NSTX

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

# Control Development for NSTX and the Effects of Strong Shaping

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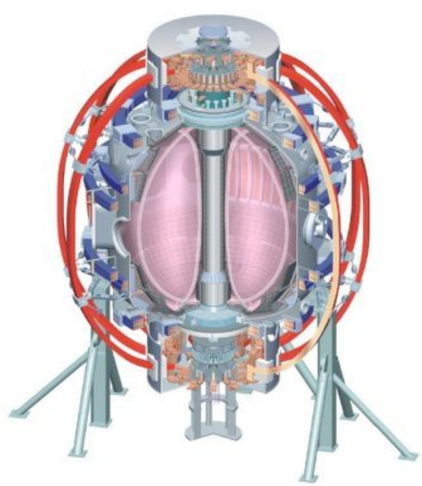
**APS Conference, Salt Lake City**
**November 2011**



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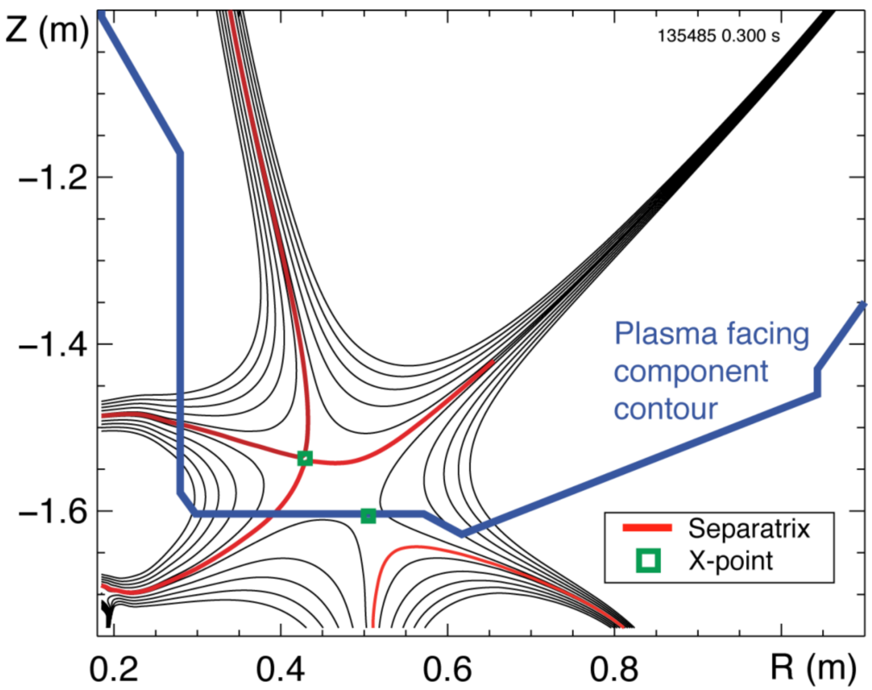
# Summary

- Real-time snowflake divertor configuration tracking
- Development of snowflake control
- Independent control of squareness ($\zeta$ )
- Effect of $\zeta$ on performance
- Effect of $\zeta$ on stability

# Snow Flake Divertor

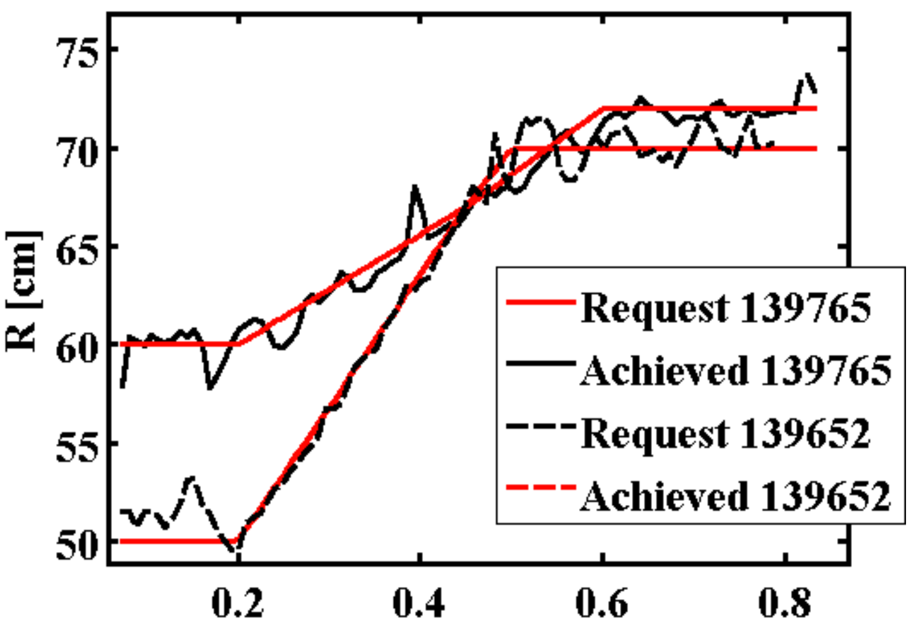



*Example "snowflake" divertor configuration in NSTX.*

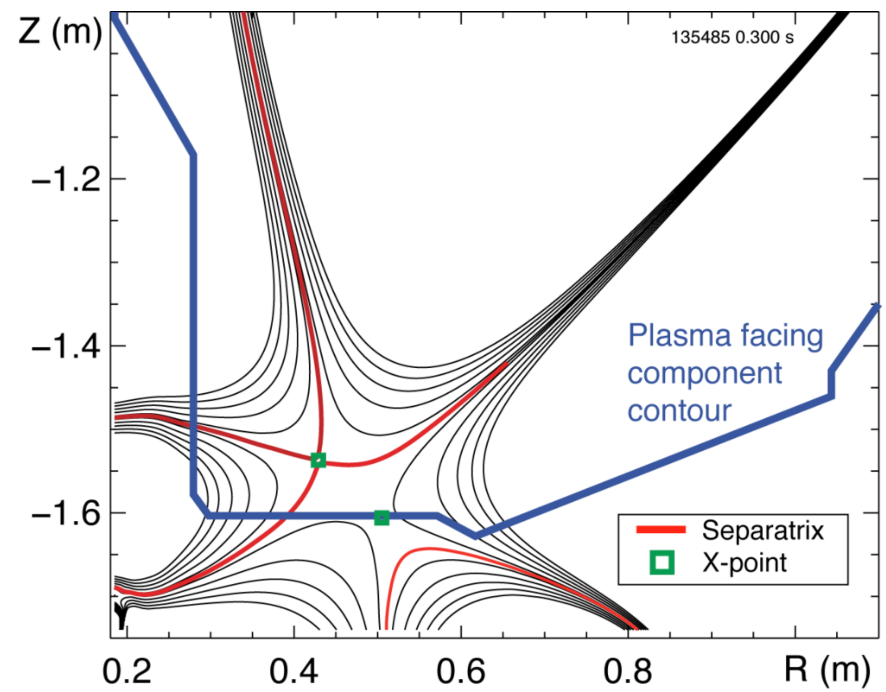
- "Snowflake" divertor configuration, a second-order null is created in the divertor region by placing two X-points in close proximity to each other.
- This configuration has higher divertor flux expansion and different edge turbulence and magnetic shear properties, beneficial for divertor heat flux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

# Combined Upper/Lower-Inner/Outer Strike Point (SP) Control

- PID control for U/L-I/O SP to enable “snowflake”, LLD operation
- 8 PF coils in Single-input-single-output control (Outer gap, vertical position and 4 SP are controlled).




