ITER Plasma Control and US Involvement

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with contributions from

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Overview

- ITER plasma control requirements are very different from those of any existing device:
  - Unprecedented accuracy/precision constraints
  - Extreme reliability, safety requirements
  - Dynamic constraints imposed by superconducting coils, operations
- Integrated model-based approaches to design and commissioning of plasma control are required for such a device:
  - Reliability and performance requirements can only be satisfied with high-accuracy validated models
  - Simultaneous high performance control of plasma state and MHD instabilities requires integrated, multivariable control algorithms
- US resources and expertise can support leadership role or strongly complement the JCT and other Parties for this approach to control:
  - US resources strong for generating plasma models, experimental validation/implementation, integrated system control simulation, but post-EDA history suggests need for US Plasma Control Working Group

ITER Plasma Control Requirements are Uniquely Demanding

- Shape/position/axisymmetric stability control requirements are unprecedented:
  - Shape control accuracy/precision = factor of 10 higher than present devices
  - Dynamic control performance requirements in presence of large disturbances (e.g. ELMs, minor disruptions, change of confinement state) highly constrained
  - Coil current and voltage limits highly optimized, greatly reduced margins
  - Coil operation constrained by AC loss limits
- Profile, divertor, heating, fueling control:
  - Reliability, accuracy, multivariable interactions, complex coupled dynamics
- Stability control:
  - High performance axisymmetric/MHD control in presence of AC loss constraints, voltage/current limits, fiducial disturbances; simultaneous coordinated stabilization
  - Error field correction with SC coils; coordination with MHD control…
- Off-normal response systems:
  - Disruption prediction, corrective action, mitigation
  - Integrated, high reliability supervisory action for many interacting subsystems
- Extreme reliability requirements throughout system

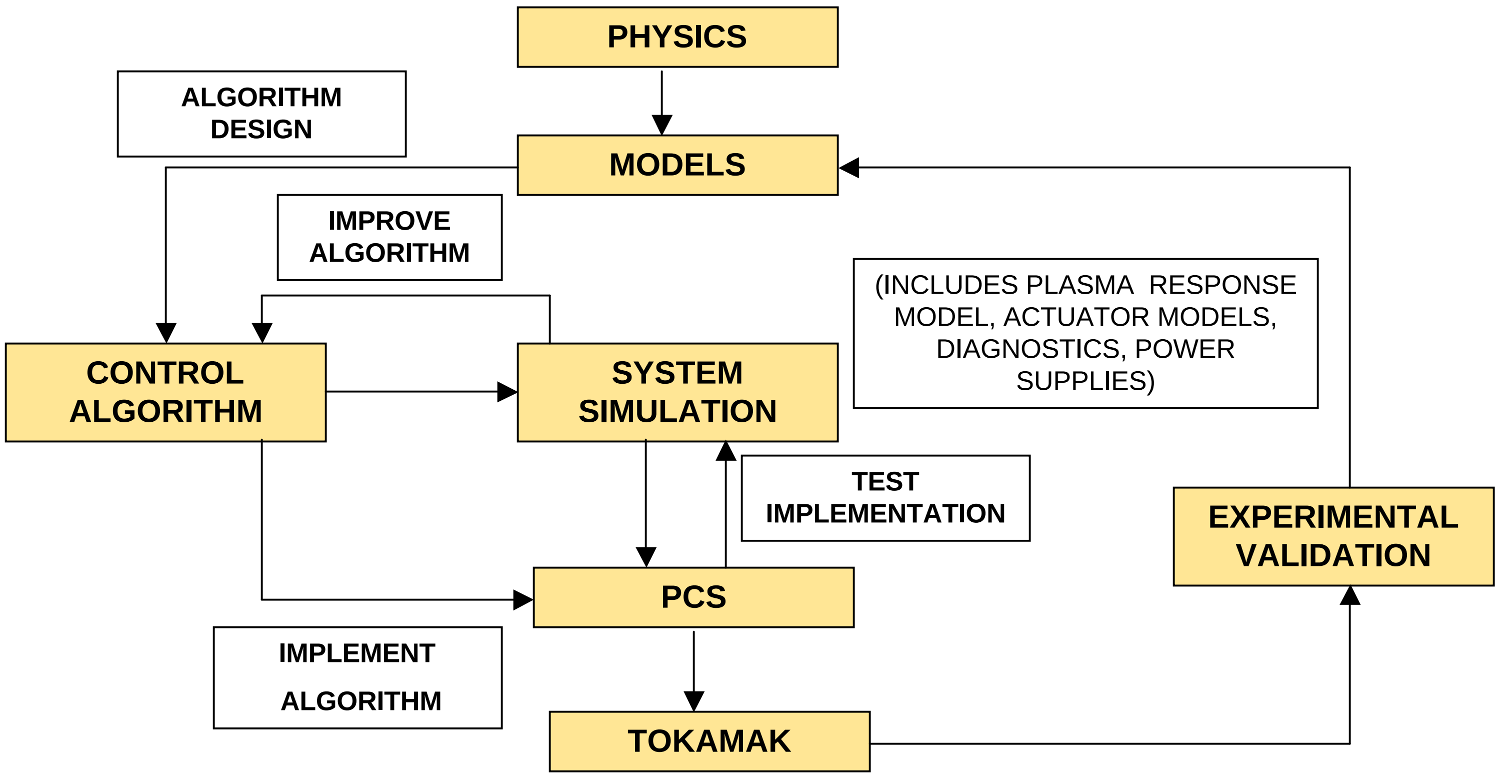
Control Design and Analysis During the ITER EDA Established Need for Integrated Model-Based Methods, Solved Major Problems

