Squareness Optimization May Enable Radiated Power Control

- LLD will likely lead to monotonous increase in radiated power due to increase in the radiation from impurities (Iron/Carbon emissions)
  - Plasma Phys. Control. Fusion 51 (2009) 124054 M G Bell et al.
  - ASDEX Team, Nuclear Fusion 29, 1959 A989
- Need ELMs to get rid of the impurities and thus radiated power.
- Most of the shape parameters (such as δ and κ) are fixed for the shots
- This year we will include squareness control.
  - Upgrade to the coil protection hardware
  - Modifications to PCS and correct gains in Isoflux control
- Squareness changes the pedestal stability boundary and may effect the ELMs
  - 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 optimization and studying the stability as squareness varies will be useful for this years shots with LLD.

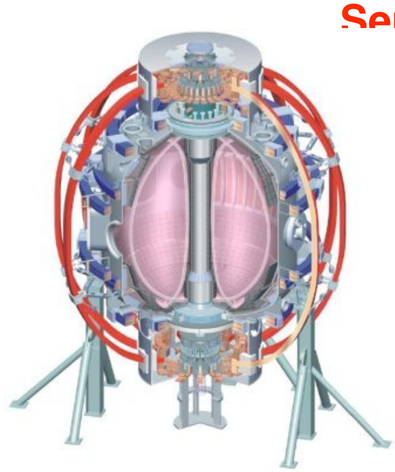
- Backup Slides

Squareness Control and its effect on inducing ELMs

College W&M
Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Maryland
U Rochester
U Washington
U Wisconsin

Egemen Kolemen, S. Gerhardt, D. Gates

2009 NSTX Results and Theory Review
Room B-318
September 15th, 2008



Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

LLD will Lead to Increasing Radiated Power

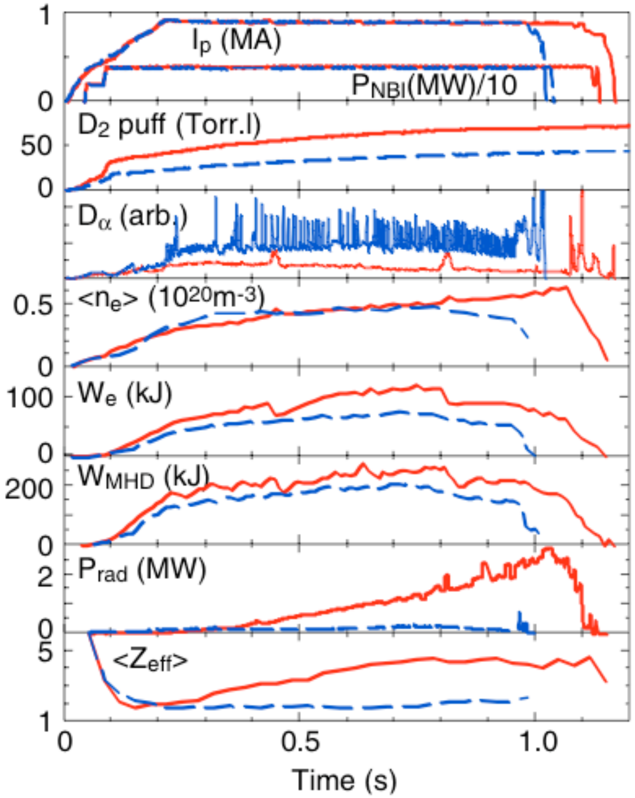


Figure 2. Time evolution of representative plasma parameters for similar discharges without (129239-blue dashed) and with (129245-red solid) 260 mg of lithium applied by the two lithium evaporators.

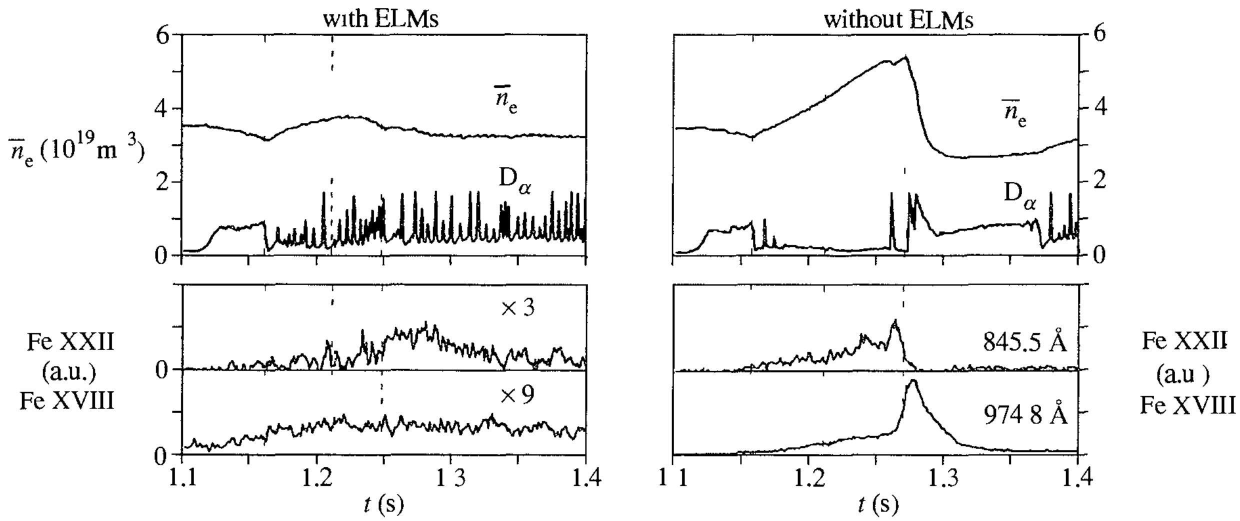
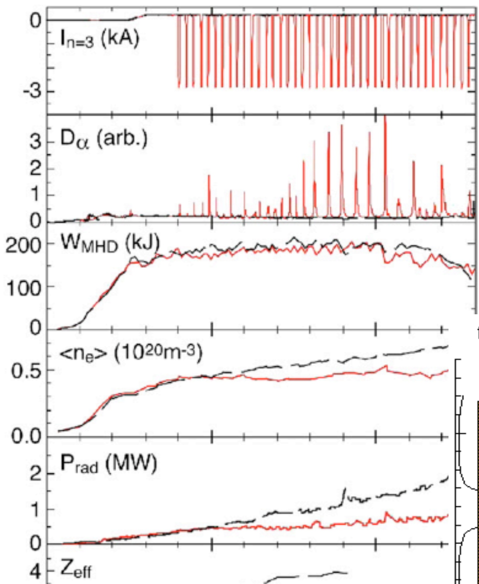
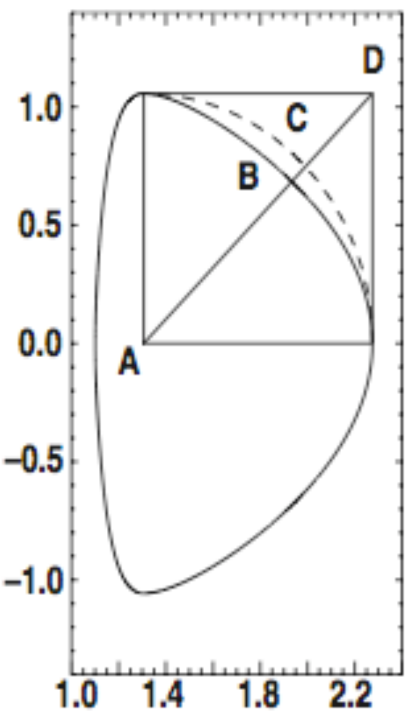


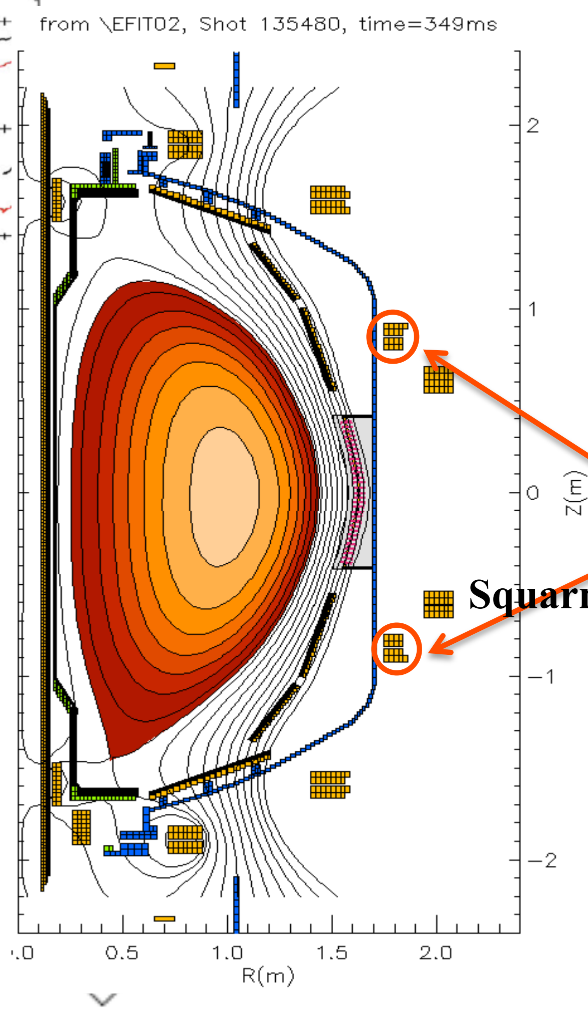
Fig. 7.17.2 Discharges with and without ELMs, showing the increase in electron density and impurity accumulation associated with the ELM-free case. Note that the iron emission line signals are amplified in the case with ELMs (ASDEX Team, Nuclear Fusion 29, 1959 A989))

