OVERVIEW

DIII-D PLASMA CONTROL SIMULATION ENVIRONMENT

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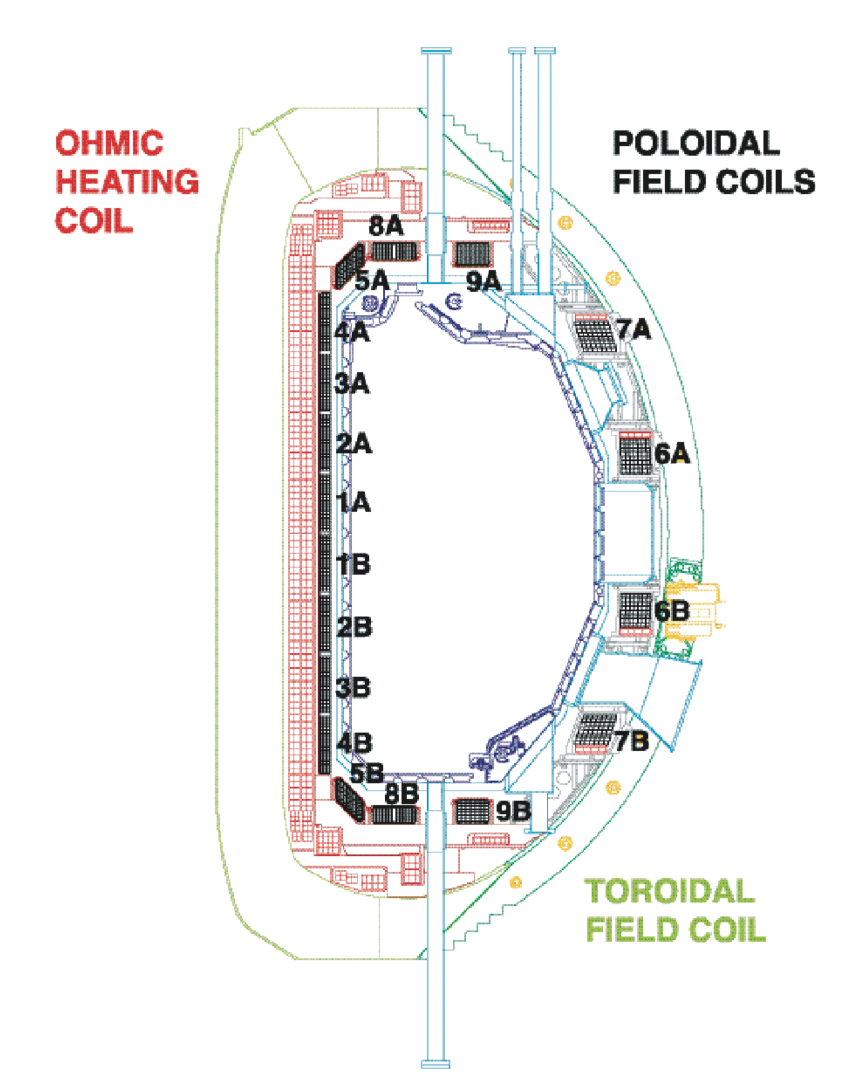
Abstract

Many advances have been made to the DIII-D plasma control simulation environment since the previously developed hardware-in-the-loop plasma shape simulation capability was reported. In the present paper we summarize the major improvements to this simulation environment, including, introduction of the non-linear plasma evolution code DINA. Comparisons with DIII-D experimental results are presented. Recent model developments in advanced neoclassical tearing mode (NTM) and resistive wall mode (RWM) control are presented.

OUTLINE

- o INTEGRATED PLASMA CONTROL MODELING APPROACH
  - DIII-D SIMULATOR ARCHITECTURE & ENVIRONMENT
  - MODEL ATTRIBUTES: PHYSICS BASED, MODULAR, VALIDATED
  - LINEAR PLASMA MODEL
- o DINA PLASMA MODEL
- o NON-AXISYMMETRIC MHD MODELING
  - NTM SUPPRESSSION MODELING
  - RWM DETECTION/ SUPPRESSION
- o SUMMARY / CONCLUSIONS

DIII-D Tokamak Coil System



SIMULATION ENVIRONMENT: LINEAR MODEL VALIDATION

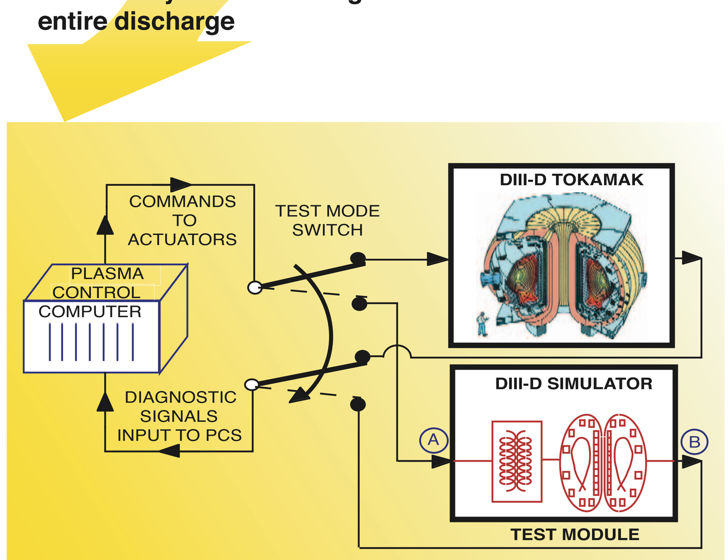
Advanced Controller Design and DIII-D Simulator Improve Performance and Add Flexibility

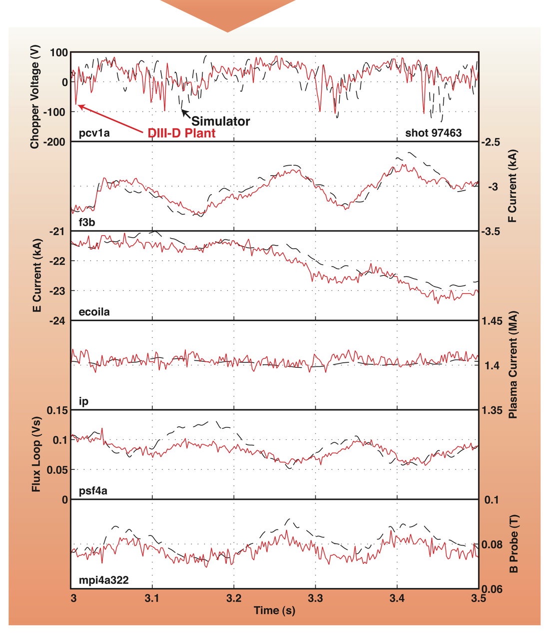
Advanced shape controllers are designed and implemented within the PCS

- o Multiple-Input-Mulitple-Output (MIMO) design
- o Completely model-based design technique
- o Design and testing can be done off-line
- o Preliminary results show good control over entire discharge

