Implementation of a Multivariable Shape Controller on DIII-D*

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ABSTRACT

A model based, multivariable shape controller has been designed and implemented in the DIII-D plasma control system (PCS). Here we describe the modeling approach, controller design, simulation, and the first successful experimental test of the controller on DIII-D. Comprehensive models of all major electromagnetic components have been developed, including a physics based, linearized plasma response model. A rigorous model based design methodology is used to develop a multiple-input-multiple-output (MIMO) control algorithm which is expected to improve static and dynamic shape and position response and provide a framework for development of advanced shape and current profile controllers. The models are incorporated in a simulator which allows validation of the control algorithm within the PCS while running in closed loop with the simulator. In the first test on DIII-D the controller provided stable operation and good steady state shape control throughout the primary part of the plasma discharge.

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OVERVIEW

- A model based, Multi-Input-Multi-Output (MIMO) shape controller was designed and implemented on DIII-D.

- Controller design is based on a linearized plant model of DIII-D consisting of poloidal field coils, resistive elements and plasma.

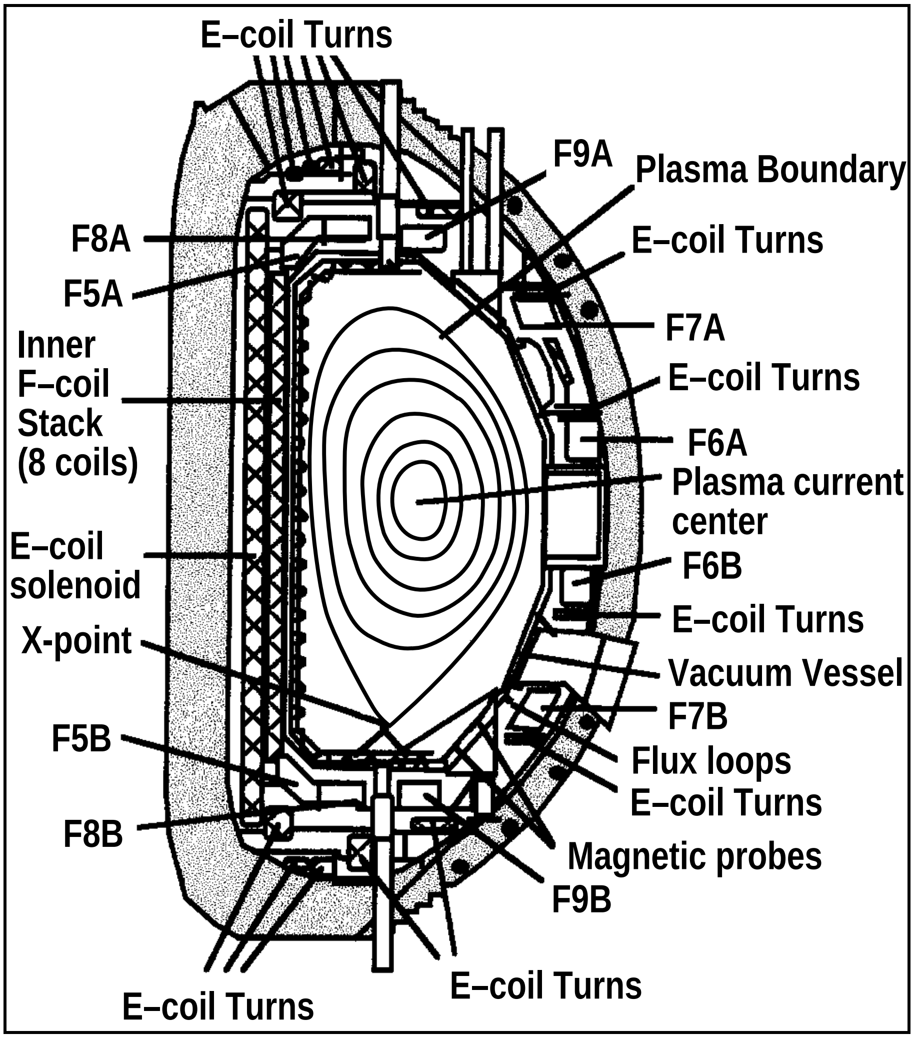
- The model based design procedure produces a state space controller with fully populated gain matrix between the isoflux control points and F-coils. (Previous DIII-D controllers use ad hoc design methods and a PID controller with a sparsely populated gain matrix.)

- The design method allows tradeoff between conflicting requirements. For the first MIMO implementation, X-point control accuracy was emphasized over shape accuracy. The implemented controller design was robustly stable.

- A simulator of the entire DIII-D poloidal field system including the power supplies was developed and used in closed loop with the DIII-D plasma control system (PCS) to validate the controller design.

- The controller was implemented within the PCS and tested on several DIII-D discharges with good success.

THE DIII-D TOKAMAK



- **Ohmic heating coil (E-coil) drives current and heats plasma through transformer action (E-coil is primary, plasma is secondary).**

- **Poloidal field coils (F-coils) F1A...F9B control shape and position of plasma.**

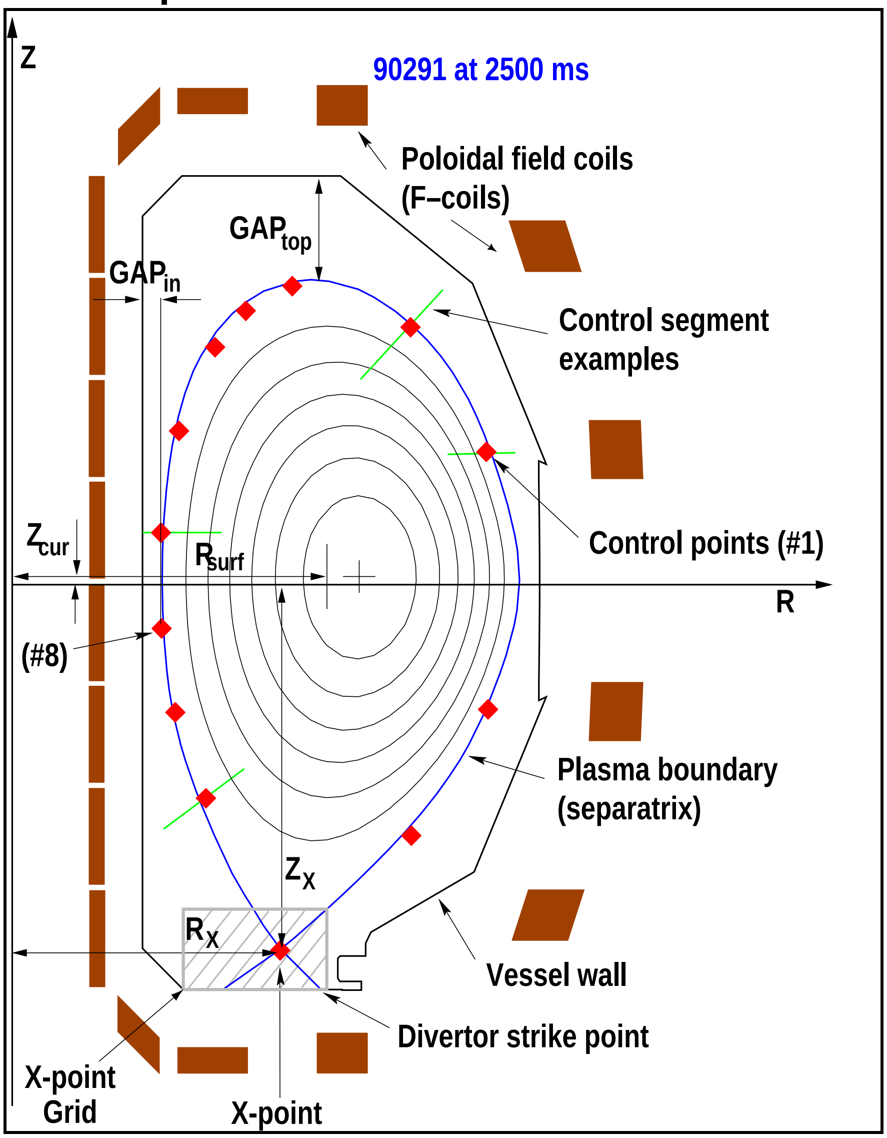
- **Plasma shape is defined by last closed flux surface or separatrix.**