- 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)

This year PF4 control we enable **Squareness!**

Squarness control with PF4 coils

Effect of Squaren

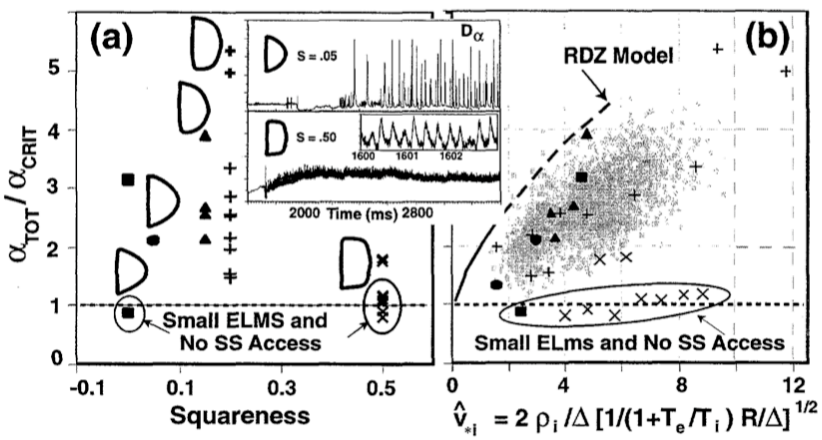


Fig. 2. Effect of squareness on edge pressure gradient relative to ballooning mode limit, α/α_{CRIT}. (a) At high and low squareness $\alpha/\alpha_{CRIT}= 1$ and small high frequency ELMs are observed where no access to the second stable regime is expected, (b) large ELM data is relatively consistent with Roger [2] model as was the original data base at for fixed shape (gray points), however small ELM discharges deviate from this scaling.

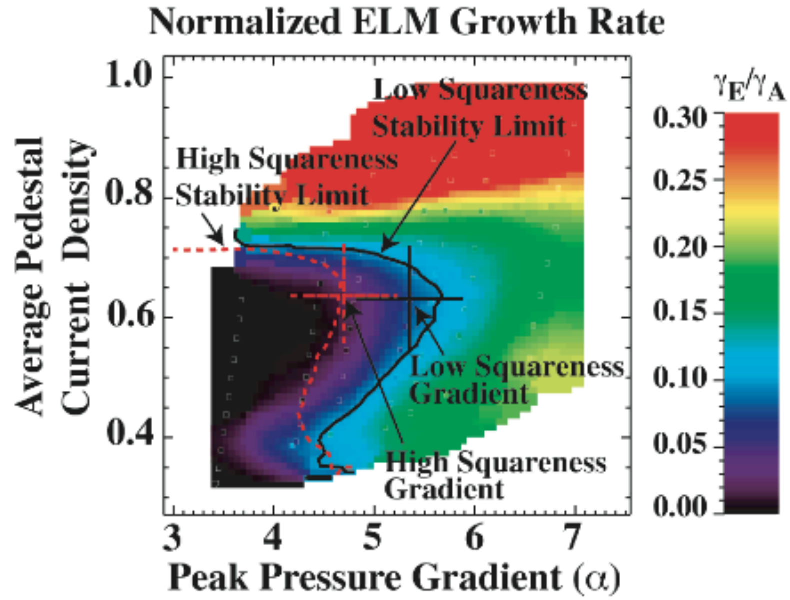


FIG. 12. The edge stability map for low squareness hybrid discharge. The stability boundary contour for $\gamma_{ELM}/\gamma_A = 0.1$ is shown by the black curve. The stability boundary contour for the higher squareness discharge is shown by the red curve.

- *In support of the view that edge second stability access allows ~ > a~~~ are experiments in which the plasma 'squareness' was varied [18]. In these experiments a sudden transition to small high frequency ELMs was observed at very high and very low squareness where simulations [1] predicted edge current density significantly exceeding the collisionless bootstrap current would be required for access to second stability [Fig. 2(a)]. This qualitative change in ELM character occurred over a narrow range in squareness and as such is unlikely to be the result of a change in fueling efficiency or impurity influx. At the transition to small ELMs the edge pressure gradient is observed to drop to the calculated first stable limit. Additional gas puffing in discharges which would otherwise have large ELMs but which are close to the small ELM shape produced a transition to small ELMs consistent with a decrease in edge bootstrap current with increased collisionality.*

- **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**

- Milestone 10.3

THE EFFECT OF PLASMA SHAPE ON H-MODE PEDESTAL

C ... al.

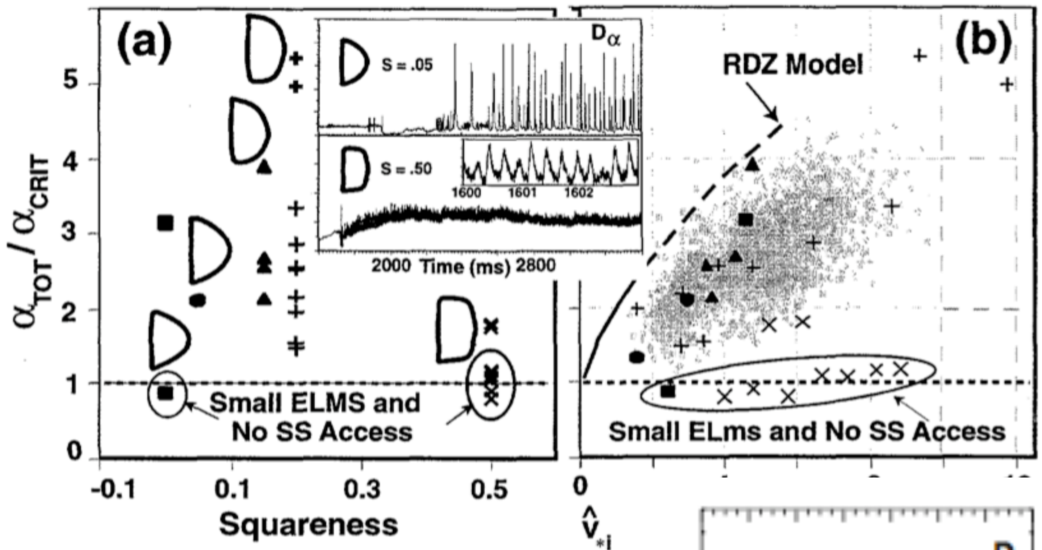


Fig. 2. Effect of squareness on edge pressure gradient
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ELMs are observed where no access to the se
large ELM data is relatively consistent with R
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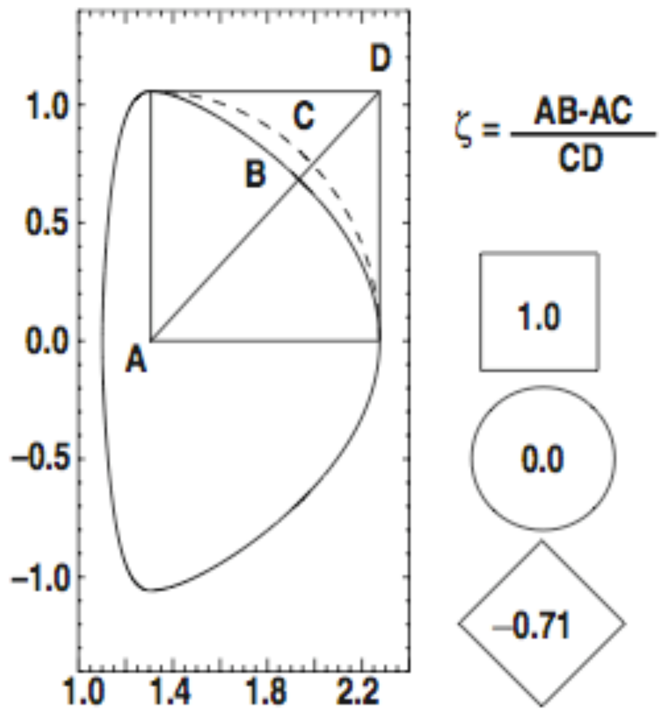
from this scaling.