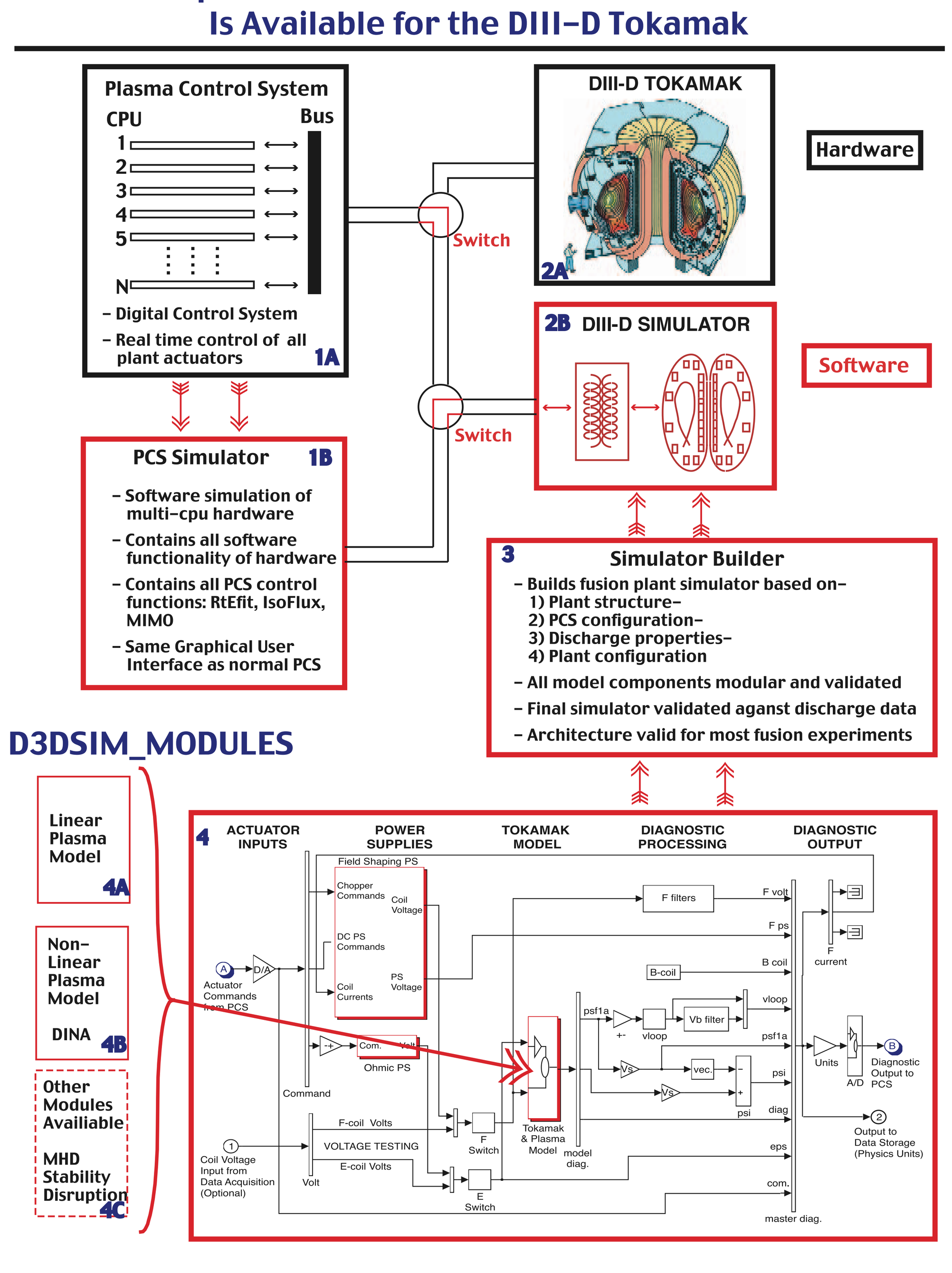
A complete simulator of the DIII-D plant has been developed

- o Models power supplies, coils and plasma
- o Runs in parallel with actual PCS in place of DIII-D
- o Excellent agreement is seen between experimental results and simulator

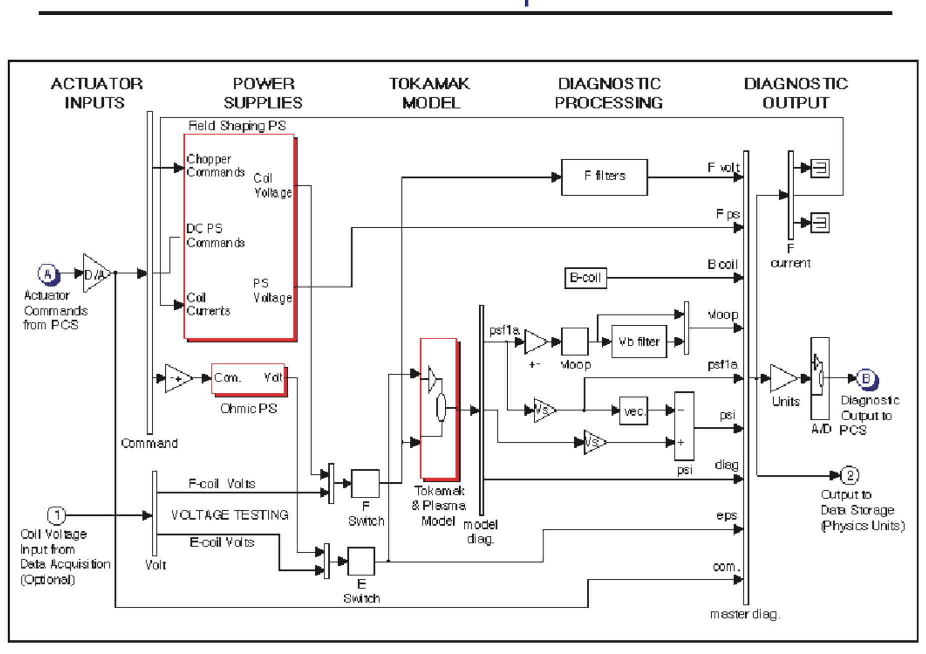




A Complete Modular Simulation Environment Is Available for the DIII-D Tokamak



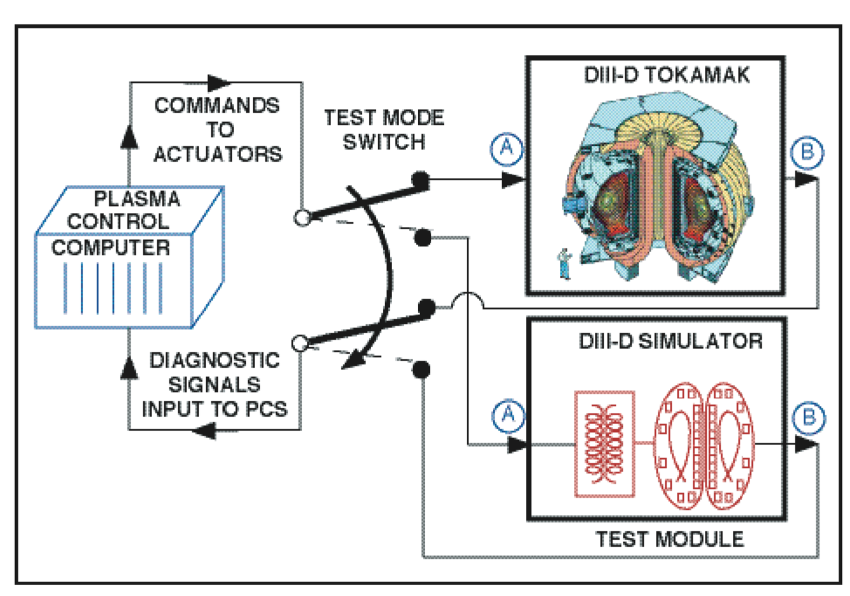
DIII-D Simulator Is Developed in Simulink™



