NSTX

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Relay Feedback and X-point Height Control

Egemen Kolemen

S. Gerhardt and D. A. Gates

2010 Results Review
Nov/30/2010

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CompX
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INL
Johns Hopkins U
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Lodestar
MIT
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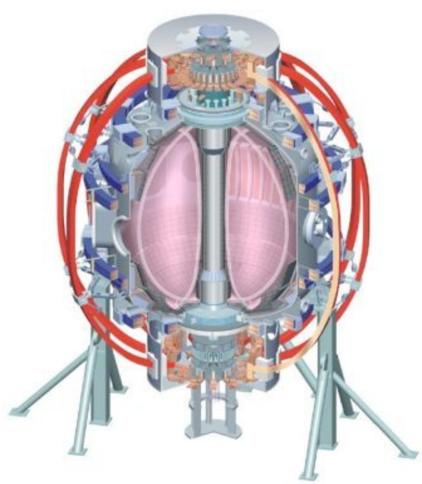

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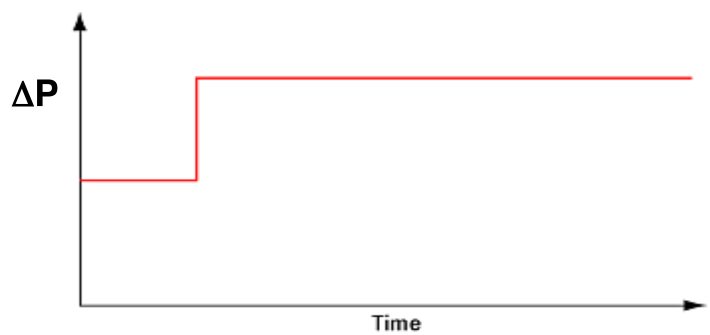
U Quebec

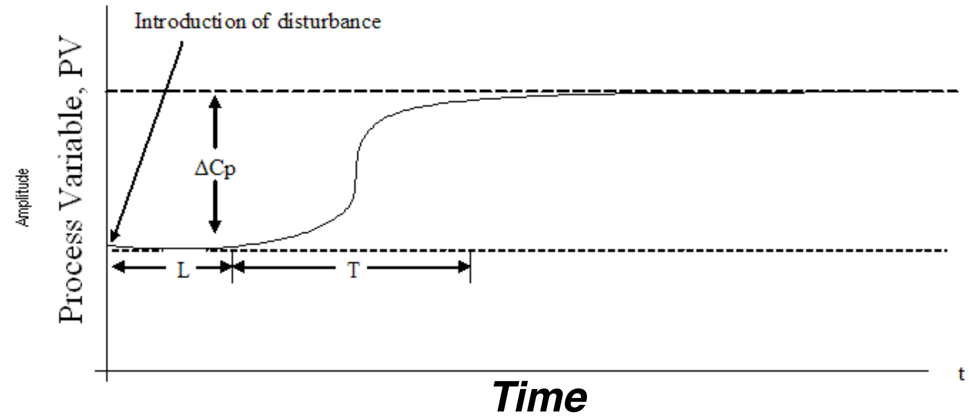
2009 Run: Experimental System ID (Open Loop)

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

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

- Reaction Curve Method





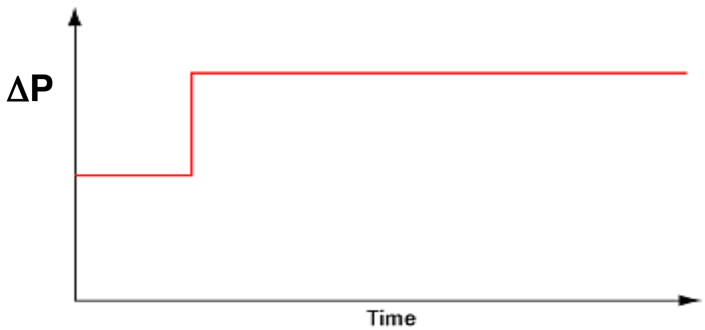
- From Step Response obtain:
  - Time delay, rise time and size of change gives the control tuning parameters.

2009 Run: Experimental System ID (Open Loop)

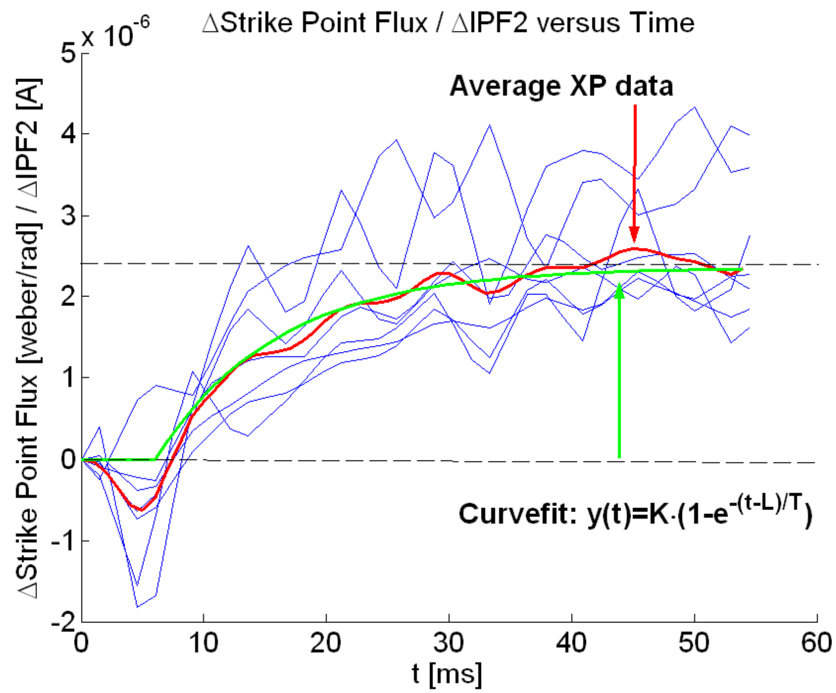
- System Id: Identify the effect of the actuator on the boundary shape.

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

- Reaction Curve Method

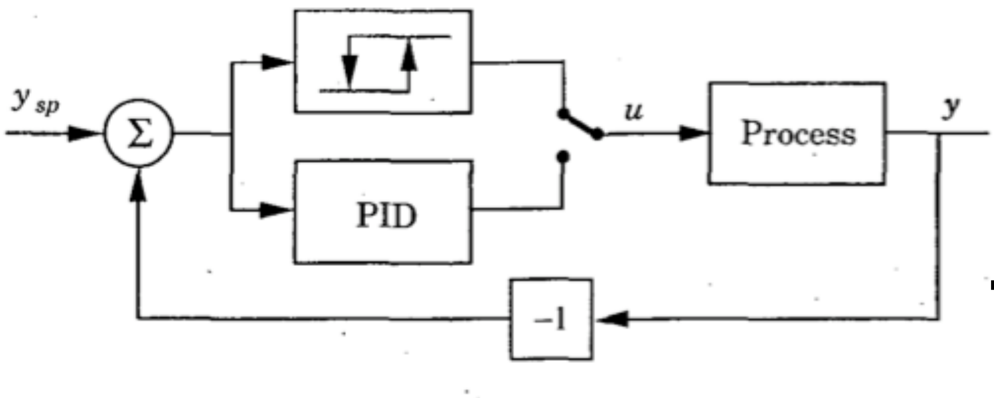


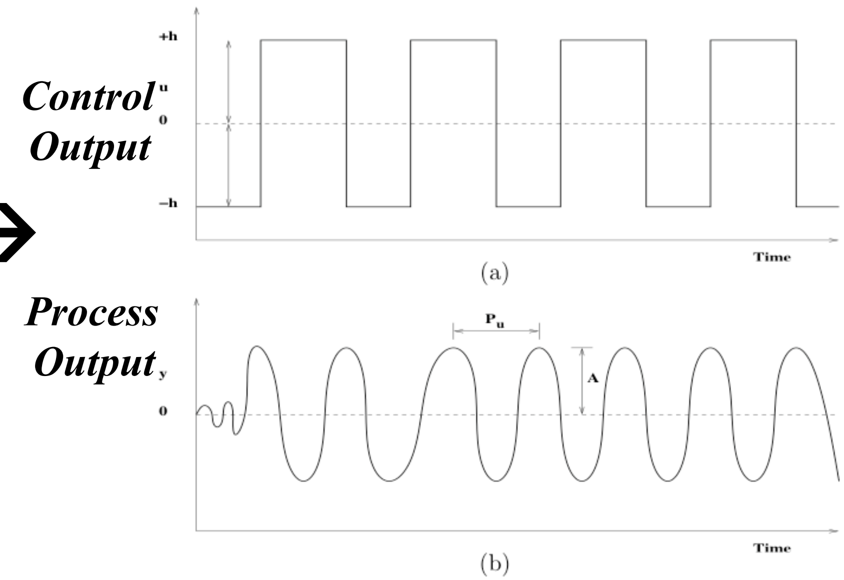
- Problem:
  - Many shots needed
  - Need the actuator in open loop.
  - Not precise



System Id results from 2009 run

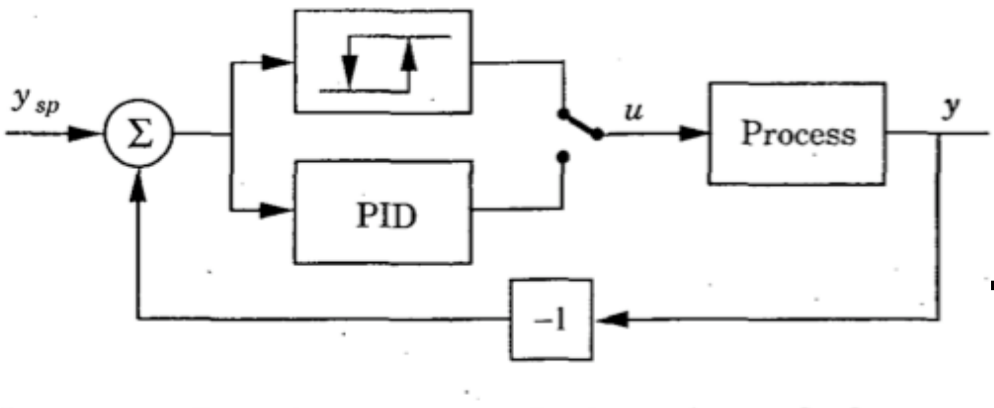
Experimental System ID:
Closed Loop Auto-tune with Relay Feedback



