Nonlinear Simulation of DIII-D Plasma and Poloidal Systems Using DINA and SIMULINK®

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A hardware-in-the-loop simulation capability [L] previously developed for poloidal shape controller testing using Matlab® SIMULINK® has been upgraded by replacing the linearized plasma model with the DINA nonlinear plasma evolution code [K]. This upgrade expands the capabilities of the simulation beyond shape and position control to allow development and study of current profile control. Real time current profile information will soon be available in DIII-D using the Plasma Control System (PCS) real time EFIT [F] calculation, enabled by an ongoing upgrade of PCS hardware. The DINA code incorporates a model of electron cyclotron current drive (ECCD). Study of open loop (e.g.,[Lu]) and, more recently, closed loop [H] interaction of ECCD with DIII-D plasmas has been a major research thrust at DIII-D in the past few years. The enhanced SIMULINK® model allows complete simulation of the interaction of controls for poloidal plasma shape and current drive with a realistic, validated DIII-D systems model. We describe the incorporation of DINA into the SIMULINK® DIII-D tokamak systems model and results of validating this combined model against DIII-D data.

[L] J.A.Leuer, et.al., 18th IEEE/NPSS SOFE, Oct.25-29,1999, p.531-34
[K] R.R.Khayrutdinov,V.E.Lukash, J. Comput. Phys 109 **(1993) 193**
[F] J.R.Ferron,et.al., Nucl.Fusion vol.38, no.7, July 1988, 1055-1066
[Lu] T.C.Luce, et.al., General Atomics report GA-A23259
[H] D.A.Humphreys,et.al., Bull. Am. Phys. Soc. 46, 299 (2001)

OVERVIEW

- Simulator of the DIII-D poloidal field system has been used for several years to aid development of plasma control algorithms.
  - Simple linear plasma response model used to simulate global plasma motion.

- Simulator contains detailed coil, power supply and passive conductor models of the components of DIII-D plant.

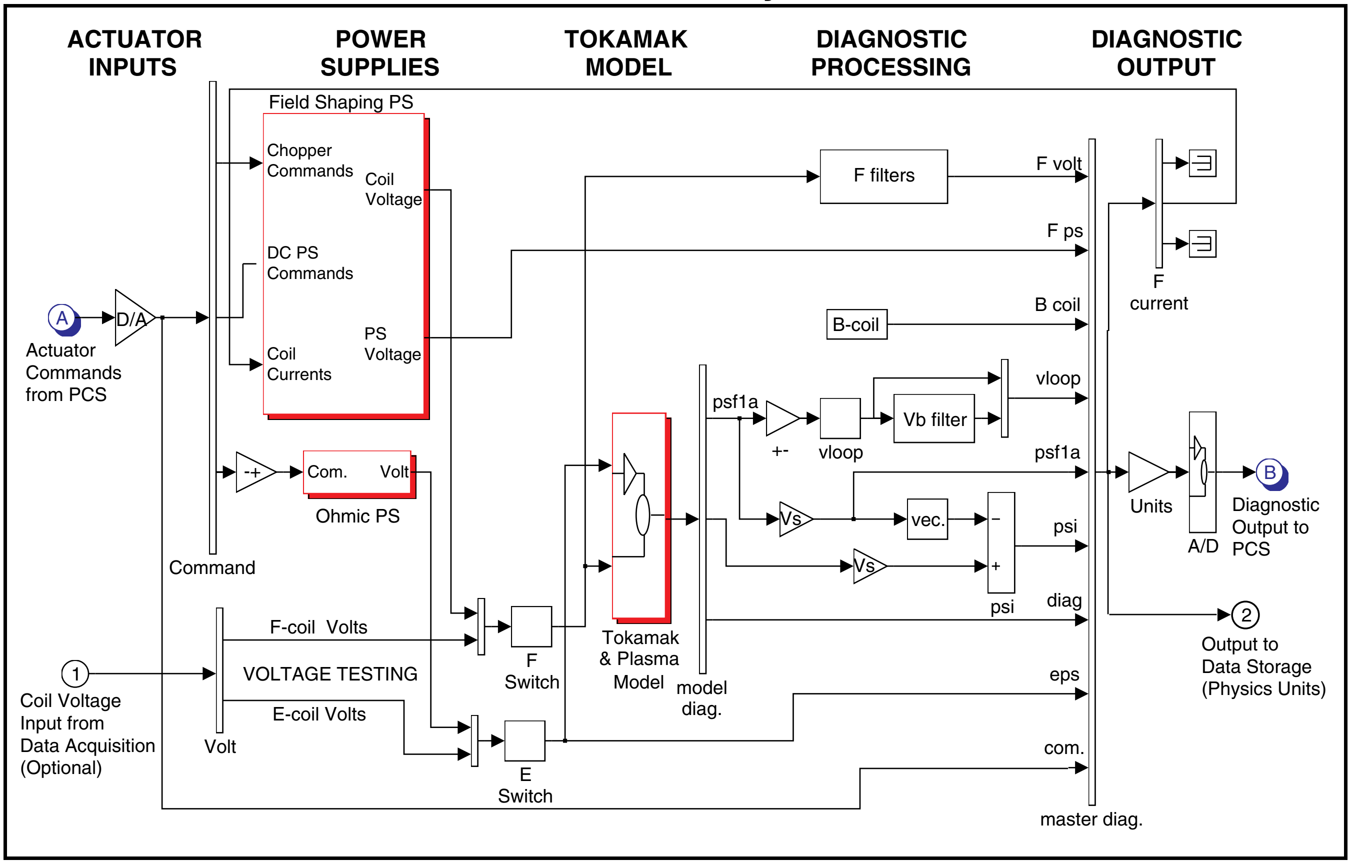
- Recent addition is use of nonlinear plasma evolution code DINA* in place of the linear plasma response model.
  - Validation of simulation with DINA nonlinear model is presented.

