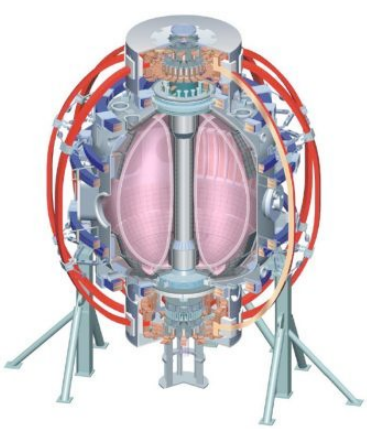
Implementation, Testing and Tuning of the Squareness Control with PF4

Egemen "Ege" Kolemen, S. Gerhardt, D. Gates

2009 NSTX Research Day, ASC
Room B-318
December 2nd, 2009



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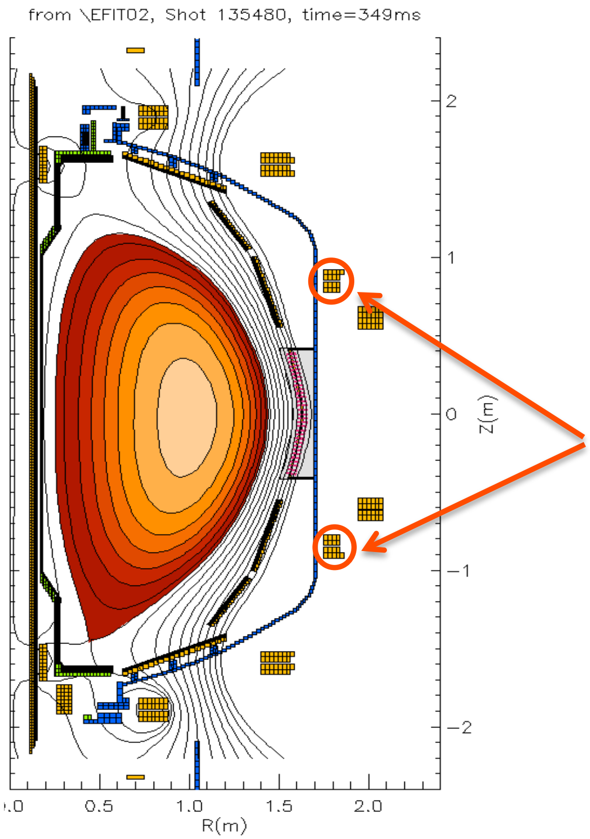
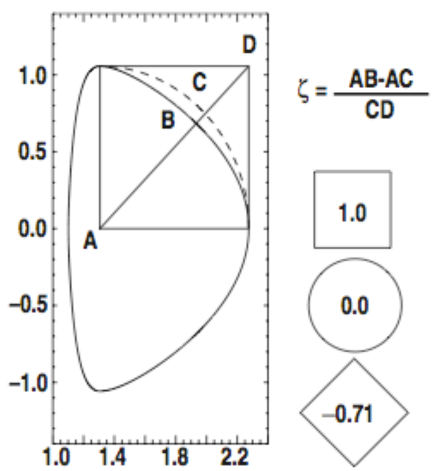
PF4 Coils Will Be Operational



PF4 coils



Squareness

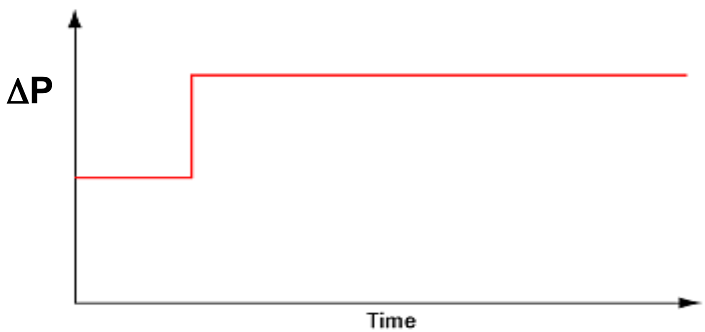
- This year PF4 control will be turned on.
- Tests:
  - Coil protection hardware
    - PF4-PF5 interaction
  - Modifications to PCS
- Incorporate real time PF4 coil inputs in the control.
- We propose to control **squareness** and **the boundary shape** via PF4 coils.

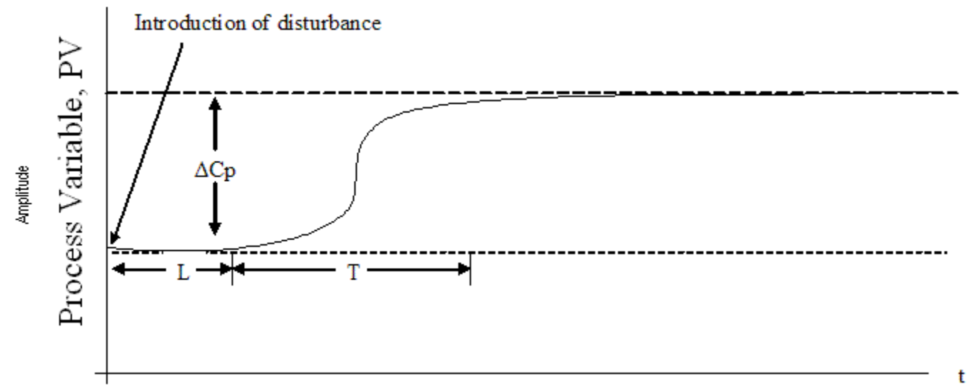
Squareness Control with PF4 Coils: System ID

- System Id: Identify the effect of these coils on the boundary shape.

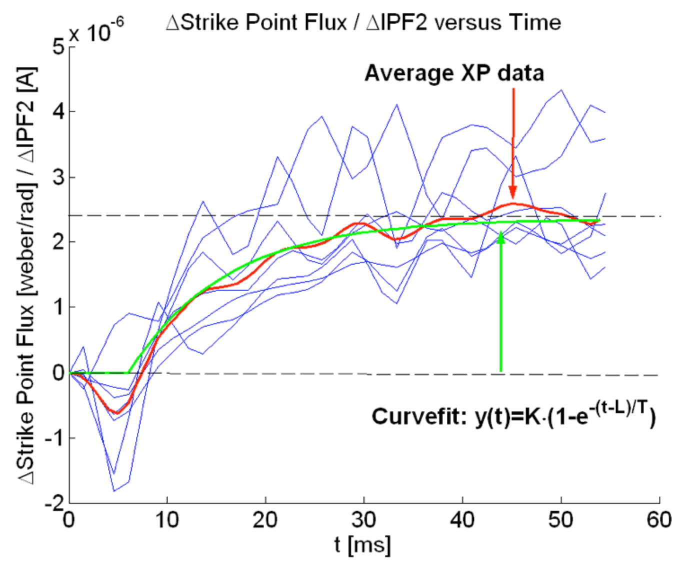
$$\dot{y}(t)T + y(t) = Ku(t - L)$$

- Last year: Reaction Curve Method





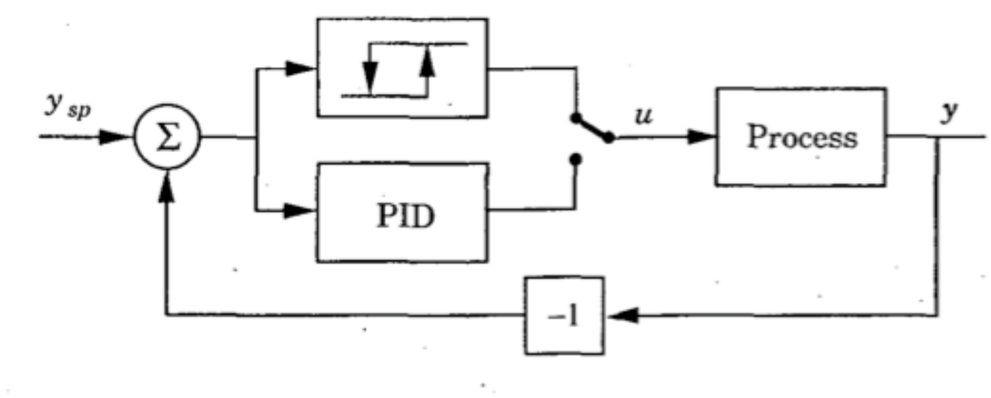
- Results from last year:
- Problem:
  - Many shots needed
  - Not precise