- *In support ... ows ~ >*
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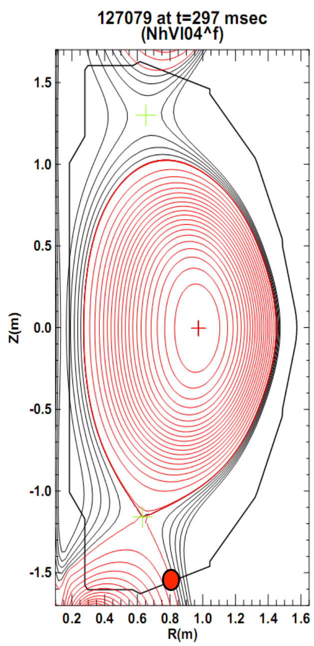
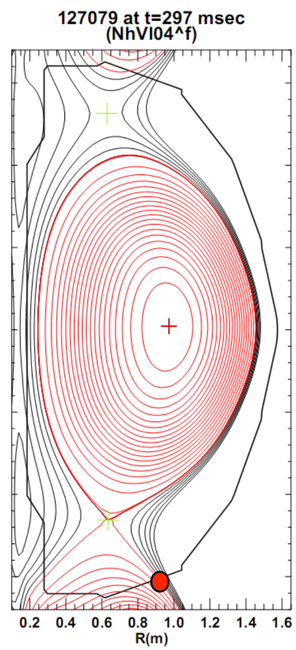
  consistent with a decrease in edge boo ... d
  collisionality.

Preliminary Study: ISolver Analysis

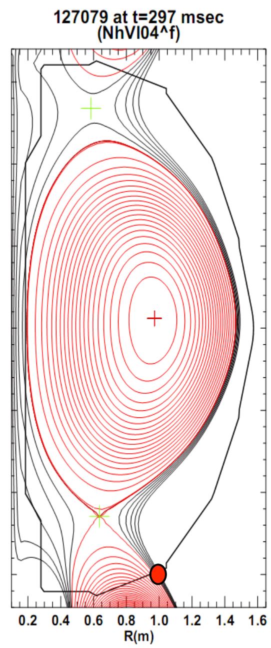
- Using ISolver showed that
  - The outer strike point predominantly depend on PF2 .
  - Analyzed the effect of PF2L in ISolver.
  - The dynamics of Single Input Single Output (PF2L current to Strike Point change) can be modeled as a first order system with time delay.



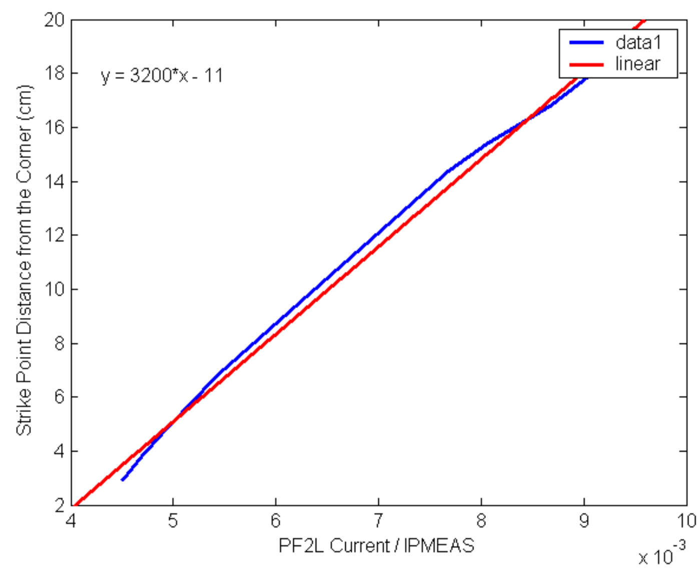
PF2L=0 kAmp



PF2L=8 kAmp



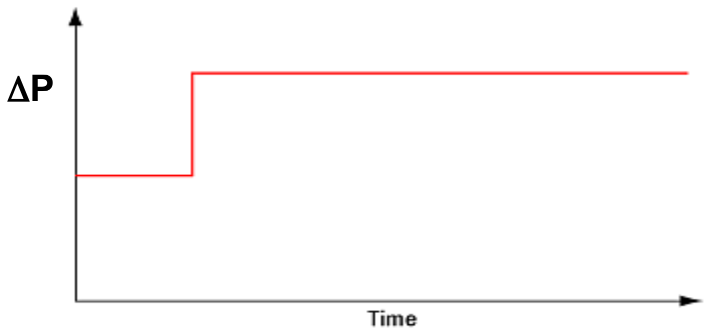
PF2L=16 kAmp

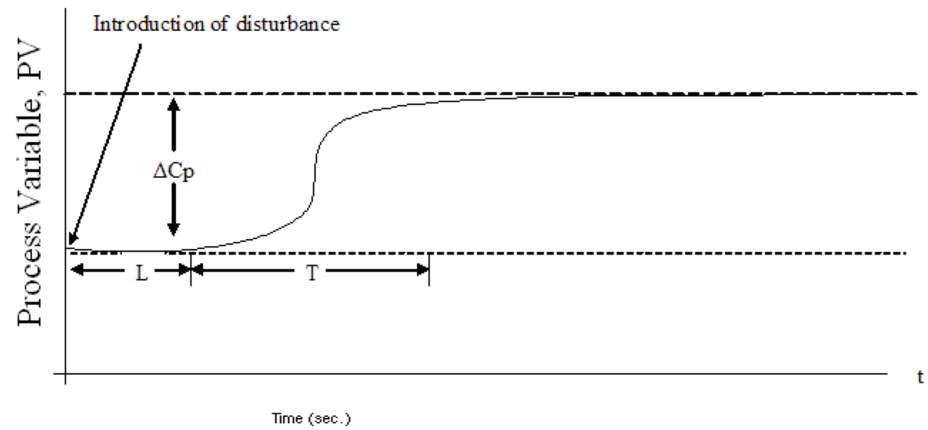


Strike Point Position versus PF2L

The change in the strike point with different PF2L current

Experiment Analysis: Step Response and PID Controller





- For this system of First Order ODE with time lag we can model it using these constants
- L = lag in time response
- ΔCp (%) = the percentage change in output signal in response to the initial step disturbance
- T = the time taken for this change to occur
- N = $\frac{\Delta C_p}{T}$; where N is the reaction rate
- Given these we define $K = \frac{P}{(NL)}$

Experiment Analysis: Step Response and PID Controller

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

	K_c	T_i	T_d
P	K		
PI	0.9K	3.3L	
PID	1.2K	2L	0.5L

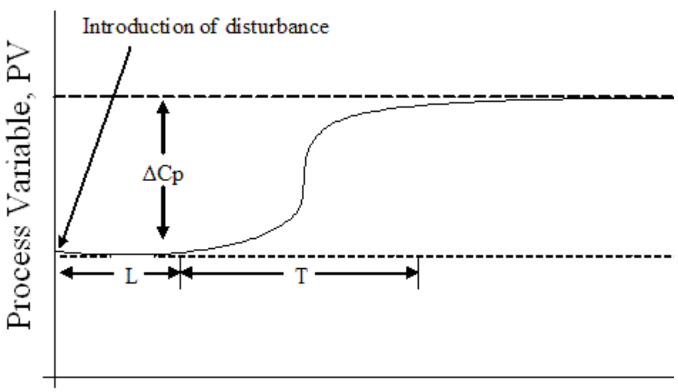
Experiment Analysis: Step Response and PID Controller

