NON-SHAPE CONTROL DEVELOPMENT:

1. ELM

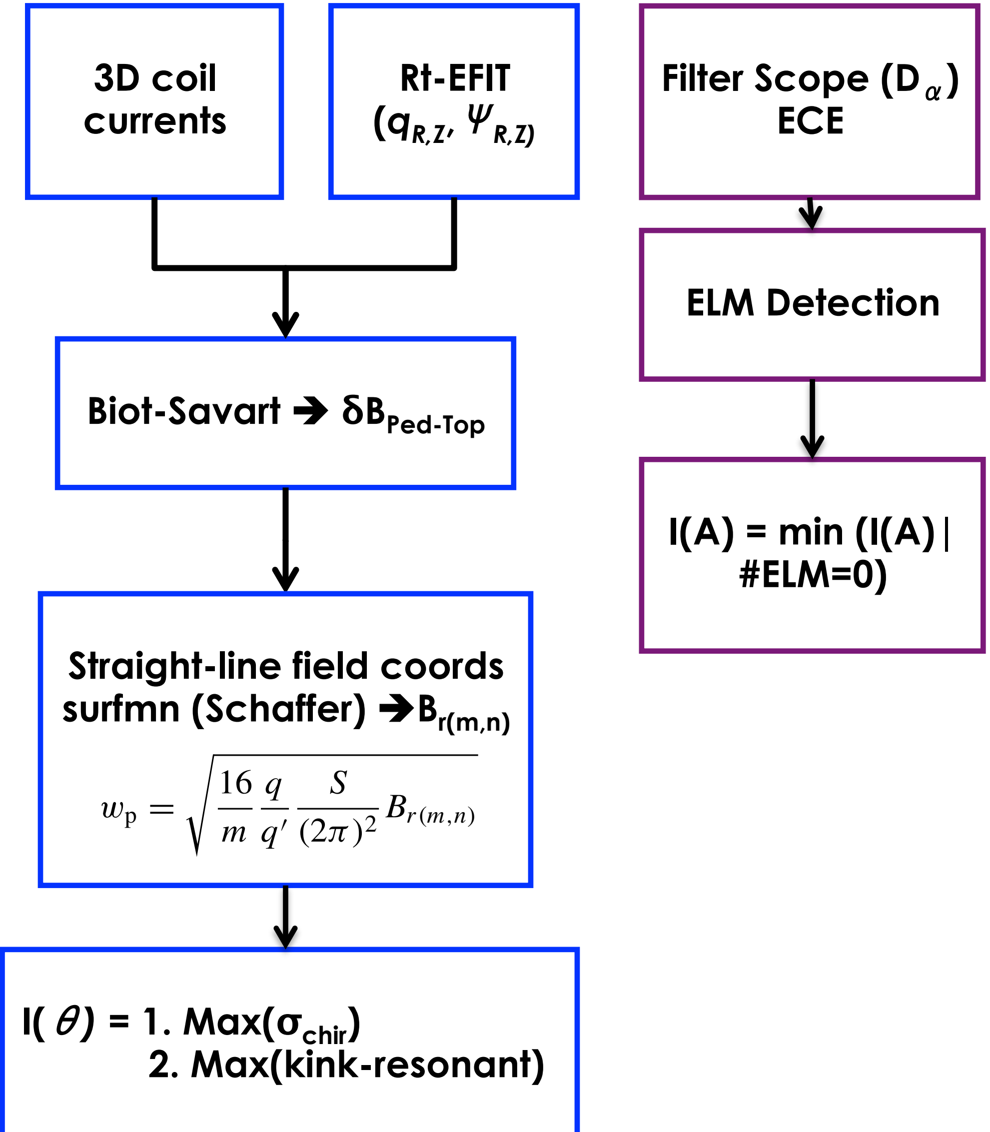
2. EFC

3. BetaN with 3D coils

4. Radiation

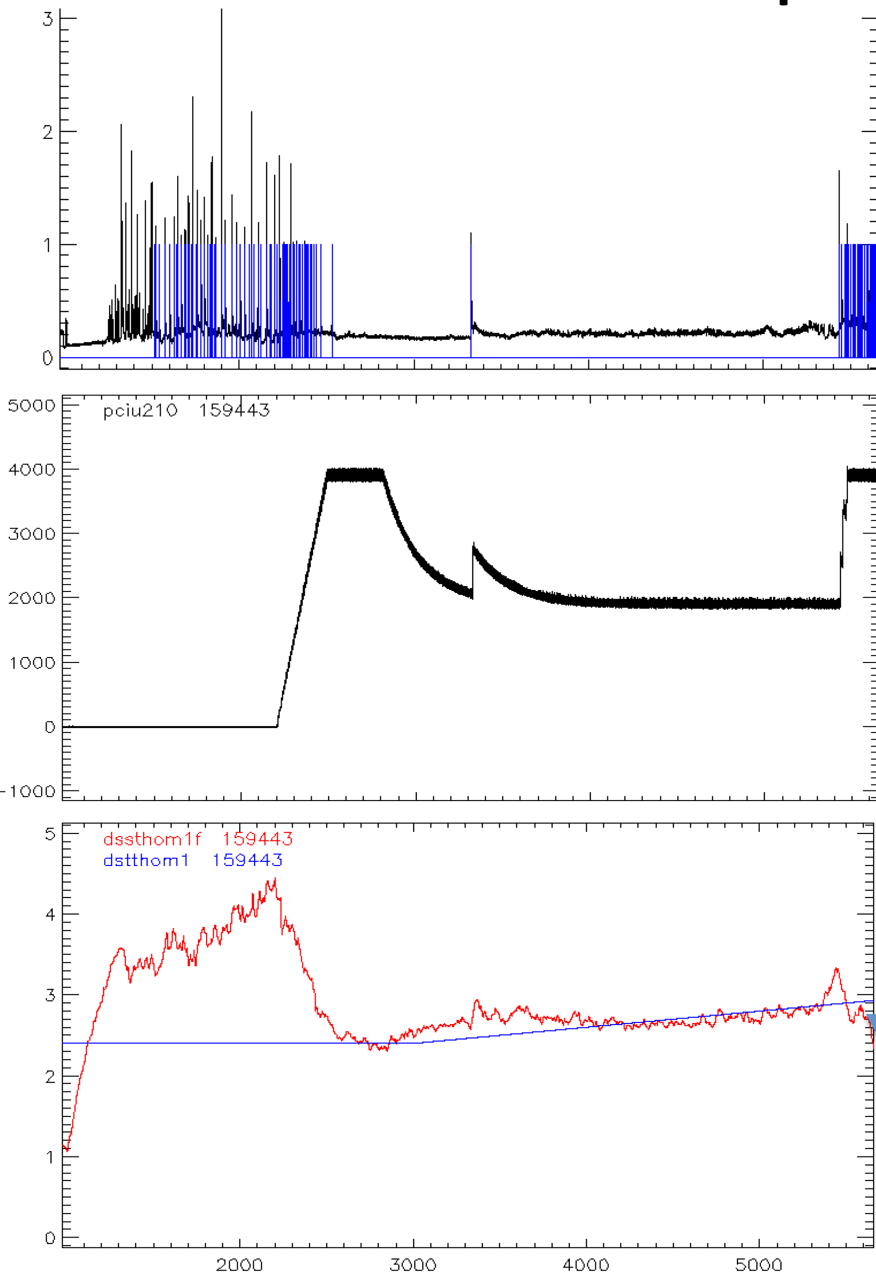
5. Pedestal

Adaptive ELM Control and Error Field Control



- In real-time calculate 3D perturbations due to 3D coils
  - Use surmnf to convert to straight-line field coordinates
  - Find the orthogonal component $B_{r(m,n)}$
  - Find the island size and σ_{chir}
- Control:
  - Choose relative phase of the coils, I(ϑ), maximize kink or σ_{chir}
  - The amplitude of current, I_C(A), minimum current with no ELMs
- Test different ELM mitigation mechanisms
- Then try EFC

Adaptive ELM Control

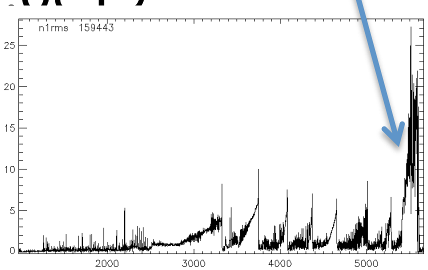


- Control the I coil amplitude based on the ELM frequency
- Control the pedestal density

- I coils adjust and keep ELM free with 1.9 kA (can go lower)