- A general architecture which facilitates collaborative model development is outlined.

*Developed by R.R.Khayrutdinov, et.al. at Triniti Labs.

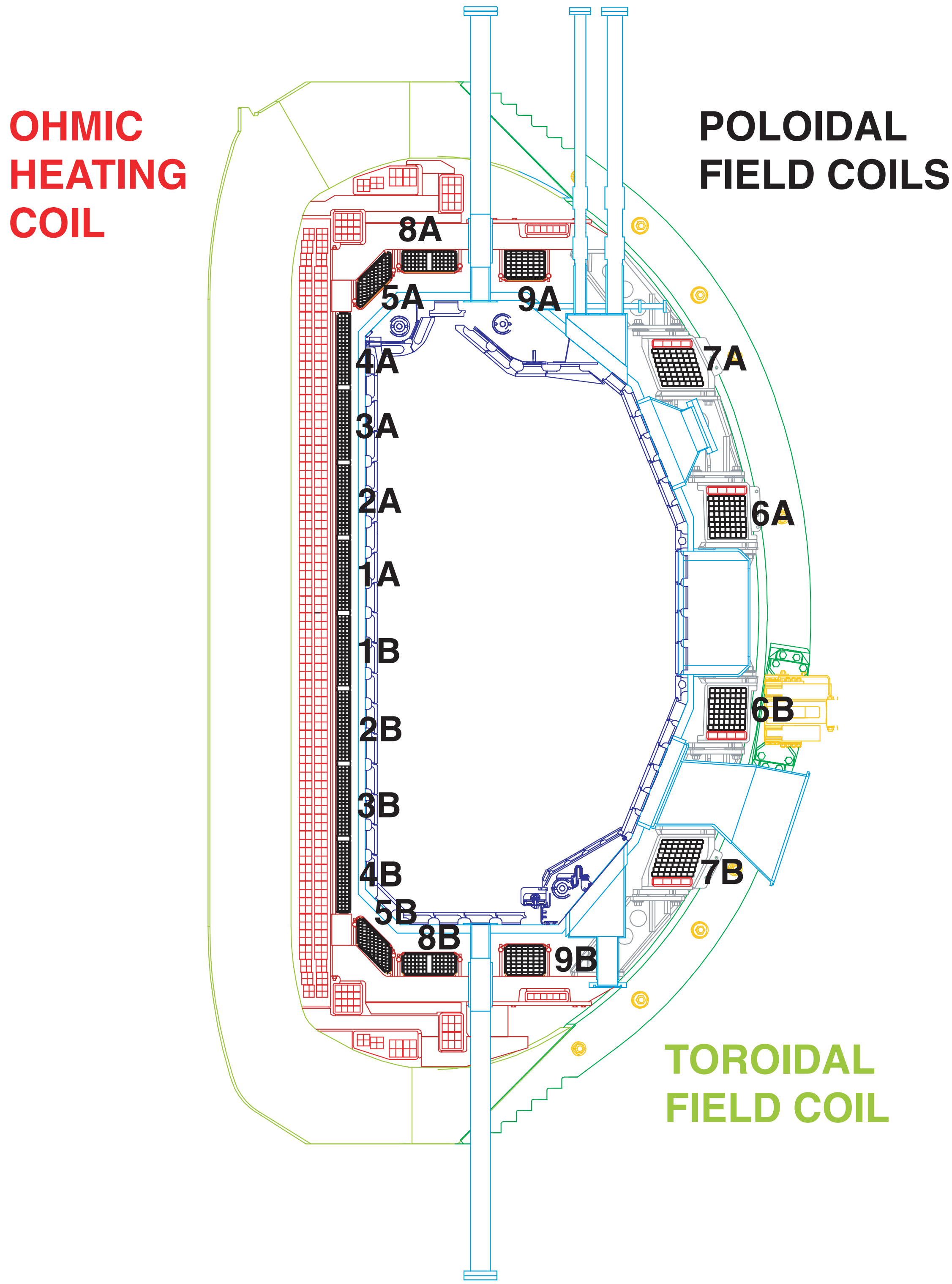
DIII-D Simulator

- Simulation model running in the MATLAB/SIMULINK™ environment in use for several years.



