NSTX

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Snowflake Control

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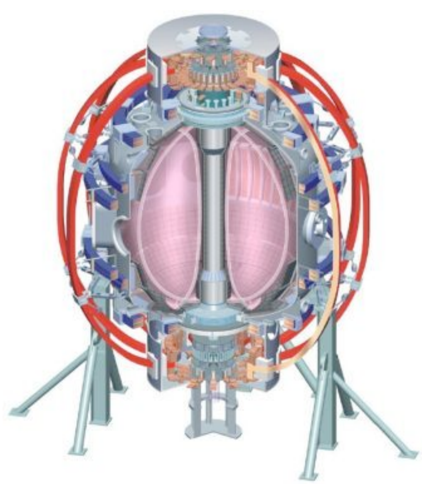
Egemen Kolemen

S. Gerhardt and D. A. Gates

J. Ferron, M. Makowski, V. Soukhanovskii

2011 Research Forum
Mar/16/2011



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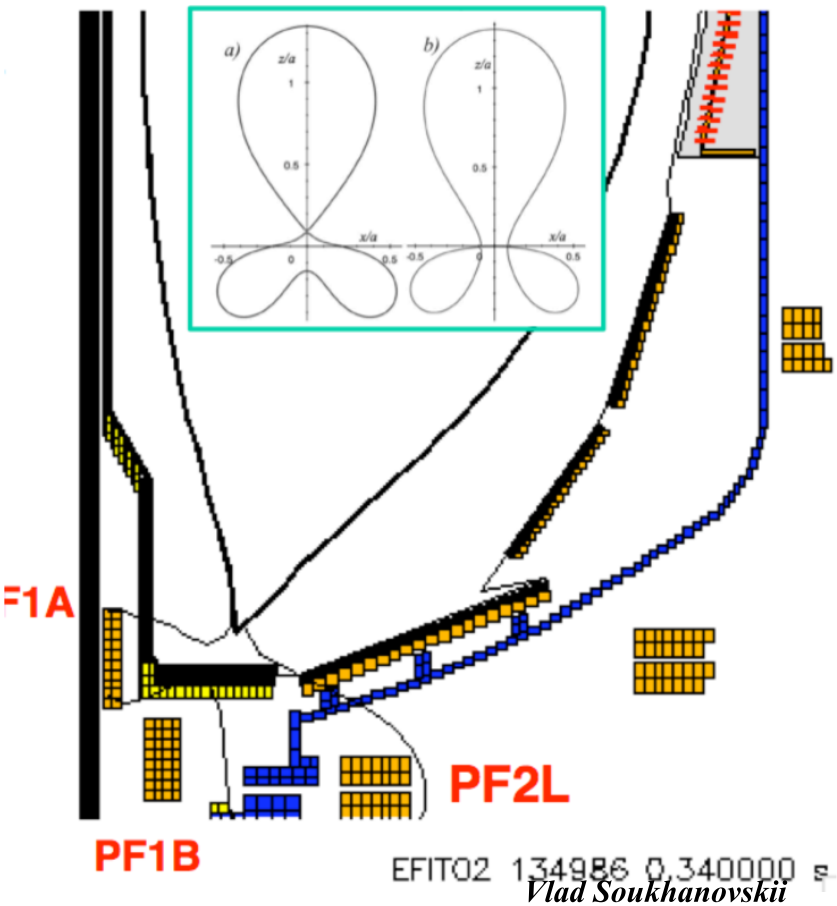
Snow Flake



Example "snowflake" divertor configuration in NSTX.

- "Snowflake" divertor configuration, a second-order null is created in the divertor region by placing two X-points in close proximity to each other.
- This configuration has higher divertor flux expansion and different edge turbulence and magnetic shear properties, beneficial for divertor heat flux reduction, and possible "control" of turbulence and ELMs.
- Implemented and used inner/outer strike point control to test the "snowflake" configuration.

Finding the 2nd X-point (In collaboration with Ferron, Makowski)

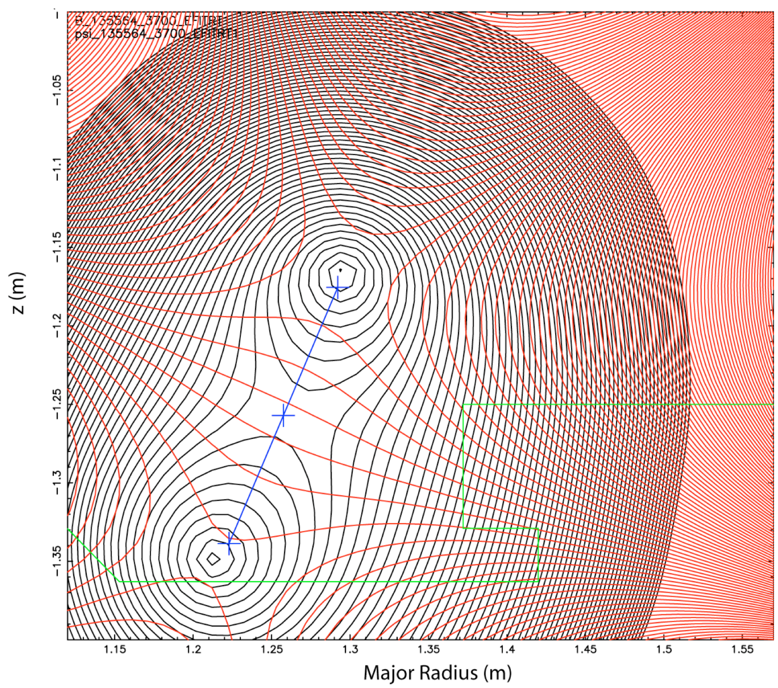


Fig. 1. Result of tracking algorithm as applied to actual data. Plotted are $|B_{pol}|$ contours (black), flux contours (red) and the snowflake center and X-points (blue crosses). The green line corresponds to the location of the floor and shelf of the lower divertor.