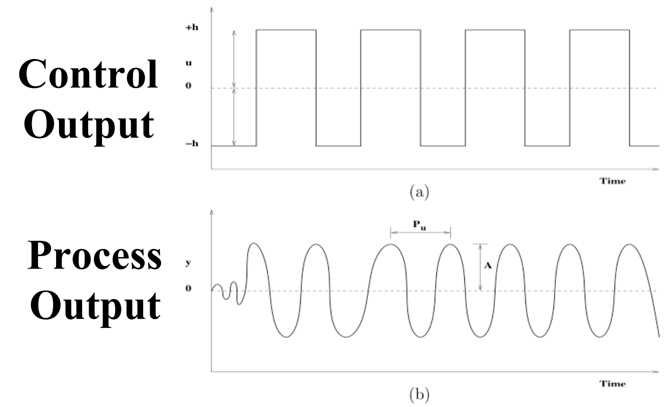


	K_p	K_i	K_d
P	$(\Delta P/\Delta C_p)\bullet(T/L)$	-	-
PI	$0.9\bullet(\Delta P/\Delta C_p)\bullet(T/L)$	$(\Delta P/\Delta C_p)\bullet(3.3\bullet T/L^2)$	-
PID	$1.2\bullet(\Delta P/\Delta C_p)\bullet(T/L)$	$(\Delta P/\Delta C_p)\bullet(2\bullet T/L^2)$	$(\Delta P/\Delta C_p)\bullet(T/2)$

Squareness Control with PF4 Coils: System ID

- This year: **Auto-tuning with Relay Feedback Method**





- When we reach this closed-loop plant response pattern the oscillation period (P_u) and the amplitude (A) of the plant response can be measured and used for PID controller tuning.

	K_c	τ_I	τ_D
P	$0.5K_{cu}$		
PI	$0.45K_{cu}$	$P_u/1.2$	
PID	$0.6K_{cu}$	$P_u/2$	$P_u/8$

where $K_{cu} = \dfrac{4h}{\pi A}$

- Only a single experiment is needed.
- Closed loop: More stable

Squareness Control with PF4 Coils: Tuning

- Control theory will be used to find the optimal squareness control.
- A multi-input, multi-output (MIMO) algorithm for squareness may be needed.
  - PF4 and PF5 coupling: Very close
  - PF1 and PF2 coils controlling inner and outer strike points.
  - First time all the coils in a feedback loop.
  - Strong possibility of the cross coupling between these control loops
    - Possible instabilities or reduce performance
- Requested Time: 1 day

- Backup Slides

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Impact of Outer Squareness on High-κ Discharge

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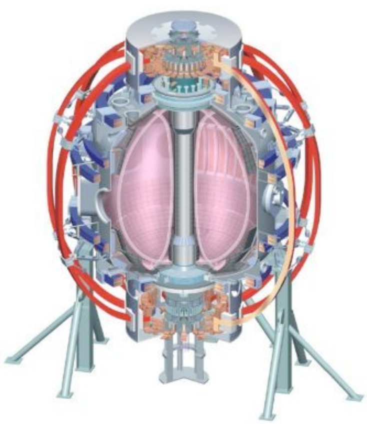

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LLD: Increasing Radiated Power

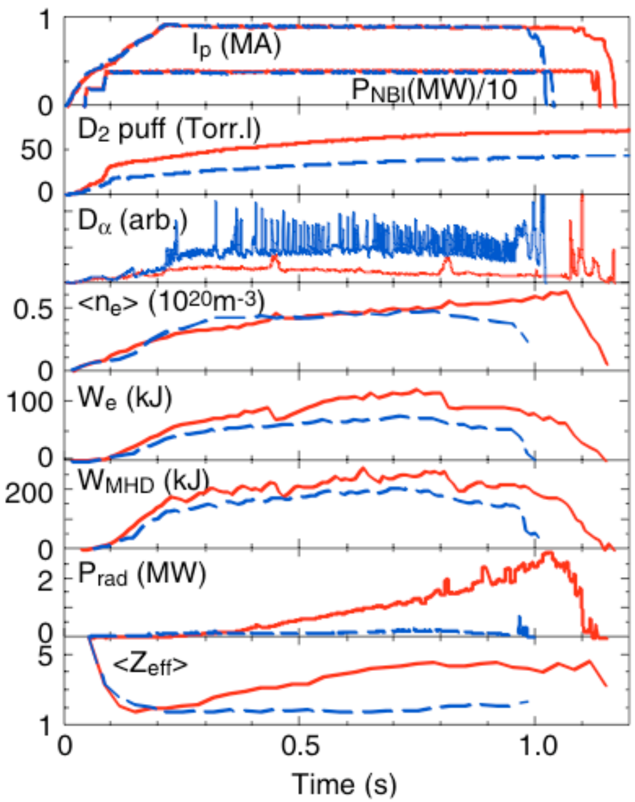


Figure 2. Time evolution of representative plasma parameters for similar discharges without (129239-blue dashed) and with (129245-red solid) 260 mg of lithium applied by the two lithium evaporators.

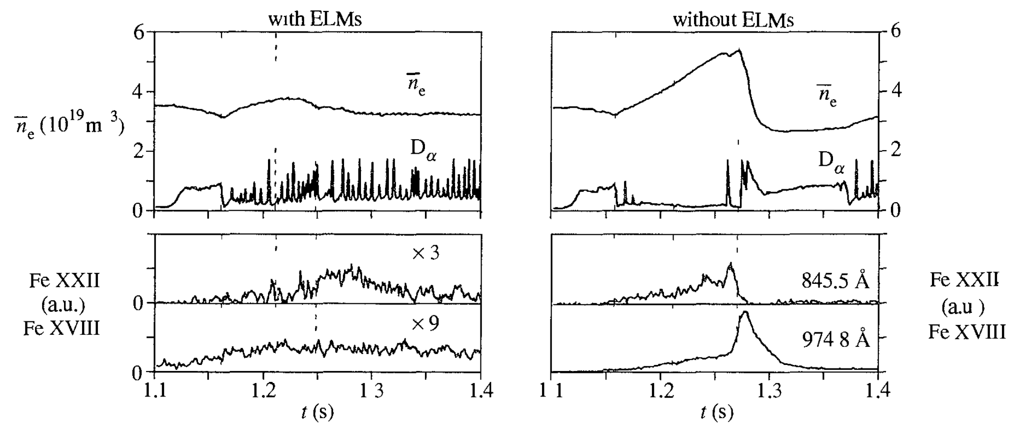
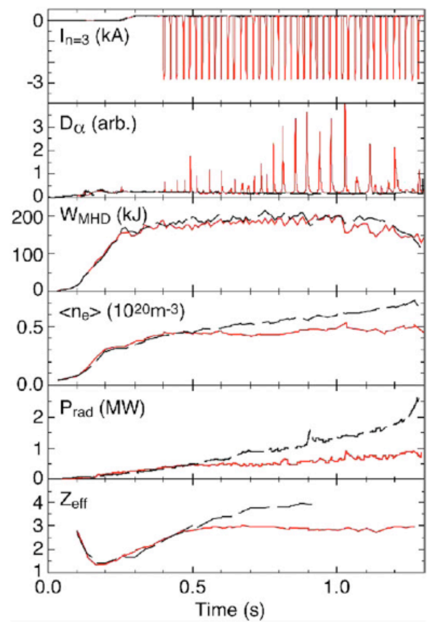


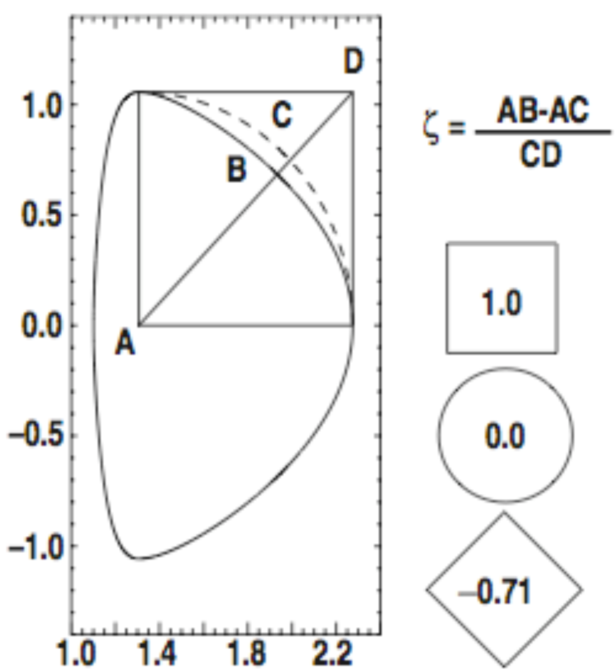
Fig. 7.17.2 Discharges with and without ELMs, showing the increase in electron density and impurity accumulation associated with the ELM-free case. Note that the iron emission line signals are amplified in the case with ELMs (ASDEX Team, Nuclear Fusion 29, 1959 A989))