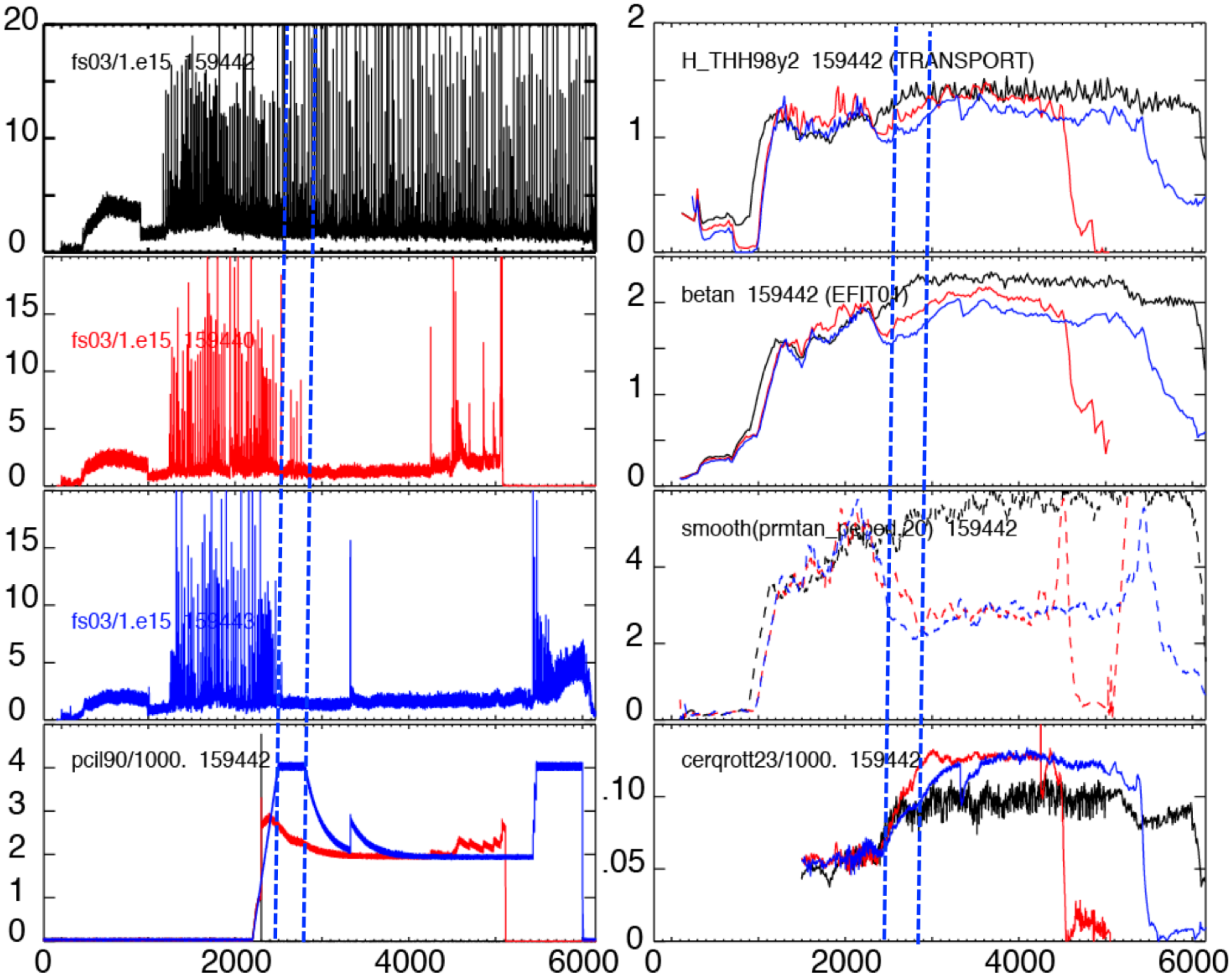
- When we reach a high density the ELMs come back again. Prm_tan_ne~3.0e19
- Lock mode kill

☺ **Raffi Density Limit** ☺ on



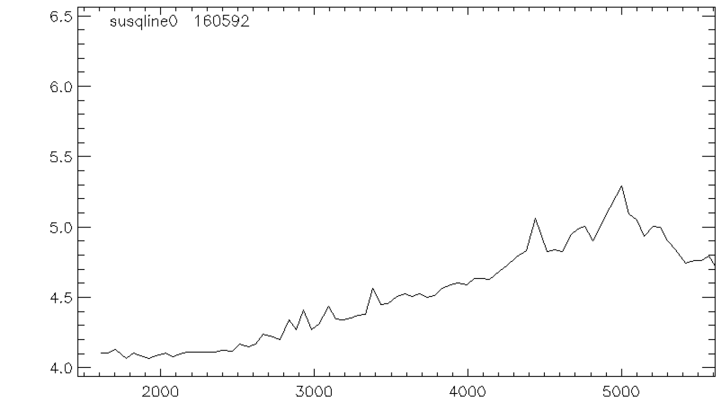
Feedback of RMP Amplitude on ELM Size Shows Promising Increases in H_{98}, β_N, p_e^{ped}

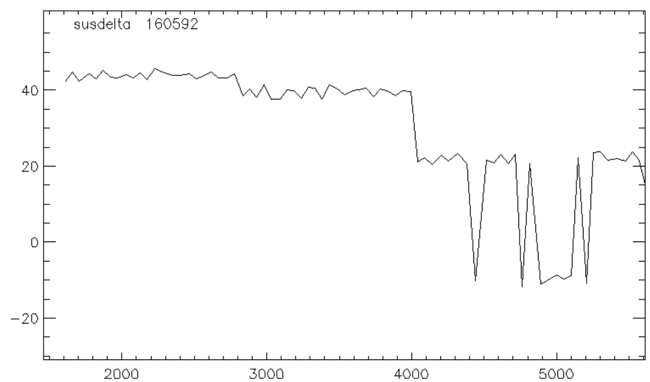
Kolemen

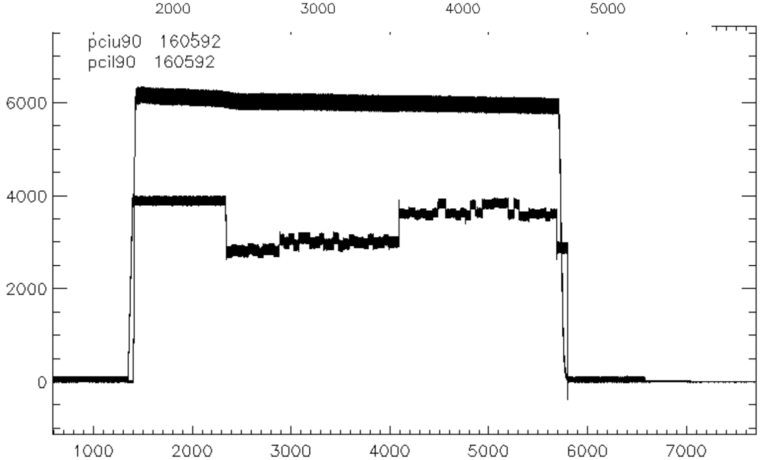


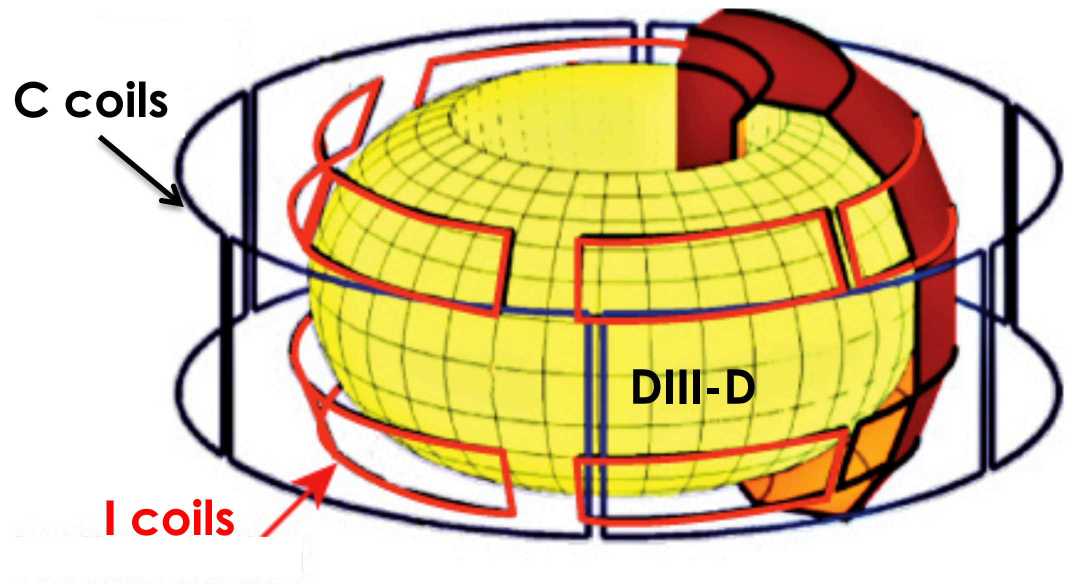
- **ELM suppression obtained with high I-coil current**
- **Feedback algorithm adjusts I-coil current down while maintaining suppression**
- **H_{98}, β_N, and p_e^{ped} increase**
- **Edge rotation increases substantially**

Phase to Maximize the Kink Resonance at D3D









- Control the I coil phase based on the surfmn kink response calculations
- Choose the direction that maximizes kink response for phase
- Control the Icoil upper
- Too high density yesterday. Not possible to test n=2 ELM suppression
- Code checked out.

Real-Time Optimal Error Field Correction

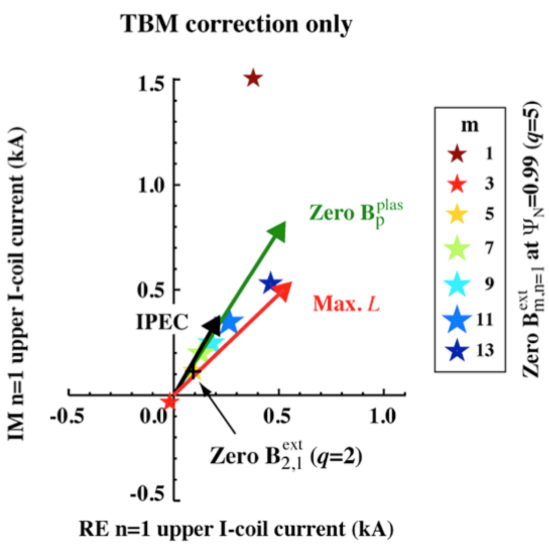
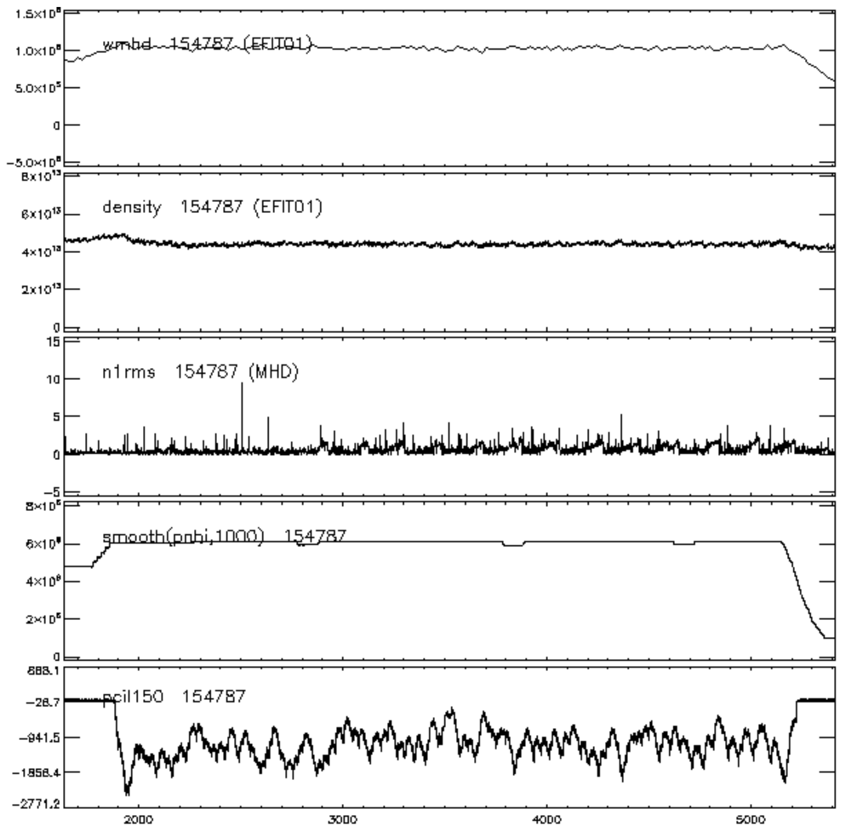