- C code already developed for PCS
- Locally expand of the Grad-Shafranov equation in toroidal coordinates:

$$(R+x)\frac{\partial}{\partial x}\left(\frac{1}{R+x}\frac{\partial \Psi}{\partial x}\right)+\frac{\partial^2 \Psi}{\partial z^2} = 0$$

- Keep the 3rd order terms and find the magnetic nulls

$$\begin{aligned}\Psi_{00} &= \Psi_f - \Psi(\rho_f\ \zeta_f) \\ &= \Psi_f - \big[\, l_2\zeta_f + q_3\zeta_f^2 + c_4\zeta_f^3 + l_1\rho_f + 2q_2\rho_f\zeta_f \\ &\quad + (-3c_1 - q_3)\rho_f\zeta_f^2 + \frac{1}{2}(l_1 - 2q_3)\rho_f^2 + (-3c_4 + q_2)\rho_f^2\zeta_f + c_1\rho_f^3 \big]\end{aligned}$$

$$\Psi_1 = \Psi(\rho_1\ \zeta_1) + \Psi_{00}$$

$$\Psi_2 = \Psi(\rho_2\ \zeta_2) + \Psi_{00}$$

- Find coefficients from sample points
- Very fast algorithm with reasonable accuracy.
- J. Ferron from GA will add this C code algorithm in the general PCS.

Snow Flake Control

- Locations of the X-points → feedback-control
- System Id:
  - Utilize Toksys to find the effect of PF1AL, PF1BL, PF2L coils on the separation of the two X-points.
  - Use the new relay feedback system ID in PCS.
- The aim of the control:
  - Primary aim is the distance between the two X-points.
  - Secondary aim relative angle between the X-points.
- Actuator: PF1B as the primary controller, PF1A/2 secondary
  - PF1B is a very effective coil in moving the secondary X-point
  - Not used in any other control loop
  - MIMO using PF1A, PF1B and PF2L will be probably be obtain control objective.

Control the 2nd X-point (In collaboration with Ferron, Makowski)

- Add this fast algorithm with reasonable accuracy in PCS.
- Control both the location of the X-points with PF coils.
  - Need 4 independent actuators for full control
  - Optimal use of the capability we have 2 or 3 PF coils (PF1AL-2L and sometimes PF1B)
  - Control the best combination of properties of interest (Relative distance/ angle between the X-points…)
- After lower snowflake divertor, extend this algorithm to control the upper snowflake configuration as well.
- Time Requested 1 day.

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XMP: Commissioning of the New PCS Phase Transition Fix for X-Point Height Control

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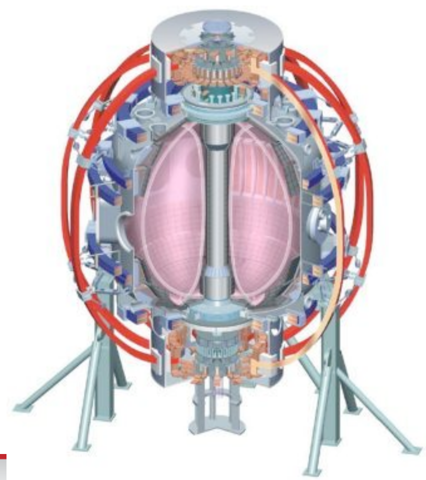

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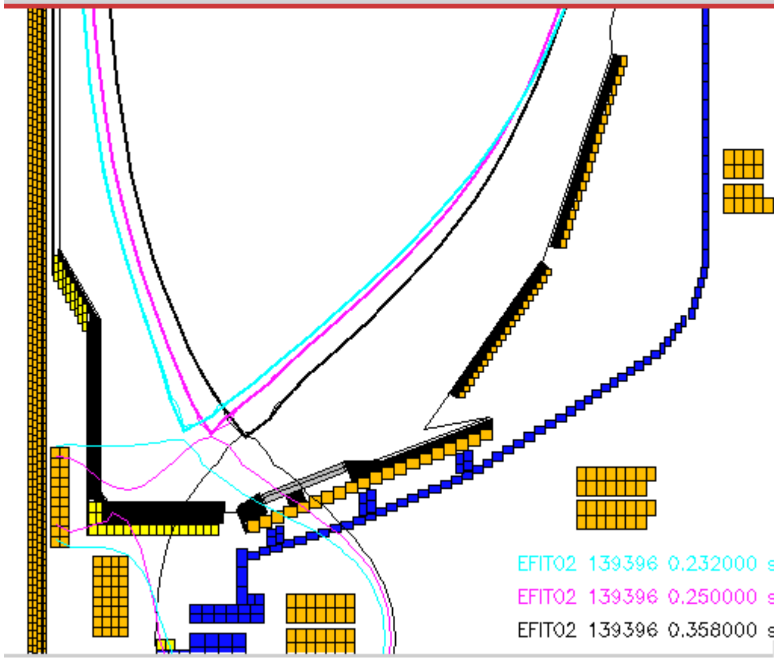
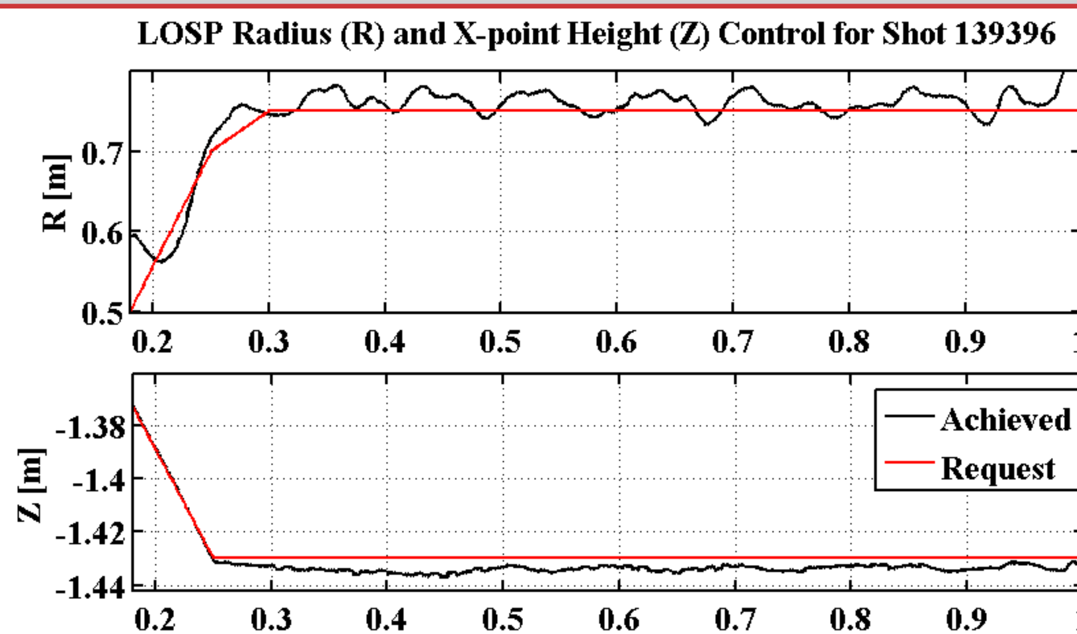
Successful Developed Combined X-point Height / SP Control





Evolution of Plasma Boundary: X-point height roughly constant as OSP ramps

- Tuned via Relay-Feedback.
- Achieved RMS <1 cm X-point height error and <2 cm SP.
- Scenario used for LLD experiments.

