NSTX MIMO SHAPE CONTROLLER DEVELOPMENT

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- **Objectives:** Develop a Multiple-Input-Multiple-Output (MIMO) plasma shape/ stability controller for NSTX. Develop a flexible tool set for rapid, model-based, multivariable controller development on NSTX.

- **Program:** 3-Year => System model development, Experimental validation, MIMO controller design, Simulation, MIMO algorithm & tool set distribution.

- **Needs** Machine parameter data, Existing models (e.g. power supplies),
  Machine time: Year 1-2: 30-40 vacuum response shots,
  Year 2-3: 20-30 plasma response shots

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NSTX MIMO BENEFITS

– Design methods enable highly accurate shape control in presence of disturbances, noise and equilibrium uncertainty.
– Model-based MIMO control exploits knowledge of response of all output control variables to all input actuators - This leads to superior control.
– Design methods provide for robust stability - Reduced sensitivity to plasma parameter variations.
– Integrated (MIMO) control is the only practical method for Advanced Tokamak (AT) Operation, which requires simultaneous control of strongly coupled internal profiles and plasma shape.
– Controller development and primary testing can be done off-line.
– Synergistic with DIII-D's AT plasma MIMO control effort. Many tools already developed for DIII-D can be readily applied to NSTX. Tool outputs readily interface to existing PCS architecture.

NSTX MIMO STRAWMAN MACHINE REQUIREMENTS

- **Vacuum Tests: Year 1-2: (2-3 shots per circuit + 10 extra => 30 - 40 shots)**
  - Single coil tests - PCS Sine wave input at different frequencies (1Hz-1kHz ?)
  - Multiple frequencies per shot (4-5 frequencies/shot ?)
  - Measure response at: PS, coils, sensors => Generate frequency response
  - Validation: power supplies, coil, passive elements & magnetic sensors
  - Extra tests useful for cross coupling & noise from other sources - TF coil ...?
  - Need date: Distributed over 2003-2004 Campaigns.

- **Plasma Tests: Year 2-3: (~10-20 shots)**
  - Vertical, horizontal plasma motion for range of Shape, Beta & l_i
  - Can be as multiple cases per shot or as piggy-backs at end of discharge.
  - Validation: plasma model, overall system model & controller properties.
  - Need date: Distributed over 2004-2005 Campaigns.

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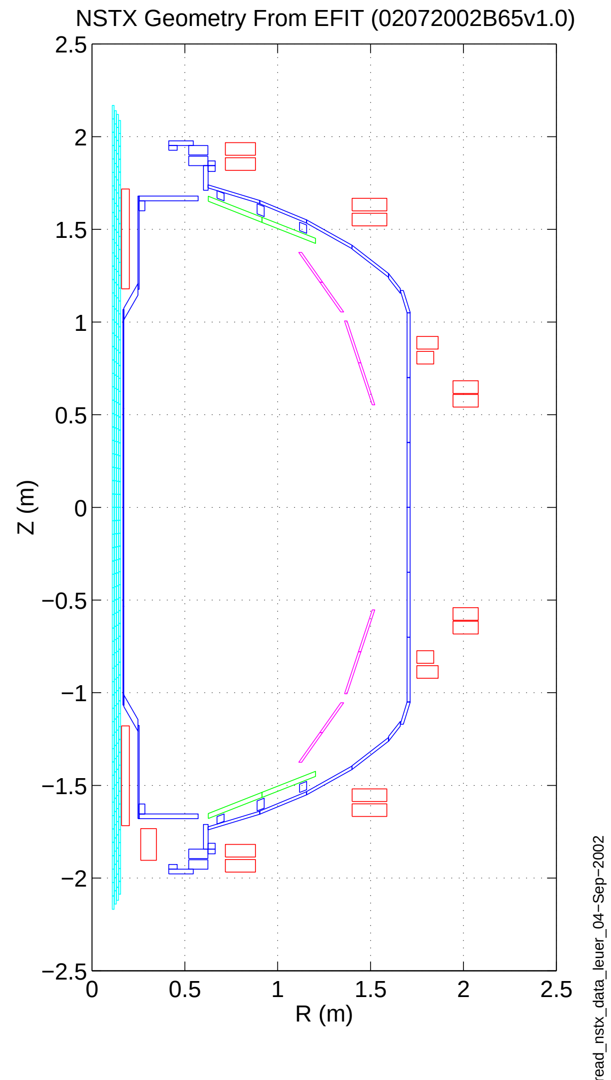
Preliminary NSTX Geometry in Matlab/Simulink (from EFIT file)



