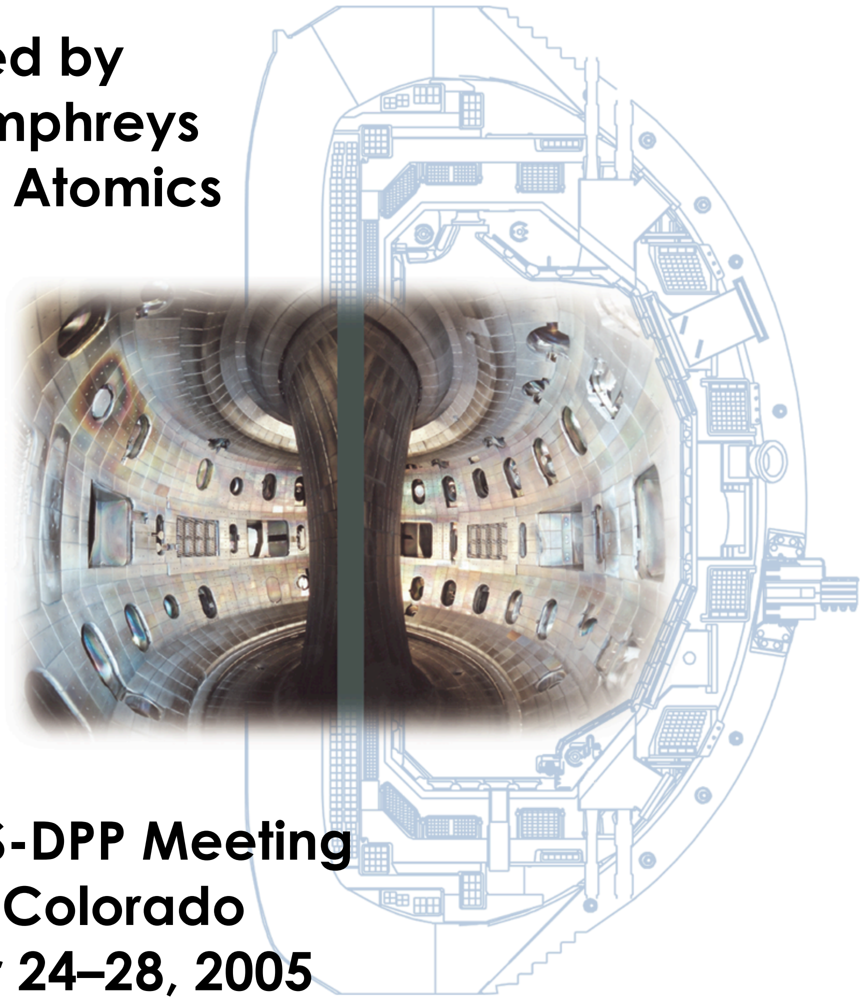
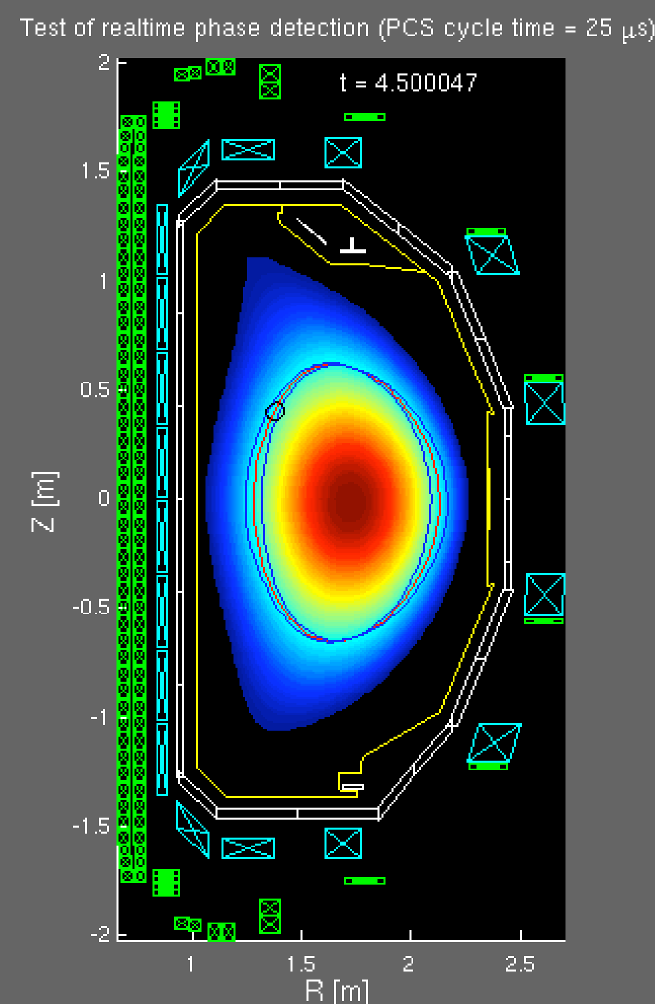
Active Control for Stabilization of Neoclassical Tearing Modes

Presented by
D.A. Humphreys
General Atomics





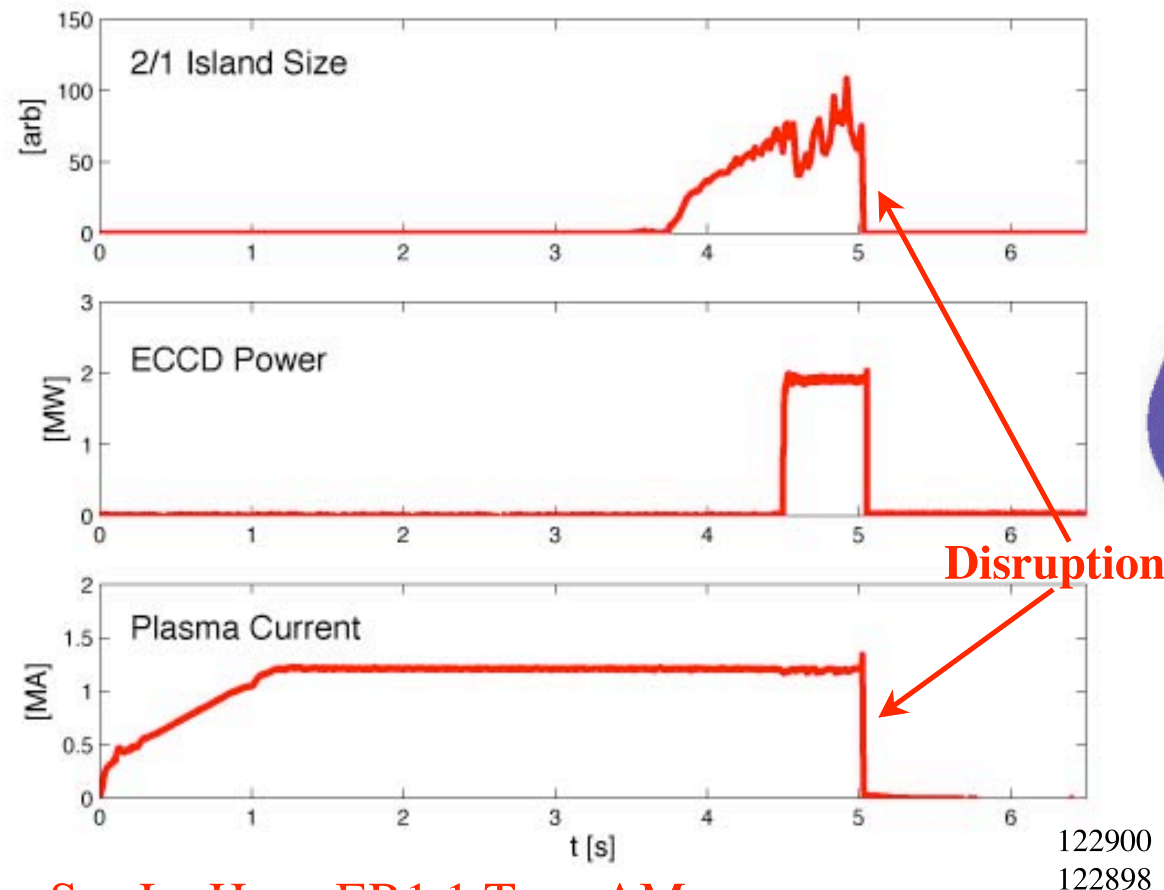
47th APS-DPP Meeting
Denver, Colorado
October 24–28, 2005

DIII-D NATIONAL FUSION FACILITY

GENERAL ATOMICS

Control of NTM's is an Important Objective for Tokamak Fusion Energy

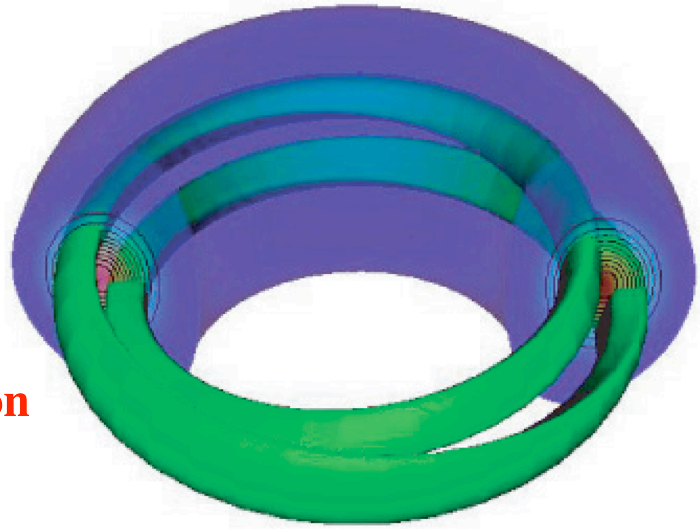
2/1 NTM can disrupt plasma if not stabilized



See La Haye ER1.1 Tues AM

m/n=2/1 NTM:

Poloidal periodicity = 2
Toroidal periodicity = 1



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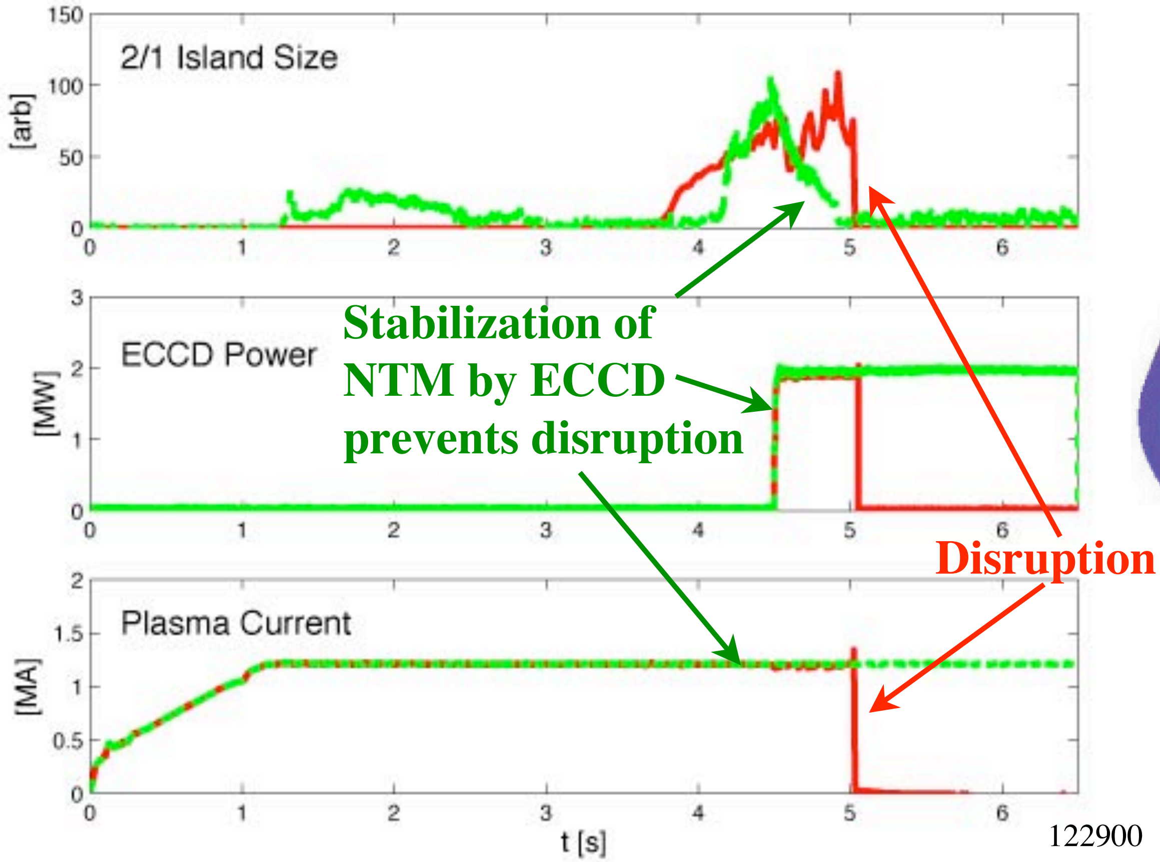

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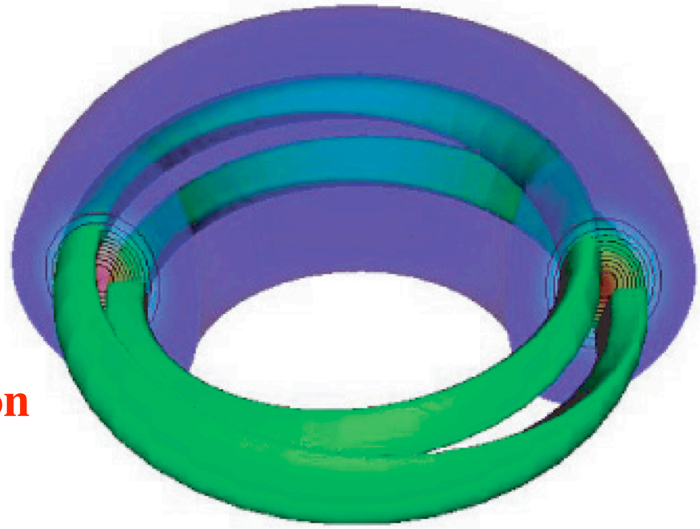
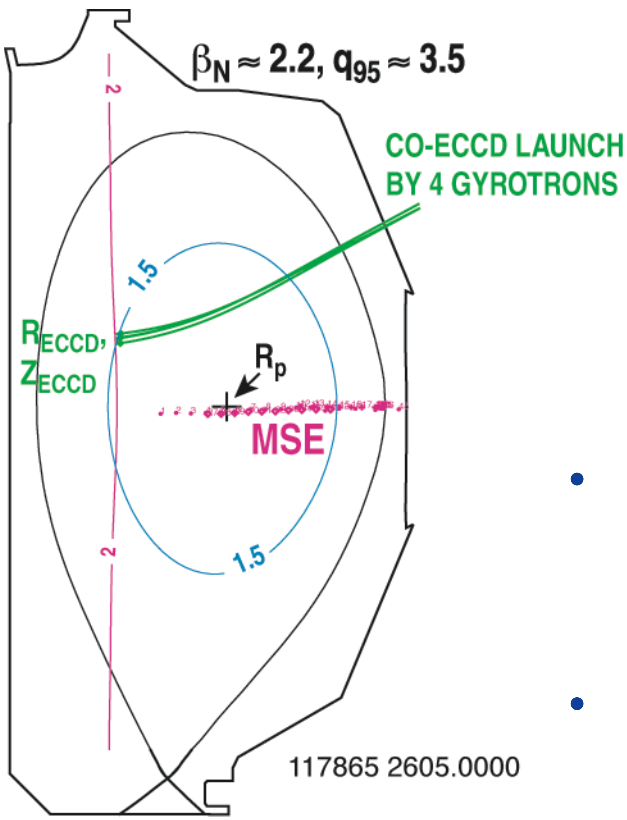


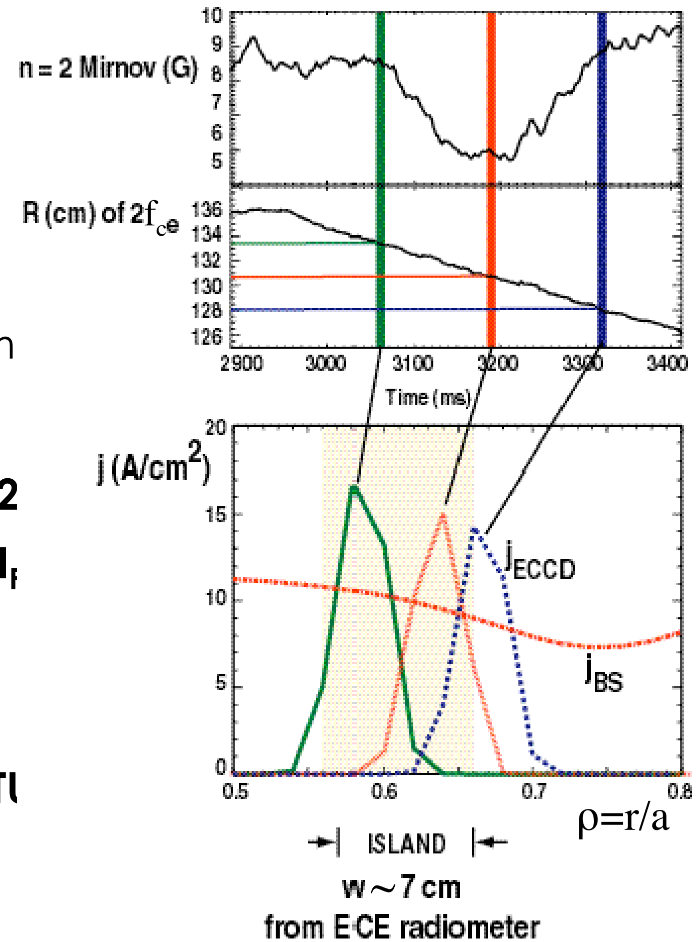
Reliable Sustained Stabilization of NTM by ECCD Requires Precise Active Control

- NTM stabilization with electron cyclotron current drive (ECCD)
- The DIII-D NTM control system: detection, actuators, algorithms, experiments
- Integrated plasma control approach to design
- DIII-D NTM control upgrades for 2006
- Thoughts on NTM control in ITER
- Summary and conclusions