- **Plasma shape/position is diagnosed using measured flux at flux loops and field at magnetic field probes.**

- **Plasma is open-loop vertically unstable.**

EXISTING DIII-D ISOFLUX CONTROL REGULATES PLASMA SHAPE

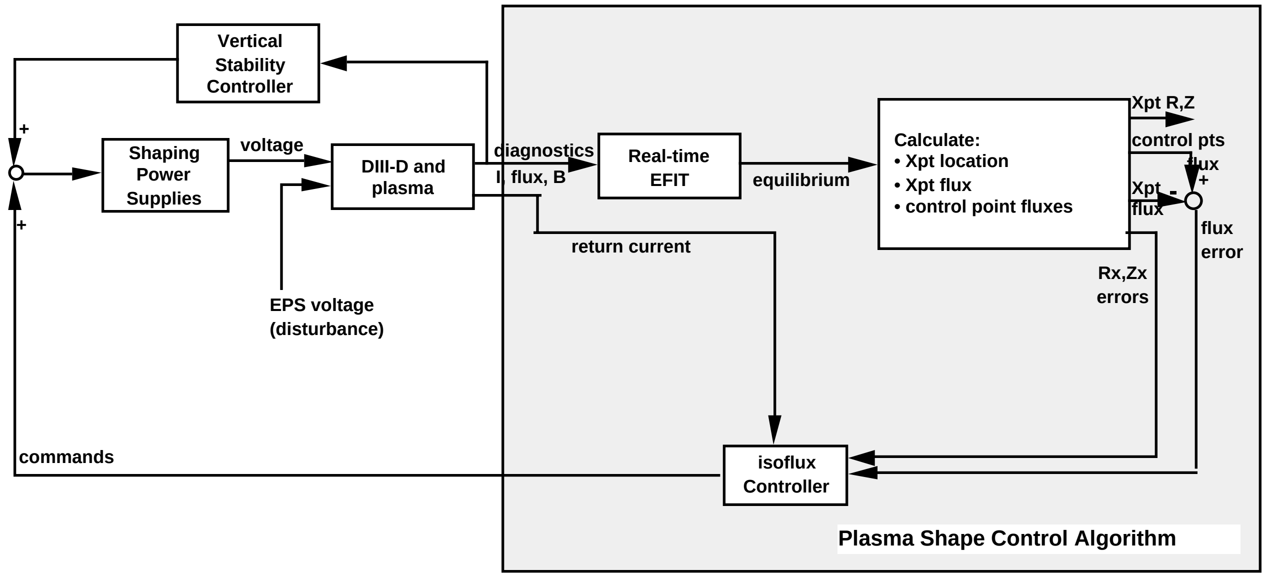
- Real time EFIT (Equilibrium FITing code) calculates flux and fields very accurately near plasma boundary.
- Controlled parameters are:
  - X-Point R and Z positions
  - Flux at boundary control points (isoflux points)
- Flux at each control point is regulated to match the flux at the X-point.



MOTIVATION:
MODEL BASED MIMO DESIGN PROVIDES SIGNIFICANT ADVANTAGES OVER CONVENTIONAL DIII-D CONTROL

- MIMO model-based control exploits knowledge of response of all output control variables to all input actuators. This leads to better control.
  - Each coil influences all control variables; the MIMO controller design incorporates these influences.
  - Dynamic characteristics of the plasma are included.
- MIMO controllers provide explicit techniques for balancing conflicting operational control requirements:
  - System limitations, such as coil voltage/current limits, are designed into the controller.
  - Relative importance of various control parameters is designed into the controller (e.g. gap vs. X-point control accuracy).
- Development method provides robust stability. Reduces sensitivity to variation in plasma parameters.
- Provides systematic plasma shape control design method for new plasma configurations or new devices.
- Controller development and primary testing can be done off-line, without the use of experimental time. This reduces new shape development time.
- Integrated (MIMO) control is the only practical method for simultaneous control of strongly coupled internal profiles and plasma shape.

EXISTING DIII-D SHAPE CONTROL ESSENTIALLY USES A SINGLE INPUT - SINGLE OUTPUT PID CONTROLLER

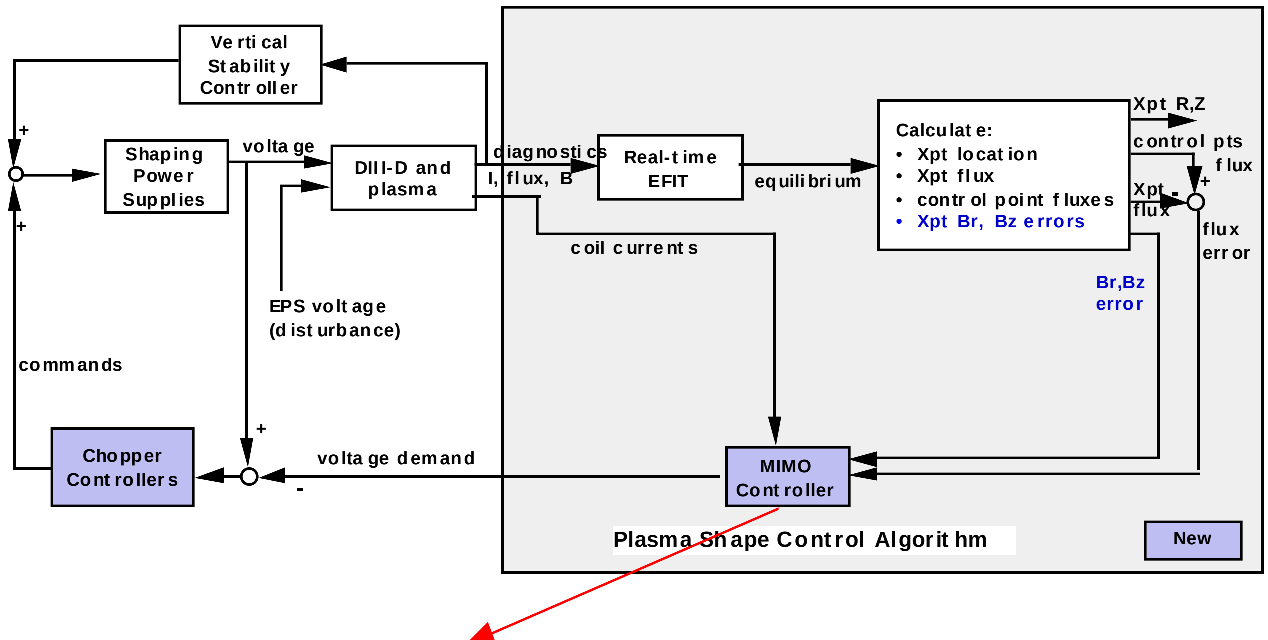


- Gain matrix between isoflux control point errors (e) and PF coil commands is very sparse and values are determined using ad hoc methods. Proportional Integral Derivative (PID) controller is governed by:

$$\mathbf{Command} = k_p\, e + k_e \frac{de}{dt} + k_i \int e\, dt$$

Coil	Isoflux error at control point, segment number:													Errors		
	1	2	3	4	5	6	7	8	9	10	11	12	13	Rx	Zx	Iret
F1A								10								
F2A							16									
F3A																
F4A				-4	-4	-10										
F5A				-4	-10	-4										
F6A	16	4														
F7A			8													
F8A				-10	-4	-4										
F9A																
F1B									10							
F2B										16						
F3B											10					
F4B														10	-10	
F5B														10	-10	
F6B	16												4			
F7B												2				0.2
F8B														10	-10	
F9B														-10	-10	