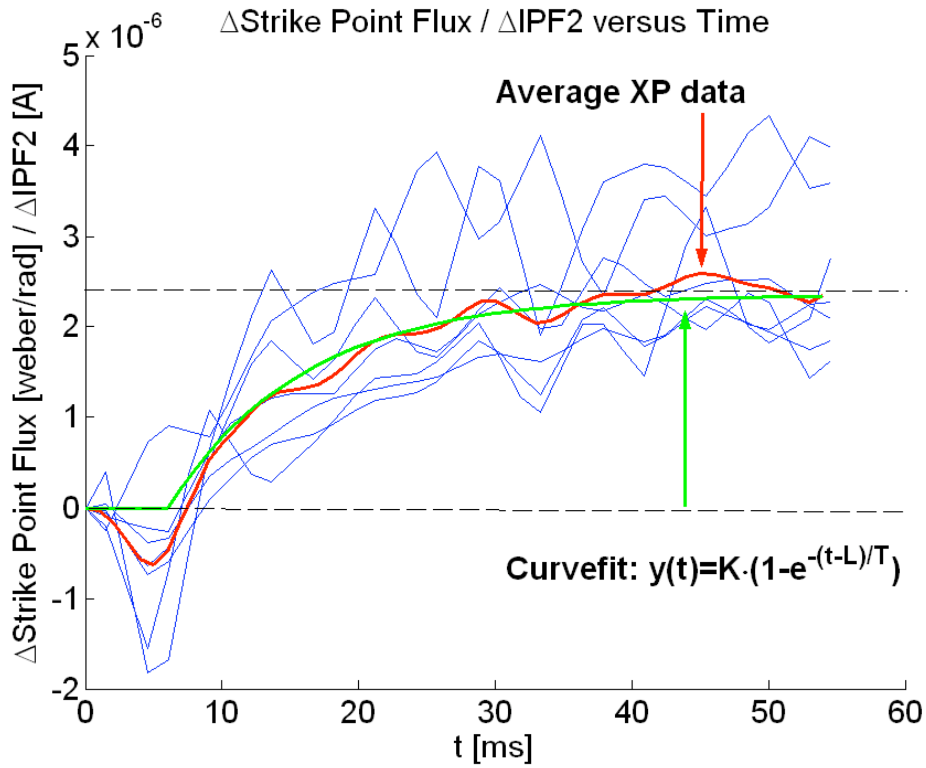
- The point of "tuning" a PID loop is to adjust how aggressively the controller reacts to errors between the measured process variable and desired setpoint.
  - If the controlled process happens to be relatively sluggish, the PID algorithm can be configured to take immediate and dramatic actions whenever a random disturbance changes the process variable or an operator changes the setpoint.
  - Conversely, if the process is particularly sensitive to the actuators that the controller is using to manipulate the process variable, then the PID algorithm must apply more conservative corrective efforts over a longer period.
- The essence of loop tuning is identifying just how dramatically the process reacts to the controller's efforts and how aggressive the PID algorithm can afford to be as it tries to eliminate errors.
- Ziegler and Nichols developed a heuristic sub-optimal but robust first guess for PID controller gains for a 1^{st} order ODE with time lag, based on their expertis

	K_p	K_i	K_d
P	P/(NL)		
PI			
PID			

	K_c	T_i	T_d
P	K		
PI	0.9K	3.3L	
PID	1.2K	2L	0.5L

Experiment Analysis: Step Response and PID Controller

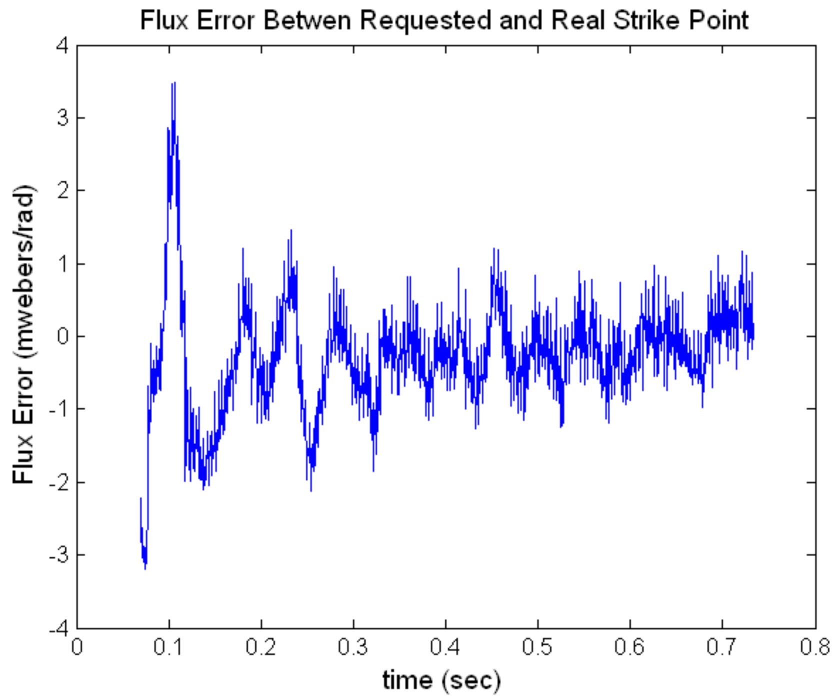


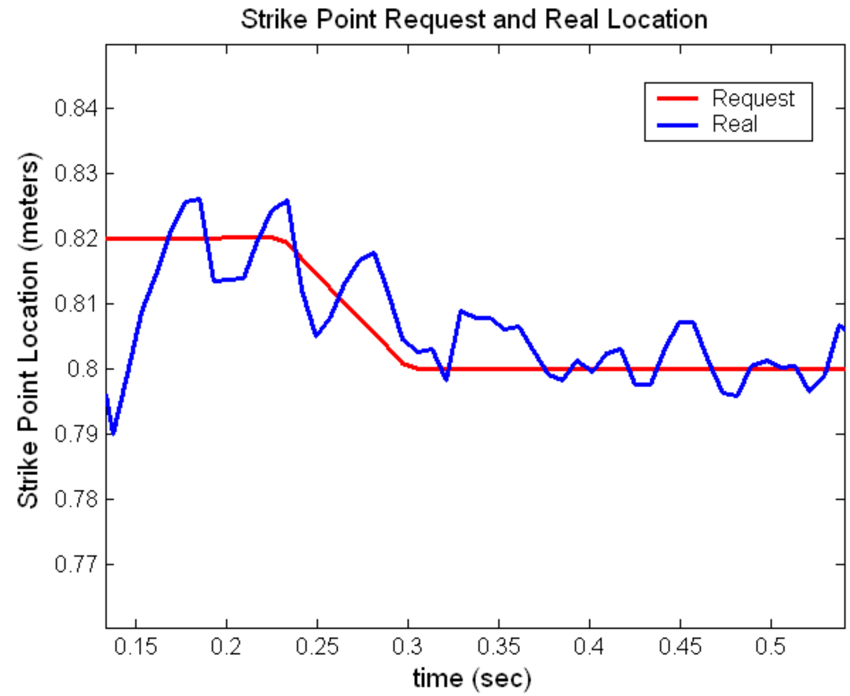


Calculated PID controller P: 170 – 550 (mean 360)

P-I has 1-2 ratio I: 340 – 1100 (mean 720)

Results: PID Controller Performance





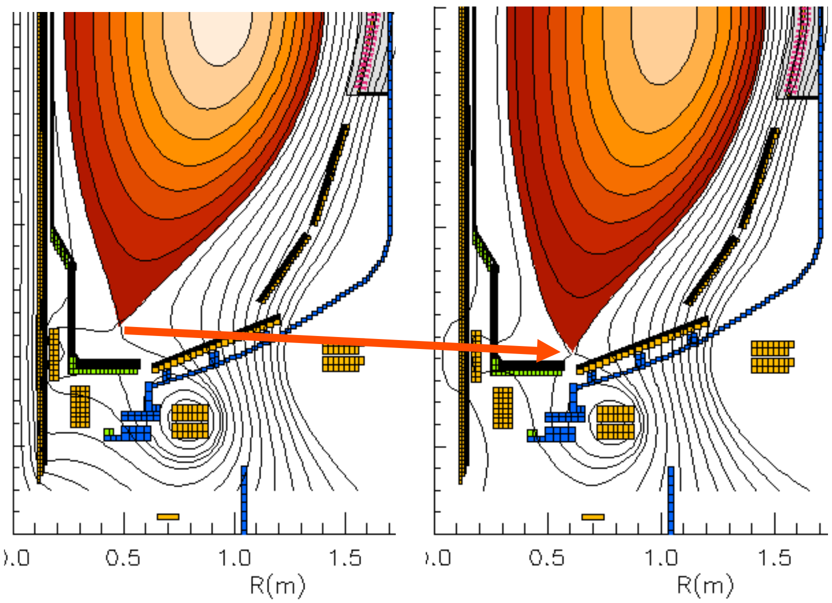
- Shot 133886:

Calculated PID controller P: 170 – 550 (mean 360)

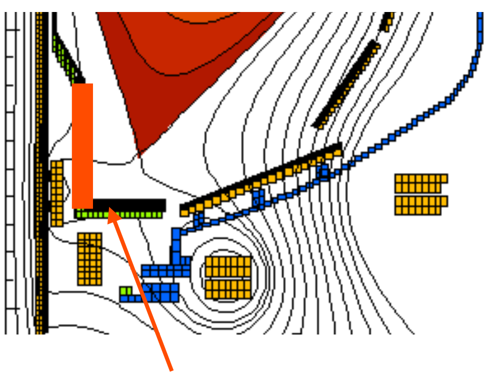
P-I has 1-2 ratio I: 340 – 1100 (mean 720)

Tuned these values in experiment to P: 400 and I: 800.

