Development and Performance of Model-Based Multi-Input-Multi-Output (MIMO) Shape Controllers

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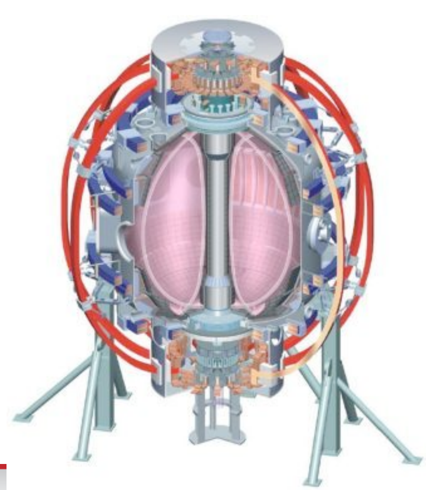

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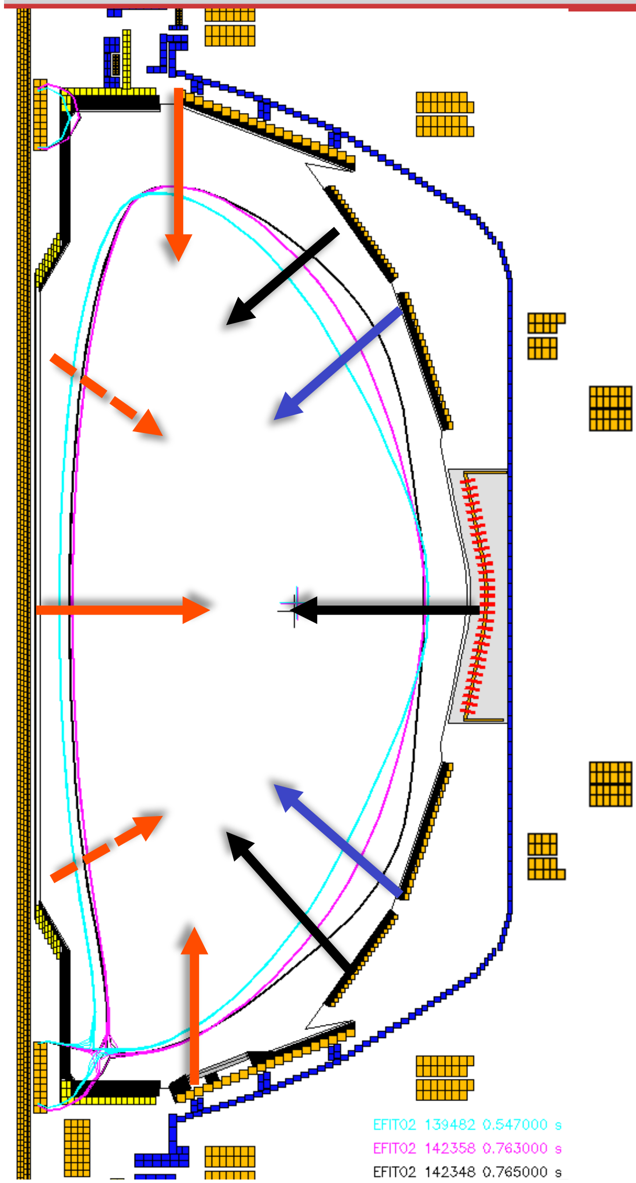
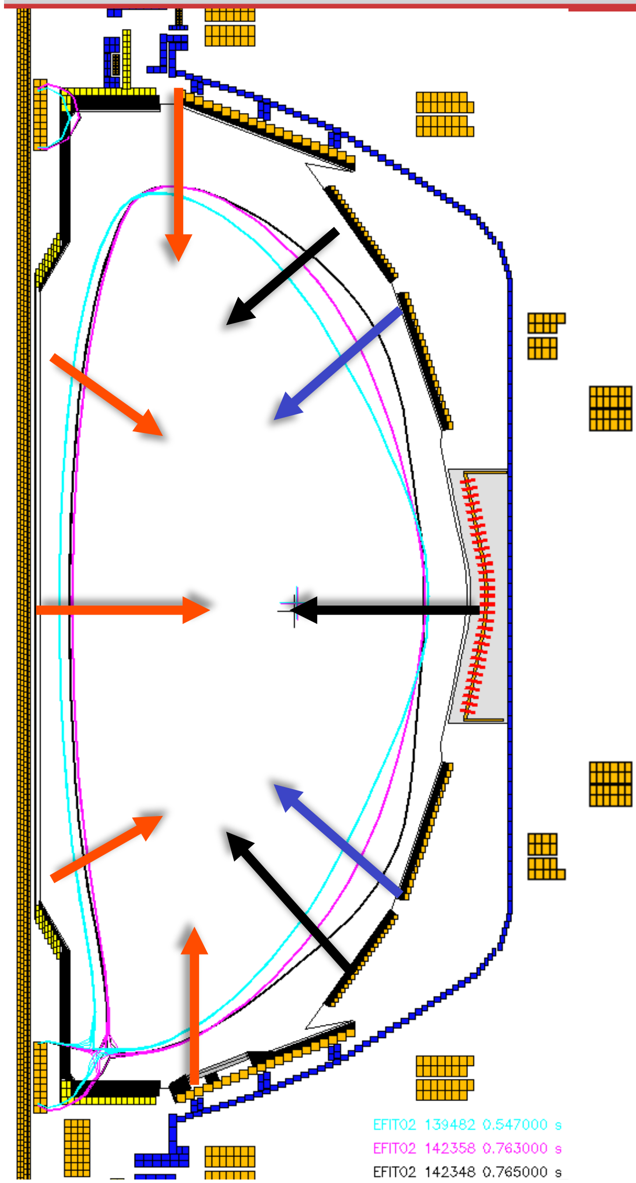
Move from Current Single Input Single Out (SISO) Control to MIMO Control