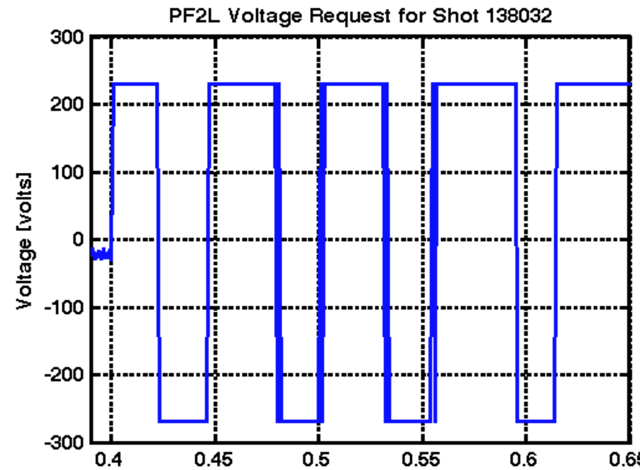


- The closed-loop plant response period (P_u) & amplitude (A) are used for PID controller tuning.
- Advantages:
  - Only a single experiment is needed.
  - Closed loop:
    1. More stable
    2. Enable system ID for actuators that can't be open loop (for example: vertical control)

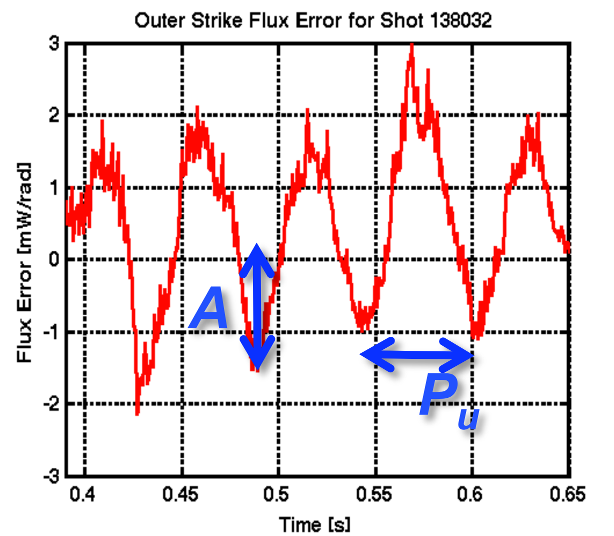
Experimental System ID:
Closed Loop Auto-tune with Relay Feedback



→ *Control Output*



Process Output



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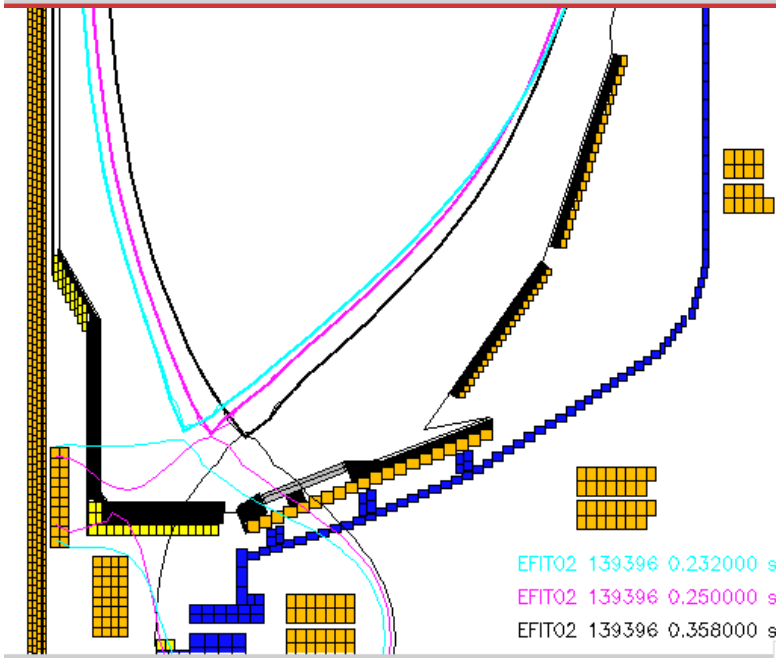
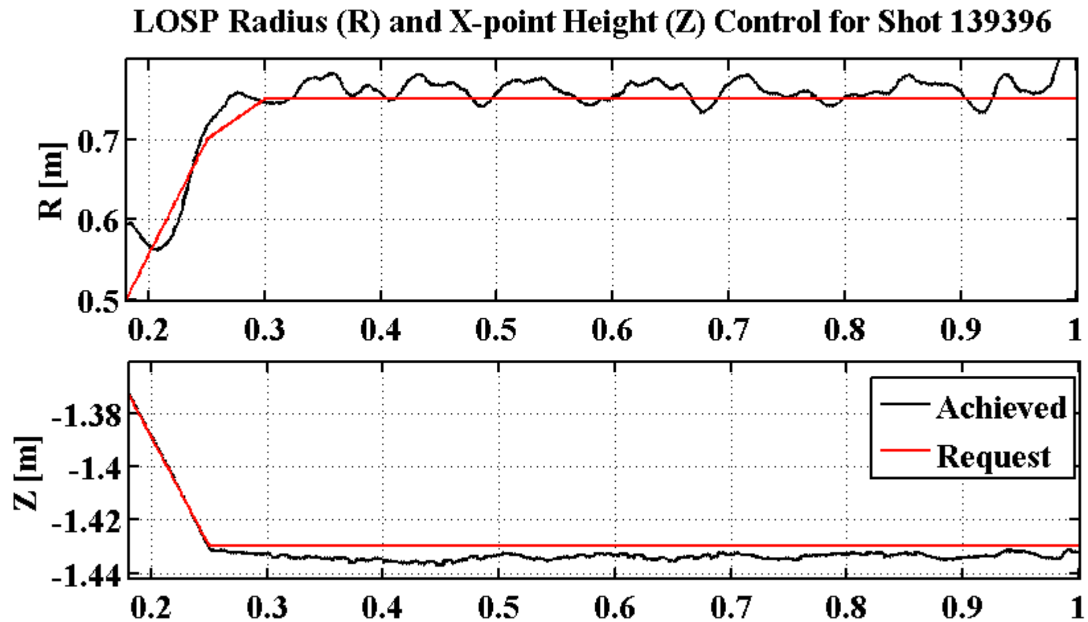
- Advantages:
  - Only a single experiment is needed.
  - Closed loop:
    1. More stable
    2. Enable system ID for actuators that can't be open loop (for example: vertical control)

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.

For 2011: Solution to "Hand-off" Problem

- Problem when changing between control phases.

- Normal Control has two parts:
  1. Trajectory control: Scenario Development (Feed forward)
  2. Feedback control: Controlling parameters close to the defined scenario.

- Need: Ability to add these two waveforms.
  - Simply be able to add PID output to the Voltage from the last phase. (We have this capability only for Relay Feedback but not for regular PID).

- Then, we will avoid "hand-off" problem

Squareness XP

College W&M
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INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
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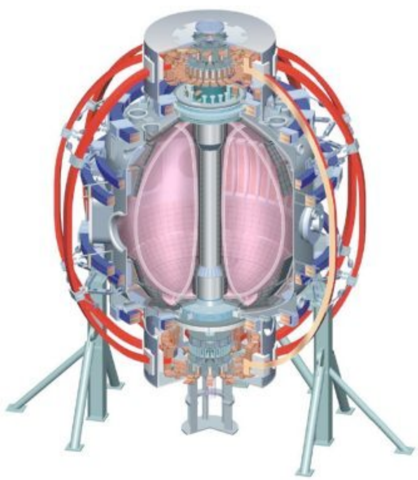
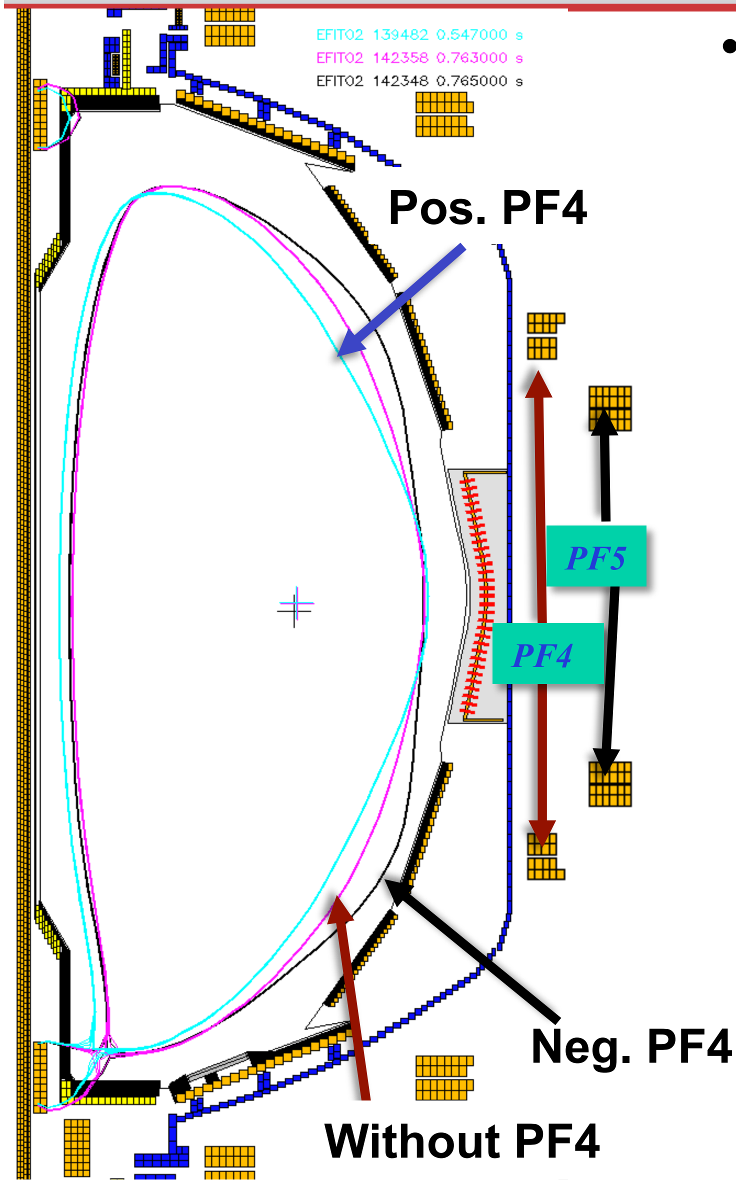
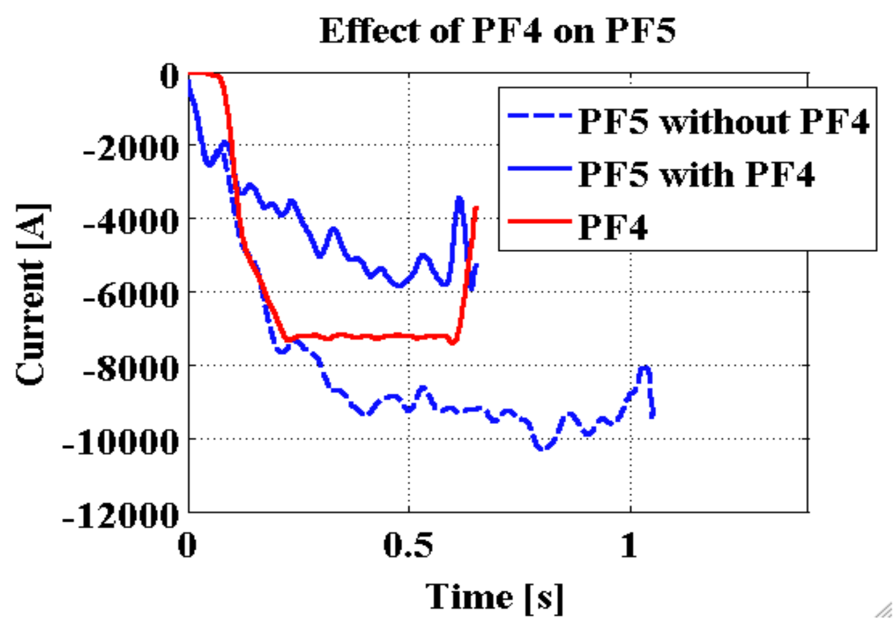