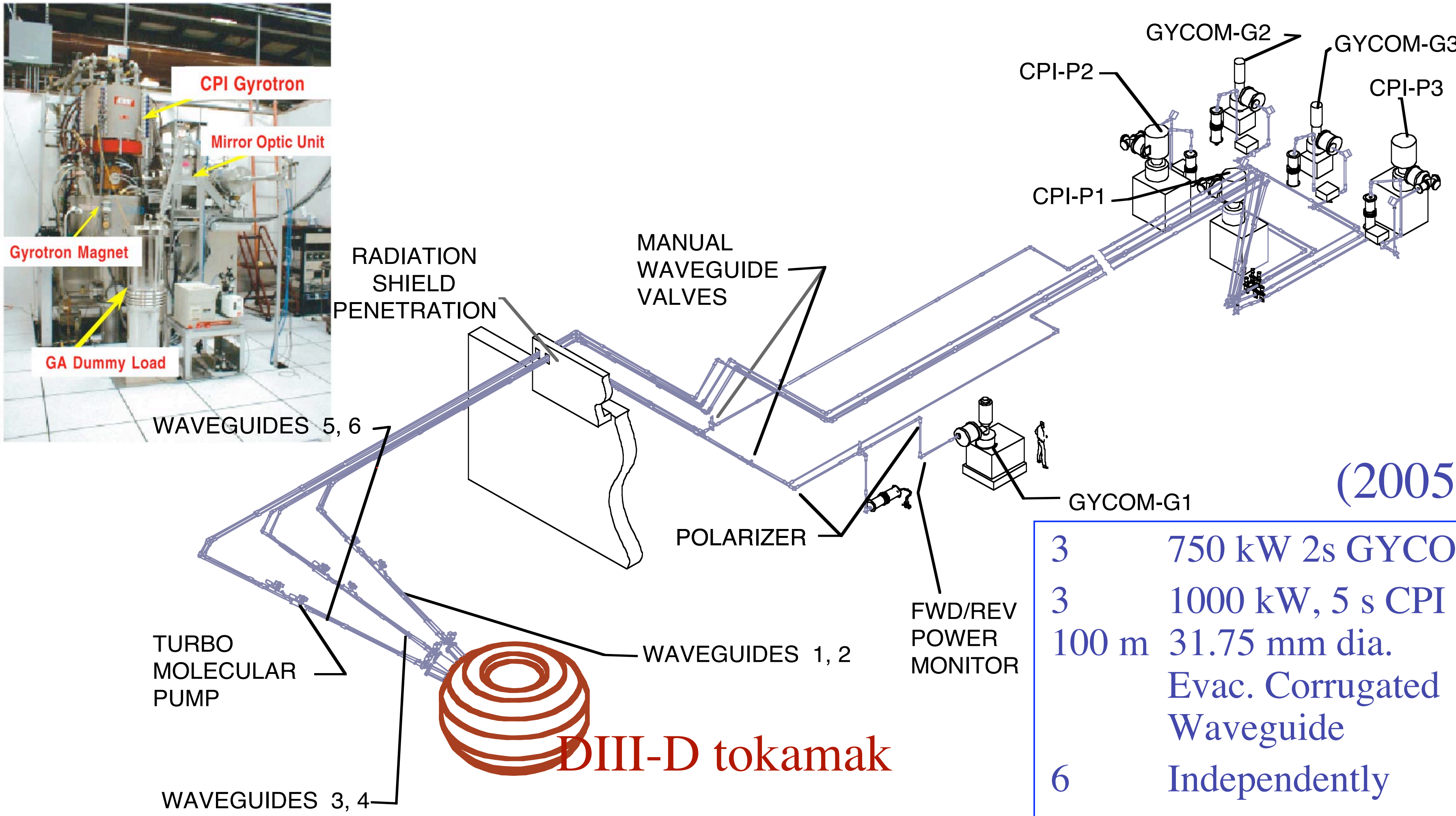
ECCD Localized at Islands Can Replace Missing Bootstrap Current and Stabilize NTM



- **ECCD deposition must be accurately positioned at q=m/n rational surface where NTM island forms**
  - Alignment accuracy required in DIII-D ~ 1 cm
- **EC total current drive (for 2 MW injected) ~30 kA ~2%I**
- **NTM control achieved at ASDEX-U, JT-60U, DIII-D, FT**



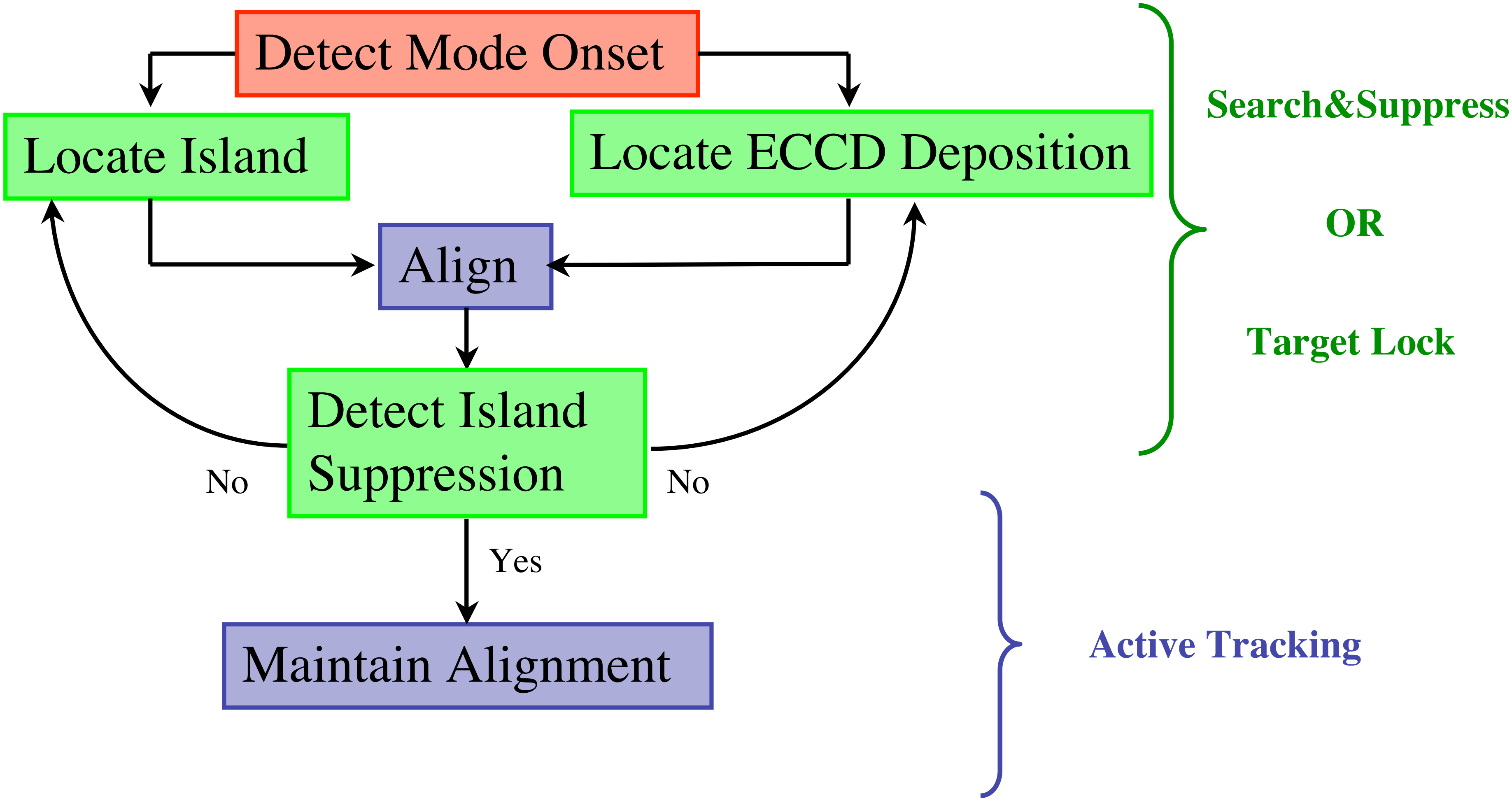
Essential Technology for DIII-D NTM Control is the 110 GHz 6 Gyrotron ECH/ECCD System



(2005)

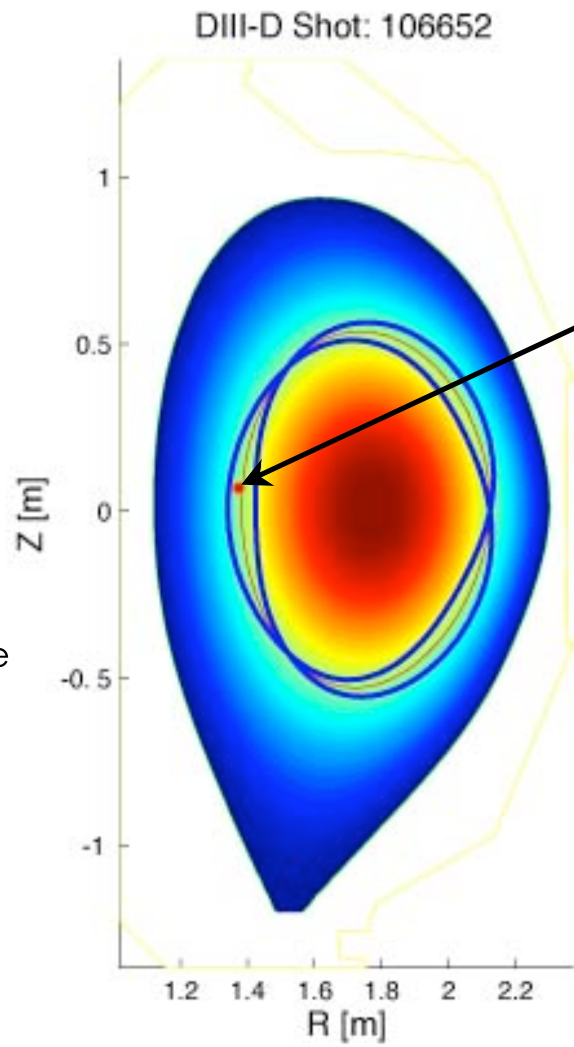
3	750 kW 2s GYCOM
3	1000 kW, 5 s CPI
100 m	31.75 mm dia. Evac. Corrugated Waveguide
6	Independently Steerable Launchers

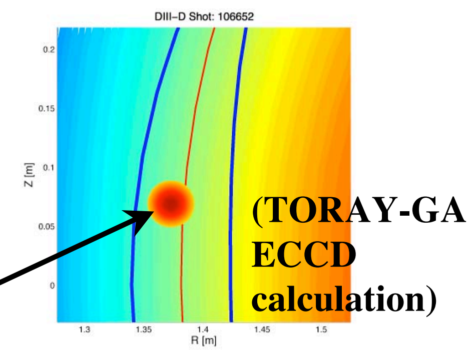
NTM Control Requires Achieving and Sustaining Dynamic Island/ECCD Alignment