*Example SP control*




*Snowflake high-flux expansion divertor obtained via SP control at NSTX*

# Snowflake Control: Finding the 2nd X-point

- Locate snowflake centroid & 2nd X-point
- 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

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

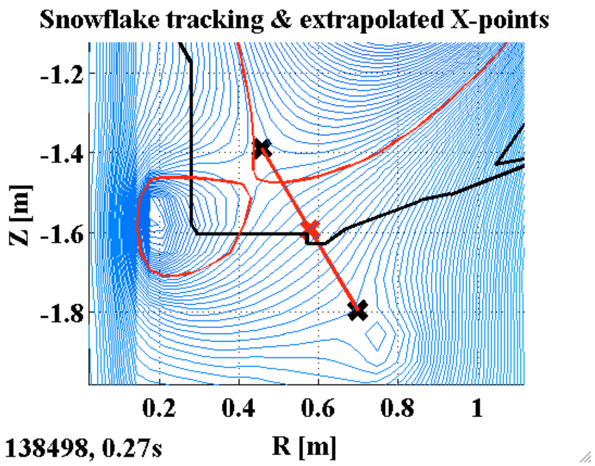
$$\Psi_1 = \Psi(\rho_1, \zeta_1) + \Psi_{00}$$
$$\Psi_2 = \Psi(\rho_2, \zeta_2) + \Psi_{00}$$

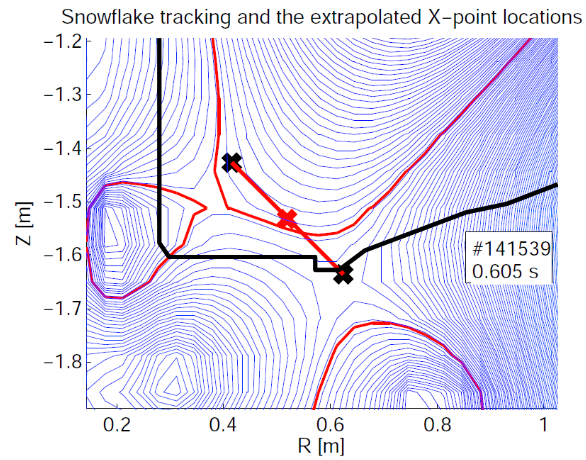
- Find coefficients from sample points
- No Iteration, one step fast algorithm with reasonable accuracy.

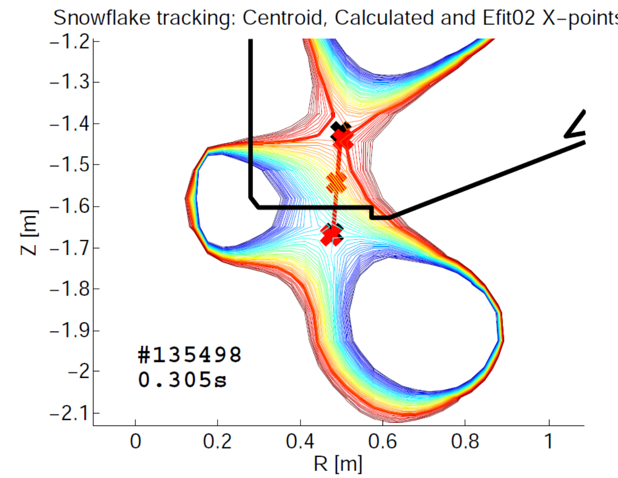
**Ref.** M.A. Makowski & D. Ryutov, "X-Point Tracking Algorithm for the Snowflake Divertor"

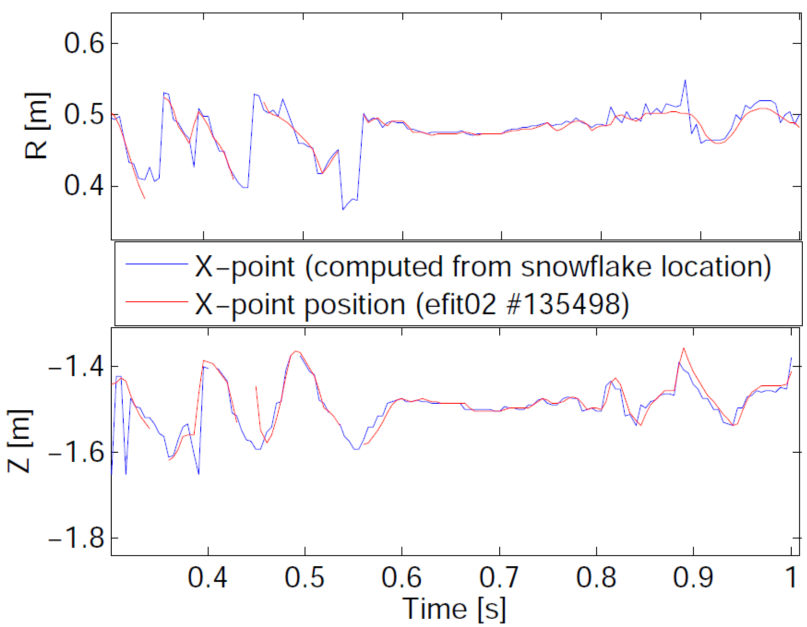
M.V. Umansky et al.. "Analysis of geometric variations in high-power tokamak divertors." LLNL-JRNL-410565.