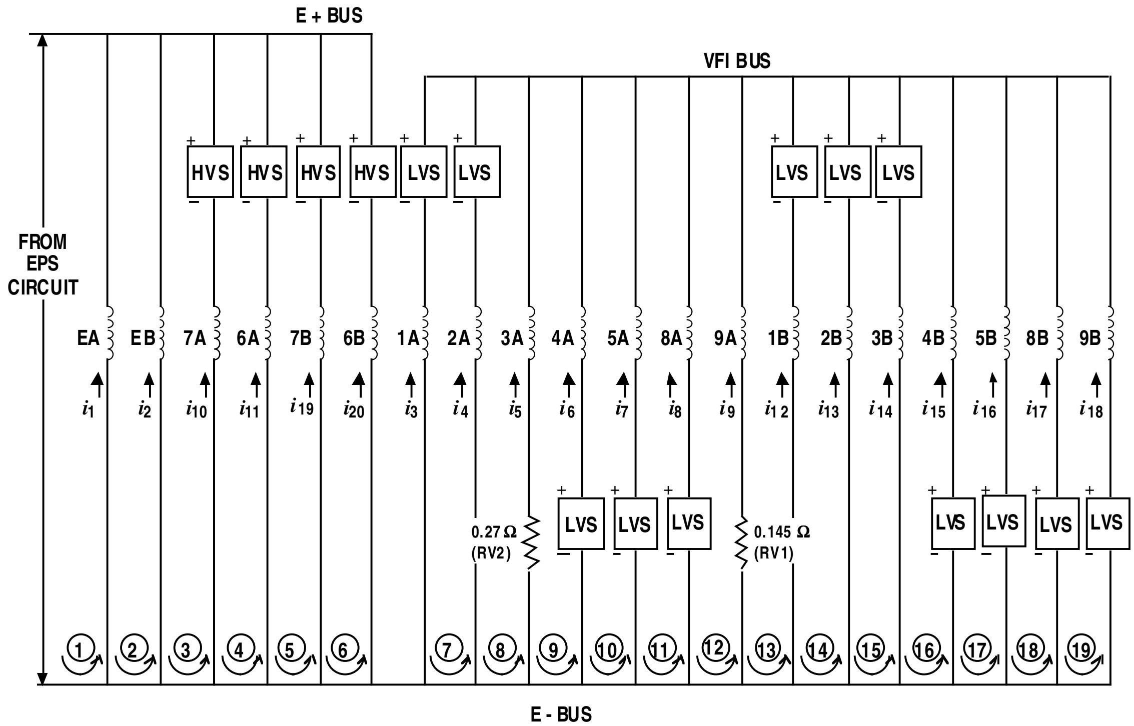
- This model (with linearized plasma response) has been extensively tested & validated:
  - acquired shot data injected (A)
  - modeled output (B) and actual diagnostic output compared
- <u>Tokamak & Plasma Model</u> block now can use DINA nonlinear plasma evolution code.

DIII-D Tokamak Poloidal Coil System



Complex, Reconfigureable Poloidal Coil Circuit is Modeled in Simulator

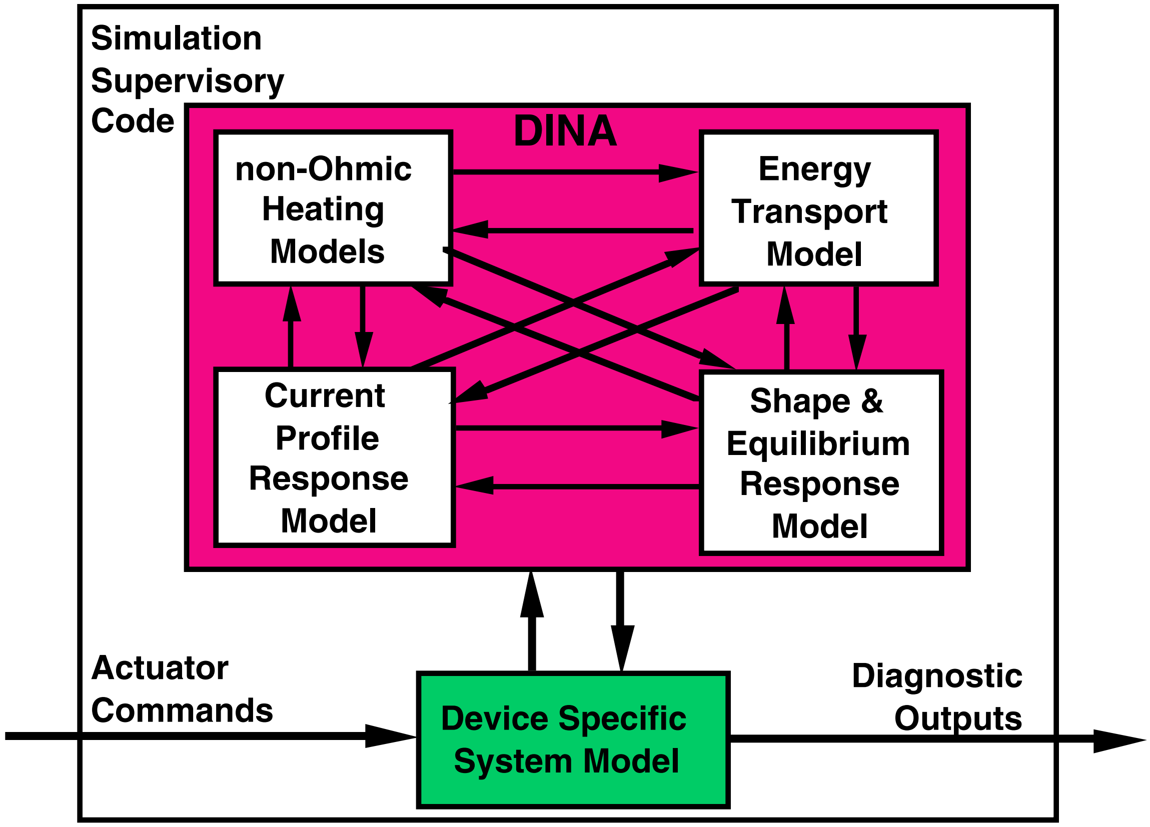
- **DIII-D uses a "patch panel" to change poloidal coil connections for different plasma configurations. For example:**



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**

"Block-Feedback" Simulation Architecture Provided by SIMULINK™



- **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?

