

TokSys Modeling and Simulation Tools for KSTAR

M.L. Walker

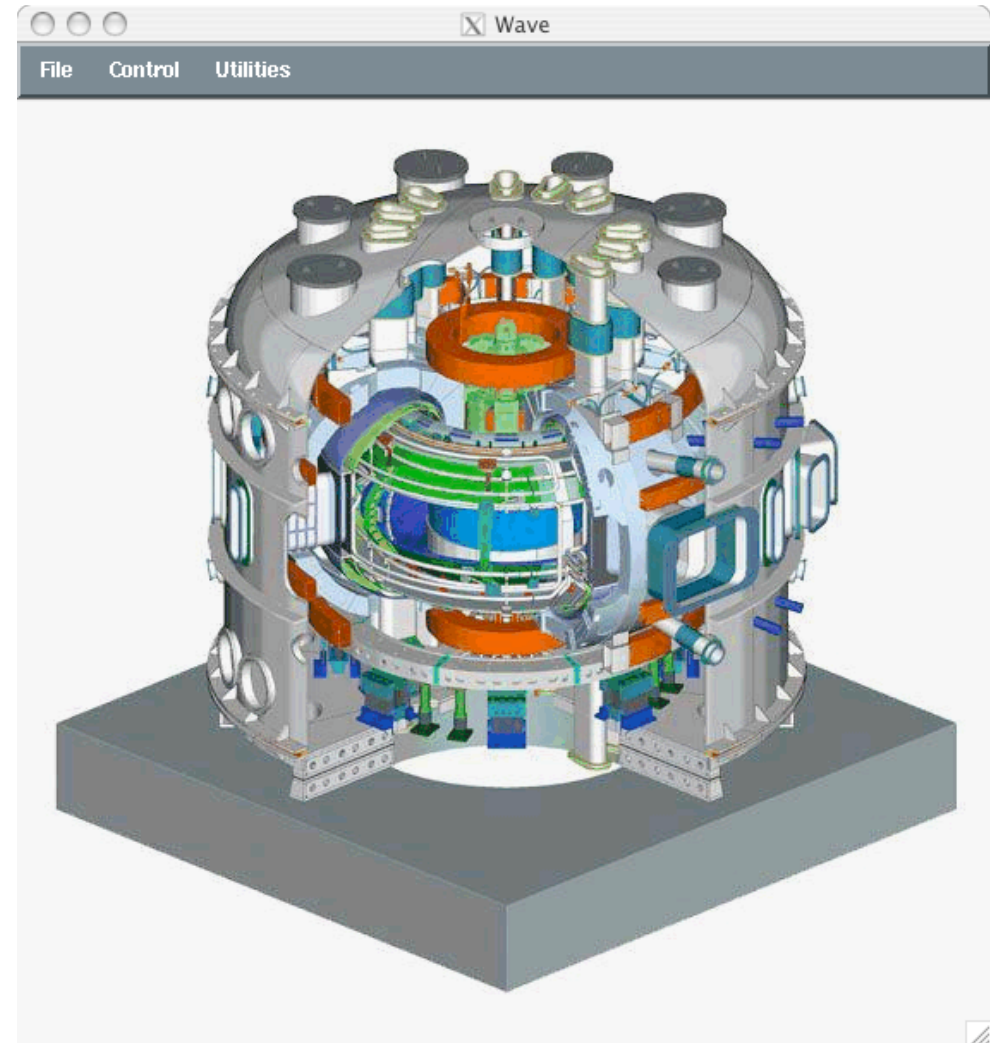
presenting for

**N.W. Eidietis, D.A. Humphreys,
A.W. Hyatt, J.A. Leuer, B. Sammuli,
M.L. Walker, A.S. Welander**

General Atomics, San Diego, USA

S.H. Hahn, Y.M. Jeon, S.W. Yoon
NFRI, Daejon, Korea

KSTAR Workshop
General Atomics, San Diego
April 15, 2009

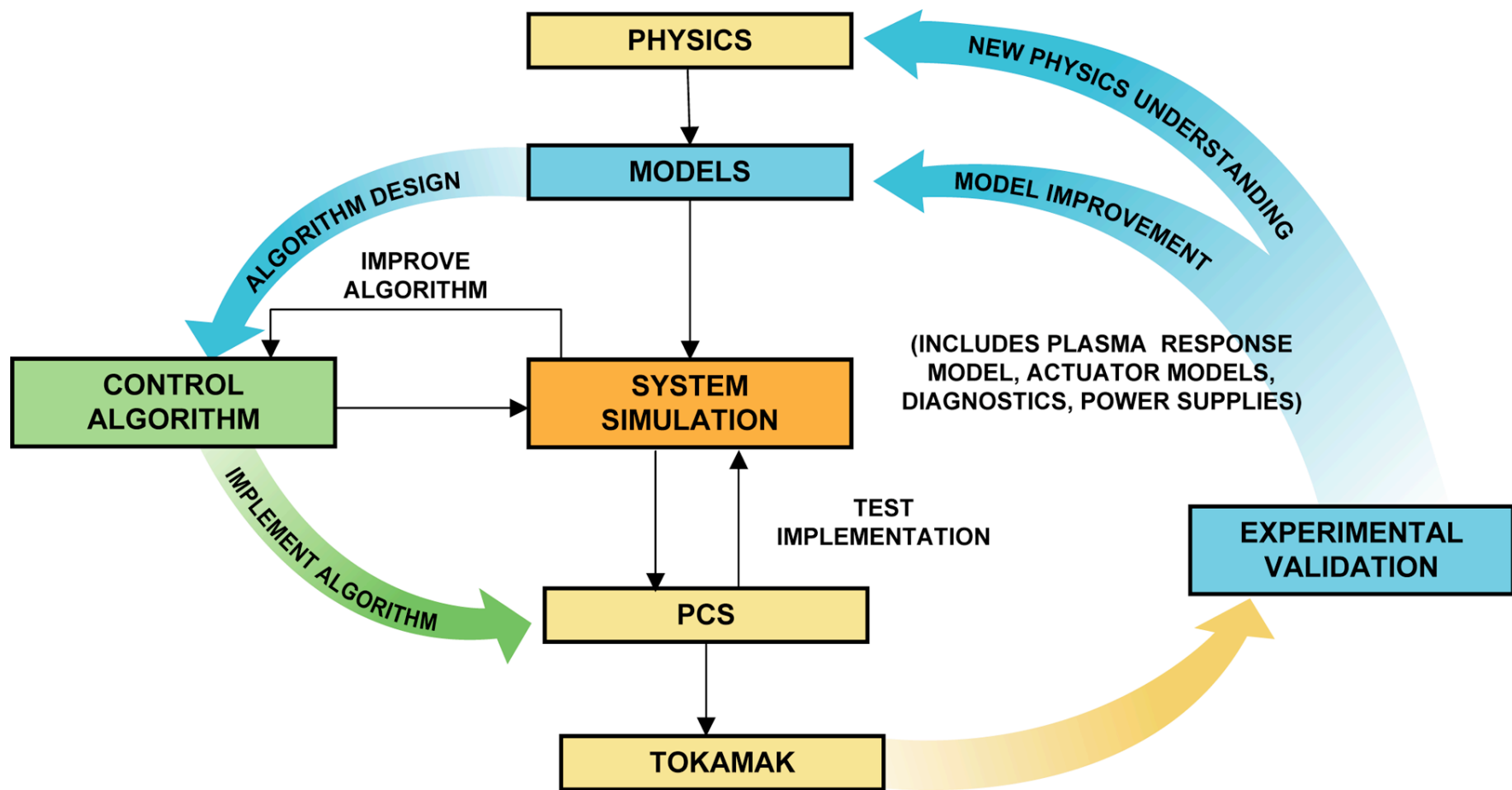


Use of TokSys in Support of DIII-D

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 and KSTAR tokamaks**

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

