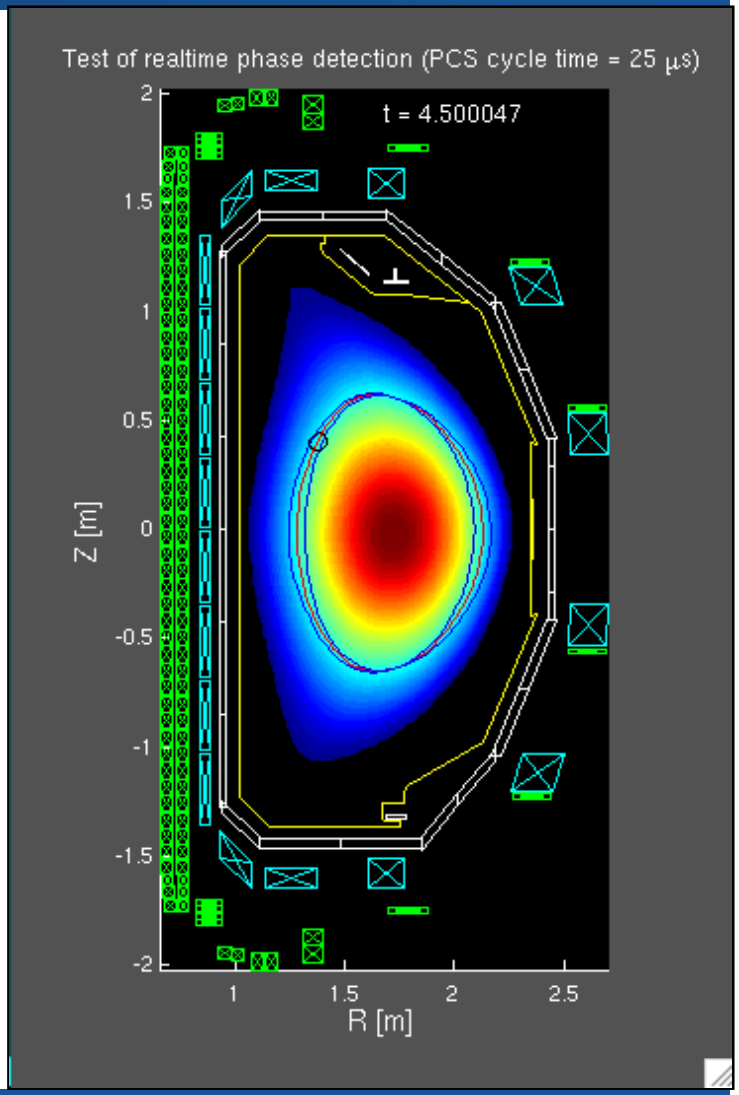
Development of ITER-Relevant Plasma Control Solutions at DIII-D

D.A. Humphreys,[1] J.R. Ferron,[1] M. Bakhtiari,[2] Y. In,[3] G.L. Jackson,[1] H. Jhang,[4] R.D. Johnson,[1] J.S. Kim,[3] R.J. La Haye,[1] J.A. Leuer,[1] B.G. Penaflor,[1] M.L. Walker,[1] H. Wang,[5] A.S. Welander,[1] D.G. Whyte,[2] B. Xiao[5]

[1]General Atomics, San Diego, California
[2]Univ. of Wisconsin-Madison, Madison, Wisconsin
[3]Far-Tech, Inc., San Diego, California
[4]NFRC/KSTAR, Daejon, Korea
[5]ASIPP/EAST, Hefei, China



21st IAEA Fusion Energy Conference
Chengdu, China
October 16-21, 2006

DIII-D NATIONAL FUSION FACILITY

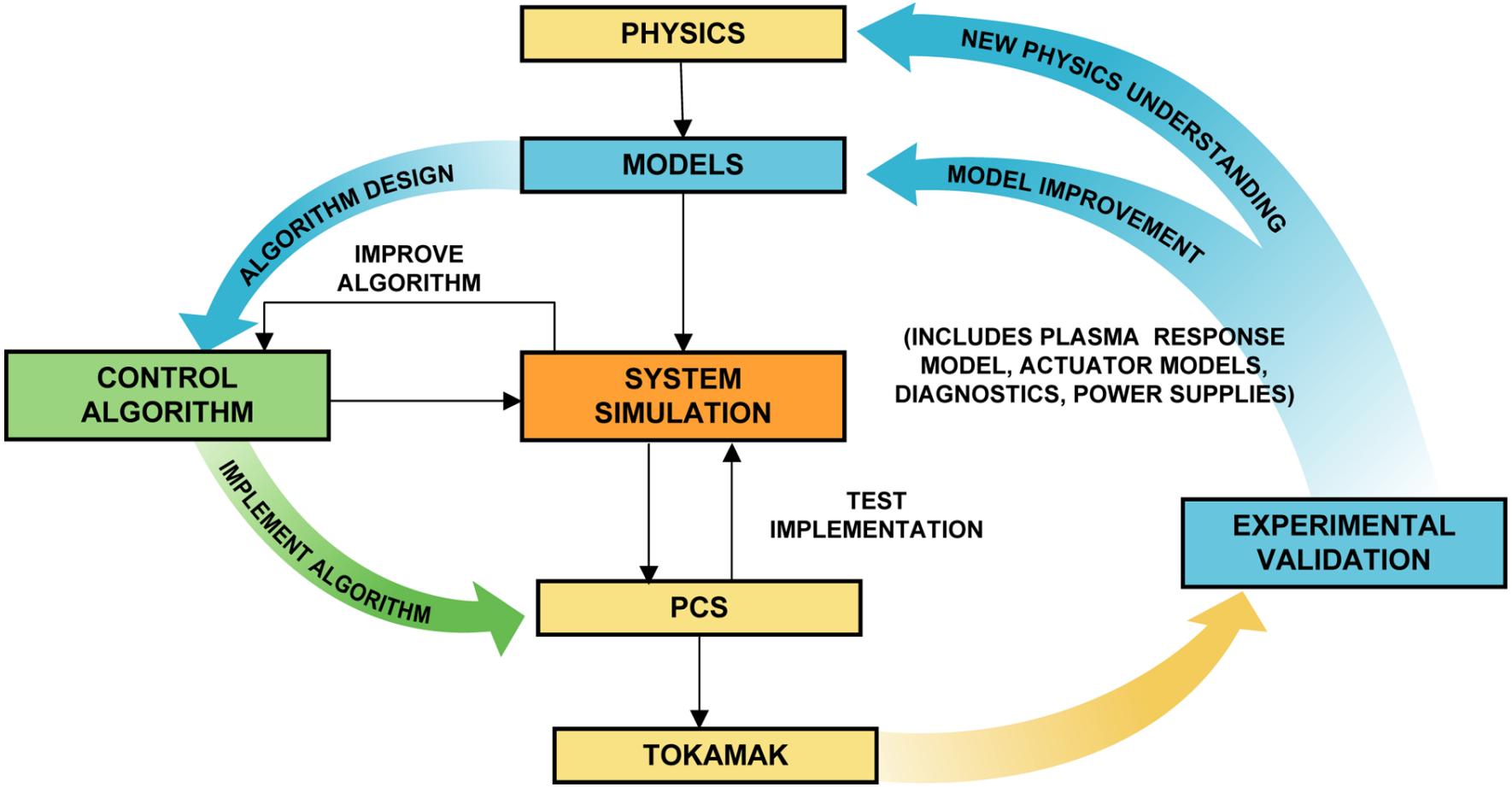
GENERAL ATOMICS

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

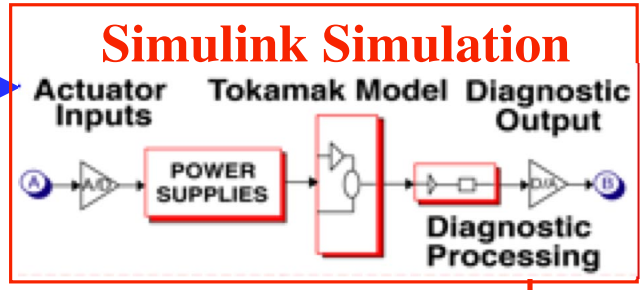
ITER Needs Systematic Design for High Confidence Performance: Integrated Plasma Control Used at DIII-D



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

TokSys:

Tokamak System Models + Controller Designs



(software)

- **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**

Plasma Control System Simulator

= Software + offline computers

Tokamak Simulator

Plasma Control System

= Software + realtime computers

(hardware)