- Established shape/stability criteria, fiducial equilibria/disturbances
- Control schemes, design/testing tools developed
- Major constraining issues identified and methods developed for appropriately incorporating constraints in design
- Suite of modeling/simulation tools developed and applied
- Controllers designed and simulated satisfying all performance specs for FDR:
  - High performance axisymmetric equilibria, stability control in presence of AC loss constraints, voltage/current limits, fiducial disturbances, demonstrated robust multivariable performance in many different simulation codes
  - Error field correction
  - Off-normal responses
- Key engineering design results produced to guide FDR

ITER-FEAT Requires Extended Control Design and Analysis Well Beyond FDR

- Enhanced AT mission: Stronger need for integrated operating regime/MHD control, off-normal response
- Increased MHD stability control requirements
- More demanding performance envelope (e.g vertical growth rate, control tolerances)
- Similar but more demanding actuator constraints (e.g. AC losses, power limits, heat load limits)
- New or remaining unresolved issues from FDR (e.g. T-retention, ELMs, disruption effects tolerance/mitigation)
- Next phase requires licensing and commissioning plan: increased demands on reliability and risk quantification

Extreme Accuracy/Reliability Constraints of ITER Require Model-Based Integrated Plasma Control

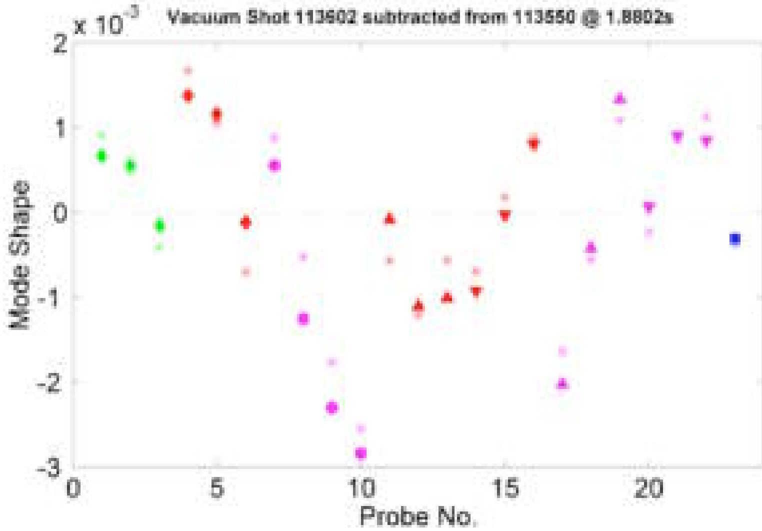


ITER Plasma Control Task Structure and Context

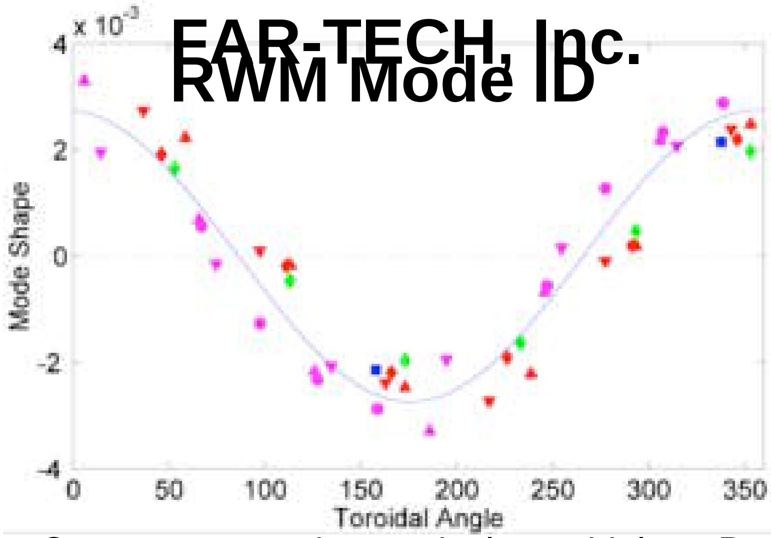
- Technology package is under CODAC = Control and Data Acquisition Computer