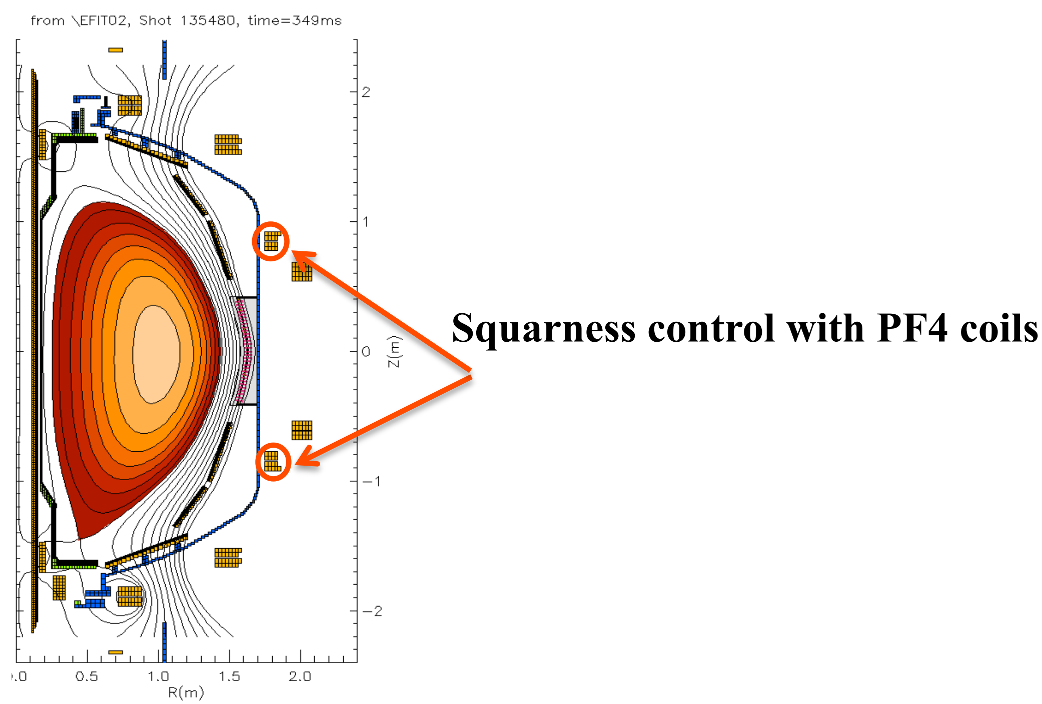
- Monotonous increase in P_{rad}, radiated power. (Plasma Phys. Control. Fusion 51 (2009) 124054 M G Bell et al.)
- Due to increase in the radiation from impurities (Iron/Carbon emissions)

Induce ELMs to Take the Impurities Out

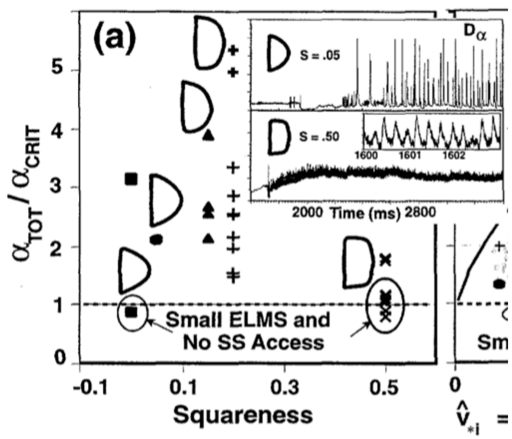


- Induce ELMs to get rid of the impurities
- What are the free shape parameters we have to change the instability boundary?
  - Triangularity (X)
  - Elongation (X)
- PF4 coils gives squareness control.





Effect of Squareness on Stability



Effect of squareness on edge pressure gradient relative to ballooning limit

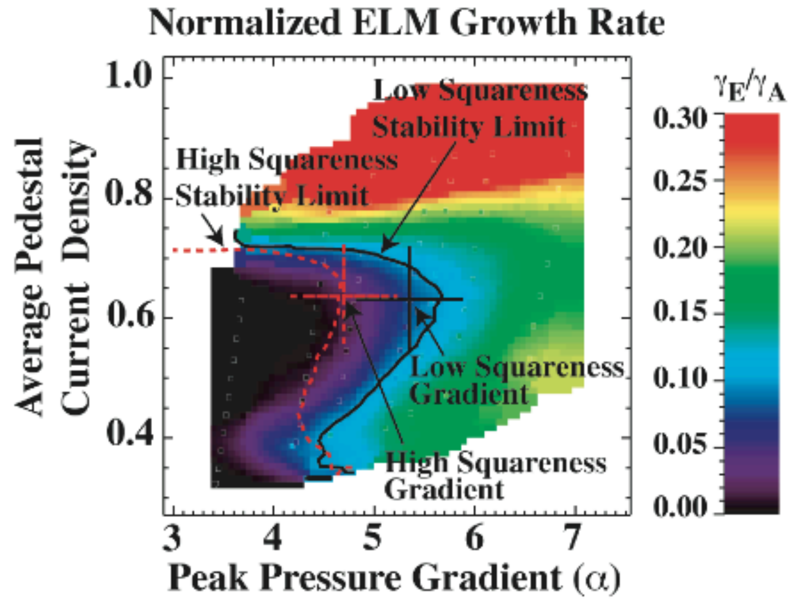
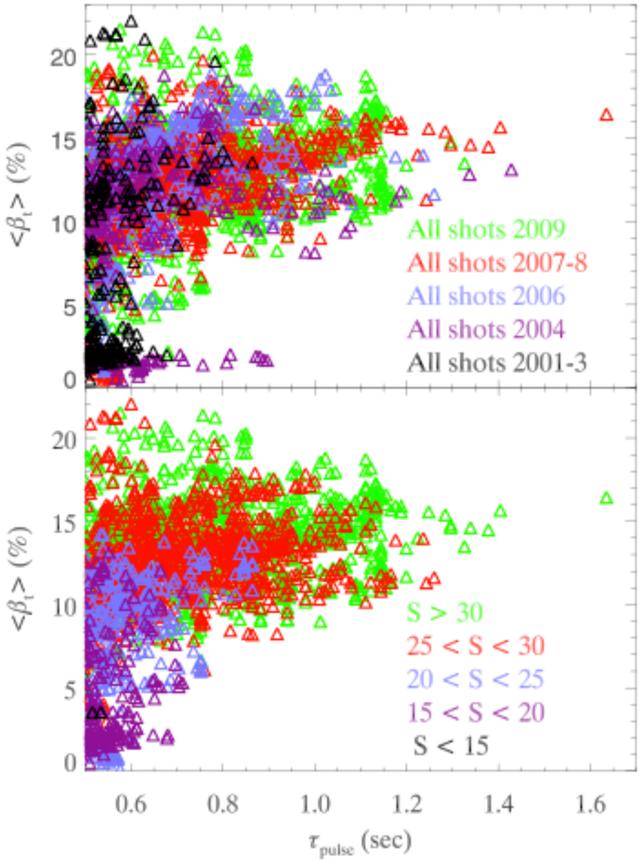


FIG. 12. The edge stability map for low squareness hybrid discharge. The stability boundary contour for $\gamma_{ELM}/\gamma_A = 0.1$ is shown by the black curve. The stability boundary contour for the higher squareness discharge is shown by the red curve.