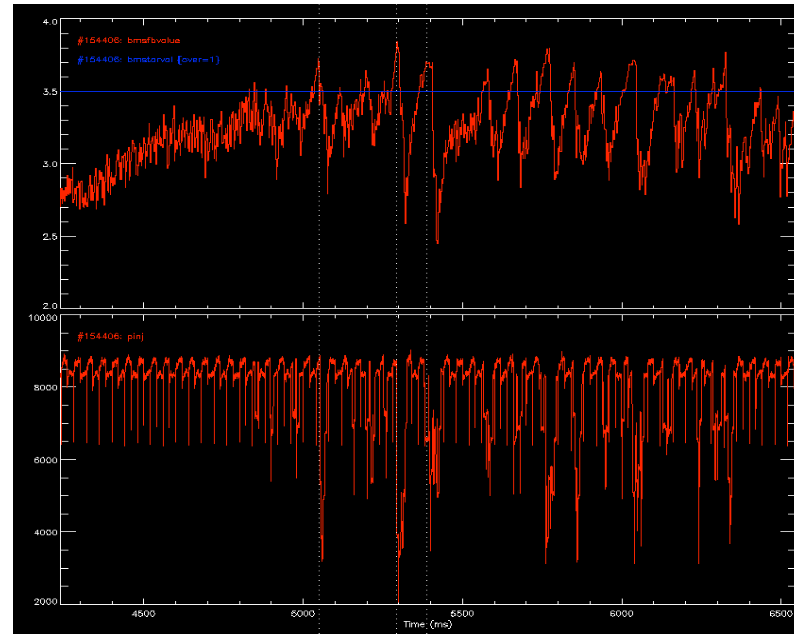
FIG. 5 Comparison of the optimal n=1 I-coil EFC of the TBM field obtained by maximizing the angular momentum L (red) and zeroing the magnetic plasma response B_p^{plas} *(green) and an IPEC prediction (black) with I-coil currents that cancel various poloidal mode components with the same helicity as the equilibrium field.*

C. Paz-Soldon

- n=1 mode error field correction is crucial for n=1 mode suppression
- We can in real-time change the EFC to match the optimal calculations
- Progress in the optimal EFC modeling.
  - Optimal can be calculated from the EFIT shape, boundary and the coil currents (***without perturbing the plasma***).
  - Calculation and the compass scan are indistinguishable!
- Every shot will have real-time optimal EFC! Great improvement over current situation.

3D Coils for BetaN (Wmhd) Control





Example from the DIII-D Experiment where the NBI modulation for the NBI leads to instabilities

- Result: Extremely stable plasma profiles
- *Suggestion: Use Icoil BetaN control and pedestal instead of core density.*

PRINCETON PLASMA PHYSICS LABORATORY

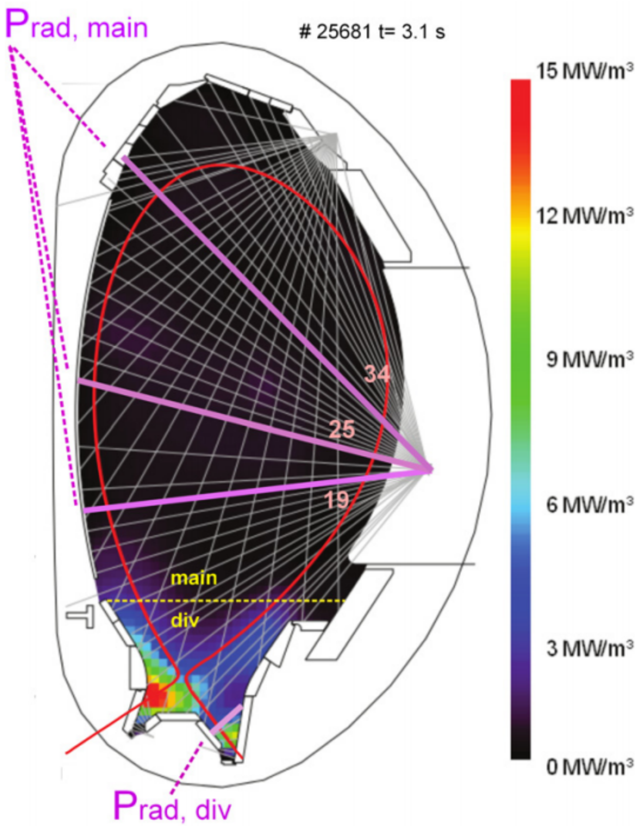
Optimized tokamak power exhaust: Gas Injection Control Development for Radiation and Detachment

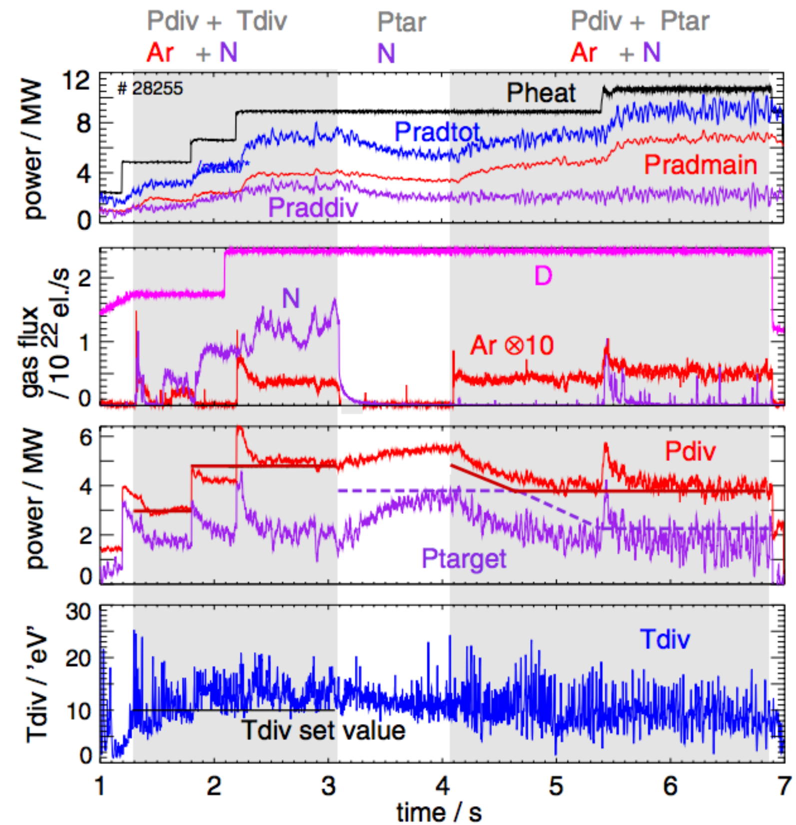
Why?
- The combination and maximization of main chamber and divertor radiation enables maximization of the power handling capability of a tokamak.

How?
- Measure the radiation at various location in the plasma (main, divertor, ...) using bolometer channels.
- By using these real-time measurements, adjust the gas injection of various species (Argon, Neon,...) to keep power exhaust, detachment, and many other parameters at desired values.

Experiment:
- **Initial assessment data for control development**
- **Multi specie comparison (Argon, Neon,...) density scans**
- **Gas valve injection location scan**
  - **Initial results from D3D showing detachment variation with injection location**