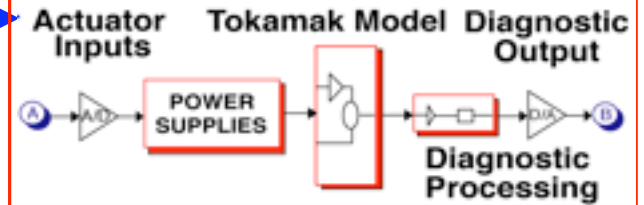


TokSys is an Integrated Plasma Control Environment That Allows Systematic Design and Testing of Controllers

TokSys:

Tokamak System Models
+
Controller Designs

Simulink Simulation



- **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

(software)

Tokamak Simulator

Plasma Control System
= Software + realtime computers

(hardware)

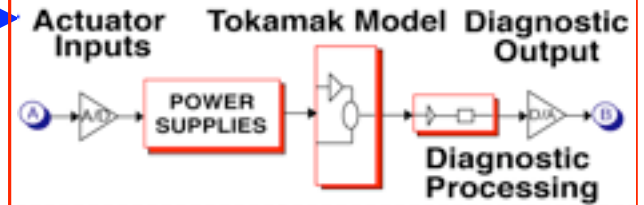
Tokamak


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

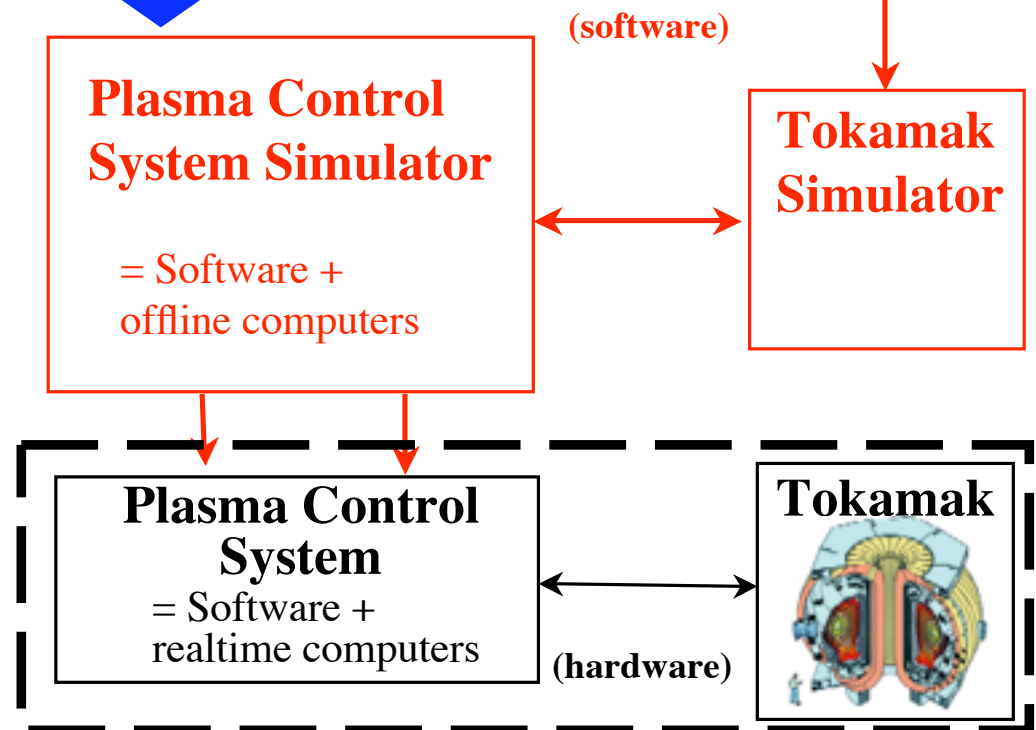
TokSys:

Tokamak System Models
+
Controller Designs

Simulink Simulation



- **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**

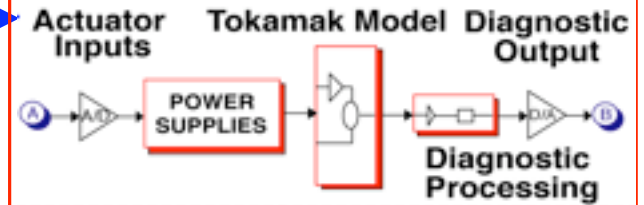


TokSys is an Integrated Plasma Control Environment That Allows Systematic Design and Testing of Controllers

TokSys:

Tokamak System
Models
+
Controller Designs

Simulink Simulation



- **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

(software)

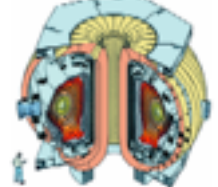
Tokamak Simulator

Plasma Control System

= Software +
realtime computers

(hardware)

Tokamak

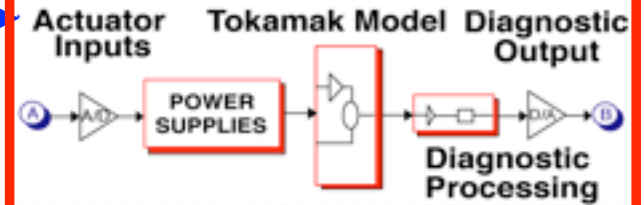


TokSys is an Integrated Plasma Control Environment That Allows Systematic Design and Testing of Controllers

TokSys:

Tokamak System Models
+
Controller Designs

Simulink Simulation



- **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**

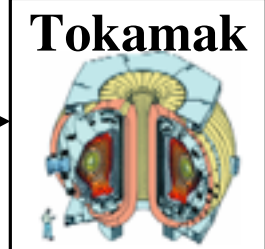
Plasma Control System Simulator
= Software + offline computers

(software)

Tokamak Simulator

Plasma Control System
= Software + realtime computers

(hardware)

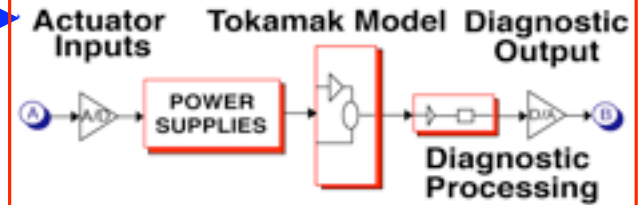


TokSys is an Integrated Plasma Control Environment That Allows Systematic Design and Testing of Controllers

TokSys:

Tokamak System Models
+
Controller Designs

Simulink Simulation



- **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

(software)

Tokamak Simulator

Plasma Control System
= Software + realtime computers

(hardware)

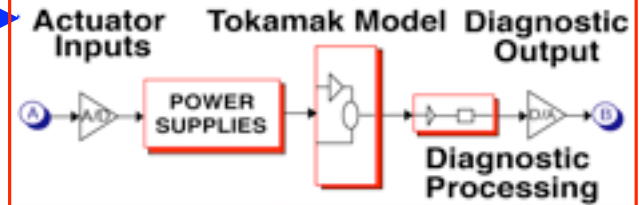
Tokamak


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

TokSys:

Tokamak System Models
+
Controller Designs

Simulink Simulation



- **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

(software)

Tokamak Simulator

Plasma Control System
= Software + realtime computers

(hardware)

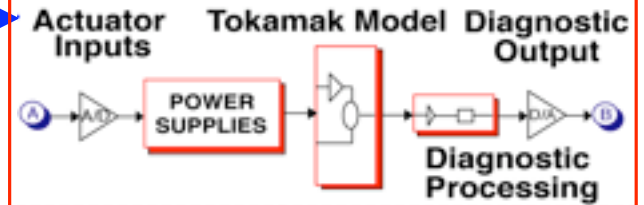
Tokamak


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

TokSys:

Tokamak System Models
+
Controller Designs

Simulink Simulation



- **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**

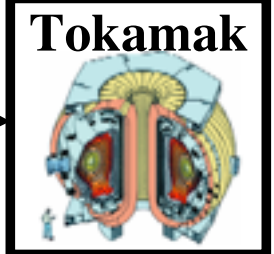
Plasma Control System Simulator
= Software + offline computers

(software)

Tokamak Simulator

Plasma Control System
= Software + realtime computers

(hardware)