- Squareness changes the stability boundary and thus effect ELM formation
  – The Effect of Plasma Shape on H-mode Pedestal Characteristics on DIII-D, T. H. Osborne
  – Pedestal Performance Dependence Upon Plasma Shape, A. W. Leonard

Squareness on Pulse Length



B_t versus t_{pulse} range for NSTX

- Even without LLD
  - Improved NSTX operation range
  - Optimization of squareness may lead to longer pulse length.
- Experiment:
  - Scan the squareness for high kappa.
  - The choice of plasma current and torodial field will be determined later.
- Time Request 1 Day

- Backup Slides

Development of Fiducial Shots with LLD: Strike Point Control Improvement and Incorporation in Regular Operation

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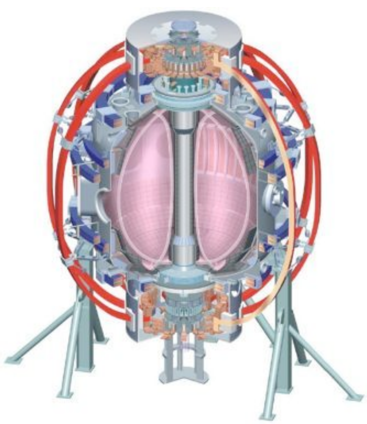
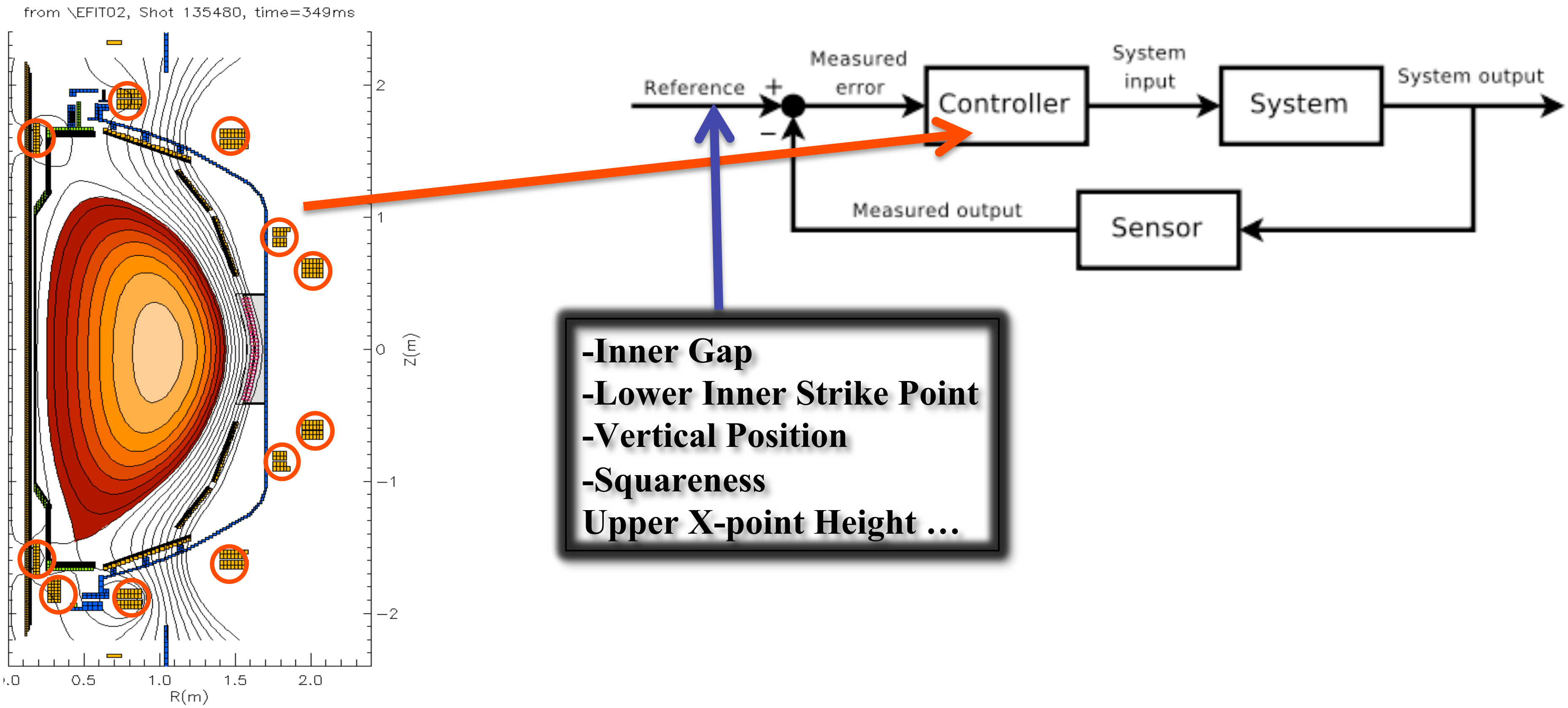


Full Multiple-Input-Multiple-Output Control



- Long term aim:
  - Use all the PF coils to control the plasma shape together.
  - Very hard to implement at once.
  - Incrementally increase the control capability to reach aim

Developing a New Fiducial with LLD

- This year NSTX will need a new fiducial shot development due to the new restrictions and requirements due to LLD installation.

- We can’t let the strike point hit the LLD (at least not routinely)

- Medium δ shots may be part of regular XPs.

- Strike point controllers are operational but they are still not part of the regular run.

Experimental Plan for the New Fiducial

We propose:

1. Improve control: We will be adding derivative gain and tuning the controllers for better performance (XMP):
   - Add I to PF3
   - Add D to PF2 for strike point control
   - Test Integral Fix

2. Add upper strike point controllers: Currently, the strike point controllers work only for the lower side, we will implement the upper strike point controller in PCS.

3. Improve transient phase: We will study and tune the start phase to avoid the plasma touching the lower plasma boundary.

- Machine Time Requested :1 day (minimum ½ day)

- Backup Slides

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Combined X-point Height and Strike Point Control

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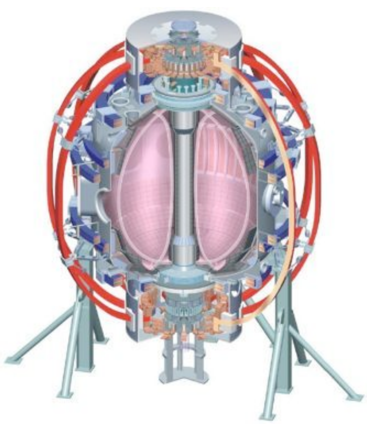

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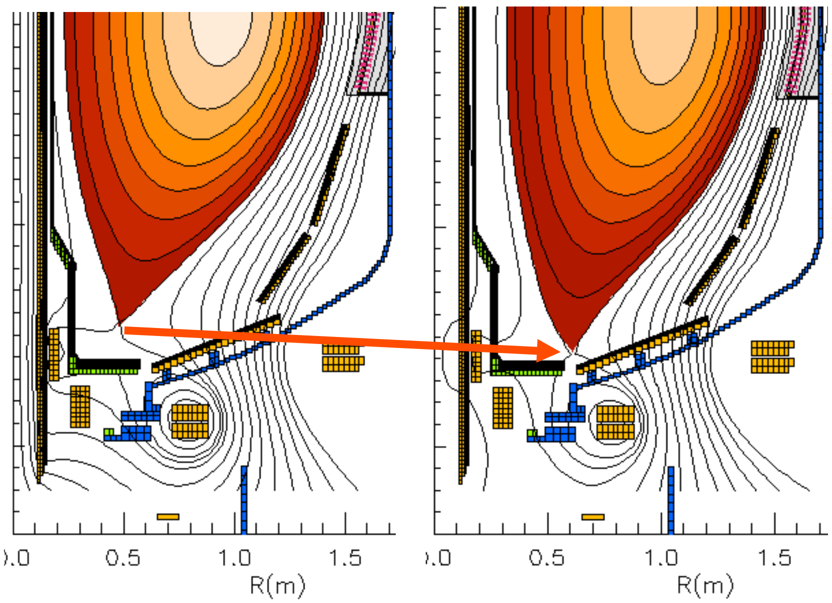
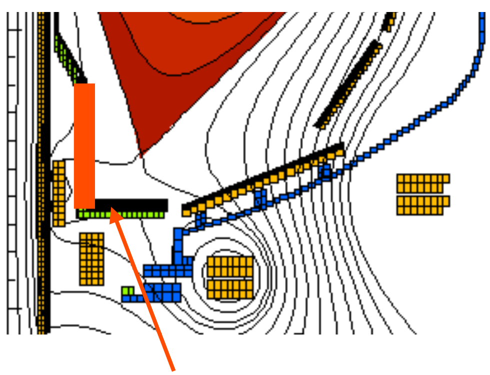
Previous Year: Inner Strike Point Control