Tokamak

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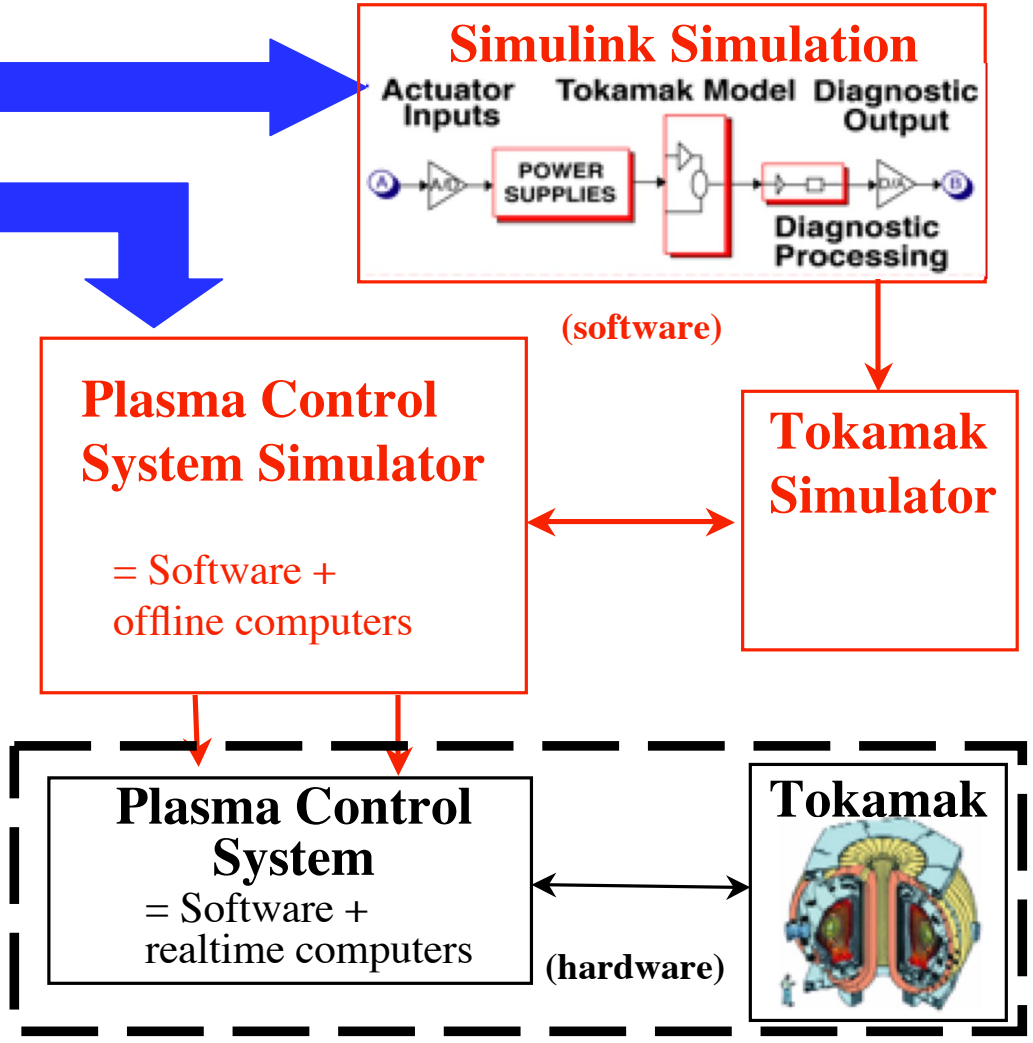

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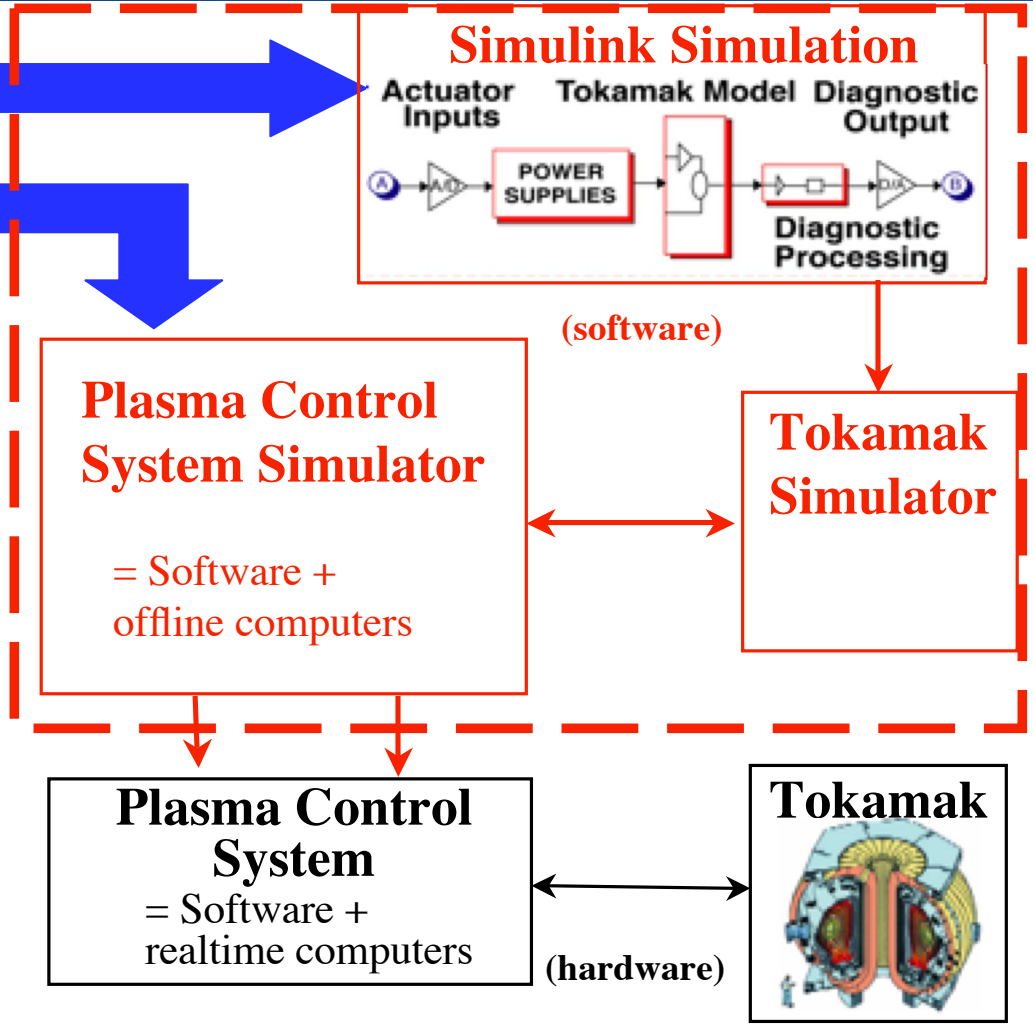

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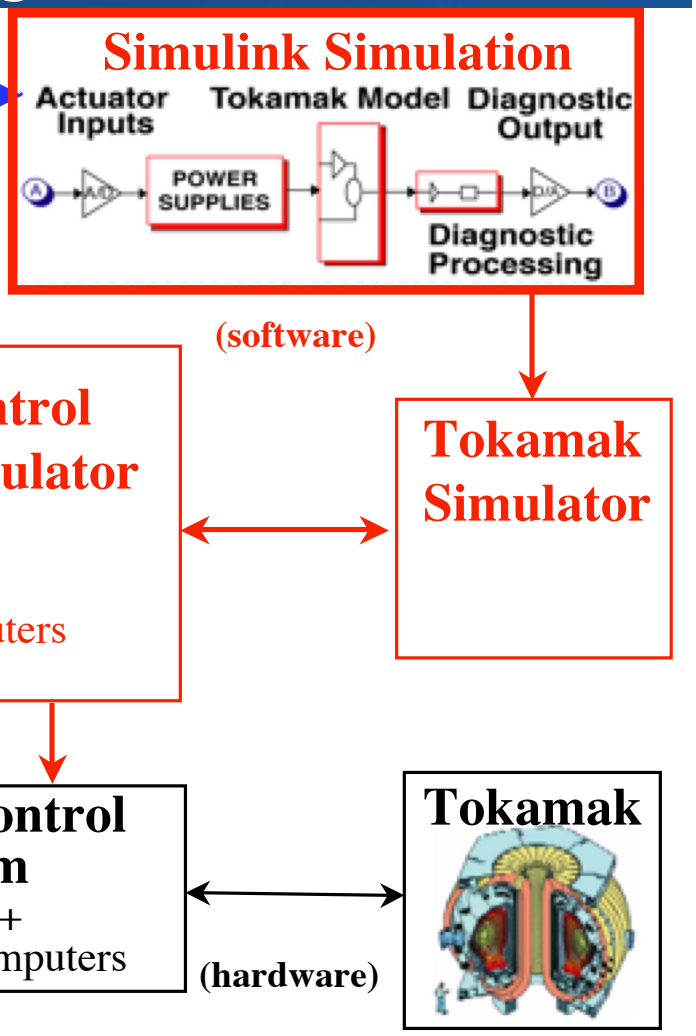

