Development of ITER-Relevant Plasma Control Solutions at DIII-D

by
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for
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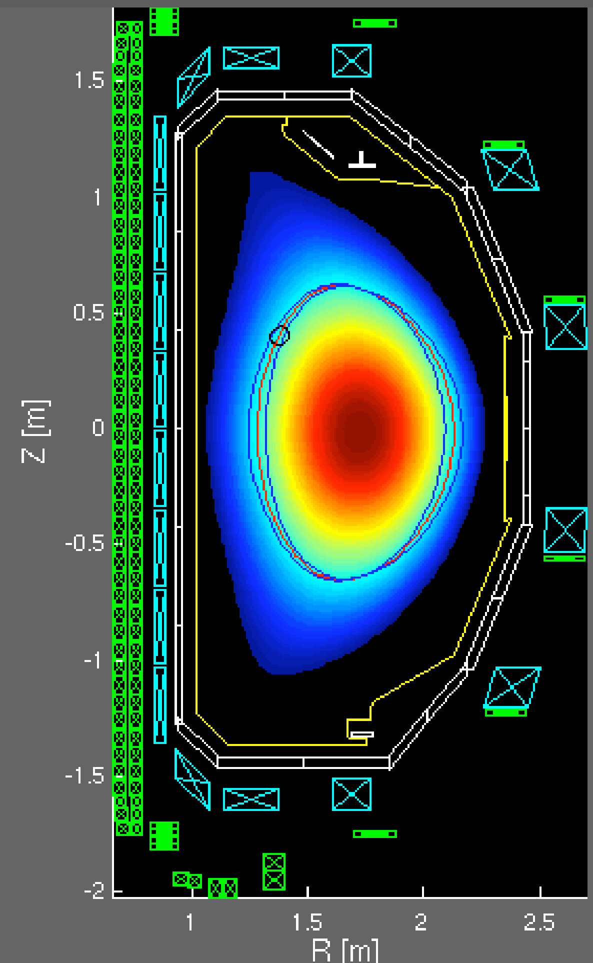
Modulated Current Drive for NTM Suppression

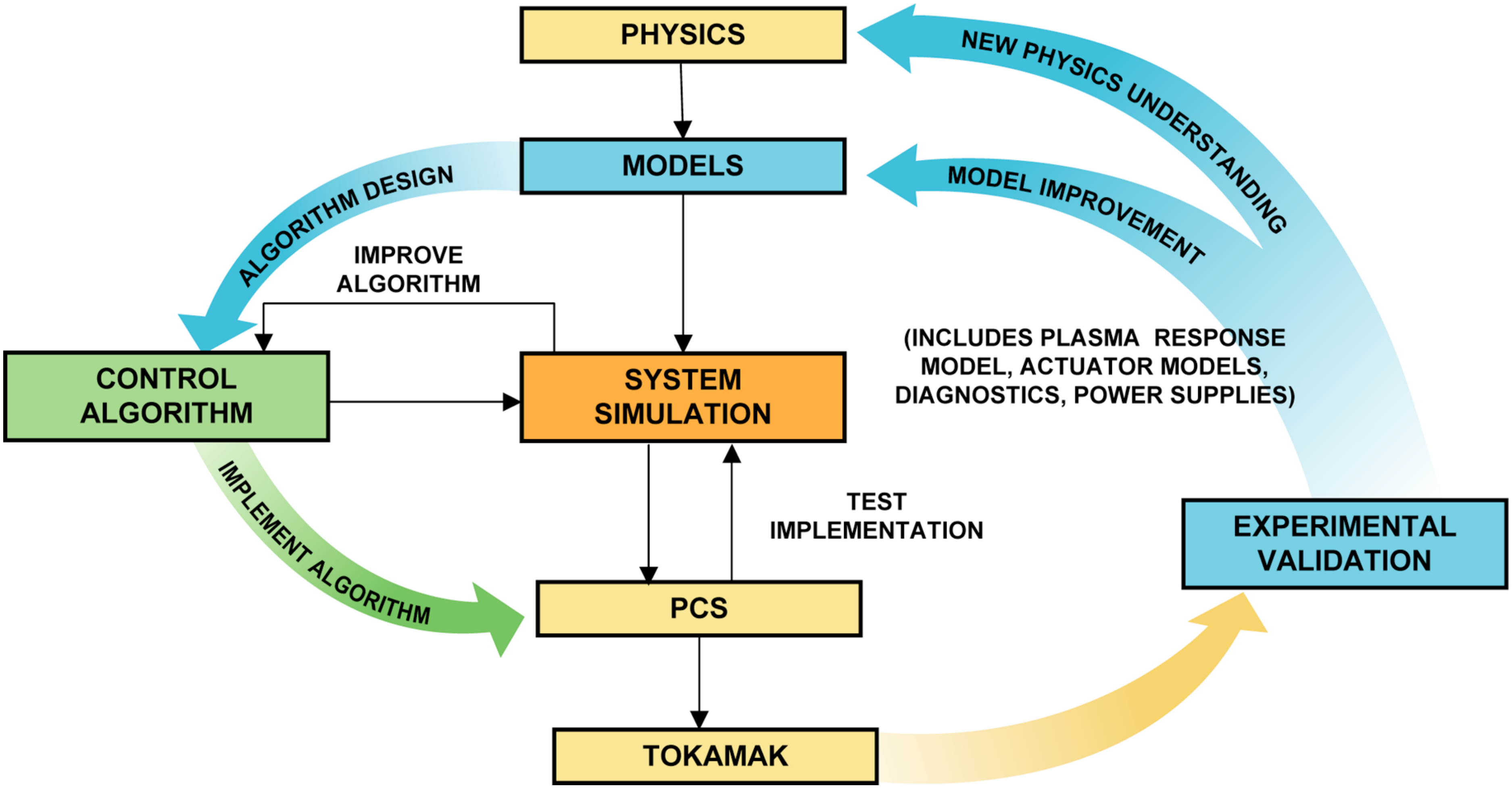


DIII-D Advanced Tokamak Program Has Motivated Developing Control Solutions Relevant to ITER

- ***TokSys*: Integrated plasma control standardized environment and tools**
  - Enables systematic design and testing of controllers
  - Enables validation on present devices and confident extrapolation to ITER
- **Examples of control solutions developed using *TokSys***
  - NTM control design tools and algorithms addressing ITER-specific limitations
  - Axisymmetric controllers with nonlinear algorithms to avoid coil current limits
  - Resistive wall mode models appropriate for ITER design
  - Control and fault response algorithms used in startup of the EAST tokamak

Integrated Plasma Control

ITER Needs Systematic Design for High Confidence Performance: Integrated Plasma Control Used at DIII-D

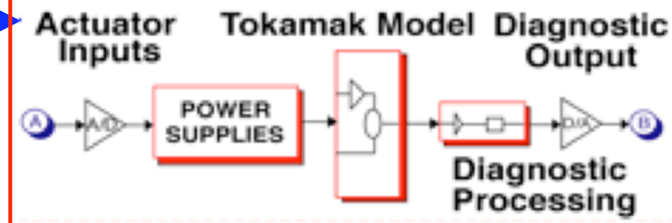


TokSys is an Integrated Plasma Control Environment that Allows Systematic Design and Testing of Controllers

TokSys:

Tokamak System Models
+
Controller Designs

Simulink Simulation



(software)

Plasma Control System Simulator

= Software + offline computers

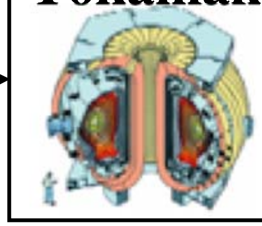
Tokamak Simulator

Plasma Control System

= Software + real-time computers

(hardware)

Tokamak



- **Control-level models:**
  - Simplified but accurate
  - Allow iterative design with multivariable controllers
- **Design tools written in international standard Matlab/Simulink**
- **Complete test of both algorithms and implementation provides confidence in real time performance**

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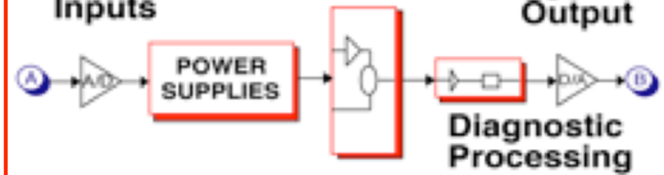
Simulink Simulation

