NSTX

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Results of the NSTX Shape Control Experiments

Egemen Kolemen

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and the NSTX Research Team

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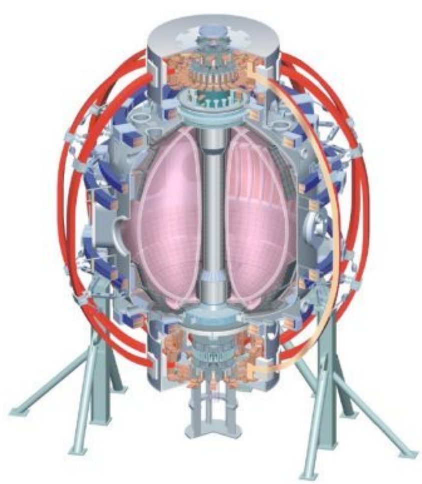

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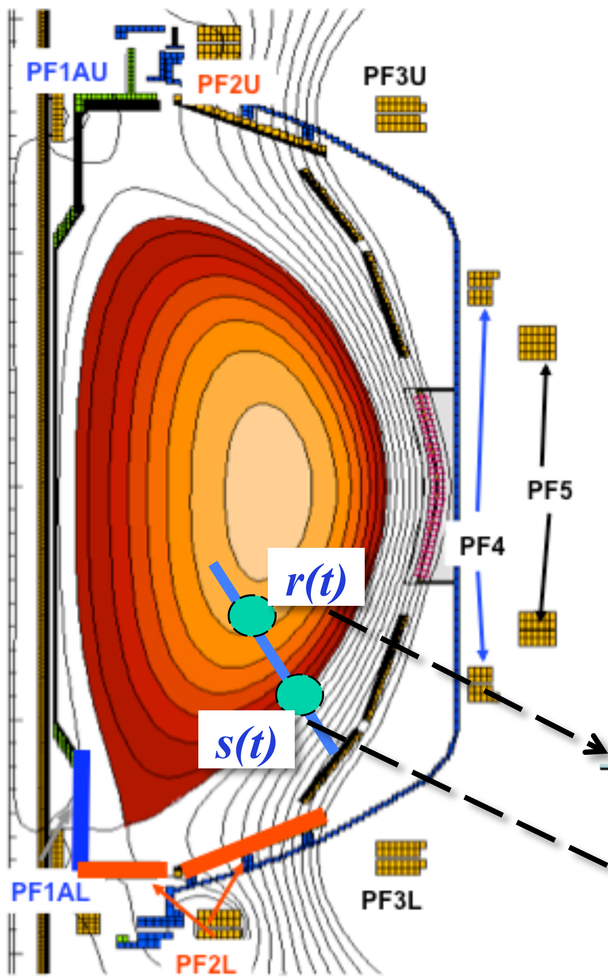
NSTX Shape Control Development Overview

- Aim of shape control development:
  - Supporting the Divertor Physics Program (such as Liquid Lithium Divertor (LLD), Snowflake Divertor).
  - Supporting the NSTX-Upgrade
  - Take full advantage of the NSTX actuator capability.
  - Explore new integrated scenarios.

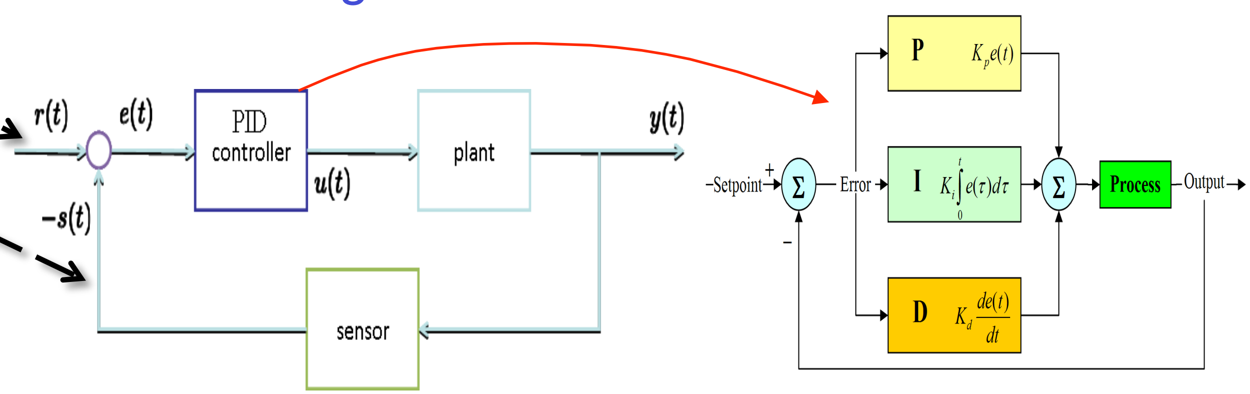
- To this aim we implement shape control scenarios
  - **Improved Strike Point (SP) Control**
  - **Combined X-point Height/SP Control**
  - **Squareness Control**

Overview of Shape Control at NSTX



NSTX Cross Section: Polodial Field coils and an example control segment.

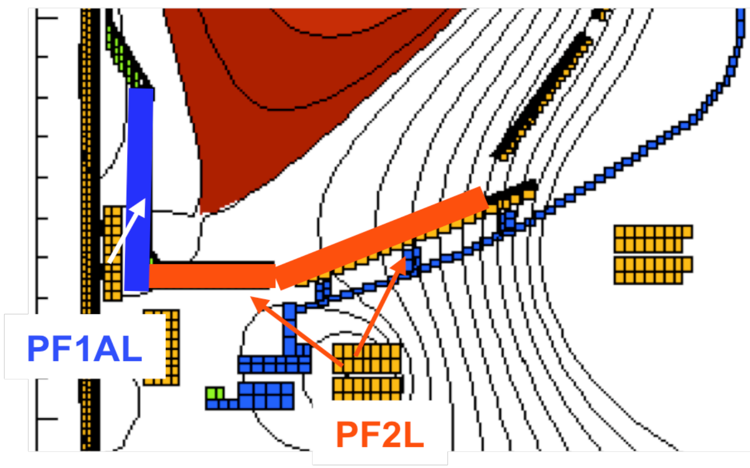
- 11 Polodial Field (PF) Coils.
- Discharge two control phases:
- 1. Preprogrammed phase:
  - Coil currents are manually entered.
- 2. Control phase:
  - Boundary is reconstructed by rtEFIT
  - Isoflux calculates magnetic fluxes
  - Segment flux error fed to PID control.