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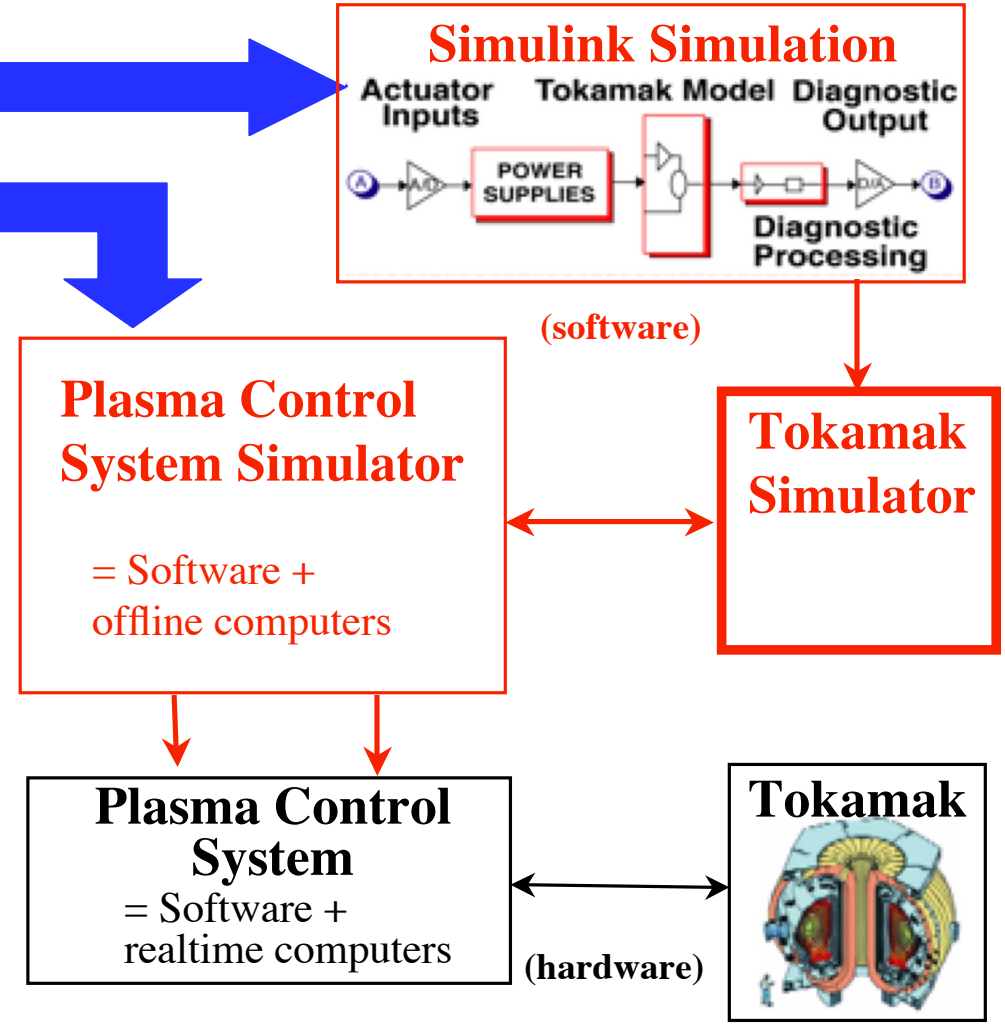

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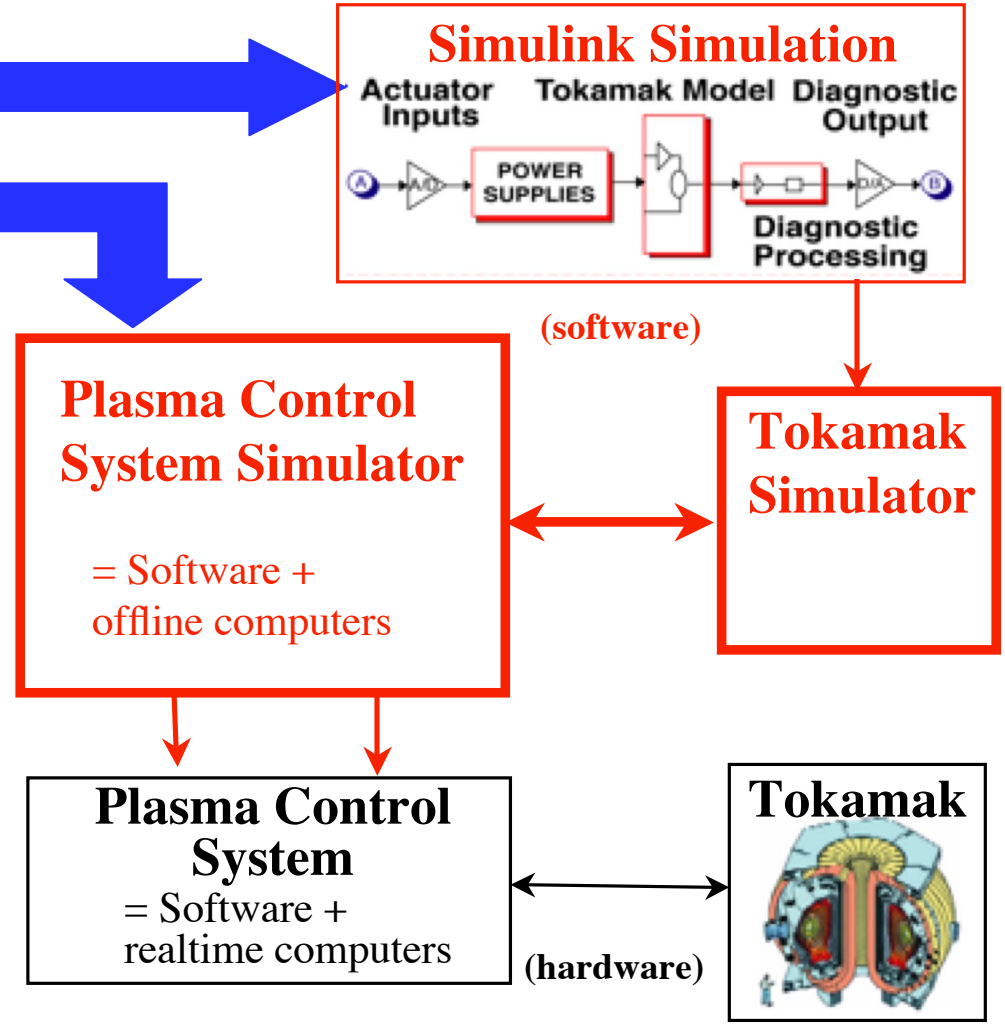

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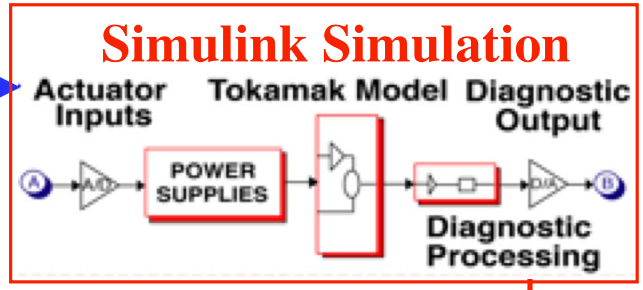

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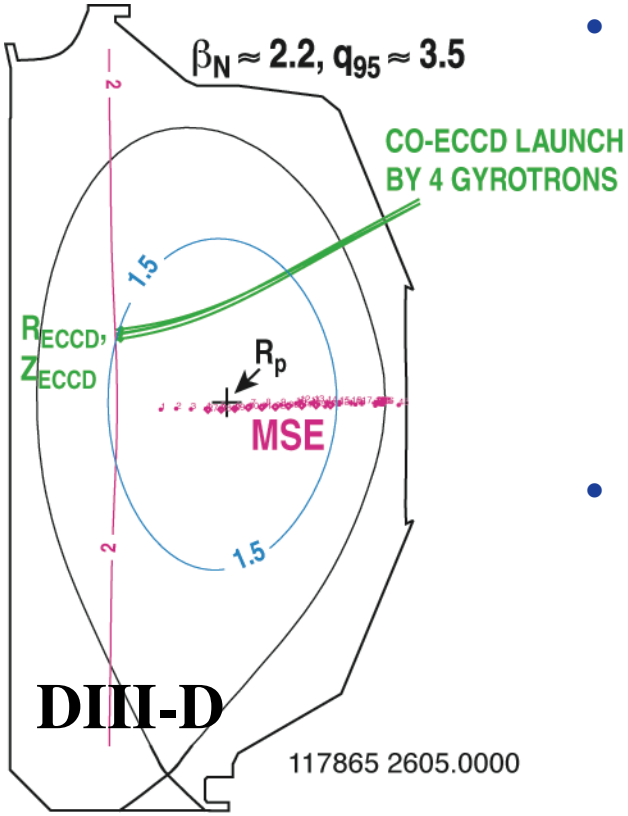
Tokamak