Handoff/Transition Issue

- Currently we can't start a control at flat-top. We can only start the control during the transition phase, 70 to 200 ms.
- Took a long time hand tune the beginning of these shots.
- Many people want to use the X-point/SP control but don't want to spend their XP time to tune the transition
- We want to be able to start any control at a given equilibrium. For day-to-day operations, this corresponds to **start**ing strike-point, squareness, x-point etc. controls at the **flat-top of the fiducial**.

For 2011: Solution to “Hand-off” Problem

- Problem when changing between control phases.

- Normal Control has two parts:
  1. Trajectory control: Scenario Development
     - Ex: Fiducial Shot, Isolver developed rough equilibrium, reload a shot that was developed before
  2. Feedback control: Starting from the Scenario Shot, controlling parameters close to the defined values.
- Need: Ability to add these two waveforms.
  - Simply be able to add PID output to the Voltage from the last phase.
  - V = V_equilibrium (flat-top) + PID(error).
- Then, we will avoid “hand-off” problem

XMP: Commissioning of the New PCS Phase Transition Fix for X-Point Height Control

- We are upgrading the PCS to transition as we like between phases.
- XMP Time Request ½-1 day.
- Test that this code is working properly.
- Load a X-point Height / SP Control shot.
- Start the control at flat-top instead of during the transition.
- After fixing possible anomalies for the phase transition, commission the new capability.

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

Egemen Kolemen

D. Humphreys, M. Walker, S. Gerhardt and D. A. Gates

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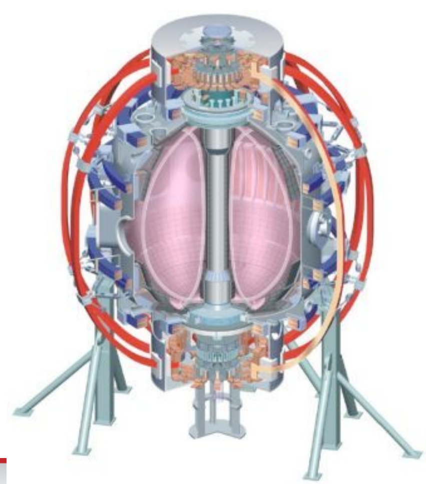
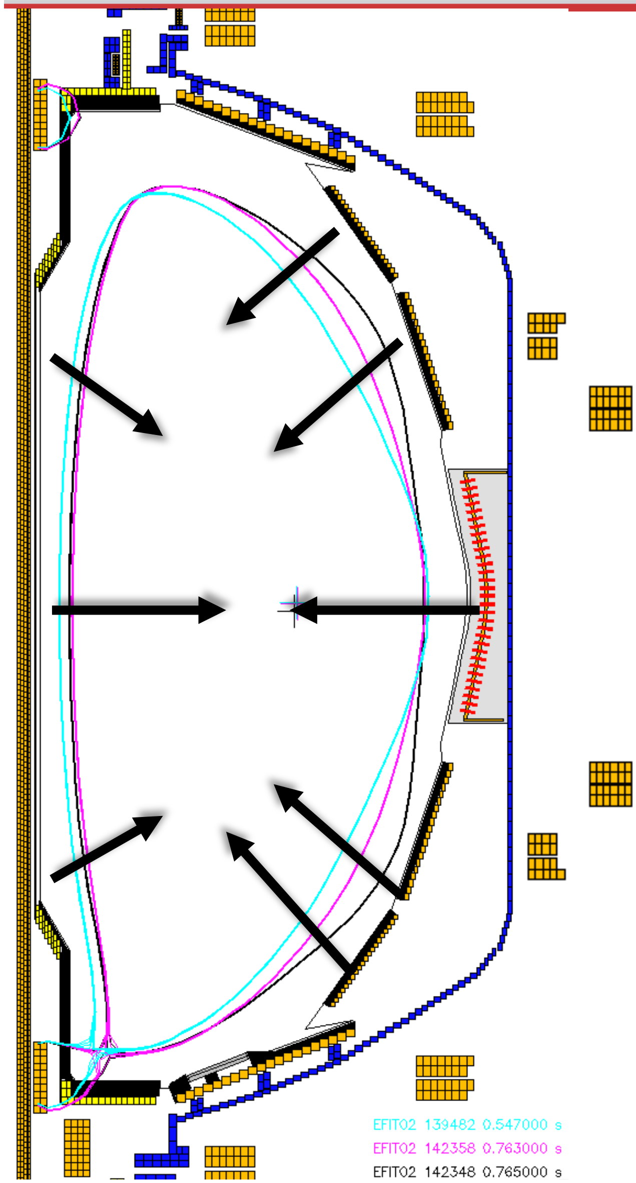
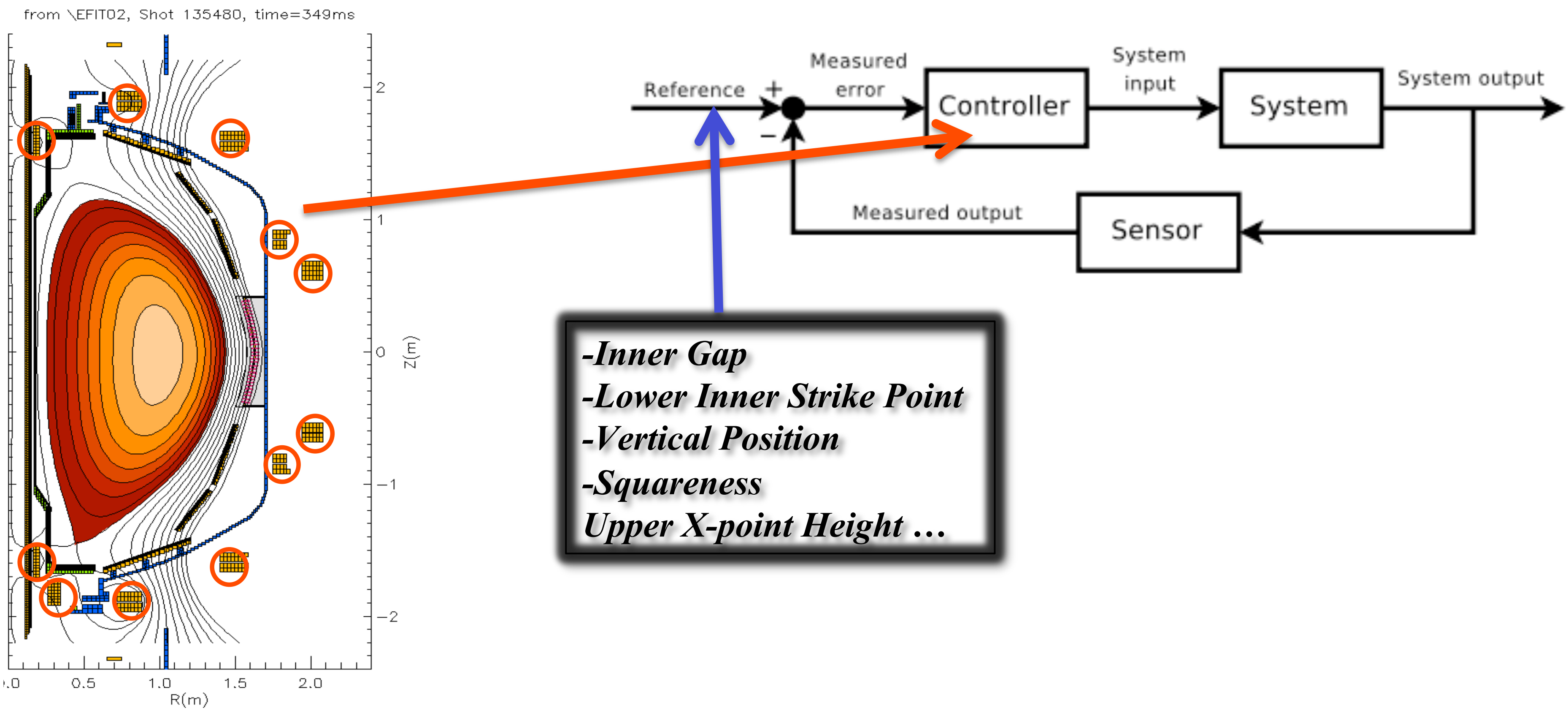