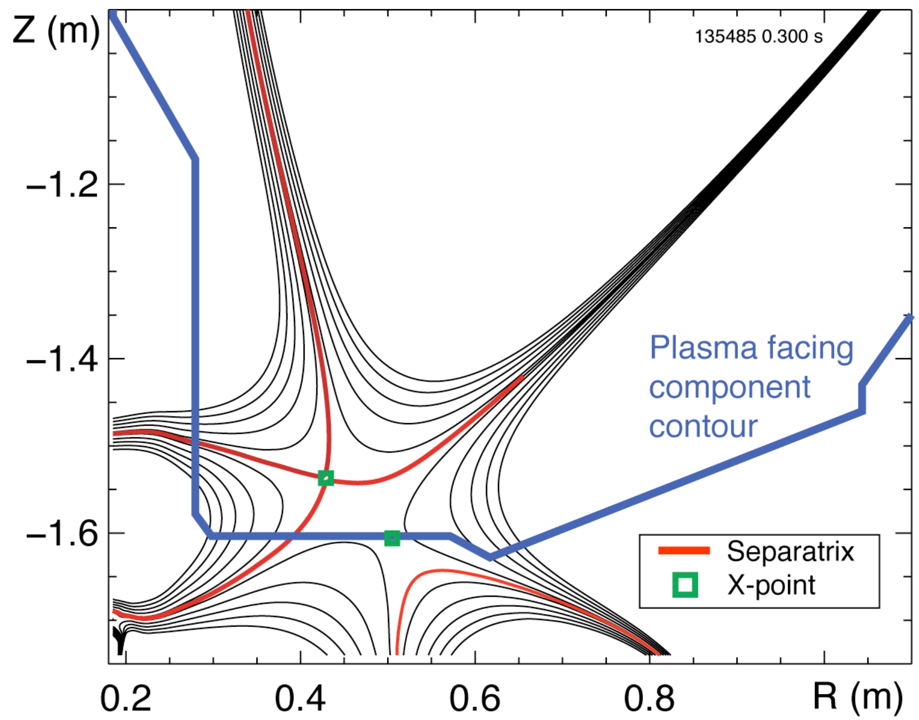
- Only outer gap via PF5 and vertical position via PF3U/L till 2009.

2009 Run: Outer/Inner Strike Point (SP) Control

- PI control for Lower Inner/Outer SP to enable "snowflake", LLD.



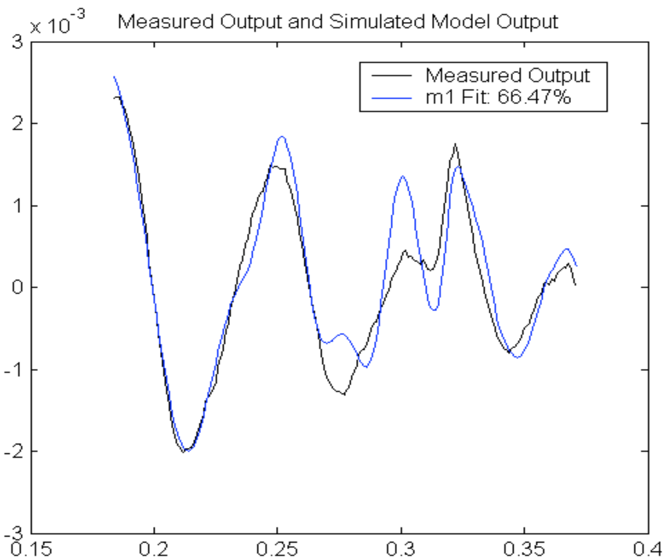
Inner/Outer SP control



Snowflake obtained via SP control at NSTX

- Achieved RMS error Z_{ISP}<1 cm, R_{OSP}<2 cm

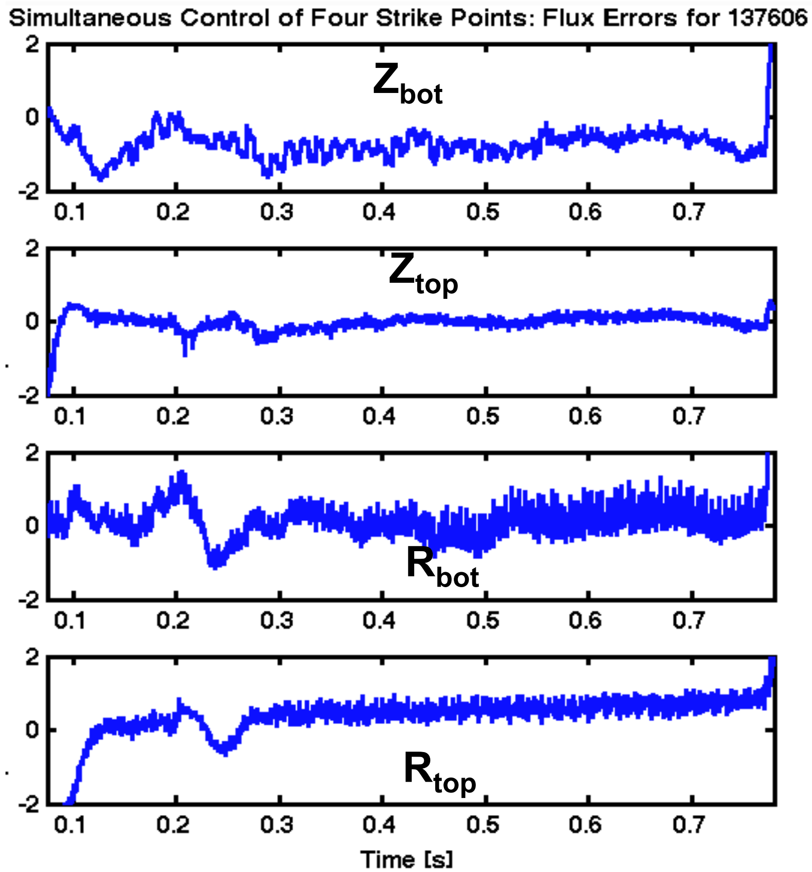
2010 Run Improvement: Offline System ID via ARMAX method

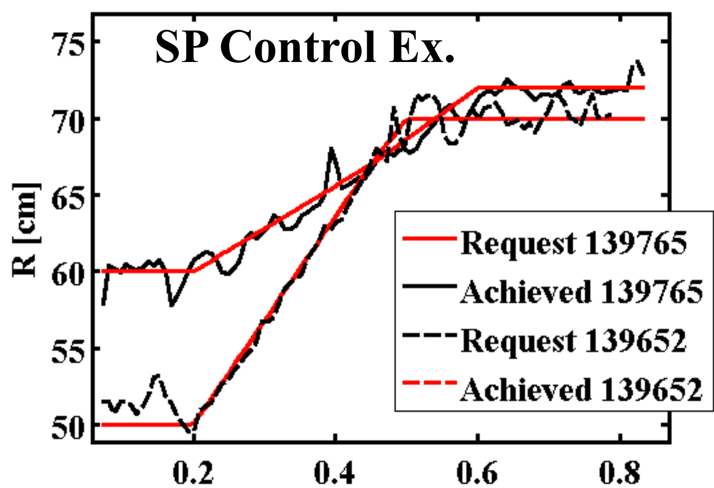


Measured error in OSP [Webers/rad] vs time [s]: black line shows the XP data and blue line the simulation

- To reduce the RMS error of OSP, dynamics modeling was used.
- To maximize the proportion of this process that is conducted offline the 2009 XP data was analyzed and an offline system ID was obtained.
- Assumed a linear gray box system:
  - Input: PF coil voltages
  - Output: measured fluxes
- Obtain model via ARMAX method.
- Data & model match reasonably.
- Based on the model, tuned the control for 2010 run.