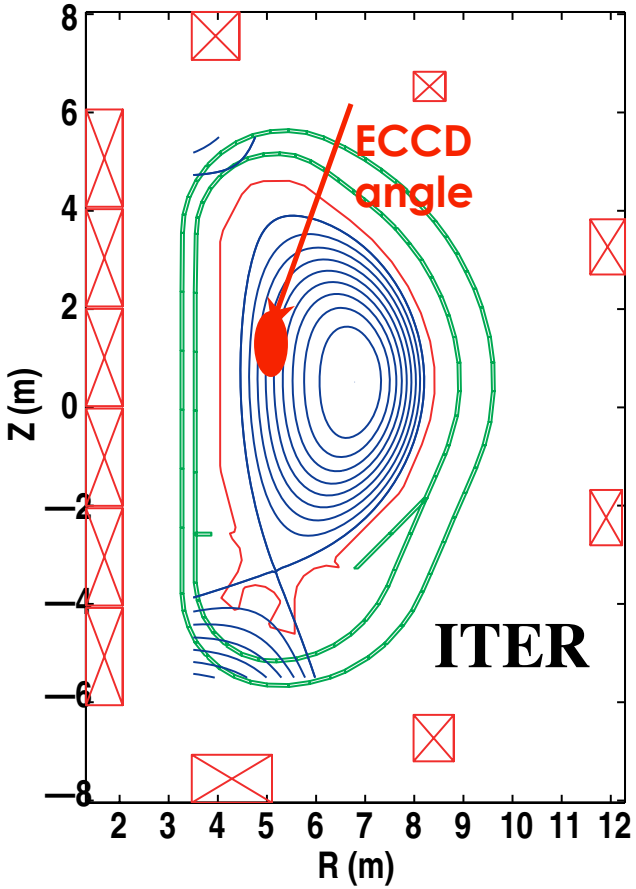
NTM Stabilization Algorithms

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



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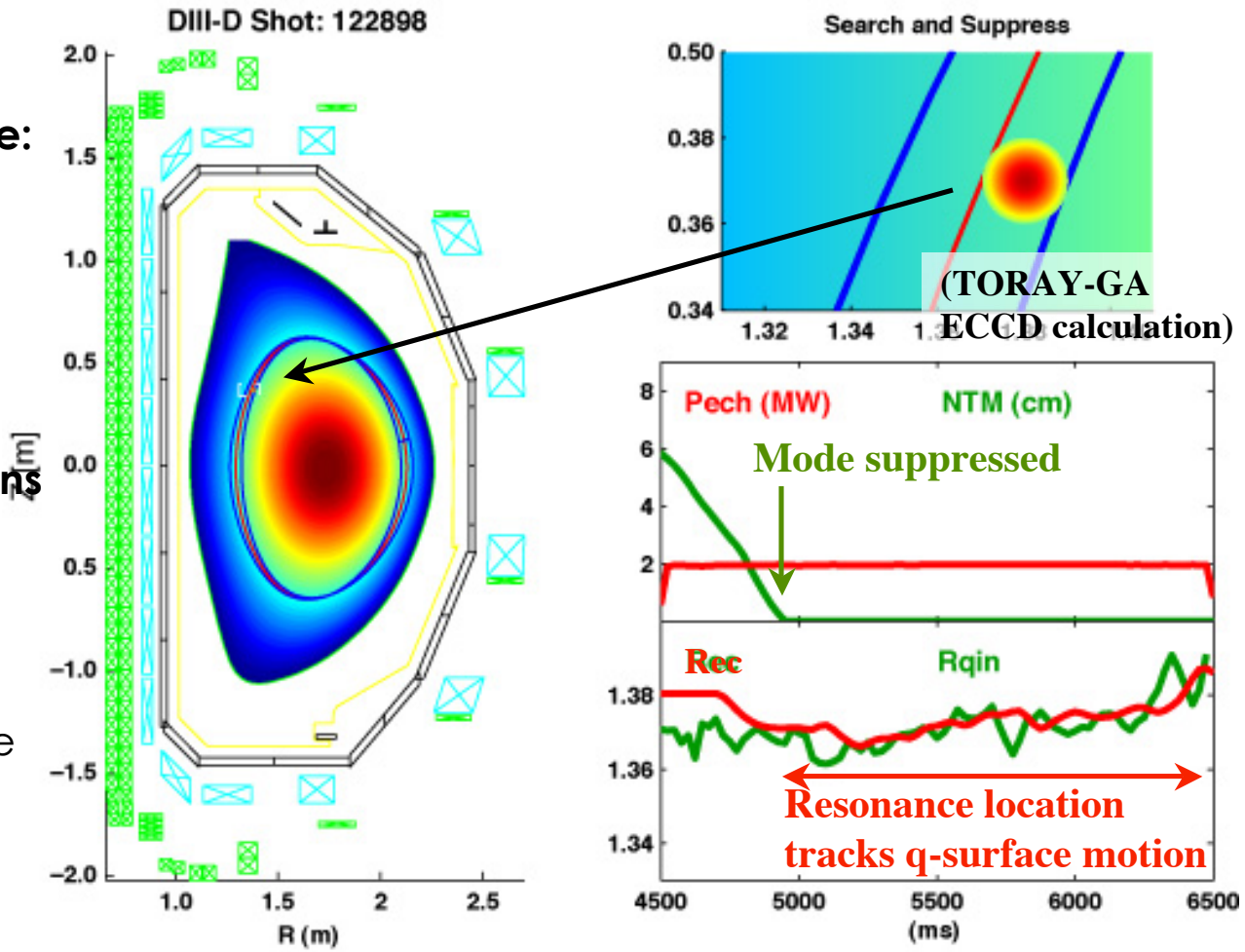
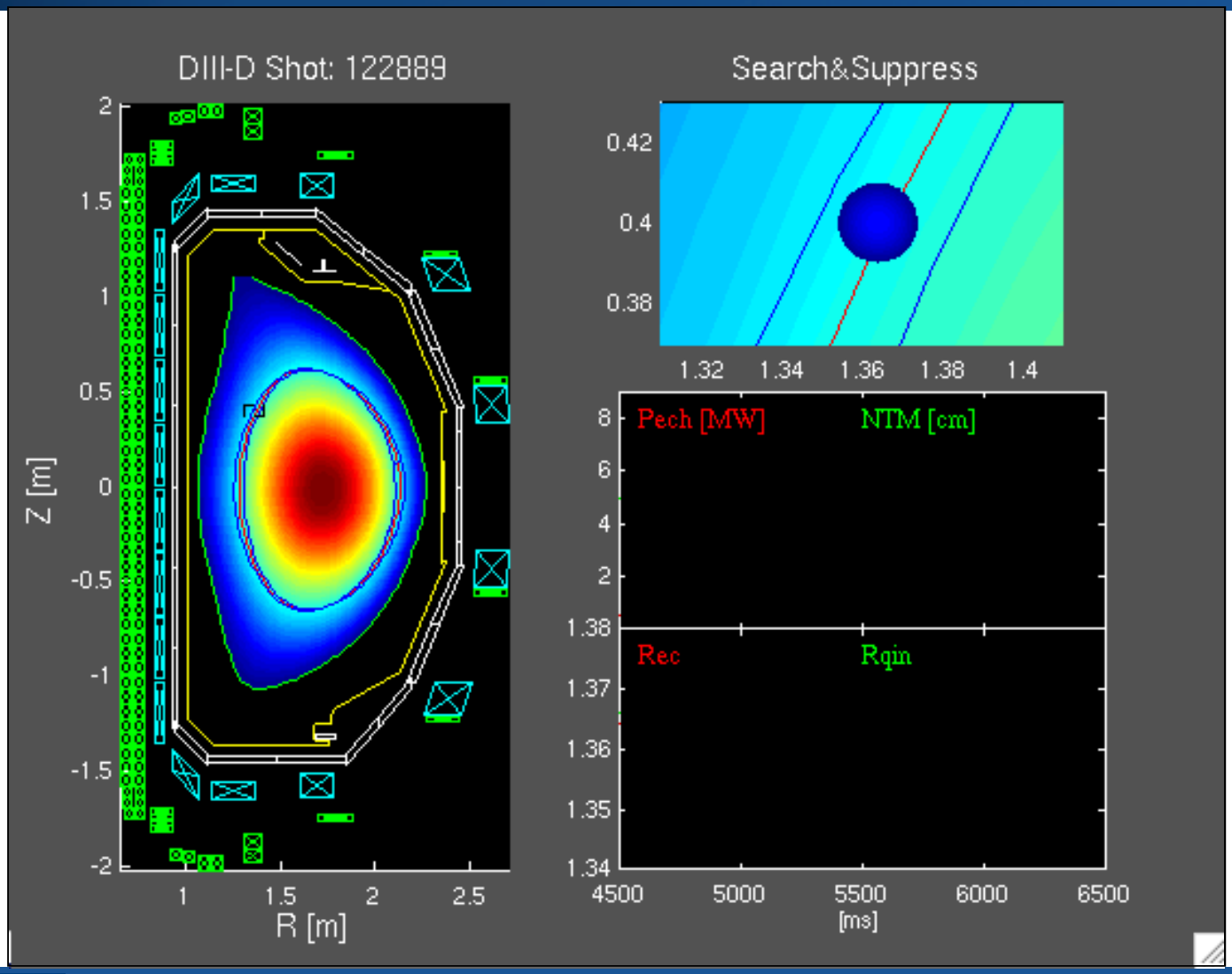
DIII-D NTM Control Demonstrates Accurate and Sustained Alignment of ECCD and Island