MIMO CONTROL CONNECTS ALL INPUTS TO ALL OUTPUTS USING A DYNAMIC STATE SPACE CONTROLLER



- State space MIMO controller description

$$\frac{d\mathbf{x}}{dt} = [\mathbf{A}_C]\,\mathbf{x} + [\mathbf{B}_C]\,\delta\mathbf{u}$$

$$\delta\mathbf{v} = [\mathbf{C}_C]\,\mathbf{x} + [\mathbf{D}_C]\,\delta\mathbf{u}$$

where:

x is the state space vector which evolves in time

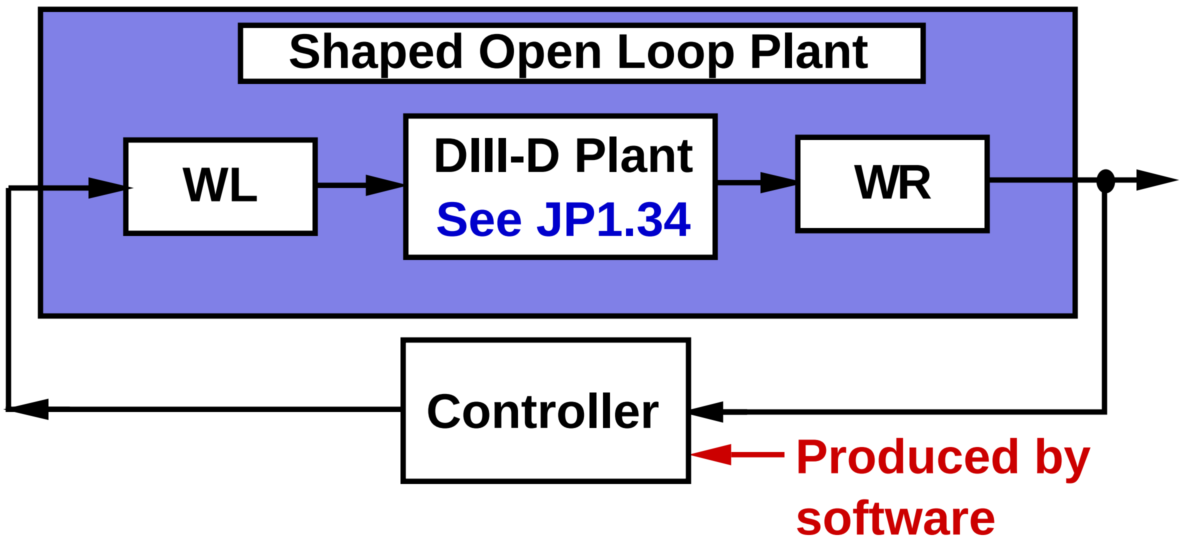
δu is the input vector consisting of:
- 13 isoflux control point errors
- Br & Bz X-point errors
- 18 coil currents
- Plasma centroid vertical position error

δv is output demand voltage vector

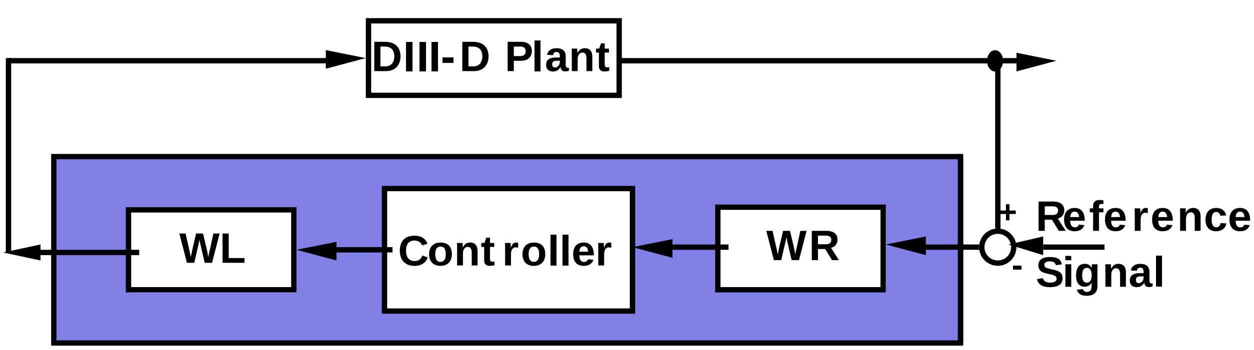
A_C ... D_C are controller state space matrices established using the NCF technique

NCF TECHNIQUE PROVIDES A SYSTEMATIC CONTROLLER DESIGN METHOD

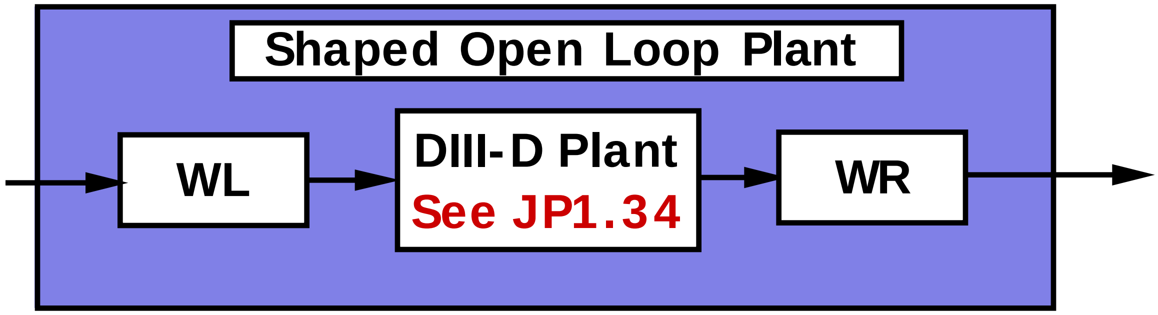
- Normalization Coprime Factorization (NCF) design technique is used in the controller development.
- DIII-D plant consists of PF coils, resistive elements & linear plasma. (See Poster JP1.34)



- User adjusted weights WL and WR are used to shape the desired open loop response of the plant. Automated design tools generate a robustly stable controller, maintaining the specified open loop response.
- Final controller is constructed from generated controller and user specified weights.



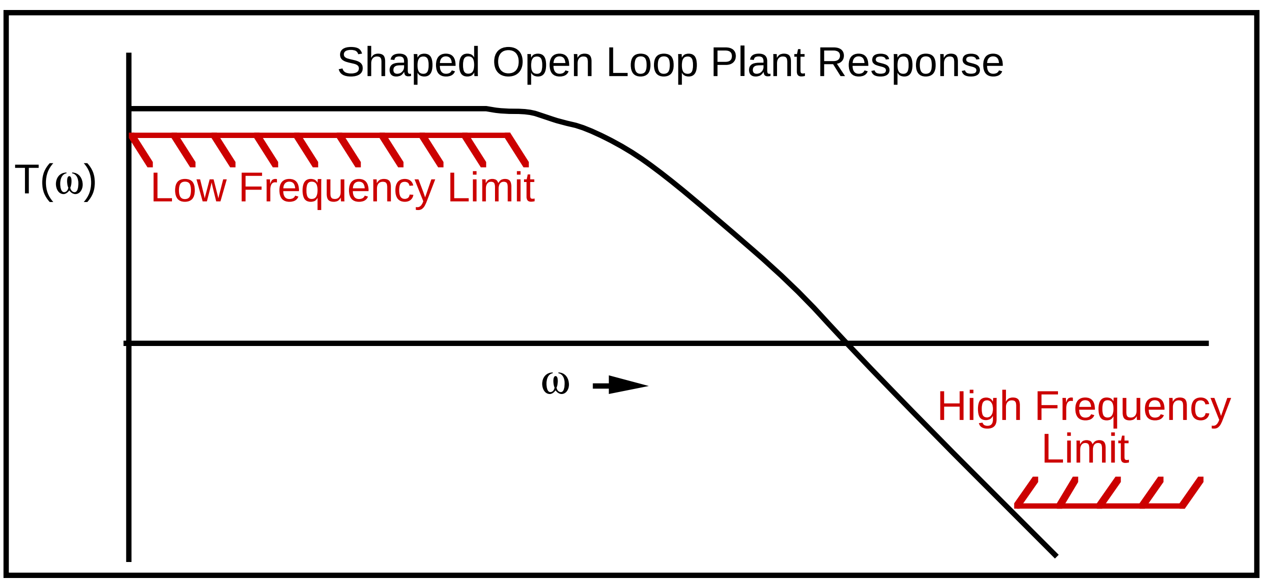
NCF MIMO DESIGN ENTAILS GENERATION OF INPUT/OUTPUT WEIGHT MATRICES WL & WR



- Input / output matrices WL & WR used in the MIMO design are diagonal with each diagonal represented as a filter with, at most, single pole characteristics:

$$W(s) = k\frac{(s^i + \alpha)}{(s^j + \beta)}; \quad \text{Where :} \quad \begin{array}{l} i = 0,1; \; j = 0,1 \\ k, \alpha, \beta = \text{constants} \end{array}$$