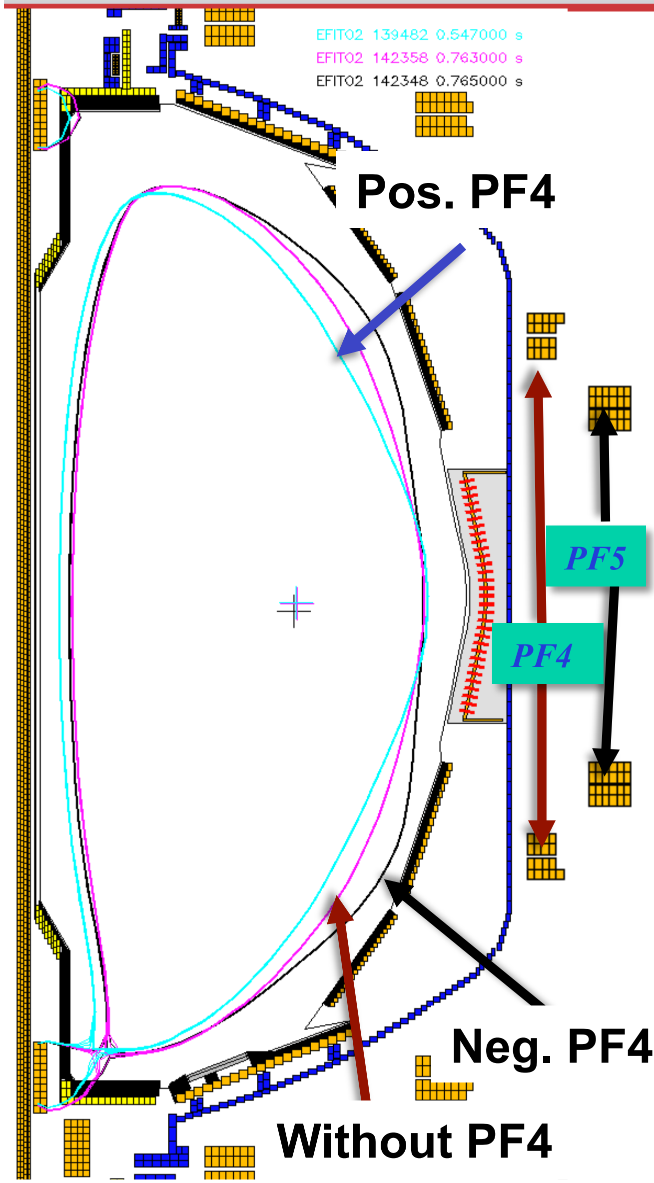
First Ever Use of PF4 for Shape Optimization



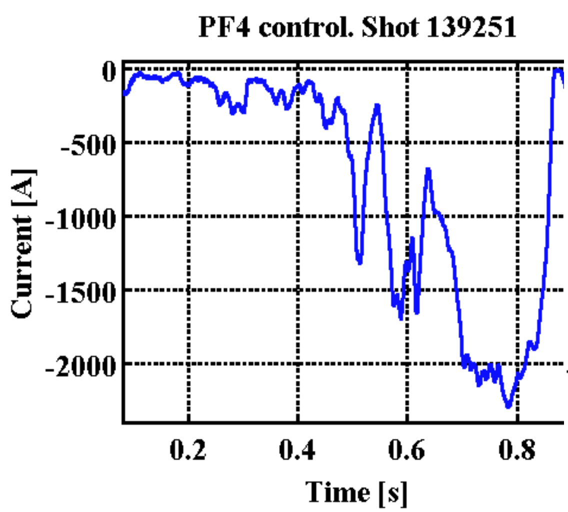
- Motivation 1: Increased current capability of NSTX Upgrade may require vertical field from the PF4 in addition to PF5.
  - Preprogram PF4 with PF5 for outer gap control

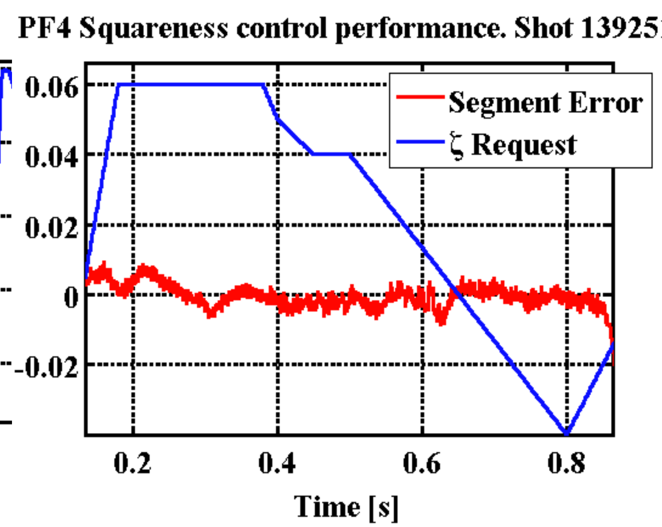


Squareness, ζ, Control with PF4

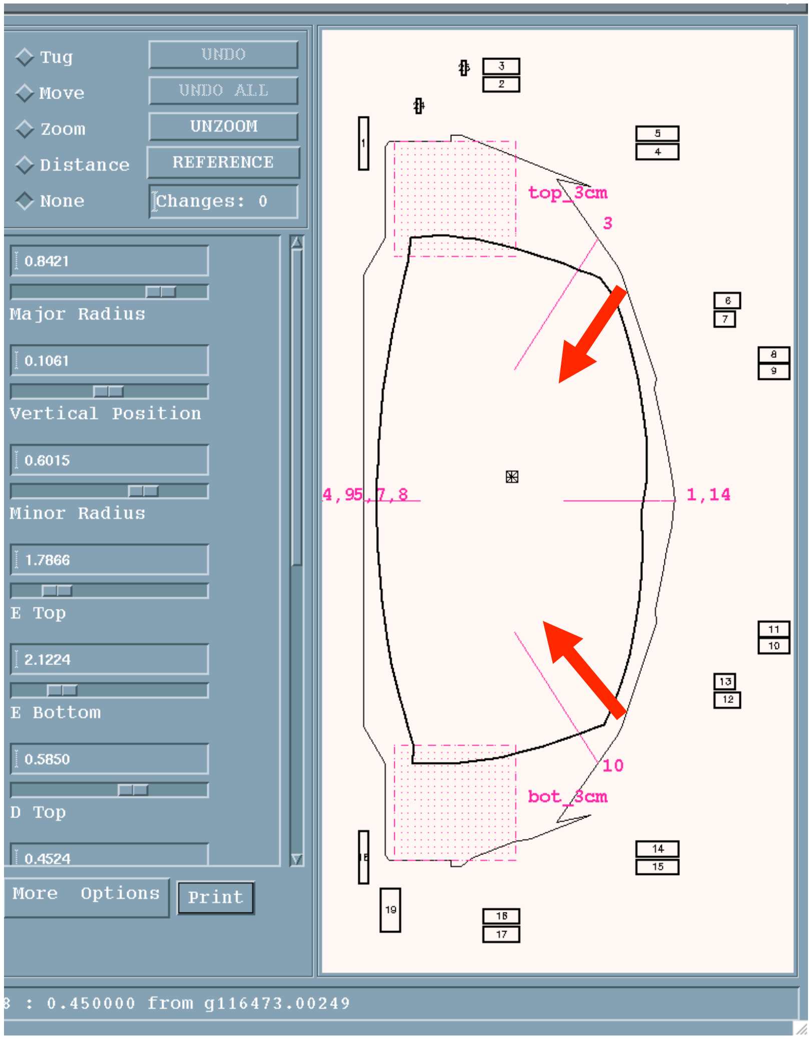


- Motivation: Assess the physics impact of squareness variation while other shape parameters are fixed.
- PF4 best ζ control candidate. PF3/PF4 effect ζ but PF3 used for vertical stability.
- Achieved stable ζ tracking via PF4.
- Effect of ζ on plasma is being studied.



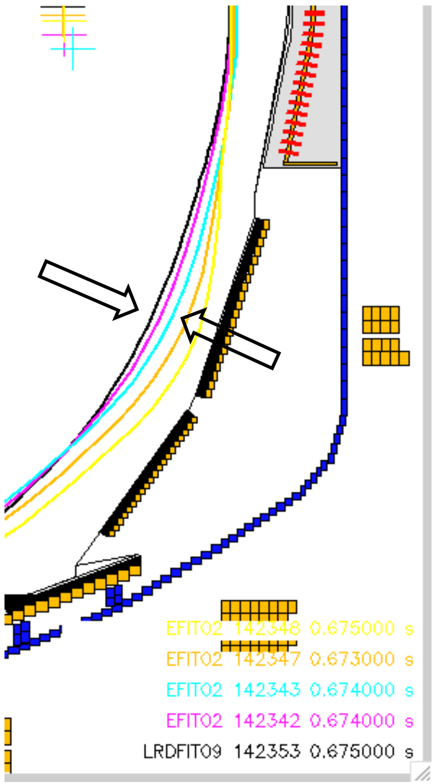


XMP Control Results: PF3-PF4 interaction

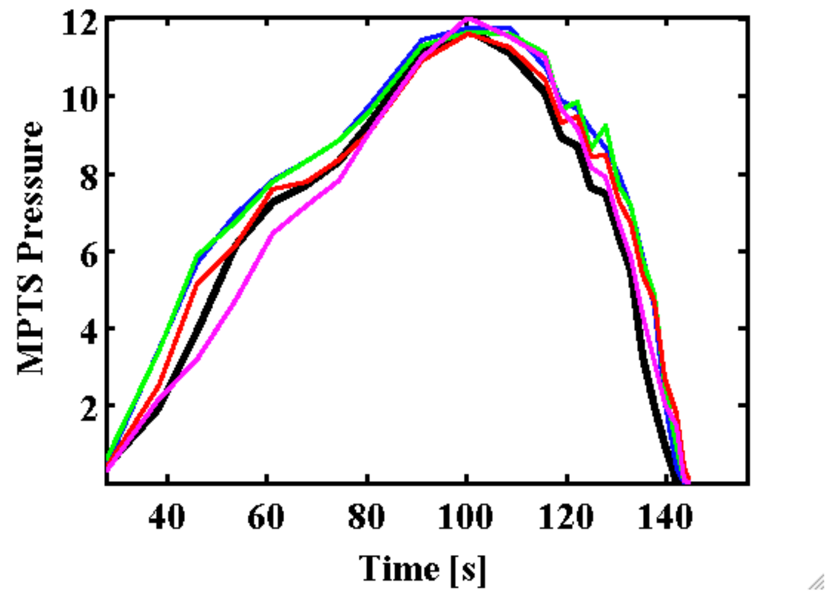


- To solve this problem, move the PF3 and PF4 control segment.
- Could not do this:
  - Problem with PCS Segment Editor.
  - Hopefully will be fixed for 2011.
- To overcome the problem without changing the segments:
- Hand adjust a non-realistic looking shape request.
- Squareness Request of +0.4 from the normal request.
- Works but don't use the squareness in these shots.