Asdex Upgrade Results

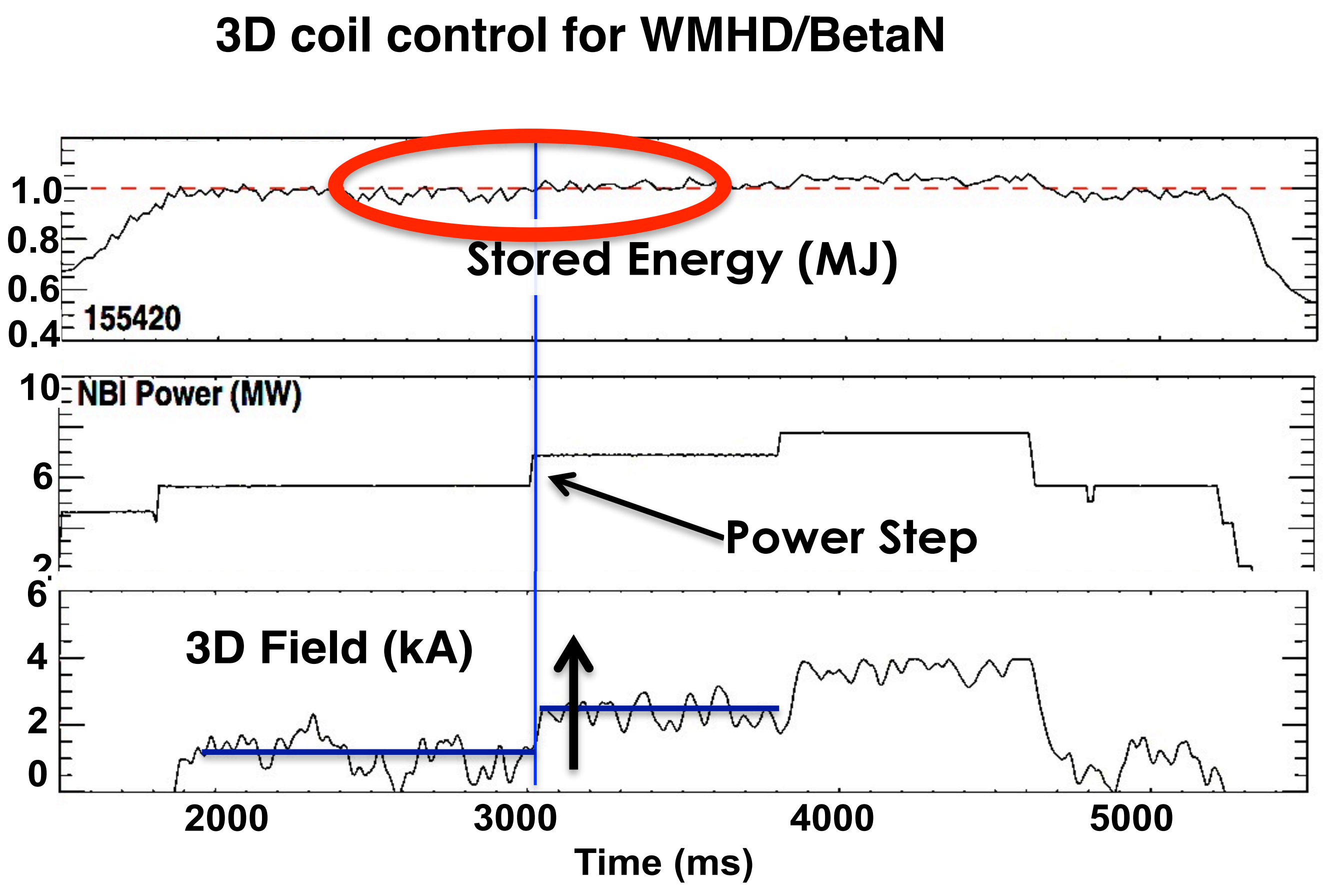




- **N, N + Ar injection**
- **➔ High values of Pheat/R = 14 MW/m**
- **➔ Divertor peak heat flux below 5 MW/m²**
- **Good plasma performance, H98(y,2) = 1 and β_N= 3.**

Kallenbach NF 2012

Keep the Pedestal High but below the ELM limit by Pedestal Pressure Control with 3D Coils (RMP)



PRINCETON PLASMA PHYSICS LABORATORY

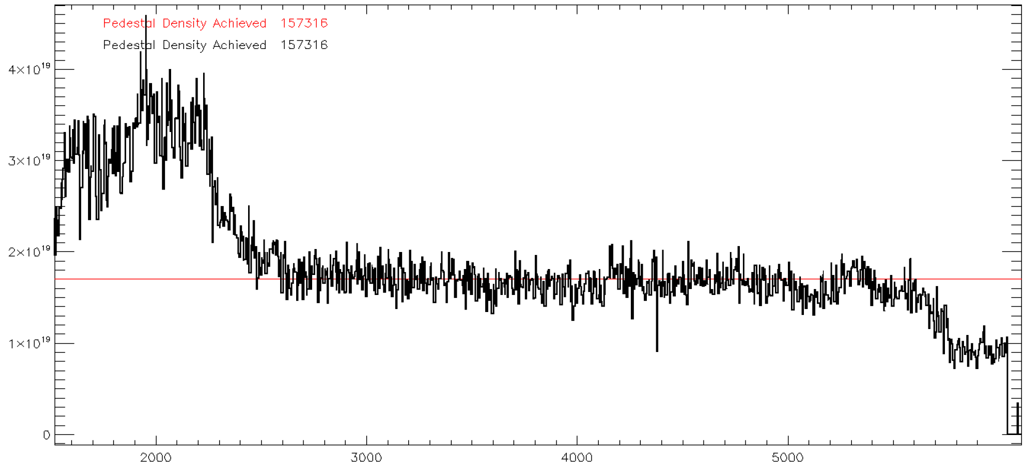
Pedestal density/pressure control with LGI

Develop LGI, PCS connection. Adjust the density with LGI

1. **Try to adjust the ELM frequency in real-time (increase or reduce the ELM frequency to adjust the density)**
2. **Turn on and off the LGI to keep density at a given level**

Pedestal density/pressure control with gas

Pedestal density/pressure control with gas



In the future, we can use Thomson. Initially, modeling of the pressure based on reconstruction.

SHAPE CONTROL DEVELOPMENT:

1. MIMO Shape Control (X-point etc.)

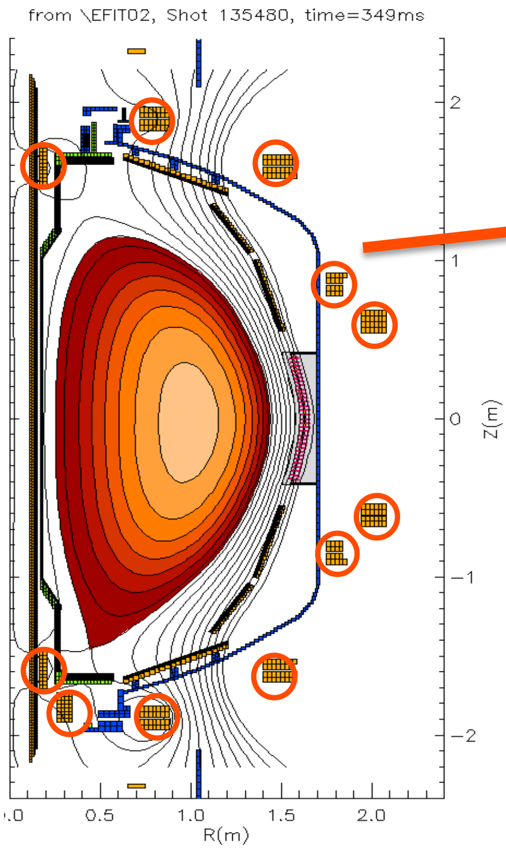
2. High Kappa Shape Development for High Perf.