- Filter characteristics (i, j) and constants (k, α & β) are adjusted to achieve desired open loop response



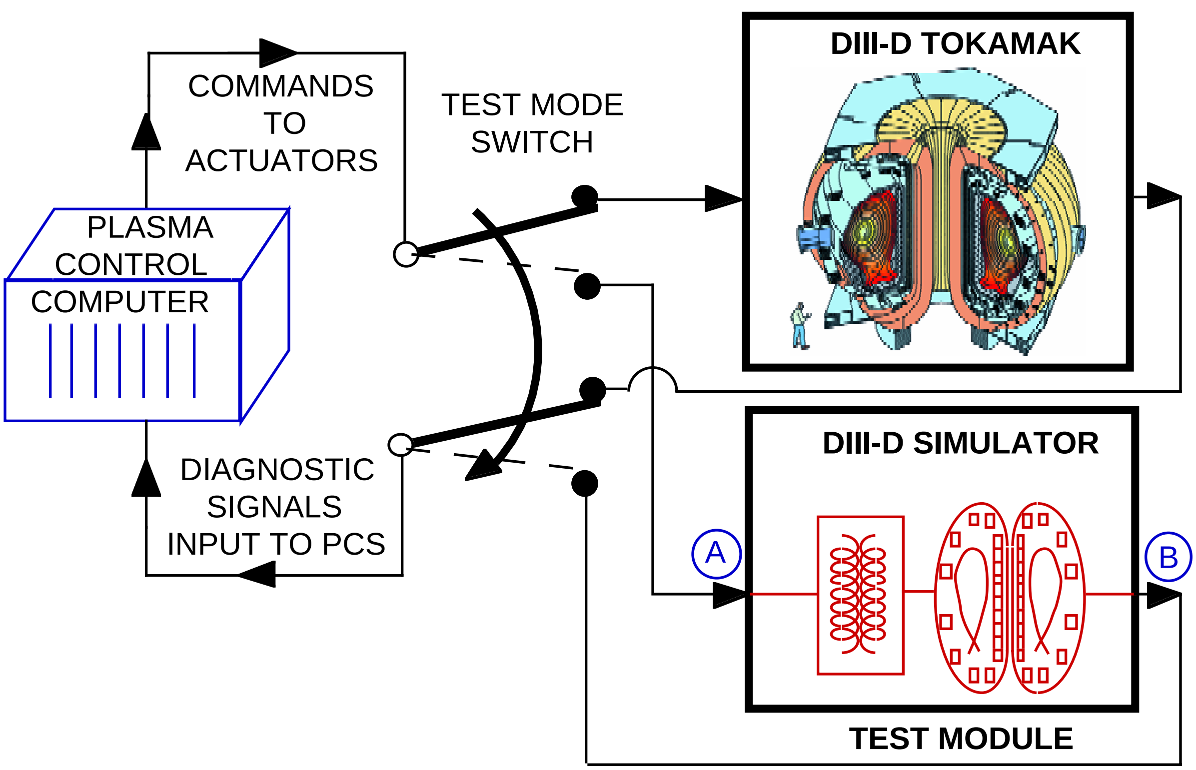
CONTROLLER IS TESTED IN THE PCS USING A NEWLY DEVELOPED DIII-D SIMULATOR

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

- Optionally, the PCS can connect to a software based test module.

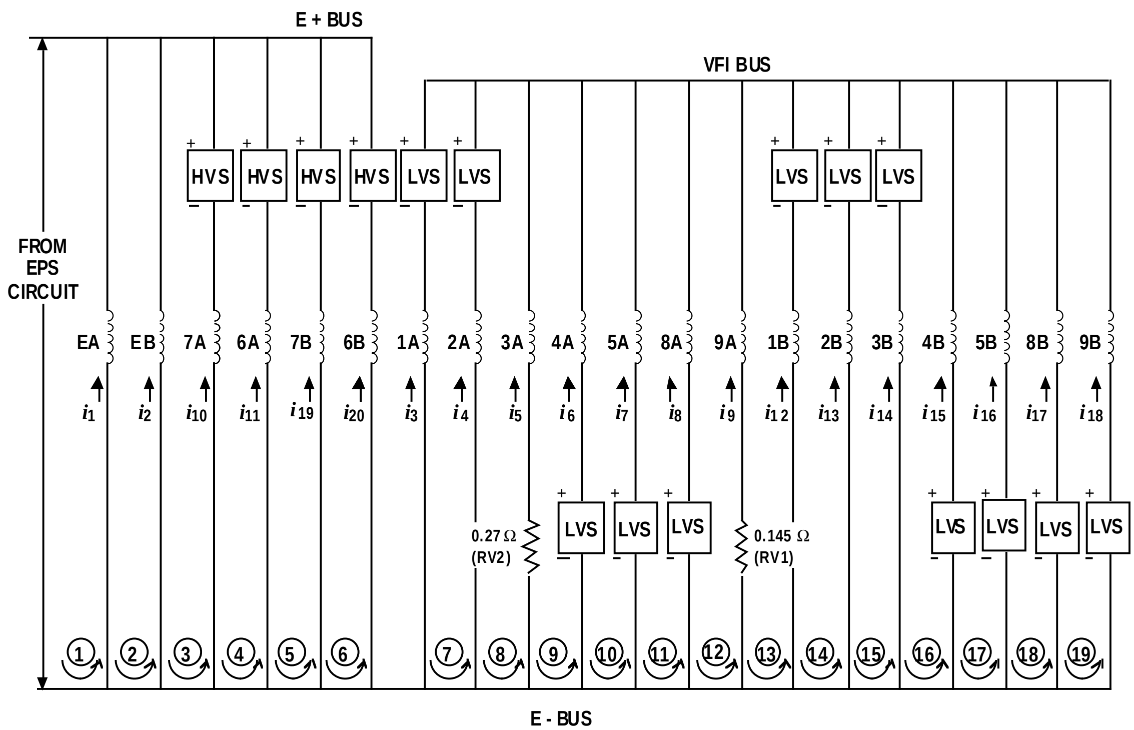
  - The test module simulates the DIII-D plant and includes: 1) DC power supplies, 2) fast switched power supplies, 3) configurational switches, 4) field shaping & ohmic heating coils, 5) passive elements, 6) plasma dynamics, 7) data figures, 8)magnetic diagnostics, 9) A/D & D/A signal converters.

  - This allows testing of the controller as implemented in the PCS without using experimental time.