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A Complete Suite of Software Tools Is Available for PCS Development

- **<u>Simserver</u>: Emulates the tokamak using shot data or a model based tokamak simulator to provide off-line testing of the PCS**

- **<u>Tokamak Models</u>: A rich set of linear and non-linear plasma models are available and integrated into our PCS development environment.**

- **<u>MIMO</u>: Multiple Input Multiple Output controller tools are available for the design of robust shape and profile controllers.**

- **<u>Tokamak Simulator</u>: A relatively complete model of a Tokamak machine (based on DIII-D) has been developed which can be generated as a stand alone Simserver which connects to the actual multi-processor PCS to allow emulation of an actual tokamak machine.**

- **<u>PCS Simulator</u>: A software model of the multi-processor, real time PCS hardware/software is available for simulation of the control algorithms within the PCS. It can be connected by sockets to the <u>Tokamak Simulator</u> for a complete off-line simulation of the Tokamak/PCS.**

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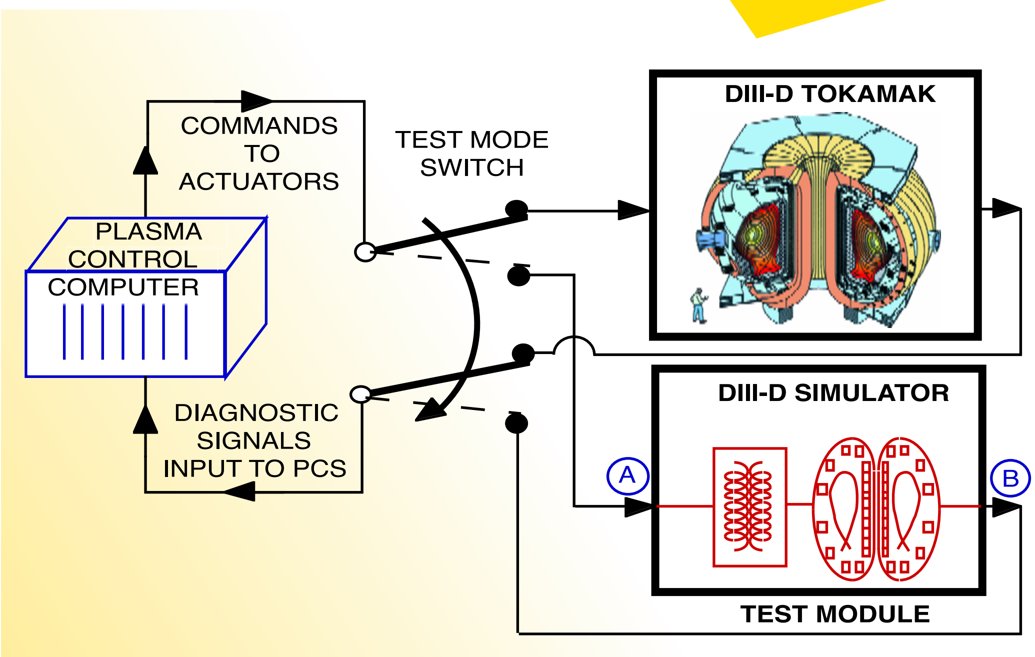
ADVANCED CONTROLLERS AND MODEL BASED SIMULATORS PROVIDE FRAMEWORK FOR ADVANCED TOKAMAK DEVELOPMENT AND OPERATION