- Large amount of R&D will also be needed to allow control system commissioning
- US has potential to take leadership role OR to strongly complement other Parties/IT with unique tools/expertise in both R&D and CODAC task
- Plasma control is an area with high impact metrics:
  - Central to ITER experimental operations and physics
  - High impact per $$
  - Area of US strength
- Following US departure from EDA, other Parties and JCT continued; EU in particular established:
  - Strong inter-organizational coordination, EU-wide integrated control program
  - Strong coupling between experimental programs and control R&D
  - Strong sustained programmatic support for control program
- These are also what the US will need in order to play a role in ITER plasma control (but largely lacks now). Providing them implies support for:
  - Continuing development of ITER-relevant plasma control methods/tools
  - Design and implementation of ITER-relevant controllers on experiments
  - Experimental time to explicitly perform predictive model construction and validation
  - Strengthened coupling between codes/theory/experiment and control design

Theory and Predictive Modeling Must Have Strong Connection to Experimental Validation and Control Design Efforts

- Example: excellent RWM prediction using ideal MHD stability codes such as GATO, DCON and vacuum field codes such as VACUUM, FARVAC
- Development, validation, and application of such predictive capability should be integral part of all control-oriented experimental efforts



sensors match predicted mode structure



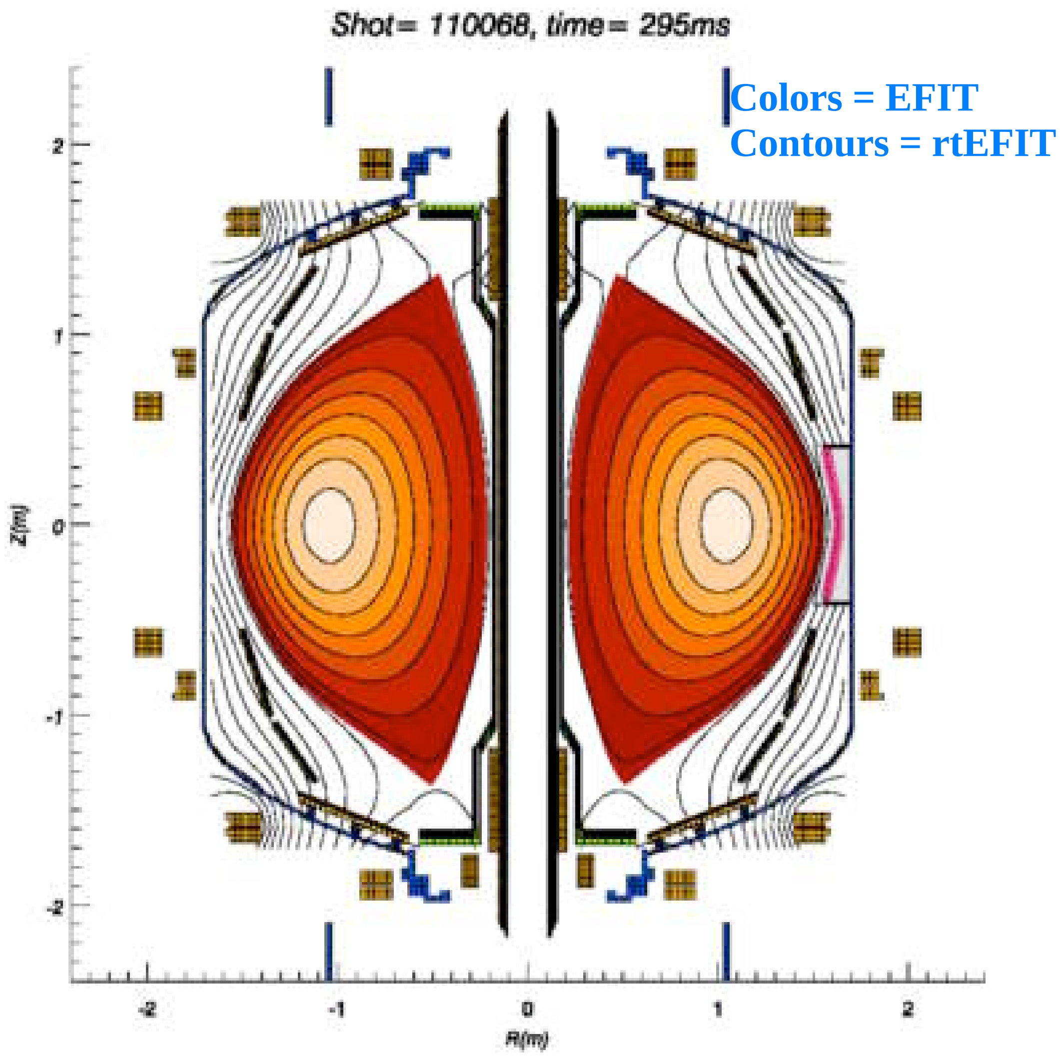
Sensors mapped to equivalent midplane B_p