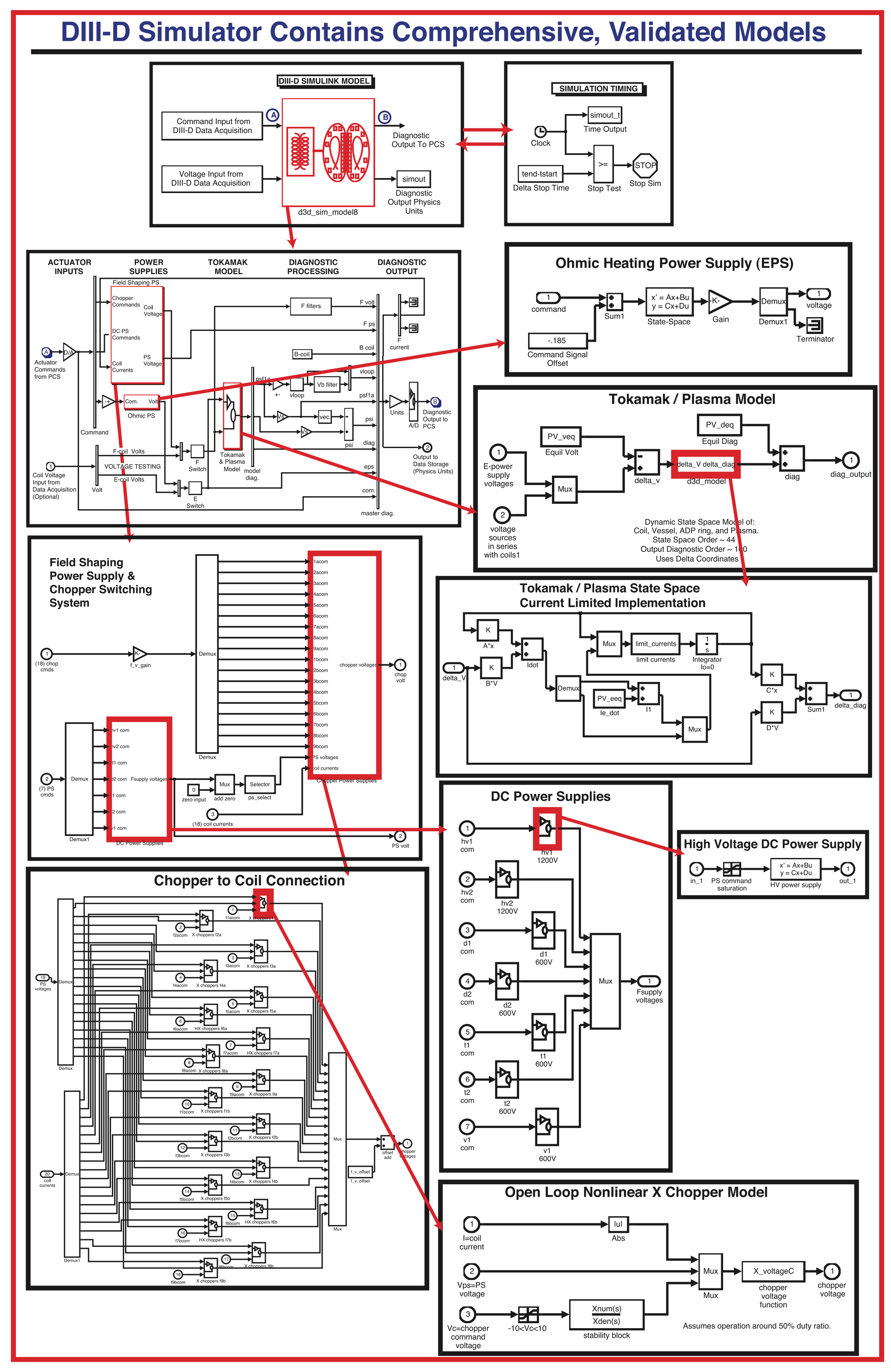
- Simulation model running in the MATLAB/SIMULINK™ environment has been in use for several years at DIII-D.
- This model (with linearized plasma response) has been extensively tested & validated:
  - acquired shot data injected at port A
  - modeled output from port B and actual diagnostic output compared
- Tokamak & Plasma Model block now can use DINA nonlinear plasma evolution code.

Simulator is Plug Compatible with DIII-D and Is Run in Closed-Loop with the Actual Plasma Control Hardware

- Stand-alone simulation executable module is generated from validated SIMULINK™ model using MATLAB Real Time Workshop™.
  - This module is called a SIMSERVER (SIMulation SERVER).
- Simserver simulation operates in Closed Loop with the PCS just like normal DIII-D experiment.
  - Vertical stability is provided by the PCS.
  - Allows testing of control algorithms without need for experimental time.

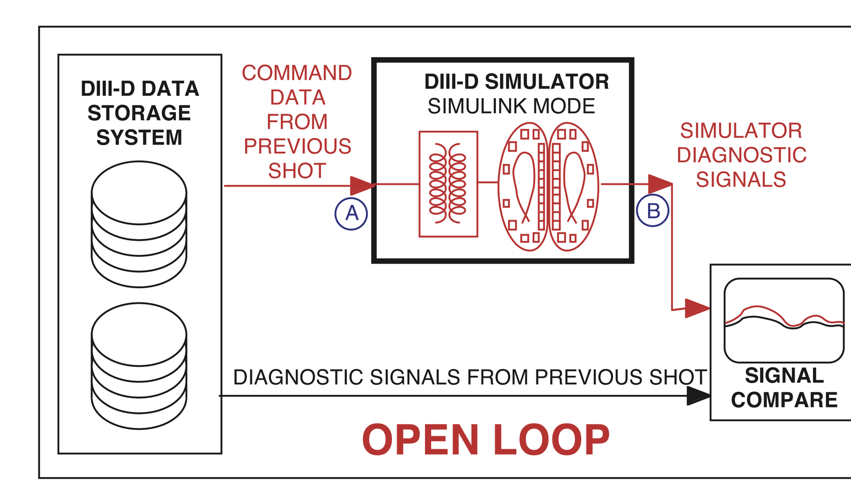


DIII-D Simulator Contains Comprehensive, Validated Models



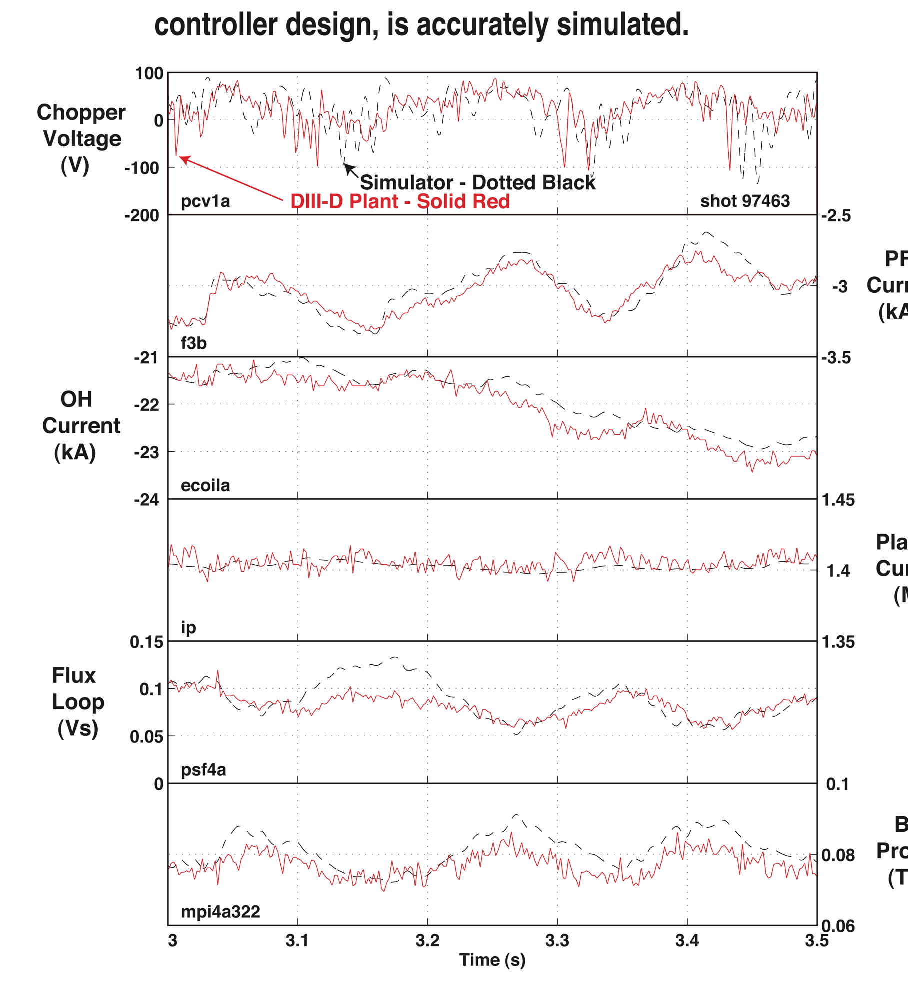
Each Simulator is Validated by Comparing Simulation and Experimental Data

- Execute in SIMULINK™ environment
- Operation in Open Loop
  - ➔ In this configuration the system is unstable to vertical motion and is stabilized with an internal feed back loop.
- Measured experimental data drives simulation
  - ➔ Either power supply voltage or power supply commands can be input.
- Simulated data is compared with data acquired from shot.