Detection: Island/ECCD Locating

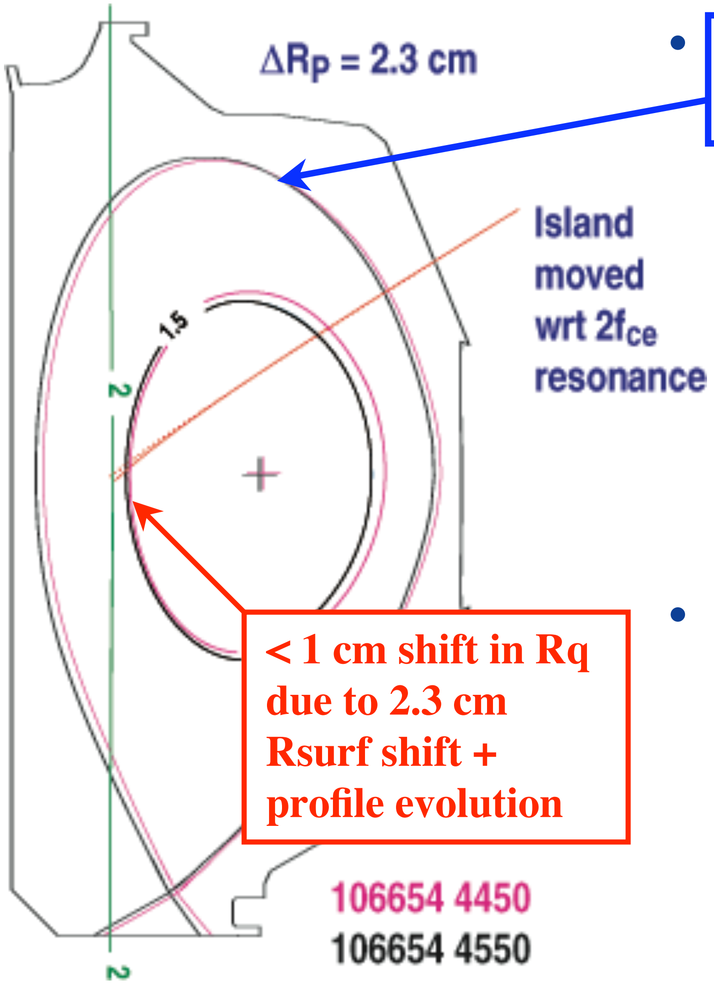
- **Island must be directly measured OR relevant resonant q-surface must be located**
- **Indirect island locating:**
  - Realtime equilibrium reconstruction with profile measurements (MSE) to determine q-surface location
- **Direct island locating (2006 in DIII-D):**
  - ECE measurement to detect flattened temperature profile
  - Magnetics measurements for phase
- **ECCD deposition locating:**
  - Pre-experiment calculation by ray-tracing code (TORAY)
  - Empirical determination in previous experiment or present discharge





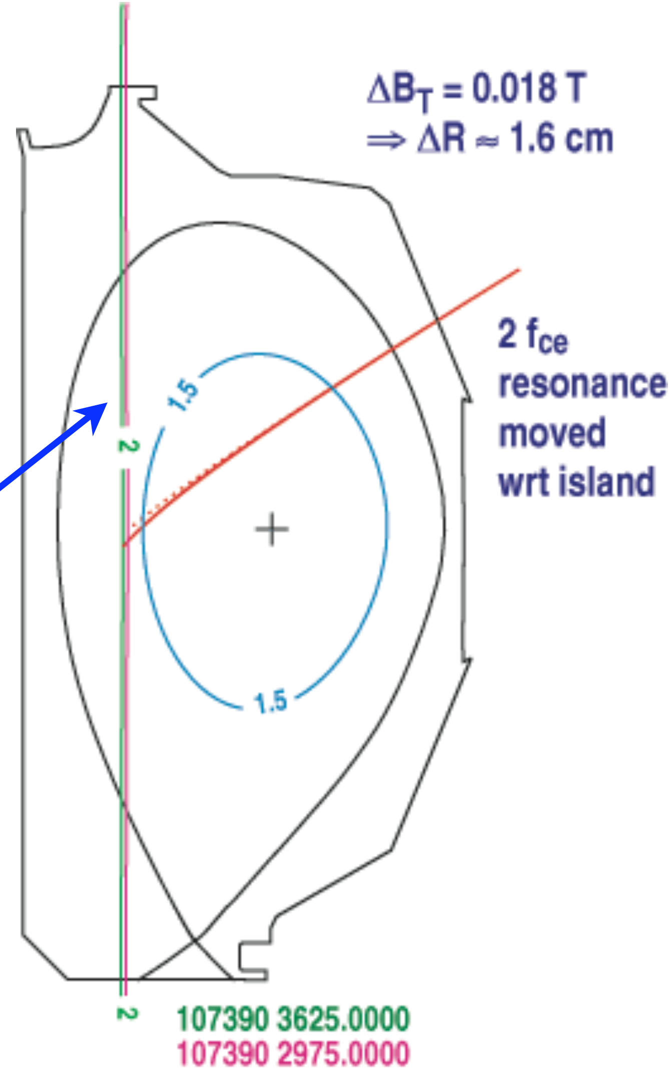
- **ECCD FWHM ~2 cm ~50% of island width**
- **Uncertainty in calculated ECCD location < 1 cm**
- **Precision of q-surface location < 1 cm**

Actuators: Variation of Plasma Position or Toroidal Field Are Used to Regulate Alignment



- Plasma surface major radius can be moved to shift island relative to ECCD

- Toroidal field can be varied to shift ECCD relative to island

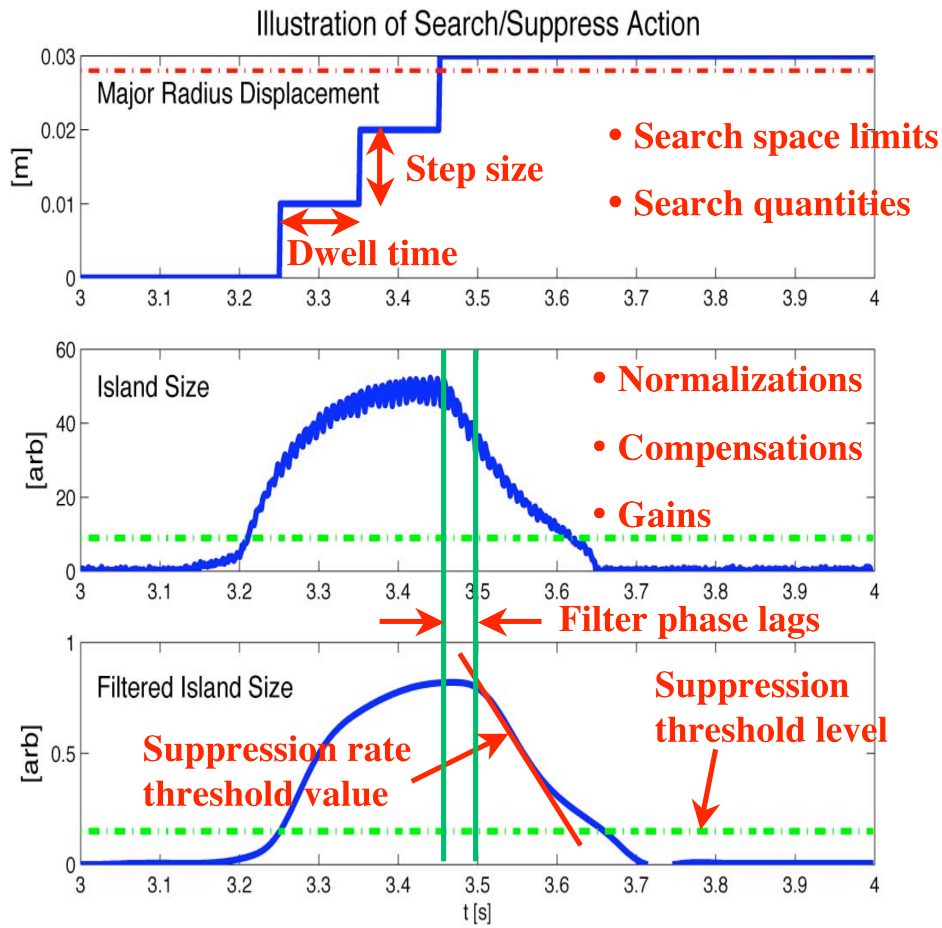


Several Algorithms Are Used to Accomplish and Maintain Island/ECCD Alignment

- **"Search and Suppress"** algorithm to find optimal alignment with *systematic search*
- **"Target Lock"** algorithm to determine optimal alignment *rapidly*
- **"Active Tracking"** algorithm to *maintain* q-surface/ECCD alignment after island suppressed

"Search and Suppress" Algorithm Uses Island Response to Detect Island/ECCD Alignment

- **Uncertainty in locations of both island and ECCD comparable to alignment accuracy required (~ 1 cm) ⇒ need systematic search**
- **"Search and Suppress" algorithm:**
  - Vary alignment in steps (e.g. plasma major radius ΔR or toroidal field ΔB_T)
  - Dwell for specified time to measure island response
  - Freeze if island suppressed
- **Adjustable feedback parameters include filters, compensation for plasma motion and rotation**
- **Actuator limits prevent plasma-limiter contact**

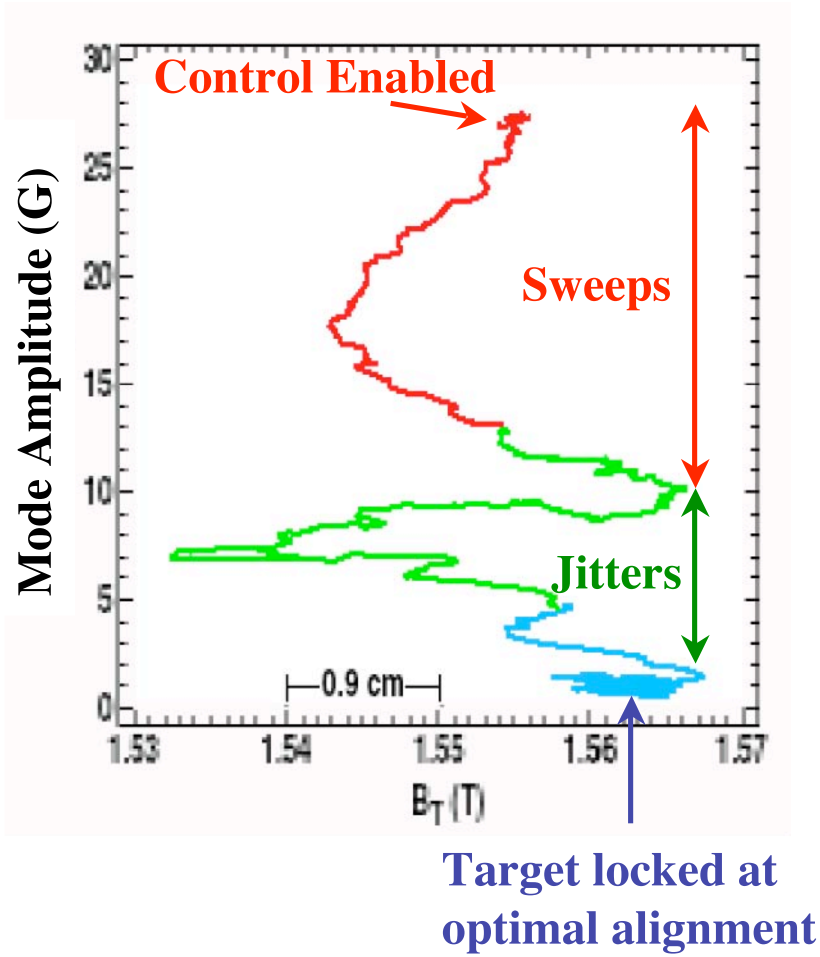


“Target Lock” Algorithm Samples Island Response Dynamically to Home-In on Optimal Alignment