Actuator Inputs | Tokamak Model | Diagnostic Output



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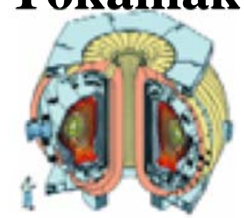

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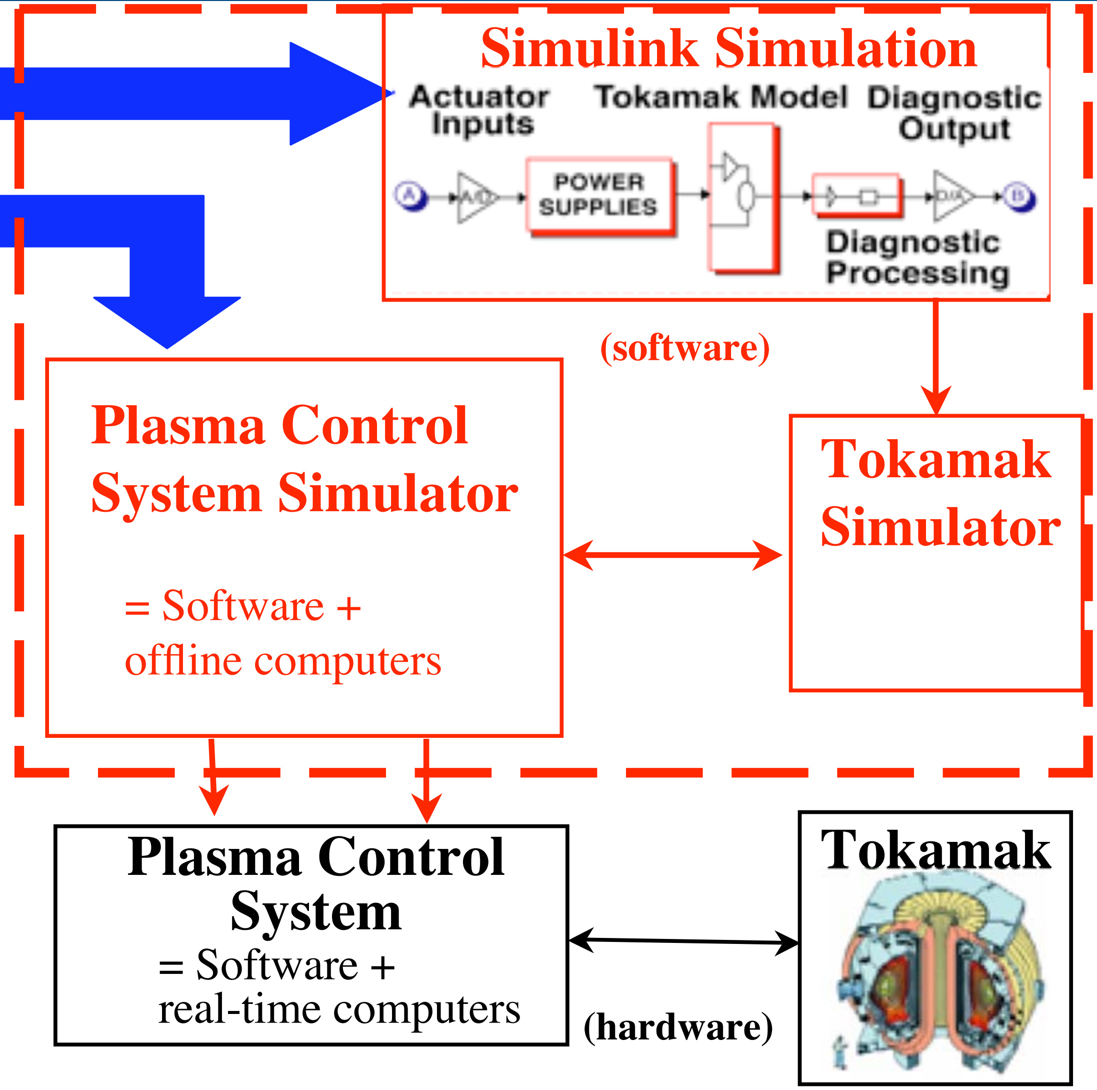

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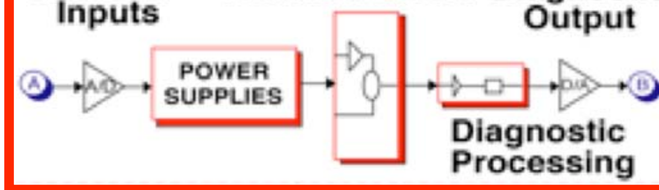

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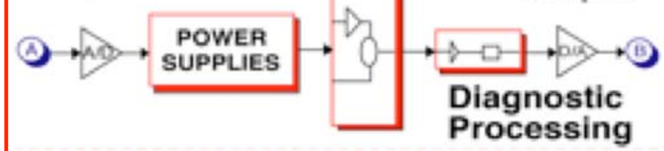

Diagnostic Processing

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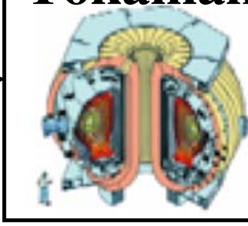

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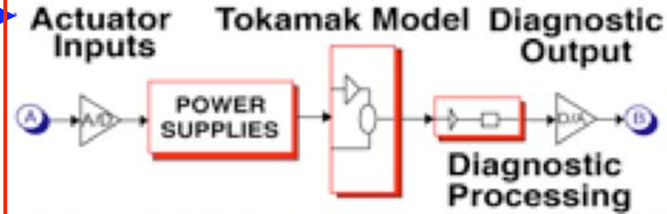

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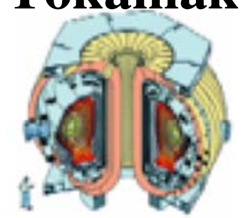

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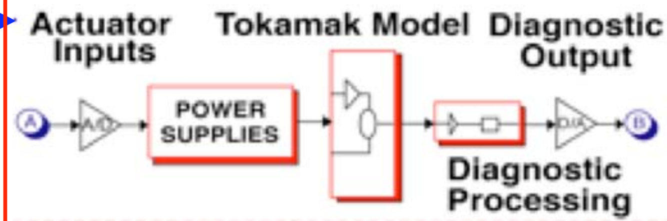