# Tracking Works for Snowflake -/+ and Non-Snowflake



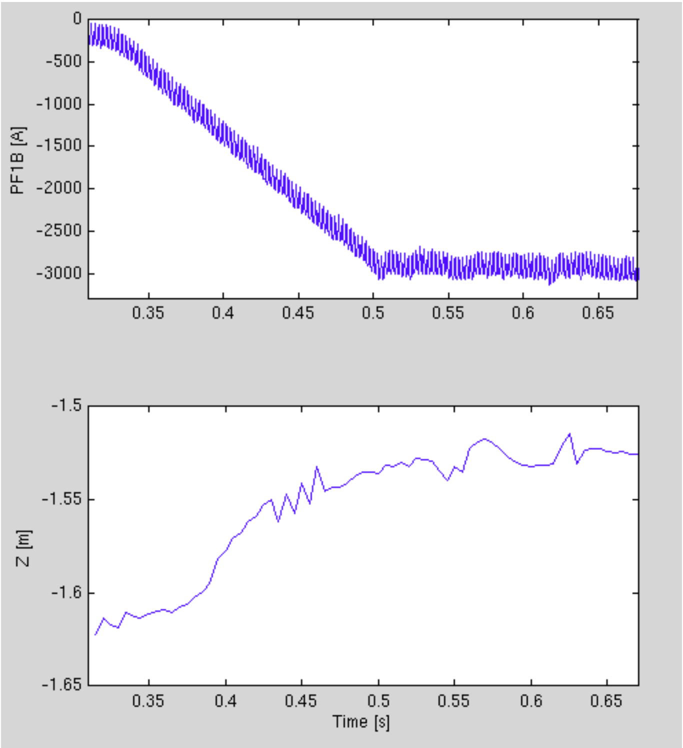




***Above: Snowflake tracking for NSTX:***

1. ***Red cross is the tracked snowflake centroid***
2. ***Black crosses are the calculated X-points locations by the snowflake tracking algorithm***

***Left: X-point position computed from the radius and angle obtained from the snowflake tracking and position of the 2nd X-point.***

# Actuators to Control 2nd X-point



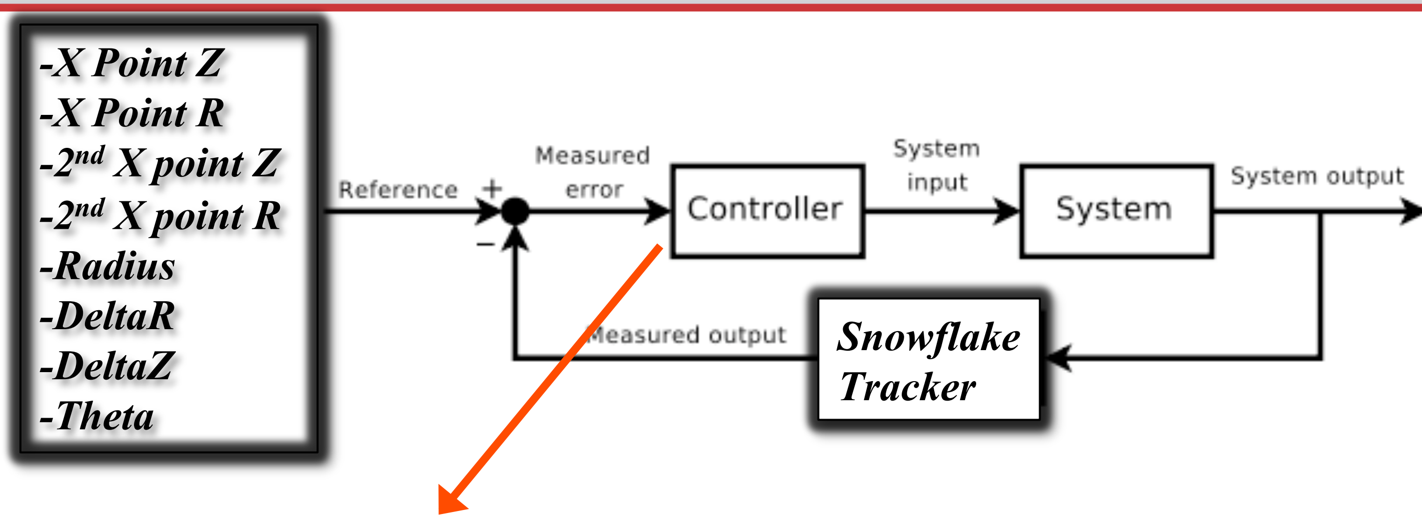

***Example: Effect of PF1B on 2nd X-point Height***

- 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 3 PF coils (PF1AL, PF2L and 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.

# Snowflake Control

- Locations of the X-points → feedback-control
- 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.

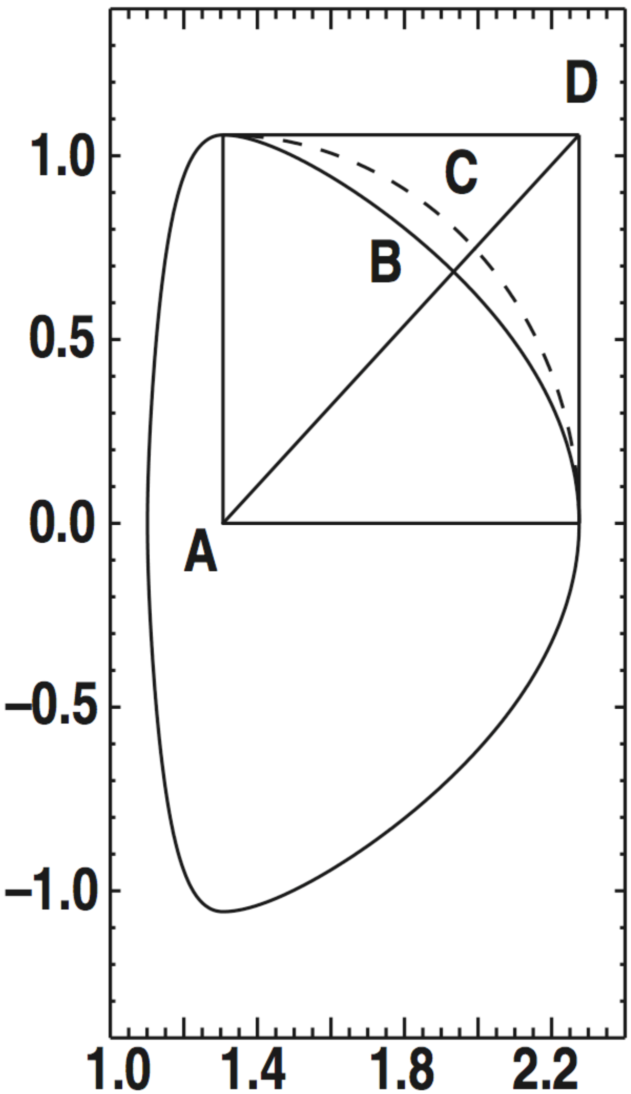
# Snowflake Control Algorithm




$$V_{PF} = X_{mat}PID(Err_{snow}) + M_{mat}PID(Err_{seg})$$

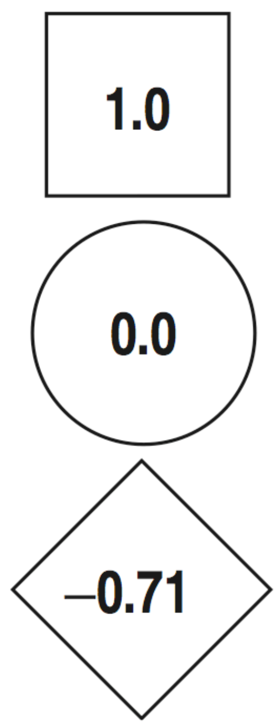
- For convenience leave all the possible references.
- Define X Matrix similar to the M matrix.
- For unused references set X row to zero.
- Add the segment PID and snowflake PID.