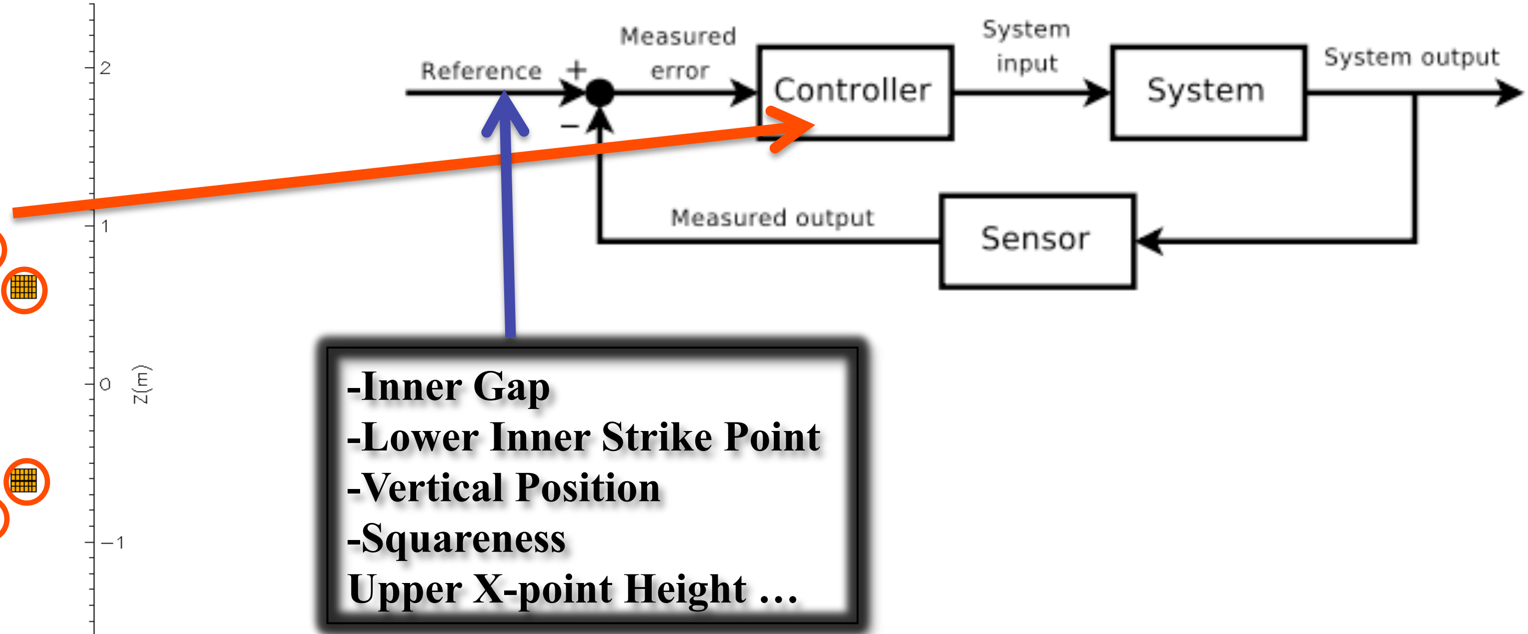
3. Snowflake Development and Assessment

4. X-Divertor Development and Assessment

5. VDEs and Vertical Growth rate

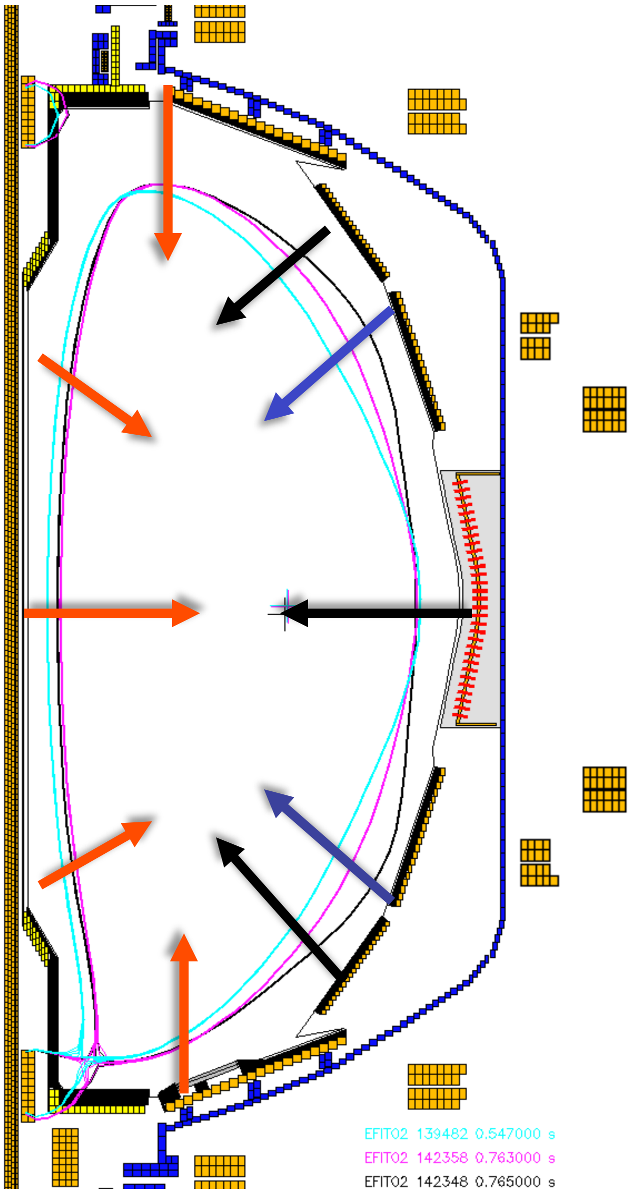
Full Multiple-Input-Multiple-Output Control





- 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

Implementation of the MIMO Control



- Aim: Be able to request **any shape from user interface** and let the control regulate to the nearest achievable shape.

- We lack the inner gap control and upper/ lower gap control for fiducial.
- These are important for high kappa, high aspect ratio shots.

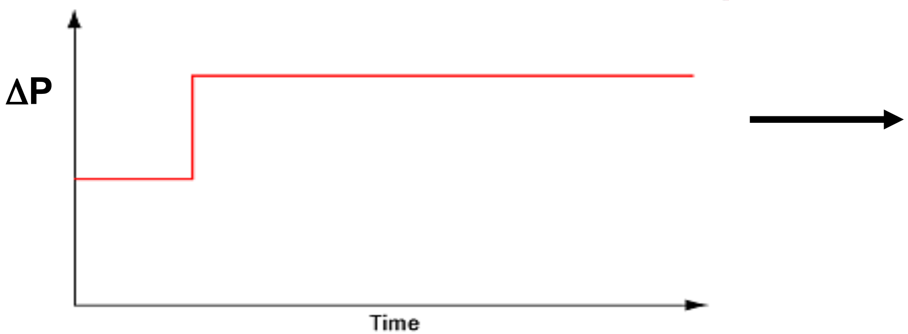
- Black segments in use in all shots.
- Blue tried segments, used for squareness control before (not in full operation).
- Red segments, will be used in this xp.

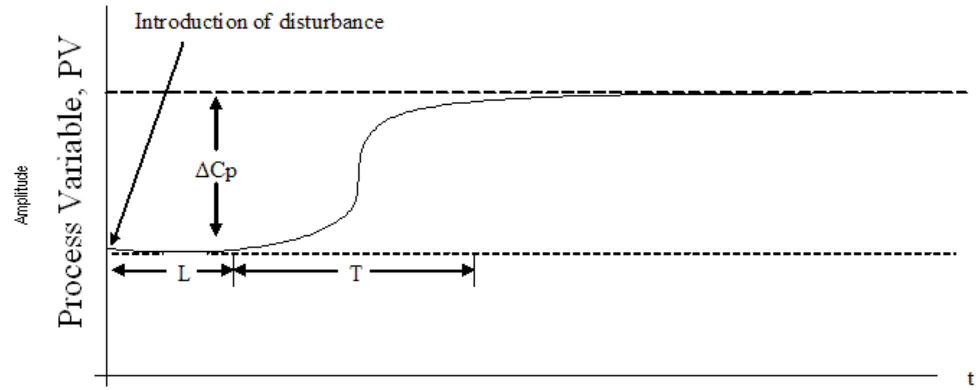
Feedforward System ID

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

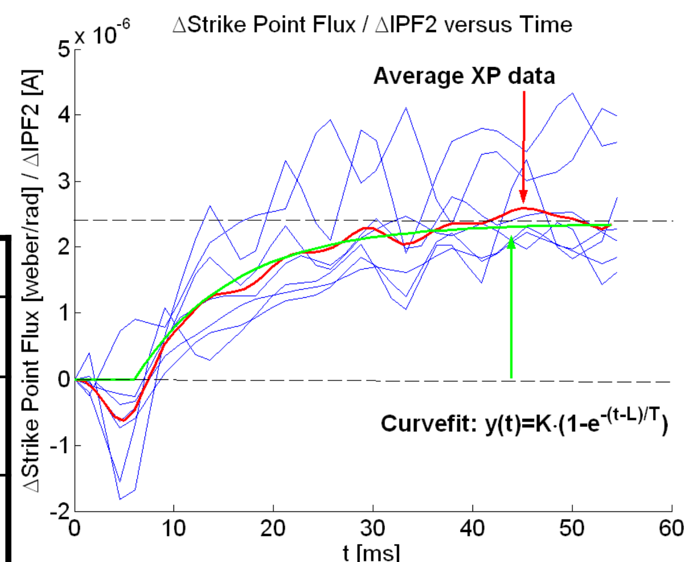
$$\dot{y}(t)T + y(t) = Ku(t - L)$$

- Last year: Reaction Curve Method





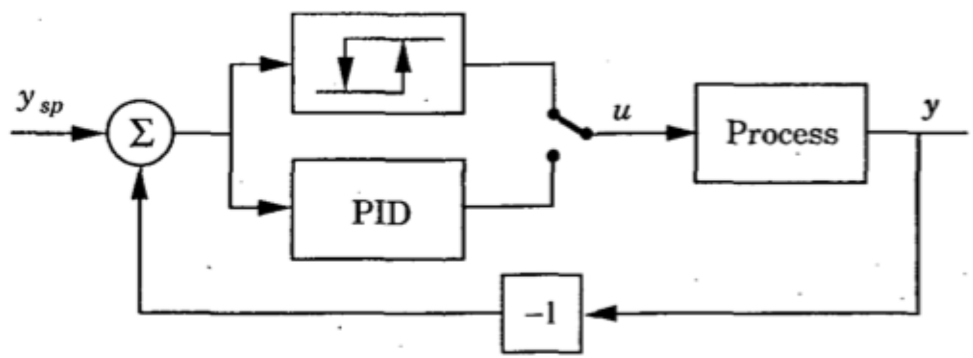
- Results from last year:
- Problem:
  - Many shots needed
  - Not precise

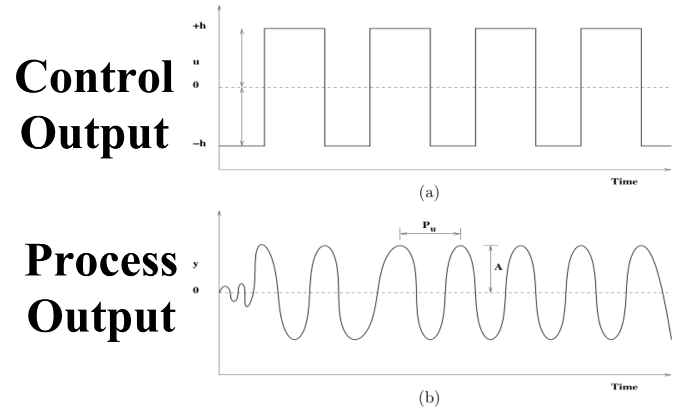


	K_p	K_i	K_d
P	$(\Delta P/\Delta C_p) \cdot (T/L)$	-	-
PI	$0.9 \cdot (\Delta P/\Delta C_p) \cdot (T/L)$	$(\Delta P/\Delta C_p) \cdot (3.3 \cdot T/L^2)$	-
PID	$1.2 \cdot (\Delta P/\Delta C_p) \cdot (T/L)$	$(\Delta P/\Delta C_p) \cdot (2 \cdot T/L^2)$	$(\Delta P/\Delta C_p) \cdot (T/2)$

Feedback 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.

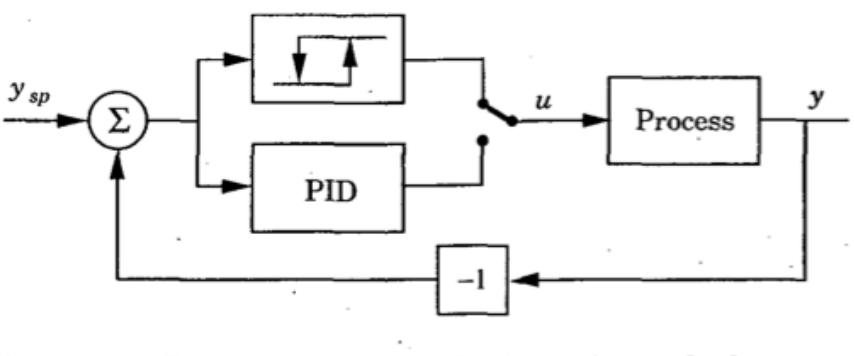
	K_c	τ_I	τ_D
P	$0.5K_{cu}$		
PI	$0.45K_{cu}$	$P_u/1.2$	
PID	$0.6K_{cu}$	$P_u/2$	$P_u/8$

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

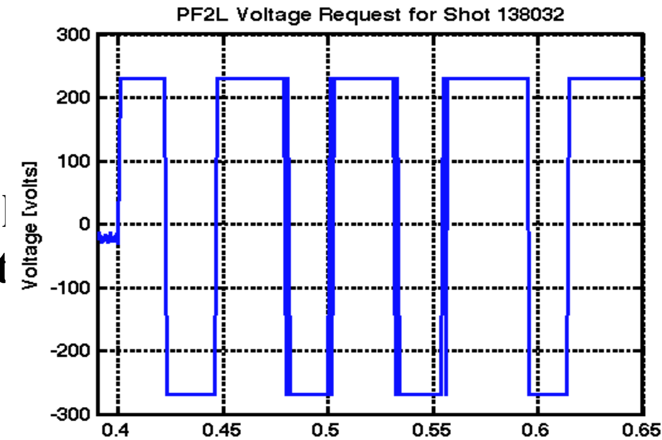
- Only a single experiment is needed.
- Closed loop: More stable