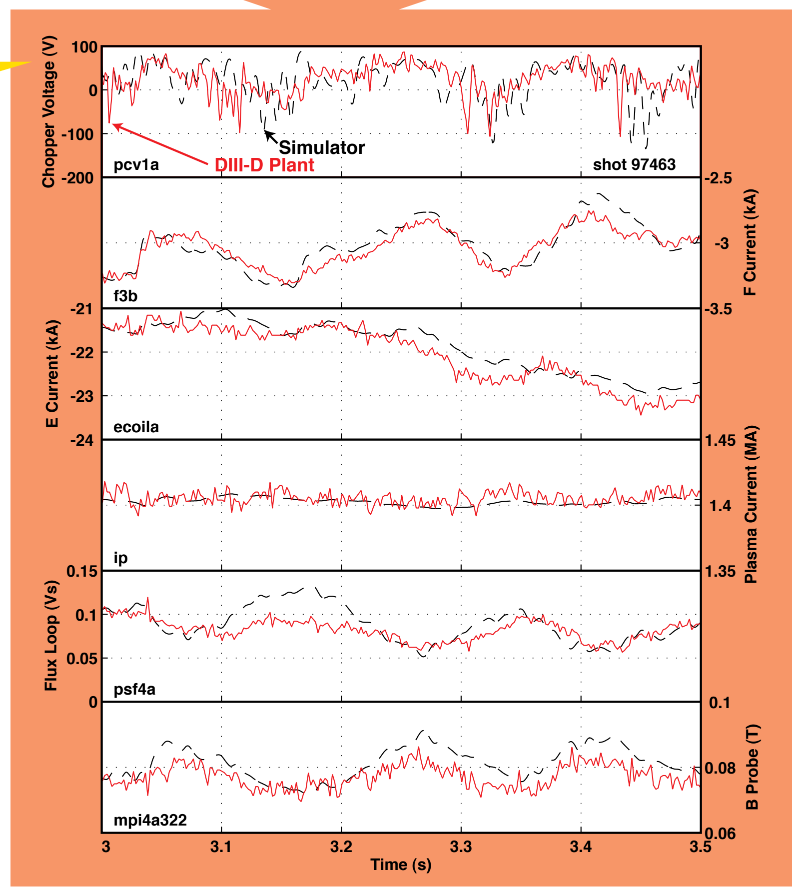
Advanced shape and profile controllers

- o Multiple-Input-Mulitple-Output (MIMO) model based design
- o Fully integrated with the plasma control system
- o Design and testing can be done off-line
- o Design of controllers for next generation machines

Complete simulators for tokamak system response

- o Models power supplies, coils and plasma
- o Enables optimization of high performance controllers
- o Allows emulation of next generation tokamaks