Move from Current Single Input Single Out (SISO) Control to MIMO Control



- 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 priorities some segments put a weight vector
  - Employ Toksys Model to develop and test the control in closed loop mode.

Full Multiple-Input-Multiple-Output (MIMO) Control



- Use all the PF coils to control the plasma shape together.

Background

- This is ITER CC (***ITPA task MDC-18)*** and also an ASC proposal.
- Model-Based Shape Control:
  - Designed based on linear models of plasma/conductor system response
  - Selected as basis for ITER control
  - Necessary to minimize need for experimental time to derive and tune control gains
  - Never used routinely on any operating device
- Infrastructure for NSTX design is mature:
  - Electromagnetic system models, plasma response models well established
  - Some further validation needed (particularly power supply models)
  - PCS in common between DIII-D and NSTX enables common use of RTEFIT/isoflux control scheme, design for PID/Matrix gains

Proposal

- Goals of experiment:
  - Continue development of model based controllers for NSTX
  - Study performance of 1st generation RTEFIT/isoflux multivariable (fully-populated) gain matrices for shape control in NSTX
  - Quantify improvement in shape control performance, validate model calculations

- Perform shape command perturbations to study dynamic response

- Assess interactions, diagonalization of commands:
  - Steps in vertical command
  - Regulation of X-points
  - Study controllability of inner gap

Experimental Approach

- Time Request 1 day
- Implement designed controllers for RTEFIT/isoflux
  - One or two target equilibria (Use the fiducial)
  - Highly reproducible, well-studied shape control target for comparison
  - Piggybacks to complete validation data needed
  - Employ Toksys Closed Loop with PCS to test and validate.
- Apply step commands and/or relay feedback mode in closed loop:
  - Compare dynamic closed loop response with standard gains to new gains
  - Triangle waveforms to quantify constant derivatives vs constant proportional signals
- Change target kappa, inner gap, X-point height
  - Quantify robustness to varying equilibria
  - Apply similar or subset of perturbations

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Real-time Toroidal Rotation Feedback Control

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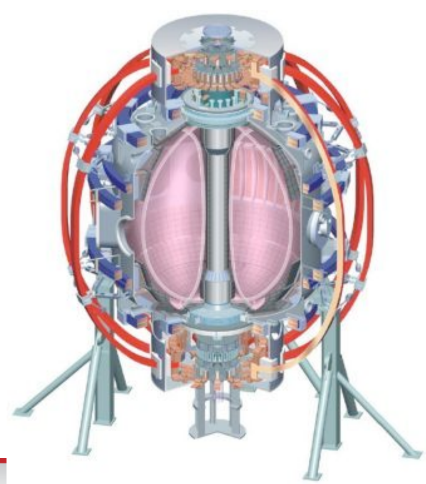