- **Align ECCD/island by varying major radius of island or resonance (future: launcher angle)**
- **After island suppressed, evolution in equilibrium detunes alignment**
- **"Active Tracking" maintains alignment as profile evolves**
  - Uses realtime q-profile reconstruction (realtime equilibrium with MSE measurement)



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



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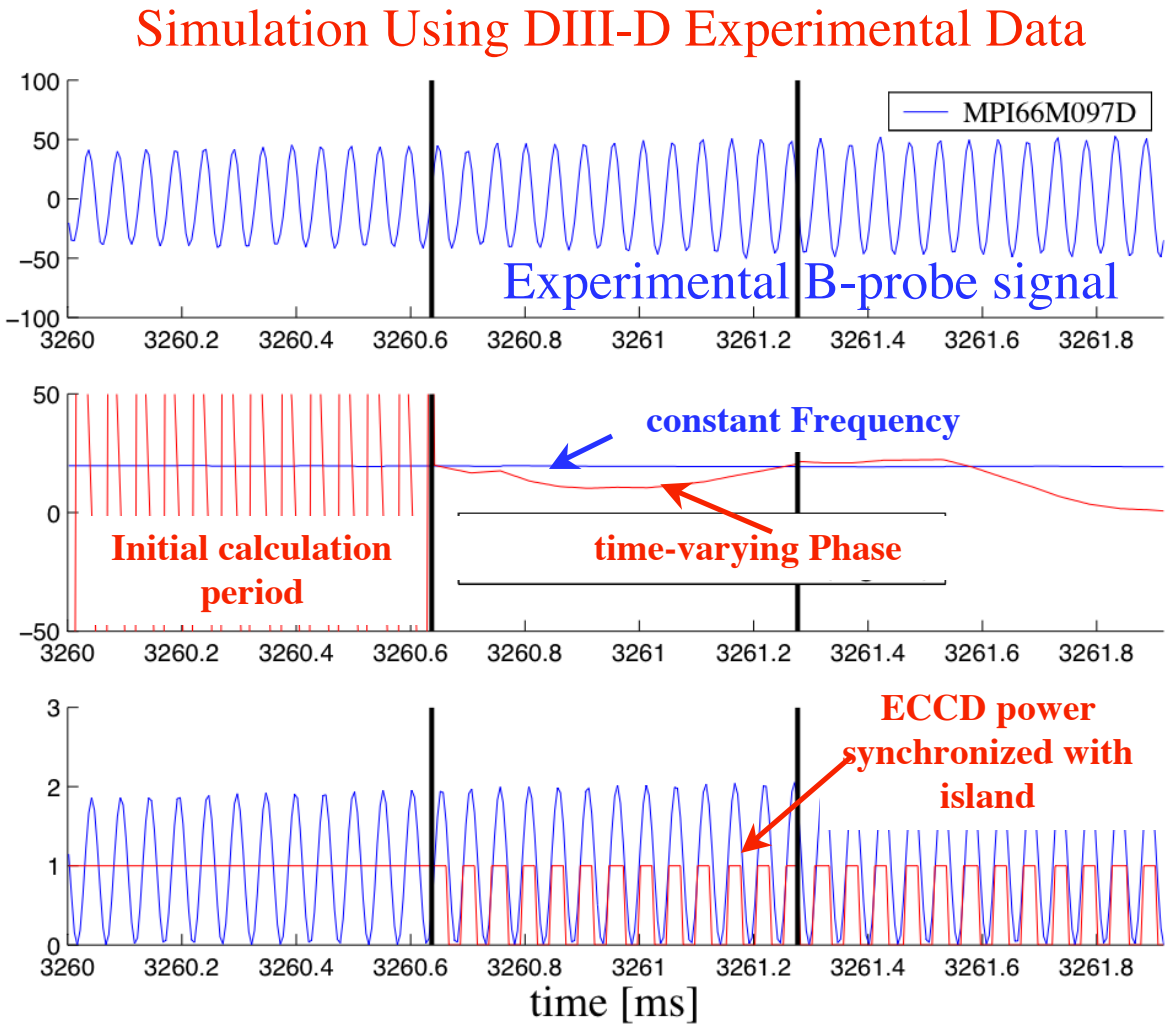
New PCS Algorithm Will Demonstrate Modulation to Synchronize Gyrotron Power with Rotating Island

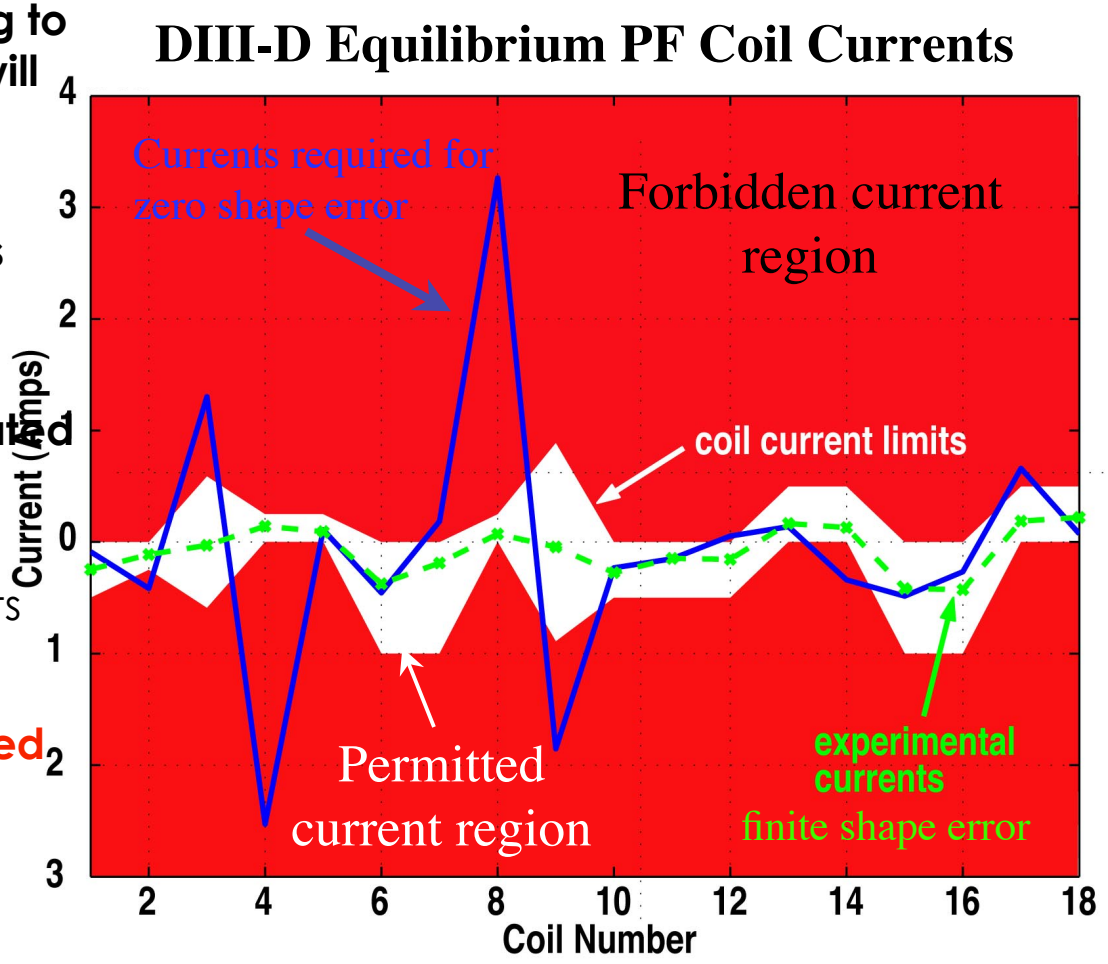
- **Realtime Fourier analysis of midplane probe signals**
- **After initial calculation period, algorithm identifies ~constant frequency, time-varying phase**
  - Phase, frequency command updated after and fixed during each calculation period
- **Command to dedicated cpu produces modulation signal for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