SIMULATOR MODELS THE COMPLEX AND FLEXIBLE CIRCUIT USED IN THE DIII-D TOKAMAK

- **Simulator circuit is dynamically configured to emulate the DIII-D circuit for a particular shot. A typical DIII-D poloidal field coil circuit is shown below:**



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

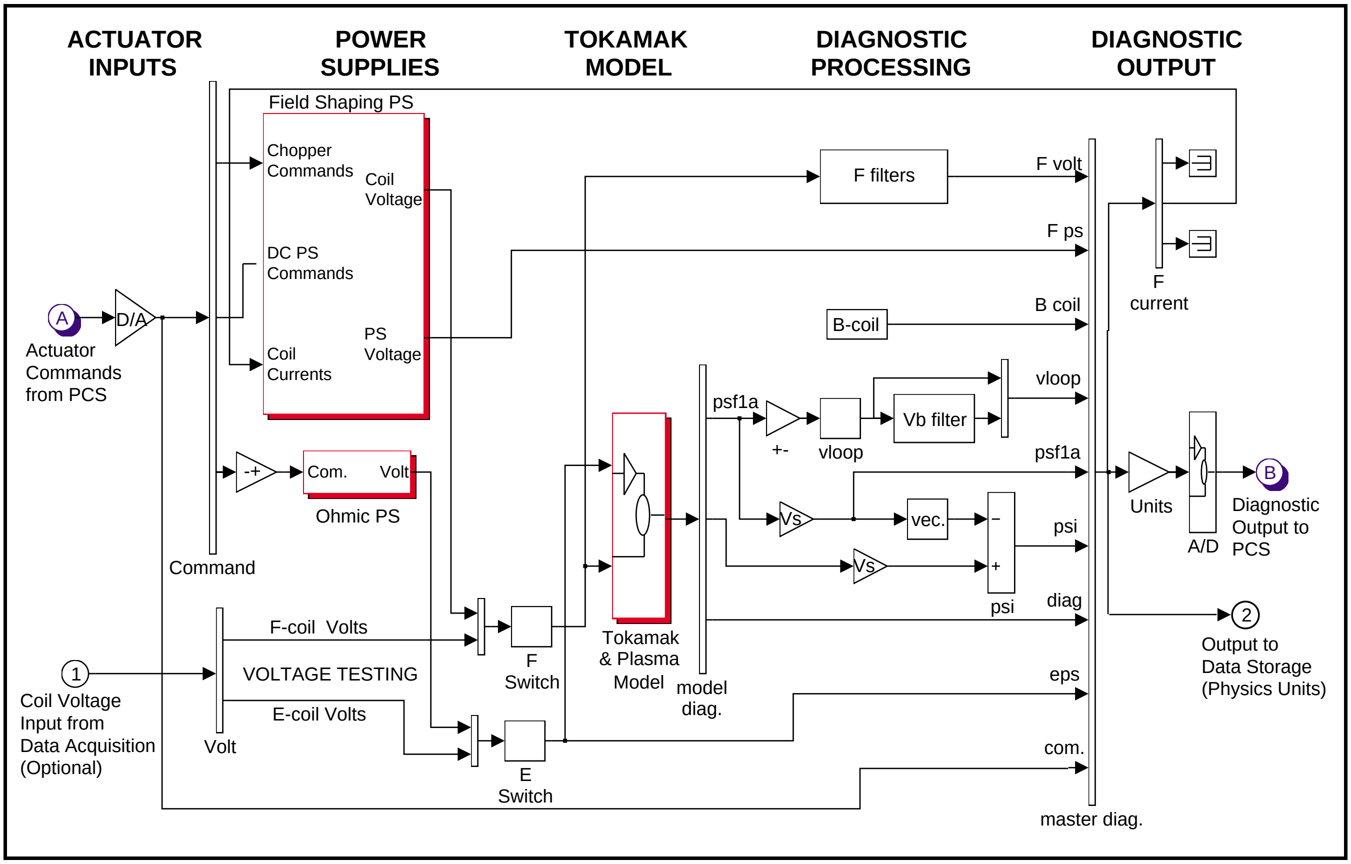
- **The simulator model contains highly nonlinear power supplies (choppers), a large, complex but linear set of circuit equations for the shaping coil and passive element currents (I_S) and a linearized plasma response model: (SEE POSTER JP1.34)**

$$M_{ss}\frac{dI_s}{dt} + R_s I_s + I_{p0}\frac{\partial M_{sp}}{\partial z_m}\frac{\partial z_m}{\partial I_s}\frac{dI_s}{dt} + I_{p0}\frac{\partial M_{sp}}{\partial R_m}\frac{\partial R_m}{\partial I_s}\frac{dI_s}{dt} + \frac{\partial M_{sp}}{\partial I_p}\frac{dI_p}{dt} = V_s$$

Mutual	Resistive	Vertical Motion	Radial Motion	Plasma Mutual	Voltage

DIII-D SIMULATOR

- A model is dynamically built for a particular DIII-D configuration in the MATLAB/SIMULINK™ environment



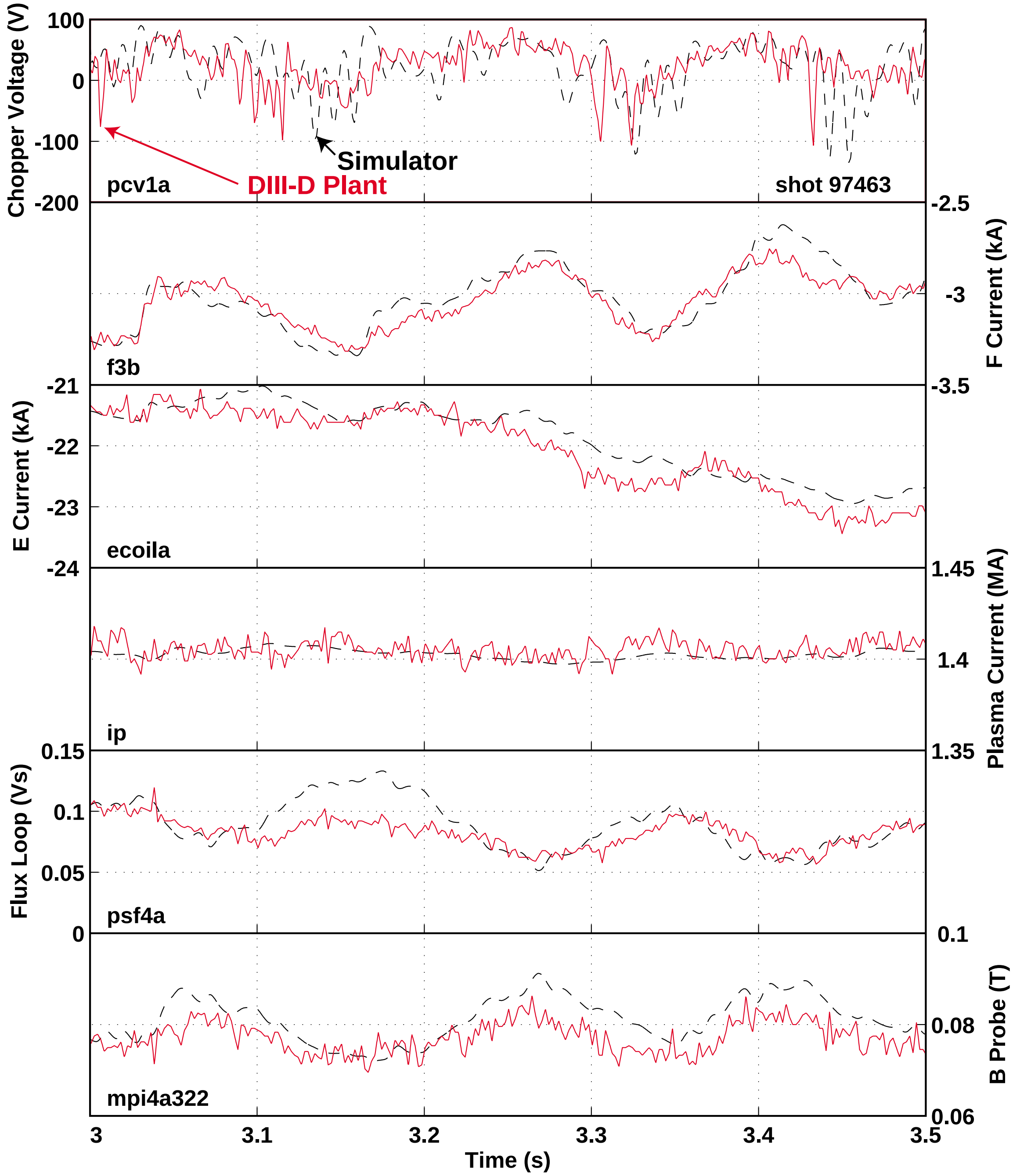
- The model is tested & validated by injecting shot data and comparing model response with actual DIII-D data.