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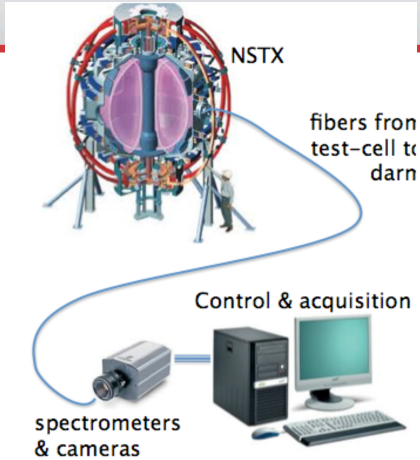
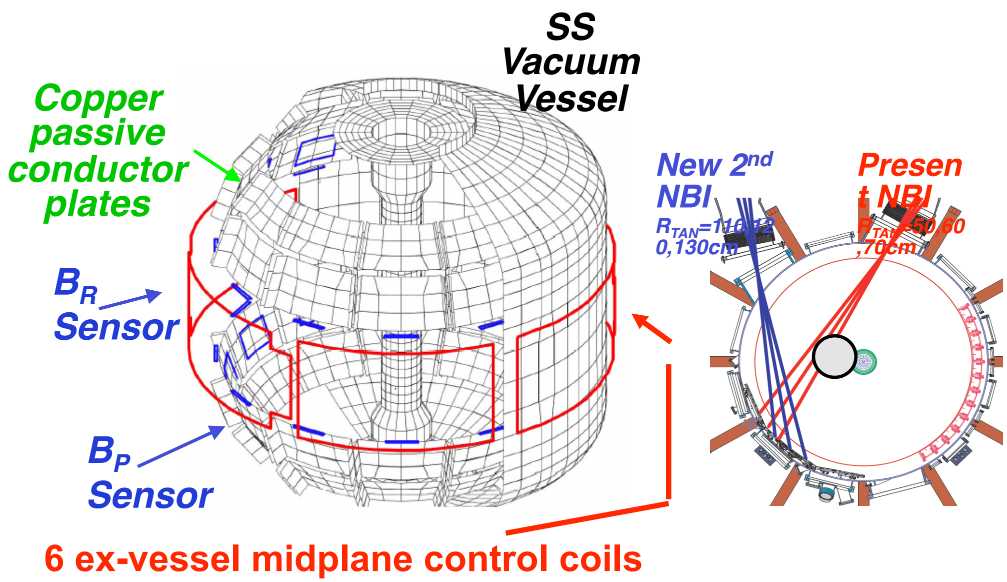
Rotation Profile Control



Real time Rotation Measurement



NSTX NB and Non-Axisymmetric Coil Actuators

- Currently installing the Real-Time Rotation Diagnostic
- Control the toroidal rotation of plasma in NSTX via this diagnostic
- Aim: To attain a desirable temporal & spatial profile
- Rotation profile: rotation shear get rid off micro instabilities small scale eddies (turbulence)
- Also, suppresses long wavelength instabilities – eddy currents

Governing Equations

- Toroidal momentum balance (Goldston, 1986)

$$\sum_i n_i m_i \left\langle R^2 \right\rangle \frac{\partial \omega}{\partial t} + \omega \left\langle R^2 \right\rangle \sum_i m_i \frac{\partial n_i}{\partial t}$$

$$+ \sum_i n_i m_i \omega \frac{\partial \left\langle R^2 \right\rangle}{\partial t} + \sum_i n_i m_i \left\langle R^2 \right\rangle \omega \left(\frac{\partial V}{\partial \rho} \right)^{-1} \frac{\partial}{\partial t} \frac{\partial V}{\partial \rho}$$

Temporal change

$$= \left(\frac{\partial V}{\partial \rho} \right)^{-1} \frac{\partial}{\partial \rho} \left[\frac{\partial V}{\partial \rho} \sum_i n_i m_i \chi_\phi \left\langle R^2 (\nabla \rho)^2 \right\rangle \frac{\partial \omega}{\partial \rho} \right]$$

Diffusion

$$- \left(\frac{\partial V}{\partial \rho} \right)^{-1} \frac{\partial}{\partial \rho} \left[\frac{\partial V}{\partial \rho} \sum_i n_i m_i \omega \left\langle R^2 (\nabla \rho)^2 \right\rangle \frac{v_\rho}{|\nabla \rho|} \right]$$

Pinch

Ignore for initial analysis

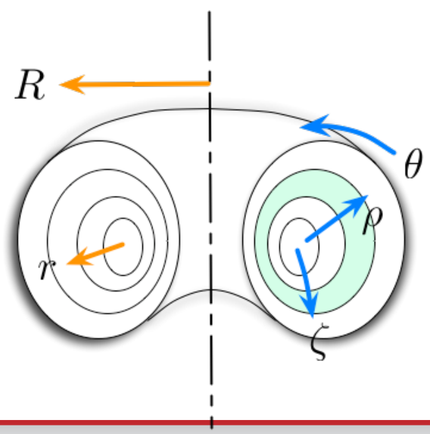
$$+ T_{\text{col}} + T_{J \times B} + T_{\text{bth}} + T_{iz}$$

Torque input

$$- \sum_i n_i m_i \left\langle R^2 \right\rangle \omega \left(\frac{1}{\tau_{\phi cx}} + \frac{1}{\tau_{c\delta}} \right)$$

0

Loss
(charge ex, ripple)



Also, temporal changes are small, ignored.