Inner Strike Point Control

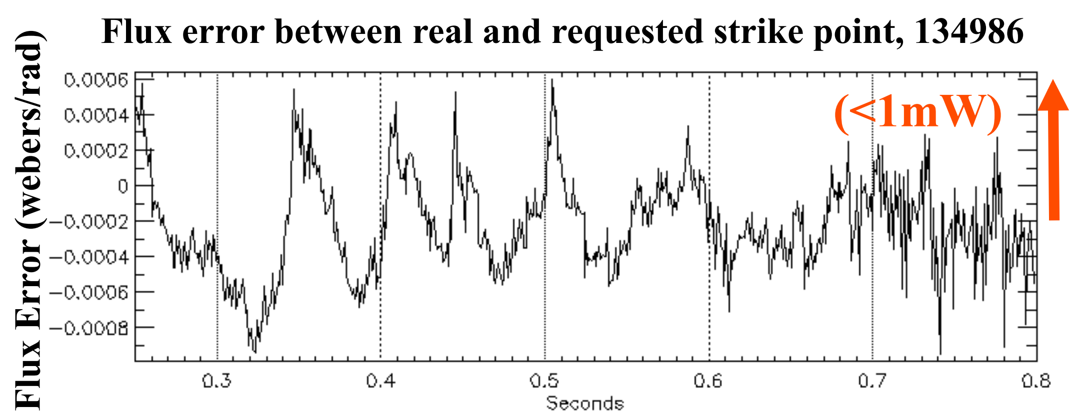


X-points bifurcation

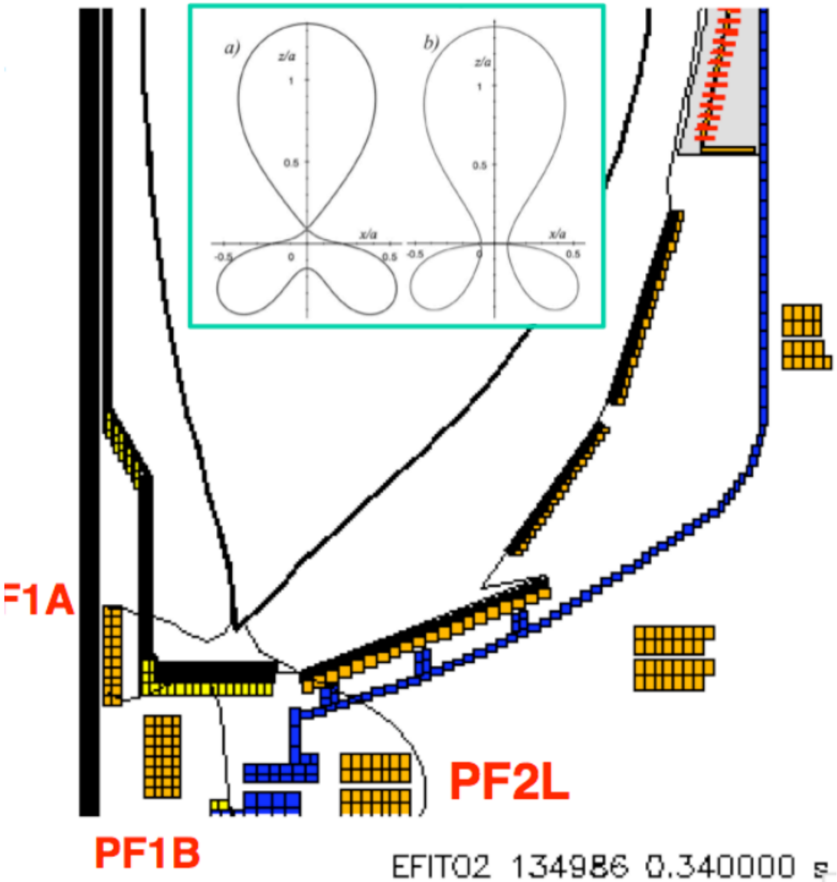


Segment to control inner strike point

- 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.



Contribution: Snow Flake Experiment



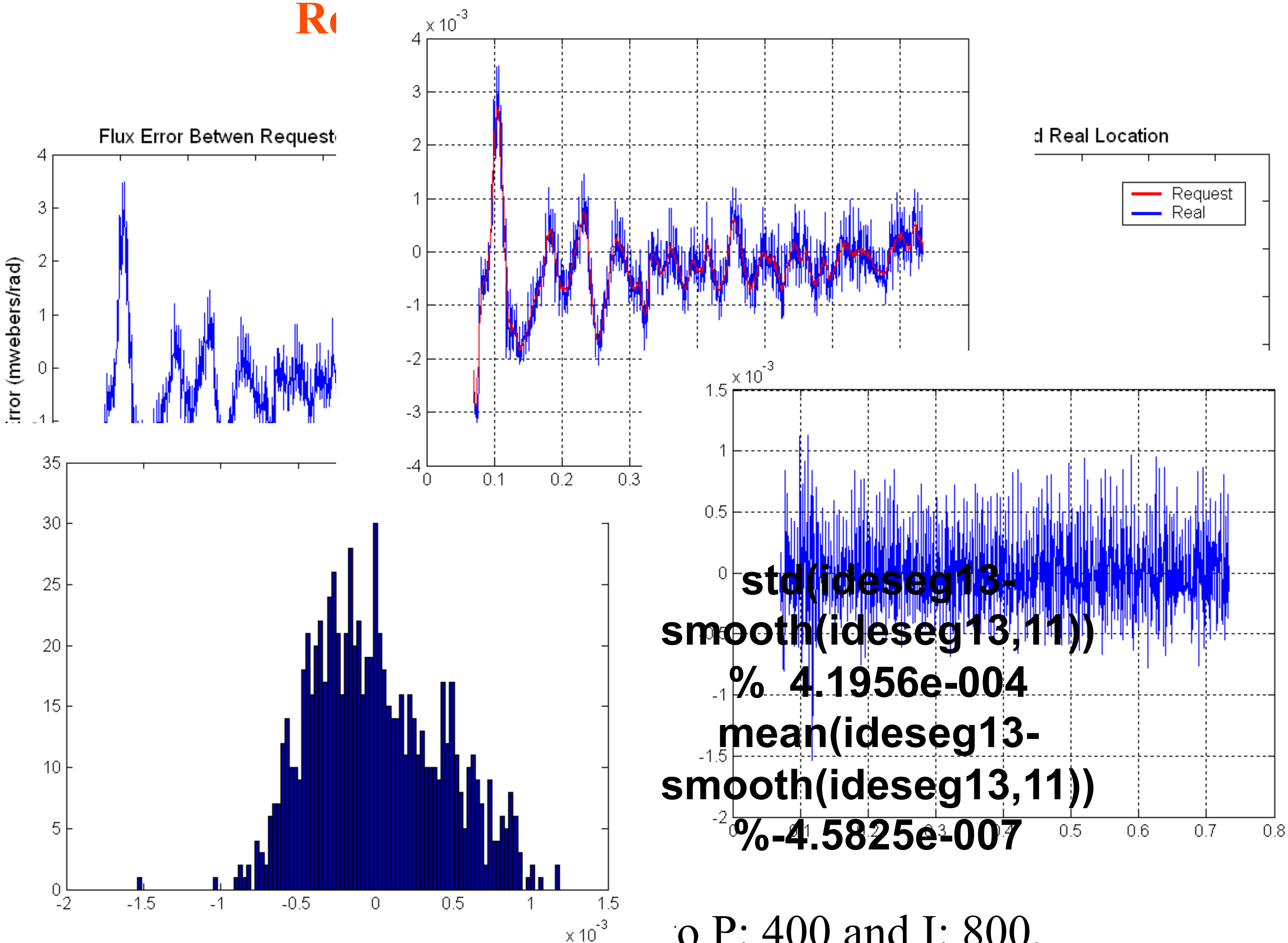
Vlad Soukhanovskii

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.