Examples of "Block-Feedback" Architecture in Use

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

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

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

(Disturbance terms have been neglected.)

Rewrite in feedback form to get Device Specific Block dynamics:

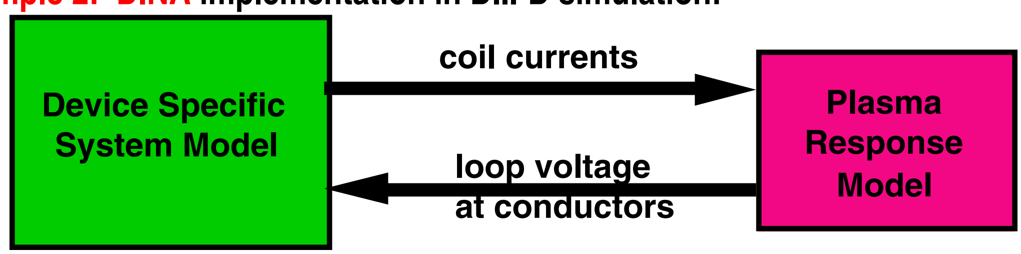
$$\frac{dI_s}{dt} = -M_{ss}{}^{-1}R_s I_s + M_{ss}{}^{-1}V_s + M_{ss}{}^{-1}V_{loop}$$

and Plasma Block dynamics:

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

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

Example 2: DINA implementation in DIII-D simulation:

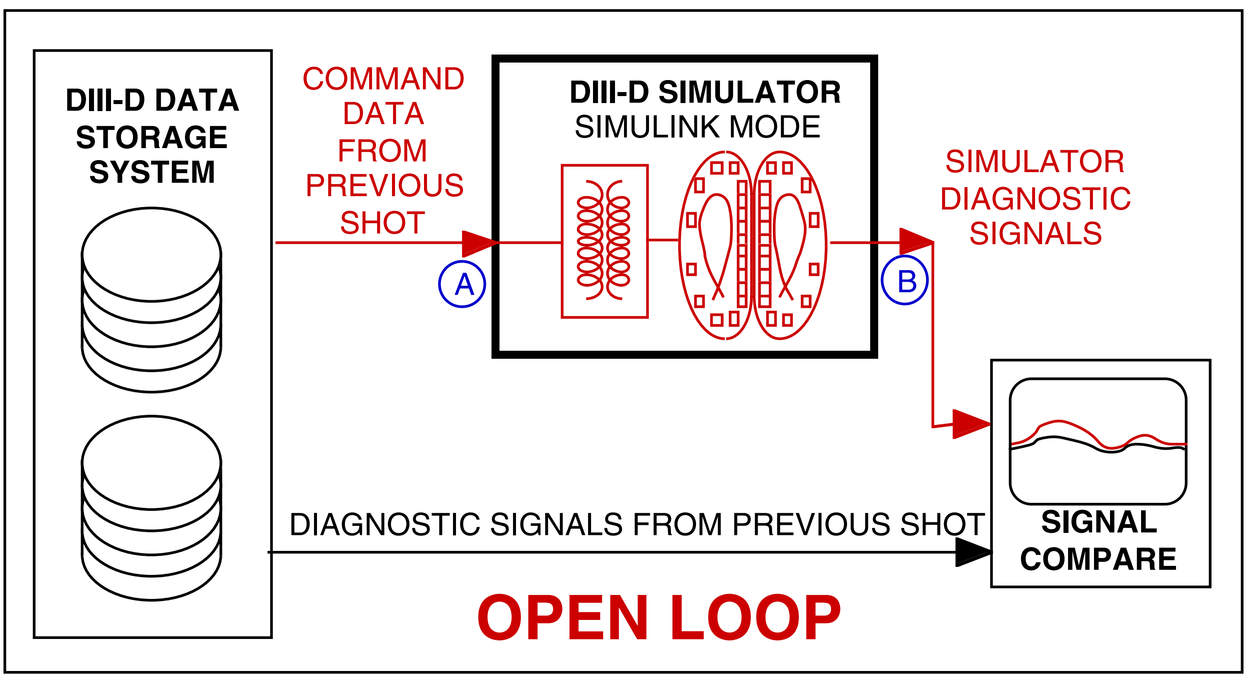


- coils
- power supplies
- vessel
- buss connections
- diagnostics
- acquisition circuits