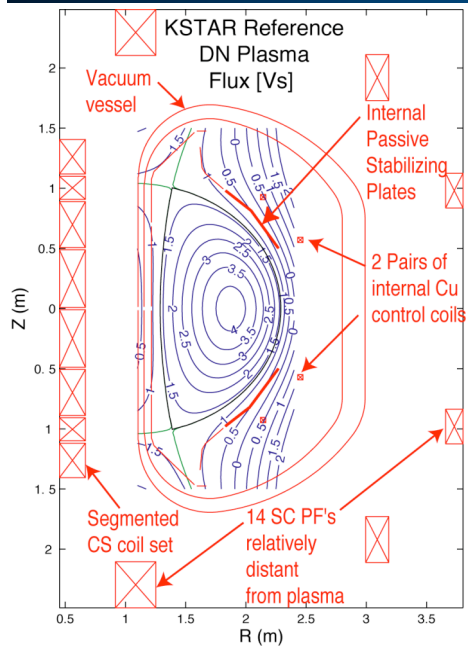
Example TokSys Applications at DIII-D

- **Development of NTM suppression with ECCD**
 - Adaptive algorithms to use continuous ECCD
 - Phase locking algorithm to use modulated ECCD
- **Multivariable shape control development**
 - Nonlinear adaptations for current and voltage limits
 - ITER (and KSTAR) relevant techniques for feedforward control
- **Integrated rotation and beta control**
- **Development of kalman filter-based algorithms for RWM stabilization**
 - Comparative analyses of modern controller schemes
- **Discharge preparation using simserver simulations**
 - Development and evaluation of feedback gains to use in PCS
 - Substantial savings in expensive experimental time
- **Solenoid-less startup analysis and experiment preparation**
- **Post-shot data analysis**
 - Vacuum field analysis, including effects of vessel currents
 - JFIT reconstruction of disrupting plasmas
 - Controllability analysis of vertical instability for ITER