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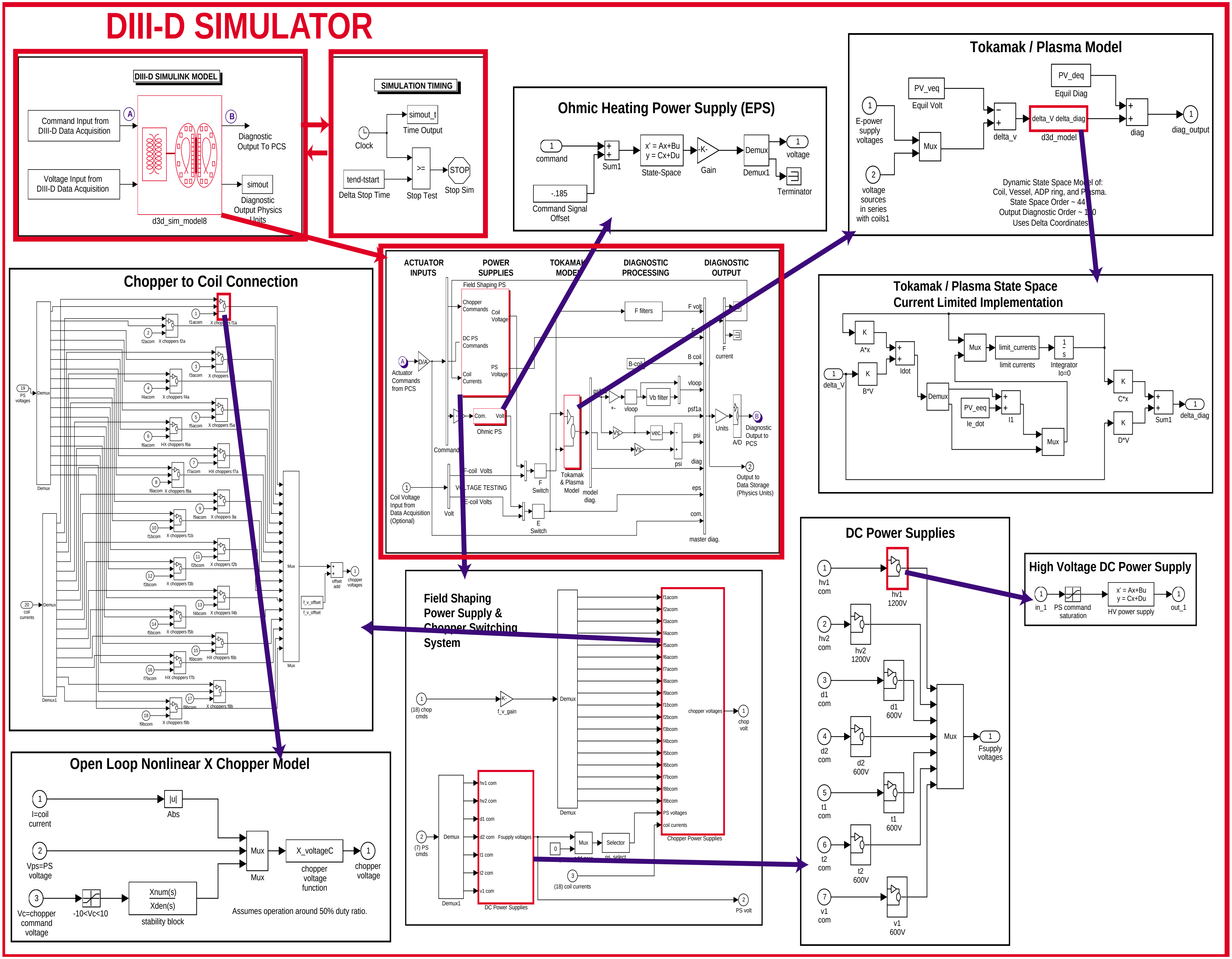
DIII-D SIMULATOR
DIII-D SIMULINK MODEL
Command Input from DIII-D Data Acquisition
Voltage Input from DIII-D Data Acquisition
d3d_sim_model8
Diagnostic Output To PCS
simout
Diagnostic Output Physics Units
SIMULATION TIMING
Clock
simout_t
Time Output
tend-tstart
Delta Stop Time
Stop Test
STOP
Stop Sim
Ohmic Heating Power Supply (EPS)
command
Sum1
State-Space
Gain
Demux1
voltage
Terminator
-.185
Command Signal Offset
Tokamak / Plasma Model
PV_veq
Equil Volt
PV_deq
Equil Diag
E-power supply voltages
voltage sources in series with coils1
Mux
delta_v
d3d_model
diag
diag_output
Dynamic State Space Model of:
Coil, Vessel, ADP ring, and Plasma.
State Space Order ~ 44
Output Diagnostic Order ~ 150
Uses Delta Coordinates
ACTUATOR INPUTS
POWER SUPPLIES
TOKAMAK MODEL
DIAGNOSTIC PROCESSING
DIAGNOSTIC OUTPUT
Field Shaping PS
Chopper Commands
DC PS Commands
Coil Currents
Coil Voltage
PS Voltage
Actuator Commands from PCS
Ohmic PS
Command
Coil Voltage Input from Data Acquisition (Optional)
Volt
VOLTAGE TESTING
F-coil Volts
E-coil Volts
F Switch
E Switch
Tokamak & Plasma Model
model diag.
F filters
F volt
F current
B coil
vloop
Vb filter
psf1a
psi
diag
eps
com.
master diag.
Units
A/D
Diagnostic Output to PCS
Output to Data Storage (Physics Units)
Tokamak / Plasma State Space
Current Limited Implementation
delta_V
A*x
B*V
Idot
limit_currents
limit currents
Integrator Io=0
Demux
PV_eeq
Ie_dot
I1
C*x
D*V
Sum1
delta_diag
Chopper to Coil Connection
PS voltages
coil currents
offset add
chopper voltages
f_v_offset
Field Shaping Power Supply & Chopper Switching System
(18) chop cmds
f_v_gain
chopper voltages
chop volt
(7) PS cmds
Fsupply voltages
DC Power Supplies
Selector
ps_select
(18) coil currents
Chopper Power Supplies
PS volt
DC Power Supplies
hv1 com
hv1 1200V
hv2 com
hv2 1200V
d1 com
d1 600V
d2 com
d2 600V
t1 com
t1 600V
t2 com
t2 600V
v1 com
v1 600V
Fsupply voltages
High Voltage DC Power Supply
in_1
PS command saturation
HV power supply
out_1
Open Loop Nonlinear X Chopper Model
I=coil current
Abs
Vps=PS voltage
Vc=chopper command voltage
-10<Vc<10
Xnum(s)
Xden(s)
stability block
X_voltageC
chopper voltage function
chopper voltage
Assumes operation around 50% duty ratio.