Model Equations

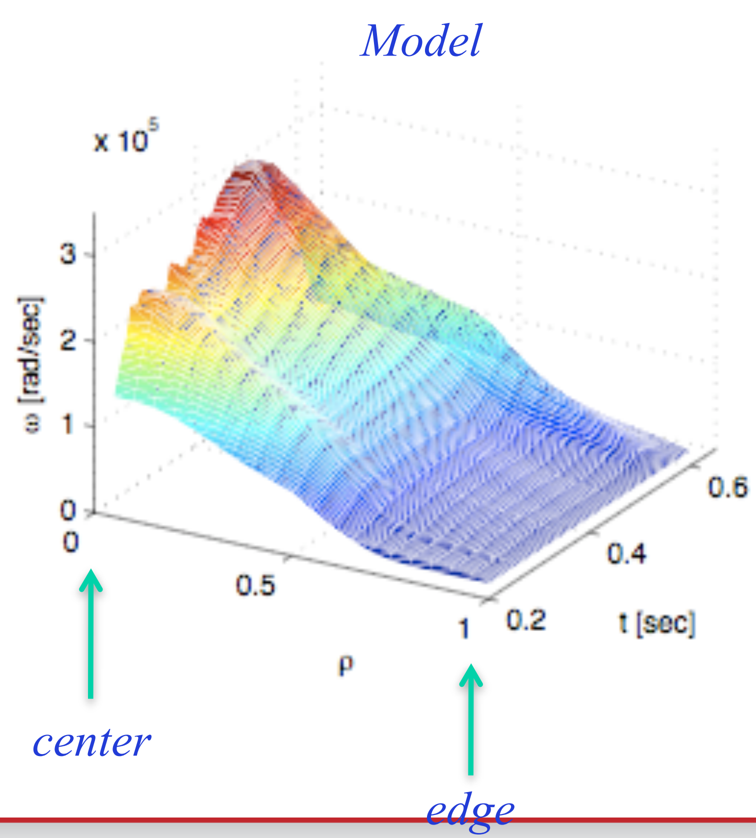
- Toroidal momentum balance

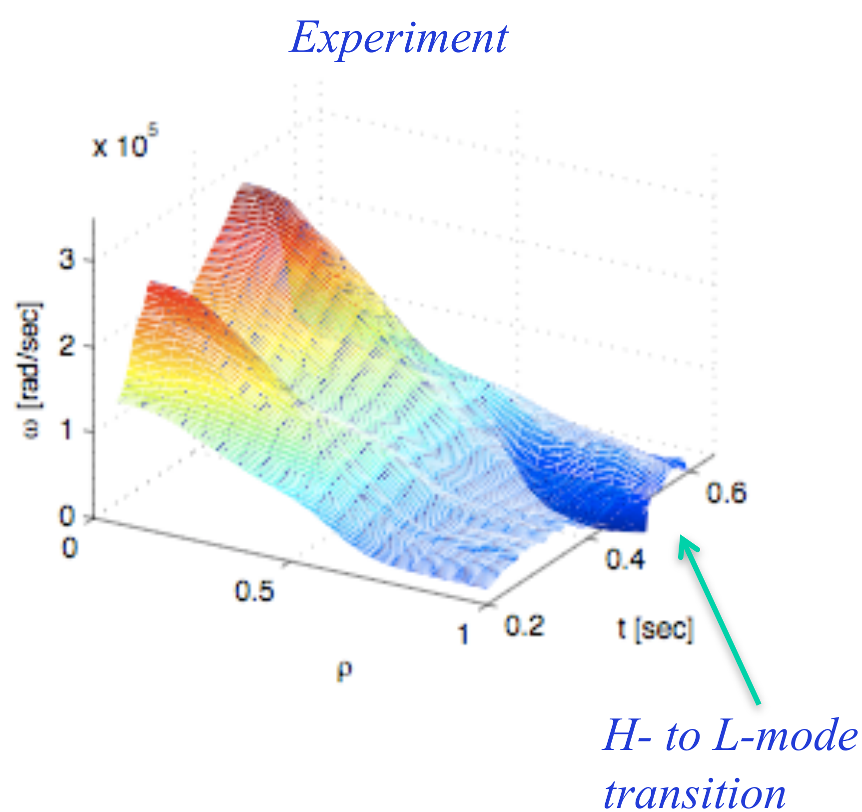
$$\sum_i n_i m_i \left\langle R^2 \right\rangle \frac{\partial \omega}{\partial t} = \left(\frac{\partial V}{\partial \rho} \right)^{-1} \frac{\partial}{\partial \rho} \left[\frac{\partial V}{\partial \rho} \sum_i n_i m_i \chi_\phi \left\langle R^2 (\nabla \rho)^2 \right\rangle \frac{\partial \omega}{\partial \rho} \right] + \sum_j T_j$$

- 1D Linear PDE (parabolic) – diffusion equation with forcing
- Neumann (ρ=0) and Dirichlet (ρ=1) BCs
- Curve fit coefficients (3 shape variables $\left\langle R^2 \right\rangle$ $\left\langle R^2 (\nabla \rho)^2 \right\rangle$,$\frac{\partial V}{\partial \rho}$)
- Coefficients to be supplied from TRANSP: χ_ϕ and $\sum_i n_i m_i$