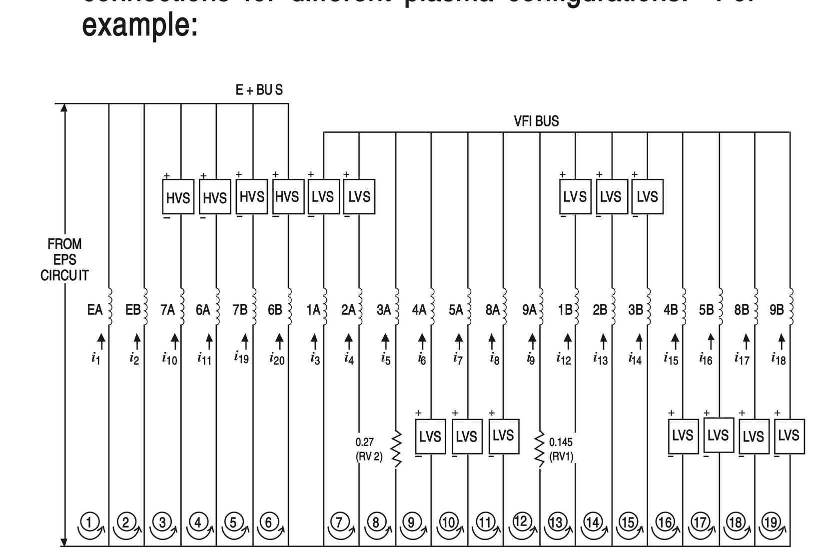
Simulator Accurately Models the DIII-D Plant

- Predictions of the coil currents and diagnostic output are typically within 10% of the actual DIII-D data over a 0.5 - 1s time period. Dynamic response, which is important for controller design, is accurately simulated.



DIII-D Is Reconfigured on Daily Basis and Simulators are Built Based on Each Configuration

- DIII-D uses a "patch panel" to change poloidal coil connections for different plasma configurations. For example:



HVS = High Voltage Supplies, LVS= Low Voltage Supplies, EPS = Ohmic Coil (E-coil) Power Supply, VFI = Return current bus

- Model is dynamically configured to emulate DIII-D circuit for a particular shot. Includes:
  - linearized or nonlinear (DINA) plasma
  - highly nonlinear power supplies
  - large, complex set of circuit equations for shaping coils and passive elements

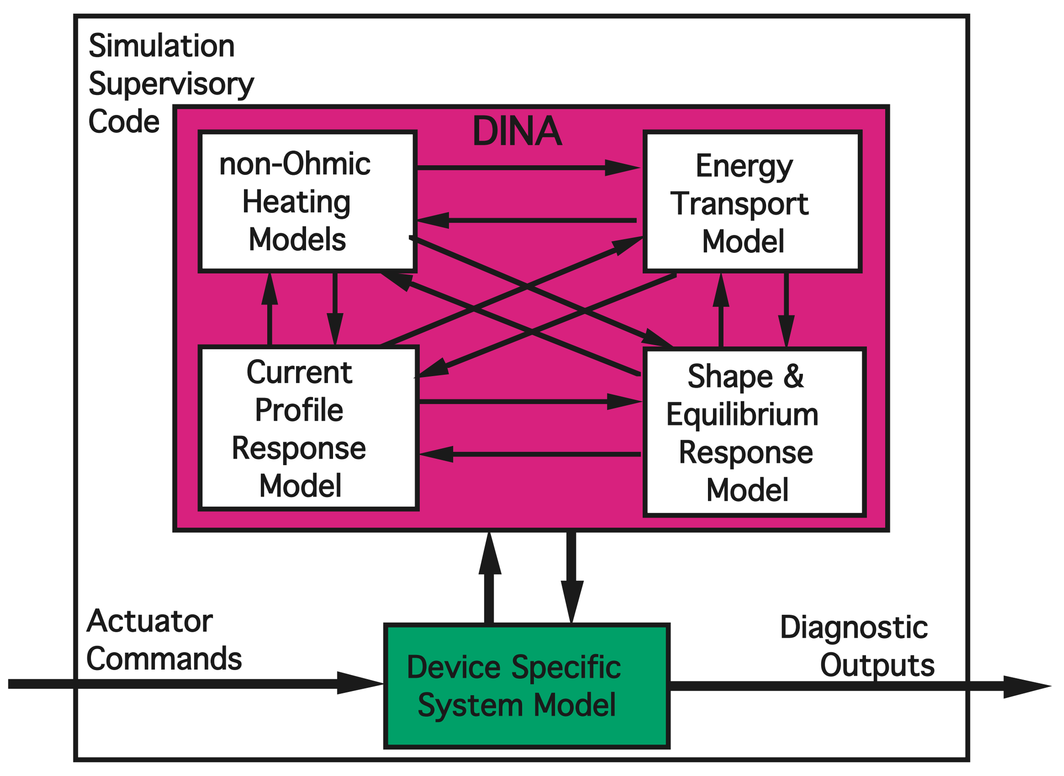
DINA IMPLEMENTATION

DINA is a 1-1/2 D Axisymmetric, Time-Dependent, Resistive MHD and Transport-Modeling Plasma Simulation Code

- **Grad-Shafranov equation solved each time step as plasma current and conductor currents evolve according to Ohm's law in each medium.**
- **"Inverse variable" equilibrium calculation for determining mapping between equilibrium flux coordinates and (2-D) grid allows rapid and accurate convergence.**
- **Simplifying assumptions and modeling choices:**
  - Massless, inviscid plasma;
  - 1-D flux surface-averaged particle/energy transport and magnetic diffusion;
  - Neoclassical plasma resistivity;
- **Control, shaping, equilibrium evolution, and disruption behavior benchmarked against DIII-D experimental data.**