Experimental Efforts Should Include ITER-Relevant High Performance Control and Model Validation at Program Level

- Predictive modeling, experimental validation:
- Offline and hardware-in-loop simulation for algorithm development and commissioning
- Design and testing of control algorithms and control approaches
- Demonstrated experimental application of ITER-relevant controls in present machine operations
- Simulation of ITER-relevant control scenarios using present experiments themselves
- Probably implies machine time dedicated to control-driven needs

Example: Accurate Realtime Equilibrium Reconstruction Essential for ITER Running on NSTX and DIII-D

- Realtime EFIT(J.Ferron) used for plasma control on NSTX and DIII-D
- Full solution of Grad-Shafranov equation at each control time step
- Measured eddy currents included in reconstruction in NSTX realtime calculation



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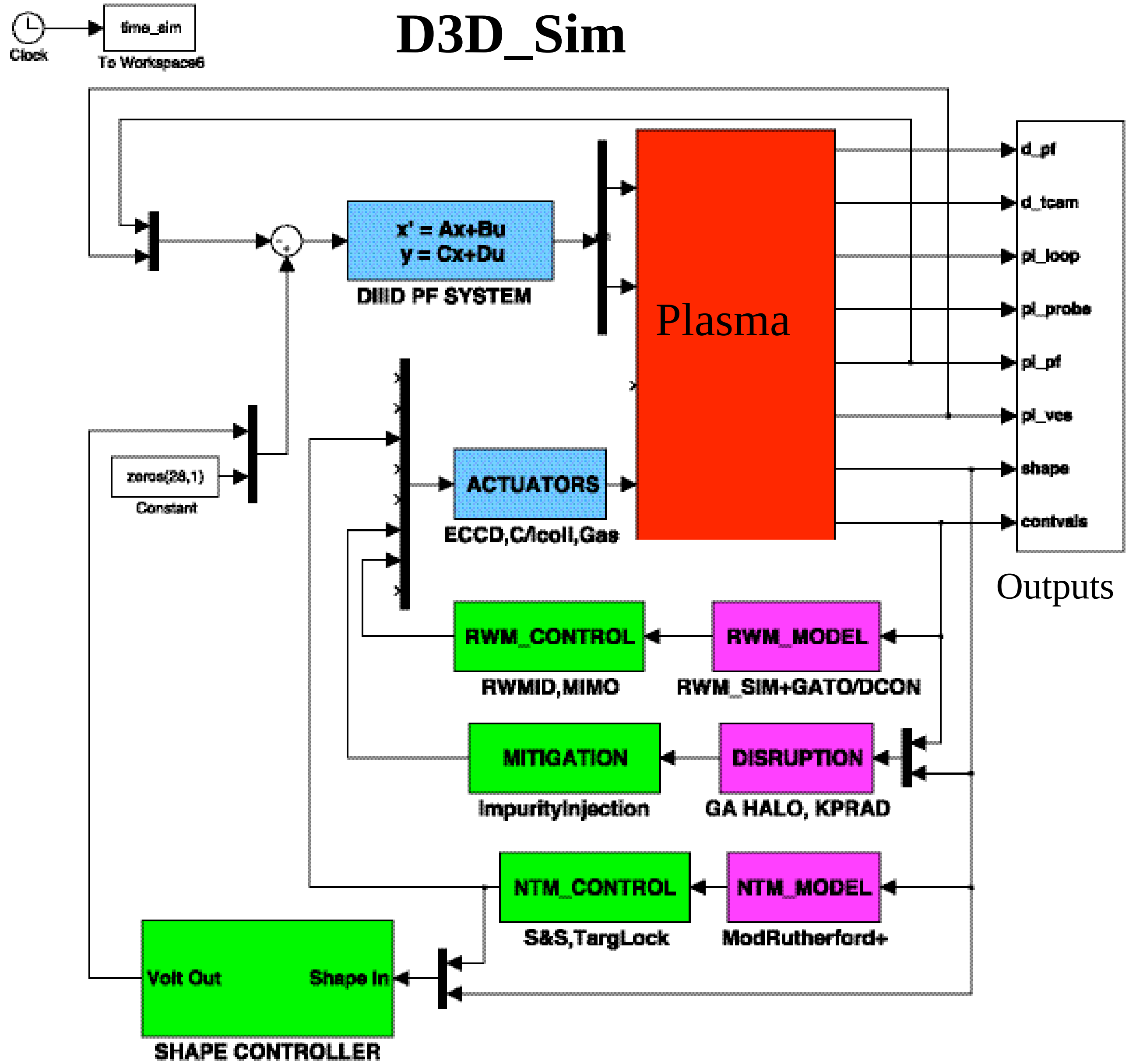
Simulation Tools Must be Closely Connected with Theory, Experiment, Control Design