Use of TokSys in Support of First KSTAR Campaign

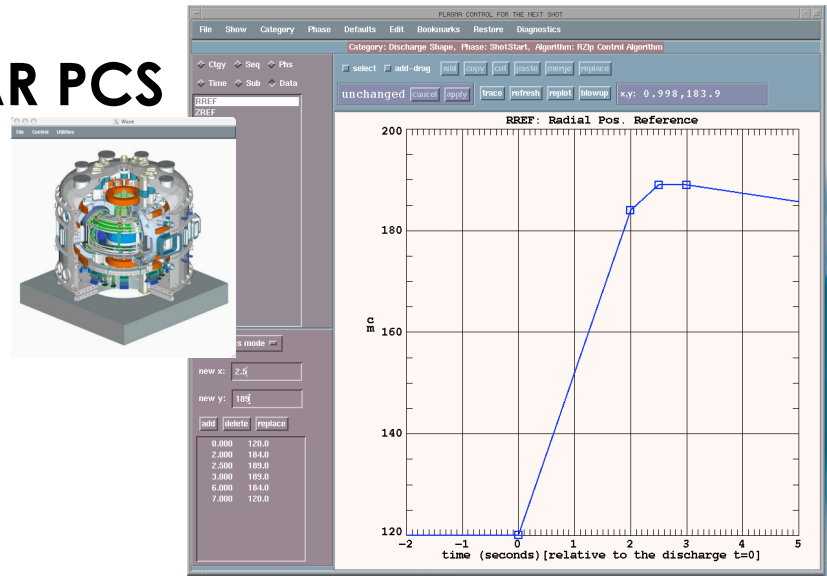


The Complete TokSys Control Development Toolset was Delivered with the KSTAR PCS

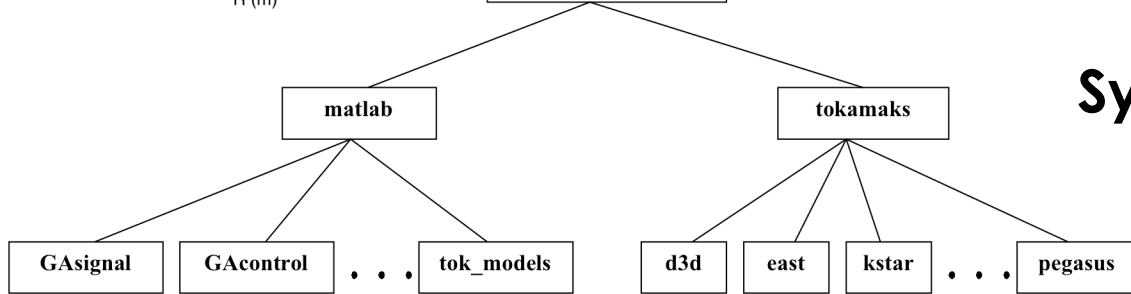


Electromagnetic Models

KSTAR PCS

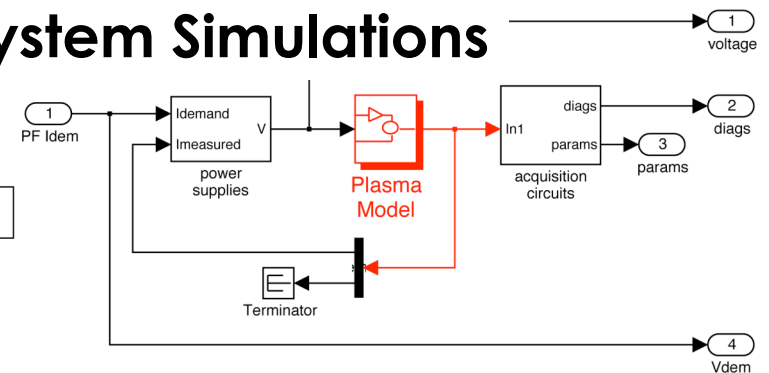


GATOOLS_ROOT

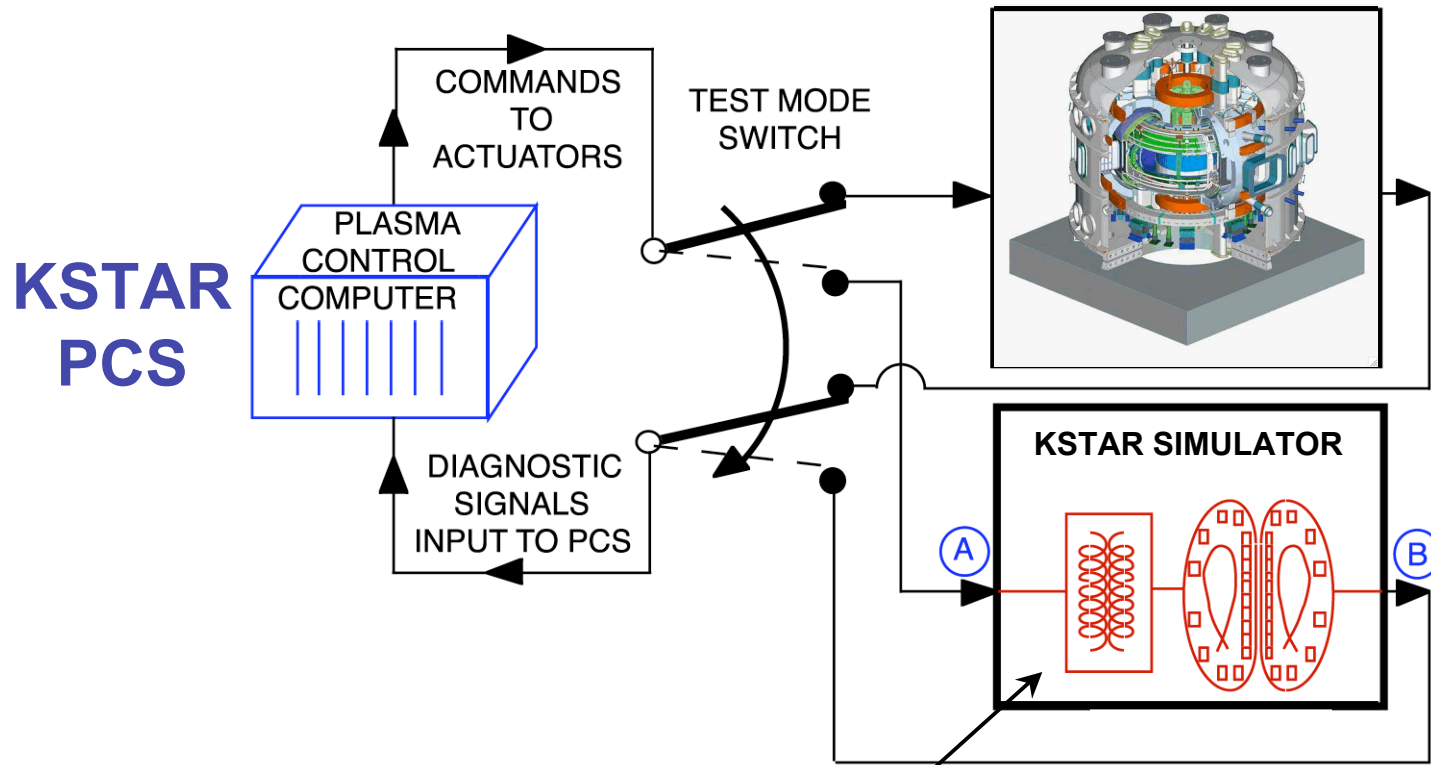


Analysis and Control Design Tools

System Simulations



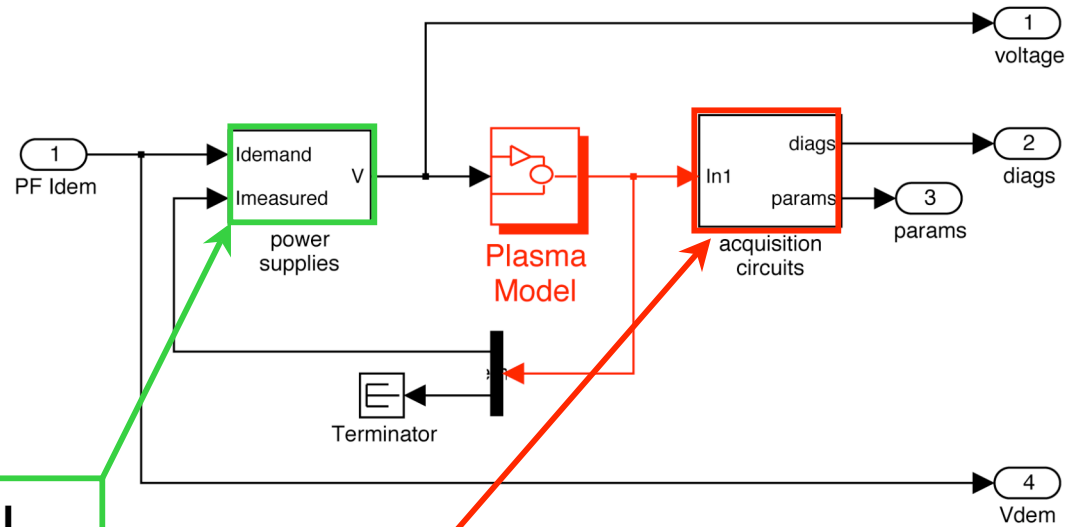
Simulations Allowed Testing of KSTAR Control Algorithms and Implementation Before Operation



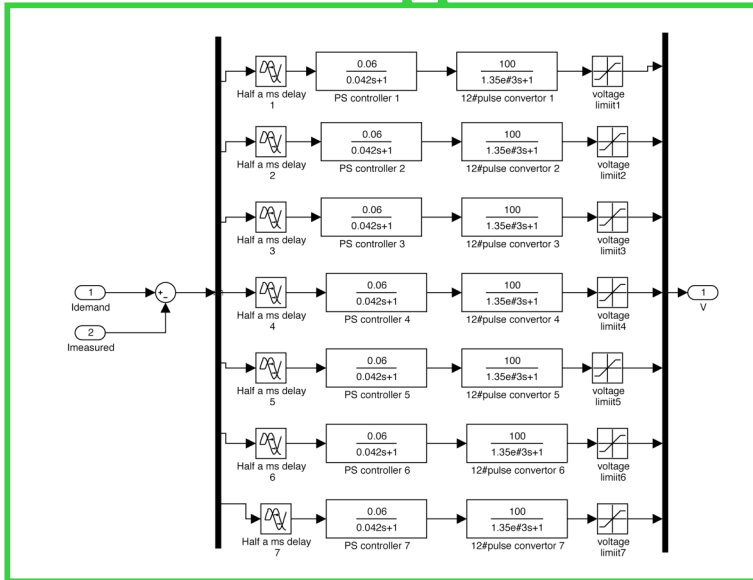
“Hardware-in-the-Loop” simulation used the KSTAR Simulator to verify actual implementation in KSTAR PCS