Backup Slides

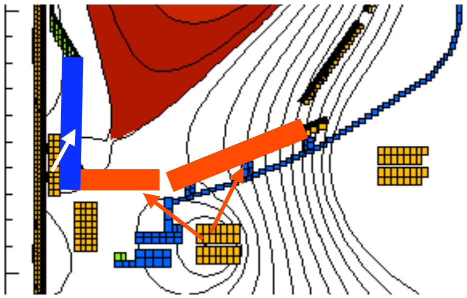
R



std(ideseg13-smooth(ideseg13,11))
% 4.1956e-004
mean(ideseg13-smooth(ideseg13,11))
%-4.5825e-007

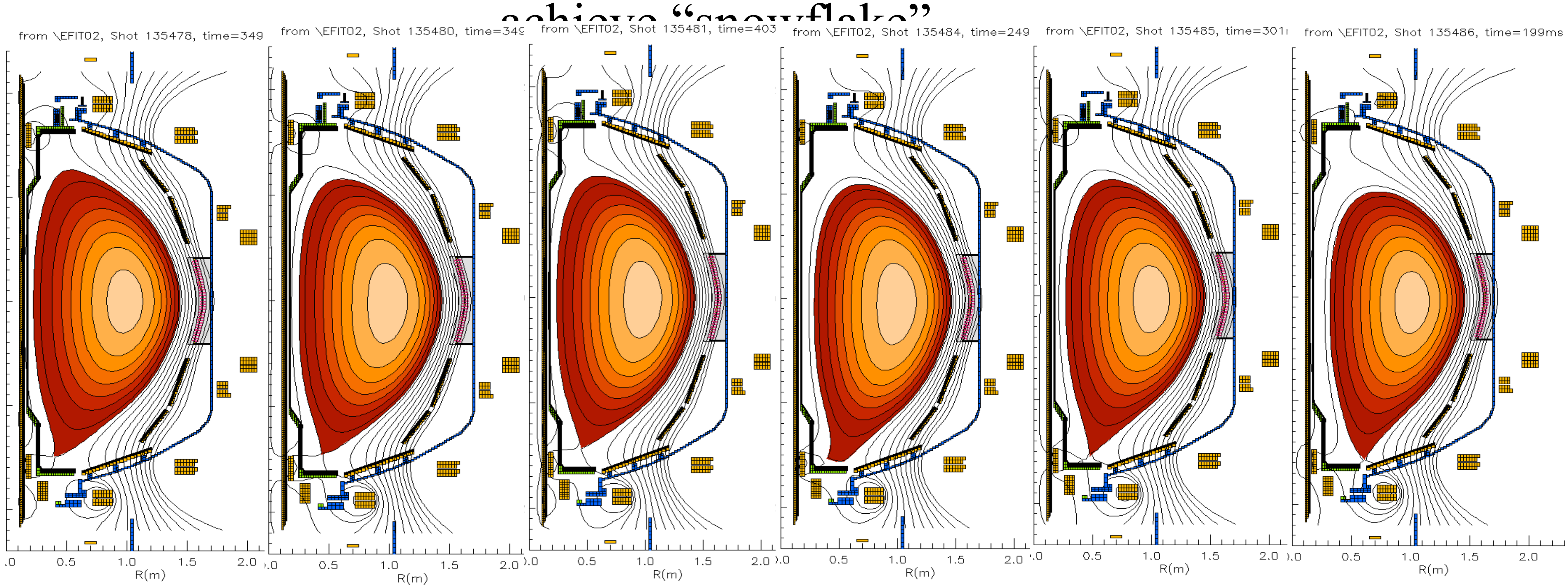
o P: 400 and I: 800.

Expanded Outer Strike Point Control



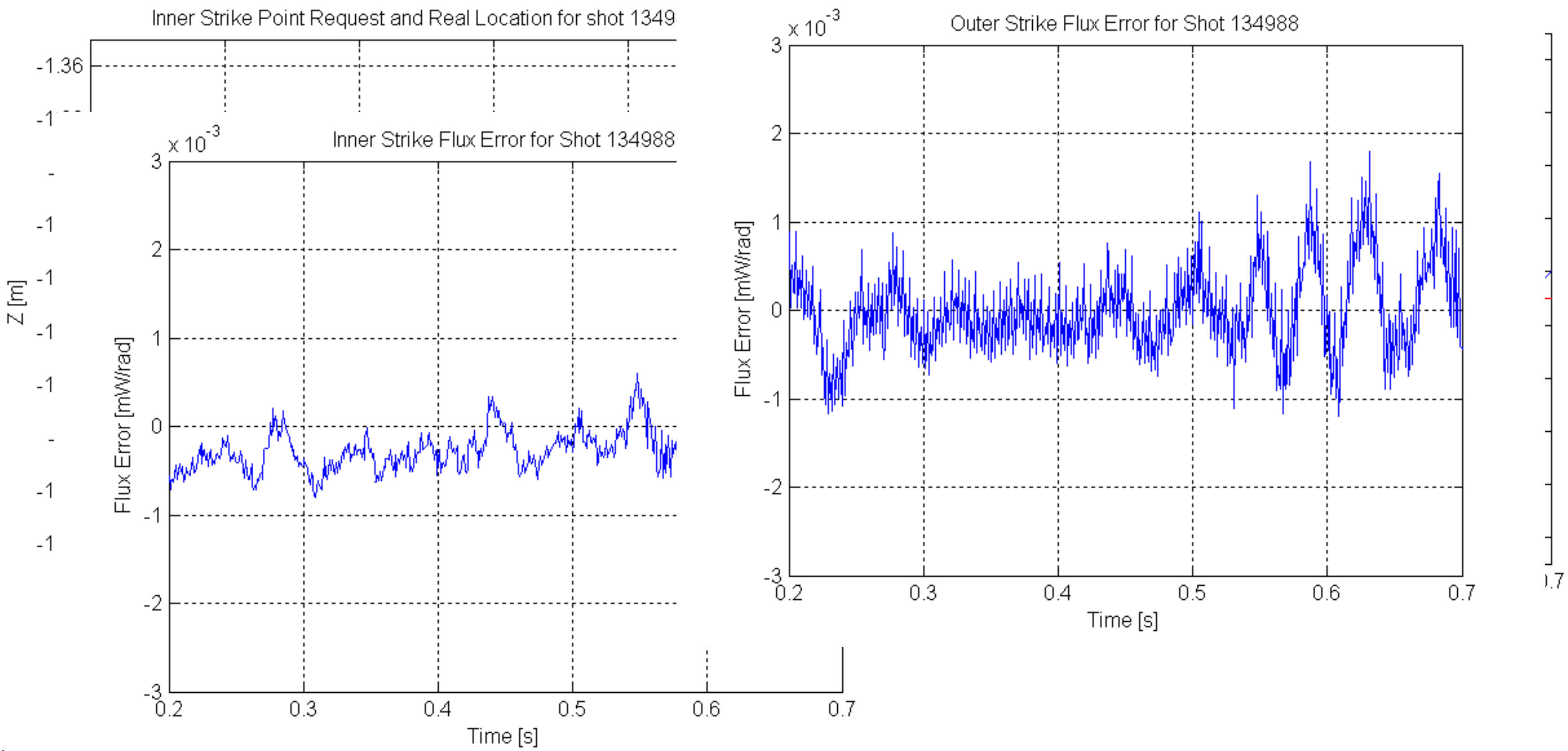
PF2L controls outer SP in red segments. PF1AL controls inner SP in the blue segment.

- System ID to develop a First-Order ODE with dead-time model for the strike point motion due change in PF current.
- PI controller with gains are tuned using Ziegler and Nichols.
- Used inner and outer strike point controller to achieve “snowflake”



Snowflake scan from 44 to 73 cm

Results: PID Controller Performance



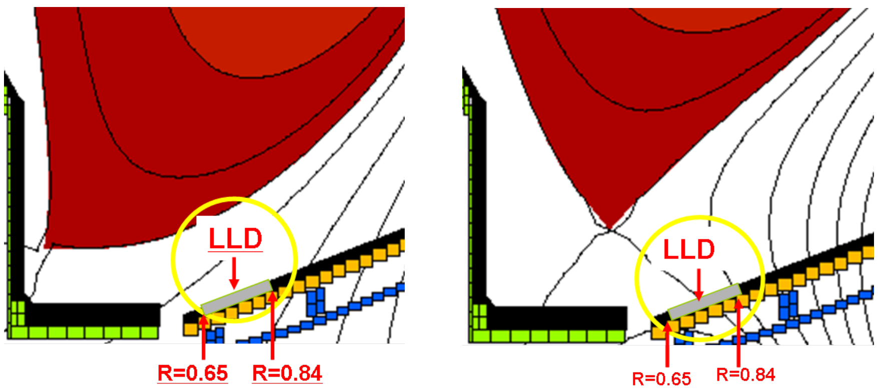
- Shot 133886:

  Calculated PID controller P: 170 – 550 (mean 360)

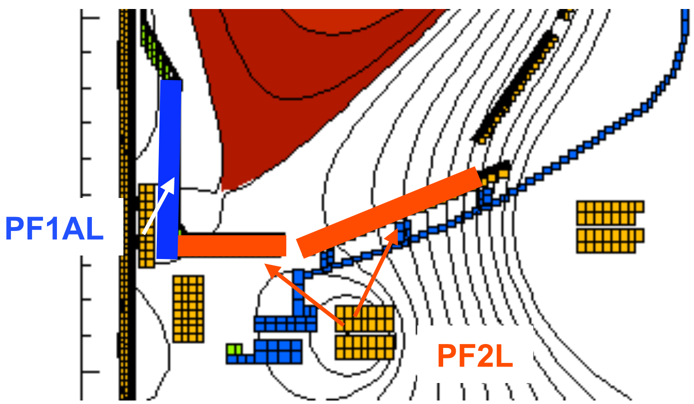
  P-I has 1-2 ratio I: 340 – 1100 (mean 720)

Tuned these values in experiment to P: 400 and I: 800.

