island Model (Sweeney NF 2015, in review)




All modes before disruption
b) The median ~100 ms before disruption
c) The time derivatives of the points in (b). The growth timescale is $\tau \approx 10$ ms.




The space spanned by li and q95 is found to determine density limit disruptions in JET

- The disruption database analysis finds very interesting agreement with radiative island theory.
- ITER with Tungsten will have a harder time with radiative island (though much slower time scales)
- Will we need CW ECH at 2/1 all times? What about the other surfaces?

# Conclusion: Good Progress in Tearing Mode Control for ITER

- **Progress on development of TM control for ITER**
- **Physics basis for the ITER TM dynamics are mostly known**
- **ECCD for TM and Sawteeth control is established at current tokamaks**
- **The TM control systems are being built**
- **Looking forward, the main focus of fusion control will be:**
  - Effect of low rotation
  - Radiative perturbations
  - Most importantly NTM avoidance methods