KSTAR Simulation Includes Power Supplies, Plasma-Conductor System, Filters, Noise Sources

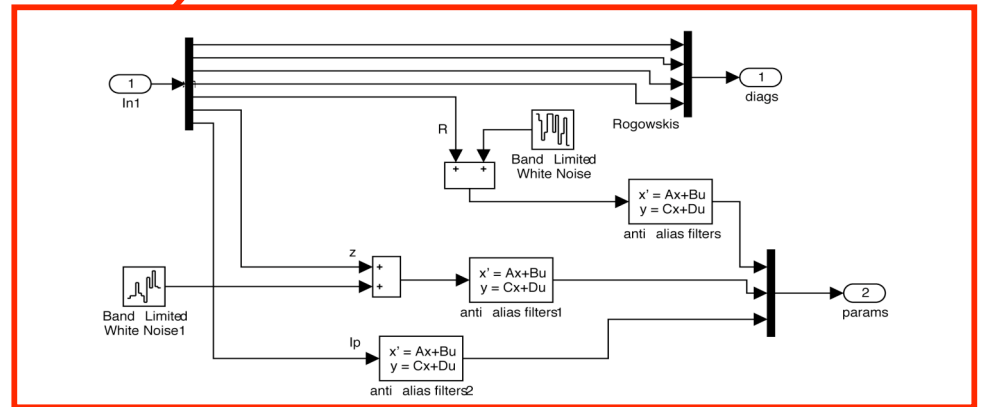
KSTAR Plasma-conductor system



PF Power Supplies



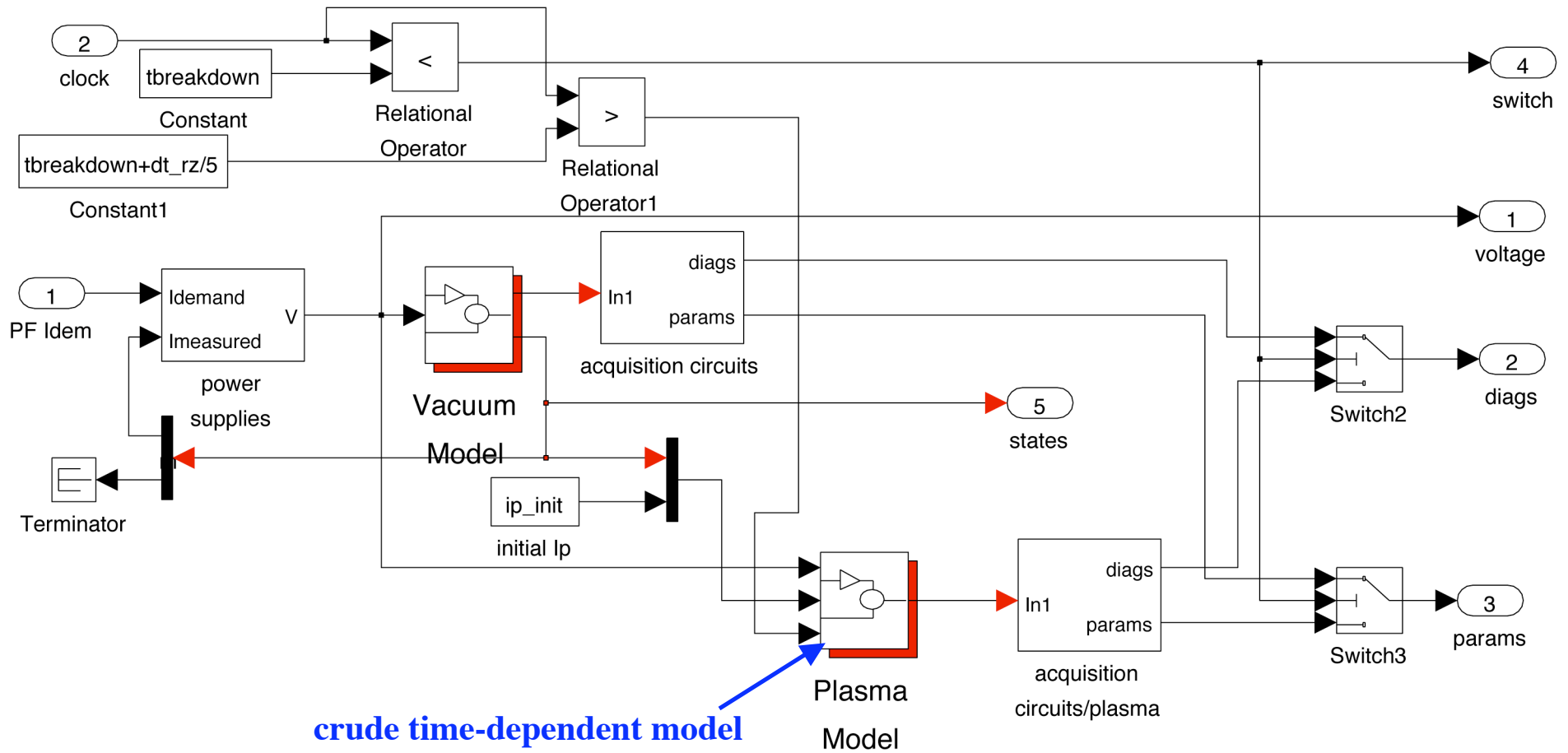
Acquisition circuits



Applications Before and During First KSTAR Campaign

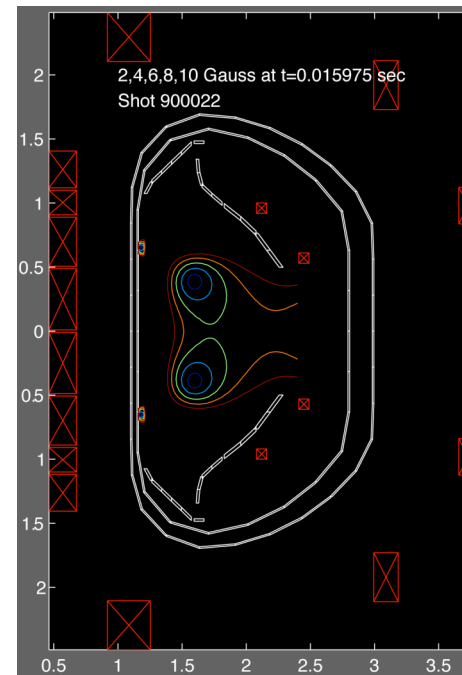
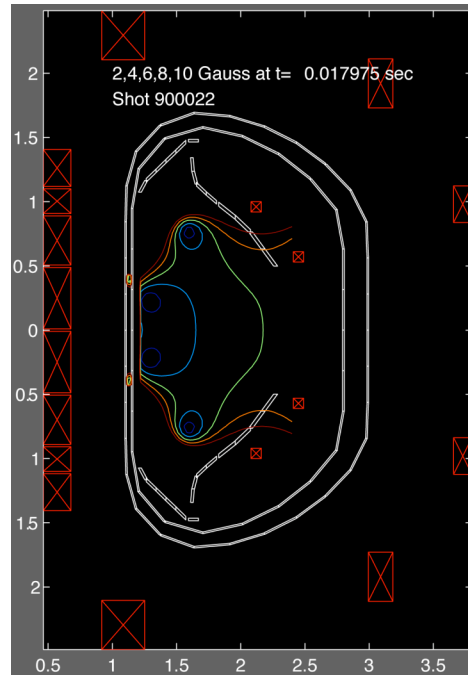
- **Testing of all control algorithms and PCS implementation before use in KSTAR commissioning and plasma operation**
- **Initial breakdown and rampup scenario analysis**
- **Shape control development**
 - Calculation of feedforward PF coil current trajectories.
 - Calculation of estimators for R and Z position to use in PCS
 - Development/Evaluation of control gains to use in PCS
- **Post-shot data analysis tools**
 - Vacuum field reconstruction, including effects of vessel currents and magnetic materials
 - Time-dependent simulation to infer vessel currents
 - JFIT reconstruction of plasma equilibria
 - Analysis of magnetic diagnostics, with feedback to calibration efforts
 - Vertical growth rate fitting

Simserver Simulation for Breakdown/Rampup



crude time-dependent model of growing plasma