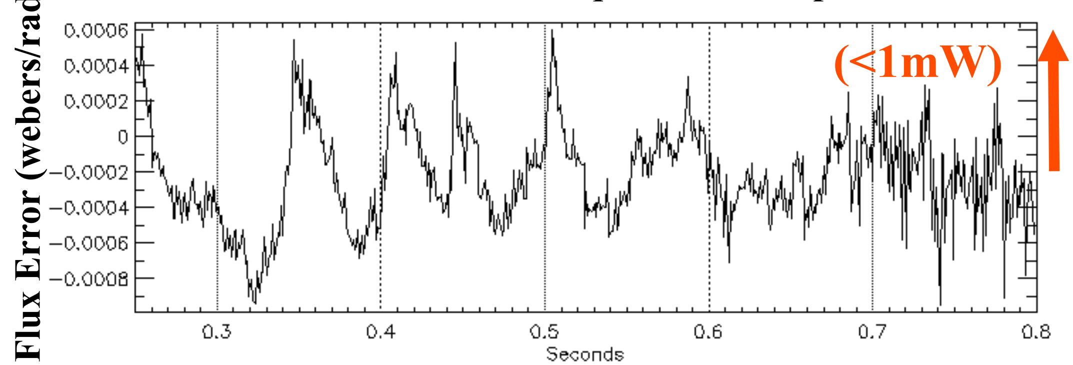
X-points bifurcation



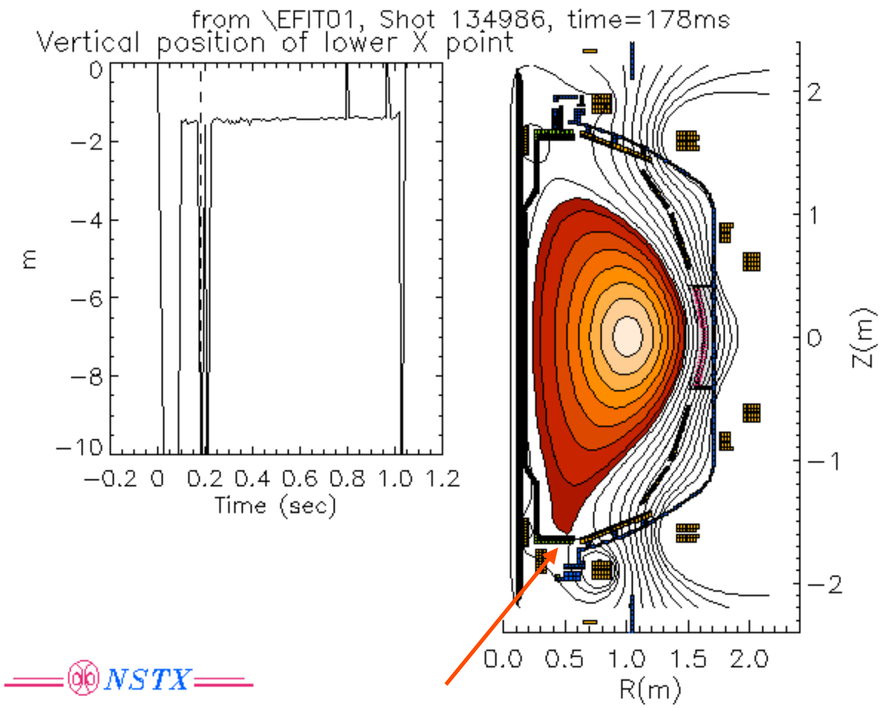
Segment to control inner strike point

- The outer-strike point controller kept the controller at requested position but problems during the transition
- During the transient phase of the discharge, equilibrium bifurcated to a nearby solution with a low X-point.
- Algorithm was jumping from one solution to the other one.
- To make more stable plasma: Added inner strike point controller.

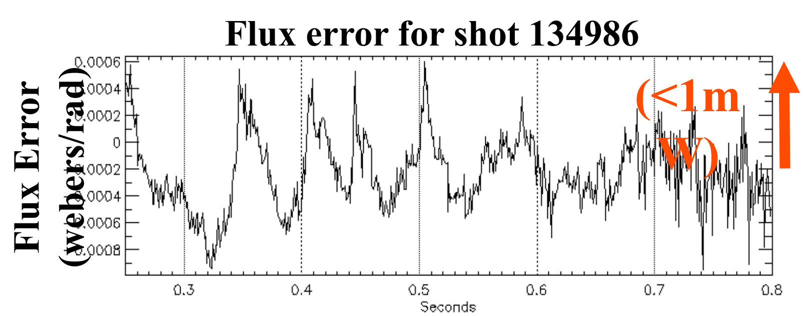
Flux error between real and requested strike point, 134986



Improvement Needed for Transient Phase: X-point Height Control



Plasma touching the vessel During transient



- Problems with the transient phase of the shots with the outer strike point controller on.
- The X-point was touching the vessel wall.
- Last year, inner-strike point control instead of X-point control
  - insufficient run time to implement X-point controller
- Use PF1AL to control X-point height
  - System Id: Relay Feedback
  - If necessary, include MIMO controller including PF2L
  - Tune PID
- Time Requested: 1/2 - 1 day

- Backup Slides

Snowflake Control

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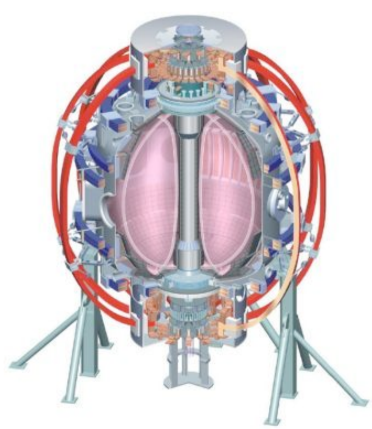

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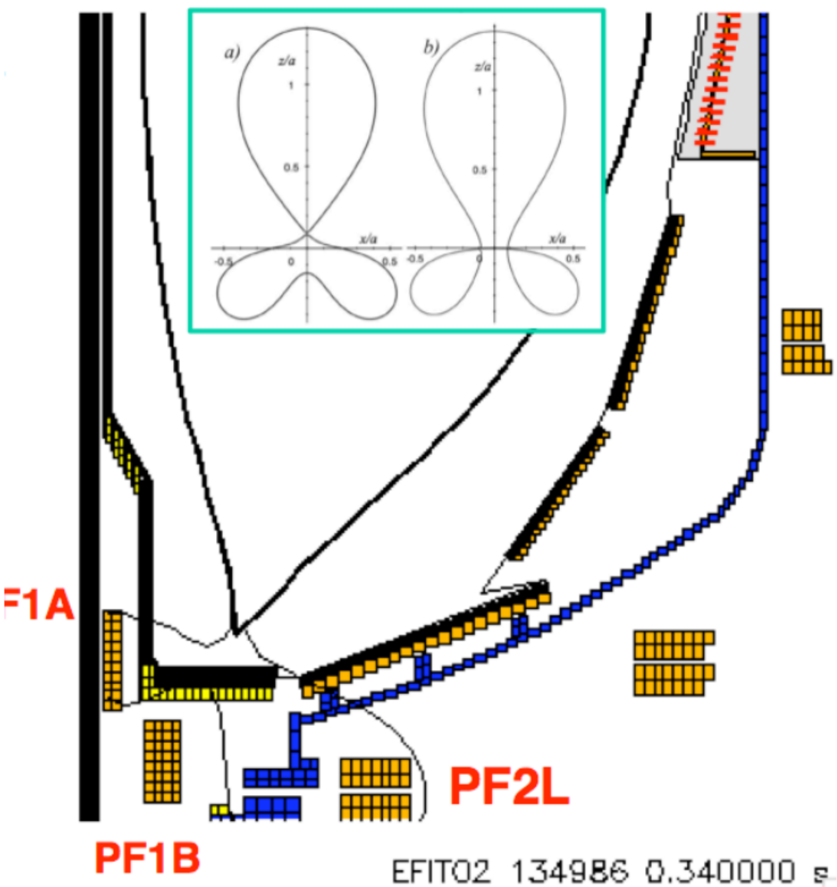
Snow Flake

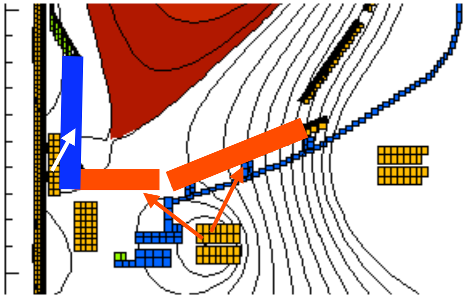


Vlad Soukhanovskii

Example "snowflake" divertor configuration in NSTX.