Strike Point (SP) Control with LLD Operations



Left: High δ, n_e reduced by 25%
Right: Low δ, n_e reduced by 50%



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

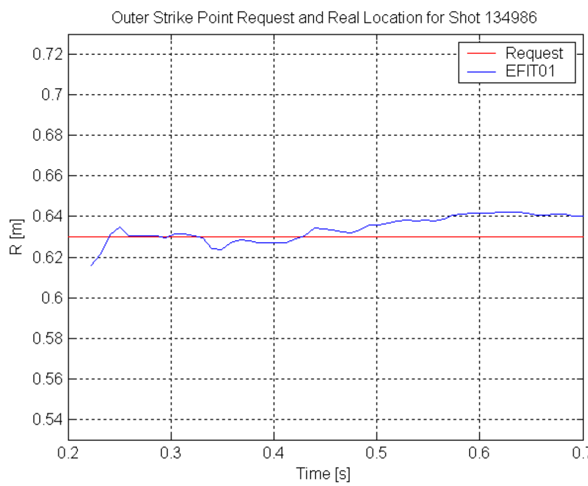
- Density reduction depends on proximity of outer SP to LLD.
- To achieve better and consistent density reduction, and to avoid contact with the LLD and CHI gap, SP needs to be closely controlled.
- System ID to develop a First-Order ODE with dead-time model for the strike point motion due to change in PF current:

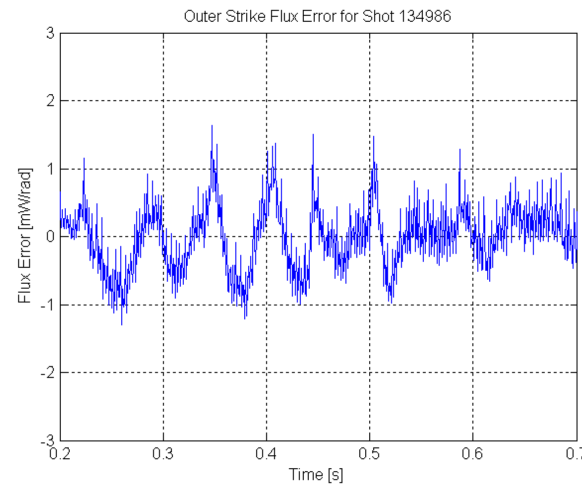
$$\frac{y(s)}{u(s)} = \frac{K}{1+sT} e^{-sL} ,$$

with K= 2.4e-6, T = 9.9 and L = 6.0.

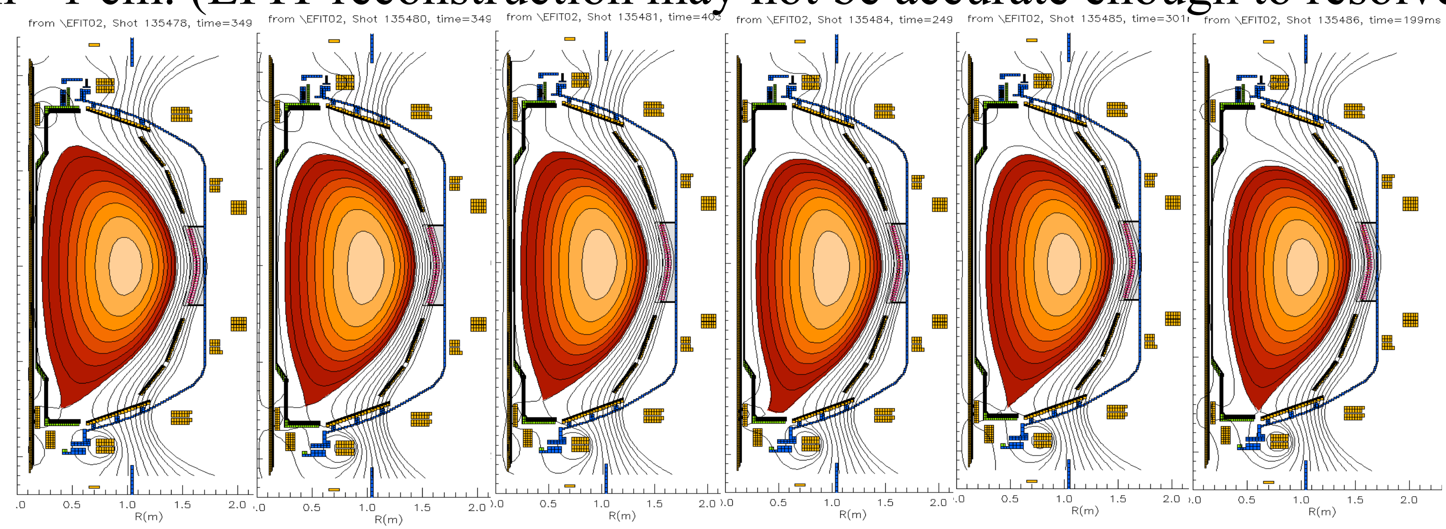
- PI controller gains are tuned using Ziegler and Nichols method to K_p=400, K_I=800 for outer strike, and K_p=5000, K_I=5000 for inner strike point.

Performance and Use of Strike Point Control



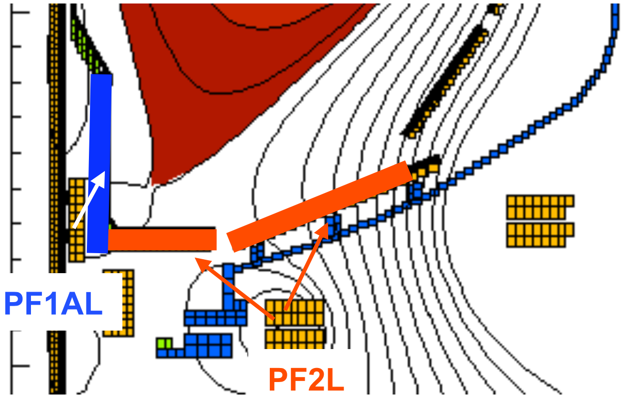


- Outer/inner strike point control flux error is controlled <1mW/rad and position to within <1 cm. (EFIT reconstruction may not be accurate enough to resolve cm scale)



- Strike point control enabled successful "snowflake" configuration experiments.
- Scanned the outer SP from 44 cm to 73 cm while keeping the inner SP constant.
- With fixed SPs, used squareness and drsep to achieve "snowflake".

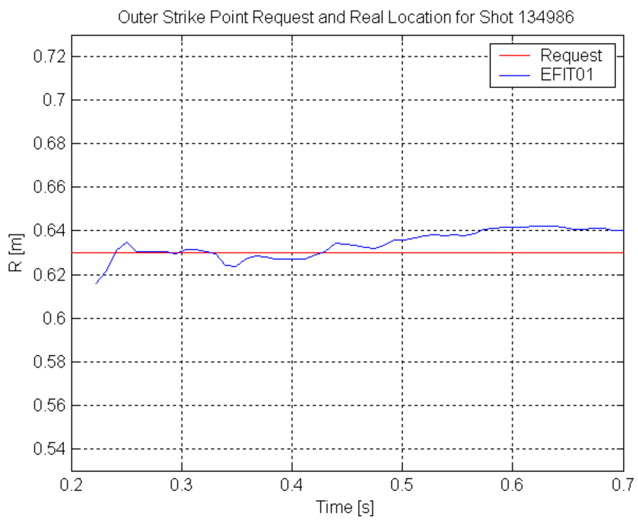
Inner/Outer Strike Point Control

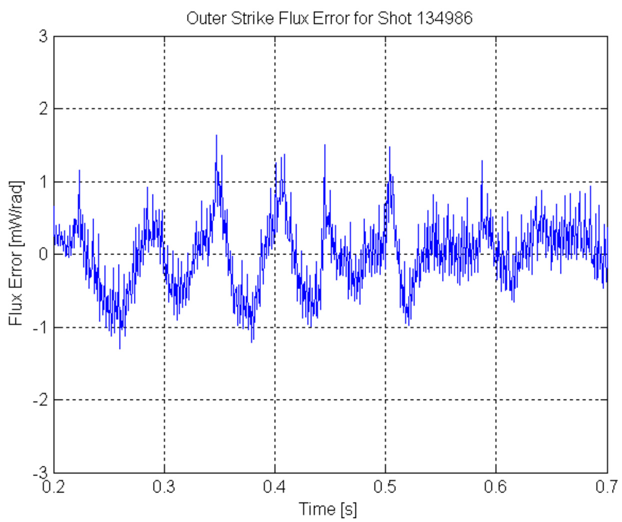


PF2L controls outer SP in red segments. PF1AL controls inner SP in the blue segment.