- equilibrium
- profile evolution

Model Response Validation

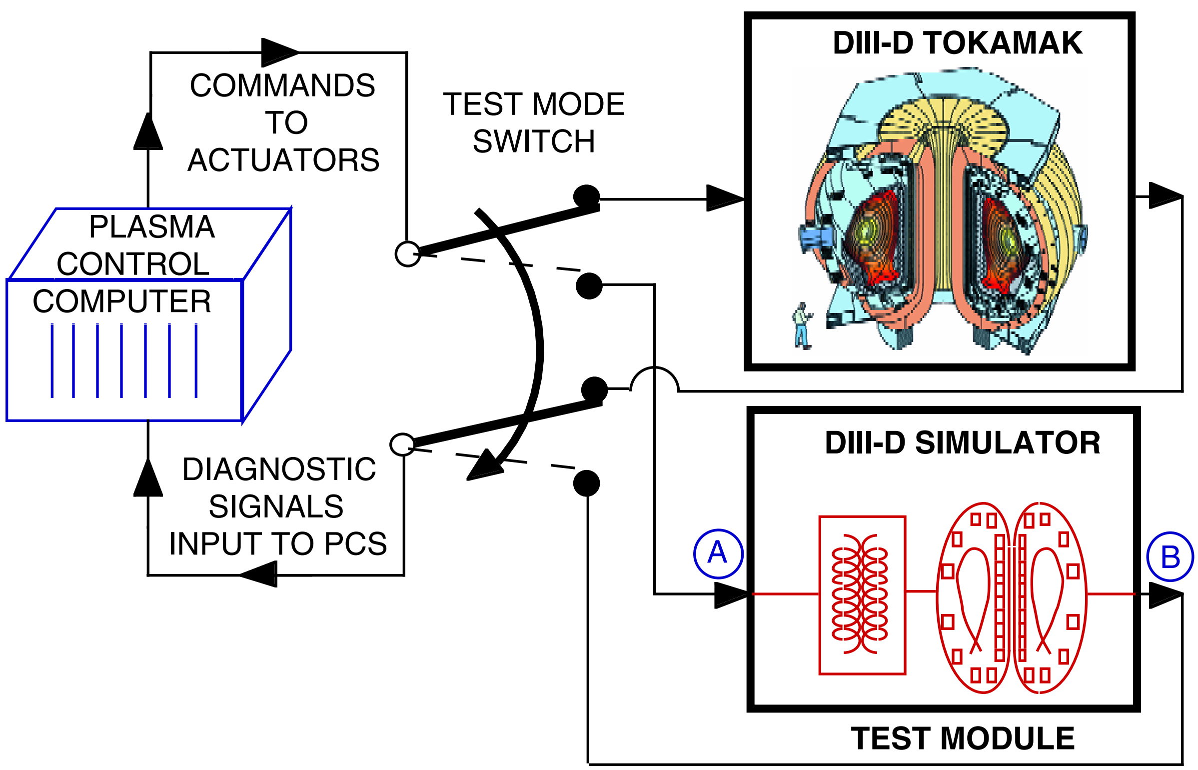
- Execute in SIMULINK™ environment
- Operation in Open Loop
- Measured data drives simulation
  - ➔ either power supply voltage or power supply commands
- Simulated data is compared with data acquired from shot



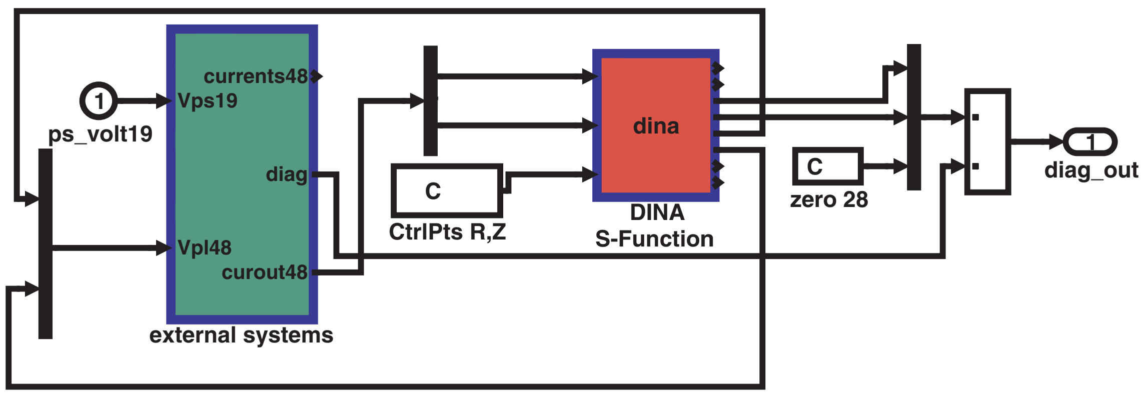
Control Analysis and Simulation

- **Stand-alone simulation executable module** is generated from validated SIMULINK™ model using MATLAB Real Time Workshop™.
  - This module is called a **SIMSERVER** (SIMulation SERVER).

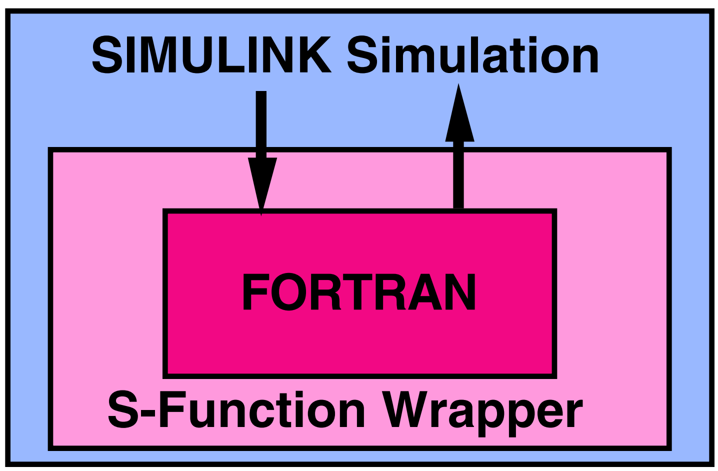
- Simserver **simulation operates in Closed Loop** with the PCS just like normal DIII-D experiment.
  - Allows testing of control algorithms without need for experimental time.