- **Search & Suppress: systematic search for optimal alignment can be slow (~400-500 ms)**

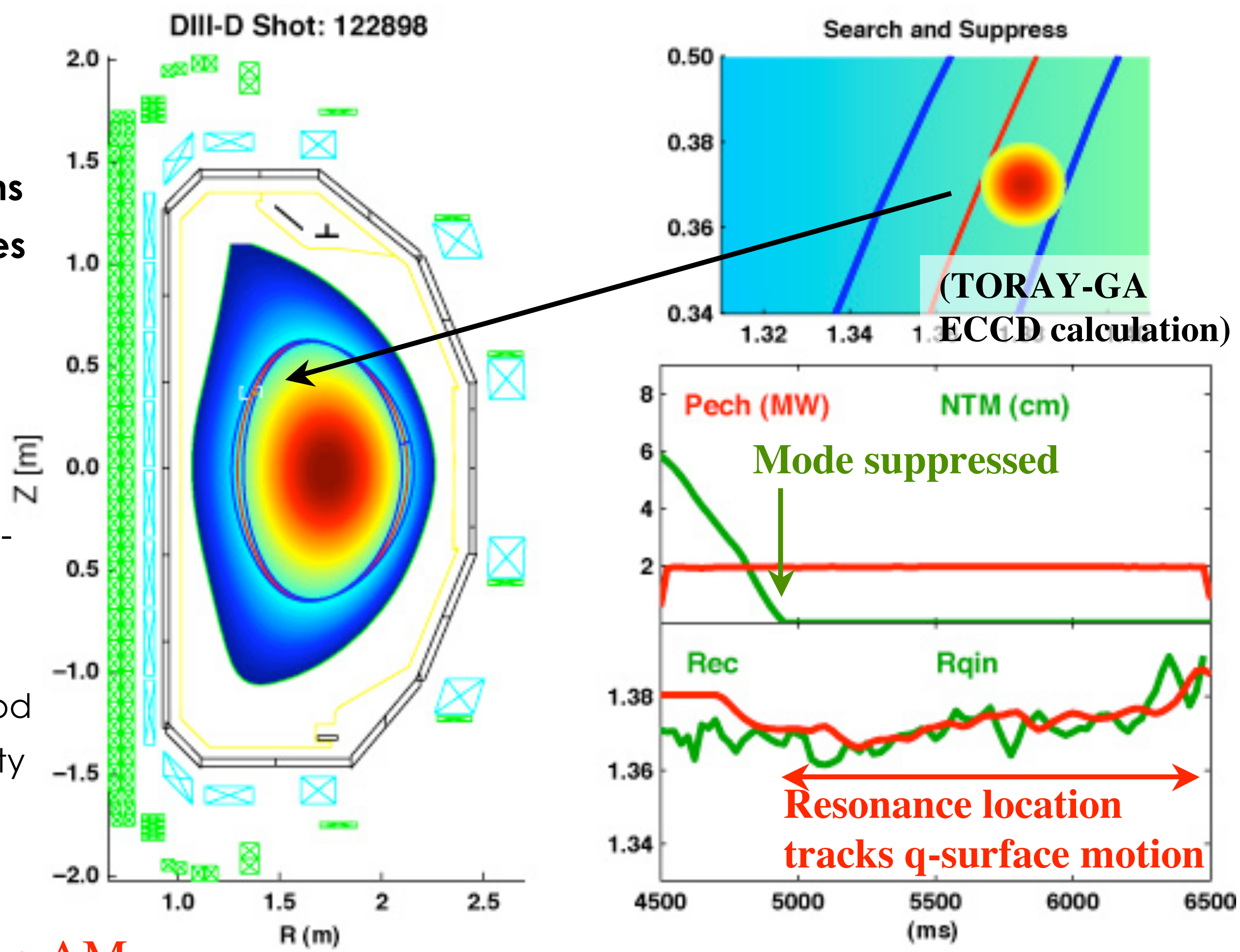
- **“Target Lock” algorithm:**
  - Builds probability function for optimal alignment based on dynamically acquired island response to motion
  - Contains modified Rutherford equation model of island response
  - Initial sweep to produce first map of probability function
  - Short “jitters” refine search, converge to optimal

- **In principle faster than Search & Suppress:**
  - In practice requires careful tuning of control parameters and good signal conditioning (high noise sensitivity)



"Active Tracking" Maintains Alignment and Suppression of Mode

- **After island suppressed, evolution in equilibrium detunes alignment**
- **"Active Tracking" maintains alignment as profile evolves**
  - Uses realtime q-profile (realtime equilibrium RTEFIT + MSE) reconstruction
  - Feedback on rational q-surface without island
  - Assumes no change in ECCD location (not good assumption when density varies and refraction is large)



See La Haye BO3.14 Mon AM

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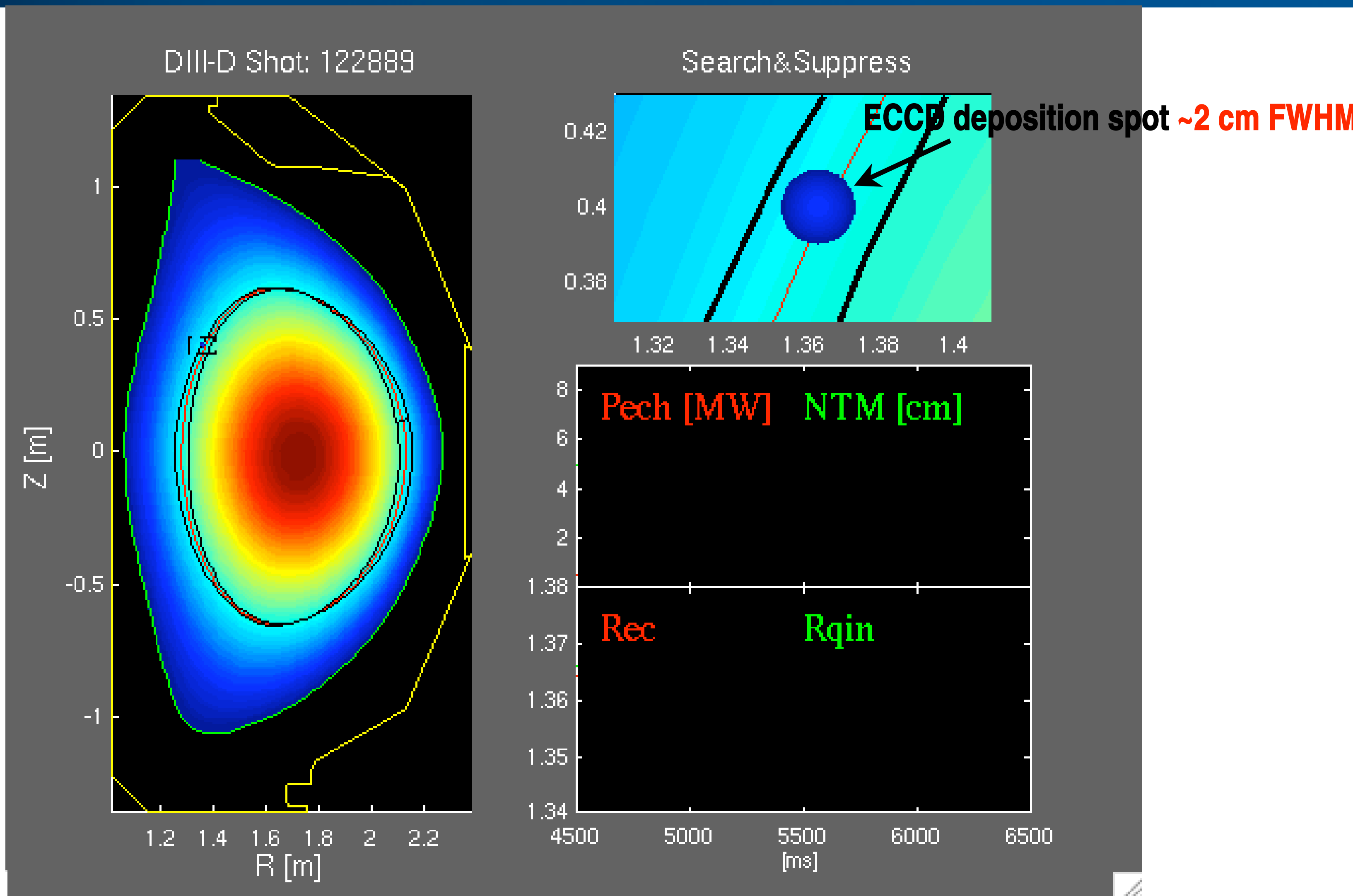
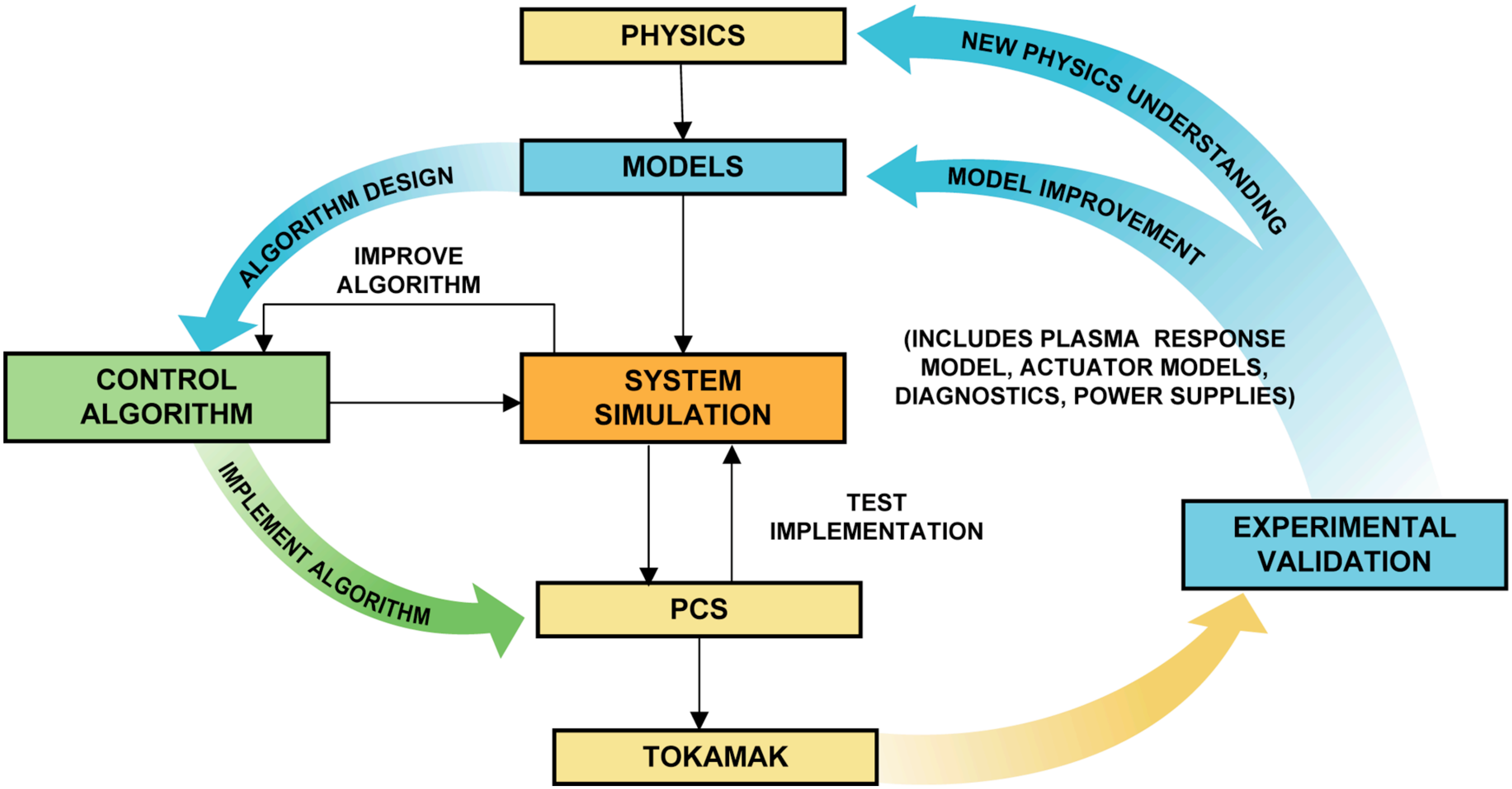
Search/Suppress + Active Tracking Stabilizes Mode and Maintains Alignment with q-Surface Feedback