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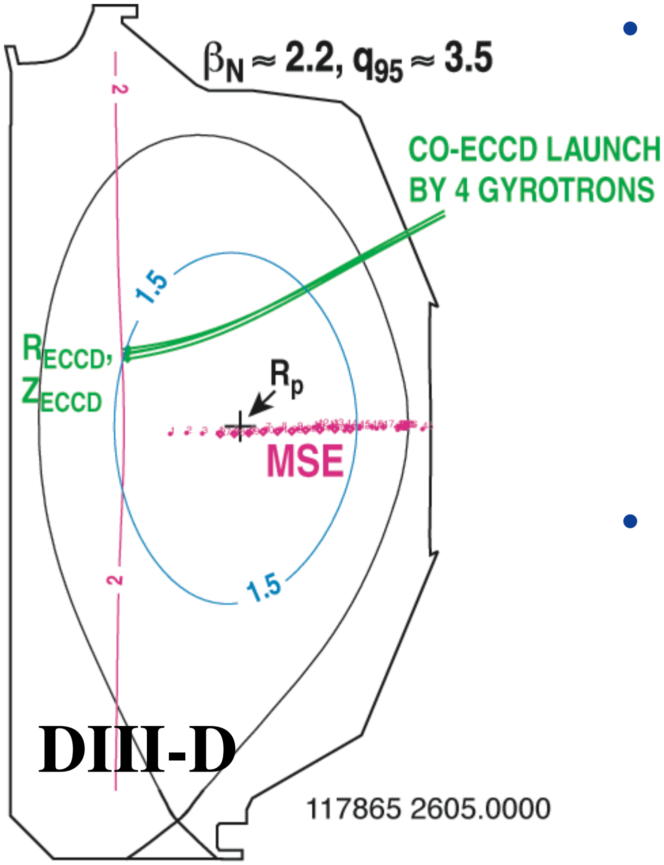
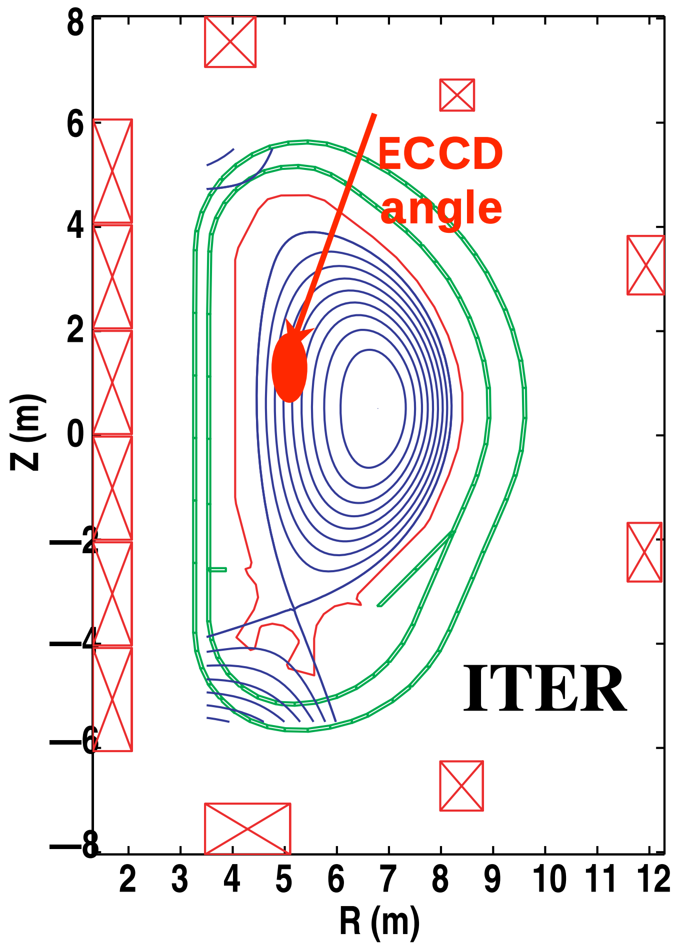
NTM Stabilization Algorithms

Using ECCD to Replace Missing Bootstrap Current and Stabilize NTM in ITER Requires High Accuracy

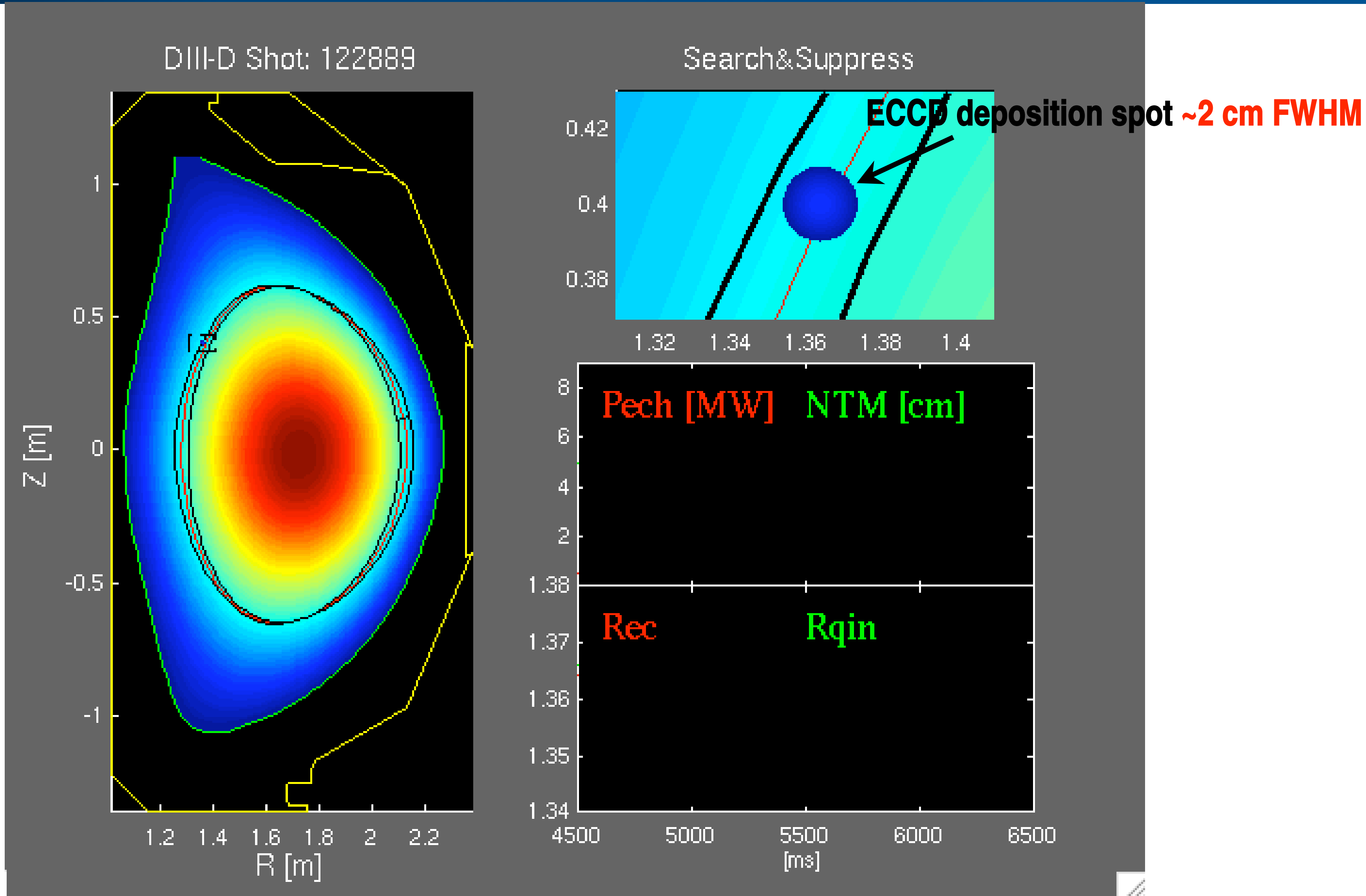


NTM control achieved at ASDEX-U,JT-60U,DIII-D, FTU

- **ECCD must be accurately positioned at q=m/n rational surface where NTM island forms**
  - Alignment accuracy need in DIII-D ~ 1 cm
- **ITER ECCD spot is large due to high launch angle**
  - Need high relative accuracy, q-surface reconstruction
  - Need modulation to increase effectiveness