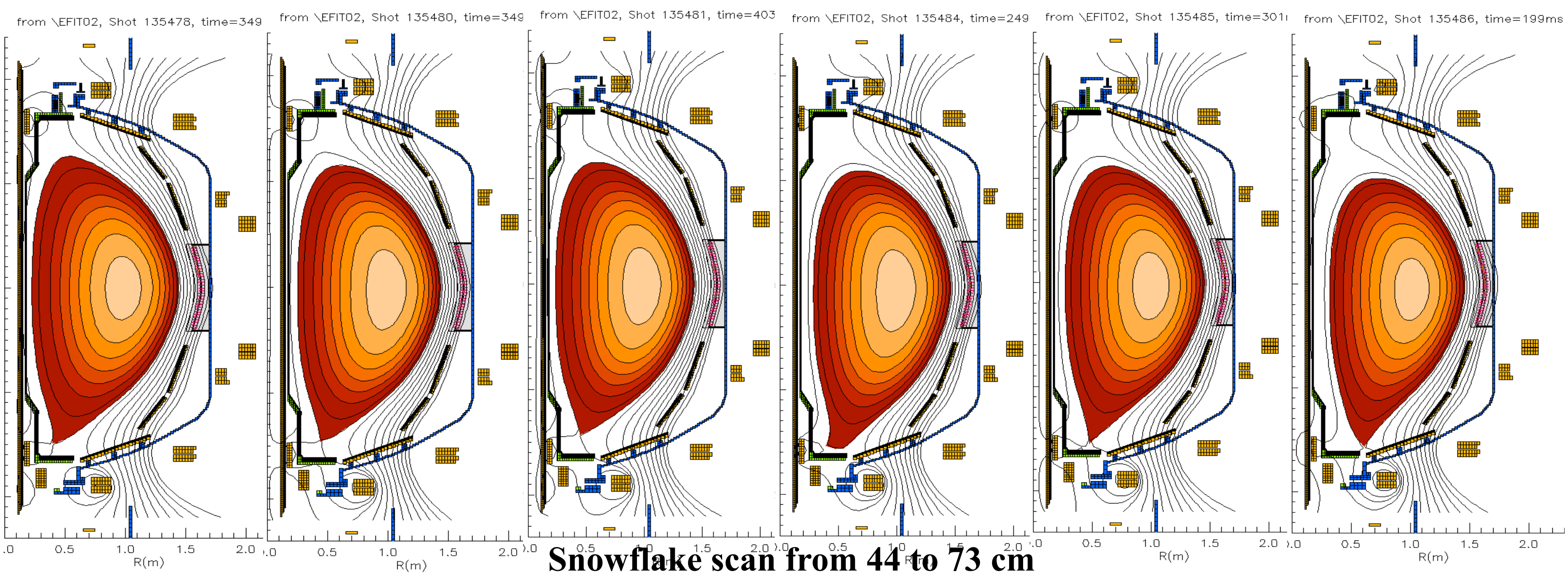
- "Snowflake" divertor configuration, a second-order null is created in the divertor region by placing two X-points in close proximity to each other.
- This configuration has higher divertor flux expansion and different edge turbulence and magnetic shear properties, beneficial for divertor heat flux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

Previous Year: Snowflake Scan with Strike Point (SP) Control



PF2L controls outer SP in red segments. PF1AL controls inner SP in the blue segment.

- Used inner and outer strike point controller to achieve “snowflake”.
- With fixed SPs, varied squareness and drsep to achieve “snowflake”.
- Scanned the outer strike point from 44 cm to 73 cm while keeping the inner strike point constant.



Snowflake scan from 44 to 73 cm

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

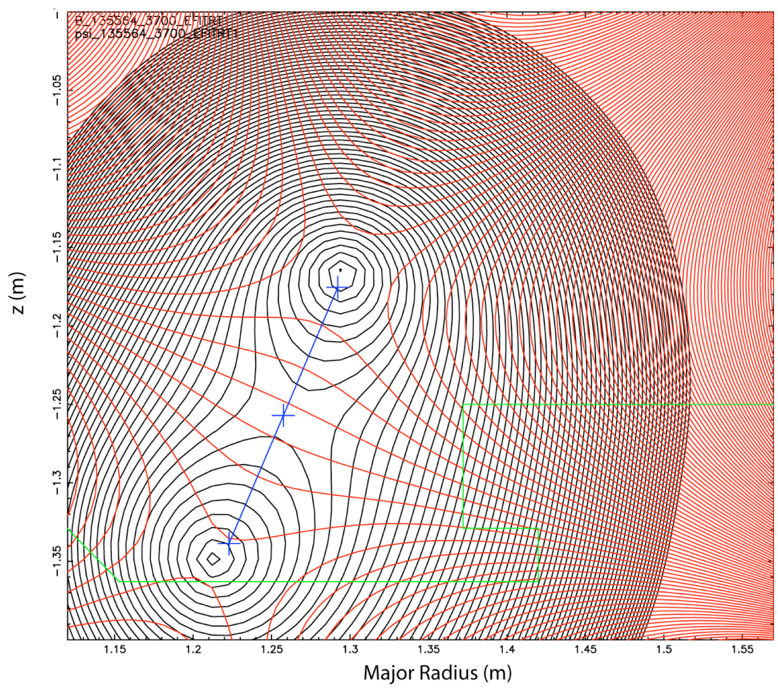


Fig. 1. Result of tracking algorithm as applied to actual data. Plotted are $|B_{pol}|$ contours (black), flux contours (red) and the snowflake center and X-points (blue crosses). The green line corresponds to the location of the floor and shelf of the lower divertor.

- 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

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

$$\Psi_1 = \Psi(\rho_1\, \xi_1) + \Psi_{00}$$
$$\Psi_2 = \Psi(\rho_2\, \xi_2) + \Psi_{00}$$

- Find coefficients from sample points
- Very fast algorithm with reasonable accuracy.
  - **See M.V. Umansky, R.H. Bulmer, R.H. Cohen, T.D. Rognlien. DLLNL-JRNL-410565**

Snow Flake Control

- Locations of the X-points → feedback-control

- System Id: 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: Distance between the two X-points.
  - Other control ideas such as relative angle can be tested, as well.

- Actuator: PF1B as the sole controller
  - Very effective coil in moving the secondary X-point
  - Not used in any other control loop
  - If this coil is not sufficient in achieving the control objective MIMO using PF1A, PF1B and PF2L will be considered.

- Time Request: 1 day

- Backup Slides

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Rotation Control

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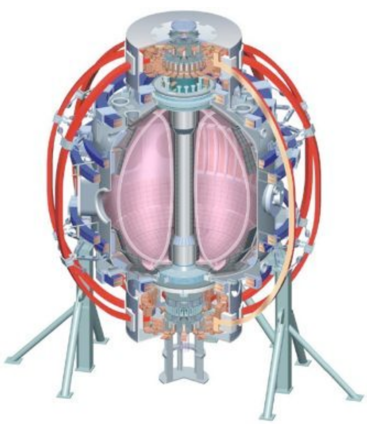

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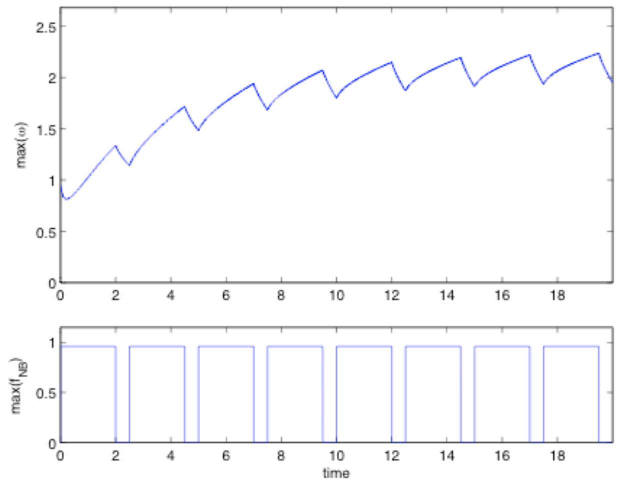
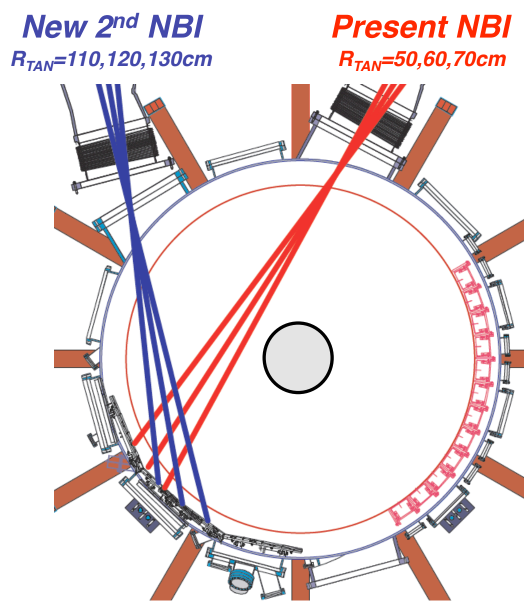
Rotation Profile Control (with Kunihiko Taira)



Example: Changing the rotation profile via NBI



NSTX neutral beam injection configuration

- Control of toroidal momentum of plasma in NSTX
- 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
- **Aim: make a reduce order model for control implementation and sufficiently sophisticated for control.**

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

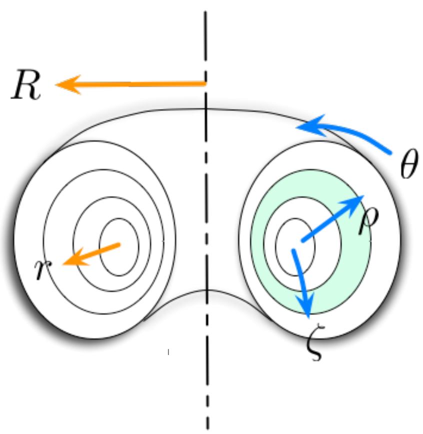
$$
+ T_{\mathrm{col}} + T_{J\times B} + T_{\mathrm{bth}} + T_{iz}
$$

Torque input

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

Loss
(charge ex, ripple)

0



Also, temporal changes are small, ignored.