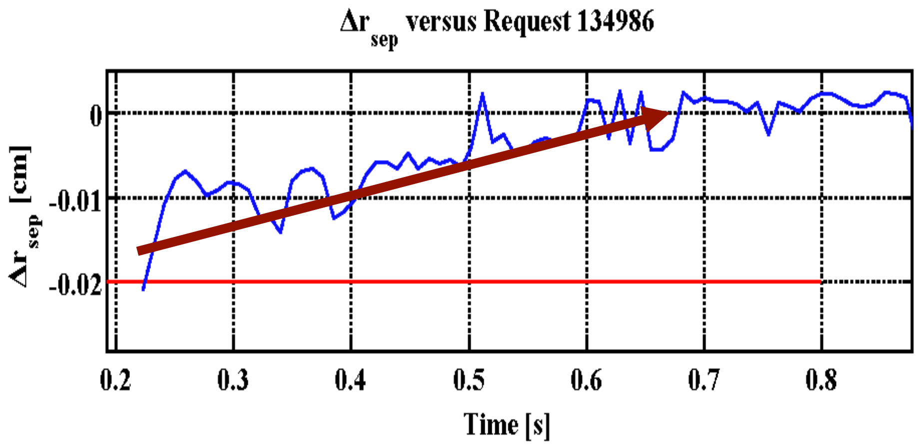
2010 Run: Simultaneous Control of Four SPs



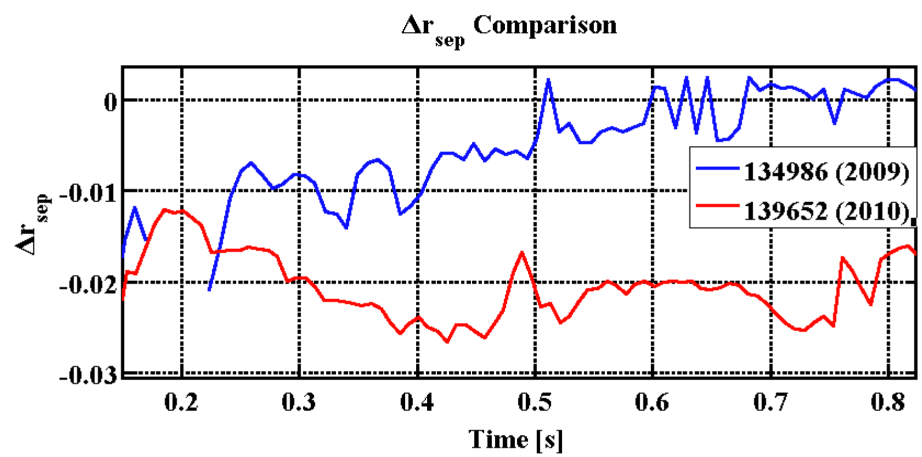


- Optimize/Tune PID gains using offline System Id.
- Two SPs → four SPs control.
- Fixed:The X-point was touching the vessel wall.
  - Control hand-off was manually done to avoid touching wall.
- Smooth PF currents achieved.
- The developed shot was used successfully in many experiments.

Δr_{sep} (or Vertical Position) Drift is Avoided with Improved Four SP Control



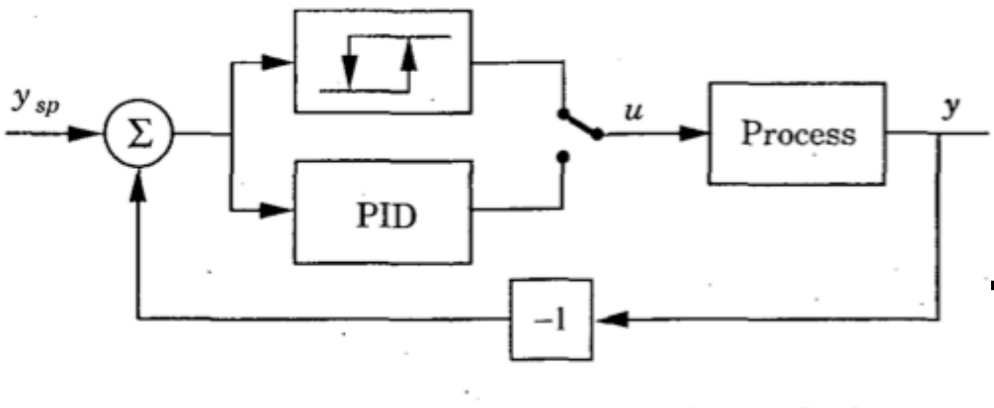
Δr_{sep} with unimproved lower only SP control.

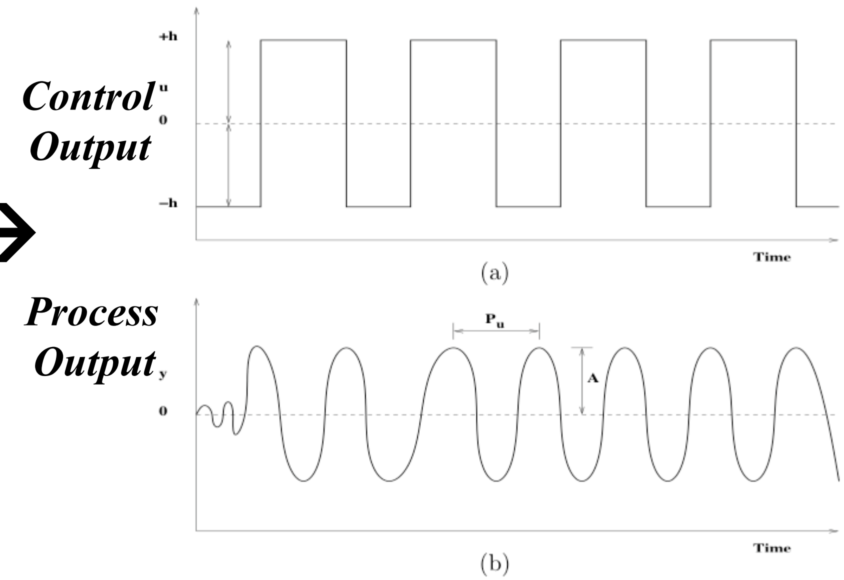


Δr_{sep} with improved upper/lower SP control

- With lower only SP contol, lower PF coils change in time while upper PF coils are constant.
- This induces problems with the Δr_{sep} drifting towards zero when SP control is on.
- When we can control both upper and lower X-point/SP, Δr_{sep} can be kept constant.