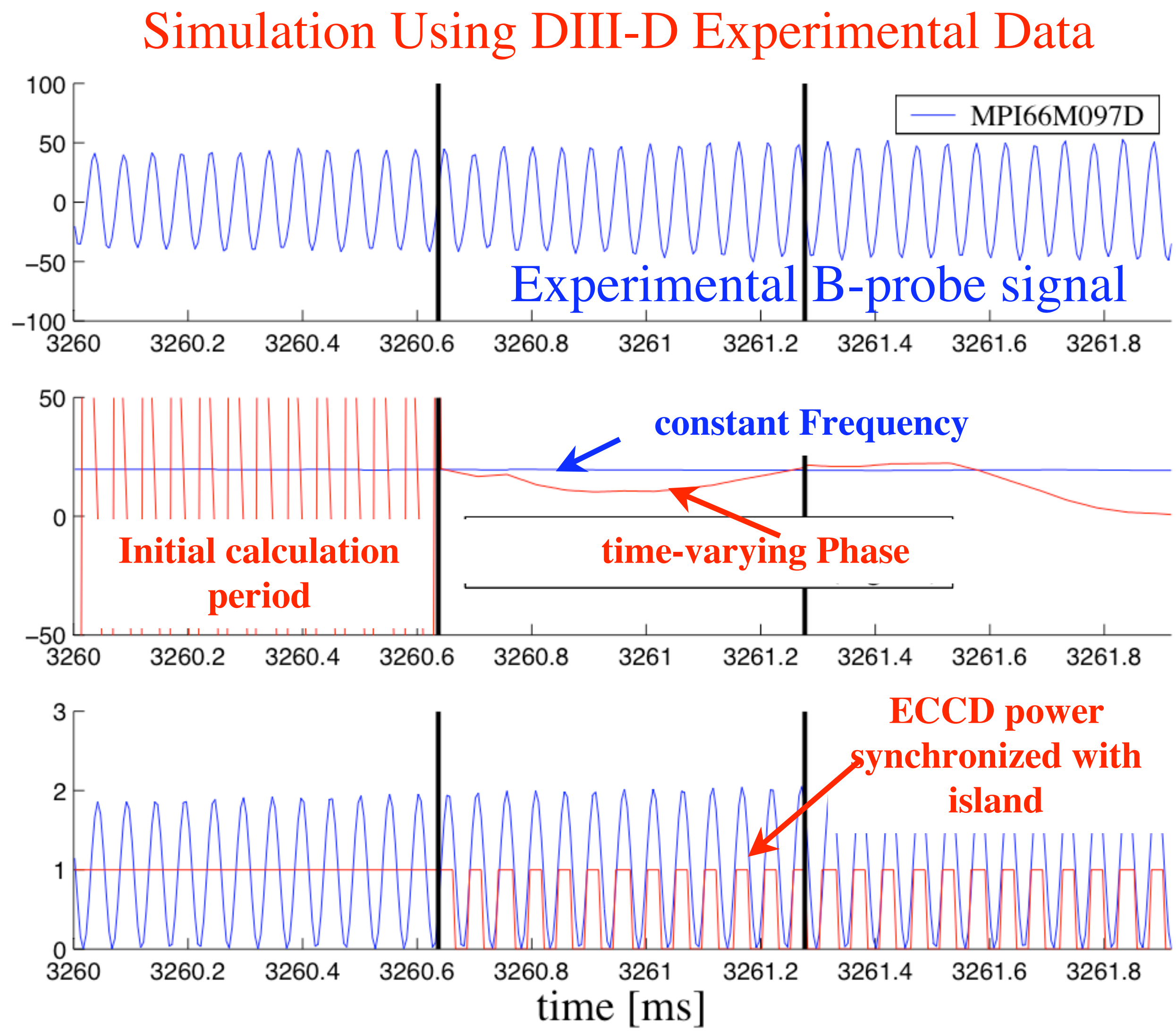


DIII-D Experiments Demonstrate Systematic Search for Alignment, Maintained with q-Surface Feedback



New PCS Algorithm Will Demonstrate Modulation to Synchronize Gyrotron Power with Rotating Island

- **Real-time Fourier analysis of midplane probe signals**
- **After initial calculation period, algorithm identifies ~constant frequency, time-varying phase**
  - Phase, frequency command updated after and fixed during each calculation period
- **Command to dedicated CPU produces modulation signal for gyrotrons phase locked to island at ECCD location**

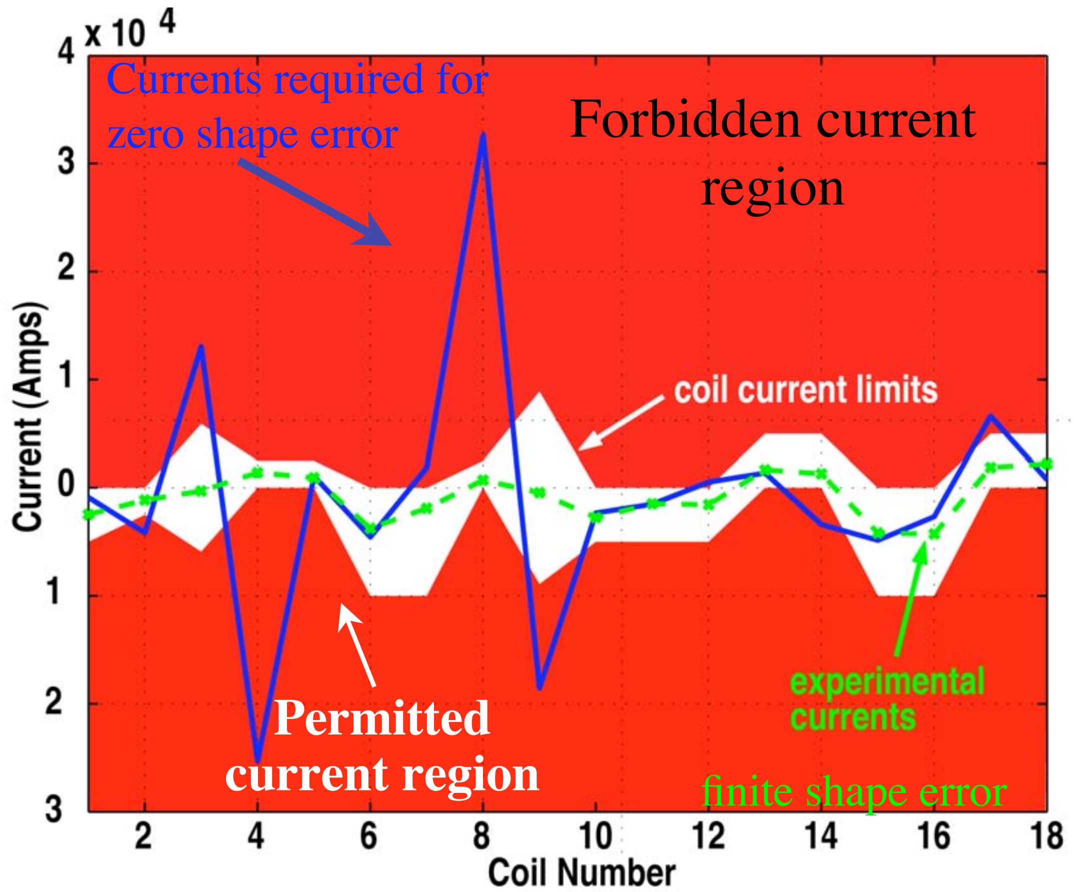


Shape Control with Coil Current Limits

Axisymmetric Control in Tokamaks Requires Avoiding Current Limits

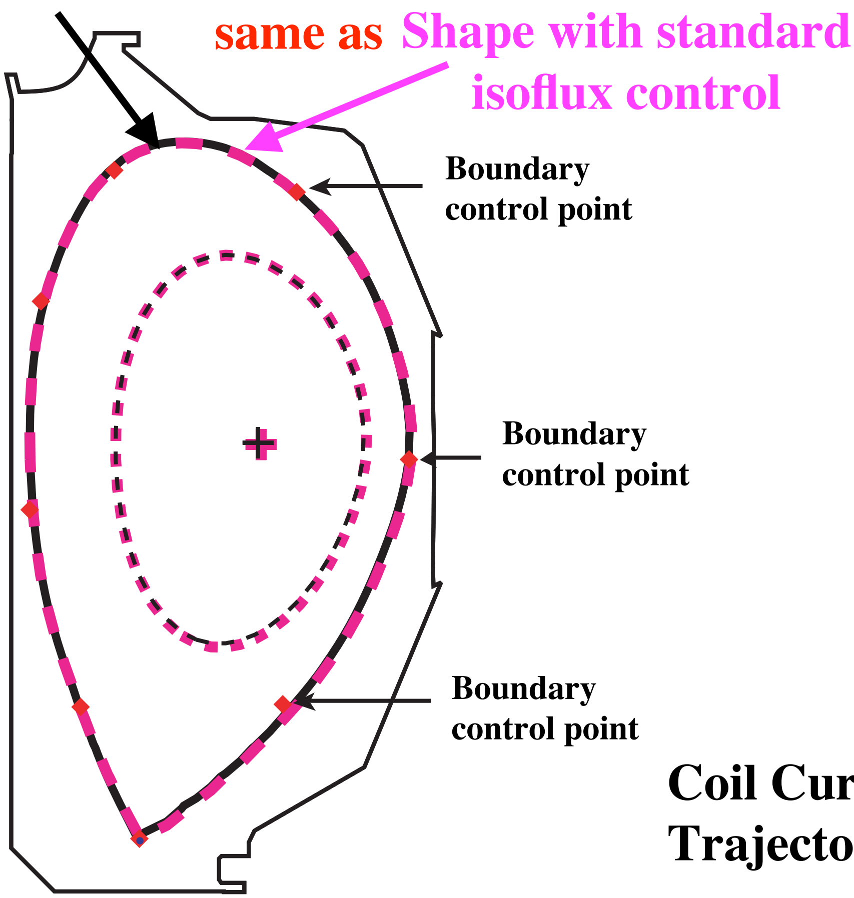
- **ITER multivariable controllers seeking to produce zero shape/position error will demand PF currents exceeding coil limits**
- **Failure to regulate PF currents allows them to drift and hit limits as plasma profiles change**
- **A nominal current trajectory calculated from plasma response models can:**
  - Minimize shape errors
  - Maximize distance to current limits
  - Reduce control gains
- **PF currents must be actively regulated in long-pulse superconducting tokamaks such as ITER**