- A SIMulation SERVER (SIMSERVER) is built from the validated model and compiled into an executable.

- SIMSERVER operates in series with the real time PCS allowing testing of newly developed control algorithms.

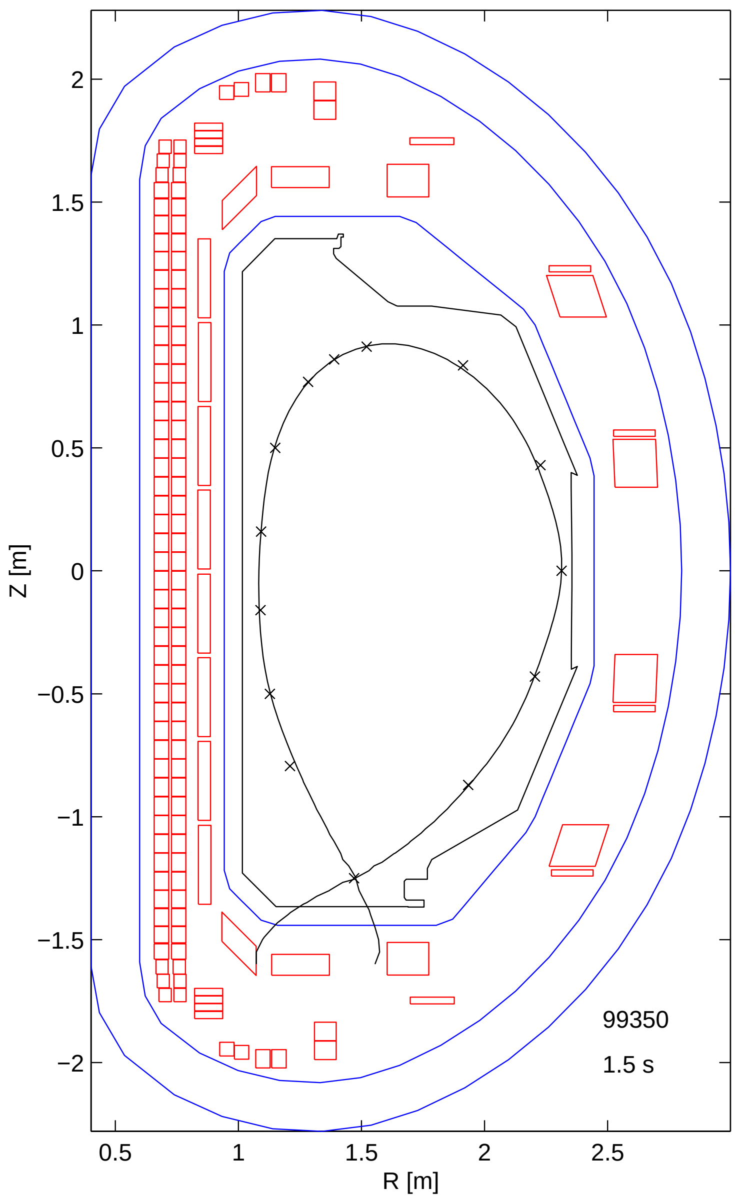
SIMULATOR MODEL ACCURATELY MODELS THE DIII-D PLANT

- **Predictions of the coil currents and diagnostic output are typically within 10% of the actual DIII-D data over a .5-1s time period. Dynamic response, which is important for controller design, is accurately simulated.**



MIMO CONTROLS DIII-D SHAPE

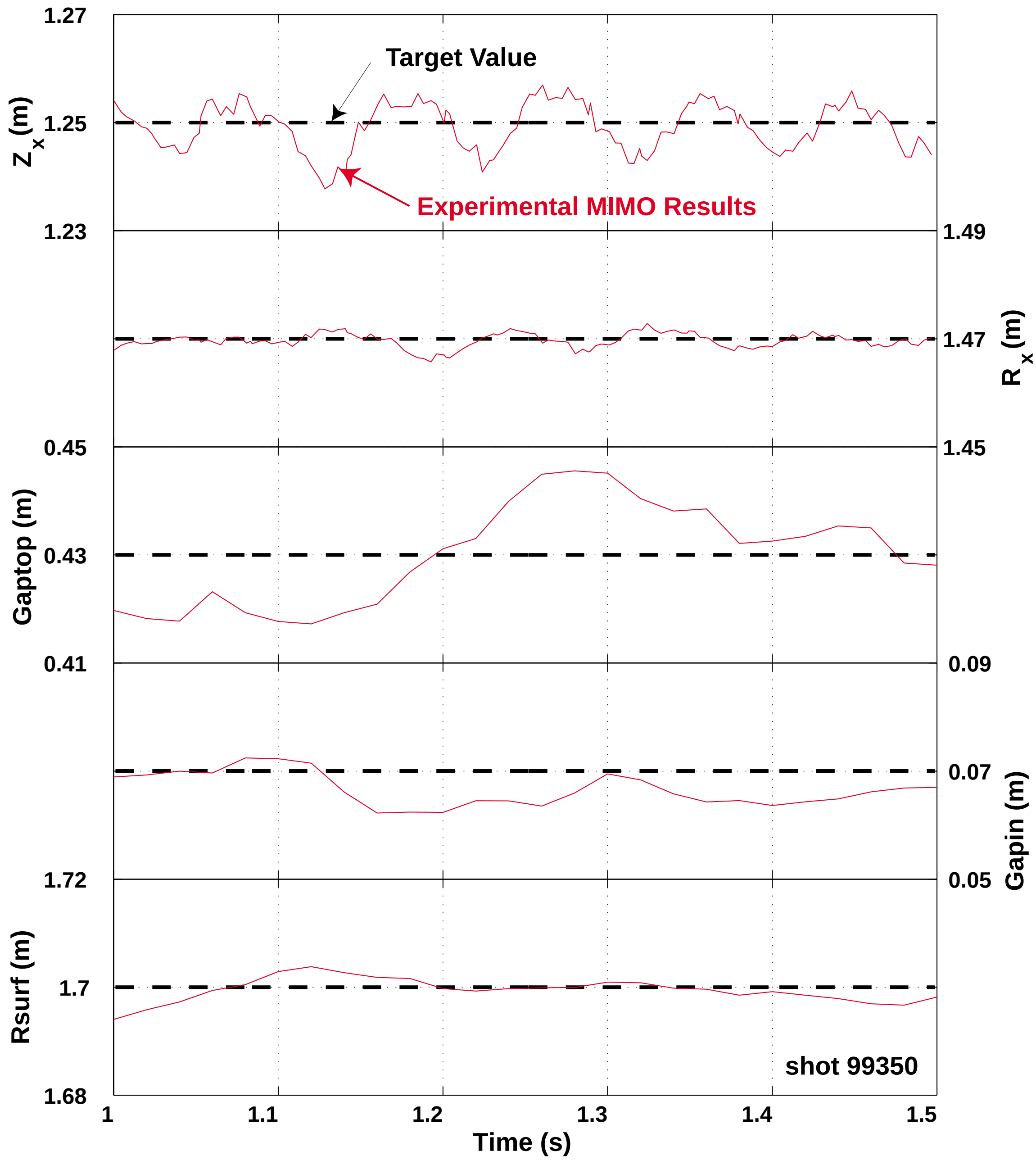
- Lower single null MIMO controller was implemented within the PCS, and tested on DIII-D.
- It was successfully used to control 14 discharges. Over half of these were controlled for the entire discharge.