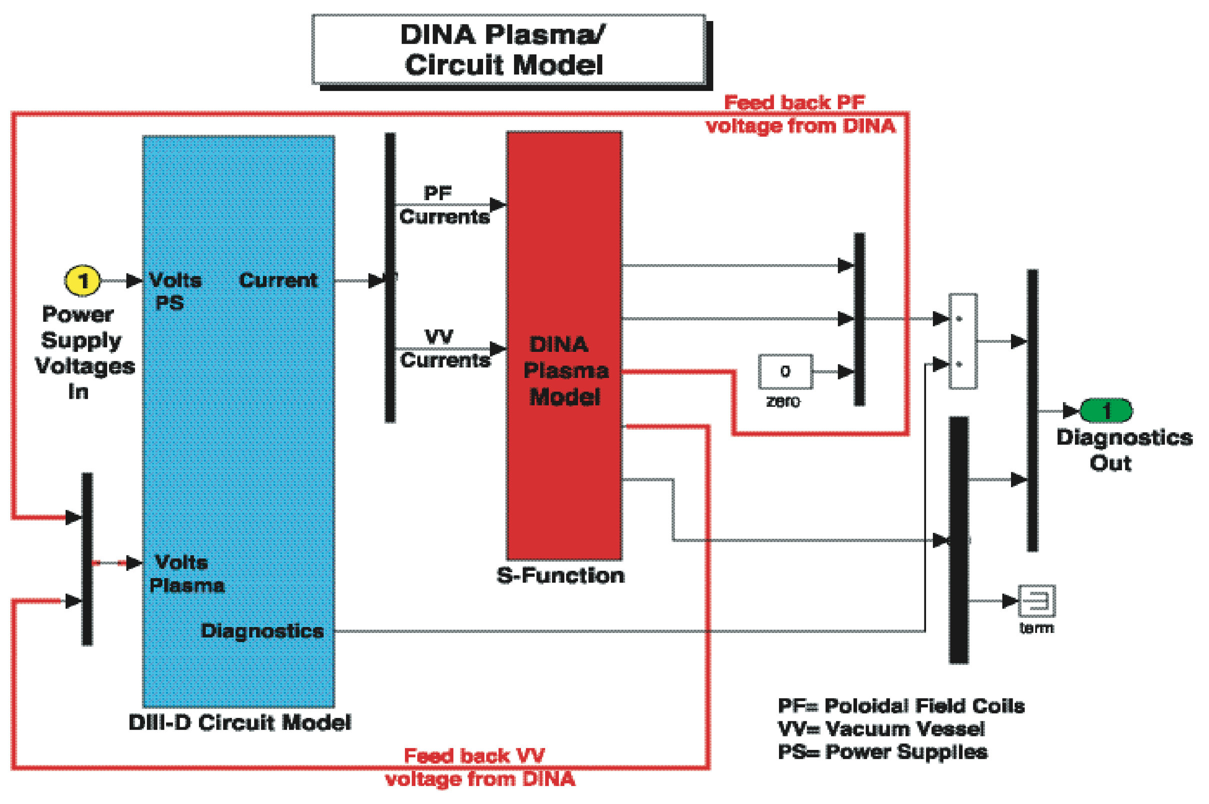
TRINITI

"Block-Centric" Simulation Architecture Provided by SIMULINK™ Is Critical for Multi-Institutional Development



- Block Centric Model Development: Each model block defines it's own inputs, outputs, and time evolution behavior.
- Model block developer provides input specifications:
  ➔ What's needed for block execution?
- Other (collaborator) block developers provide output specifications:
  ➔ What's needed from that block as input to other blocks?

DINA Module and DIII-D Circuit Model Evolve Using a Feed Back Architecture



- Each module evolves separately in time. Simulink™ advances the system using feed back loops to pass IO between modules.
- PF & vessel currents are passed to the DINA module. Voltages on the coils from the plasma are passed to the DIII-D circuit model.
- Either the linearized plasma model or the Non-Linear DINA module runs in the DIII-D simulation environment.

"Block-Feedback" Architecture Allows Separation of Device Specific and Plasma Response Models

Example 1: Rigid response model (subscripts: s=stabilizing conductors, p=plasma):

$$M_{ss}\frac{dI_s}{dt}+R_sI_s+\frac{\delta\psi_s}{\delta z_c}\frac{\delta z_c}{\delta I_s}\frac{dI_s}{dt}+\frac{\delta\psi_s}{\delta R_m}\frac{\delta R_m}{\delta I_s}\frac{dI_s}{dt}+M_{sp}\frac{dI_p}{dt}=V_s$$

$$L_p\frac{dI_p}{dt}+R_pI_p+\frac{\delta\psi_p}{\delta R_m}\frac{dR_m}{\delta I_s}\frac{dI_s}{dt}+\frac{\delta\psi_p}{\delta z_c}\frac{dz_c}{\delta I_s}\frac{dI_s}{dt}+M_{ps}\frac{dI_s}{dt}=0$$

(Disturbance terms have been neglected.)

Rewrite in feedback form to get Device Specific Block dynamics:

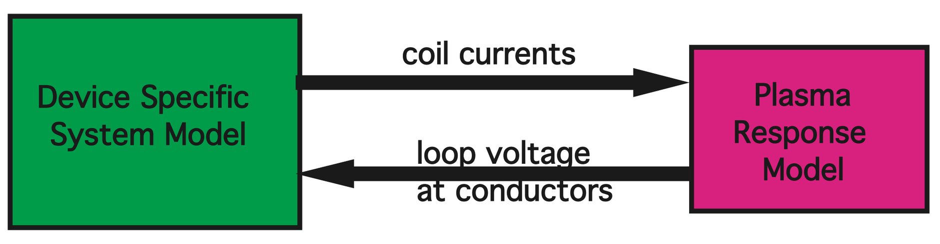
$$\frac{dI_s}{dt}=-M_{ss}{}^{-1}R_sI_s+M_{ss}{}^{-1}V_s+M_{ss}{}^{-1}V_{loop}$$

and Plasma Block dynamics:

$$\frac{dI_p}{dt}=-L_p{}^{-1}R_pI_p-L_p{}^{-1}\left(\frac{\delta\psi_p}{\delta R_m}\frac{dR_m}{\delta I_s}+\frac{\delta\psi_p}{\delta z_c}\frac{dz_c}{\delta I_s}+M_{ps}\right)\frac{dI_s}{dt}$$

$$V_{loop}=-M_{sp}\frac{dI_p}{dt}-\left(\frac{\delta\psi_s}{\delta z_c}\frac{\delta z_c}{\delta I_s}+\frac{\delta\psi_s}{\delta R_m}\frac{\delta R_m}{\delta I_s}\right)\frac{dI_s}{dt}$$

Example 2: DINA implementation in DIII-D simulation:

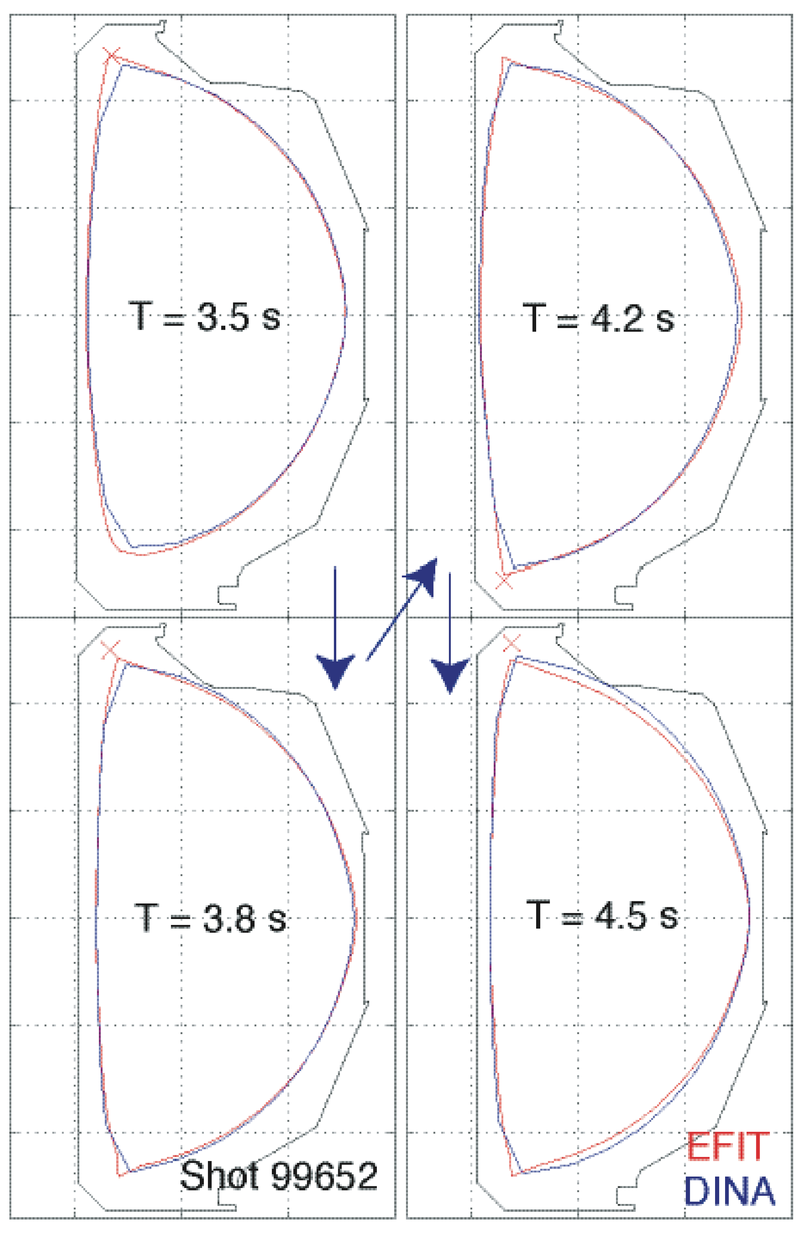


- coils
- power supplies
- vessel
- buss connections
- diagnostics
- acquisition circuits