DIII-D Equilibrium PF Coil Currents

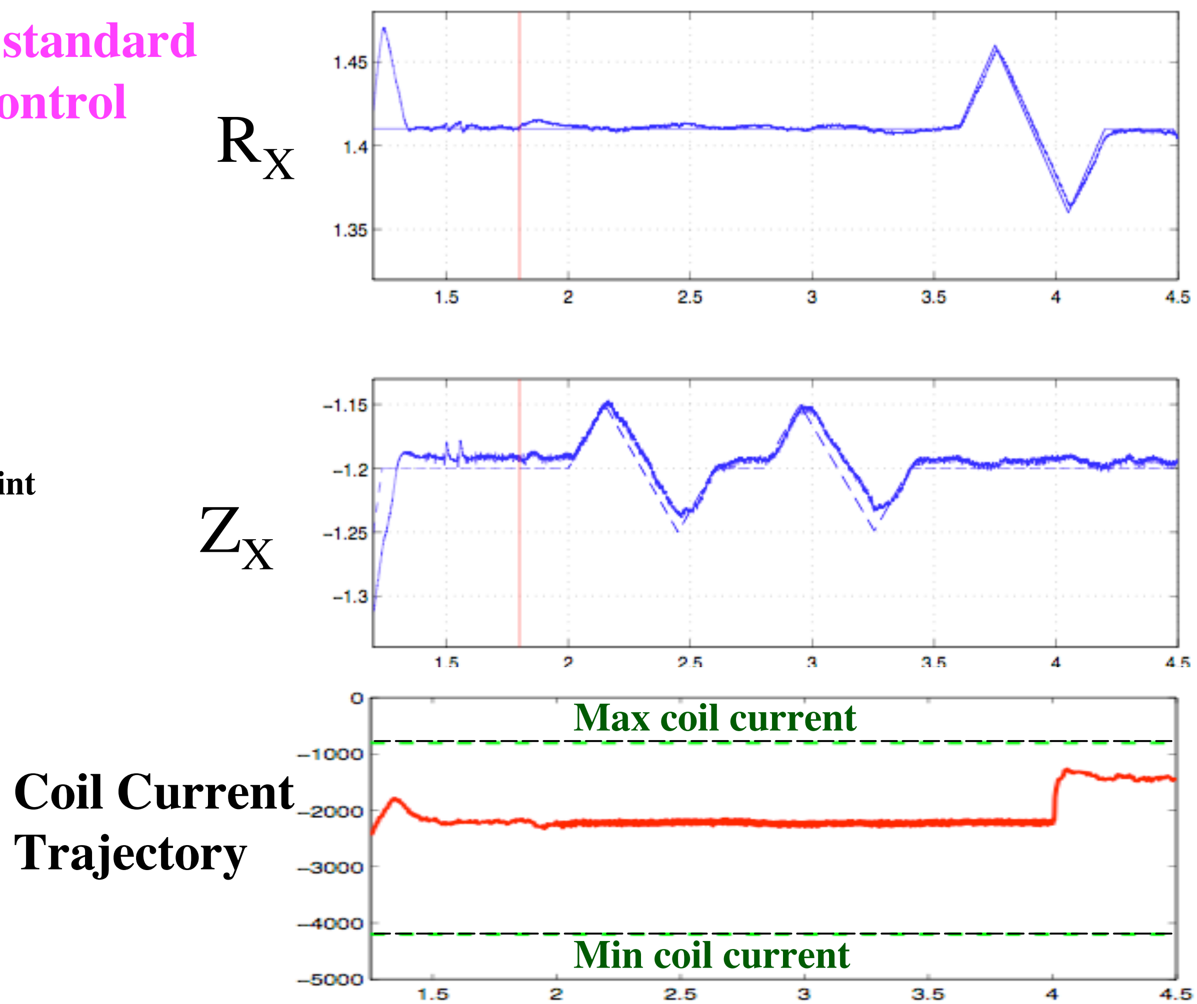


DIII-D Experiments Have Demonstrated Model-Based Multivariable Control with PF Current Regulation