New Paradigm of Systematic Design for High Confidence Performance: Integrated Plasma Control



See Welander CP1.36 Mon PM

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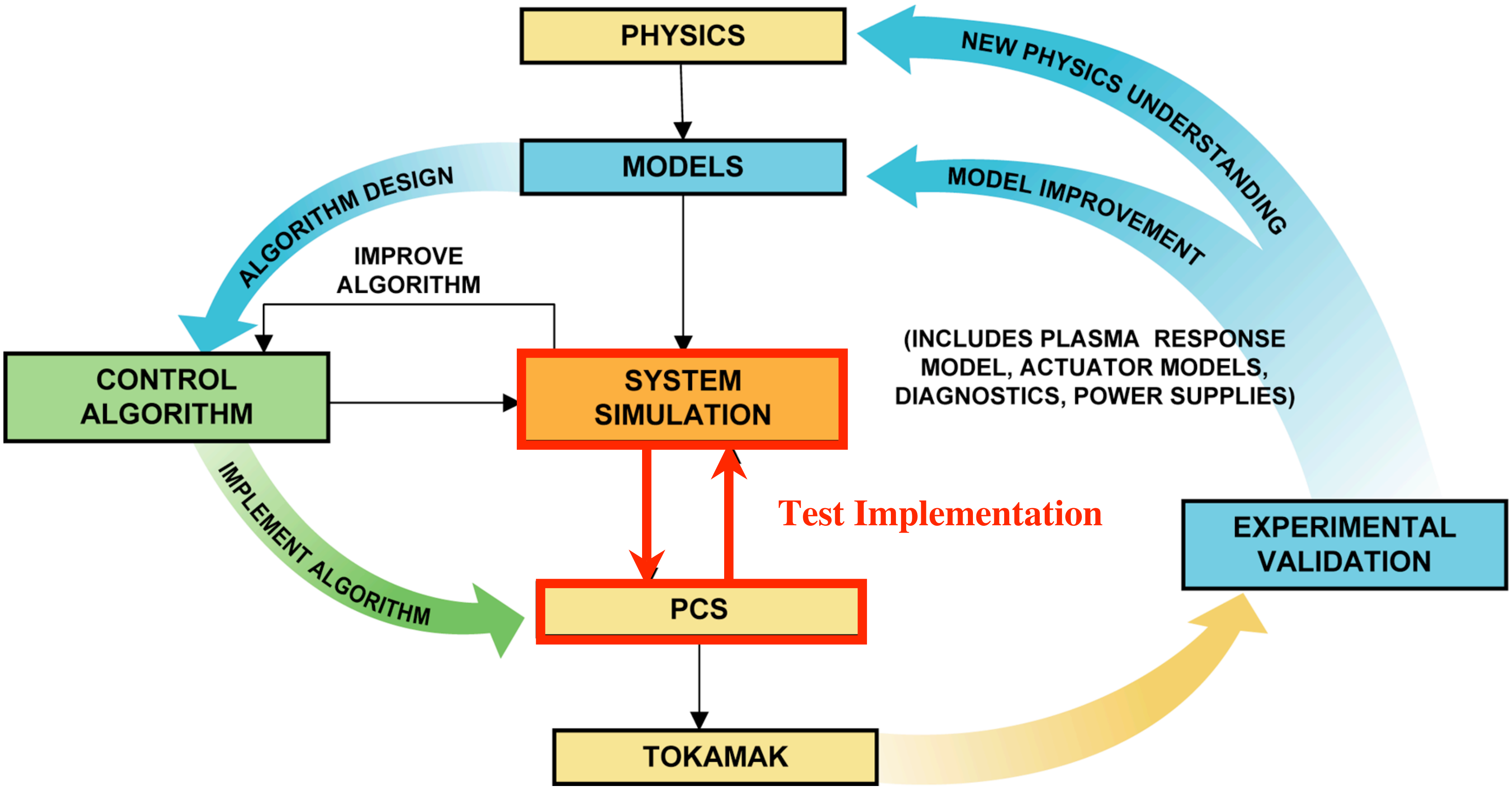
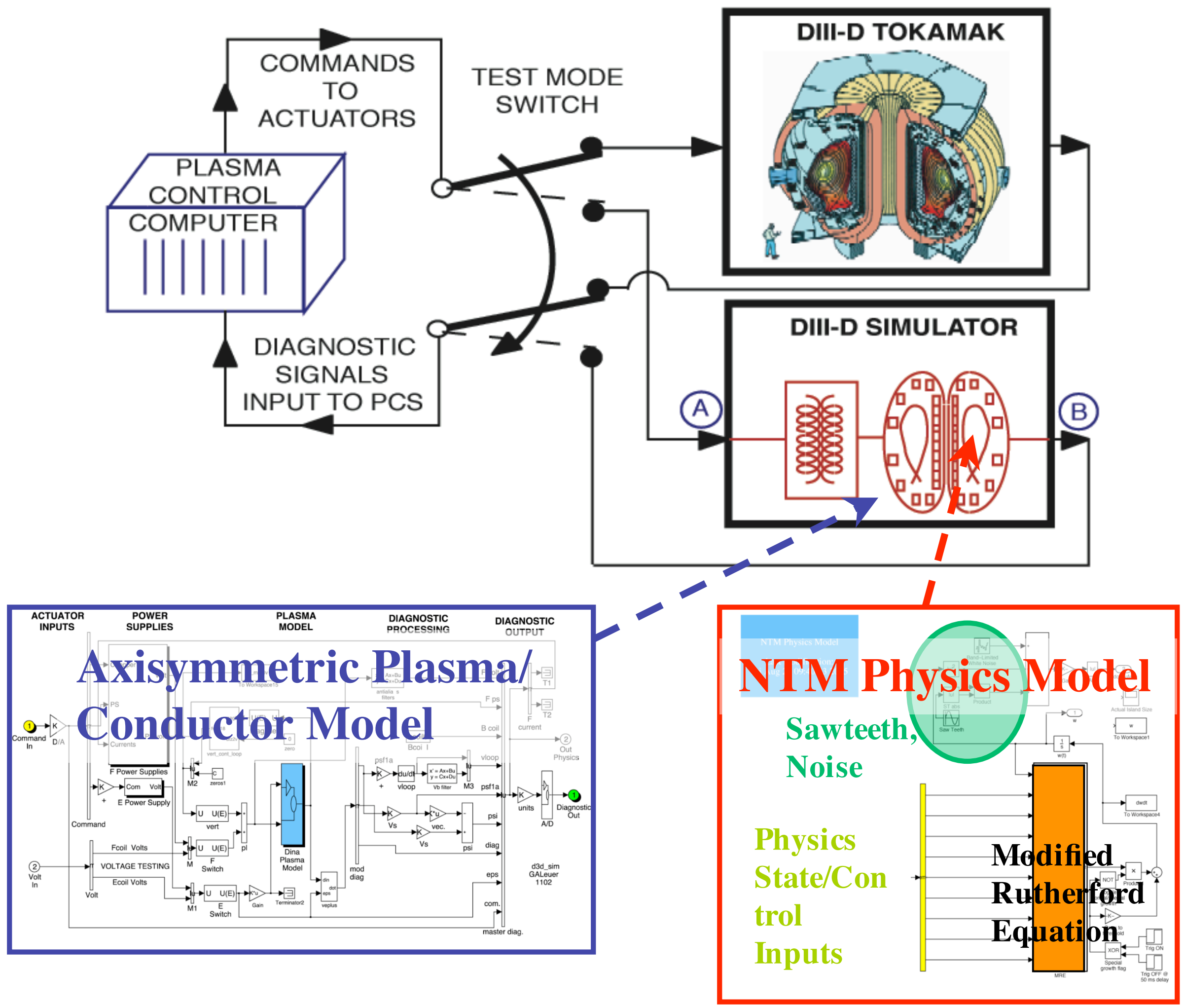