# What is Squareness, ζ ?




*Holcolmb et a. PoP 16, 056116 2009*

$$\zeta = \frac{AB-AC}{CD}$$




- Squareness is the second shape moment.
- $\zeta$ =1.0 ➔ rectangular plasma
- $\zeta$ =0.0 ➔ circular plasma

# Motivation and Study of $\zeta$

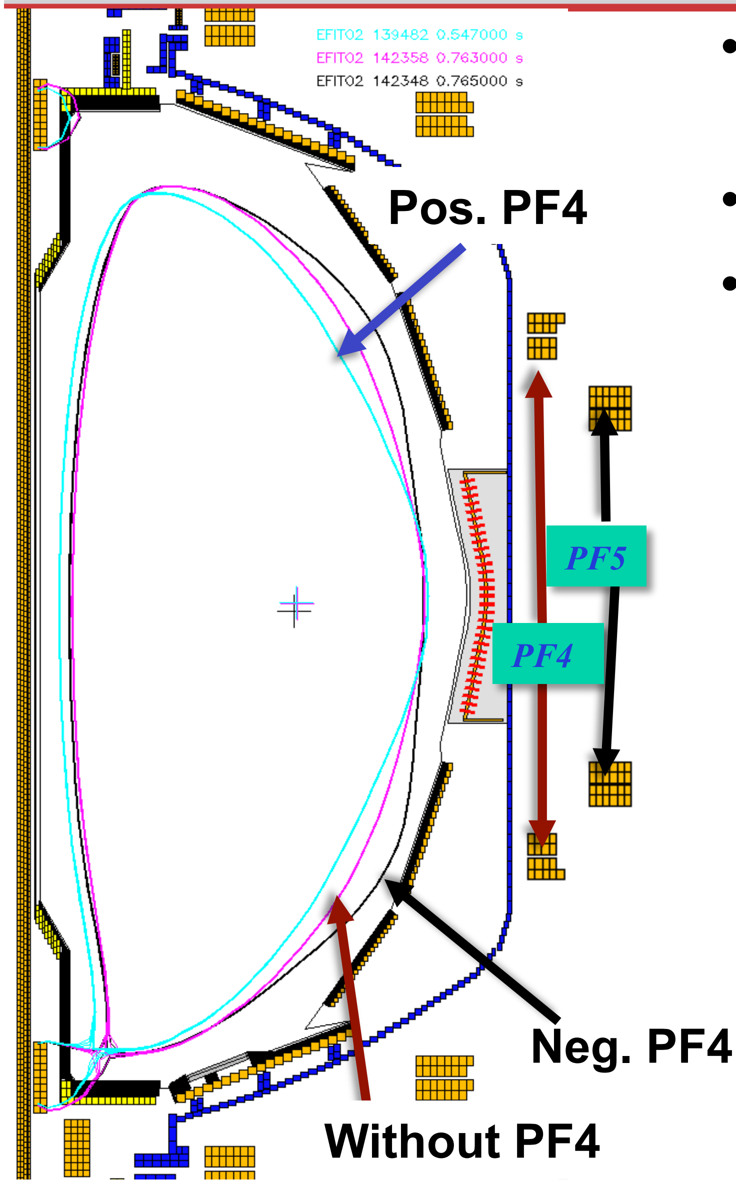
Motivation:

- STs all operate at high $\kappa$ in order to maximize the bootstrap fraction and $q^*$. In addition, the location of the outer strike point must often be fixed for effective divertor operation. As a result, neither the plasma $\kappa$ nor the $\delta$ can be modified greatly. An additional shape parameter that can help optimize plasma stability is $\zeta$.

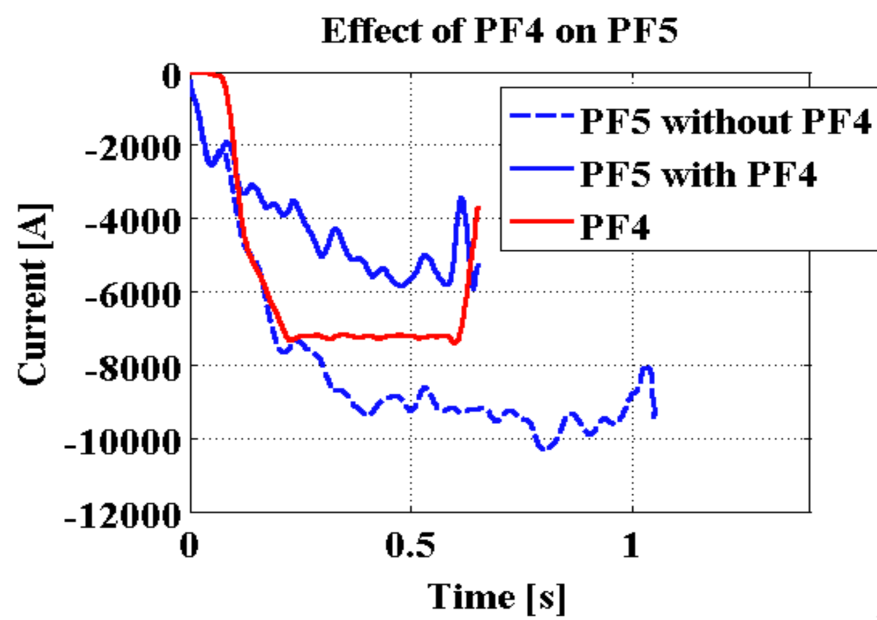
Summary:

1. Can $\zeta$ be varied without effecting the other important parameters?
2. Independent control of $\zeta$
3. Study of the effect of $\zeta$ on performance
4. Study of the effect of $\zeta$ on stability