Linear Plasma Response Model Based on Force Balance Relations

- **Simple radial force balance:**

$$B_{z_m}^{appl} = B_z^{Shafranov} = -\frac{\mu_o I_p}{4\pi R_m}\left(\ln\left[\frac{8R_m}{a\sqrt{\kappa}}\right] + \frac{2\kappa}{\kappa^2+1}\beta_p + \frac{\ell}{2} - 1.5\right)$$

- **Simple vertical force balance:**

$$0 = -2\pi R_m I_{p_o}\frac{\partial B_r}{\partial z}\delta z + \frac{\partial M_{pc}}{\partial z}\delta I_c + \frac{\partial F_z}{\partial \beta_p}\delta\beta_p + \frac{\partial F_z}{\partial \ell_i}\delta\ell_i$$

- **Circuit equation:**

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

- **State space model:**

$$\dot{I} = [A]\ I + [B]\ V$$
$$\Psi = [C]\ I + [D]\ V$$

- The plasma is modeled as a distributed current source and linearized about a distribution defined by the GA Equilibrium Fitting code (EFIT)

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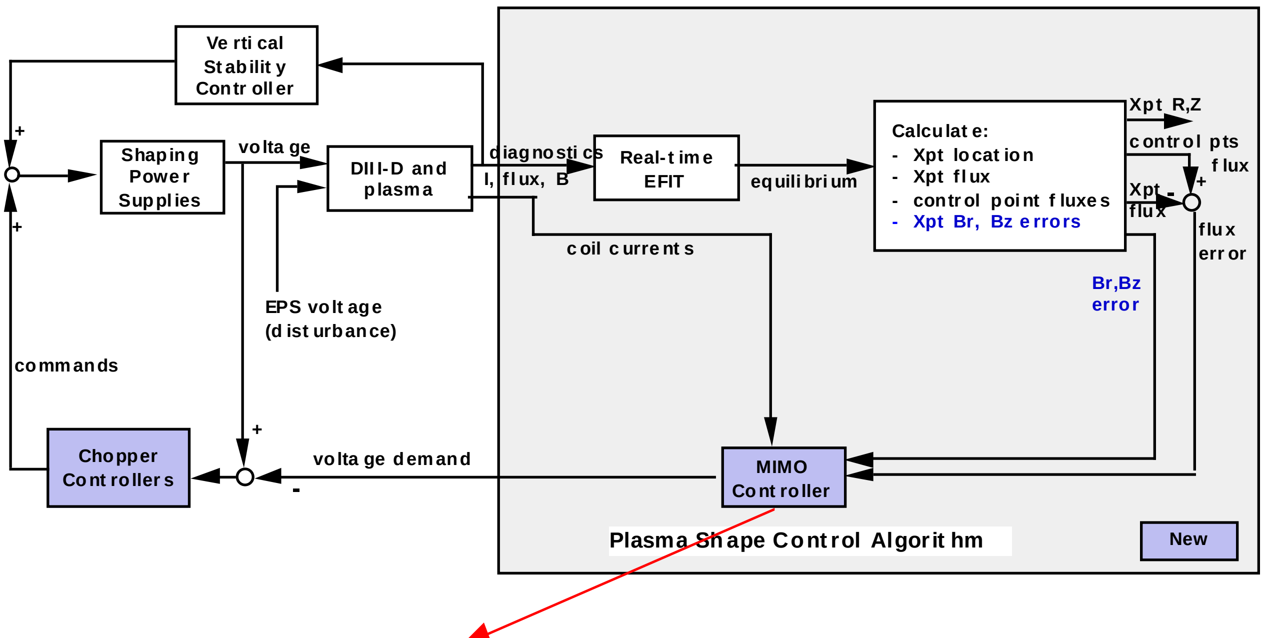
Comprehensive Development Tools are Available for Controller Design

- Multivariable controllers are used for tokamak control based on a rigorous, model based design methodology using a dynamic state space MIMO structure.