X's show target shape, solid line is actual plasma shape

MIMO STEADY STATE CONTROL IS EXCELLENT

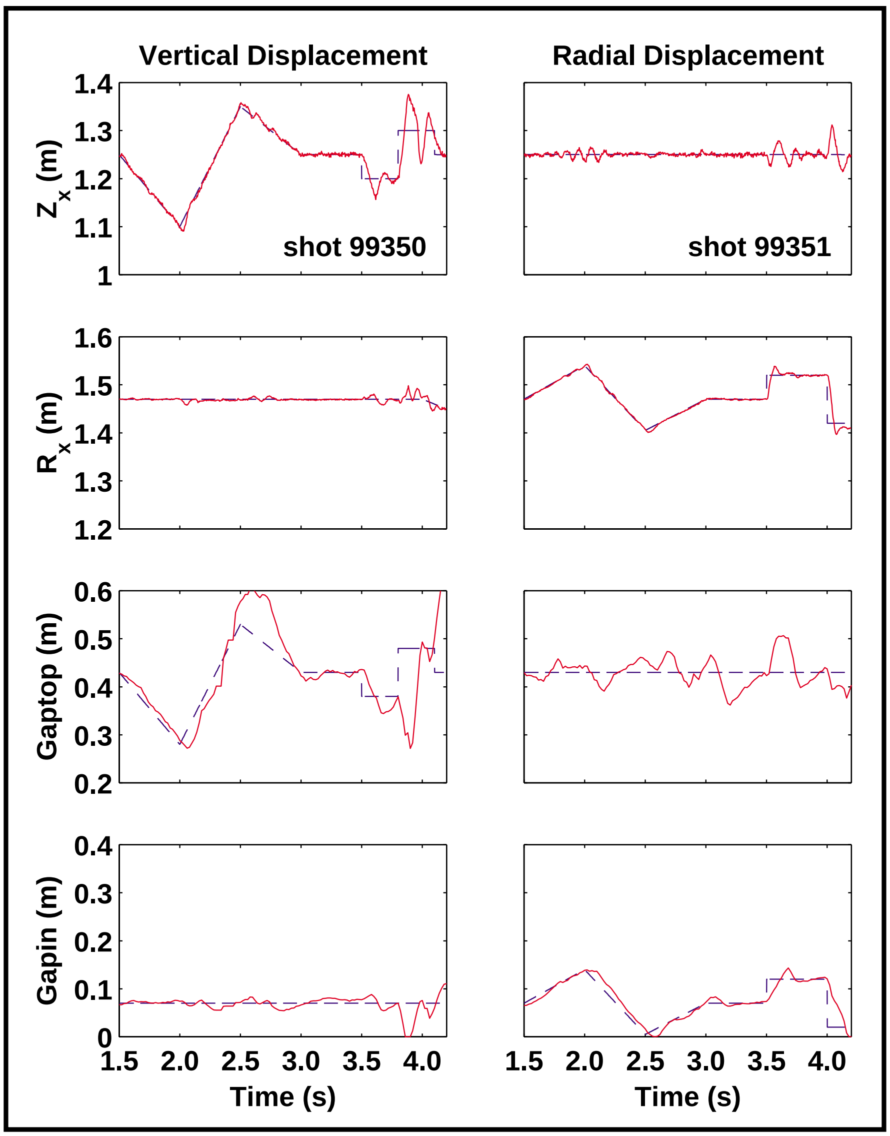
- **The MIMO controller operating on the DIII-D experiment achieves approximately a 1 cm shape accuracy in steady state. This is approximately a 2% error based on minor radius scaling.**



FOR MODEST RAMP RATES, DYNAMIC CONTROL OF THE X-POINT IS EXCELLENT

- X-point control was emphasized in the MIMO controller design (higher weights). This produced excellent control of the X-point location (I).

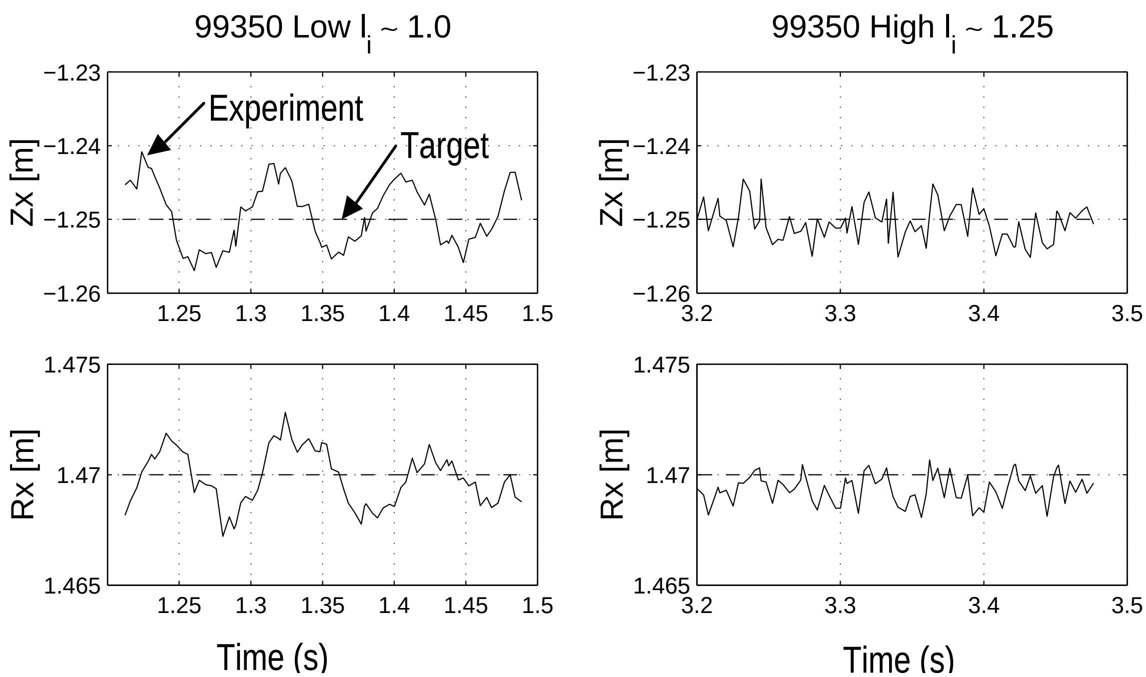
- Other shape parameters are less accurately controlled (II). High frequency response will improve with improved models of the vertical control loop (III).