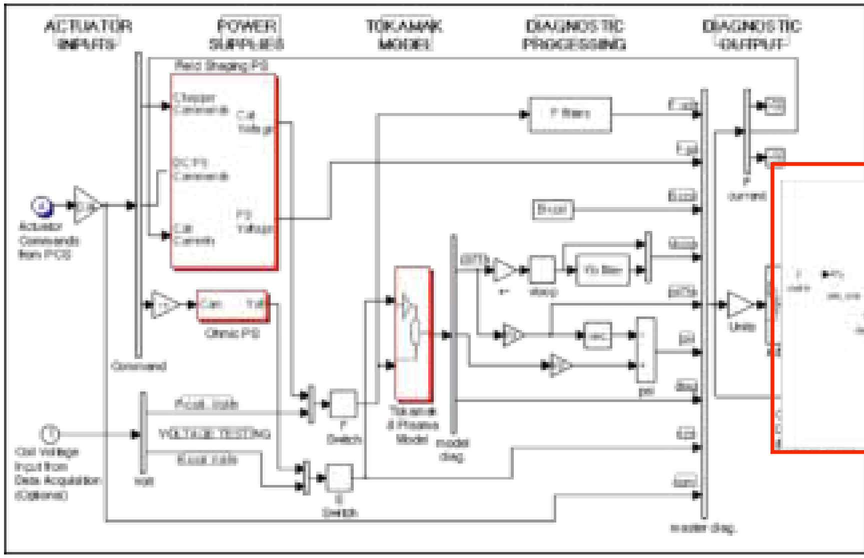
- Three general types of simulation needed:
  - System code: simple models, event sequence testing, simulates entire plant
  - Control-level simulation: simple to moderate models, control performance, simulates (nearly) entire plant
  - Detailed physics-level simulation: complex models, elements of control performance, subsystem simulation (e.g. plasma core, relevant plasma physics + actuators)
- Extremely important for integrated design is control-level simulation:
  - Flexible simulation of selected or combined control elements
  - Full plant behavior available as needed by control design requirements (e.g. may include grid loading, coil quench scenario, disruption or other off-normal event detection/response, etc…)
  - Should accept modular elements from virtually any code source, manage multiple timescales, execute rapidly
  - Generation and validation of modules for use in control-level simulation is large task which requires direct and close coupling with theory (e.g. detailed physics-level simulations) and experiment

Control-Level Simulation of Integrated Systems Requires Accurate Models of Interacting Subsystems