Model Equations

- Toroidal momentum balance

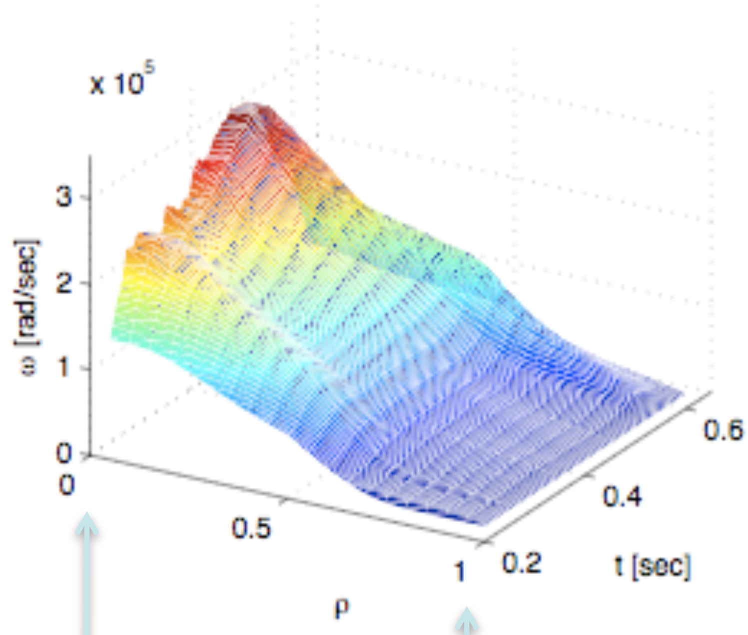
$$\sum_i n_i m_i \left\langle R^2 \right\rangle \frac{\partial \omega}{\partial t} = \left(\frac{\partial V}{\partial \rho}\right)^{-1} \frac{\partial}{\partial \rho}\left[\frac{\partial V}{\partial \rho} \sum_i n_i m_i \chi_\phi \left\langle R^2 (\nabla \rho)^2 \right\rangle \frac{\partial \omega}{\partial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