Pressure Profile Change as PF4 Increases

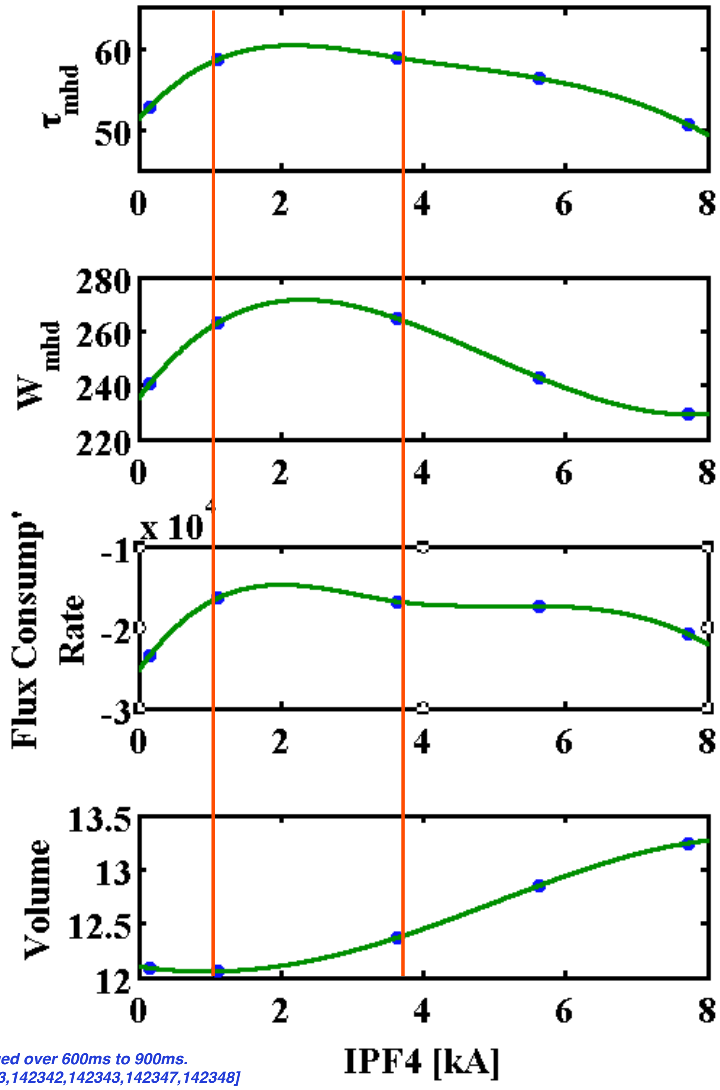


PF4= 0, 1, 4, 6, 8



- PF4 (opposing PF5) up to 5 kA (~2 inches in figure) increases pressure
- Too high PF4 interacts with the wall and plasma is not as good.

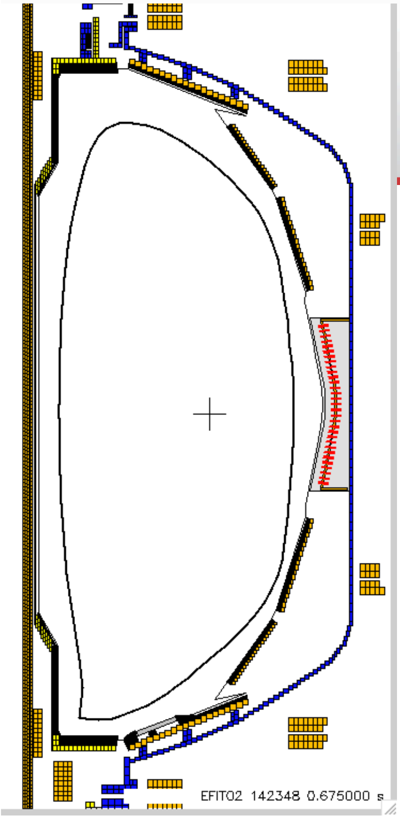
Higher Performance: PF4 of 1-4 kA

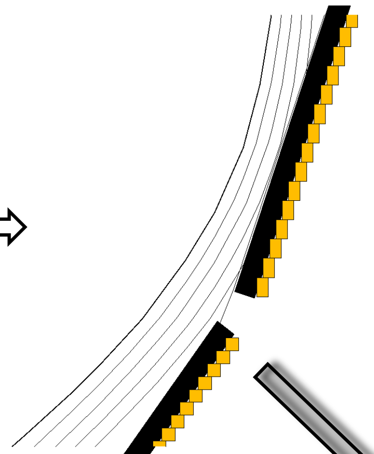


Averaged over 600ms to 900ms.
[142353,142342,142343,142347,142348]

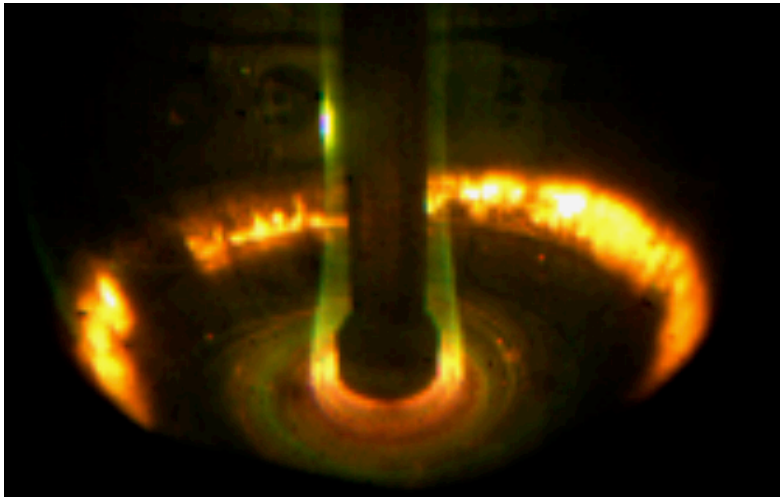
- Optimal PF4 ~1-4 kA for performance.
- Confinement time increases
- Energy confinement increases
- Flux consumption reduces.
- Too high PF4 interacts with the wall and plasma is not as good.
- **Note for comparison:**
- Negative squareness results were **all** worse than PF4=0 fiducial case.

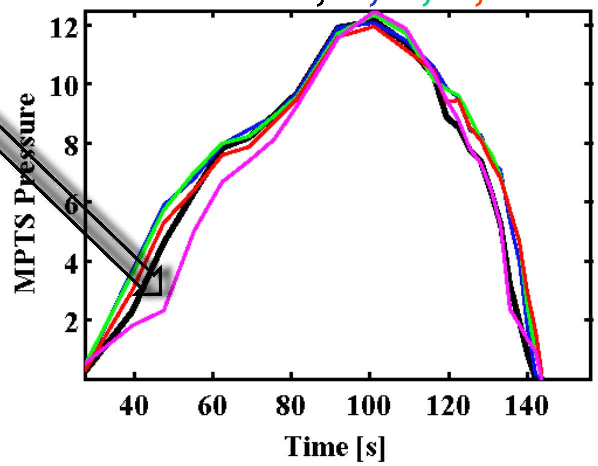
PF4 at 8 kA, High Squareness





Each Line is 1 cm apart





- As PF4 gets close to 8 kA:
- Last closed flux surface gets 3-4 cm close to the wall.
- Pressure profile degrades

NSTX

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Vertical Stability for NSTX and NSTX-U

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D. A. Gates, S. Gerhardt

Monday Physics Meeting
PPPL, NJ
Nov/15/2010

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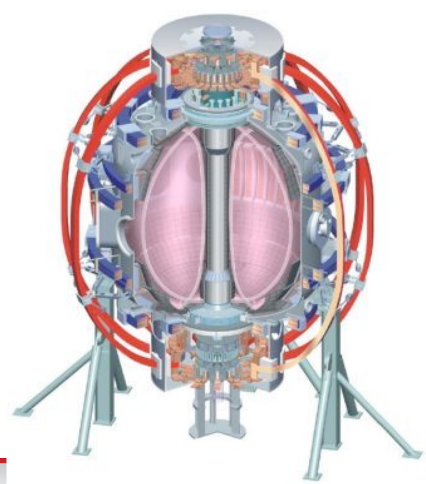