Shape Control with Coil Current Limits

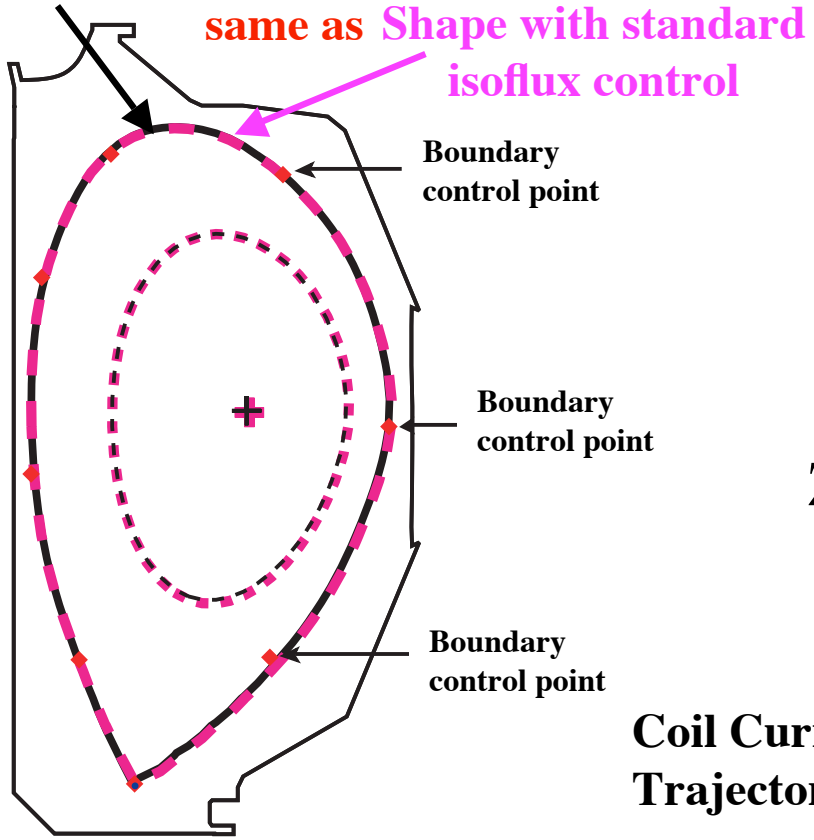
Axisymmetric Control in Tokamaks Requires Avoiding Current Limits

- **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**

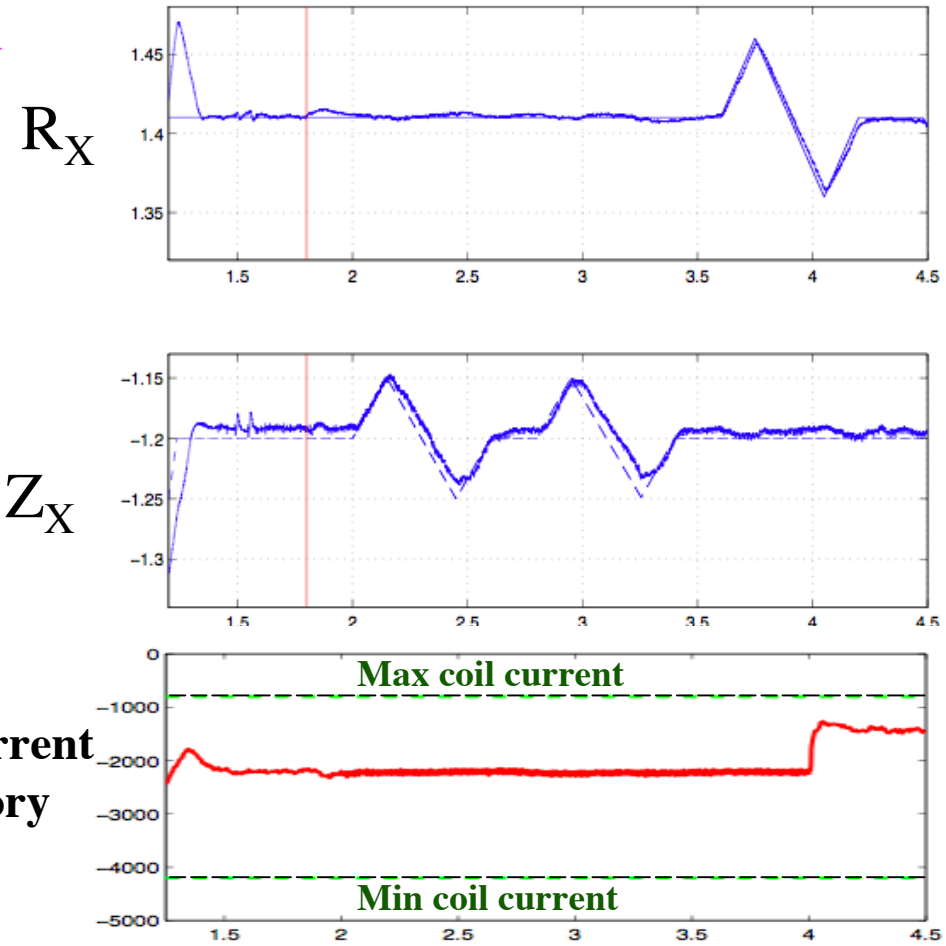


DIII-D Experiments Have Demonstrated Model-Based Multivariable Control with PF Current Regulation

Shape with Feedforward Nominal Current Trajectory



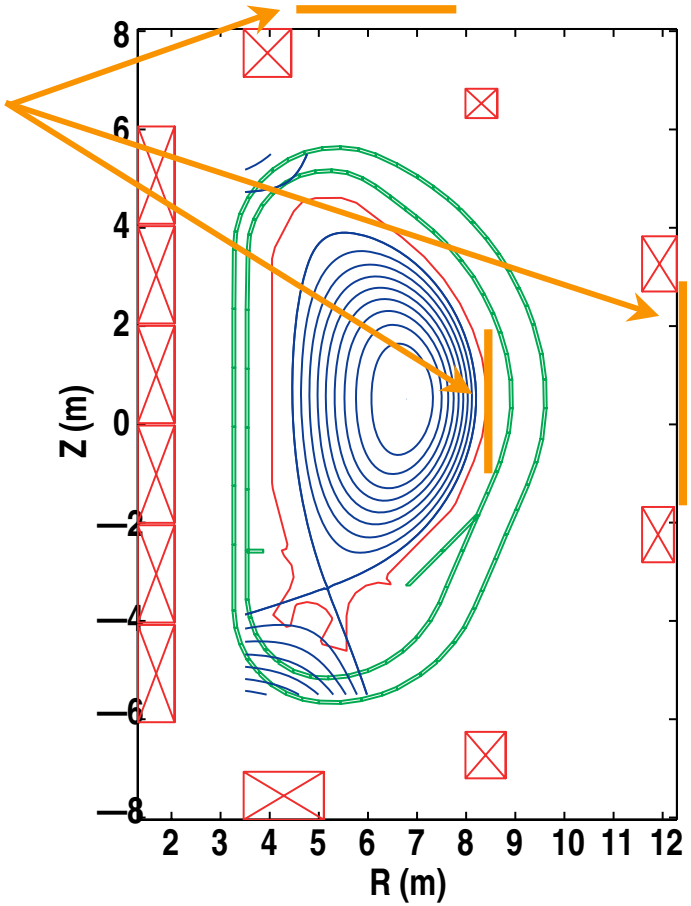
Demonstration of Closed-Loop Control with Nominal Current Trajectory