Shape with Feedforward Nominal Current Trajectory



Demonstration of Closed-Loop Control with Nominal Current Trajectory

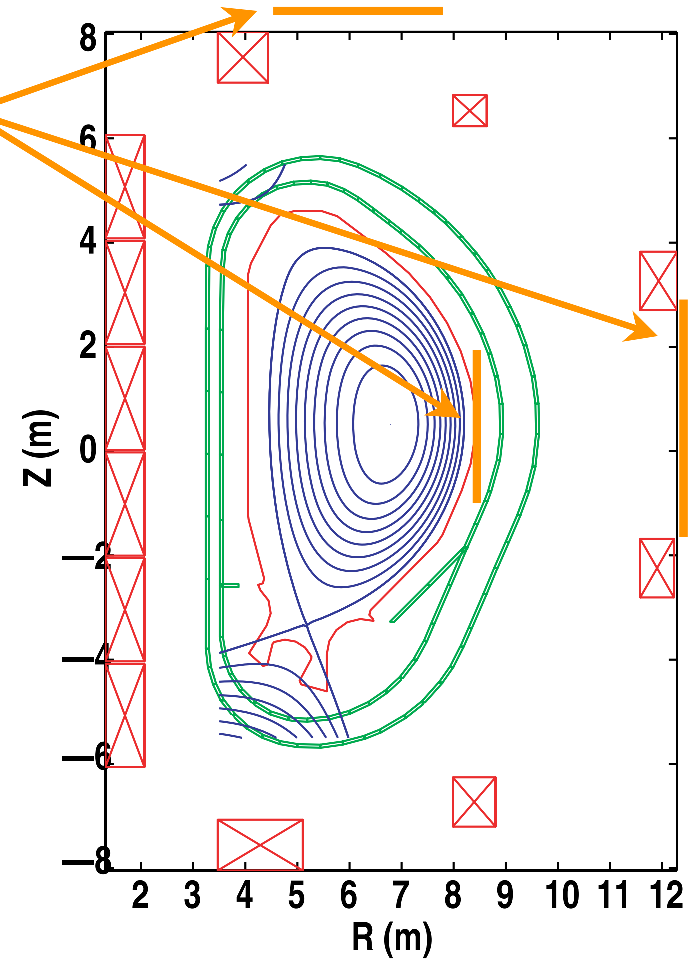


Models for RWM Stabilization Design

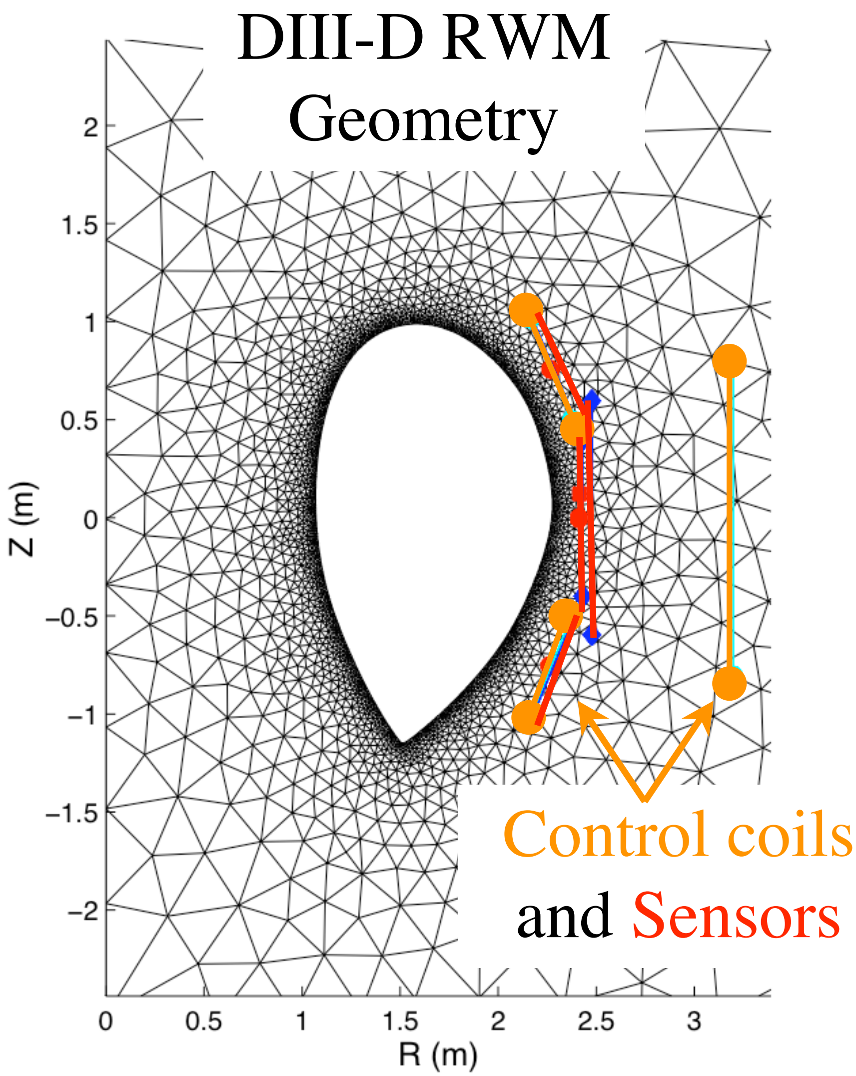
ITER Requires Model-Based Control Design for RWM Stabilization Systems

- **Direct extrapolation from experiment not possible:**
  - Many **candidate RWM control coil designs different** from those on present devices
  - ITER system/controller dynamics very different from present devices

- **RWM design models must be:**
  - Validated on present devices
  - Control-level, relatively simple, allowing systematic design and iteration
  - Include sufficient detail to describe essential dynamics and physics



Eigenmode Finite Element Mesh Approach Allows High Accuracy for Complex Structures



- Finite element model produces eigenmode representation of conductor-plasma-sensor mappings
- Select desired number of modes to retain in system dynamics

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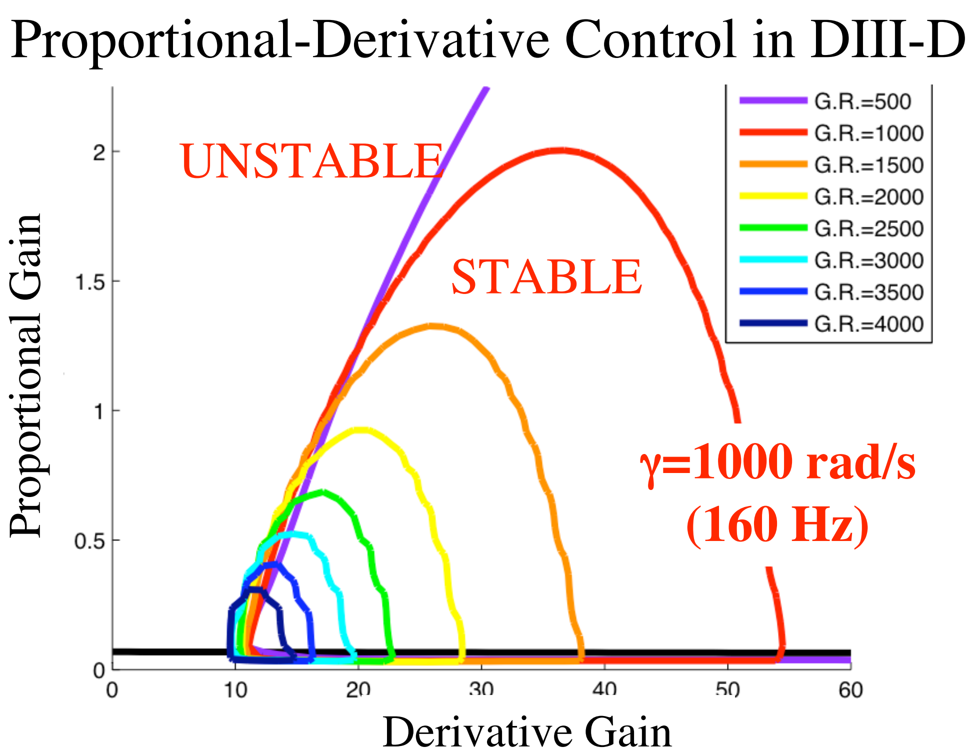
Accurate Models Enable Stabilization of Large Range of Growth Rates with Single Controller



- **Eigenmode system: stable gain space shrinks with increasing growth rate (agrees with previous studies)**
- **PD control allows operation up to growth rate of 4200 rad/sec if model sufficiently accurate**
- **Full multivariable controllers allow stabilization up to ideal limit in DIII-D (5000 rad/sec) with accurate models**

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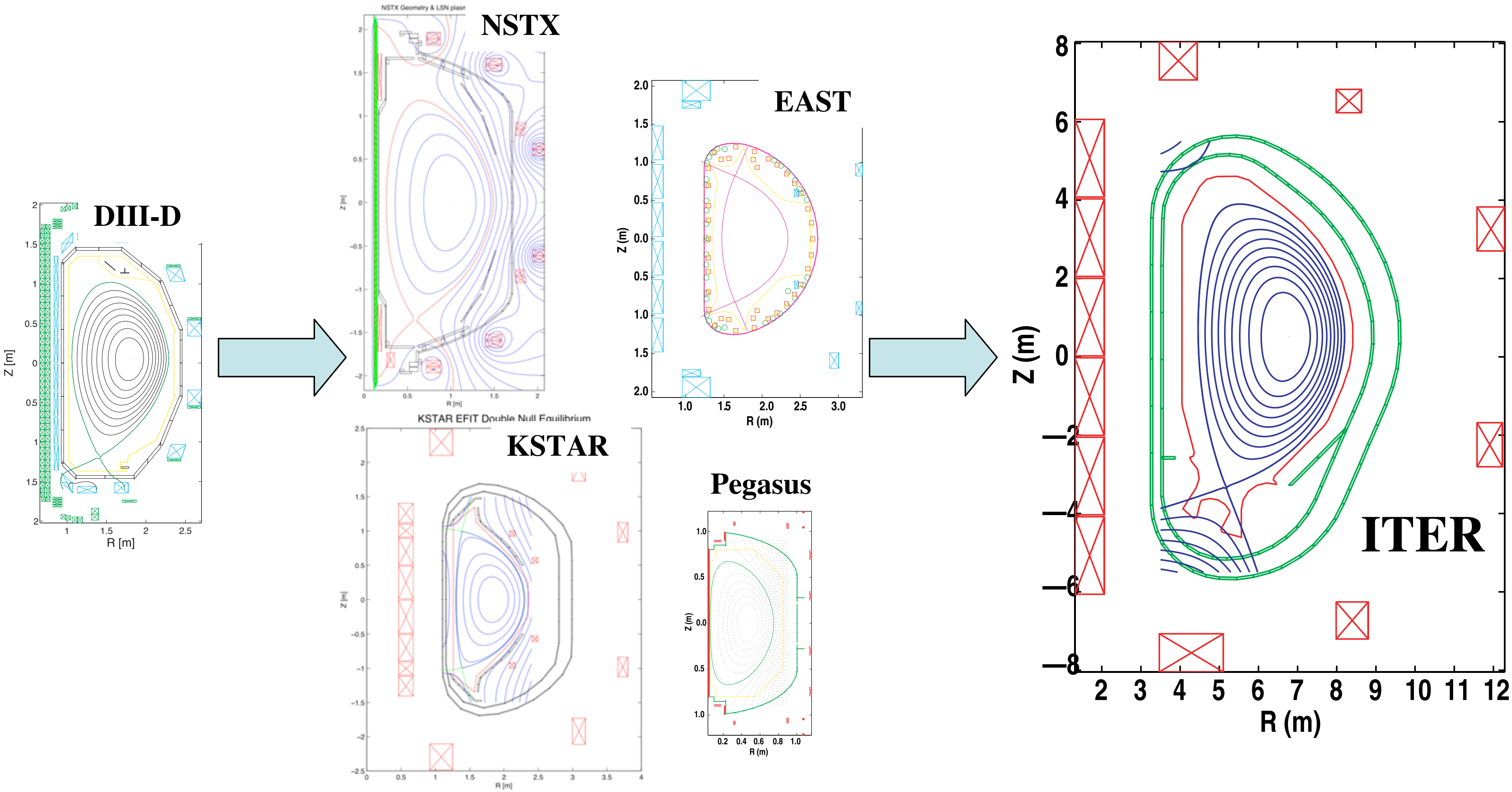
Control Applications Beyond DIII-D