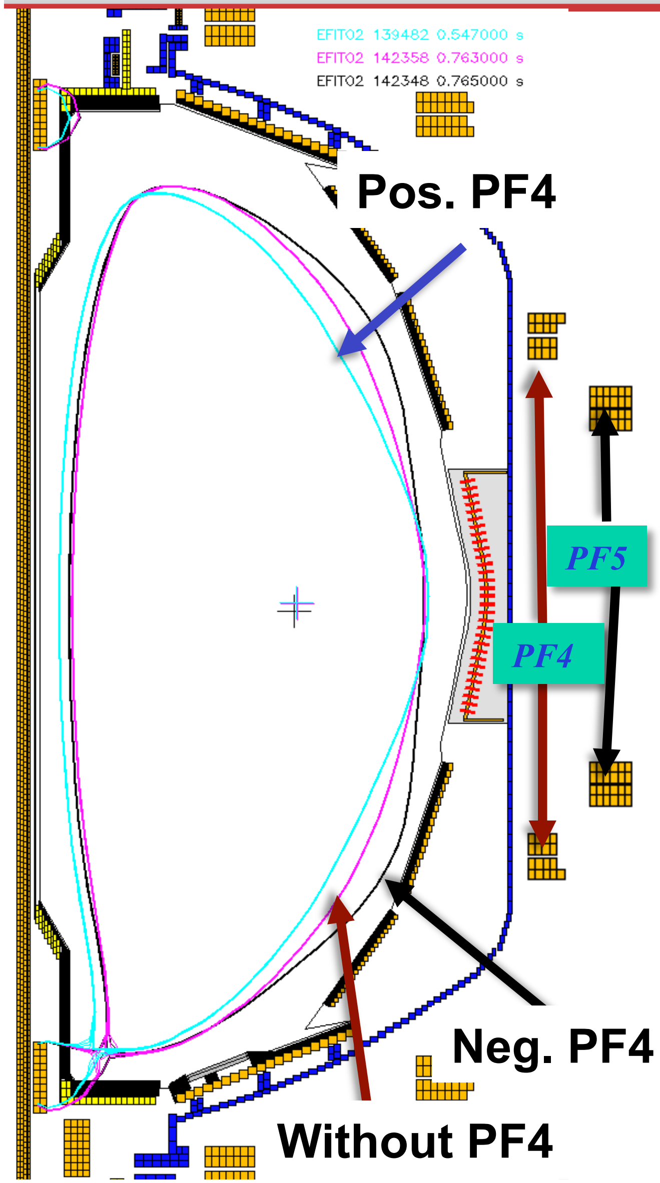
# PF4 can change ζ with minimal side effect



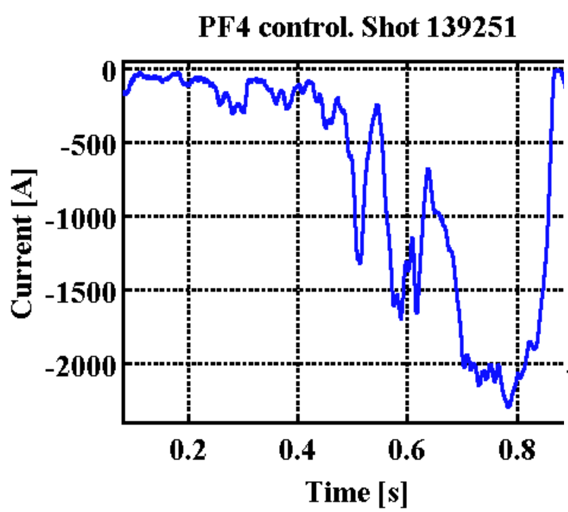

- Preprogram PF4 with PF5 for outer gap control
- Squareness varies with PF4.
- Keep other things the same.

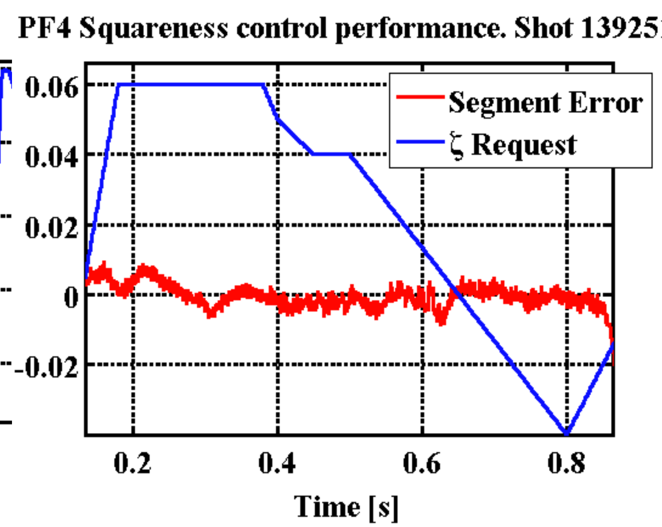


# ζ Control with PF4



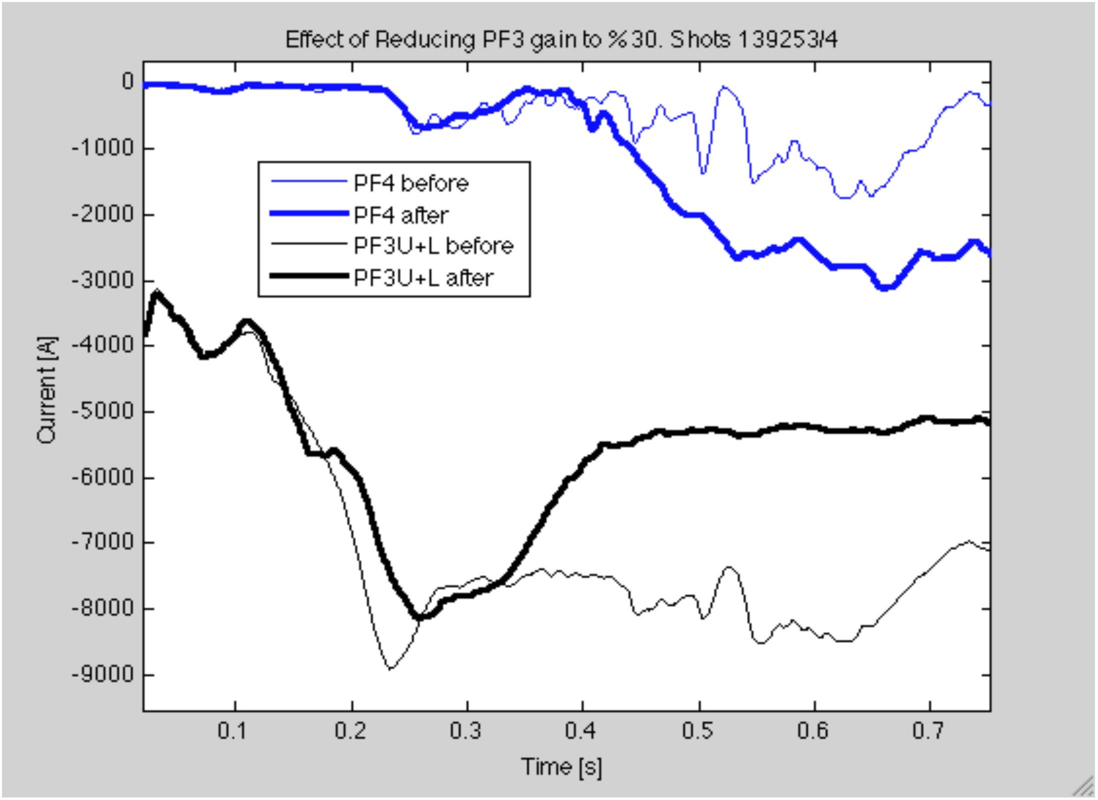

- Motivation: Assess the physics impact of squareness variation while other shape parameters are fixed.
- PF4 best ζ control candidate. PF3/PF4 effect ζ but PF3 used for vertical stability.
- Achieved stable ζ tracking via PF4.
- Effect of ζ on plasma is being studied.