Simserver Simulations Enable Realistic Evaluation of System Capability for Breakdown



- **Simulation allows knowledge of vessel currents in field reconstruction**
- **Incoloy 908 magnetic material not yet incorporated into simulation models**
 - Finite element analysis developed by Dr. Yoon combined with vacuum models to provide guidance for KSTAR breakdown experiments.

Use of TokSys in Support of Upcoming KSTAR Campaigns



Preparation for FY2009 Campaign

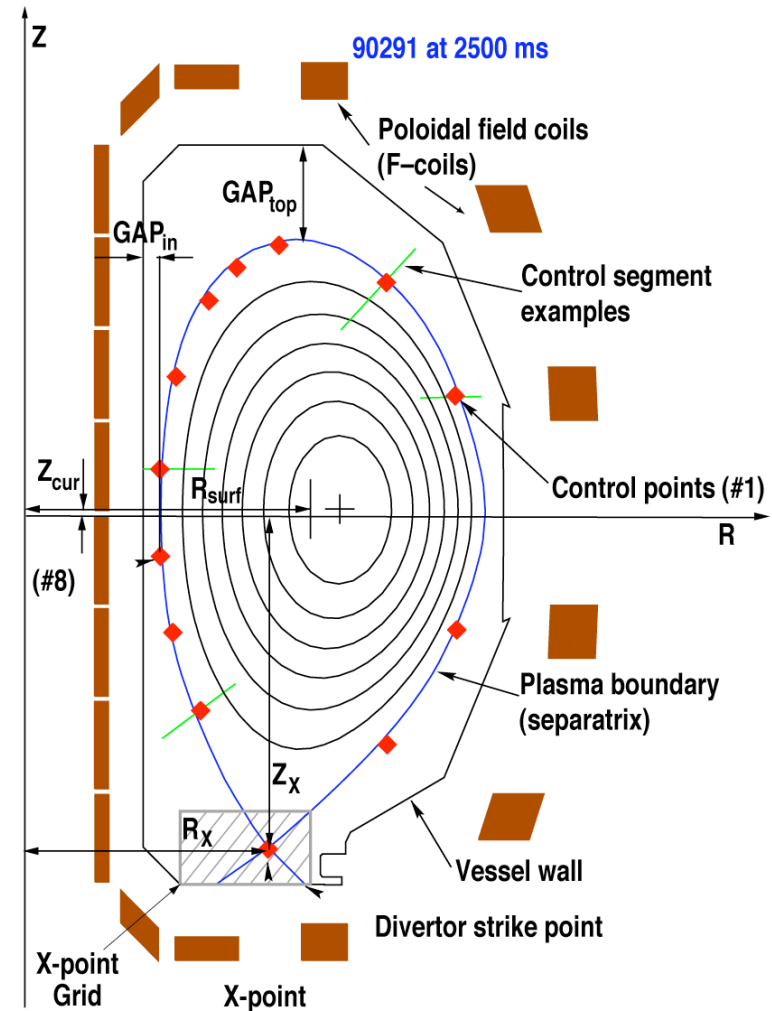
- **Analysis of vertical control growth rates for PS specification**
- **Support of magnetics analysis**
 - Embedding Yoon FE tools into TokSys
- **Algorithms for dealing with current cross-over in real-time control**
- **Physics operator training/discharge preparation using simserver simulations**
 - New operators gain experience in programming a discharge
 - Experienced operators develop and evaluate shape estimator data and feedback control gains
- **Other Possibilities ...**
 - Evaluation of passive plate shielding and controllability
 - Participate in magnetic materials experiment design and analysis
 - Participate in planning of control experiments