Linearized Plasma Replaced by DINA in Feedback with Device Model



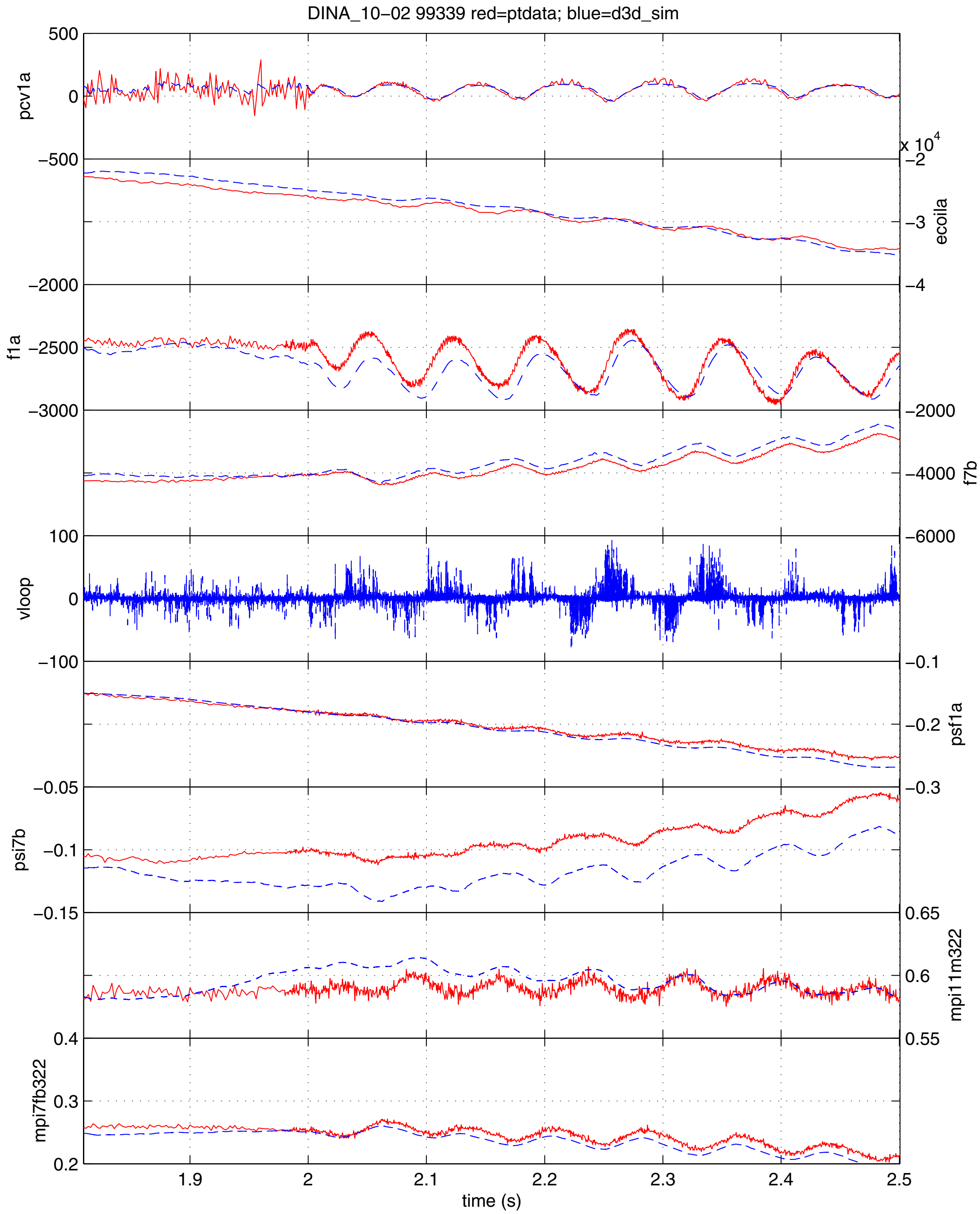
- DINA code remains in original FORTRAN.
  - SIMULINK™ S-function wrapper of DINA (written in C) provides I/O interface to simulation.



- SIMULINK™ S-functions provide easy method for incorporating legacy model codes.