TokSys Has Been Applied to Many Devices Including Those Sharing the DIII-D Plasma Control System



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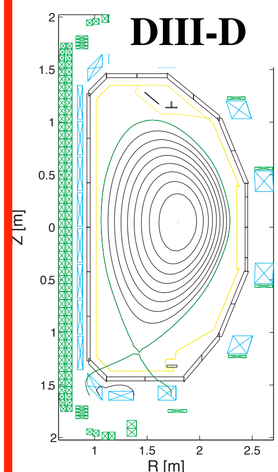
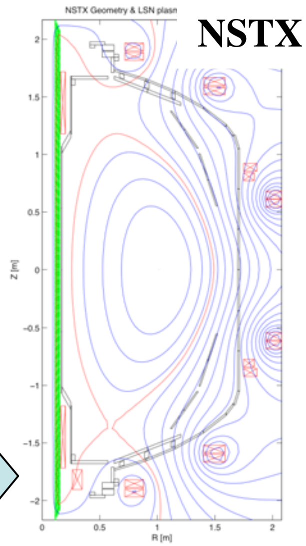
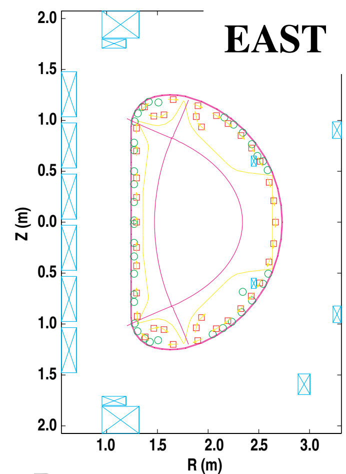
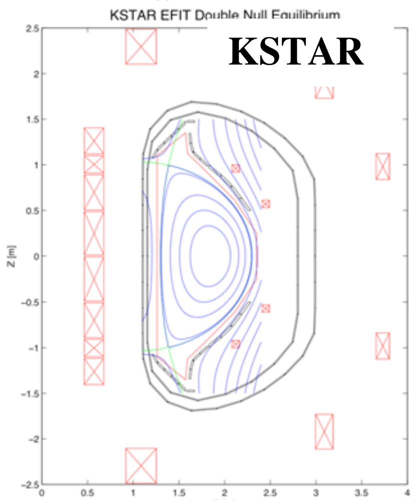
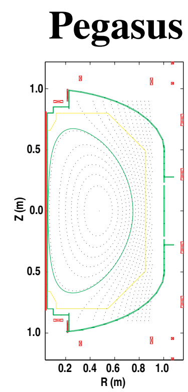
Devices Using DIII-D PCS











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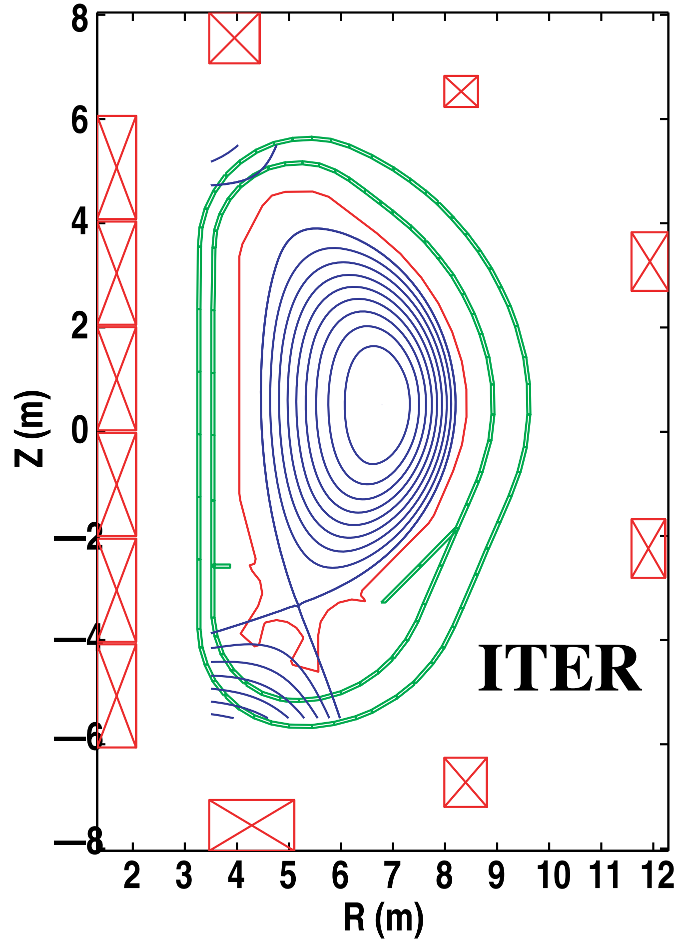
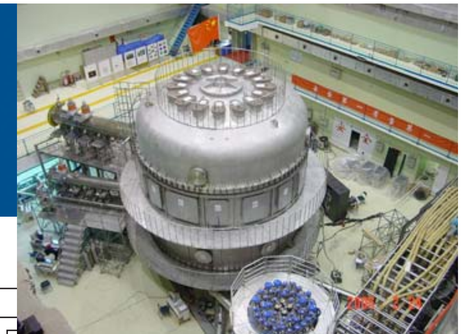
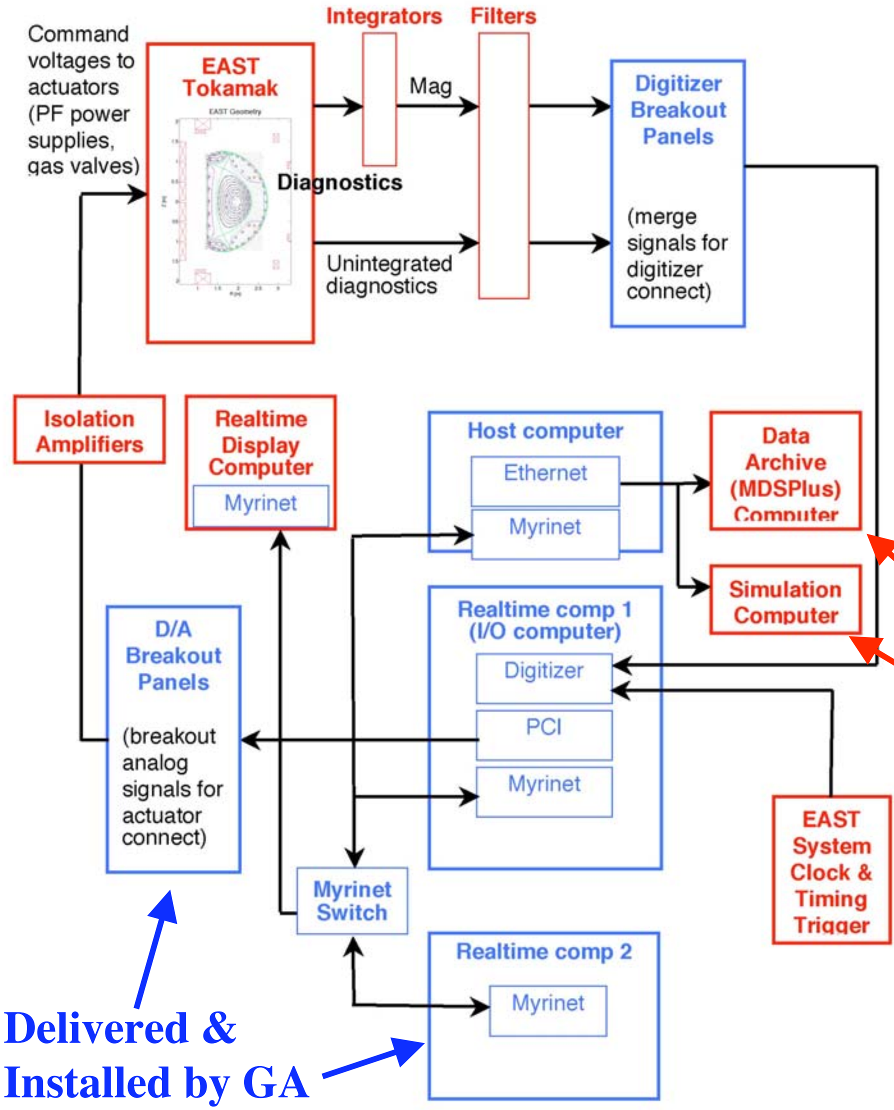