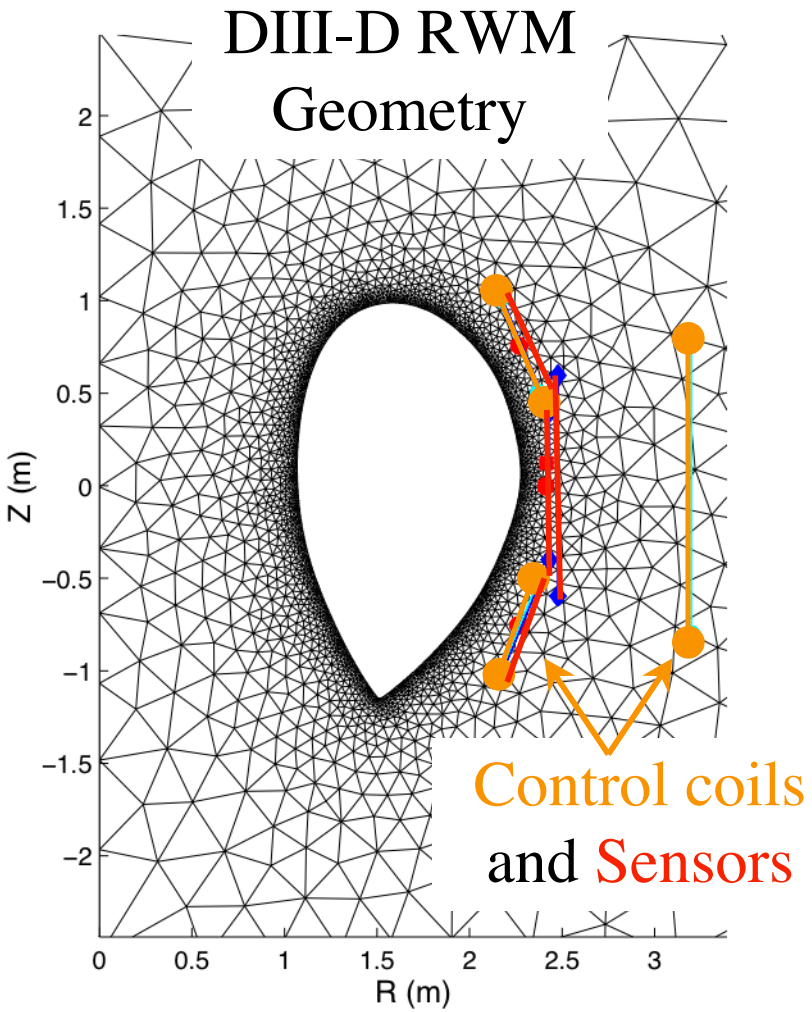
Models for RWM Stabilization Design

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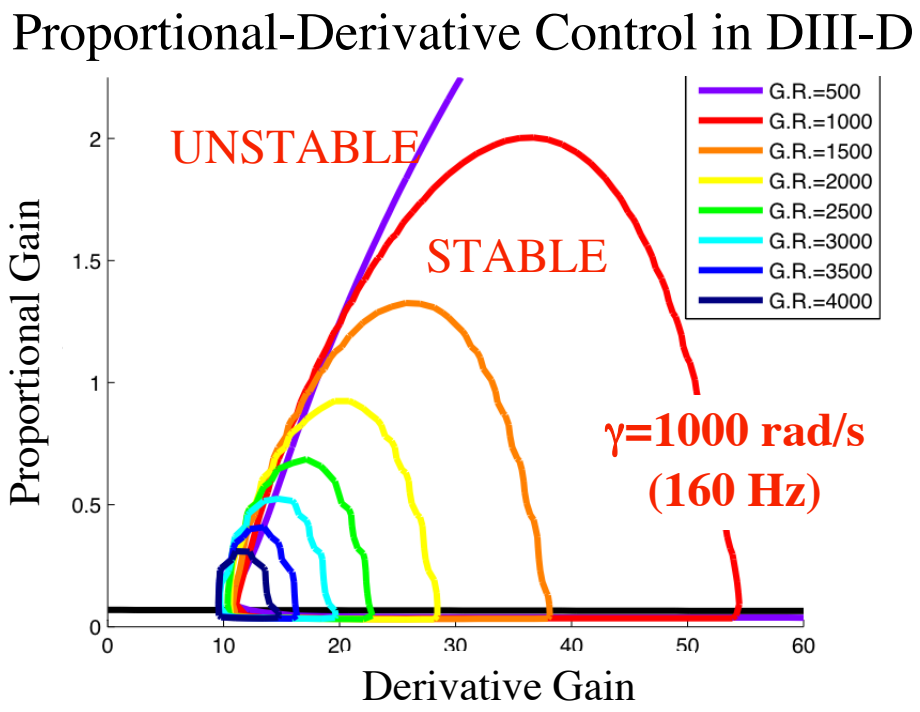
Accurate Models Enable Stabilization of Large Range of Growth Rates with Single Controller



- 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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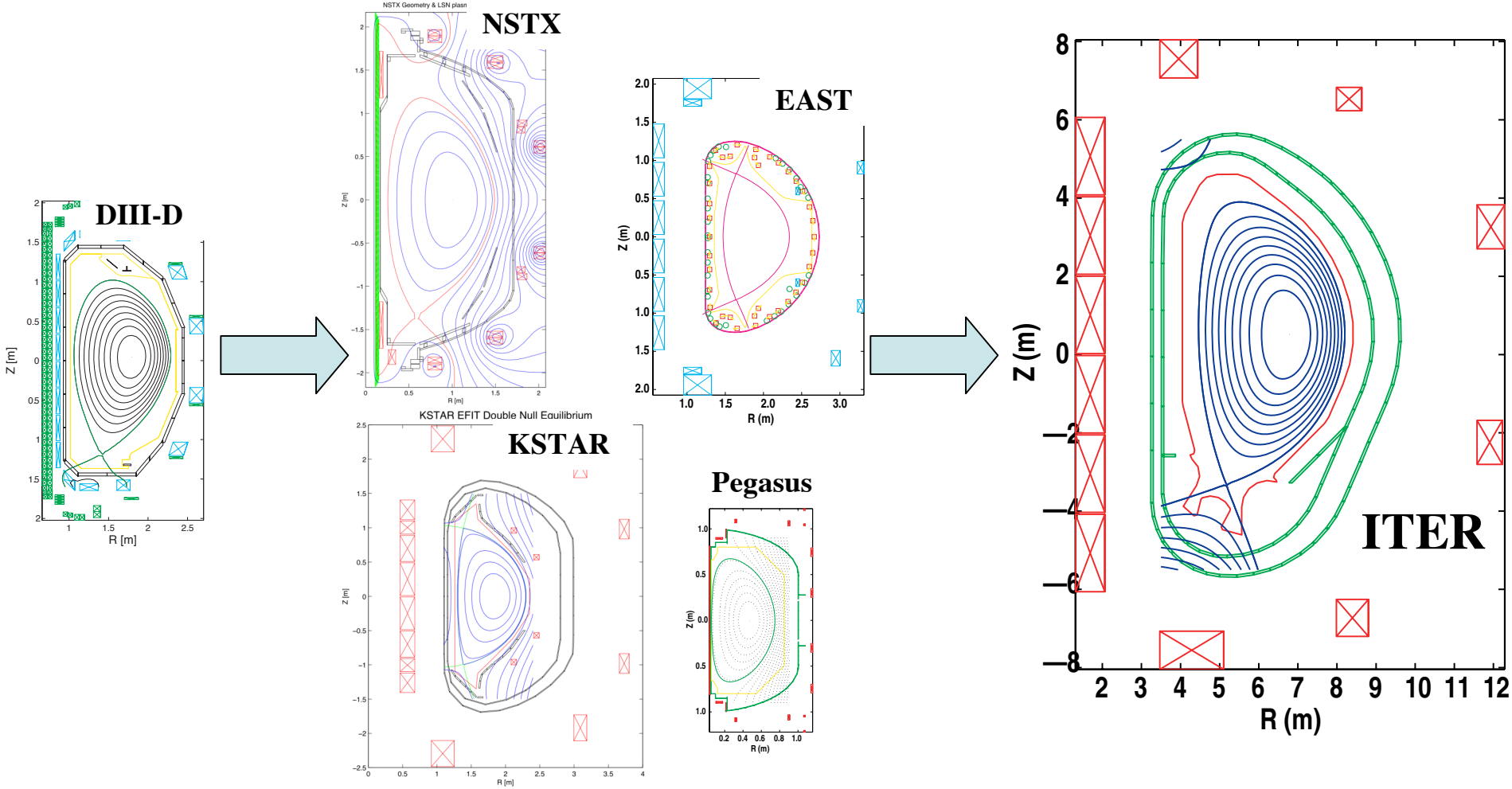
FARTECH

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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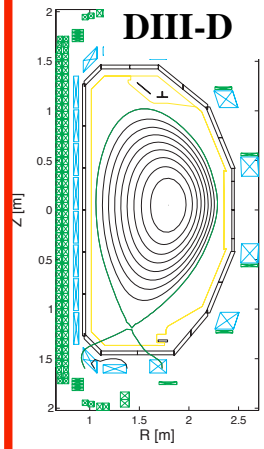
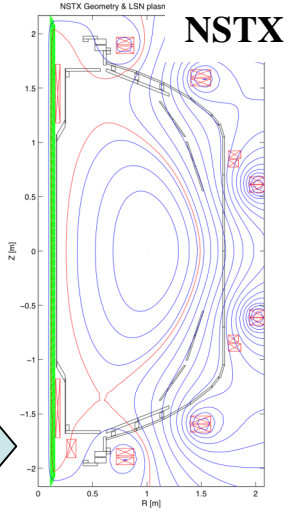
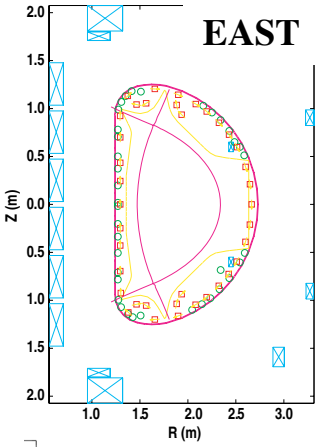
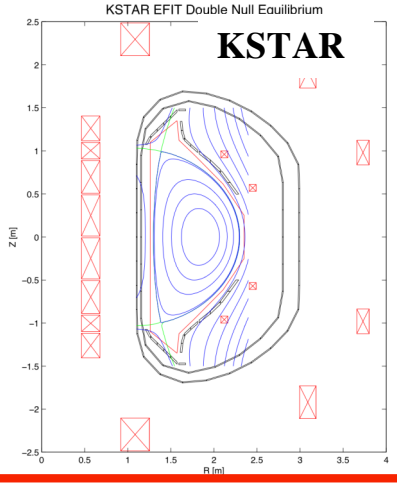
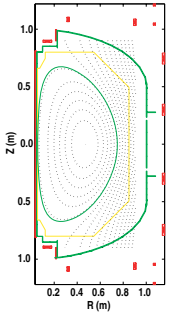
Devices Using DIII-D PCS