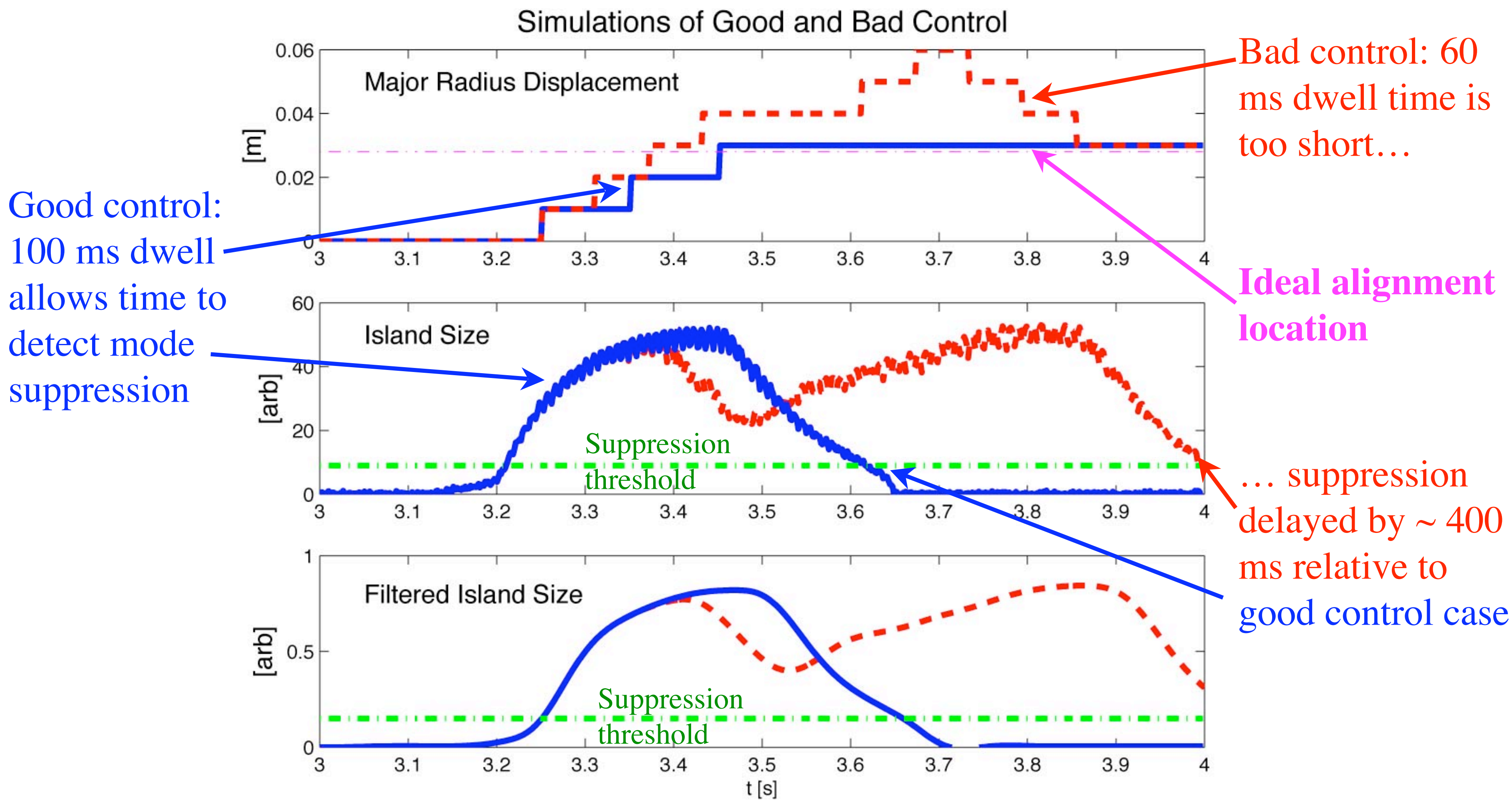
See Welander CP1.36 Mon PM

Integrated Plasma Control Simulations Allow Systematic Design and Testing of Controllers

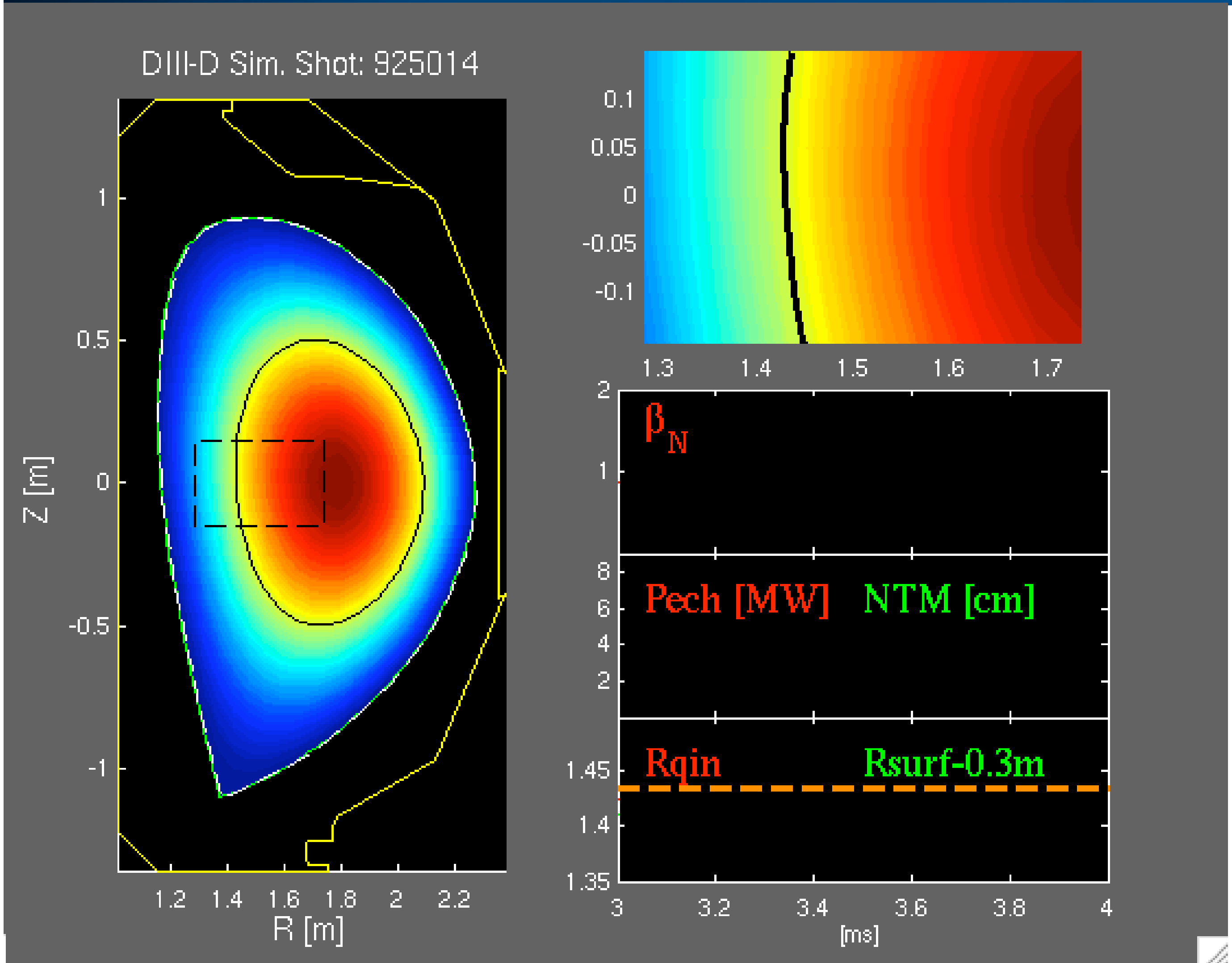
- Control-level simulations: sufficient detail to describe relevant elements of control action
- Simulations connect to actual DIII-D Plasma Control System to allow verification of implementation, performance
- Essential capability for commissioning high-confidence controllers
- Allows development and testing without consuming experimental time



Simulations Allow Development of Algorithms and Testing of Actual PCS Implementation



Simulations Confirm Performance of Actual Algorithm Implementation Prior to Use in Experiment



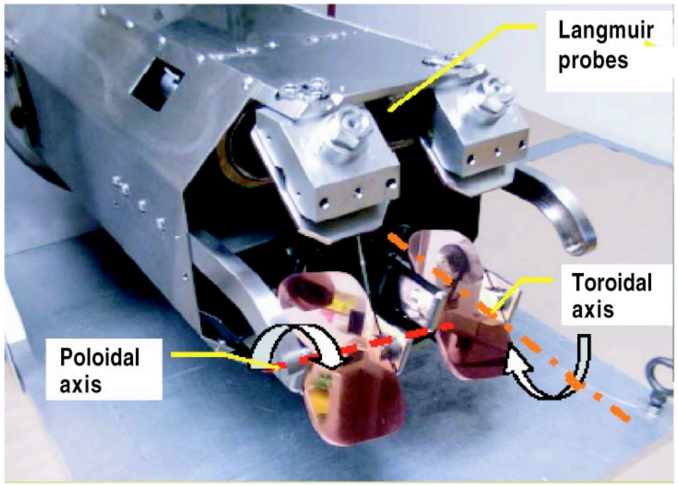
Integrated plasma control design and simulation resulted in successful NTM control in first-time use on DIII-D:

⇒ High confidence control implementation

⇒ Ability to commission algorithms

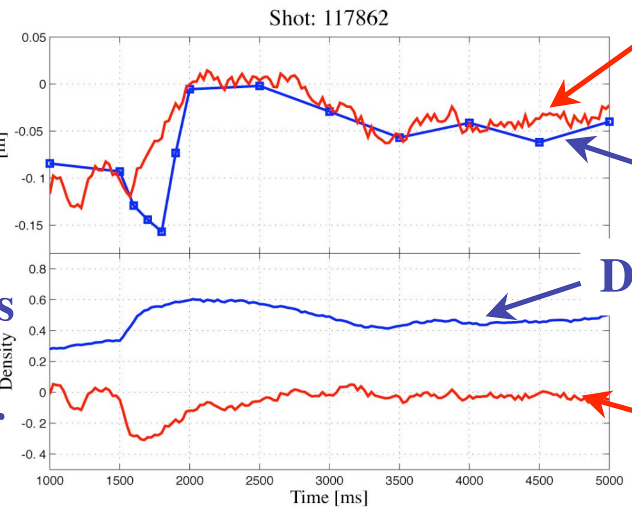
DIII-D Control Elements 2006: Multi-mode, Modulation, Alignment Drift Compensation, Mirror Steering

- **Multiple modes: launcher mirror steering, additional gyrotrons**
- **Improved power efficiency via ECCD modulation**
- **Improved Detection:**
  - ECE detection of island
  - Island phase detection with fast magnetics
- **Improved Accuracy: compensation for deposition drift due to density/refraction changes**



Mirror steering:

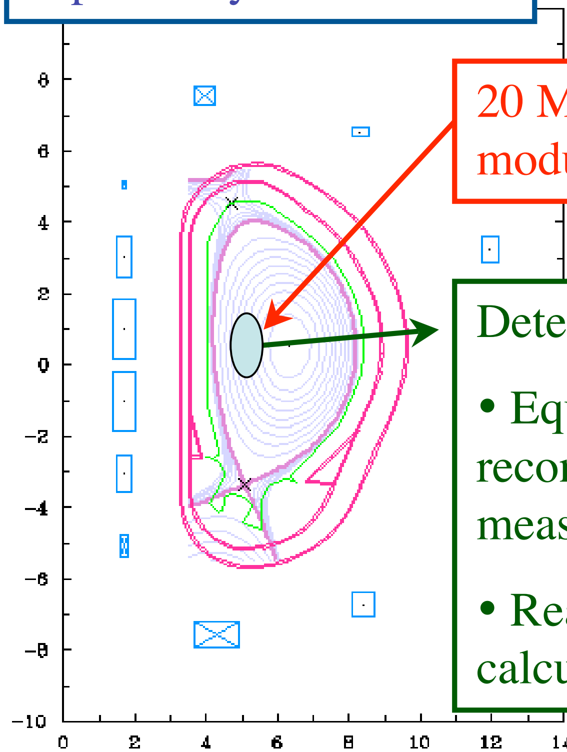
- 0.1 deg/ms ⇒ ~ 0.1 cm/ms ~ 1 cm/10 ms
- Latency/acceleration time < 10 ms << dwell times ~ 50-100 ms



NTM Control in ITER Will Need Many Elements Already Operational in DIII-D

- **170 GHz Gyrotrons: 20 MW delivered power**
  - Capable of 3/2 or 2/1 suppression in ITER
  - Modulation may improve effectiveness
- **Realtime equilibrium reconstruction for tracking rational surface/island**
- **Robust algorithms for detection, alignment, and active tracking**
- **Verification of actual PCS implementation against simulations essential for commissioning ⇒ integrated plasma control**

Robust algorithms; supervisory coordination



20 MW ECCD power, modulation improves

Detection:

- Equilibrium reconstruction + profile measurements
- Realtime EC deposition calculation (future)

Most of these essential tools have already been demonstrated

Stabilization of NTMs Through Active Control Has Reached a High Level of Performance in DIII-D

- **Active NTM control in DIII-D**:
  - Aligns island/ECCD, stabilizes 3/2 or 2/1 NTM (separately), maintains suppression
  - Is an experimental tool, no longer limited to a research topic

- **Integrated plasma control** method enables high-confidence, high reliability control performance:
  - **Systematic design** of controllers based on control-level models
  - **Verification** of controller performance, including operation of actual control hardware and software against simulations
  - **NTM control successful in first-time use** on DIII-D due to integrated plasma control

- Most elements required for **ITER NTM control** are now in hand but further development still needed:
  - Faster robust algorithms
  - Internal measurement solution for profile reconstruction
  - Realtime EC deposition calculation

Modified Rutherford Equation Describes Stabilizing Effect of Current Drive in NTM Islands

Classical stability

$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta_0' r + \delta\Delta' r + a_2 \frac{j_{bs}}{j_{\parallel}}\frac{L_q}{w}\left[1 - \frac{w_{marg}^2}{3w^2} - K_1 \frac{j_{ec}}{j_{bs}}\right]$$

Island growth/decay | ECCD effect on Δ′ | ECCD stabilization

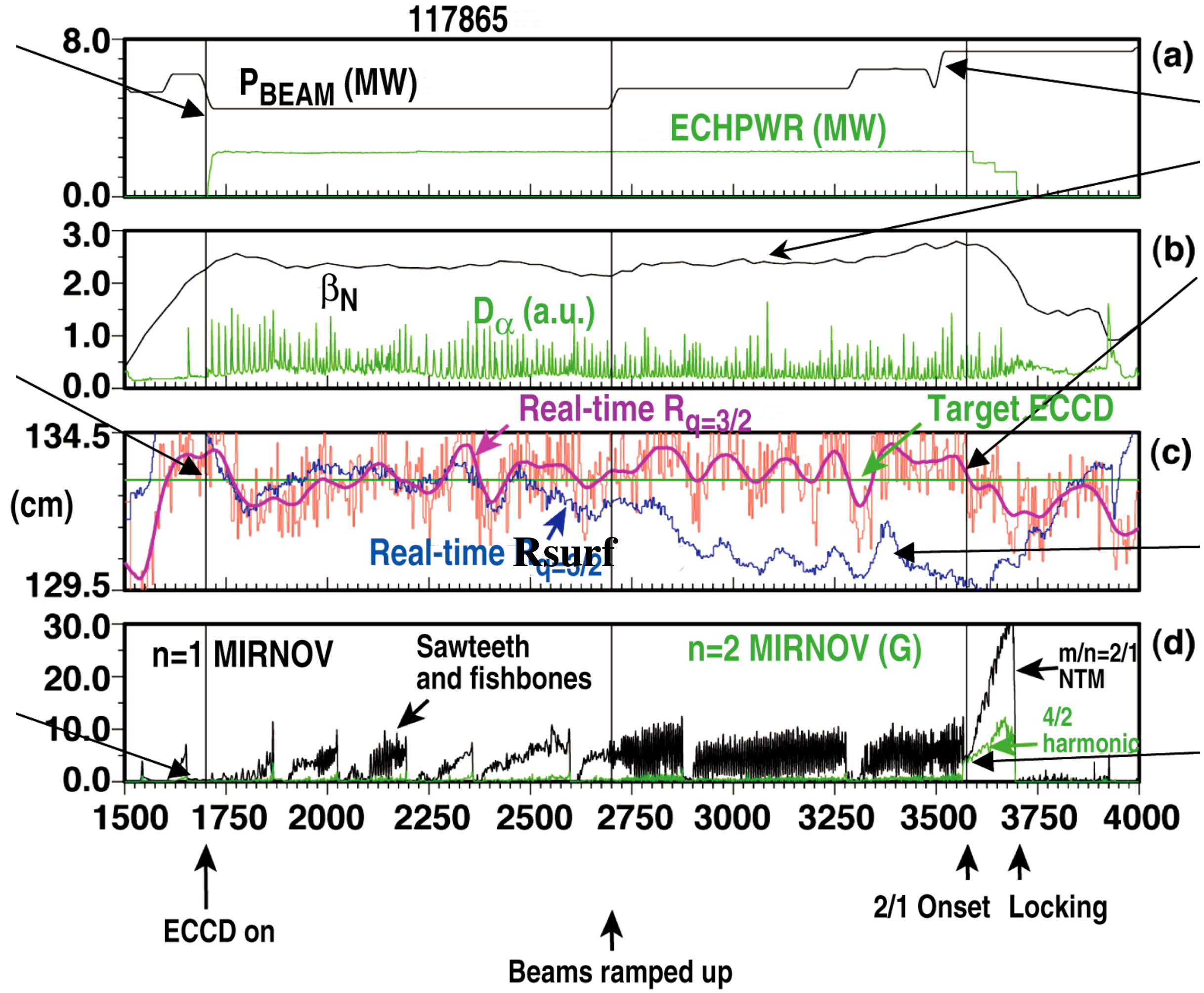
- **Modified Rutherford equation:**
  - Describes growth/damping rate of island
  - Island suppressed by negative Δ' and current drive replacing missing bootstrap current
- **Requires sufficient current driven inside island**
  - Deposition sufficiently well-aligned with island (effectiveness factor K_1)
  - Deposition profile sufficiently narrow
- **Continuous current drive stabilizes because co-current drive effect is greater in island than at X-point**

Active Tracking of q-Surface Motion Enables Preemptive NTM Suppression

ECCD and control enabled

ECCD initially ~ aligned with q=3/2 surface

No NTM initially



Beam power and β_N are increased...

..alignment is maintained with realtime q=3/2 surface reconstruction..

...by moving plasma major radius rigidly

3/2 NTM suppression sustained