- Currently each PF coil is used for a single control purpose via a single segment.
- Problem:
  - NSTX-U will be running with taller and higher aspect ratio plasmas. I.e. less vertically stable. Need better coordination between various control efforts specially for the bottom/top gap.
  - Inner gap does not have a PF coil to control.
  - Many control segments are effected by the PF coil that does not control it.
  - No bottom/top gap control segment (We use X-point/SP control segments instead)
- Solution:
  - Use all the segments (add a bottom/top gap segment) together in MIMO control.
  - To prioritize some segments put a weight vector
  - Employ Toksys Model and experimental tuning to develop and test control in closed loop mode.

Implementation of the MIMO Control



- Aim: Be able to request **any shape from user interface** and let the control regulate to the nearest achievable shape.

- We lack the inner gap control and upper/lower gap control for fiducial.
- These are important for high kappa, high aspect ratio shots.

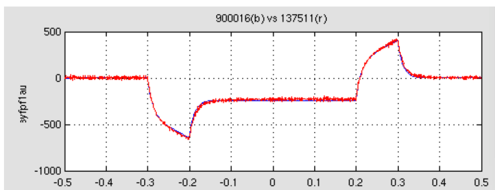
- Black segments in use in all shots.
- Blue tried segments, used for squareness control before (not in full operation).
- Red segments, will be used in this xp.

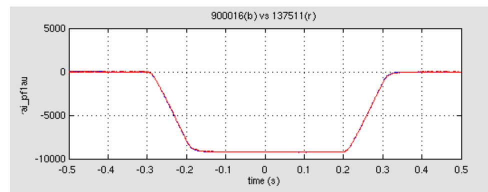
Implementation of the MIMO Control

- MIMO control design: Use the linear toksys model

$$\dot{\mathbf{x}} = A\mathbf{x} + B\mathbf{u}$$

- There is progress in the PS model and toksys integration into NSTX (shown PF1AL response, model versus data).