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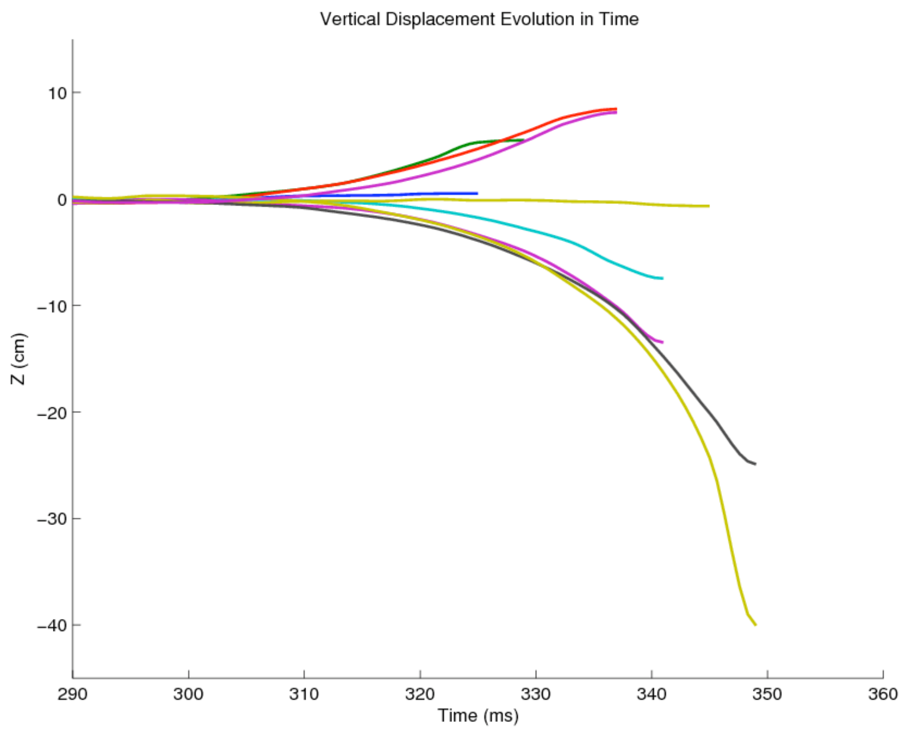
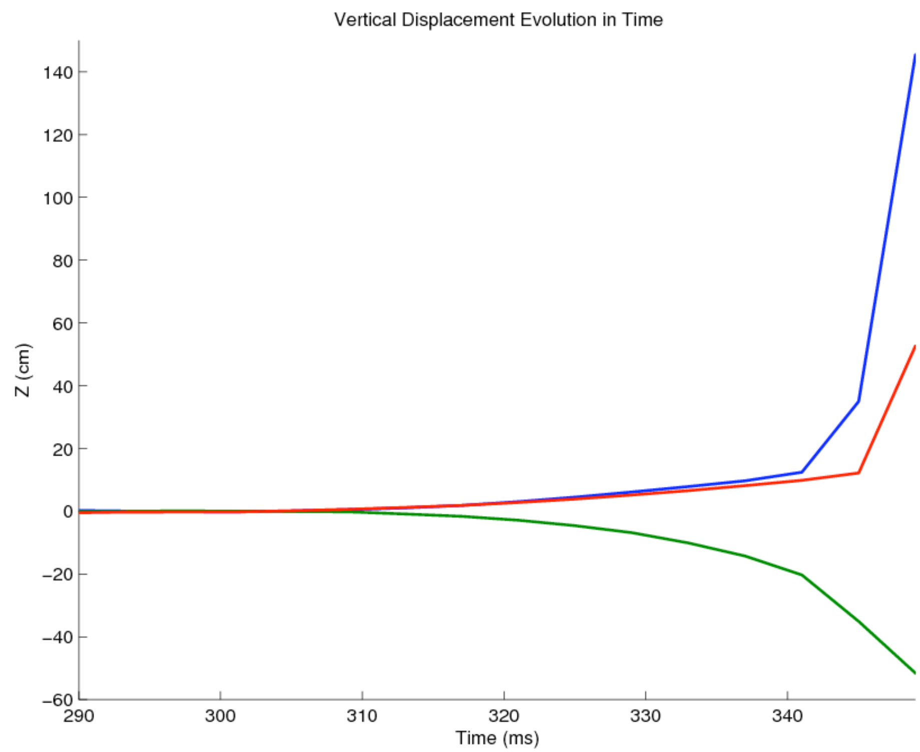
U Quebec

2008 Run: Vertical Displacement Measurements



Vertical displacement for controllable shots
(Cut off at the point of return)

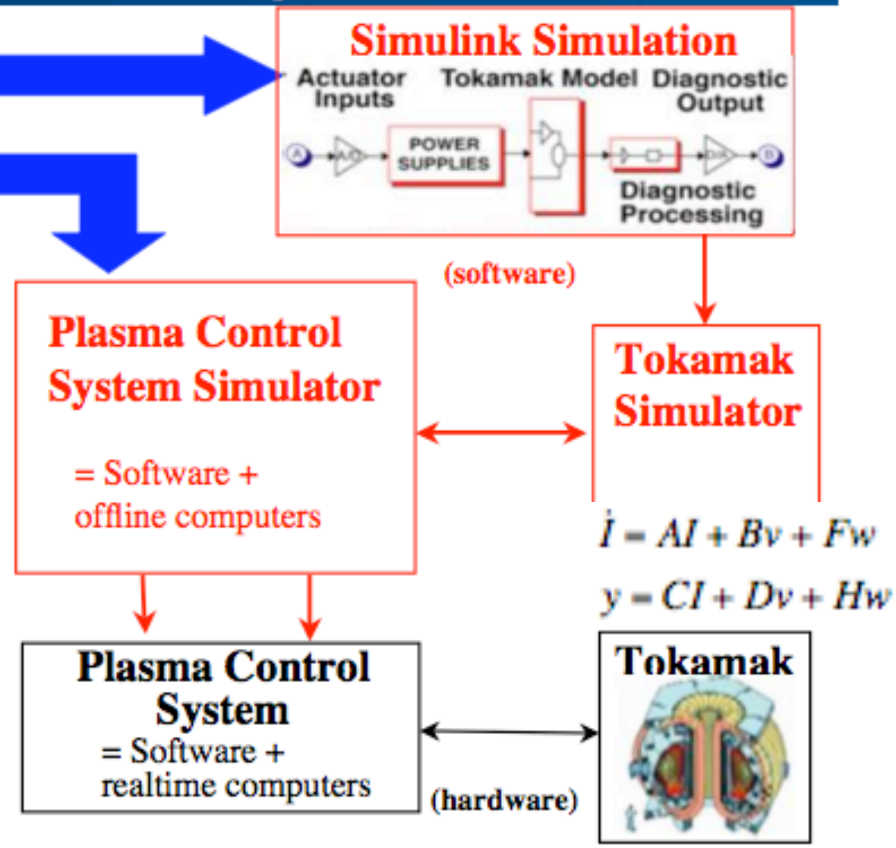


Vertical displacement for uncontrollable shots

- At 300 ms, we turned the controller off and let the plasma drift.
- When we turned the control back on some of the shots recovered while others hit the wall.

TokSys is an Integrated Plasma Control Environment That Allows Systematic Design and Testing of Controllers

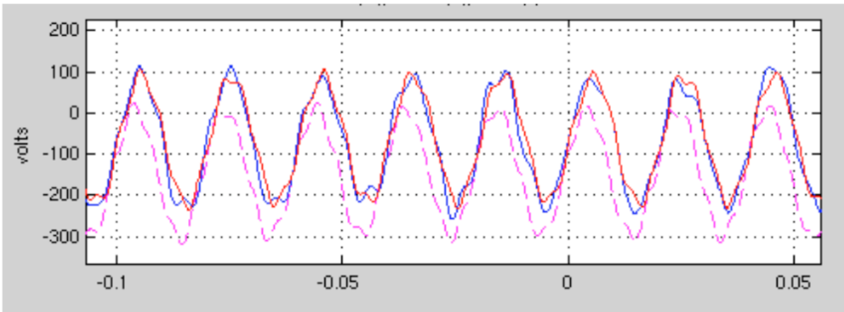
TokSys: Tokamak System Models + Controller Designs

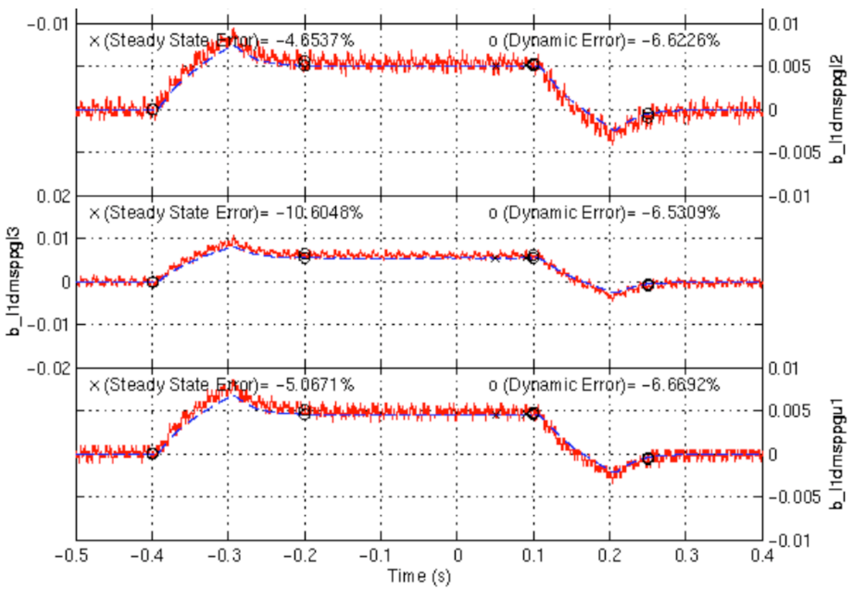


- **Control-level models:**
  - Simplified but accurate
  - Allow iterative design with multivariable controllers
- **Design tools written in international standard Matlab/Simulink**
- **Complete test of both algorithms and implementation provides confidence in real time performance**

DIII-D NATIONAL FUSION FACILITY

How the Model was Obtained?



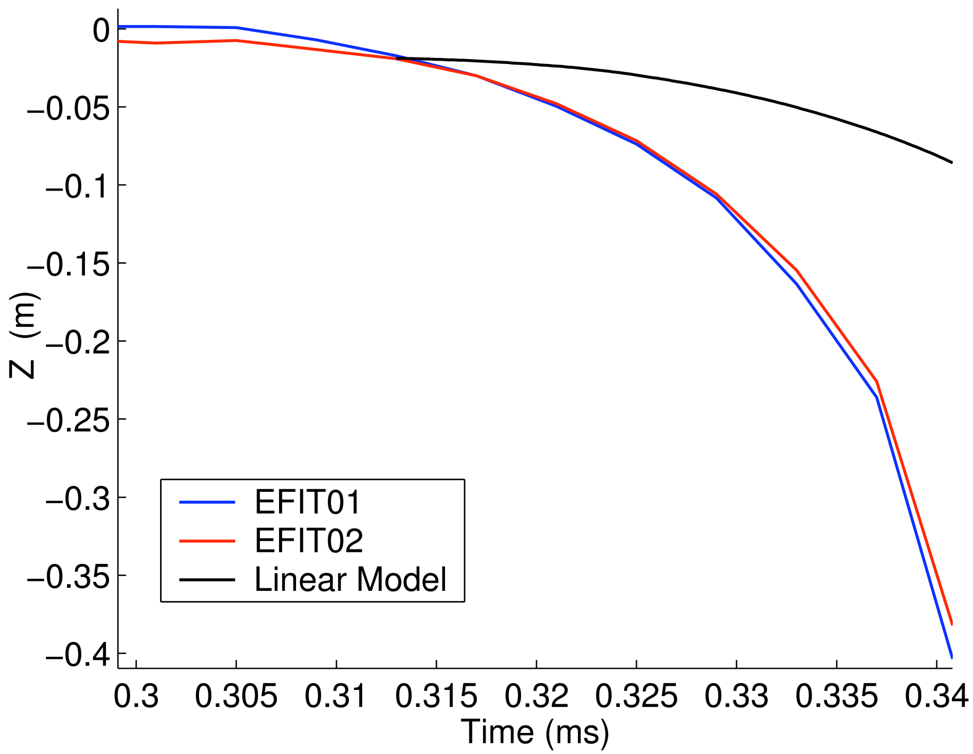


Comparison of model/experimental B-Probe traces for OH coil. Red trace is experiment, blue trace is model. Steady state and dynamic error values are % differences between model & exp and are defined between X's for steady state and O's for dynamic.