- equilibrium
- profile evolution

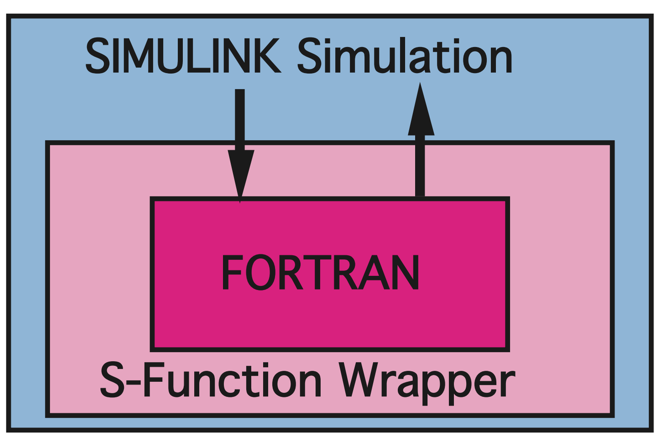
D3DSIM / DINA Shape Evolution Compares Well With EFIT Reconstruction

- Plasma is rigidly moved in the radial direction from 3.5 to 4.5s
- Small variations in shape are partially a consequence of lower resolution DINA grid and internal profile changes not modeled in DINA.



Legacy C and Fortran Code Like DINA is Implemented Using a S-Function Wrapper to Incorporate Into Simulation™

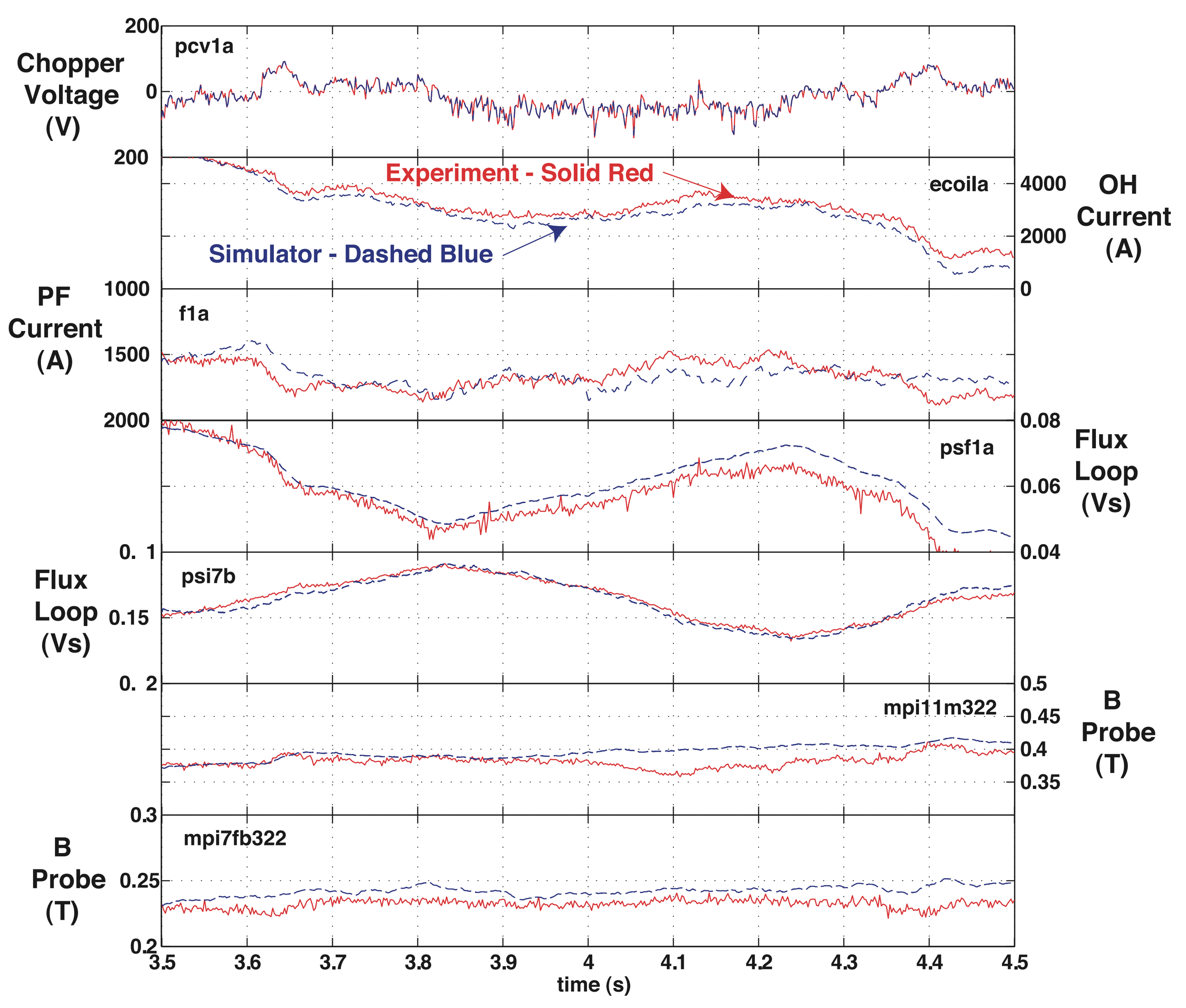
- DINA code remains in original FORTRAN.
  - SIMULINK™ S-function wrapper of DINA (written in C) provides I/O interface to simulation.



- SIMULINK™ S-functions provide easy method for incorporating legacy model codes.
- This is also important for multi-institutional collaboration.

DINA in the D3DSIM Environment Accurately Reproduces Experimental Diagnostic Signals

- **Shot has a preprogramed rigid radial plasma shift from 3.5 to 4.5 seconds using a sawtooth wave form.**
- **Simulation is initialized using an EFIT reconstruction at 3.5 s and evolution is through Ohmic current diffusion. Kinetic transport is not simulated.**