Simulator Accurately Reproduces Experimental Diagnostic Data

- **Data shown (shot 99339) has control driven instability at 2s.**



Not All Shape Parameters are Accurately Simulated Yet

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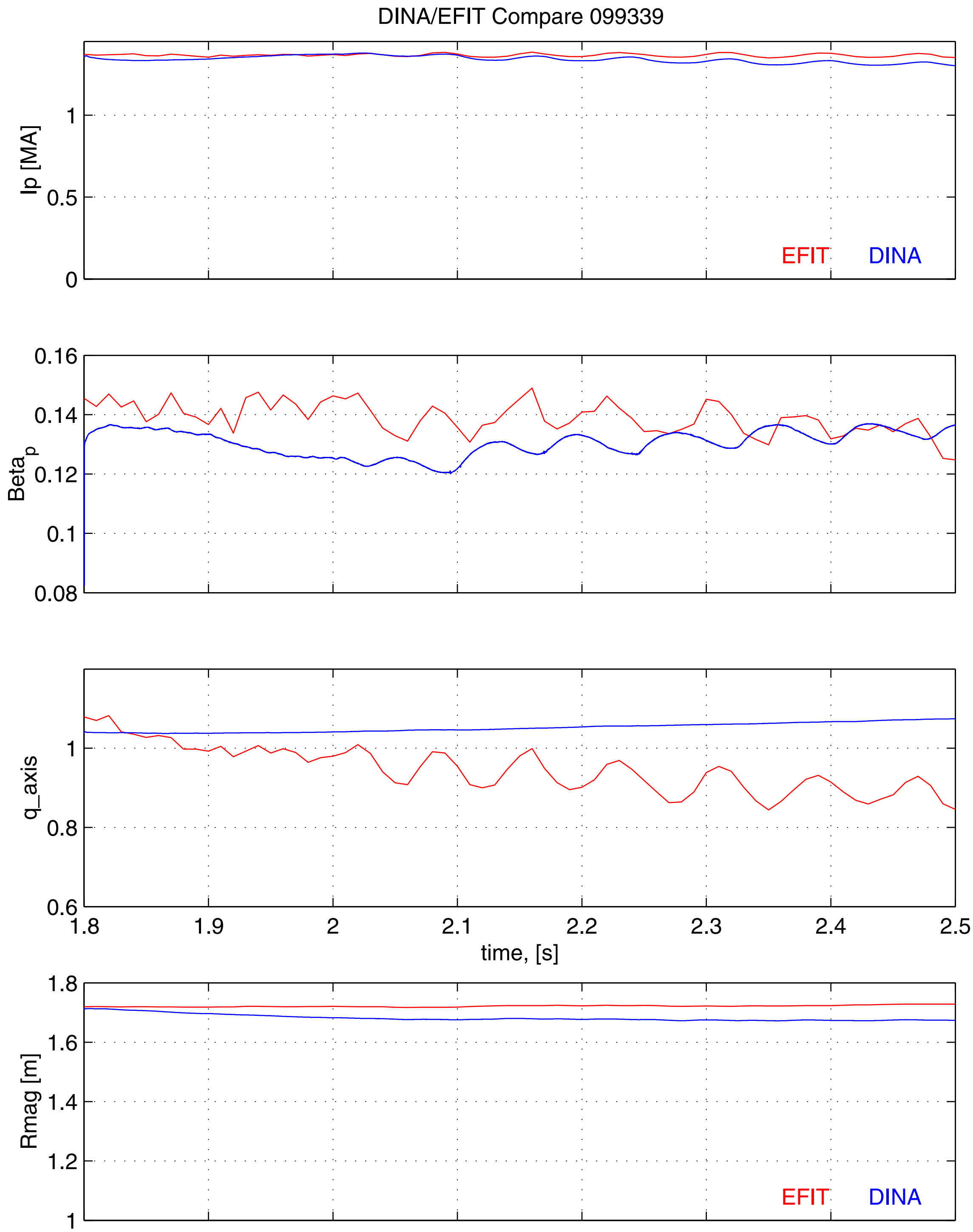