Preparation for FY2010 Campaign

- **Development and evaluation of vertical control algorithm in PCS**
- **Development and implementation of isoflux control**
 - Verify proper execution and good reconstruction of RTEFIT
 - Development of feedback control gains
 - Verify implementation in PCS with simserver simulations
- **Magnetics characterization - non-symmetric configurations**
 - Finer control requires more detailed understanding of magnetics
- **Other possibilities (develop control models, controllers, simulation) ...**
 - Beam control feedback (beta control)
 - ICRF coupling control
 - Real-time control of ECH deposition by plasma position
 - Puff and pump density control

Incorporation of Real Time EFIT and Isoflux Control Planned for KSTAR PCS v.3.0

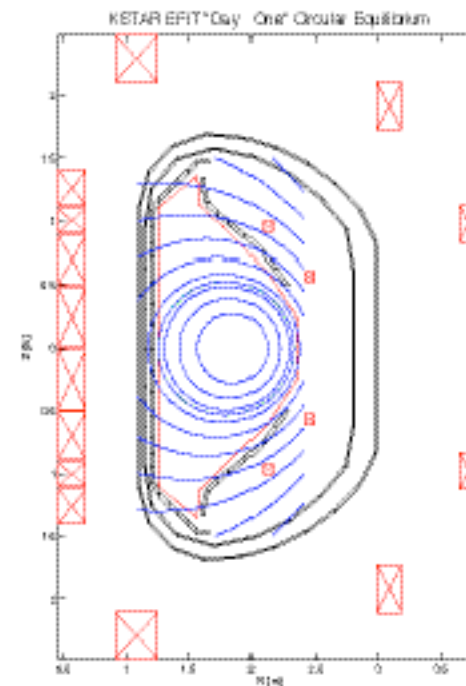
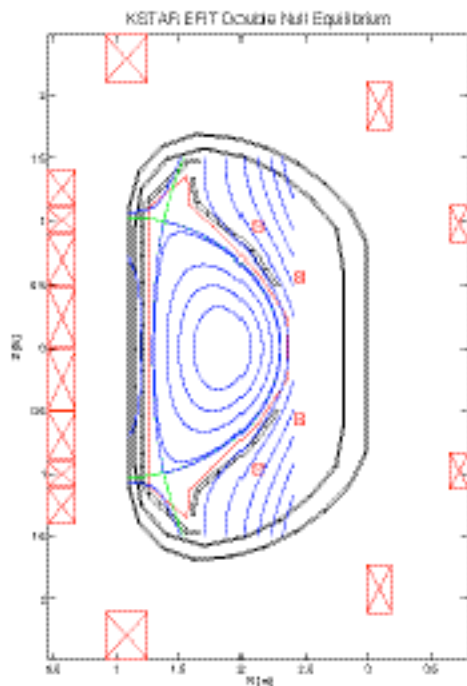
- Realtime EFIT reconstruction accurately calculates flux near plasma boundary
- Flux at control points controlled to equal X-point flux
- X-point grid allows accurate calculation and control of X-point location
- Standard PID or MIMO control operates on flux & X point errors to drive PF coils



Backups

KSTAR Plasma Response Model Starts with a KSTAR EFIT Equilibrium

- KSTAR EFIT constructed at GA from standard EFIT distribution
- Diagnostic set reflects our best understanding of present KSTAR configuration, with revisions needed to ensure robust convergence
- DND & “Day-One” circular plasmas generated for control modeling
- KSTAR EFIT available for use at GA or in collaboration with KBSI



Linear Axisymmetric System Model Constructed from Faraday's Law Circuit Equations

- Linear circuit equation formalism describes either **rigid** (1-2 plasma degrees of freedom) or **nonrigid** (all fluid elements free to move) plasma models:

Plasma response: flux change ψ_s at conductors due to displacement vectors ξ_z, ξ_R of fluid elements

Conductor current equation:

$$M_{ss} \dot{I}_s + R_{ss} I_s + M_{sp} \dot{I}_p + \frac{\partial \psi_s}{\partial \xi_z} \dot{\xi}_z + \frac{\partial \psi_s}{\partial \xi_R} \dot{\xi}_R = V_s$$

Plasma fluid element equation (resistive magnetic diffusion):

$$M_{pp} \dot{I}_p + R_{pp} I_p + M_{ps} \dot{I}_s + \frac{\partial \psi_p}{\partial \xi_z} \dot{\xi}_z + \frac{\partial \psi_p}{\partial \xi_R} \dot{\xi}_R = 0$$