Experimental System ID: Closed Loop Auto-tune with Relay Feedback





- The closed-loop plant response period (P_u) & amplitude (A) are used for PID controller tuning.
- Advantages:
  - Only a single experiment is needed.
  - Closed loop:
    1. More stable
    2. Enable system ID for actuators that can't be open loop (for example: vertical control)

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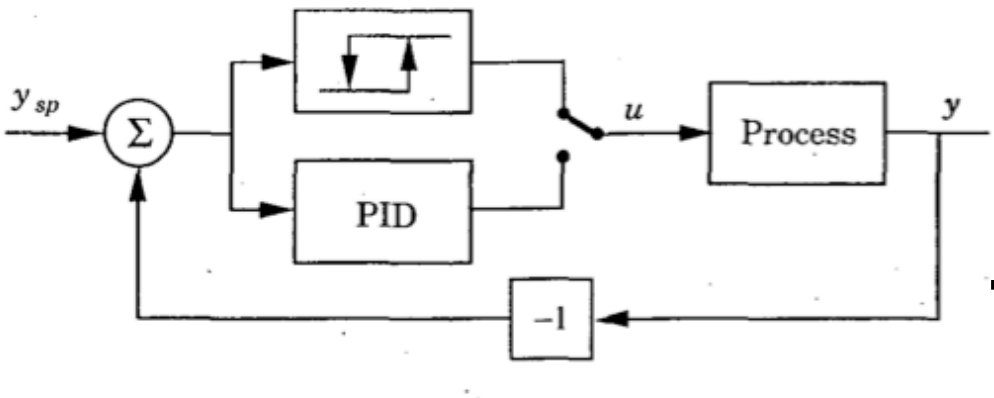
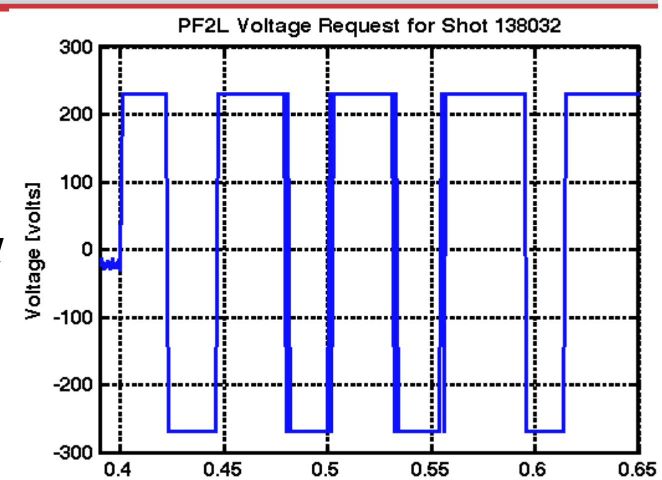
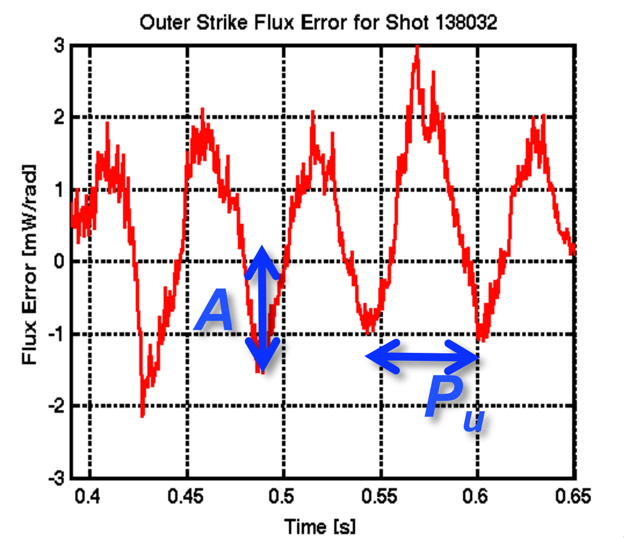


→ *Control Output*



Process Output



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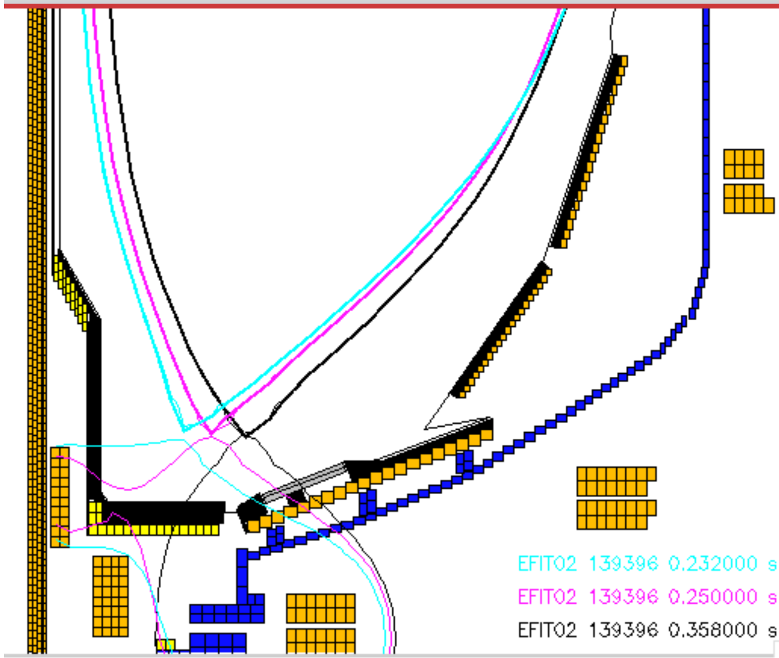
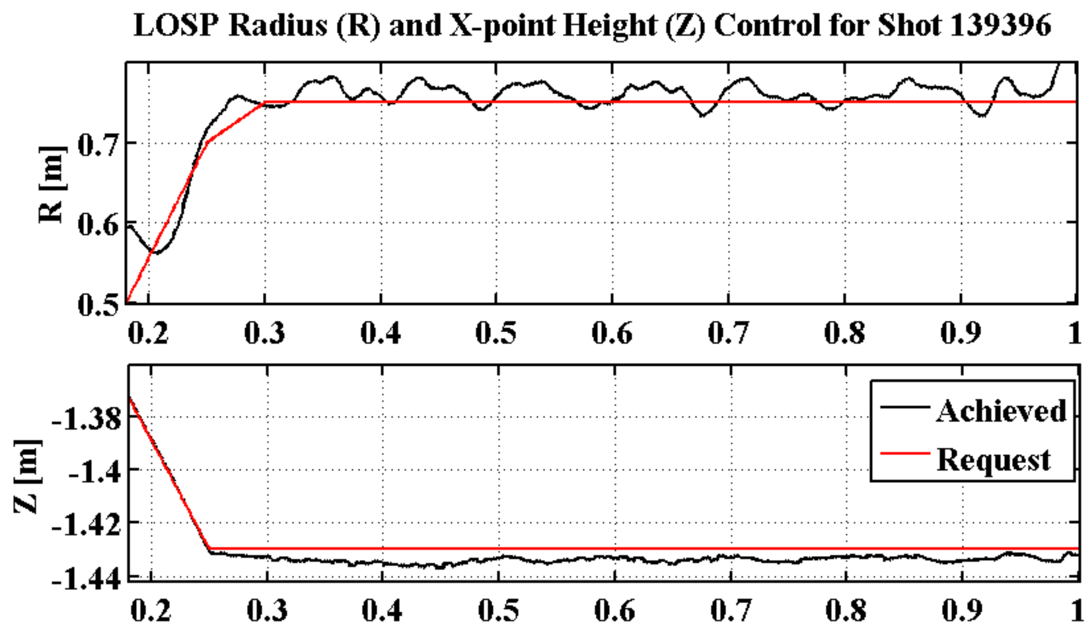
Successful Developed Combined X-point Height / SP Control