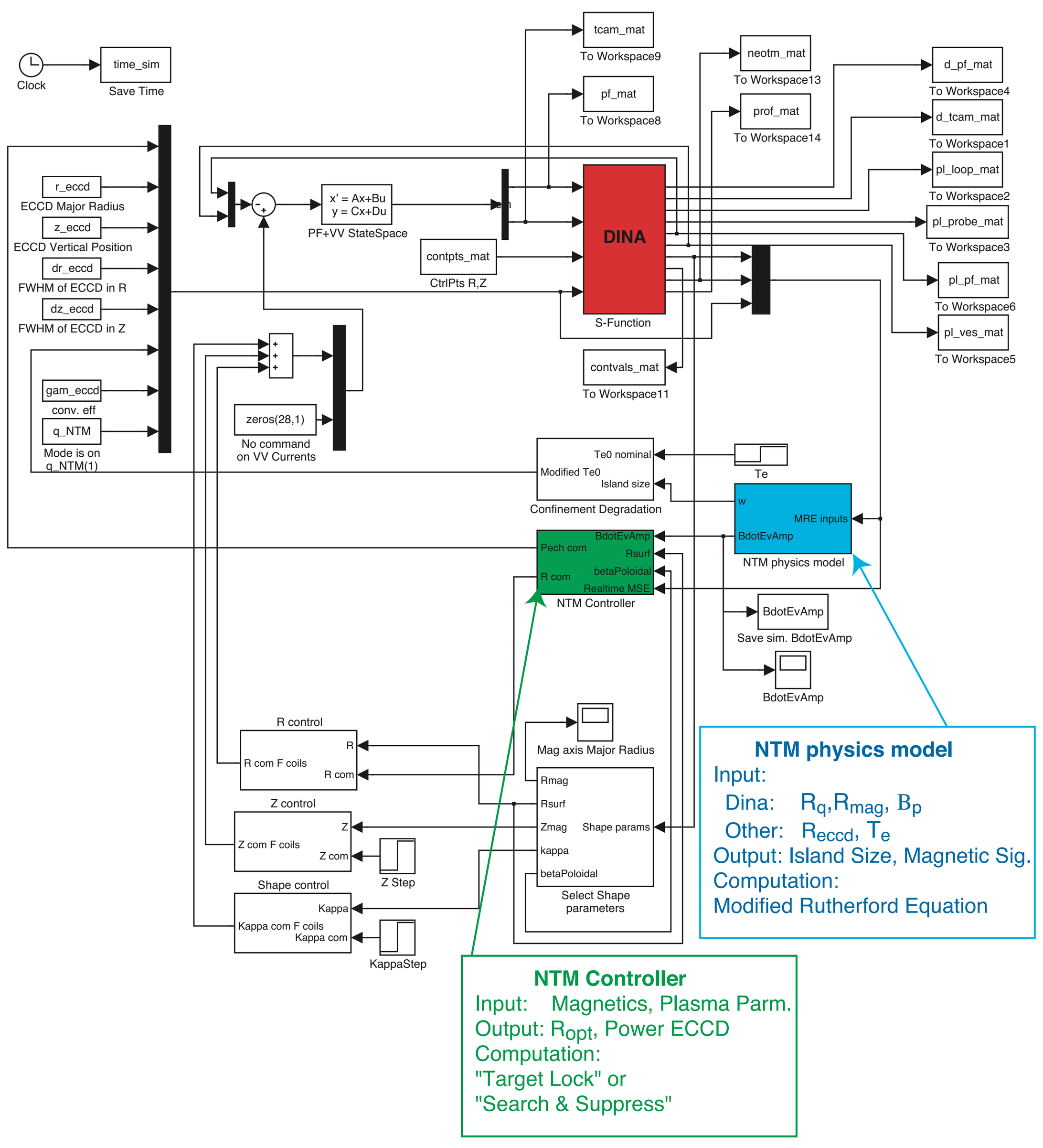


NONAXISYMMETRIC MHD MODELING

Controllers for Suppression of Neoclassical Tearing Modes Have Been Developed and Implemented on DIII-D Using Many of the Tools Developed for Axisymmetric Control

- Neoclassical Tearing Mode (NTM) suppression in DIII-D is achieved by the application of electron cyclotron current drive (ECCD) at the island location to replace missing bootstrap current which characterizes the mode.
  - Unstabilized NTM's degrade confinement and can cause disruptions.
- Model and control algorithms have been developed for active suppression of the MHD instabilities associated with RWM modes, using the framework and many of the tools developed for axisymmetric control.
  - DIII-D/DINA module is used for plasma characterization
  - Modified Rutherford Module describes NTM island dynamics.
  - Two NTM controllers have been designed and implemented and tested within the PCS:
    - Search & Suppress
    - Target Lock.
  - "First time use" of the controllers on DIII-D plasmas performed as predicted by modeling, showing the benefit of physics based simulation and the comprehensive testing environment available for controller development on DIII-D

NTM Controllers Have Been Developed Using Validated Simulation Tools



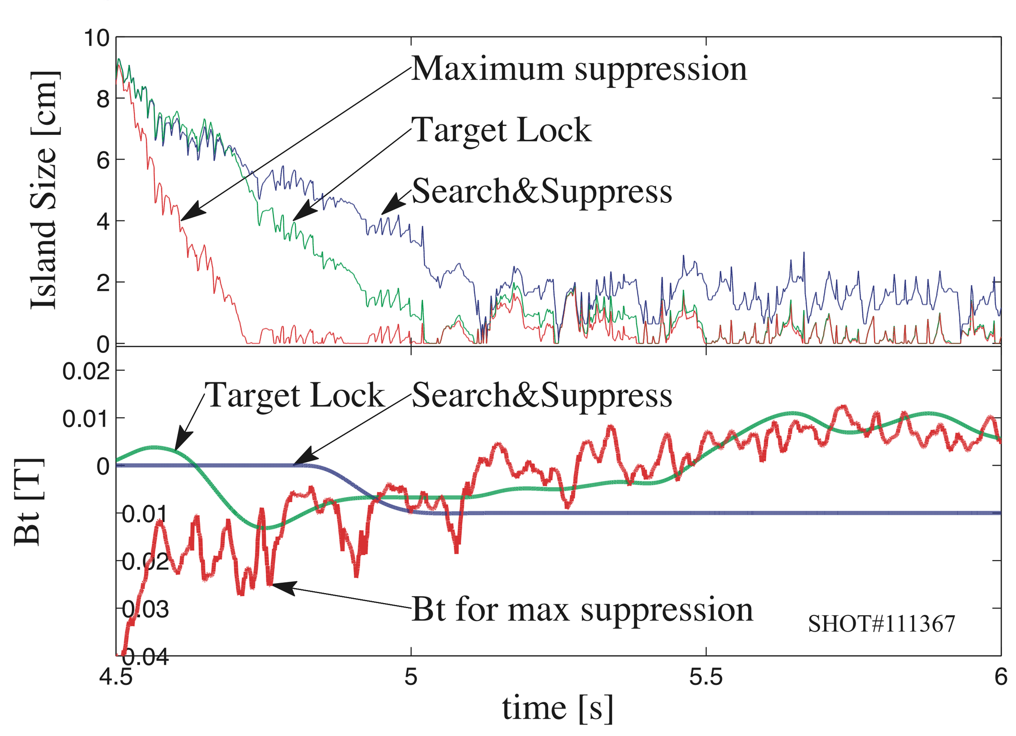
Target Lock Control Shows Superior NTM Supression Based on DIII-D Experimental Data

NTM Control Algorithms

Search & Suppress - Moves the plasma or adjusts B_t in discrete steps and monitors mode amplitude. Searches, dwells, and freezes based on mode amplitude and threshold settings.

Target Lock - Moves plasma or adjusts B_t using the mode amplitude dynamic response and the corresponding island response based on predictions of the Modified Rutherford Equation.

Maximum suppression - Assumes perfect ECCD depostion alignment with island location.

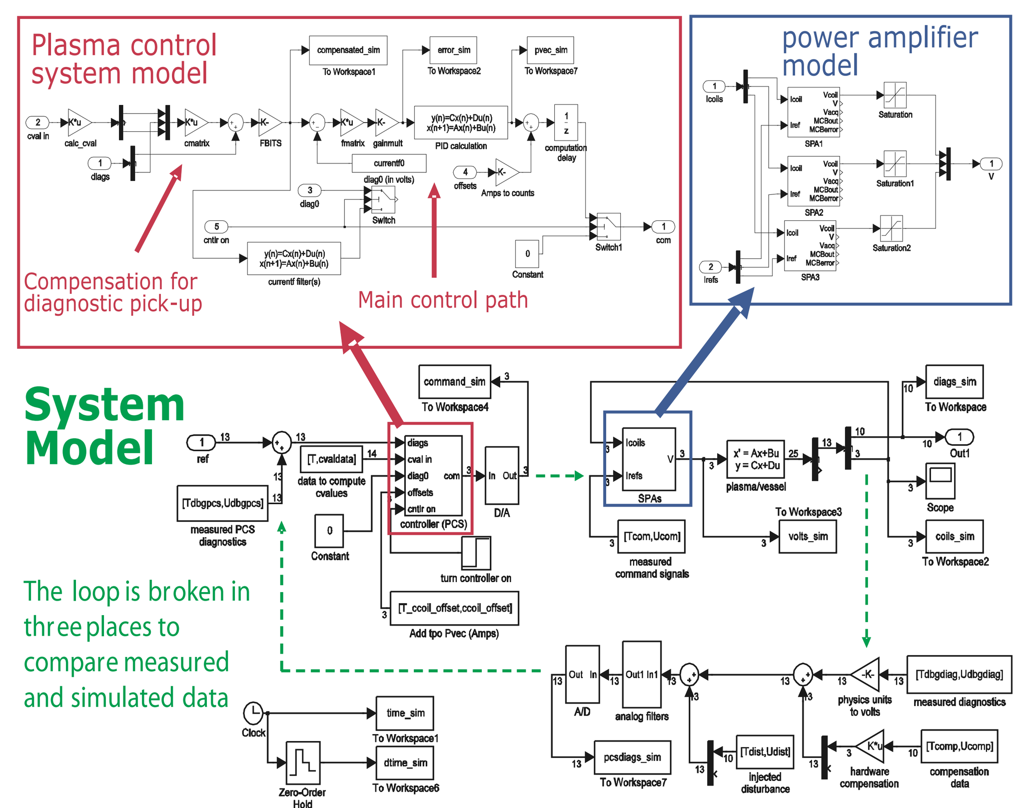


Resistive Wall Mode Control on DIII-D Has Been Simulated and Edge Localized Modes Shown to Be Important to Controller Stability