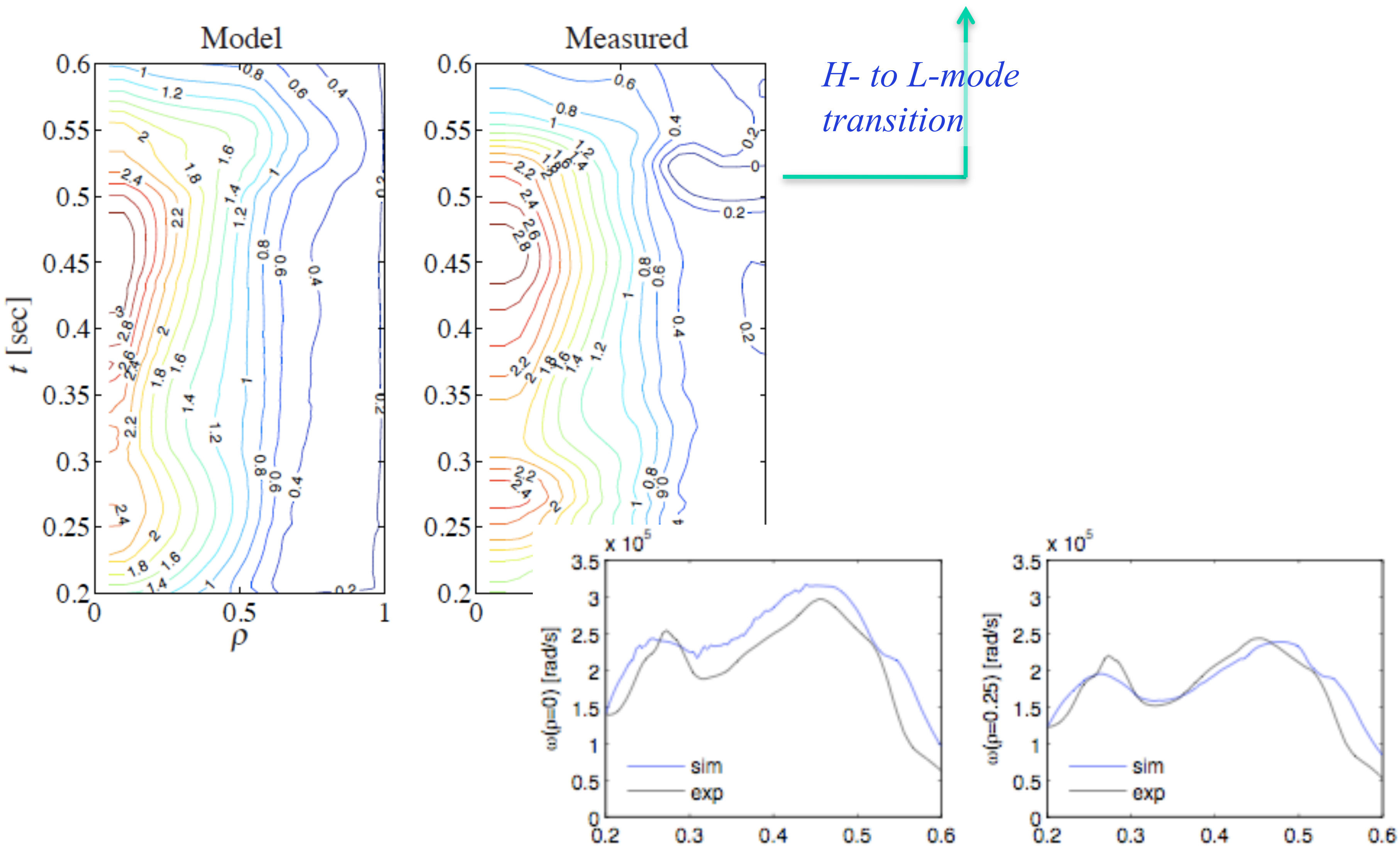
Model Comparison with Experiment

- Numerically solved the reduced order PDE using adaptive time steps (parabolic PDE solver)

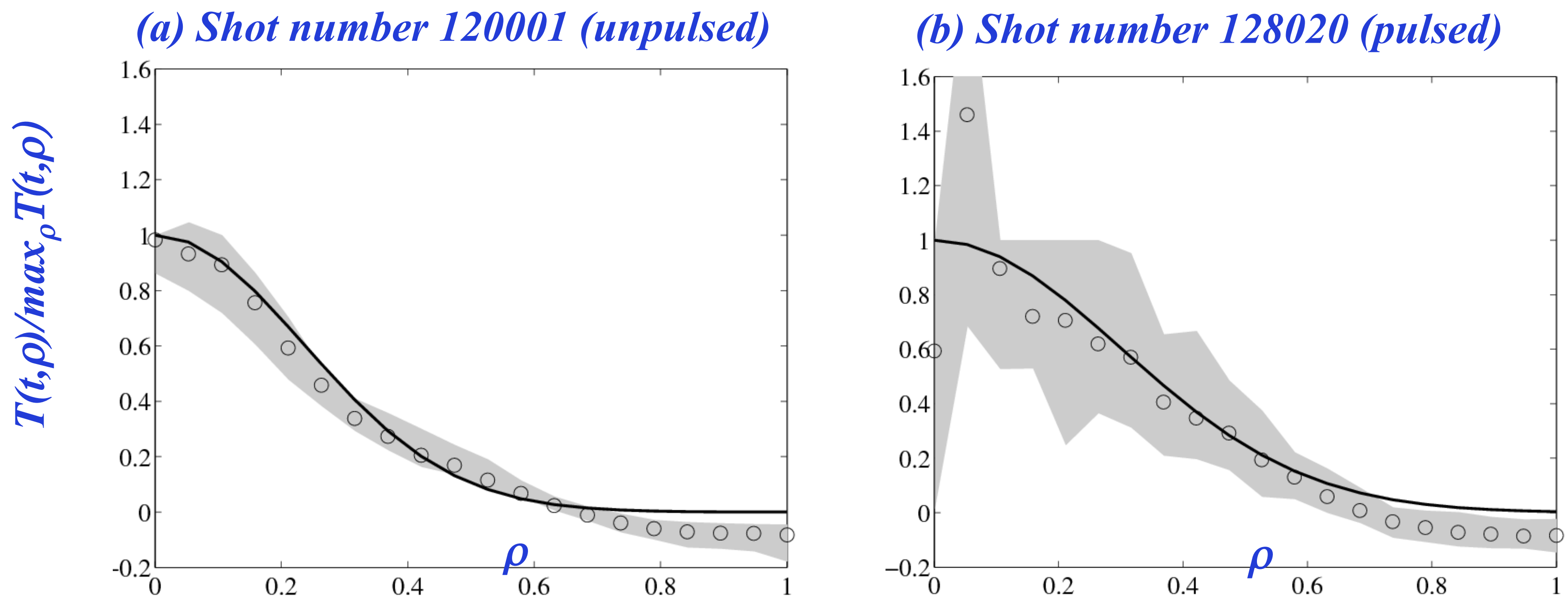




Model Comparison with Experiment



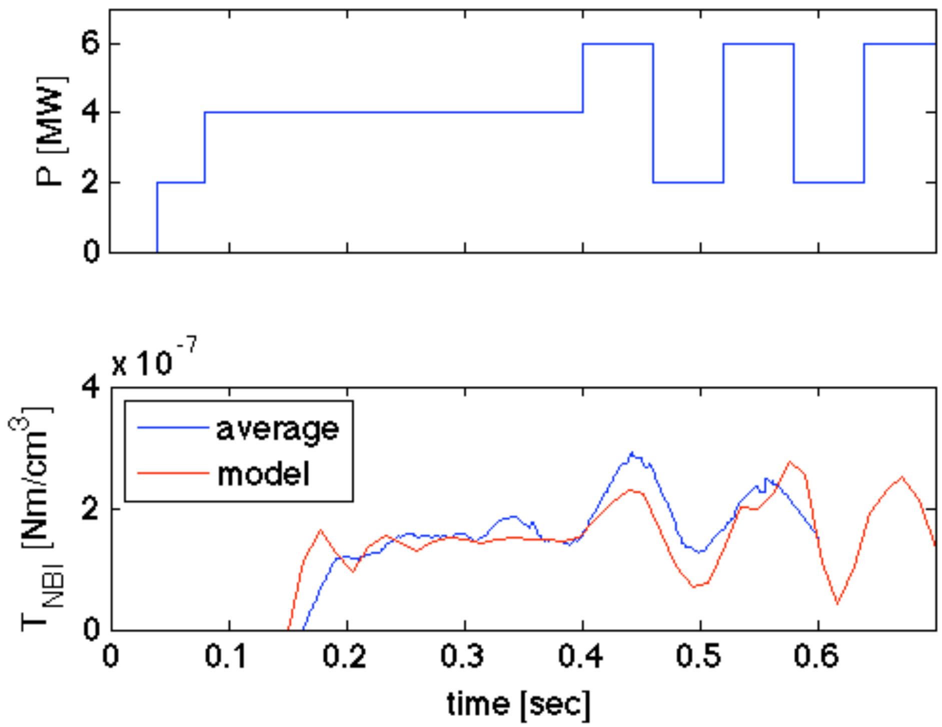
Beam Torque Model



$$T_{NBI}(\rho,t) = \alpha \bar{T}_{NBI}(t) exp\left(-\frac{\rho^2}{2\sigma_{NBI}^2}\right)$$

- Ratio of the T_{NBI} to maximum spatial T_{NBI} at each time point is roughly a Gaussian distribution.
- Separated Neutral Beam Torque in two parts, spacial and time dependent.