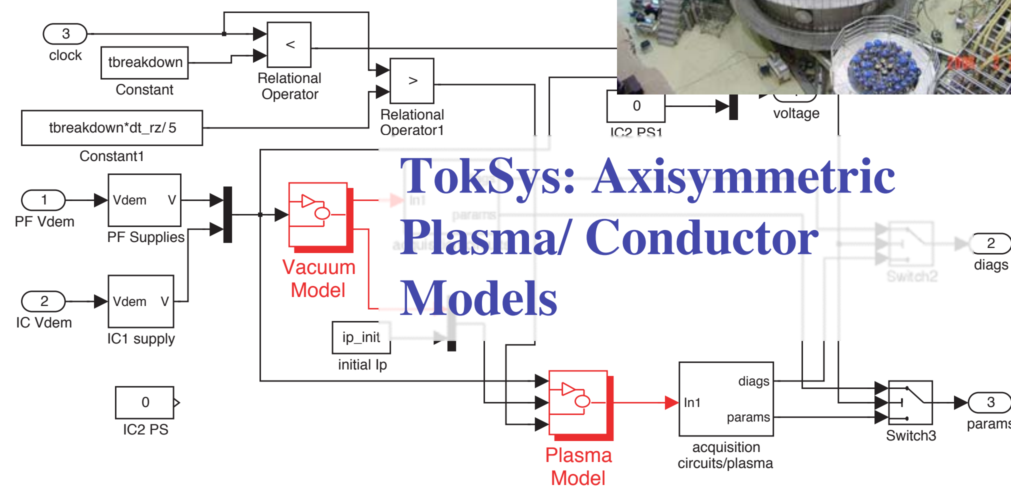
EAST PCS Based on DIII-D PCS Was Commissioned at ASIPP in March 2006





Provided by ASIPP

Delivered & Installed by GA

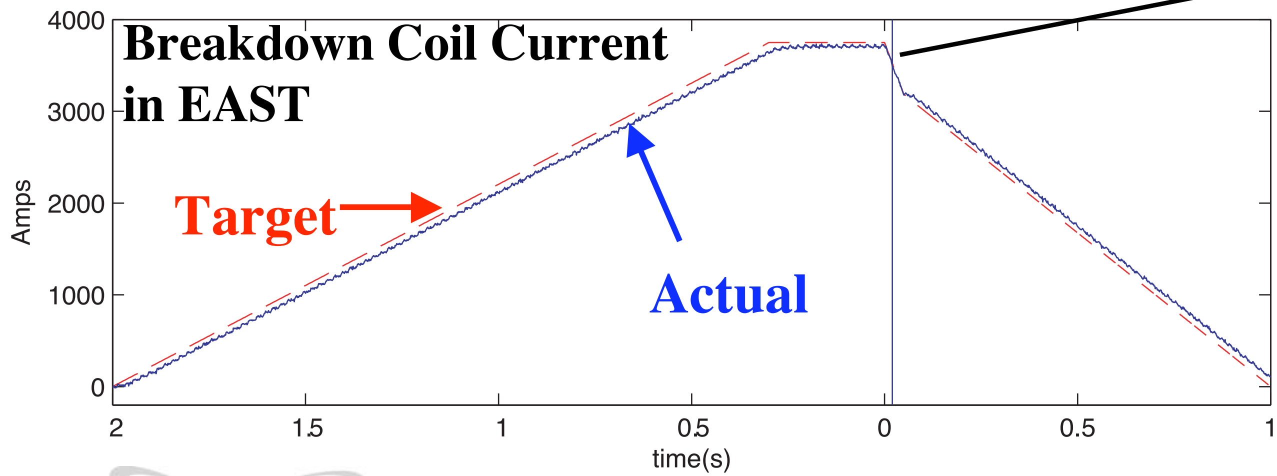


TokSys: Axisymmetric Plasma/ Conductor Models

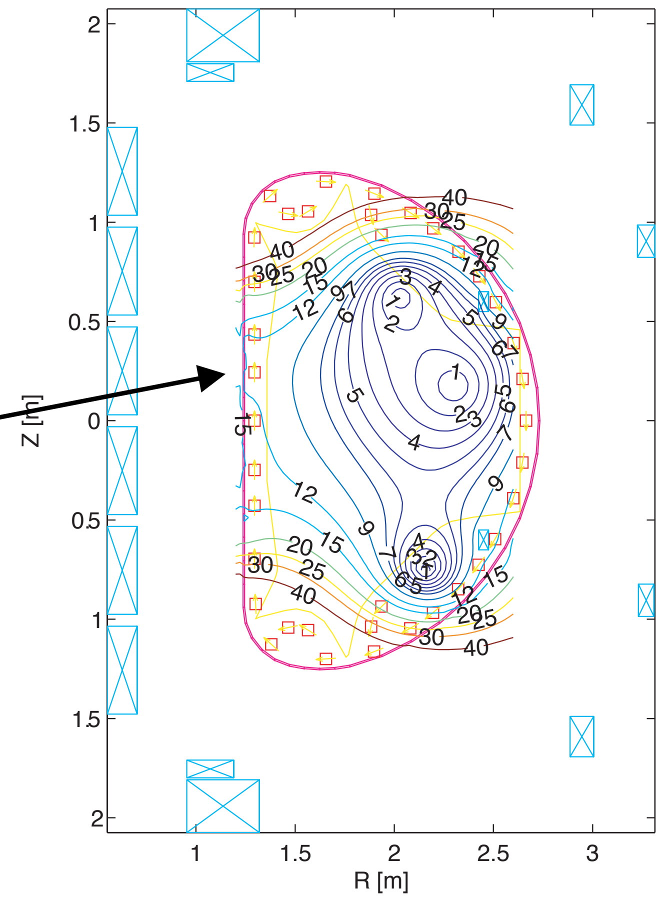
Tokamak Startup Operations with EAST/DIII-D PCS began August 2006

Use of EAST/DIII-D PCS and TokSys Environment Has Contributed to Recent Success of EAST Startup

- **Breakdown scenario calculation (current/voltage trajectories, resistor values)**
- **PCS execution of scenario with coordinated breakdown elements:**
  - Initial magnetization, current trajectory feedback control
  - Synchronized breakdown resistors
  - Voltage feedforward trajectories
- **Plasma current, shape control algorithms**
- **Fault detection and response algorithms**



Vacuum B_P(G) Fields at 20ms



Summary and Conclusions

- **ITER requires many novel control solutions owing to its nuclear mission and unique control limitations**
- **Integrated plasma control can enable high-confidence, high-reliability control performance for ITER:**
  - Systematic design of controllers based on control-level models
  - Verification of controller implementation in simulations before experimental use
- **Active NTM control in DIII-D is addressing ITER requirements:**
  - Robust and sustained island/ECCD alignment with real-time q-profile reconstruction
  - Recent progress in gyrotron modulation capability, demonstrated with detailed simulations
- **Simultaneous current limit avoidance and shape control demonstrated in DIII-D is essential for ITER**
- **RWM control design based on high accuracy low-order models, multivariable design and analysis essential for ITER design**
- **EAST/DIII-D PCS and TokSys models have contributed to successful EAST startup**