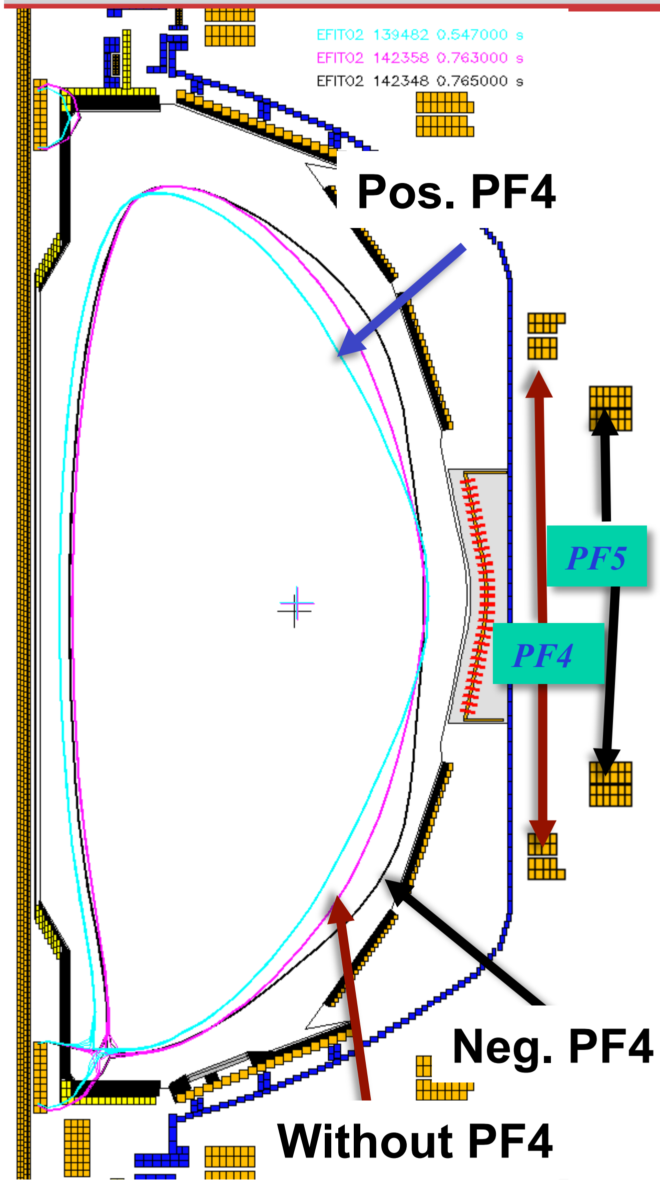




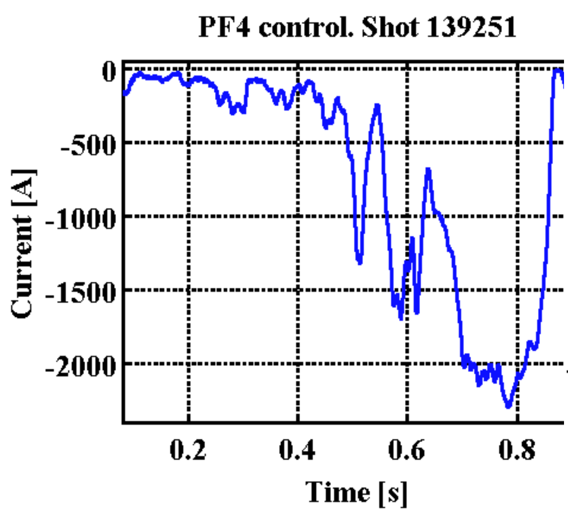
Evolution of Plasma Boundary: X-point height roughly constant as OSP ramps

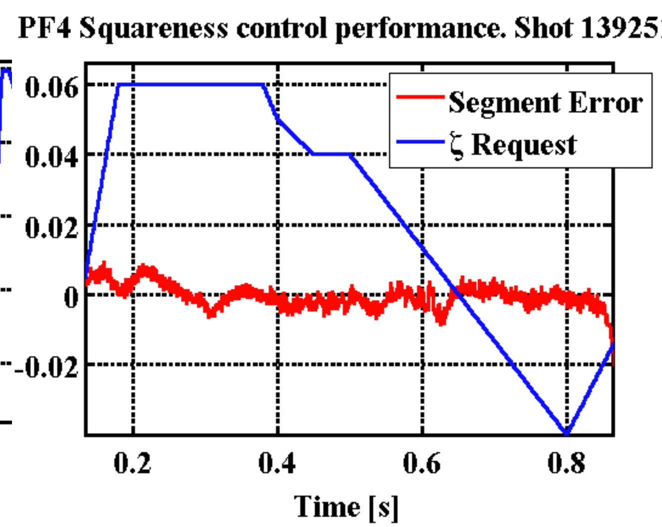
- Tuned via Relay-Feedback.
- Achieved RMS <1 cm X-point height error and <2 cm SP.
- Scenario used for LLD experiments.

Squareness, ζ, Control with PF4



- Motivation: Assess the physics impact of squareness variation while other shape parameters are fixed.
- PF4 best ζ control candidate. PF3/PF4 effect ζ but PF3 used for vertical stability.
- Achieved stable ζ tracking via PF4.
- Effect of ζ on plasma is being studied.