- It is a linear set of circuit equations.
- All we need is A, B, C matrices.
- Set of System ID experiments on NSTX 2003-4.
- Model obtained to fit the sensor/probe measurements as good as possible.
- Rigid plasma model

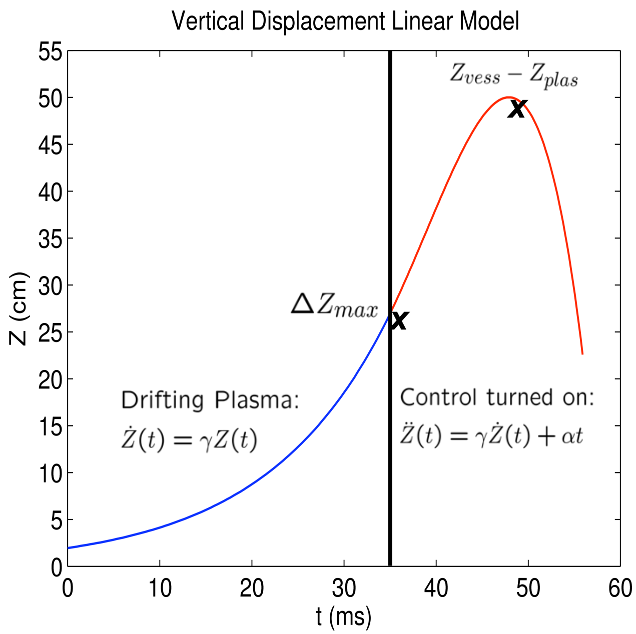
Mismatch Between XP and Toksys

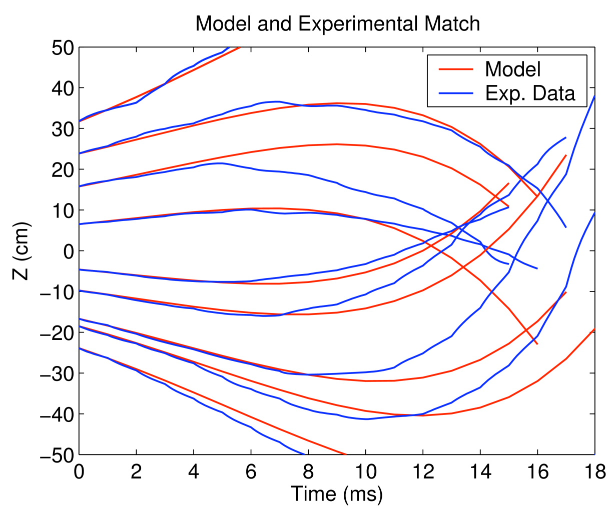
- XP data 3-4 times more unstable (20-25 Hz versus 54-95) than the model.



Example of a mismatch between TokSys numerical plasma model and the experimental data. Depending on how the model is used plasma or te coil model.

All XPs Can Be Modeled with a Linear Equation With the Same Two Parameters





- Where $\gamma = 75 s^{-1}$. The first order effect of the coils on the vertical motion is assumed to be:

$$\dot{Z}(t) = \gamma Z(t)$$

i.e. the current changes the velocity of the rigidly moving plasma. Also during the ramp up I is proportional to t. Combining these two effects, we can find an approximation for the dynamics of the vertical motion after the control is turned on as:

$$\ddot{Z}(t) = \gamma \dot{Z}(t) + \alpha t$$

α is found by data fitting as 4.5e5

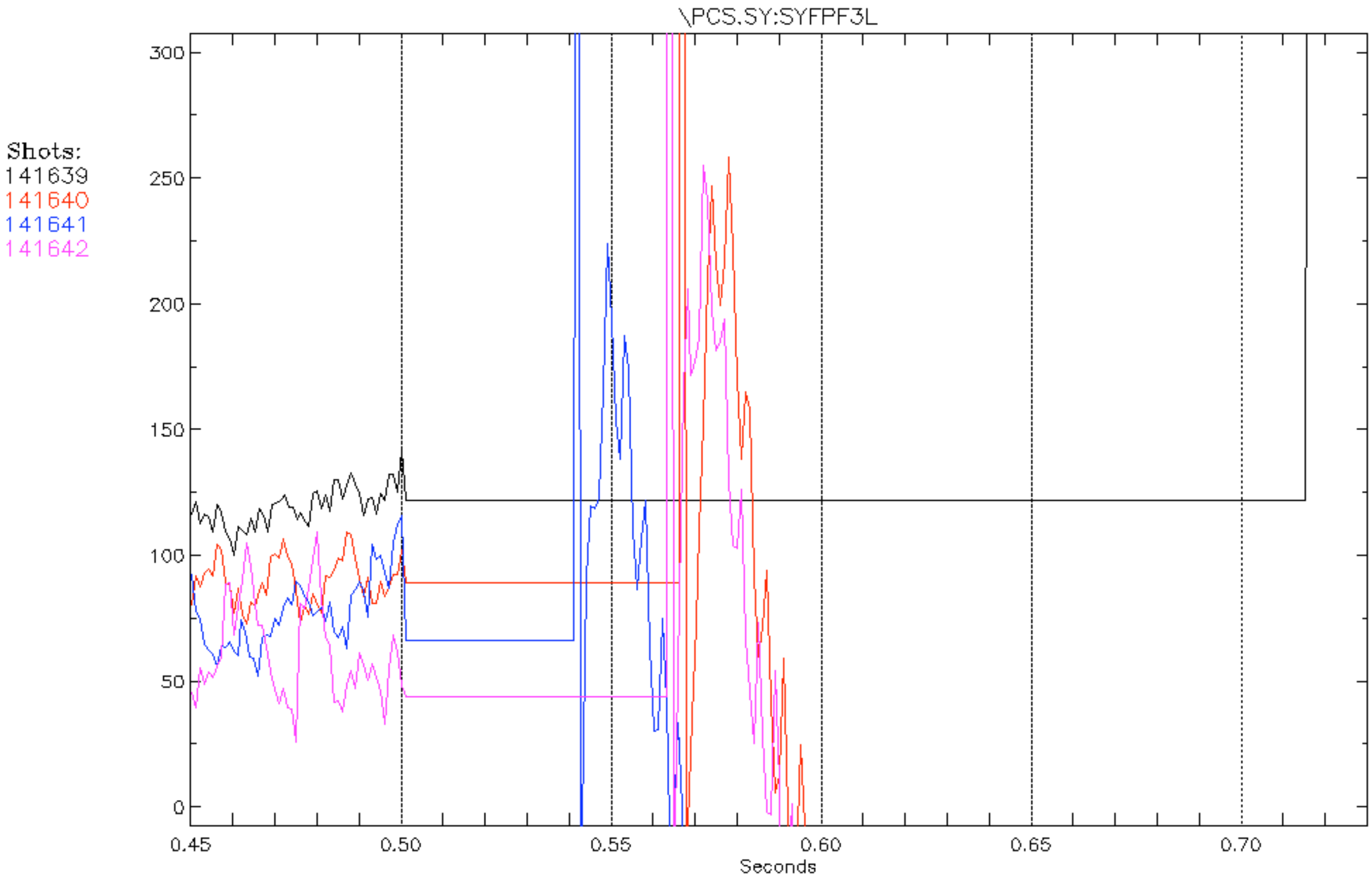
How Can it be Improved?

1. Solving perturbed Grad-Shafranov Equation
   This option was discussed. Probably can increase accuracy

2. 3D field effects. Better model the axisymmetric model that corresponds to the 3D pieces that make the plasma wall

3. Run updated new shots to improve the System ID.

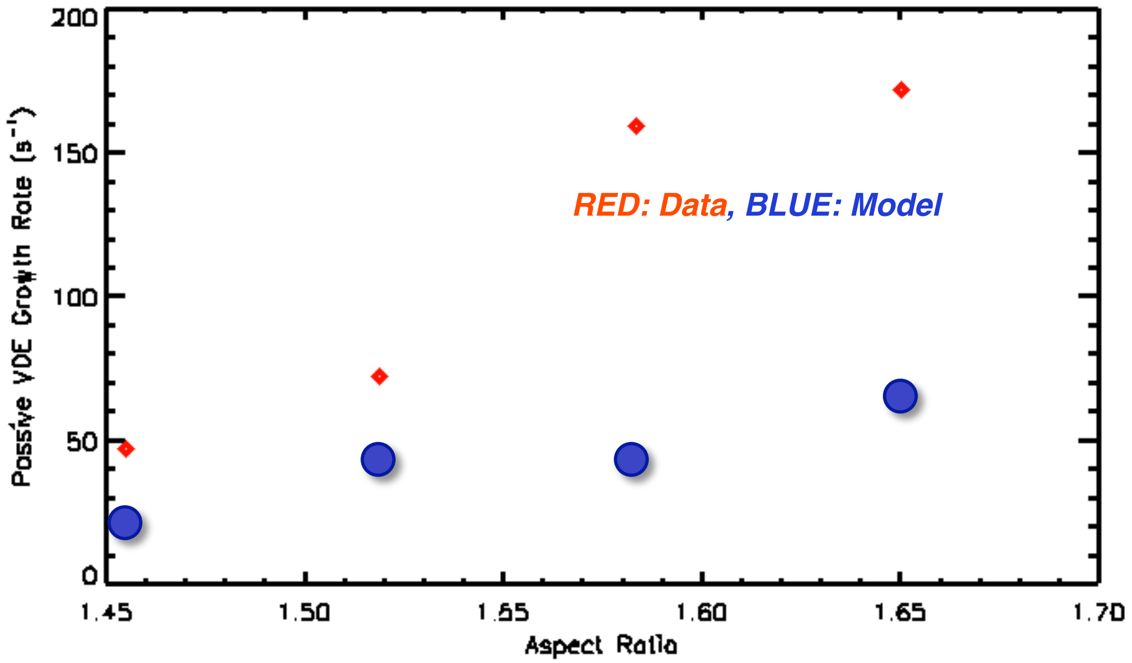
2010 Experiment: High Aspect Ratio Vertical Growth Rate



- Thanks to Relay Feedback, we were able to freeze voltage request in Isoflux for the first time.
- This enabled vertical growth rate measurements

New Experimental Growth Rate (Gamma) 45-170 s^-1 versus 10-42 s^-1 for Model

- High Aspect Ratio More Unstable
- Need better vertical control for Upgrade



- Trying to fix the TokSys model
- Also, trying to update the Power Supply model (with R. Hatcher)
- Probably need better models (3D?).