- Use LQR with a weight matrix, *Q*, to prioritize the control segments of interest (outer gap for example). Defining the cost function

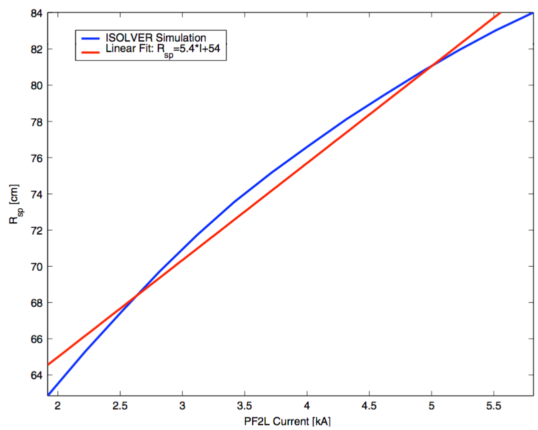
$$J = \int_0^\infty (\mathbf{x}^T Q\mathbf{x} + \mathbf{u}^T R\mathbf{u})dt$$

- The feedback control law that minimizes the value of the cost is

$$\mathbf{u} = -K\mathbf{x}$$

- where *K* is found by solving the Riccati equation (not shown here).

Implementation of the MIMO Control



I_{PF2} versus R_{osp} location via ISOLVER simulations. DC Gain ($\Delta R_{osp}/\Delta I_{PF2}$) Can be obtained via these simulations.

Table 2. Ziegler and Nichols PID controller gains.

Controller type	K_p	T_i	T_d
P	$\frac{1}{K}\frac{T}{L}$	—	—
PI	$\frac{0.9}{K}\frac{T}{L}$	$3.33L$	—
PID	$\frac{1.2}{K}\frac{T}{L}$	$2.0L$	$0.5L$

Sample Tuning based on the K (DC gain), T (Rise time), L (Delay)

- We will compare the toksys MIMO control design to previous year method based on PID tuning based on three parameters (Kolemen, NF 2010)

- In this method, we use K, the DC gain (obtained from ISOLVER), L the delay in the system (known parameter), T the rise time of flux response to the voltage input. The only unknown here is the T which is a function of the T_{coil} and T_{plasma}. T_{coil} is known (Inductance/Res.), T_{plasma} (wall penetration time) can be guessed based on previous experiments.

Experimental Approach (~25 shots 1/2-1 day)

- Depending on the success of the controlled shots, load X-point Height/OSP controlled shot (#139396) or the fiducial (if time permits try the other one after the first half of the xp) (1 shot).
- Add PF4 control developed last year, in the increasing squareness direction which has stabilizing effect (1-2 shots). May skip this if there are issues (not critical).
- Implement designed controllers for RTEFIT/isoflux at the beginning of the flat-top.
  - Add the new bottom and inner gap segments, test (2 shots)
  - Update the M matrix with the previously found values from Toksys Closed Loop or System ID of the experimental data. Detune the optimal gains by ½ to start with (1 shot). Increase gains if no problem (2 shot)
- Tune the control parameters by applying step commands and/or relay-feedback in closed loop:
  - If the control is poor we will focus on retuning during the experiment to get a reasonably stable control to start working with, if it is OK, we will focus on getting more plasma response data (analyzing stability).
  - Retune: Use relay-feedback to tune each coil (PF1AL/U, PF2L/U, PF3U/L, PF4, PF5). We can tune lower set first and use the same values for the upper set (5-10 shots)
  - Response: For each parameter we control change target in a step fashion. Inner gap, bottom/top gap, outer gap, drsep, triangularity and squareness (8 shots). We will try to do multiple parameter scans in one shot but we are not sure if this will work out.
- Towards the end of the XP update the gains based on the information we gather, test control in NSTX-U shapes (5-10 shots).
  - Quantify robustness to varying equilibria. We will try to get NSTX-U extreme shapes (high kappa, elongated plasmas) if the control development is successful.
  - Apply subset of perturbations, in these equilibria to test controllability.