Conclusion

- **Tokamaks have very fast time scales and large unmodeled disturbances, but limited and expensive experimental control-development time.**

- **In preparation for ITER, the control tuning and the system-identification methods that fit these constraints must be developed and incorporated in current tokamaks.**

- **Shown some implementations and effectiveness of these methods:**
  - **Combined 10 PF coil control:**
    - **Upper/Lower, I/OSP control**
    - **X-Point Height/OSP control**
  - **Squareness control.**

Slide title

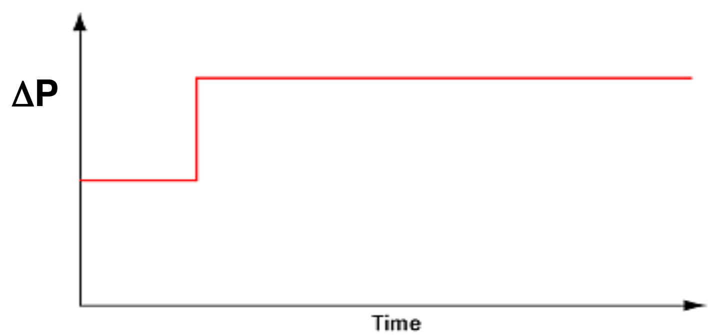
- Important main point
  - Important detail
    - Another important sub-detail

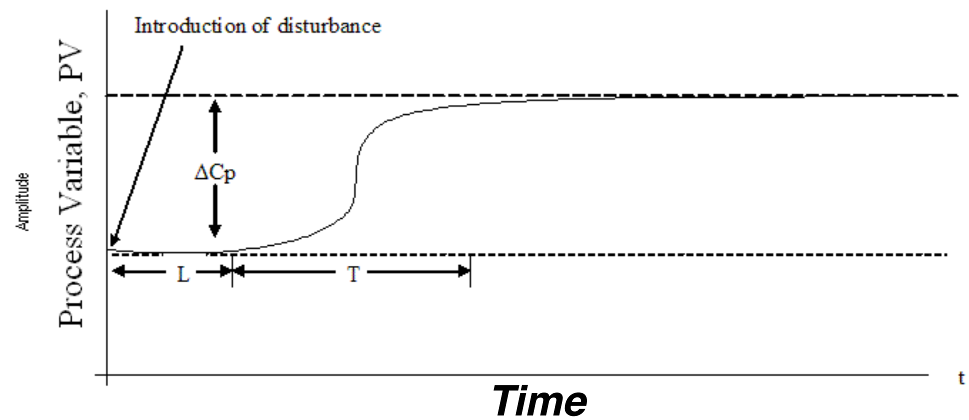
2009 Run: System Identification

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

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

- Reaction Curve Method





- From Step Response obtain:
  - Time delay, rise time and size of change gives the control tuning parameters.

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

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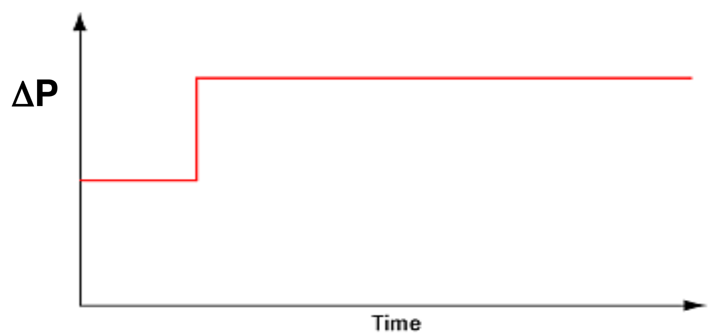
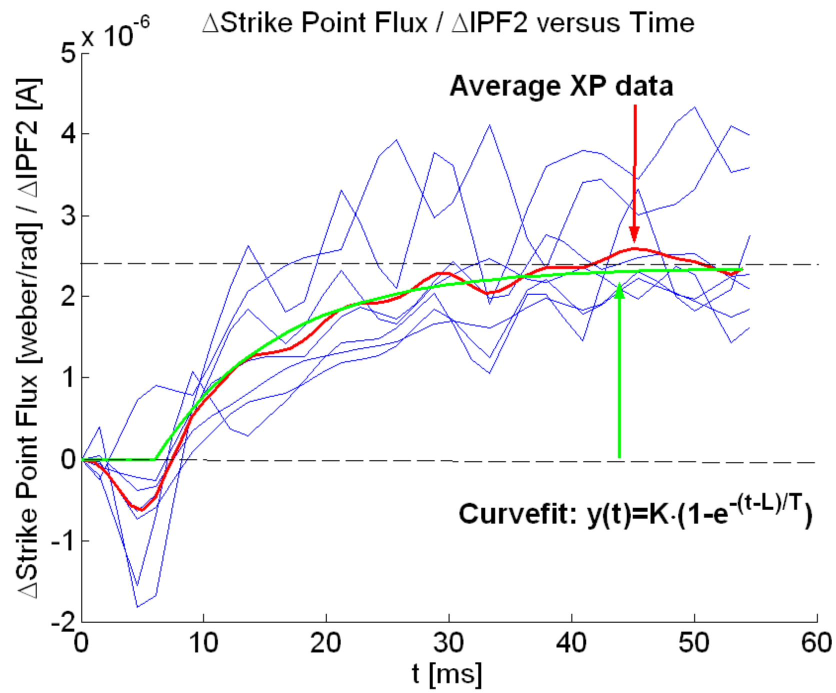
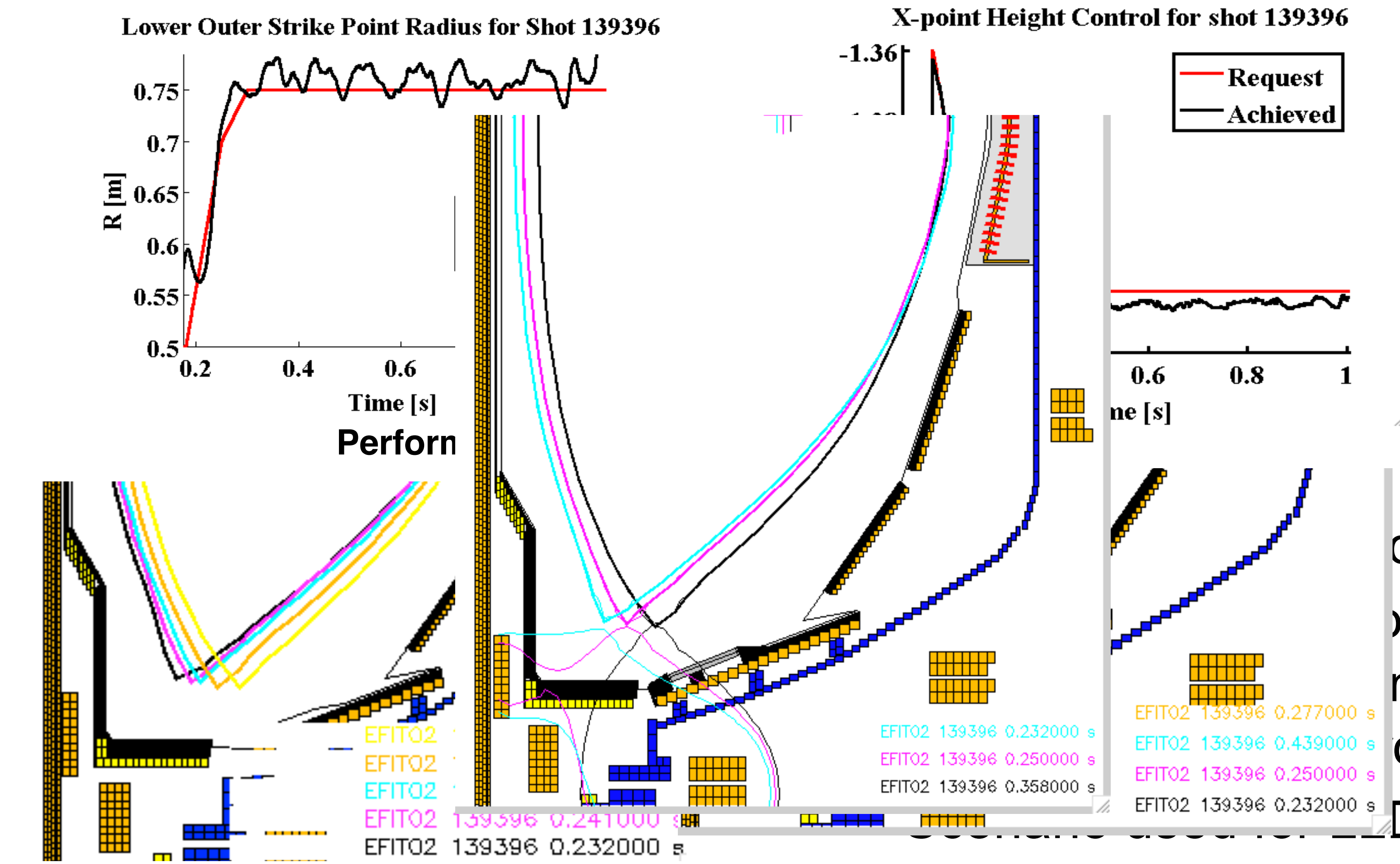