END

What are the Alternatives?

1. Solving perturbed Grad-Shafranov Equation
   This option was discussed. Probably can increase accuracy

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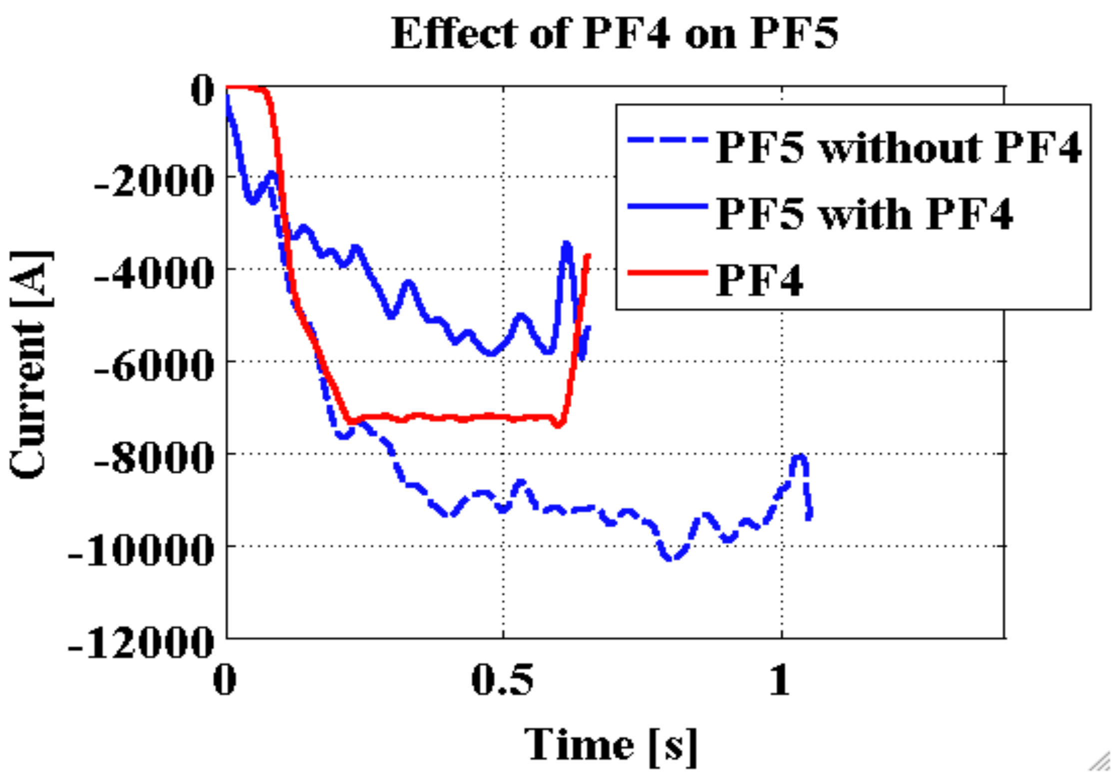
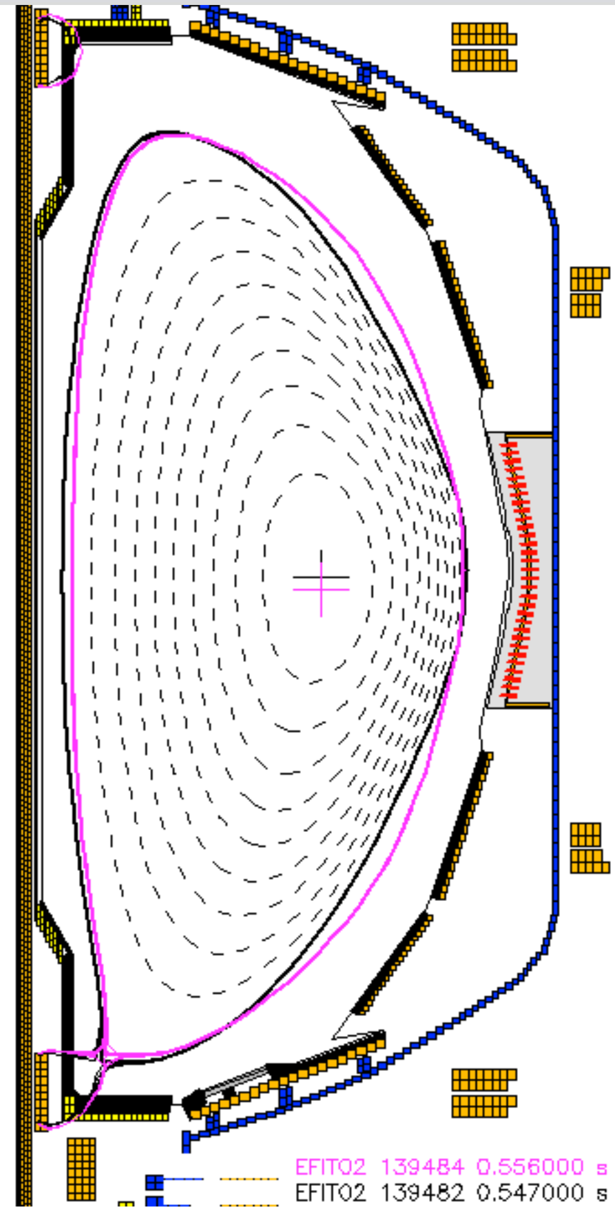
First Ever Use of PF4 for Shape Optimization

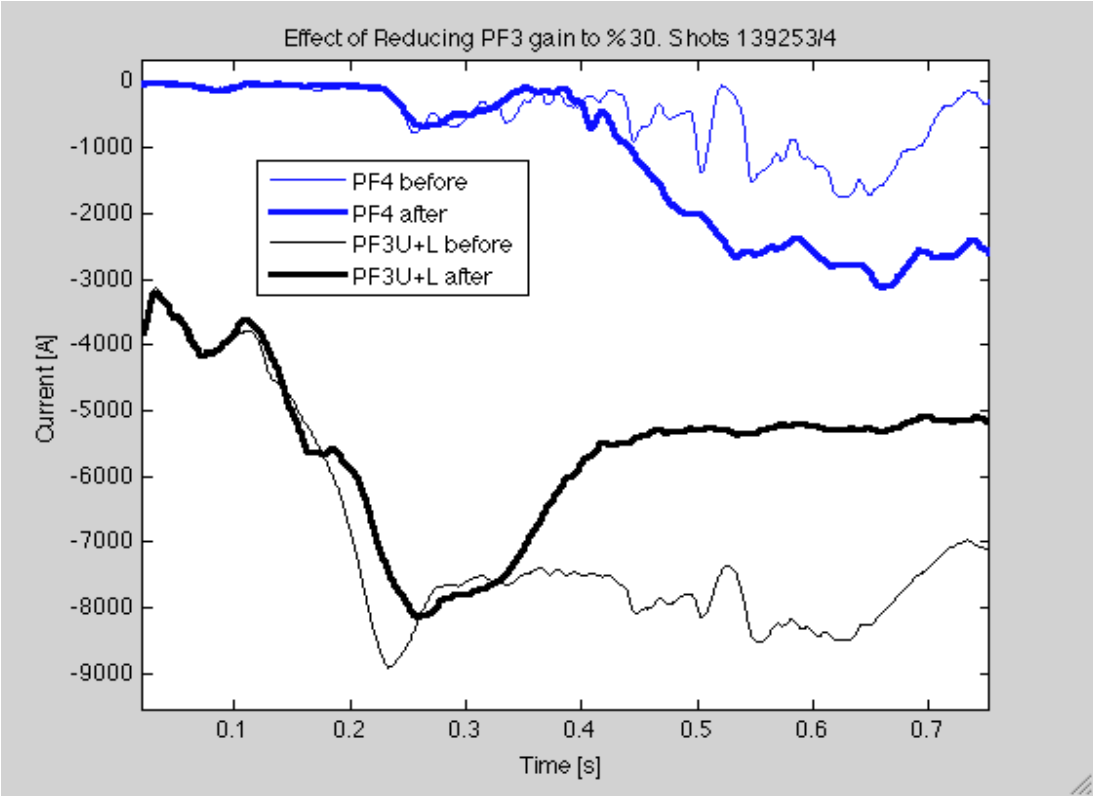




- Ramp PF4 to 7 kA
  - PF1A decreased to give the same kappa.
- PF5 decreases as PF4 increases.
- Squareness decreases.
- Keep other things the same.

XMP Control Results: PF3-PF4 interaction

- With PF4 control on, we reduced the gain for PF3 %30 at 360 ms.
- PF4 compensated for the loss of inward pushing effect of PF3.
  - PF4 can offset both PF3 and PF5.