- System ID to develop a First-Order ODE with dead-time model for the strike point motion due change in PF current.

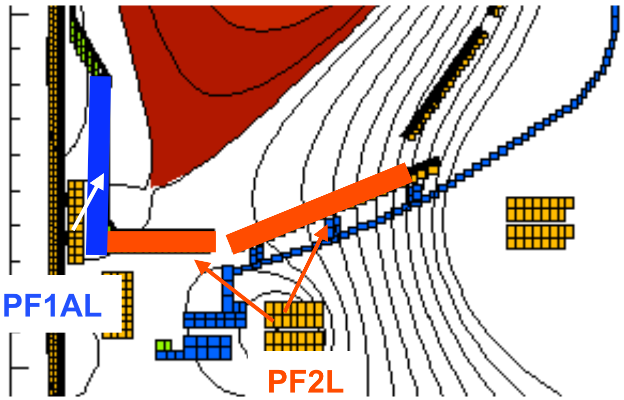
- PI controller gains are tuned using Ziegler and Nichols to [400, 800] for outer strike point and [5000, 5000] for inner strike point.





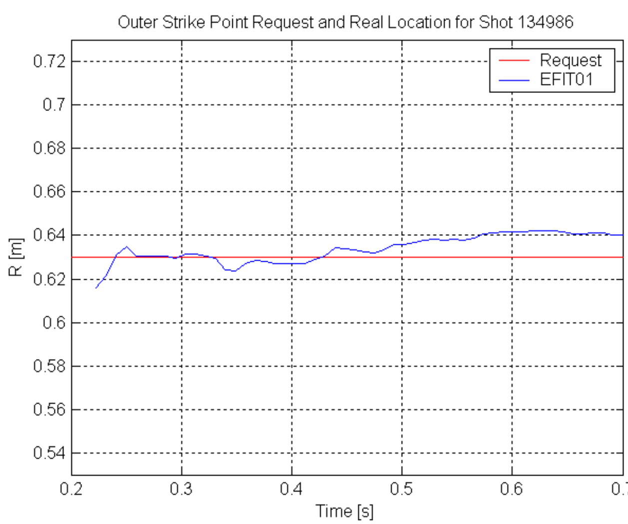
Outer Strike Point Control flux error is controlled <1mW/rad and position to within <1 cm.

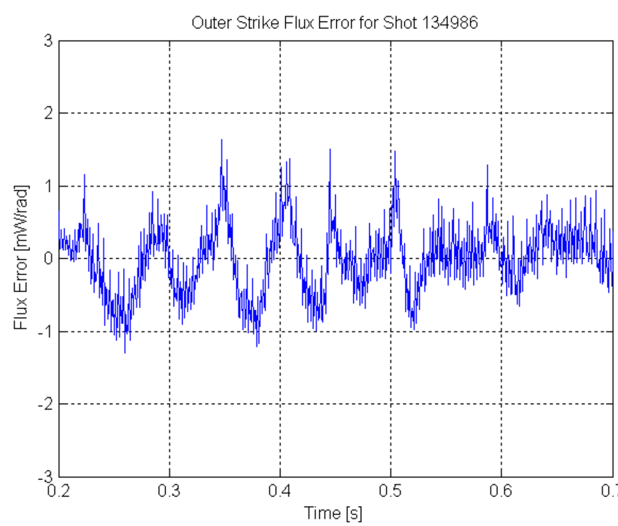
Inner/Outer Strike Point Control



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

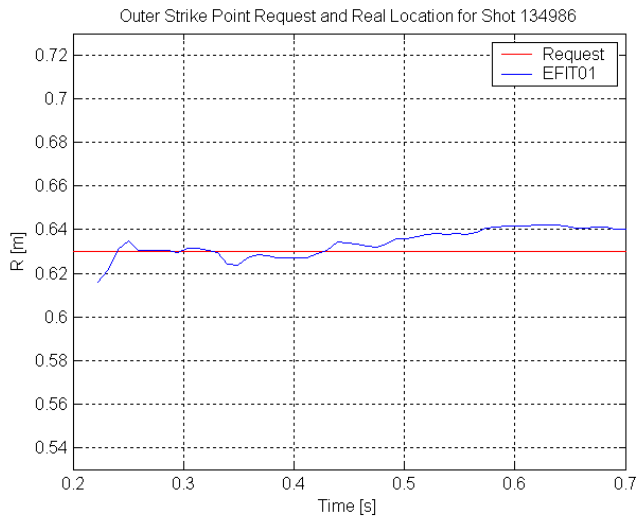
- System ID to develop a First-Order ODE with dead-time model for the strike point motion due change in PF current.
- PI controller gains are tuned using Ziegler and Nichols to [400, 800] for outer strike point and [5000, 5000] for inner strike point.

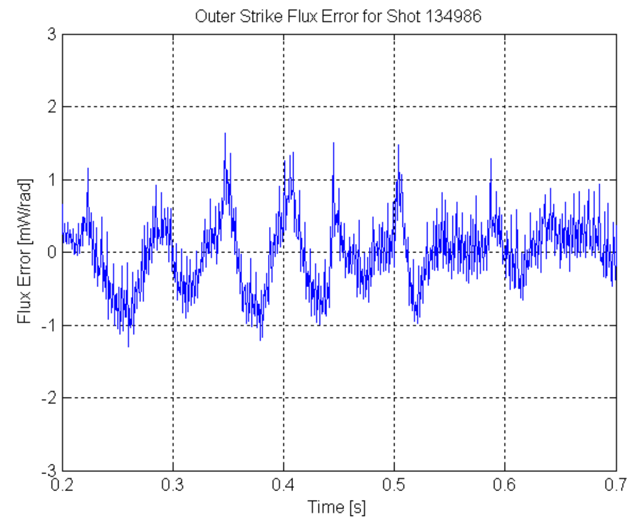




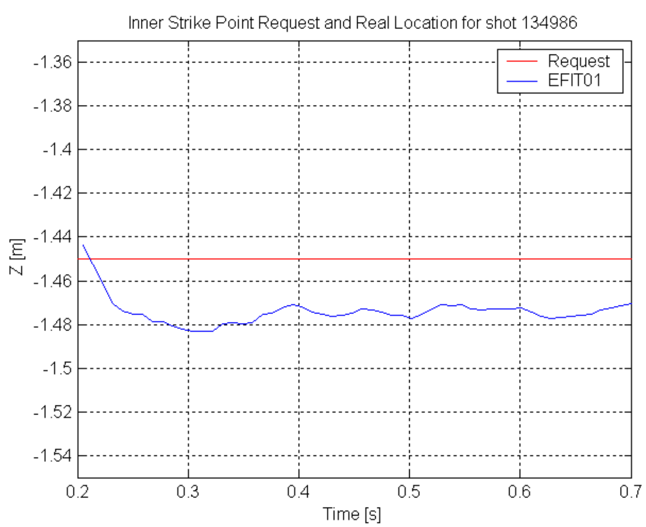
Outer Strike Point Control flux error is controlled <1mW/rad and position to within <1 cm.

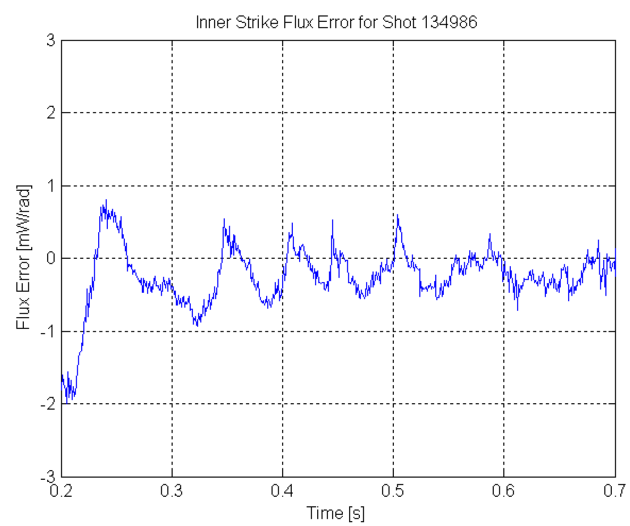
Results: PID Controller Performance





Outer Strike Point Control flux error is controlled <1mW/rad and position to within <1 cm.





Inner Strike Point Control flux error is controlled <1mW/rad. Position is kept to within <1cm. Reconstructions by EFIT is suspected for the bias error.

0. System ID with relay
1. Strike point for high elongation
   - Add upper strike control
   - Coordinate with squareness
2. X-point with strike

   MIMO (add off diagonal)

- XMP
  - Add I to PF3
    - Add D to PF2
    - To strike point
  - Integral Fix

- Plasma models
  - CREATE-L France
  - DINA Moscow
  - CORSICA LLML
  - TSC PPPL