System Id results from 2009 run

- Problem:
  - Many shots needed
  - Need the actuator in open loop.
  - Not precise

Successful Developed Combined X-point Height / SP Control



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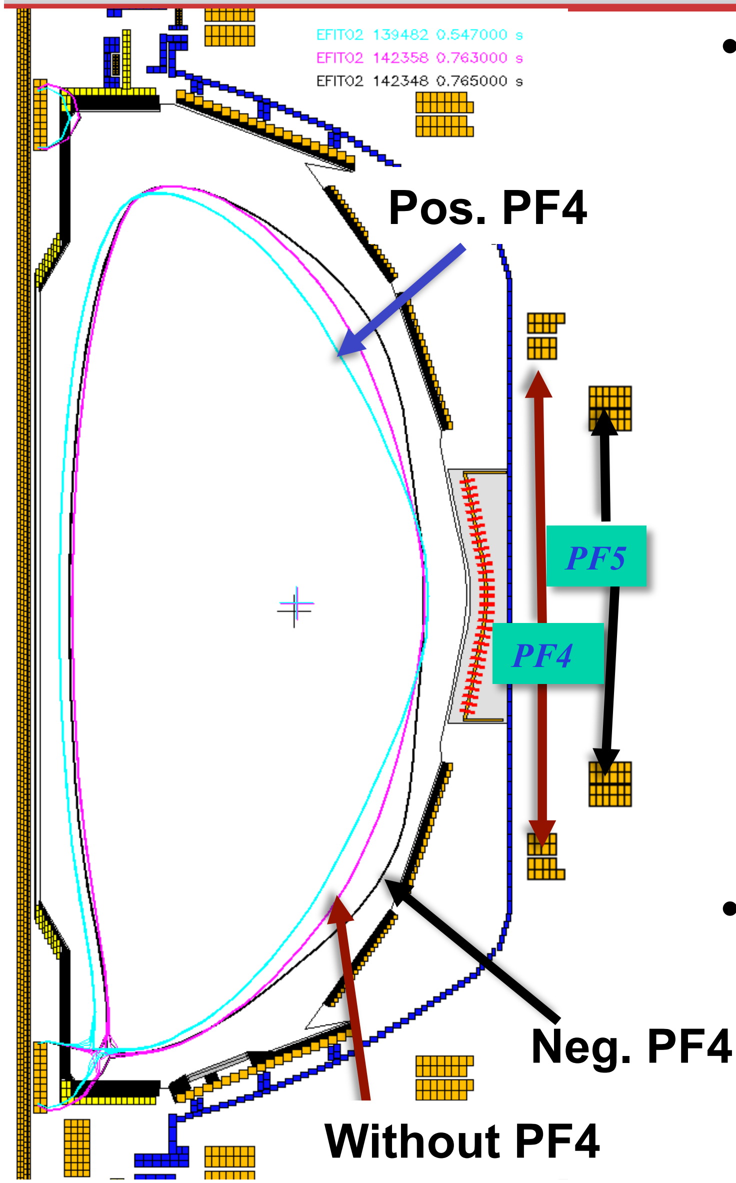
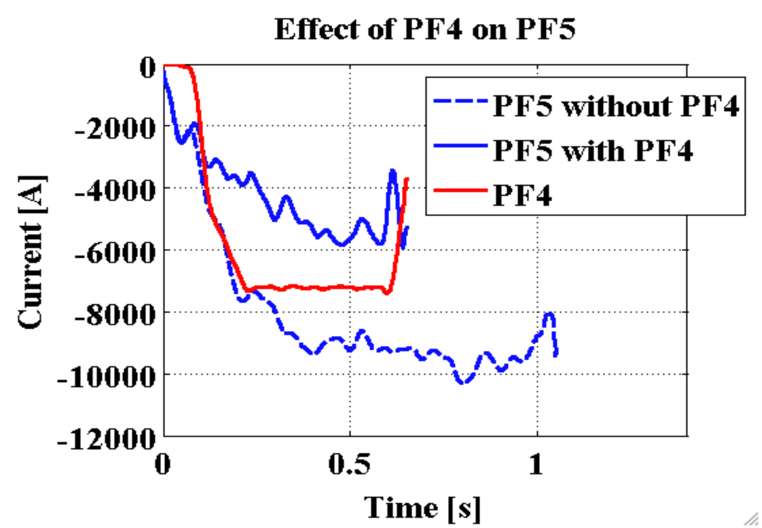
First Ever Use of PF4 for Shape Optimization