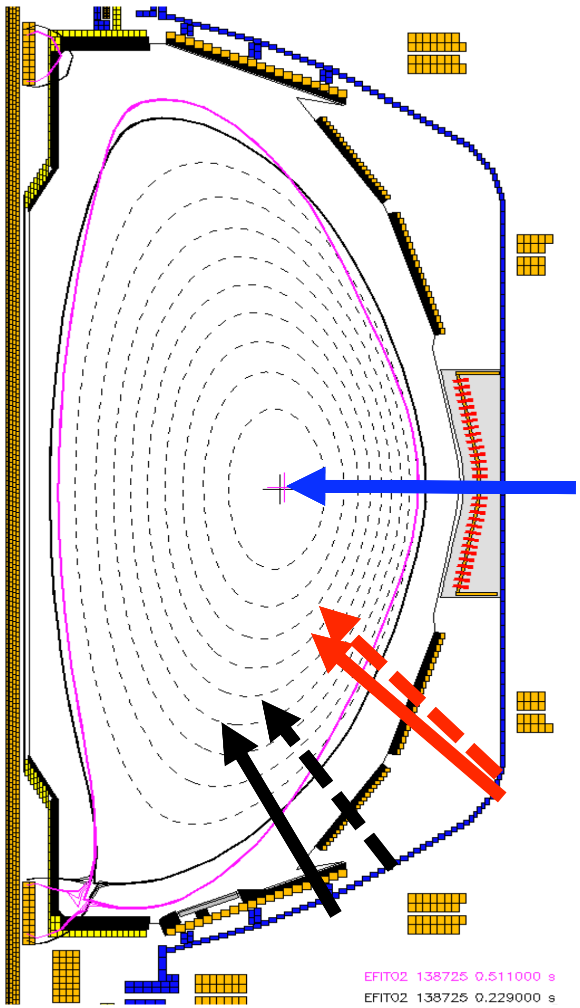



# Control Results: PF3-PF4 interaction

- 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.

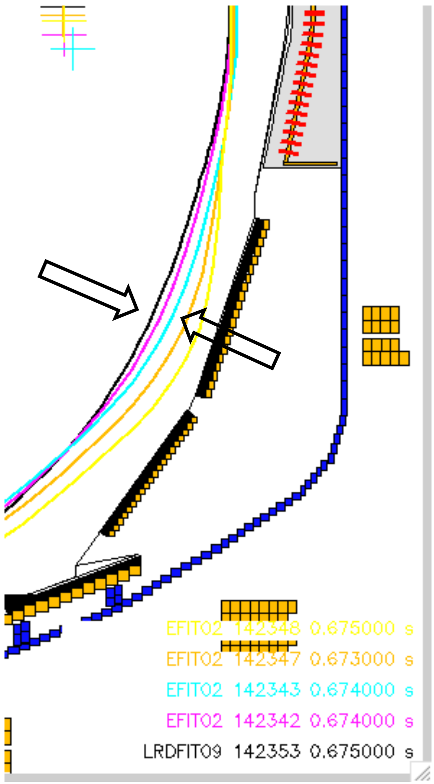


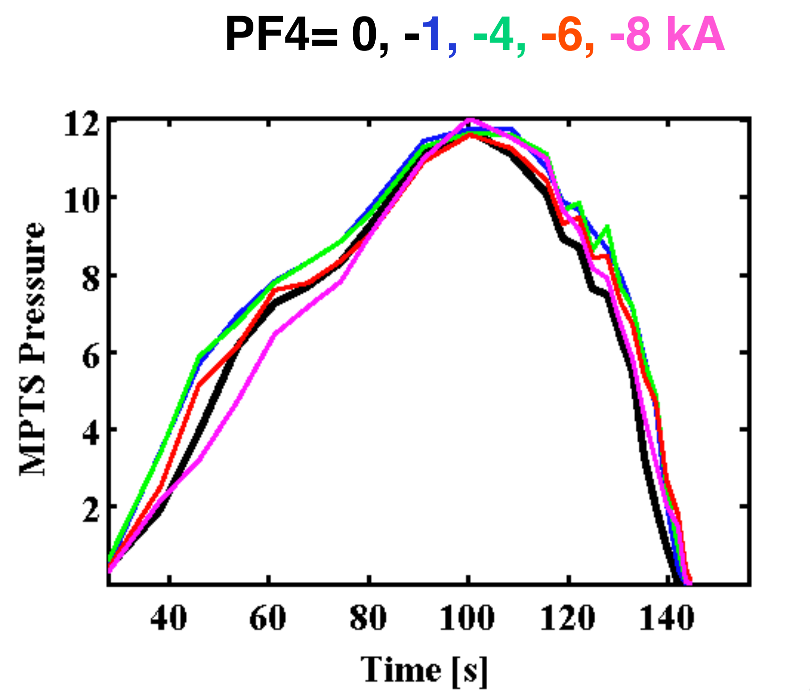
# Control Results: PF3-PF4 interaction




- 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.