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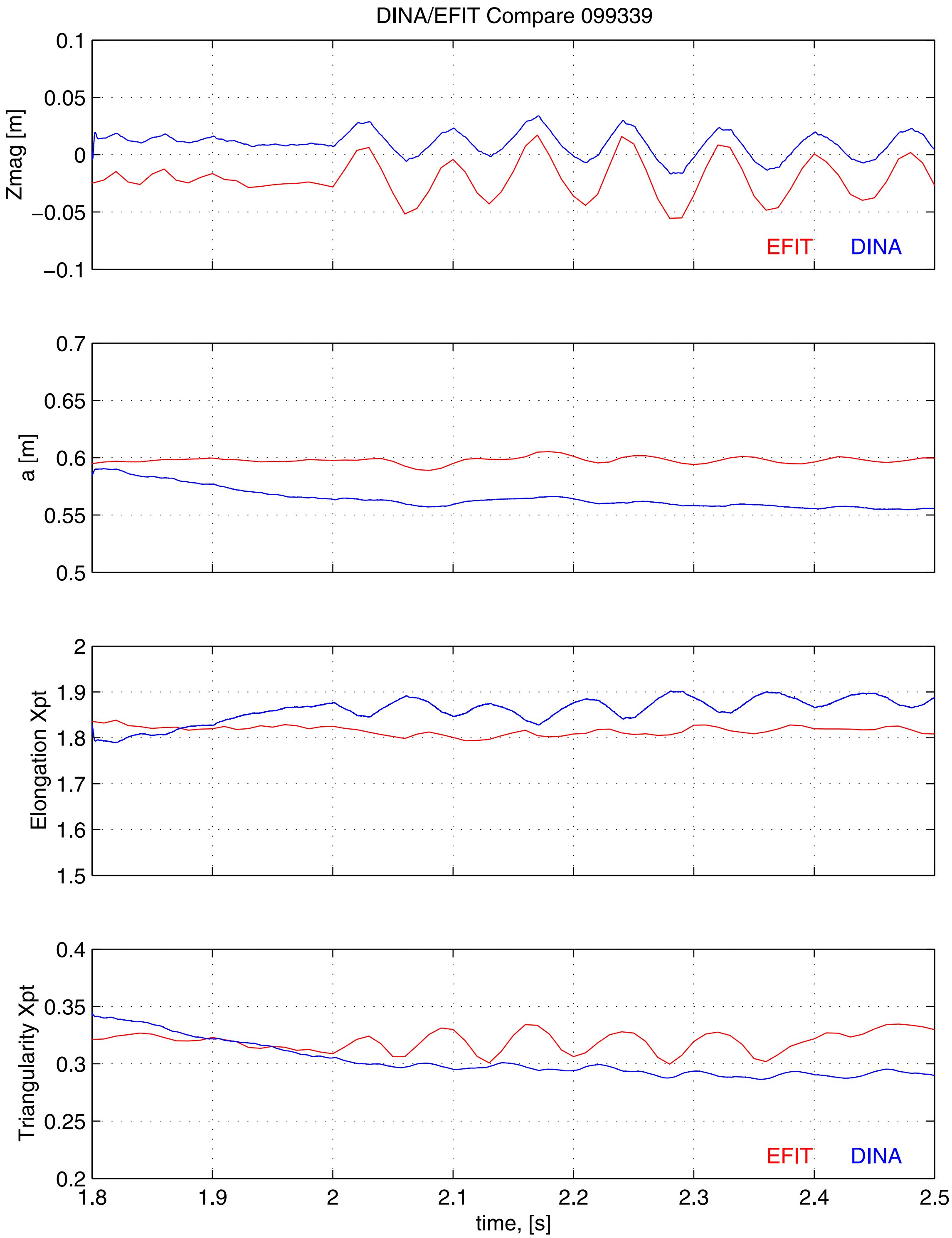
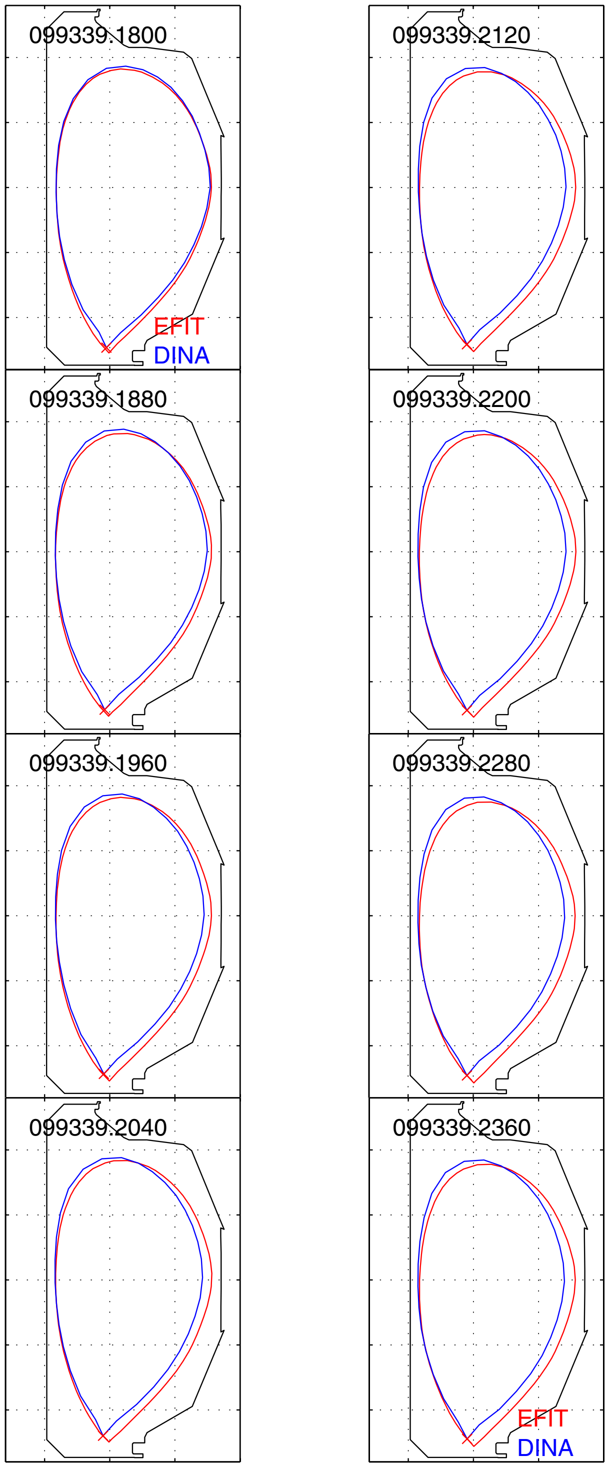


DINA Shape Evolution

- **DINA has approximately constant radial and vertical shift relative to EFIT reconstruction.**



SUMMARY

Simulator Reduces Experimental Time Needed for Controller Development and Testing

- PCS normally connects to the DIII-D tokamak for real time control of the plant

- For testing, PCS can connect directly to software simulation.

  - Simulation currently models all systems important for axisymmetric control:
    - DC power supplies
    - fast switched power supplies
    - configurational switches
    - field shaping & ohmic heating coils
    - passive conductors
    - plasma dynamics
    - magnetic diagnostics
    - data filters
    - A/D & D/A signal conversions

  - Allows testing of controllers as implemented in PCS without using experimental time.

- Simulation is expanding to include other control loops.

Validated Simulations Can Provide Basis for Systems Codes for Future Devices

- Block-feedback architecture proposed for collaborative development of general systems codes.
  - Based on our experience with DINA integration.
  - Individual block "plug-in" structure facilitates collaborative development of systems models
    - Block input/output requirements define interfaces between blocks.

- SIMULINK™ was specifically designed for this approach.
  - Creating block diagram produces executable simulation
  - User built (e.g. legacy code) or SIMULINK™ provided model blocks
  - Automatic variable time-step and multiple time-scale integration (both continuous- and discrete-time)

- Work begun on individual components:
  - non-axisymmetric simulation models:
    - RWM (see Fransson QP1.079)
    - NTM (see Welander QP1.078)
  - Simple parametric physics models (see Deranian RP1.039)