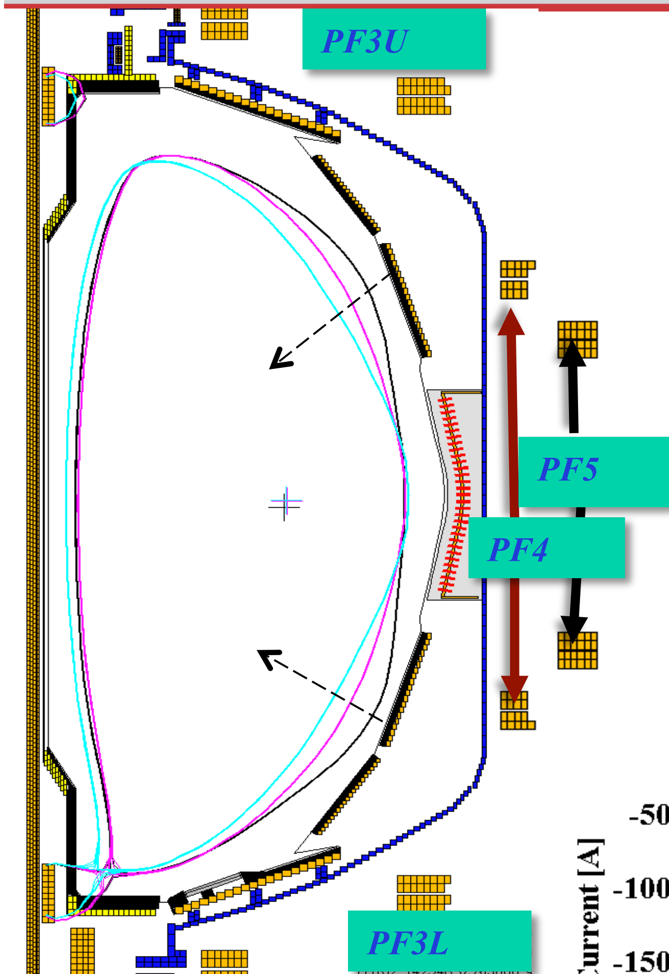


- Motivation 1: Increased current capability of NSTX Upgrade may require vertical field from the PF4 in addition to PF5.
  - Preprogram PF4 with PF5 for outer gap control

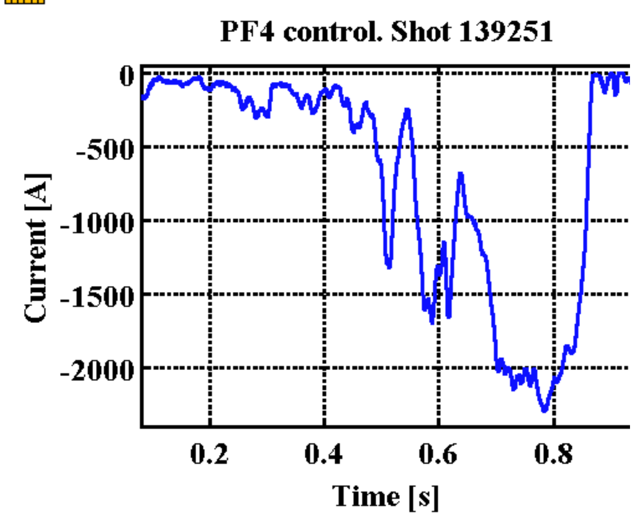


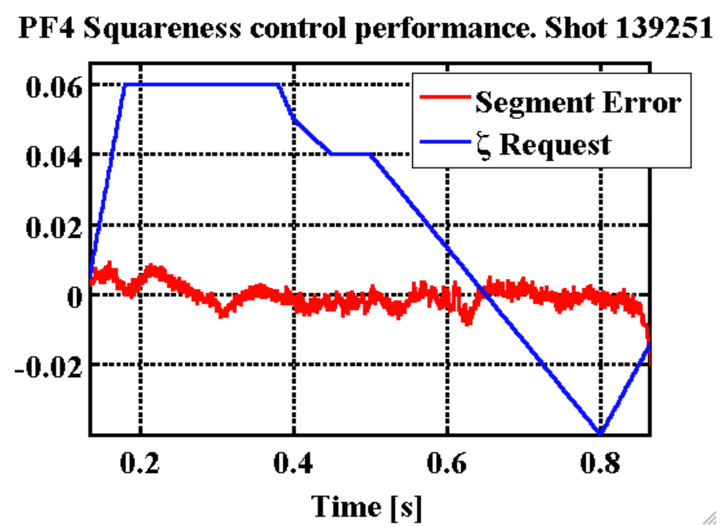
- Motivation 2: Assess the physics impact of squareness variation at other shape parameters fixed.
  - Full Isoflux control.

Squareness, ζ, Control with PF4



- PF4 best ζ control candidate. PF3/PF4 effect ζ but PF3 used for vertical stability.
- ζ control of the plasma boundary via PF4.
- The error along this segment was fed to the PF4 voltage request with a PID control.
- Achieved stable tracking of ζ request with minimal error using PF4 control.
- Effect ζ plasma is currently being studied.





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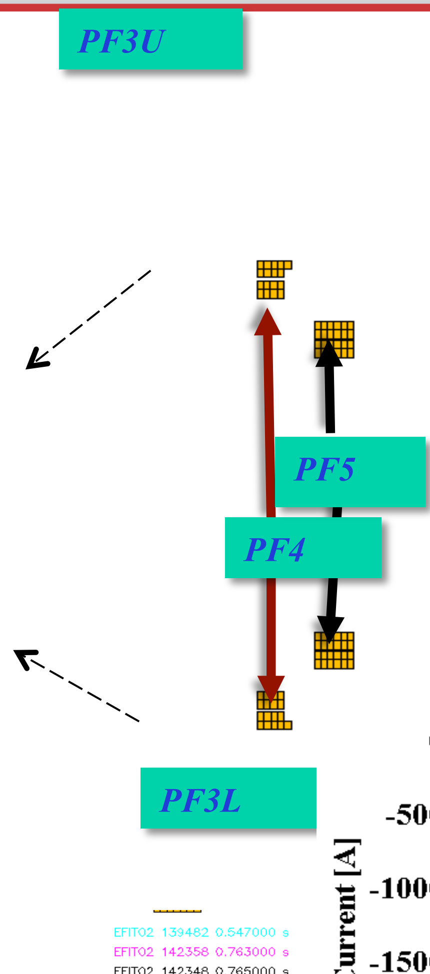

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