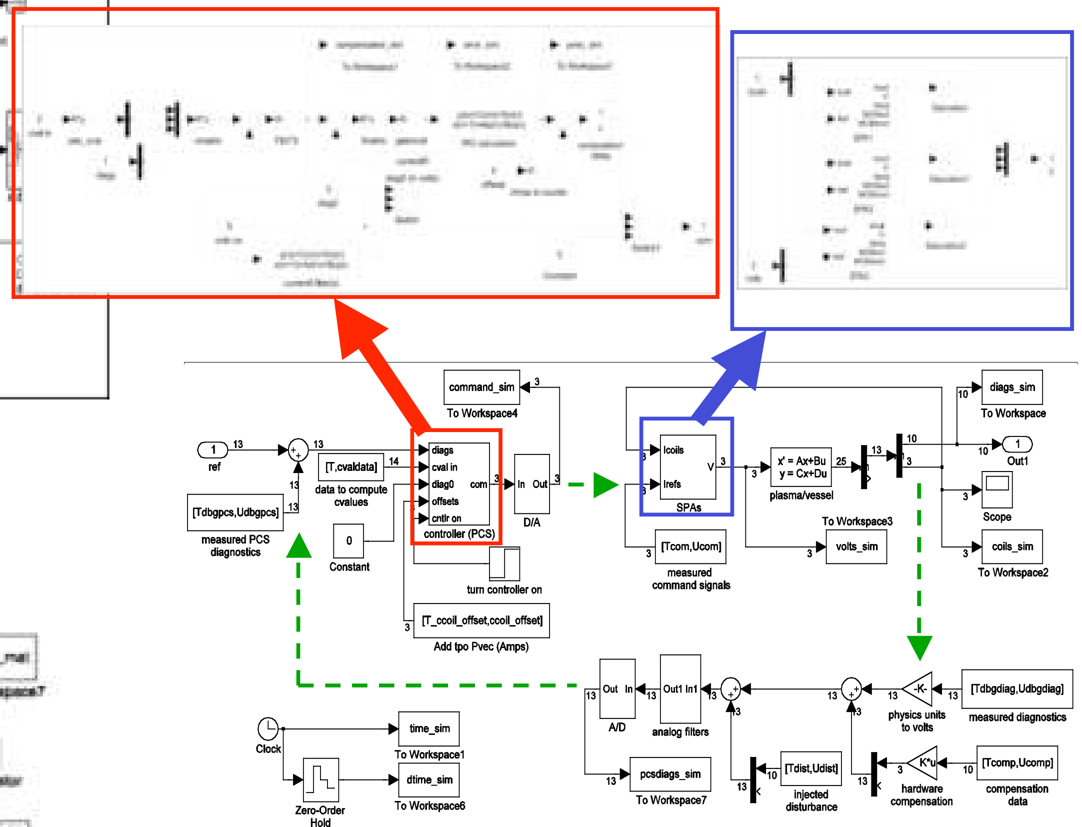


Individual Blocks in Control-Level Simulation Can be Very Complex and Can Contain Detailed Physics

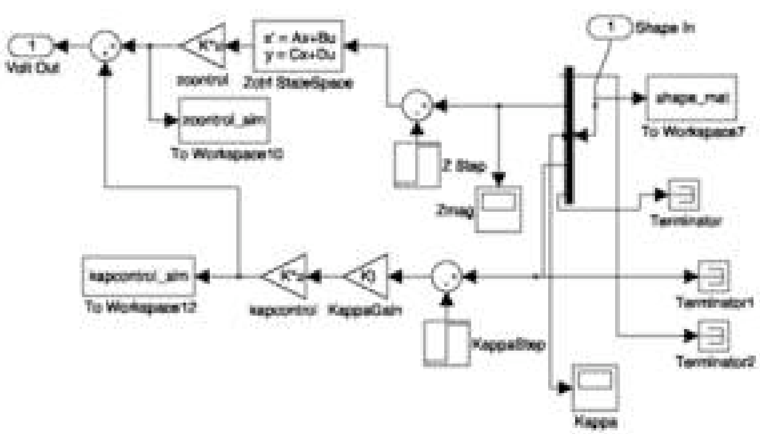
PF System



RWM Model



Shape Controllers



Summary

- ITER control is uniquely demanding:
  - Control design must build into design process all the constraints imposed by the high performance, burning plasma mission
  - Providing necessary reliability requires model-based, multivariable integrated control design
- US has all elements needed to (and should) either provide a leadership role OR seek to strongly complement other Parties and International Team, BUT…
- To play a role in ITER plasma control, the US should strongly support:
  - Continuing development of control tools
  - Design/implementation of ITER-relevant controllers on present experiments
  - Use of experimental time to explicitly support model construction and validation
  - Strengthening of coupling from codes/theory/experiment to control design efforts
- Strongly suggests need for a US Plasma Control Working Group…
- "We will sell no control without a predictive model and simulation…"