2010 Run: Experimental Closed Loop Auto-tune System ID

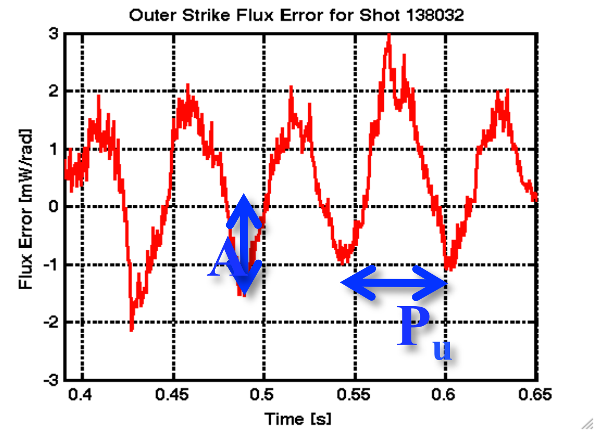
- This year: **Auto-tuning with Relay Feedback Method**



Control Output



Process Output



- The closed-loop plant response gives oscillation period (P_u) & amplitude (A) which are used for PID controller tuning.
- Pros:
  - 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)

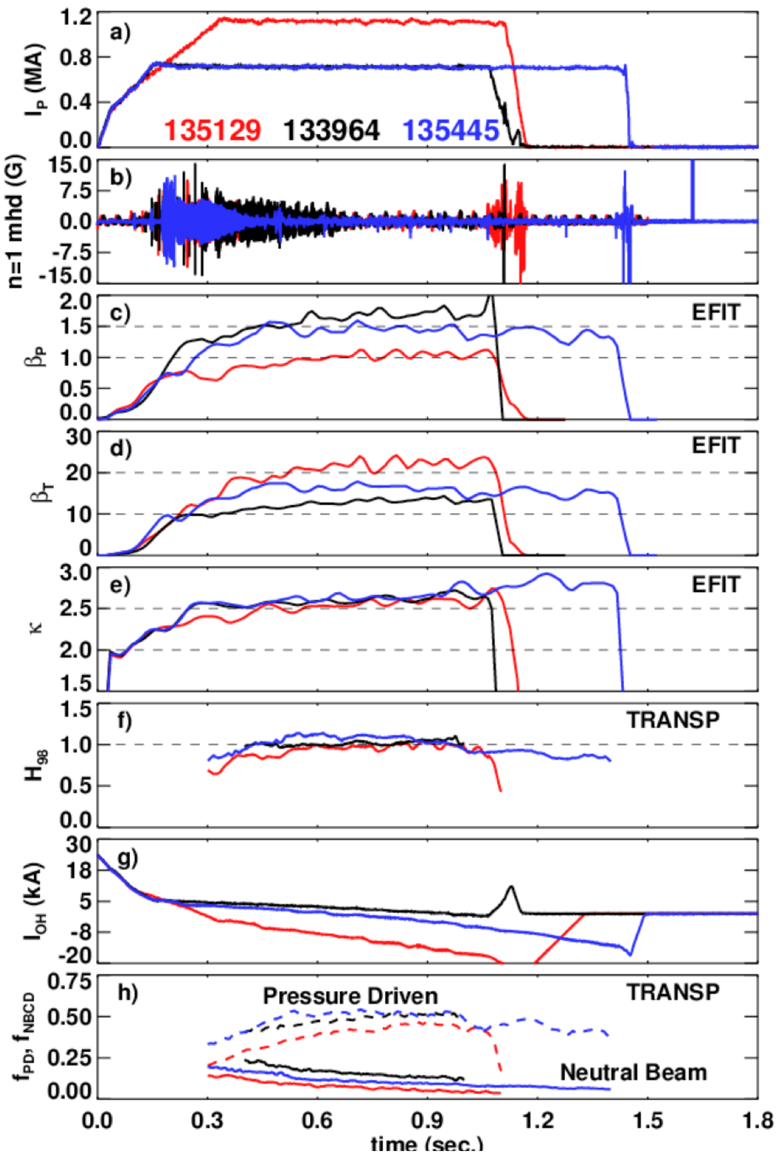
High-Elongation Configurations Developed to Challenge Limits in β_T, Non-inductive Current Fraction and Sustainment

- β_N>4 in all cases.
- H_{98}>=1 for greater than $5\tau_e$ (>300 msec).
- q*=3.9 & 4.7 maintain q_{min}>1 for >$2.5\tau_R$
  - with no large core MHD...

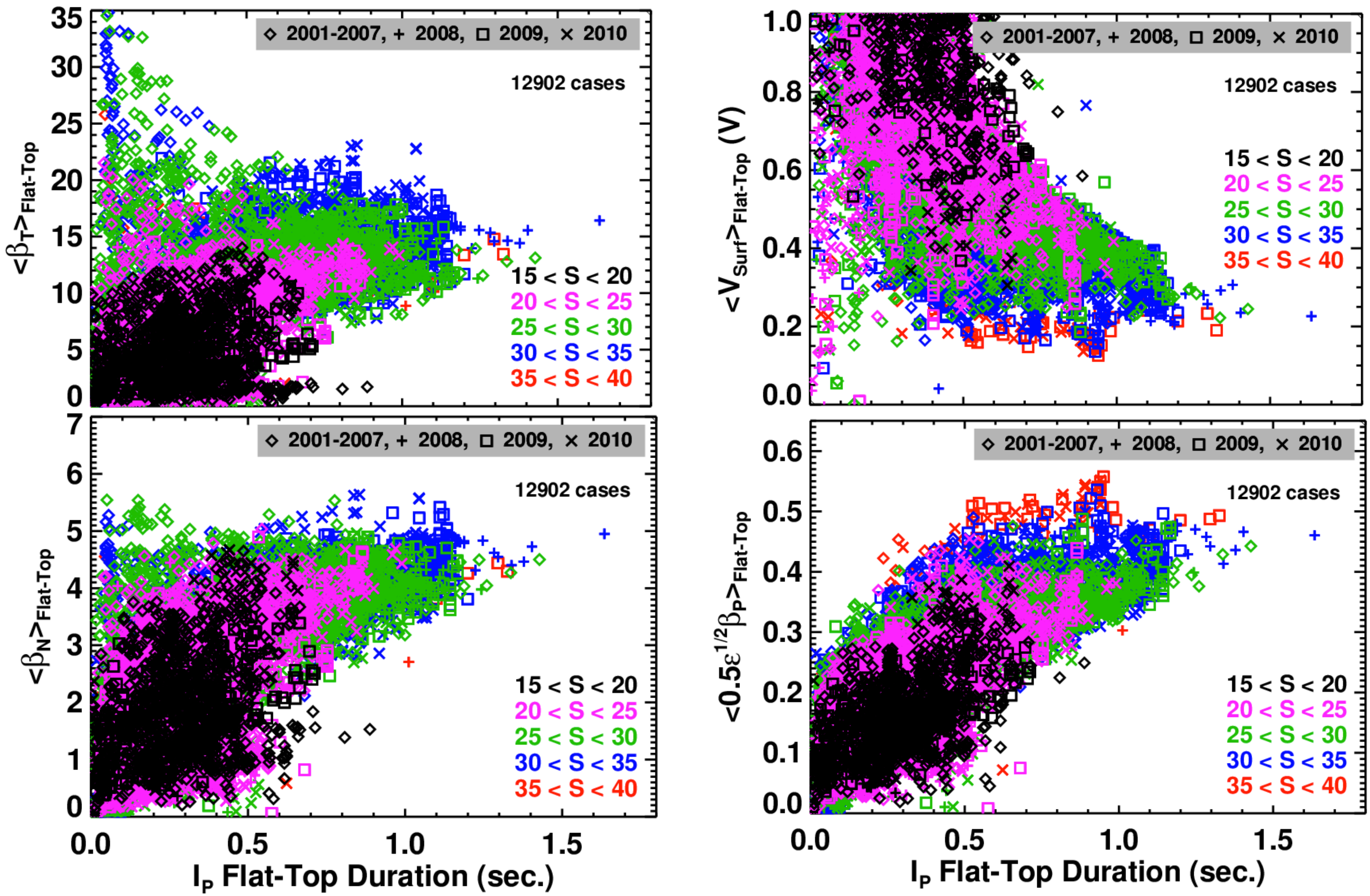
These appear to meet all the criteria for "Hybrid" discharges.

$$q^* = \frac{\varepsilon(1+\kappa^2)\pi a B_{T0}}{\mu_0 I_P}$$

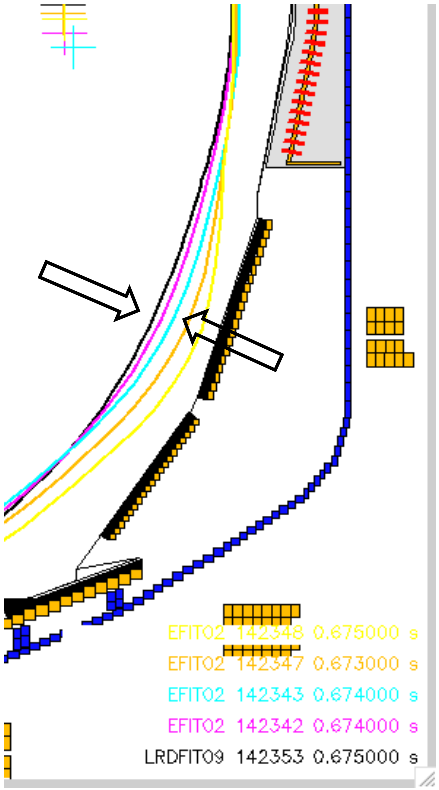
- **<u>High-β_T</u>**
  - *q*=2.8*
  - *B_T=0.44 T*
  - *I_P=1100 kA*
- **<u>Long Pulse</u>**
  - *q*=3.9*
  - *B_T=0.38 T*
  - *I_P=700 kA*
- **<u>High-β_P</u>**
  - *q*=4.7*
  - *B_T=0.48 T*
  - *I_P=700 kA*
- **<u>All</u>**
  - *H_{98}>=1*
  - *κ=2.6-2.7*