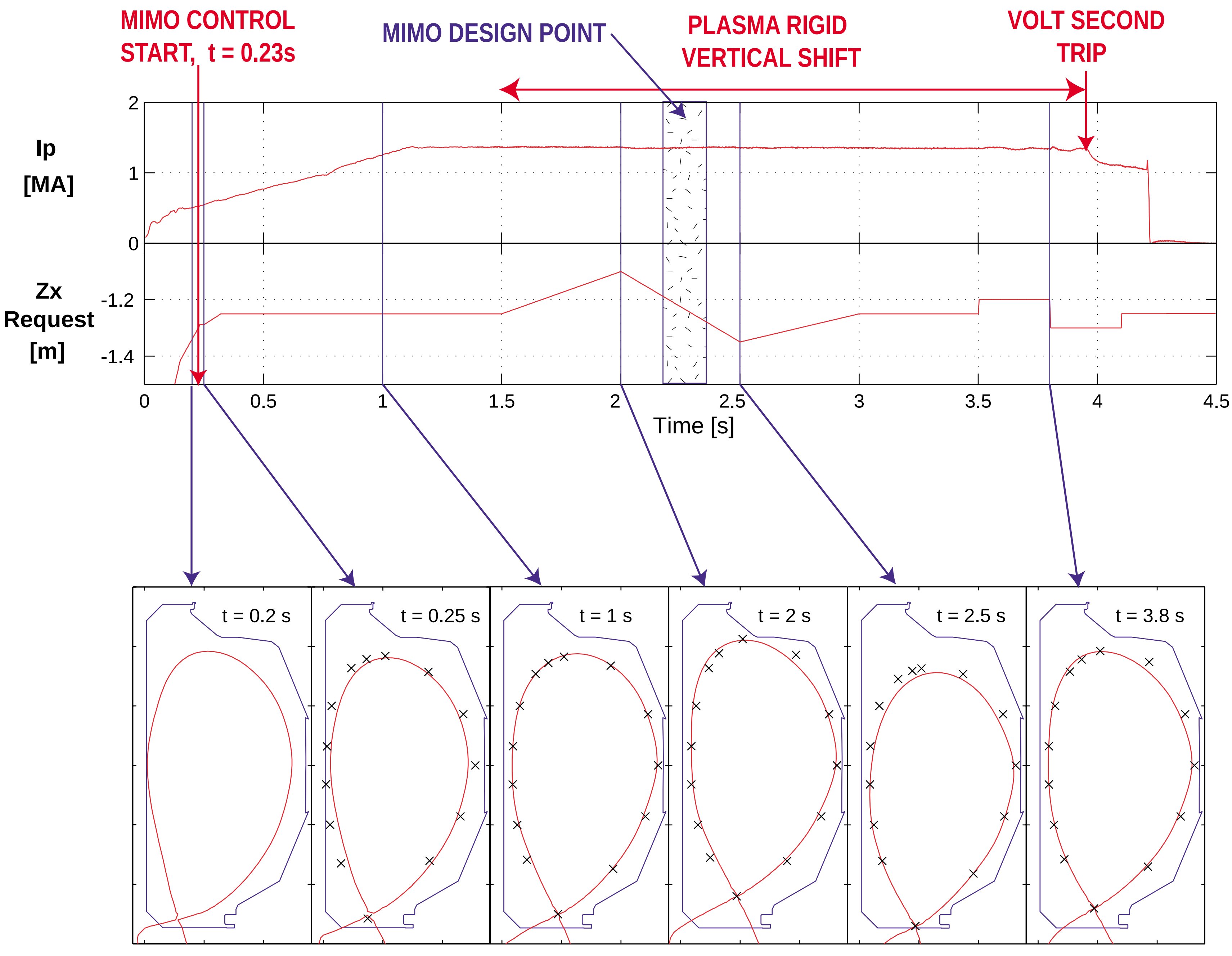
CONTROL QUALITY DEPENDS ON li

- **Controller performance is best at high li where the controller was optimized.** **li strongly influences vertical growth rate which, in turn, strongly affects controller design and response.**

- **Scheduling of controllers can be used to produce similarly good results over a wide range of β_p & l_i.**

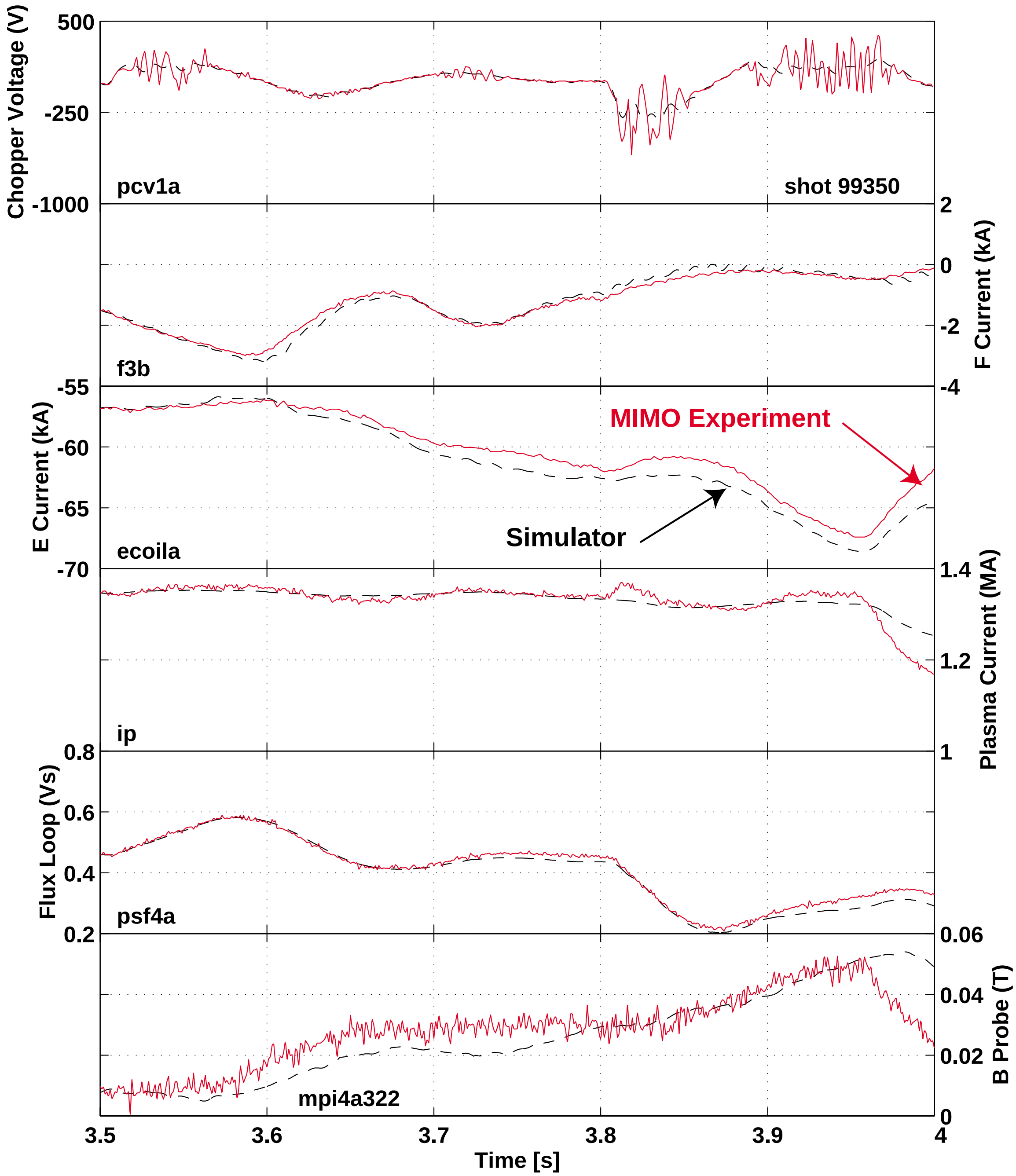


MIMO CONTROLLER LINEARIZED ABOUT SINGLE POINT CONTROLS ENTIRE DISCHARGE



SIMULATOR ACCURATELY REPRODUCES RESULTS OF THE MIMO EXPERIMENT

- Experimental results from the MIMO experiment are accurately reproduced by the simulator, except at the end of the discharge where a plasma disruption occurs.



- A comprehensive, model based controller design methodology has been developed for DIII-D control.

- A model based, multivariable, dynamic shape (MIMO) controller has been developed, implemented and tested on the DIII-D tokamak.

- A comprehensive simulator of the DIII-D plant has been developed. This simulator operates in closed loop with the PCS and allows development and testing of control algorithms in the PCS without requiring experimental machine time.

- Experimental results of the MIMO controller show robust control of the plasma shape over the entire discharge:
  - Steady state shape control of ~ 1cm was achieved.
  - Dynamic control of X-point is good due to emphasis placed on this parameter in MIMO design. Other boundary shape parameters were less controlled.
  - Internal plasma parameters impact quality of control.
  - Stable operation was achieved over the entire discharge.

- Initial results are encouraging. Future development will allow integrated shape and current profile controllers to be designed and tested off-line based on rigorous model based procedures. Methodology provides a framework for development of controllers for future fusion devices.