# Performance: Pressure Profile Change as ζ Increases

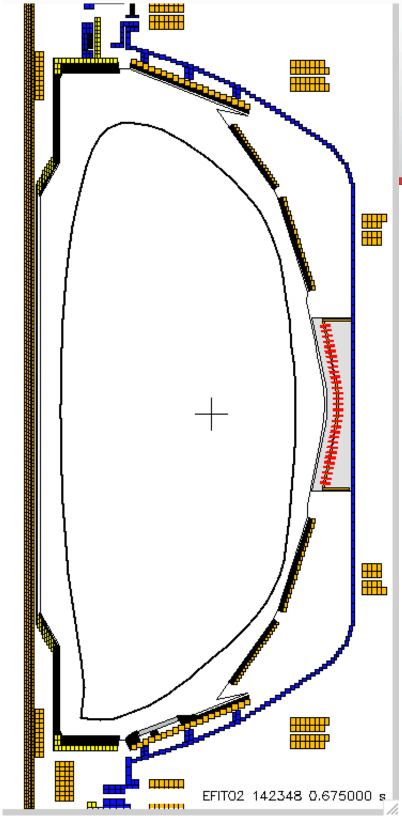


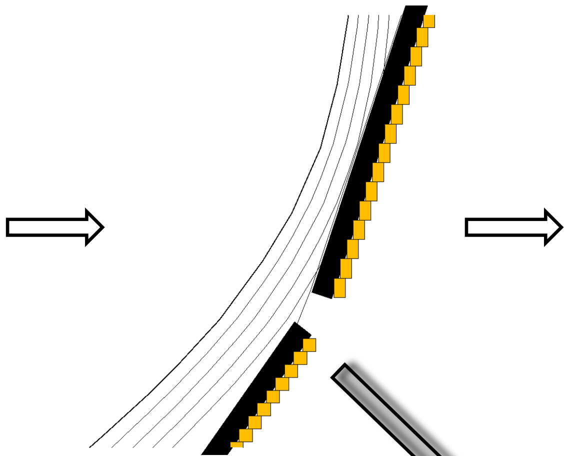




PF4 (opposing PF5) up to -5 kA (~2 inches in figure) increases pressure

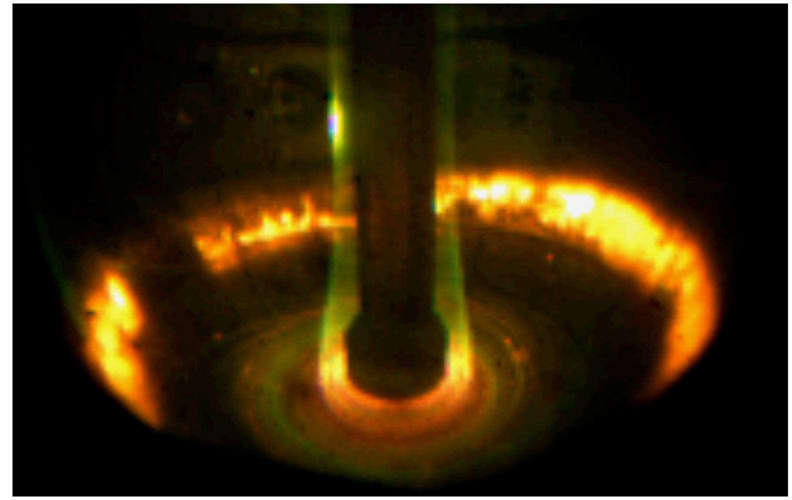
Too high squareness interacts with the wall. Pressure drops.

# Performance: High ζ Wall Interaction

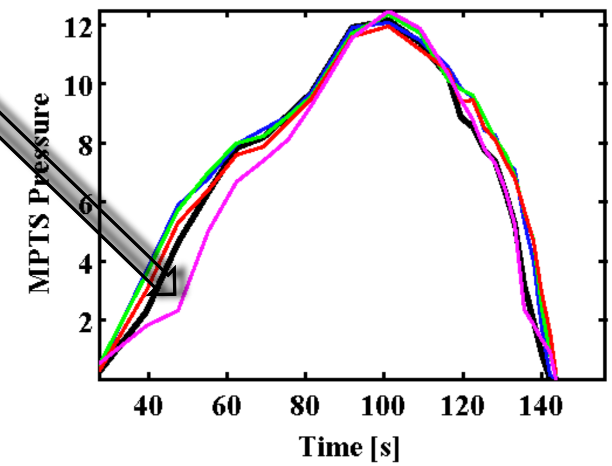


*Each Line is 1 cm apart*



**PF4= 0, -1, -4, -6, -8 kA**

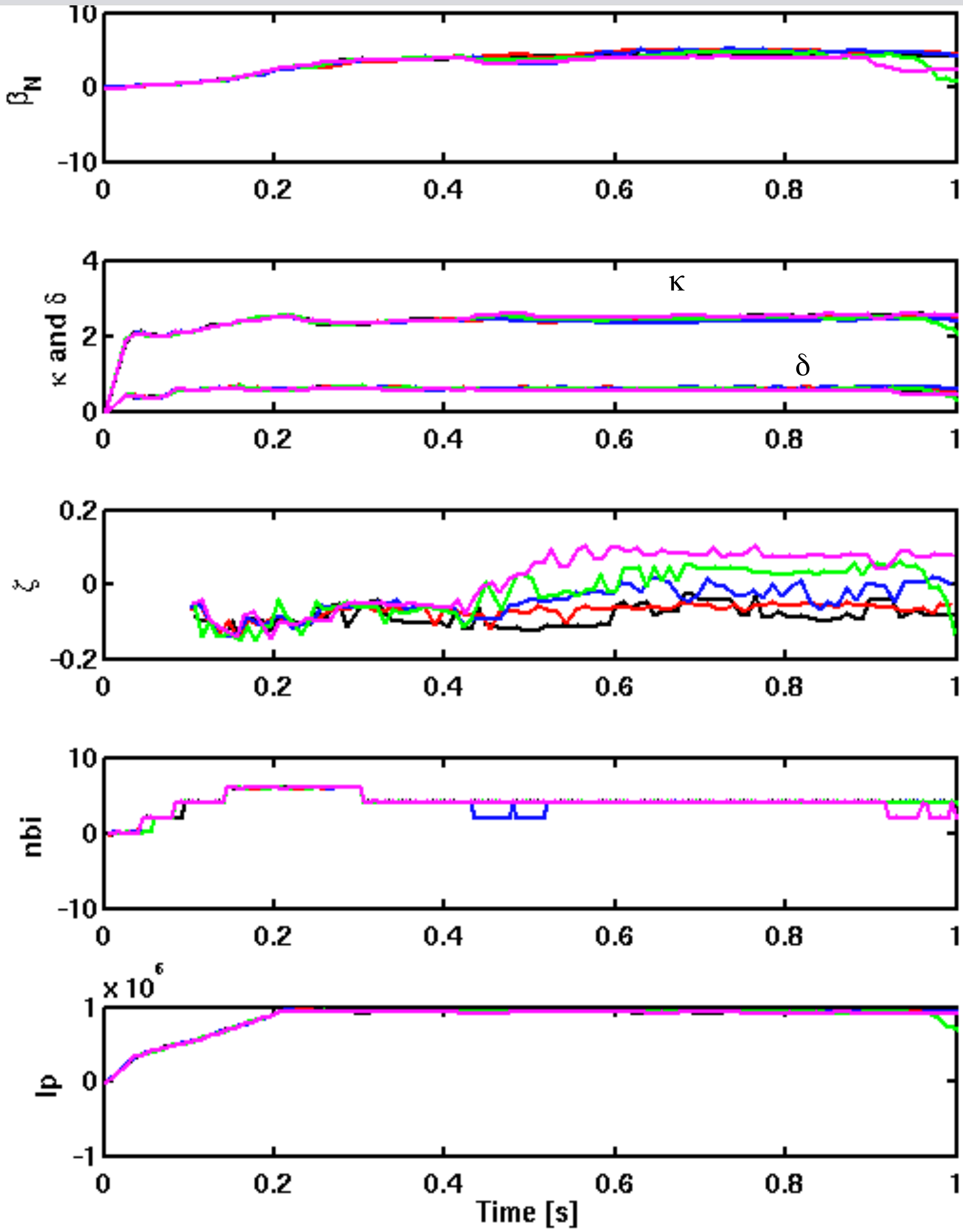



As PF4 gets close to -8 kA:

Last closed flux surface gets 3-4 cm close to the wall.