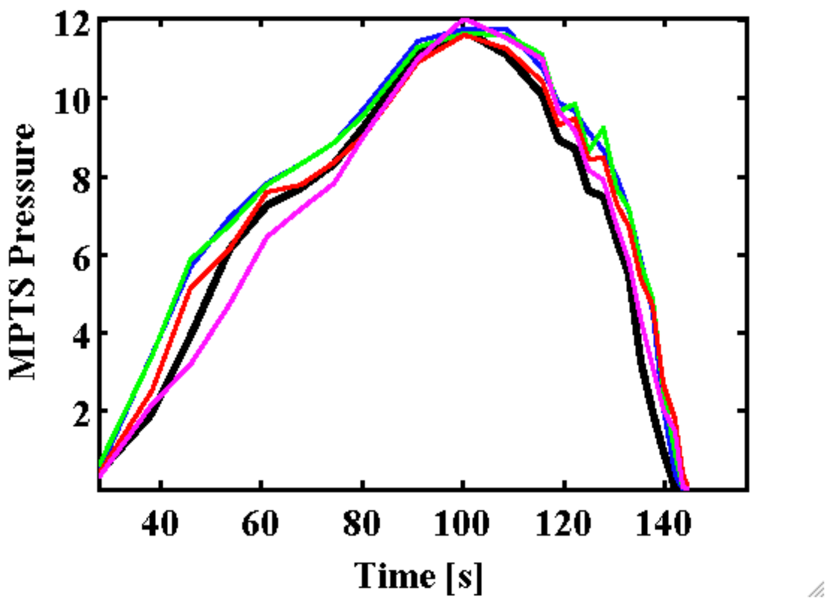
Strong Shaping has Helped NSTX Make Continued Progress on a Range of Optimization Targets



Pressure Profile Change as Squareness Increases



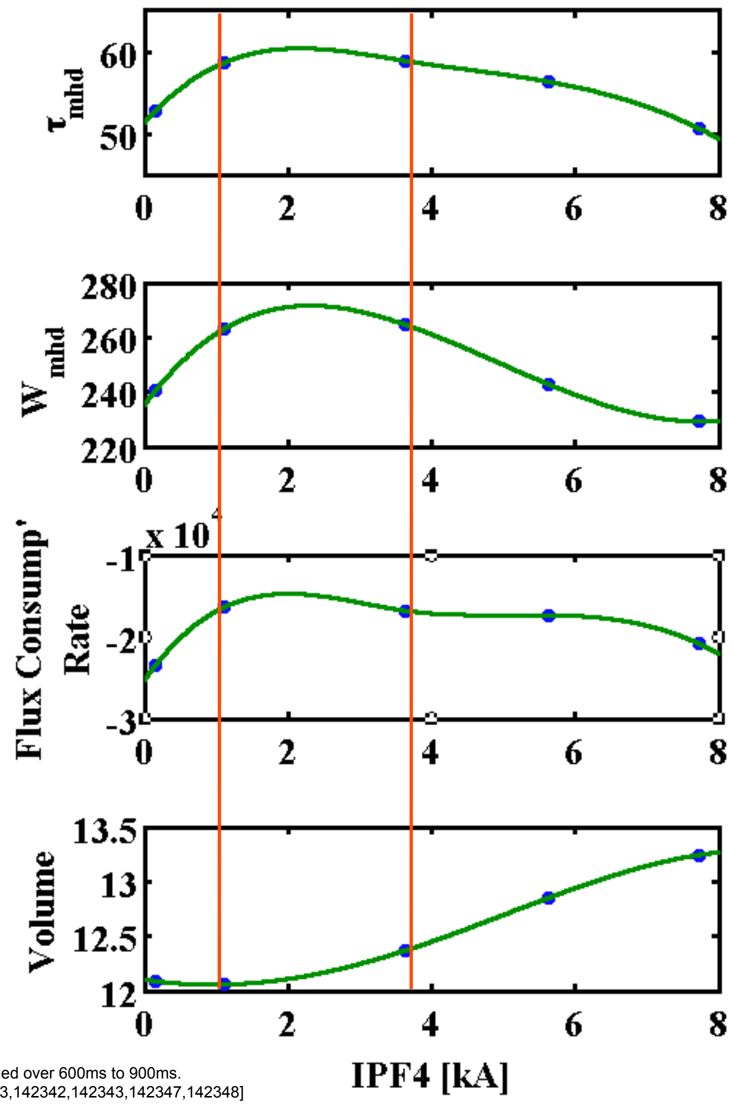
PF4= 0, -1, -4, -6, -8 kA



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

Too high squareness interacts with the wall. Pressure drops.

Optimal Squareness for Performance



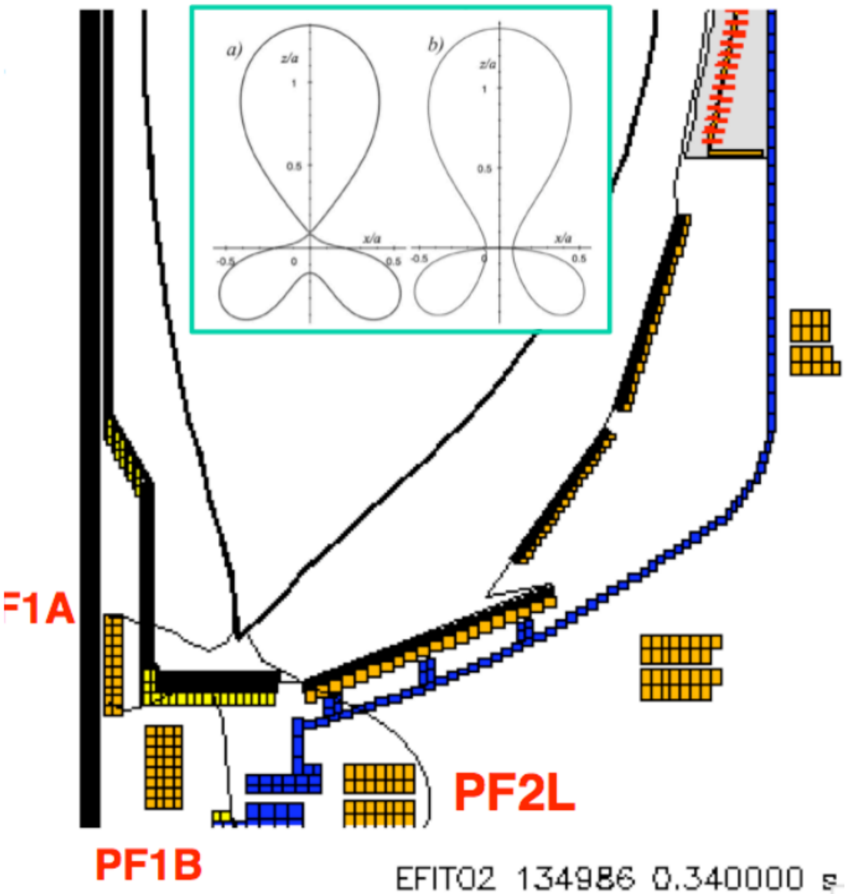
Averaged over 600ms to 900ms.
[142353,142342,142343,142347,142348]

- 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.

Snowflake Development and Control

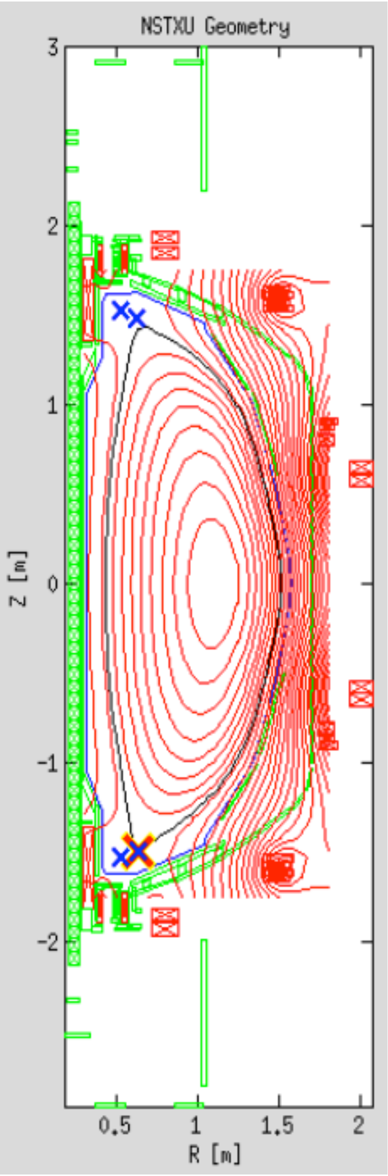


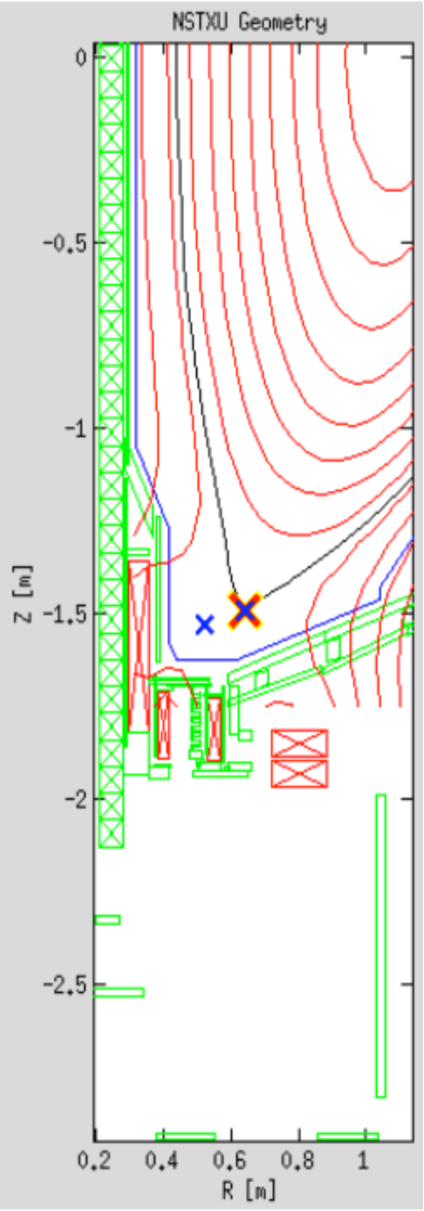
Example "snowflake" divertor configuration in NSTX.