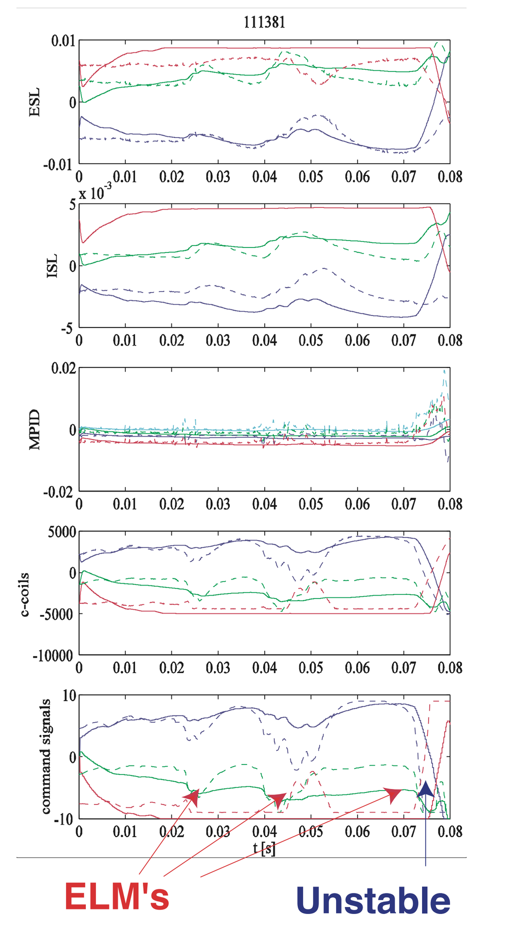
- Resistive Wall Modes (RWM) stabilization in DIII-D is provided by feedback control of non-axisymmetric coils configured to produce an n=1 magnetic perturbation in the plasma.
- A complete closed looped, physics based model of the system was developed
  - Complete model of non-axisymmetric coils, power supplies, and PCS control functions.
  - 3-D magnetics of DIII-D non-axisymmetric coils and vessel.
  - RWM mode identification using dynamic Kalman filter techniques for edge localized modes (ELM) rejection.
  - Closed loop simulation including validation with DIII-D data.
- Simulation showed that without ELM rejection the present control system can be driven unstable from ELM pickup in the diagnostic signals.

Closed Loop RWM Simulation Using DIII-D Data Shows ELM Rejection to be Important to Controller Stability

Closed Loop Simulation Model

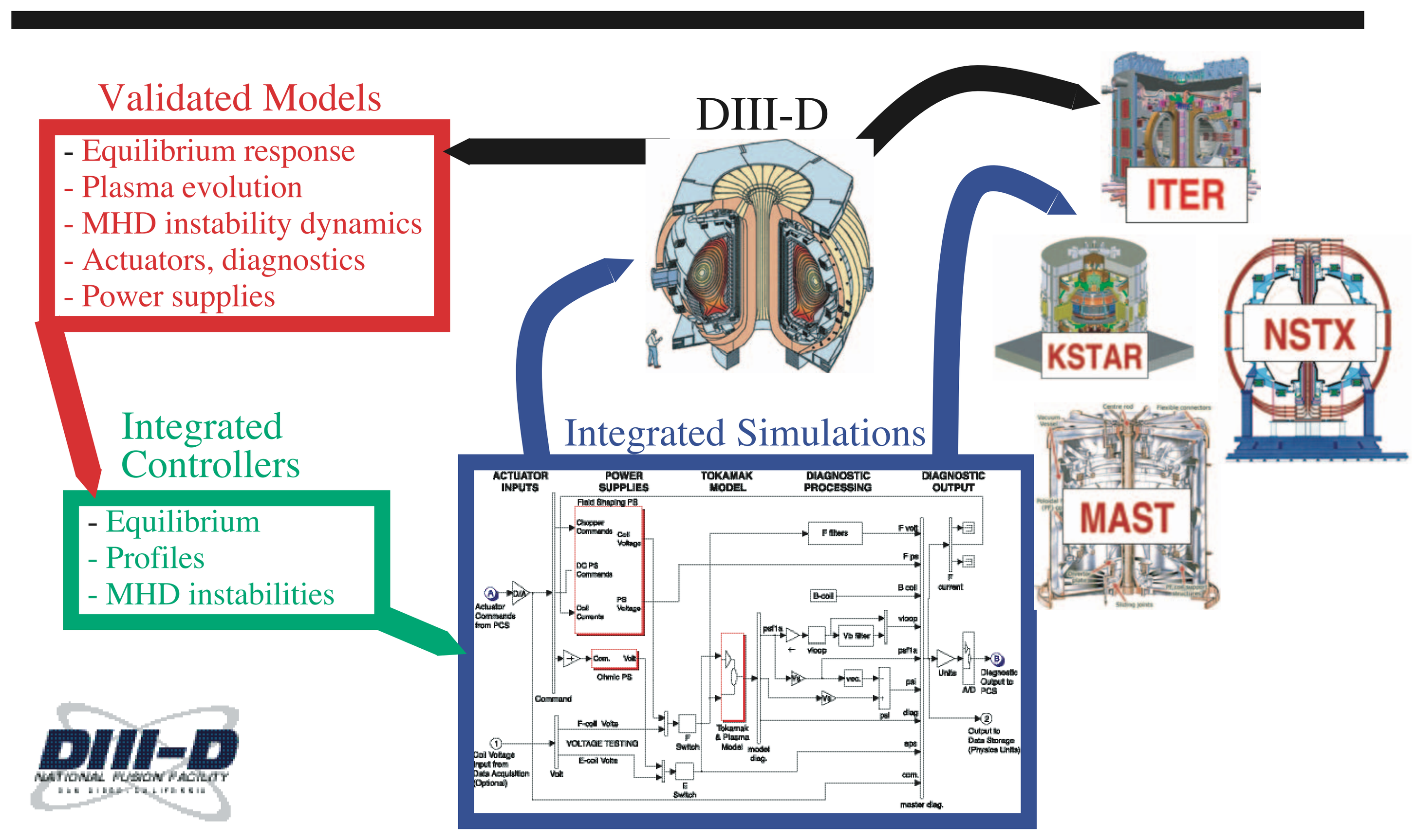


Validation with DIII-D Experiment



SUMMARY & CONCLUSIONS

Plasma Based Models Validated on DIII-D and Important for Control of Advanced Tokamak Plasmas are being Applied to Other Machines and to Next Generation Devices



Summary & Conclusions

- A comprehensive, physics based, integrated control environment exists for controller development on DIII-D. (See O1B-1 Humphreys)
- A software simulator of the DIII-D machine and PCS is available for closed loop simulation of the system.
  - This allows testing of controllers as implemented in the PCS without using experimental time.
- Both linear and non-linear (DINA) plasma models are validated with DIII-D experimental data.
- DIII-D tools are being used to develop control algorithms for suppression of non-axisymmetric MHD instabilities
  - Controllers for NTM suppression have been developed, validated, implemented and tested on the DIII-D machine with excellent performance.
  - Closed loop simulation of RWM control in use in DIII-D has been completed.
- The model based tools are modular and extensible to other devices and are being used to study control issues for other tokamaks. (See P2-52 Walker)