- 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 $\sum_i n_i m_i$

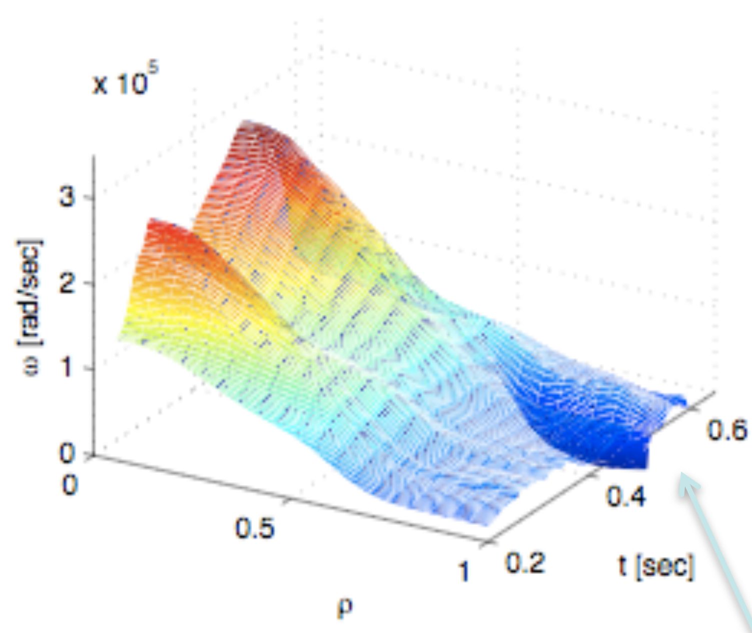
Model Comparison with Experiment

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

Model



Experiment

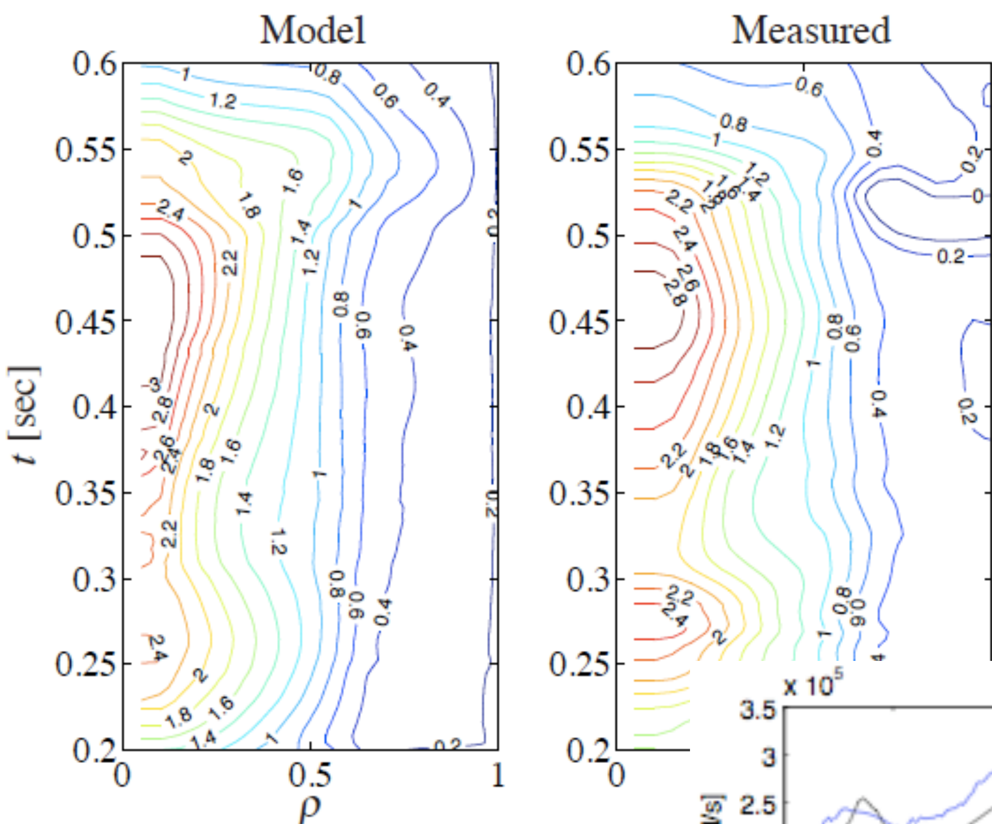


center

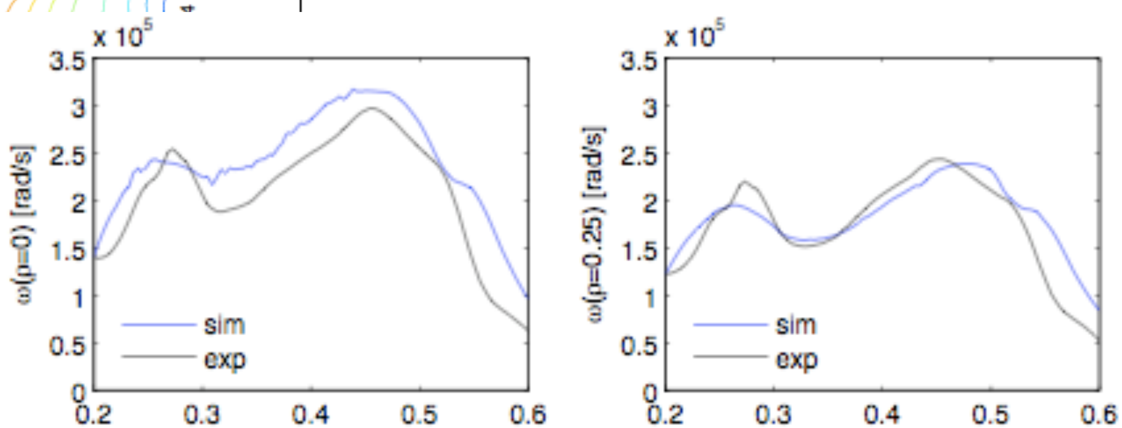
edge

H- to L-mode transition

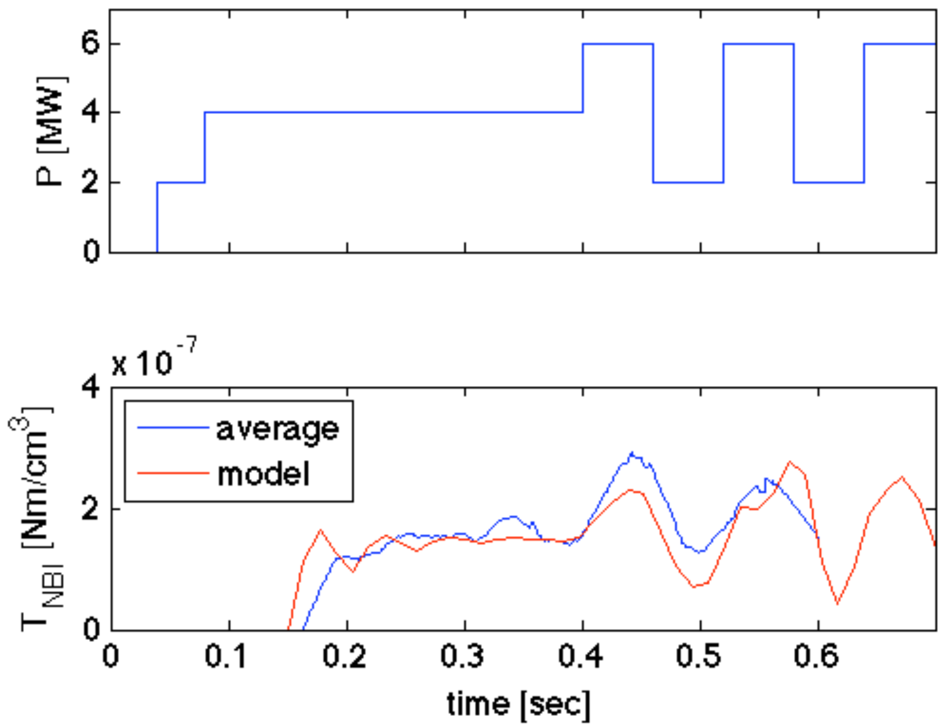
Model Comparison with Experiment



H- to L-mode transition



Beam Torque Model

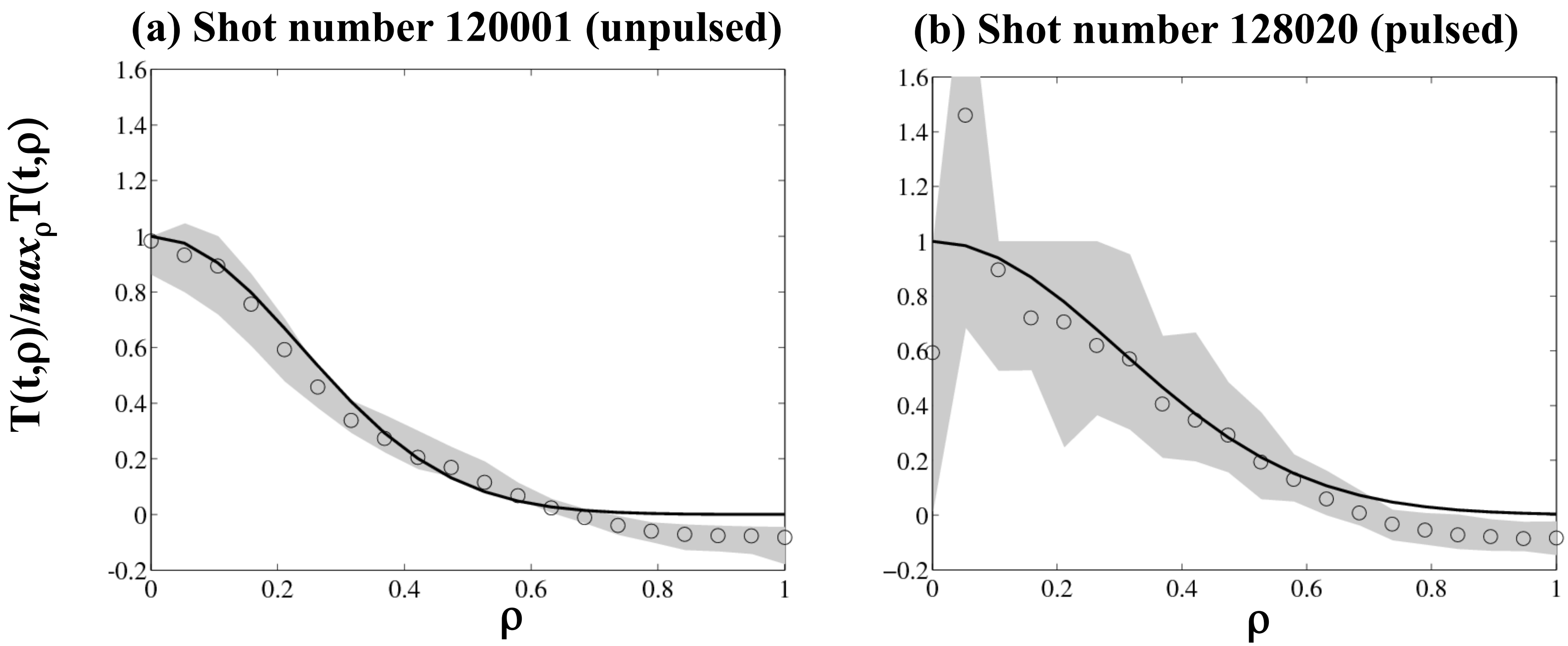


Model versus data for Torque profile

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

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

Beam Torque Model



- 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.

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

Neoclassical Toroidal Viscosity

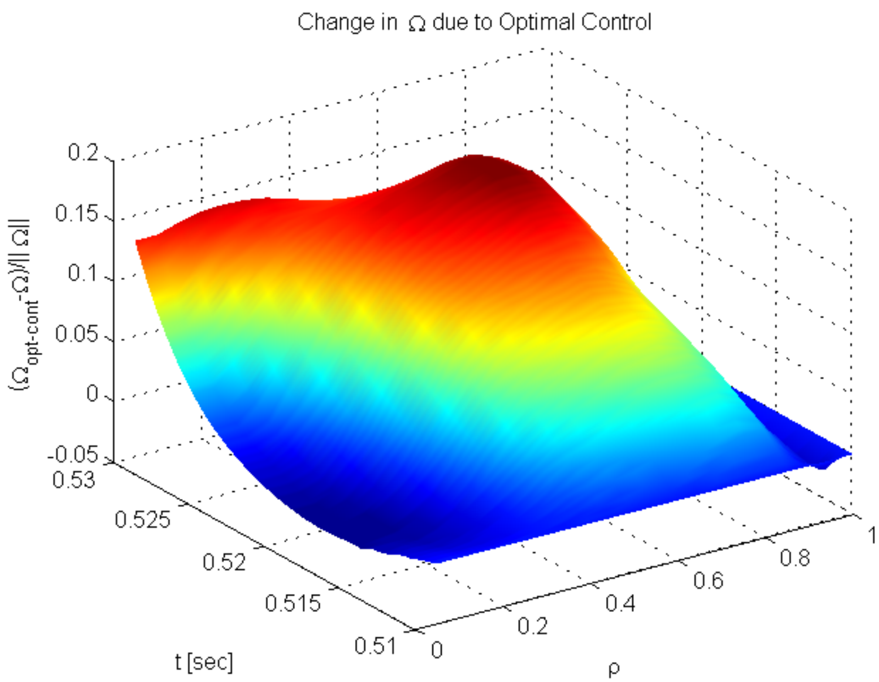
- Use NTV torque to control Edge Rotation

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

- Model based on S. Sabbagh and J. K. Park's previous work and Xps on NSTX.

- Waiting for real-time CHERS data for control measurements

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.

- Backup Slides