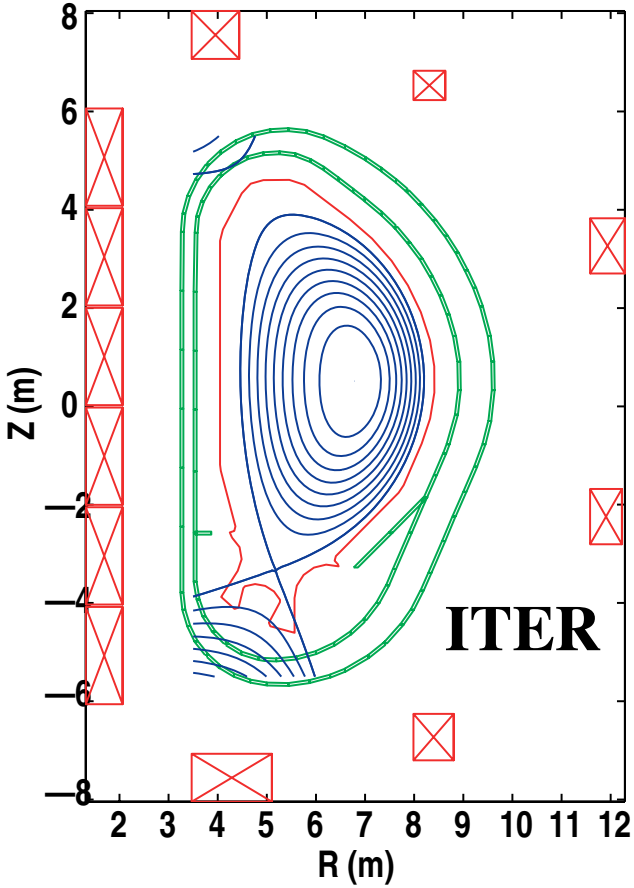








+ MAST



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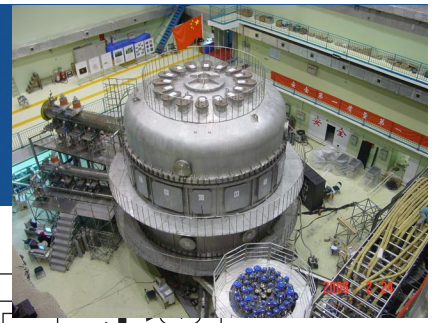
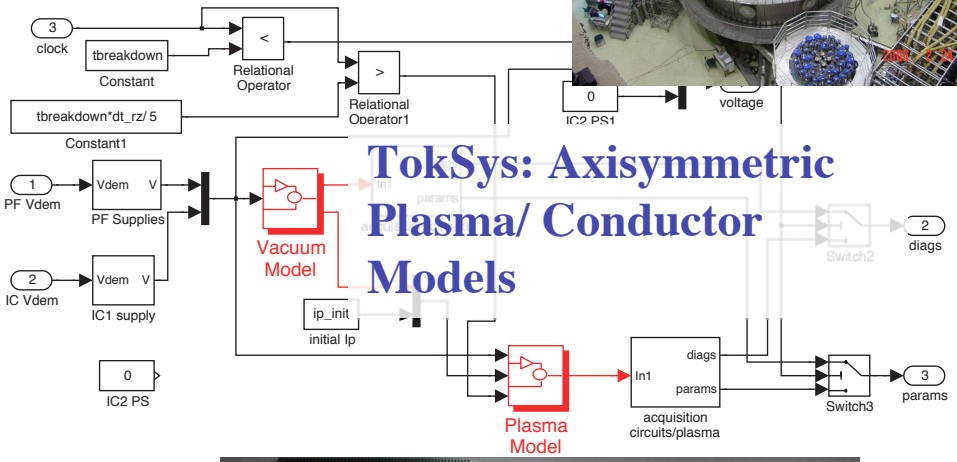
EAST PCS Based on DIII-D PCS Was Commissioned at ASIPP in March 2006





TokSys: Axisymmetric Plasma/ Conductor Models

Command voltages to actuators (PF power supplies, gas valves)

EAST Tokamak

Integrators — Mag

Diagnostics

Unintegrated diagnostics

Filters

Digitizer Breakout Panels (merge signals for digitizer connect)

Isolation Amplifiers

Realtime Display Computer — Myrinet

Host computer — Ethernet, Myrinet

Data Archive (MDSPlus) Computer

Simulation Computer

Realtime comp 1 (I/O computer) — Digitizer, PCI, Myrinet

D/A Breakout Panels (breakout analog signals for actuator connect)

Myrinet Switch

Realtime comp 2 — Myrinet

EAST System Clock & Timing Trigger

Provided by ASIPP

Delivered & Installed by GA

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

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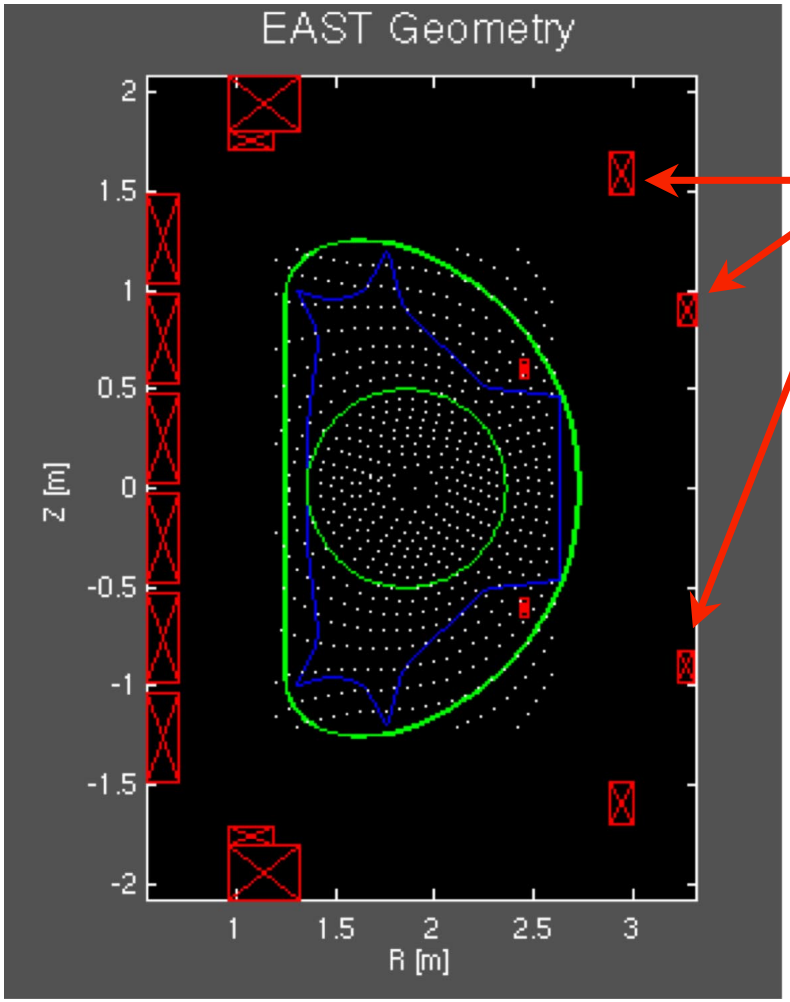
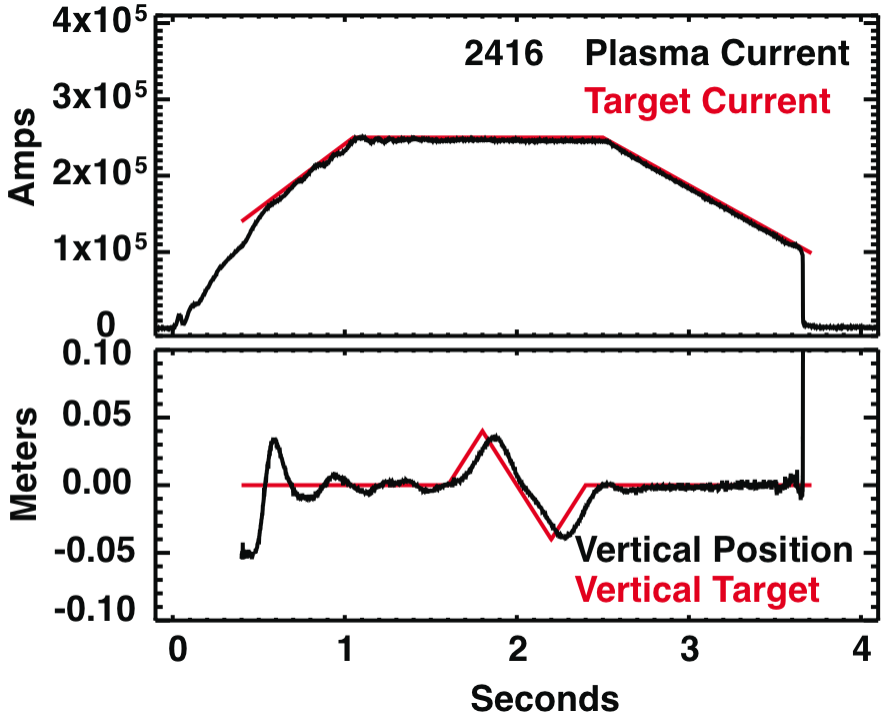
Use of EAST/DIII-D PCS and TokSys Environment Has Contributed to Recent Success of EAST Startup



- Successful use of calculated breakdown scenario
- Demonstrated fault detection/response algorithms
- Distant, superconducting coils: challenge to control
- Demonstrated control of plasma current, position



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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 realtime 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