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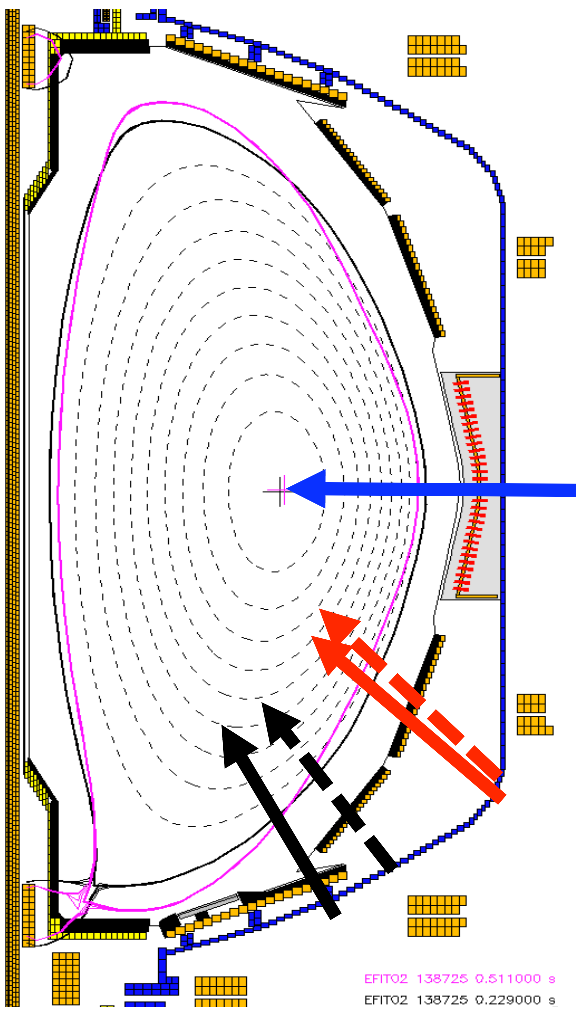
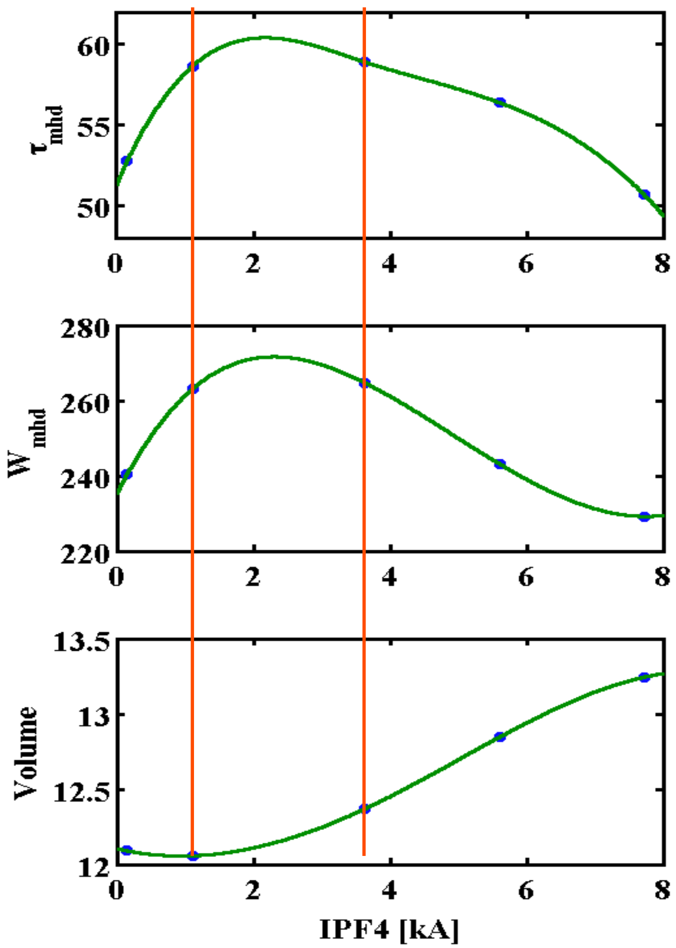
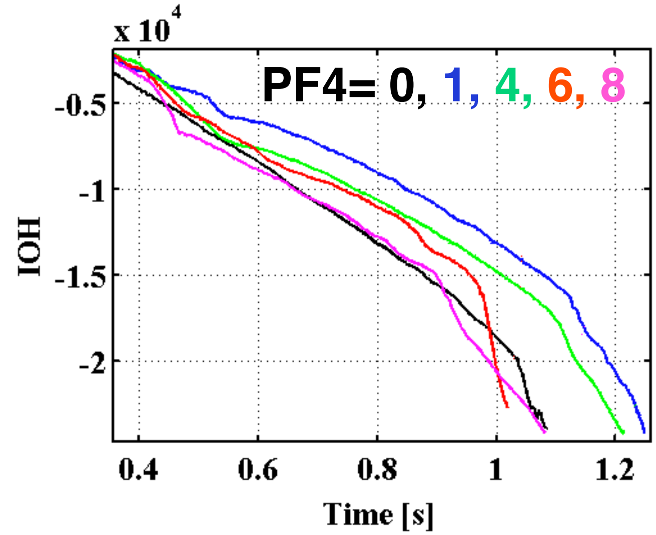


- Figure show the result of a ramp on PF4 from 0 to 2.6 kA.
- As PF4 increases, squareness change.
- In order to align, PF3/4/5 control points (shown in dashed black, dashed red and blue) X-point moves down.
- To solve this problem, move the PF3 and PF4 control segment. Shown in solid red, black.
- Could not do this:
  - Problem with PCS Segment Editor.
  - Hopefully will be fixed for 2011.

Higher Performance: PF4 of 1-4 kA





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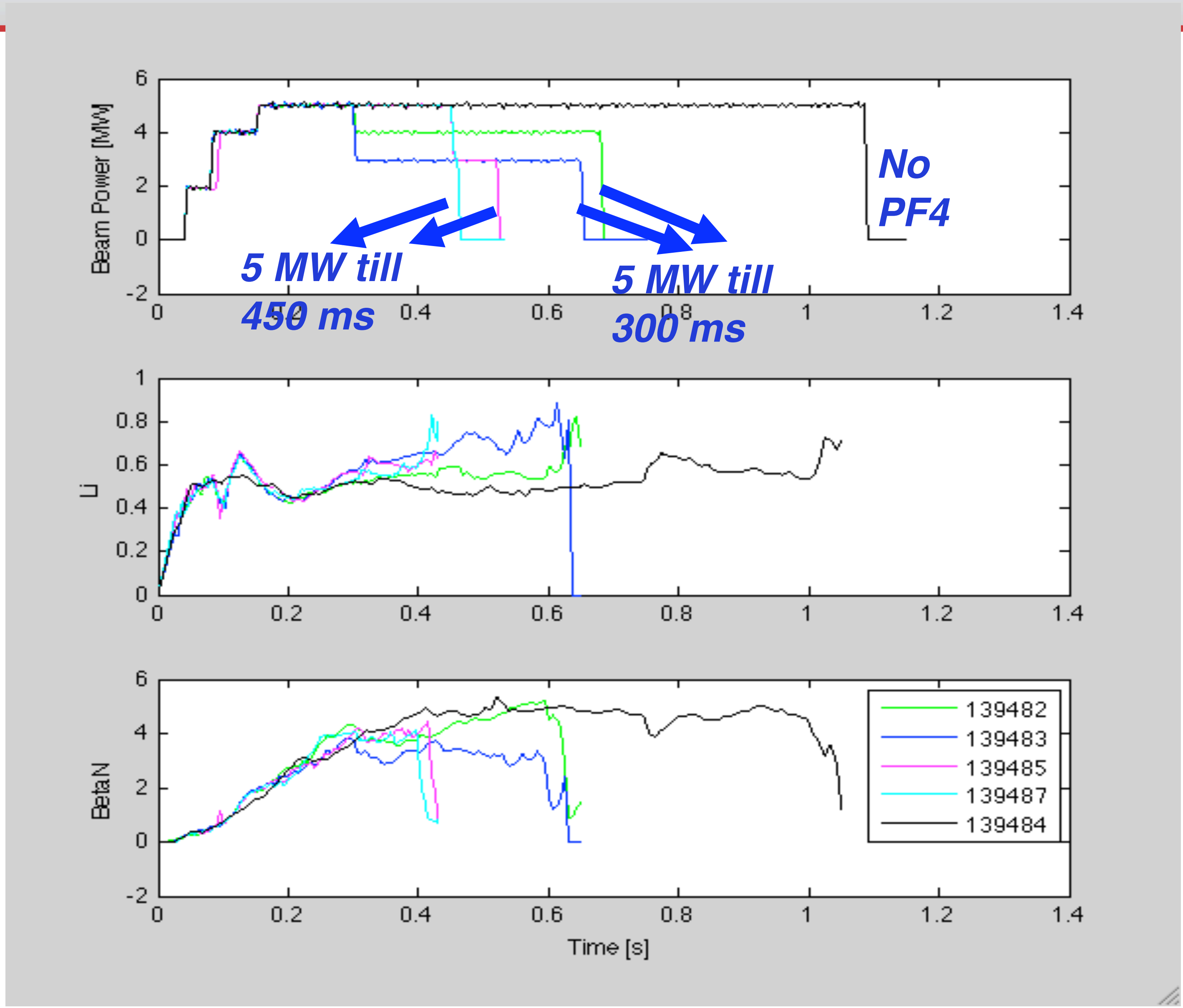
- Confinement time increases
- Energy confinement increases
- Flux consumption reduces.
- Too high PF4 interacts with the wall and plasma is not as good.

[142353,142342,142343,142347,142348]

Lower BetaN Limit for PF4 in the positive direction



Toksys Results Growth Rate (Gamma) 20-25 s^-1

Shot #	Gamma s^-1
127077	23
127078	25
127079	24
127080	22
127081	24
127082	22
127083	20
127084	20
127085	21
127086	23
127087	21

Experimental LRDFIT Growth Rate (Gamma) 54-95 s^-1

	Egemen #	Shot	ms	Control Turned Off t_0	z_0	li_0	Control Turned On t_turn	z_turn	li_turn	Peak Plasma Displacement t_f	z_f	li_f	*Gamma* s^-1	Voltage ave Pf3U&2L
VDE +Z	1	127074	20	0.301	-0.0018	1.3436	0.32	0.0046	1.3865	0.325	0.005	1.3939	*no vde at all*	
	2	127075	20	0.301	0.0005	1.3774	0.32	0.0344	1.4927	0.329	0.0552	1.61	*95*	600
max controlled	**3**	**127076**	**30**	**0.301**	**-0.0025**	**1.4768**	**0.33**	**0.0663**	**2.1936**	**0.337**	**0.0845**	**3.5009**	*70*	**1400**
	14	127087	30	0.301	-0.003	1.3482	0.33	0.0587	1.6485	0.337	0.0814	2.0792	*74*	1200
un-controlled	10	127083	40	0.301	-0.002	1.378	0.34	0.1176	3.5021	0.341	0.1244	3.7423	*78*	1600
un-controlled	13	127086	40	0.301	-0.0025	1.3885	0.34	0.0943	3.3401	0.349	0.5268	6.3724	*64*	1600

VDE -Z	5	127078	35	0.301	-0.0013	1.3602	0.335	-0.0509	1.1928	0.341	-0.0746	1.1584	*61*	800
	6	127079	35	0.301	-0.0009	1.3592	0.335	-0.0865	1.1954	0.341	-0.1347	1.1683	*73*	1300
	7	127080	40	0.301	-0.0037	1.4283	0.34	-0.005	1.46	0.345	-0.0066	1.4403	*no vde - control made unstable*	
	8	127081	40	0.301	-0.0034	1.4129	0.34	-0.1369	1.1969	0.349	-0.2491	1.0877	*69*	1500
max controlled	**12**	**127085**	**40**	**0.301**	**0.0027**	**1.3899**	**0.34**	**-0.1504**	**1.1748**	**0.349**	**-0.4006**	**0.9388**	*54*	**1600**
un-controlled	11	127084	40	0.301	0.0001	1.3759	0.34	-0.1879	1.1783	0.353	-0.6069	0.7328	*67*	1600

straight VDE	4	127077	none	*74*