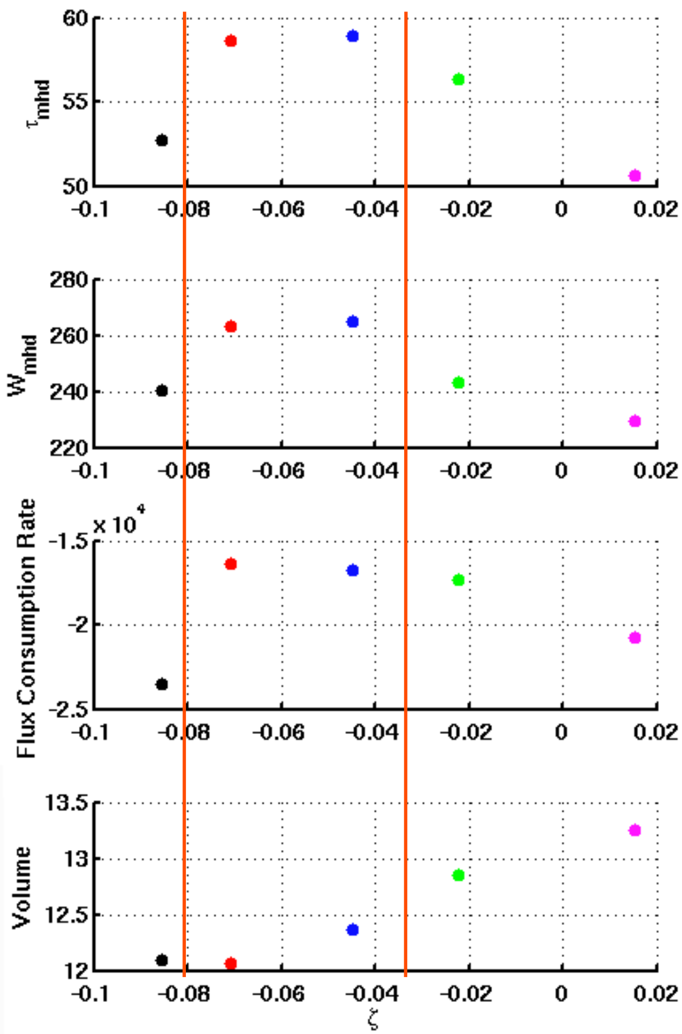
Pressure profile degrades

# Optimal Squareness for Performance




- Squareness scan
- IPF4: 0 to -8 kA
- Keep $I_p$, NBI, $\beta_N$, $\kappa$, $\delta$ constant
- To compare the effect of $\zeta$, we average the results when the plasma is stable
- 600-900 ms average

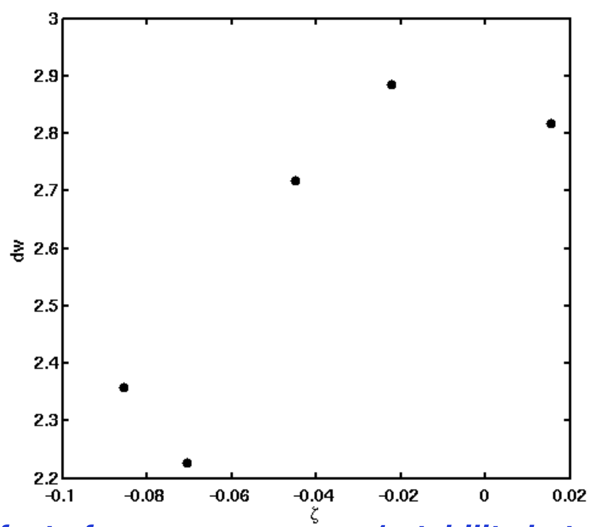
# Optimal Squareness for Performance



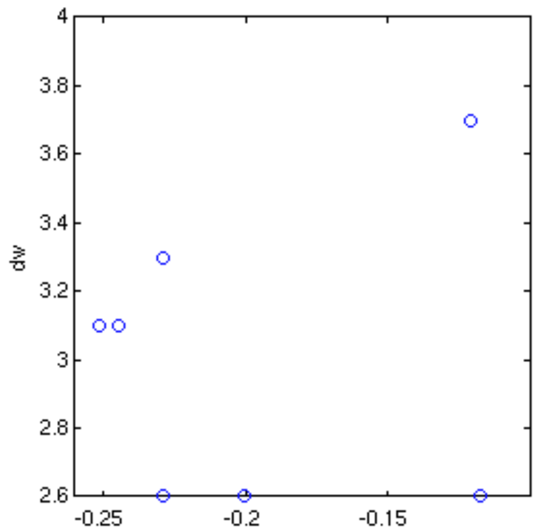

*Averaged over 600ms to 900ms.*
*[142353,142342,142343,142347,142348]*

- Optimal ζ ~ -0.06
- Optimal PF4 ~-1 to -3 kA for performance.
- Confinement time increases
- Energy confinement increases
- Flux consumption reduces.
- Too high ζ interacts with the wall and plasma is not as good.
- **Note for comparison:**
- ζ less than the fiducial (PF4=0) results are worse than the fiducial case.

# Stability Analysis: n=1 Stability




*Effect of squareness on n=1 stability between shots with same condition*




*Effect of ζ on n=1 stability within 140689*

- We used DCON to look at the effect of squareness on vertical stability.
- The analysis did not show consistent correlation with squareness variation and n=1 stability.
- Neither when the squareness is ramped within a shot (140689) or under same conditions in different shots.
- Better LRDFIT reconstructions are needed to study the stability.
- Further analysis continuing.

# Stability Analysis: Vertical Stability

- We used Toksys to look at the effect of squareness on vertical stability.
- There seems to be no correlation with squareness and vertical stability.
- Further analysis will be conducted.

# Summary

- An effective real-time snowflake divertor configuration tracking is implemented at NSTX. Snowflake control algorithm based on the snowflake tracking is developed.

- An independent squareness control is on NSTX.

- As squareness increases, the pressure profile broadens and plasma performances increase. Then, performance degrades as further increase in squareness and finally starts interacting with the wall.

- The correlation between squareness and vertical and n=1 stability is weak. We were not able to find clear correlations.

- Further analysis is needed to clarify the effects of squareness on stability but we expect the effects to be small.