- Tools and models are integrated with the PCS, and applicable to other machines.



x is state space vector
13 isoflux control pts.
Br & Bz @ X-point
18 coil currents
Plasma centroid for vertical control
δu demand voltage
Ac ..Dc controller state space matrices from MIMO design

- State space MIMO controller description

$$\frac{dx}{dt} = [A_C]\,x + [B_C]\,\delta u$$

$$\delta v = [C_C]\,x + [D_C]\,\delta u$$

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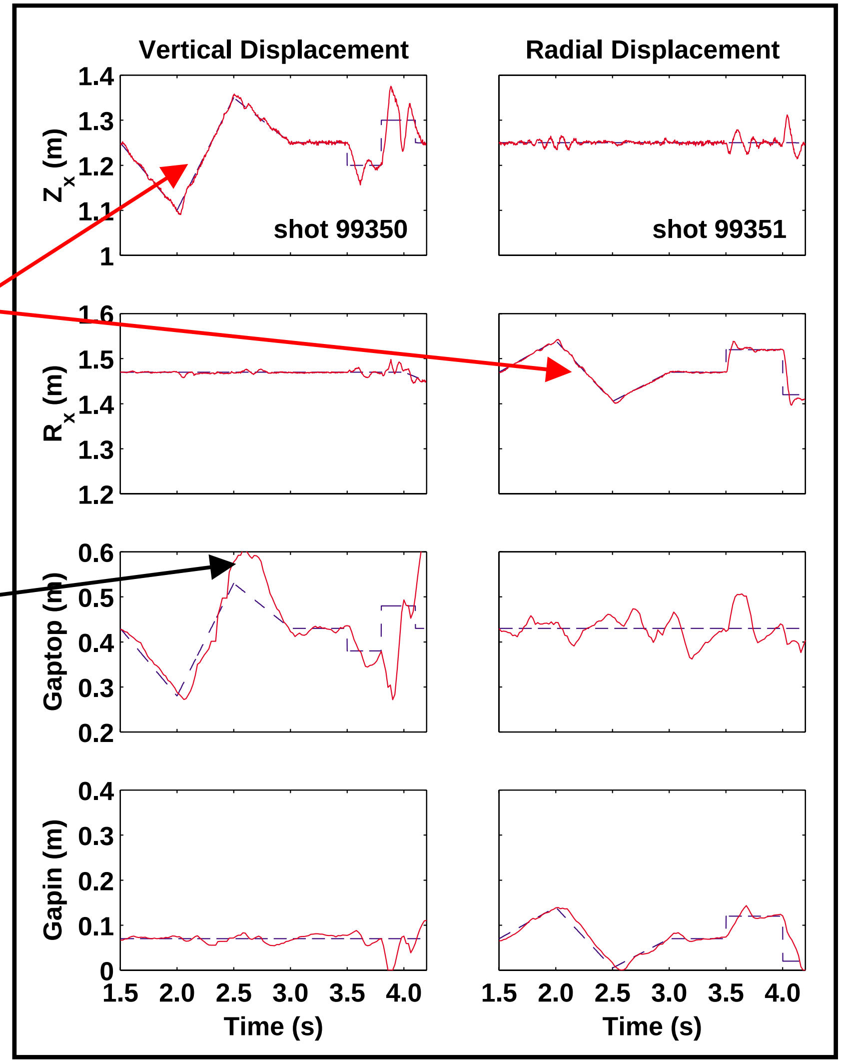
MIMO CONTROLLER, OPTIMIZED FOR X-POINT CONTROL, SHOWS EXCELLENT DYNAMIC PERFORMANCE