Beam Torque Model



Model versus data for Torque profile

- Time dependent part can be modeled as first order order differential equation with I_p as the forcing function

$$\frac{\partial \bar{T}_{NBI}}{\partial t} + \frac{1}{\tau}\bar{T}_{NBI} = \kappa P$$

Neoclassical Toroidal Viscosity

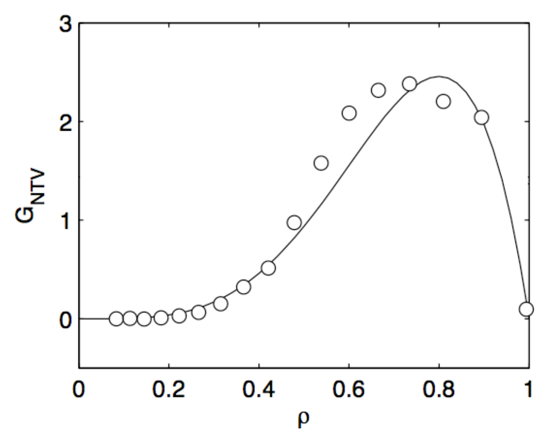
- Motivation: Use NTV torque to control Edge Rotation

$$\sum_i n_i m_i \langle R^2 \rangle \frac{\partial \omega}{\partial t} = \left(\frac{\partial V}{\partial \rho}\right)^{-1} \frac{\partial}{\partial \rho}\left[\frac{\partial V}{\partial \rho} \sum_i n_i m_i \chi_\phi \langle R^2 (\nabla \rho)^2 \rangle \frac{\partial \omega}{\partial \rho}\right] + \sum_j T_j + T_{\mathrm{NBI}} + \mu \left(\frac{B_0}{B_{\mathrm{eff}}}\right)^2 (\omega - \omega^*)$$

- Analyzing TRANSP outputs for various shots to find a simplified torque model for the neo-classical effect of the 3D coils.

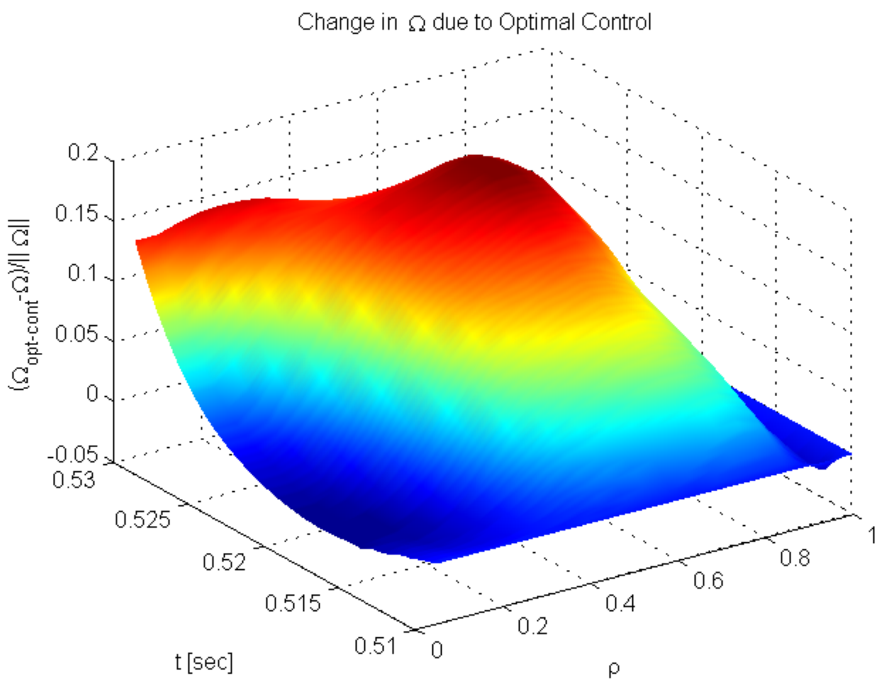
- Simple model as

$$\frac{T_{\mathrm{NTV}}(t,\rho)}{\omega(t,\rho)} = -\overline{G}_{\mathrm{NTV}}(t) G_{\mathrm{NTV}}(\rho)$$



- Need updating after SPA-U in piggy-back mode.

Optimal Control for Rotation Profile



Optimal Ω control with full state control

- Converted PDE to ODE for control purpose

$$\frac{d\Omega}{dt} = A(t)\Omega + B(t)u$$

- Solve the optimization problem to minimize the cost function

$$J = (\Omega(t_f) - \Omega_{req})^T S(\Omega(t_f) - \Omega_{req}) + \int_{t_0}^{t_f} u^T R u$$

- The feedback control law that minimizes is given by differential Riccati equation.

- Example shows where an average of 10% change in Ω is requested to be achieves in 20 ms.

XP Prerequisites/Time Request

- Time Request 1 day.
- Before the XP, We expect to do offline analysis in the piggyback mode while other experiments are running and test the control algorithm in the Toksys close loop simulation.
- Prerequisite:
  - Update PCS to take the rotation measurements.
  - Add a new control in PCS to take these measurements and use it to control the beam and SPAs
  - Beam control is similar to BetaN control, SPAs will need to be added.
- In the XP
  - Test the Beam control of rotation magnitude.
  - Test the RWM coils to change the rotation gradient at the edge of the plasma.
  - Finally, we combine these two sets of actuators to control the full rotation profile.