- Results of 1st MIMO experiments on DIII-D ('99) were very successful.
- X-point control was emphasized in the MIMO design (higher weights). This produced excellent control of the X-point location
- Vertical/shape control interactions and lesser design emphasis on other shape parameters led to reduced control accuracy.
- Subsequent work has resolved vertical/shape control conflicts. (SOFT 2002)



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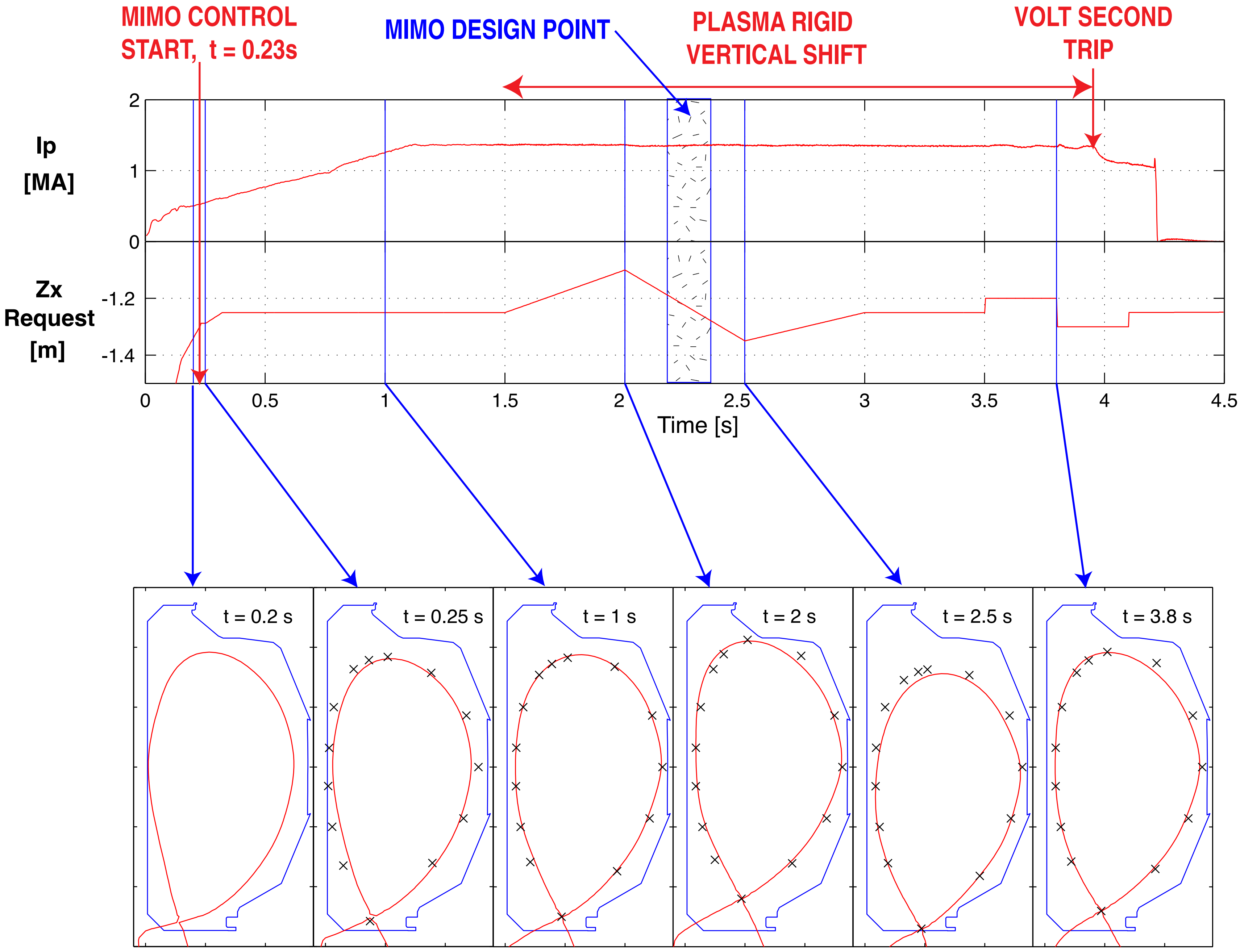
MIMO Controller Linearized About a Single Point Controls an Entire DIII-D Discharge



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