- Three options
  - Feedforward coil currents
  - Strike point control with + feedforward
  - Full Snowflake Control

- Develop the stages of control needed for NSTX-U

NSTX-U Snowflake

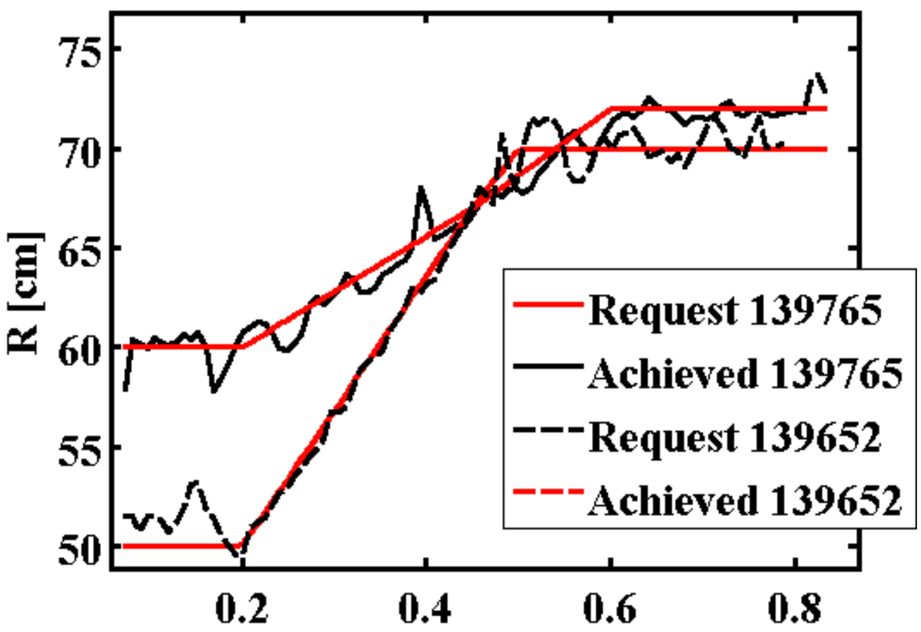




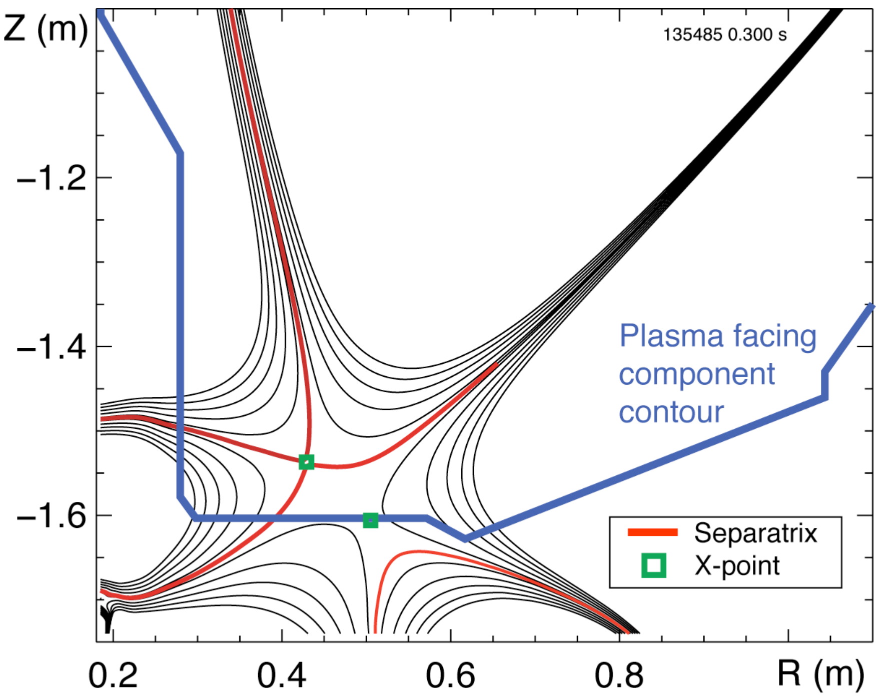
- Toksys for NSTX-U is mostly working
- Pat Vail is helping with the development.

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).

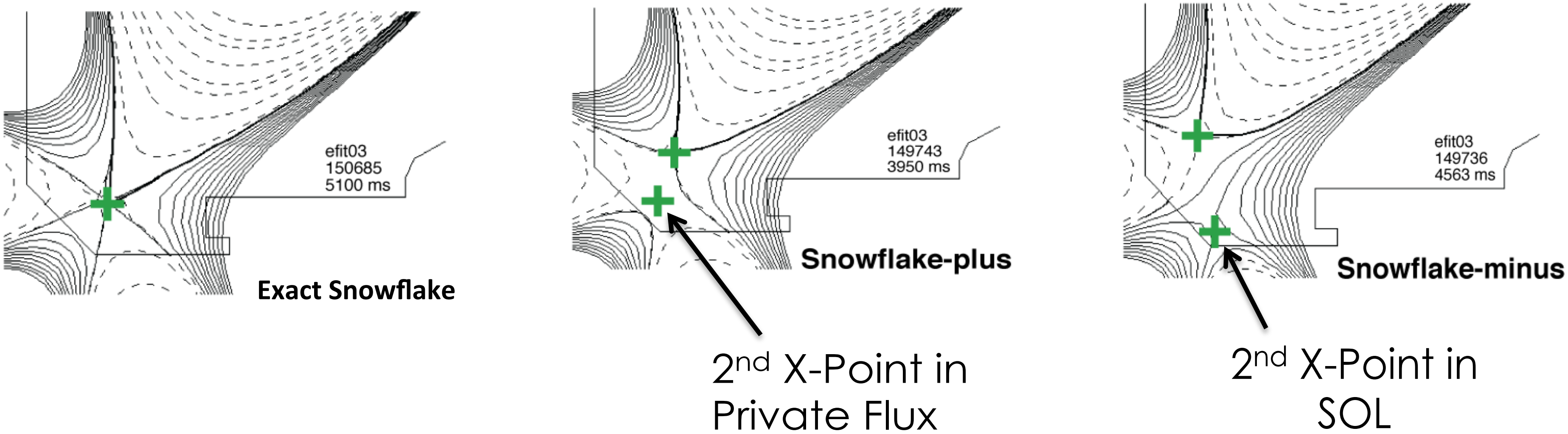


Example SP control



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

Snowflake Divertor Development and Control



- Snowflake divertor: second-order null (2 X-points)
- Geometric changes compared to standard divertor can lead to:
  - High poloidal flux expansion, large plasma-wetted area ➔**reduce peak q_{div}**
  - Four strike points ➔ **share P_{div}**

Snowflake Control: Finding the Two X-points

- Locally expand the Grad-Shafranov equation in toroidal coordinates:

$$r\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial \Psi}{\partial r}\right)+\frac{\partial^2 \Psi}{\partial z^2}=0$$

- Keep the 3rd order terms and find the magnetic nulls

$$\Psi_{\exp}=\Psi(c_{\exp},\delta r,\delta z)$$

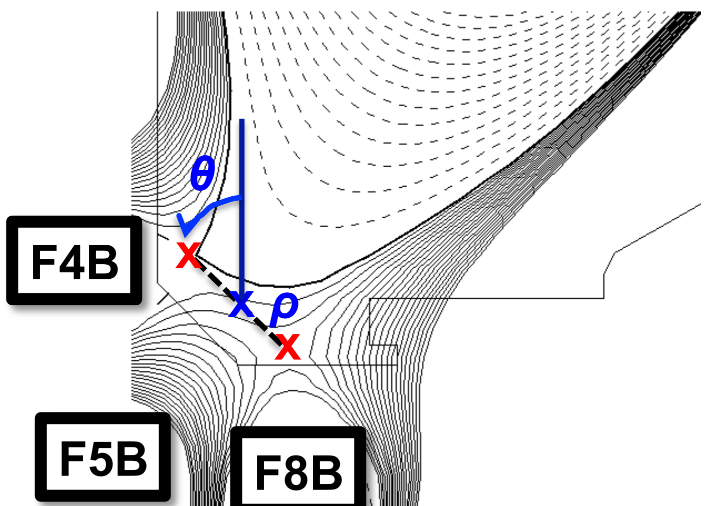
- Find coefficients, c_{exp}, from sample points
- Find the null points (X-points)

$$B_r=-\frac{1}{r}\frac{\partial \Psi_{\exp}}{\partial \delta z}=0=B_z=\frac{1}{r}\frac{\partial \Psi_{\exp}}{\partial \delta x}=0$$

➔ $$\{\delta r_{X_1}(c_{\exp}),\delta z_{X_1}(c_{\exp}),\delta r_{X_2}(c_{\exp}),\delta z_{X_2}(c_{\exp})\}$$

- Real-time calculation (<< 1 ms) with reasonable accuracy

Snowflake Control: Controlling the PF Coils



Location of the X-points and Centroid

- To control, we need to know how PF coils affect the X-point locations

$$\frac{\partial \delta r_{X_1}}{\partial \delta I_{PF}} = \frac{\partial \delta r_{X_1}}{\partial c_{\exp}} \left(\frac{\partial c_{\exp}}{\partial B_r} \frac{\partial B_r}{\partial I_{PF}} + \frac{\partial c_{\exp}}{\partial B_z} \frac{\partial B_z}{\partial \delta I_{PF}} \right)$$

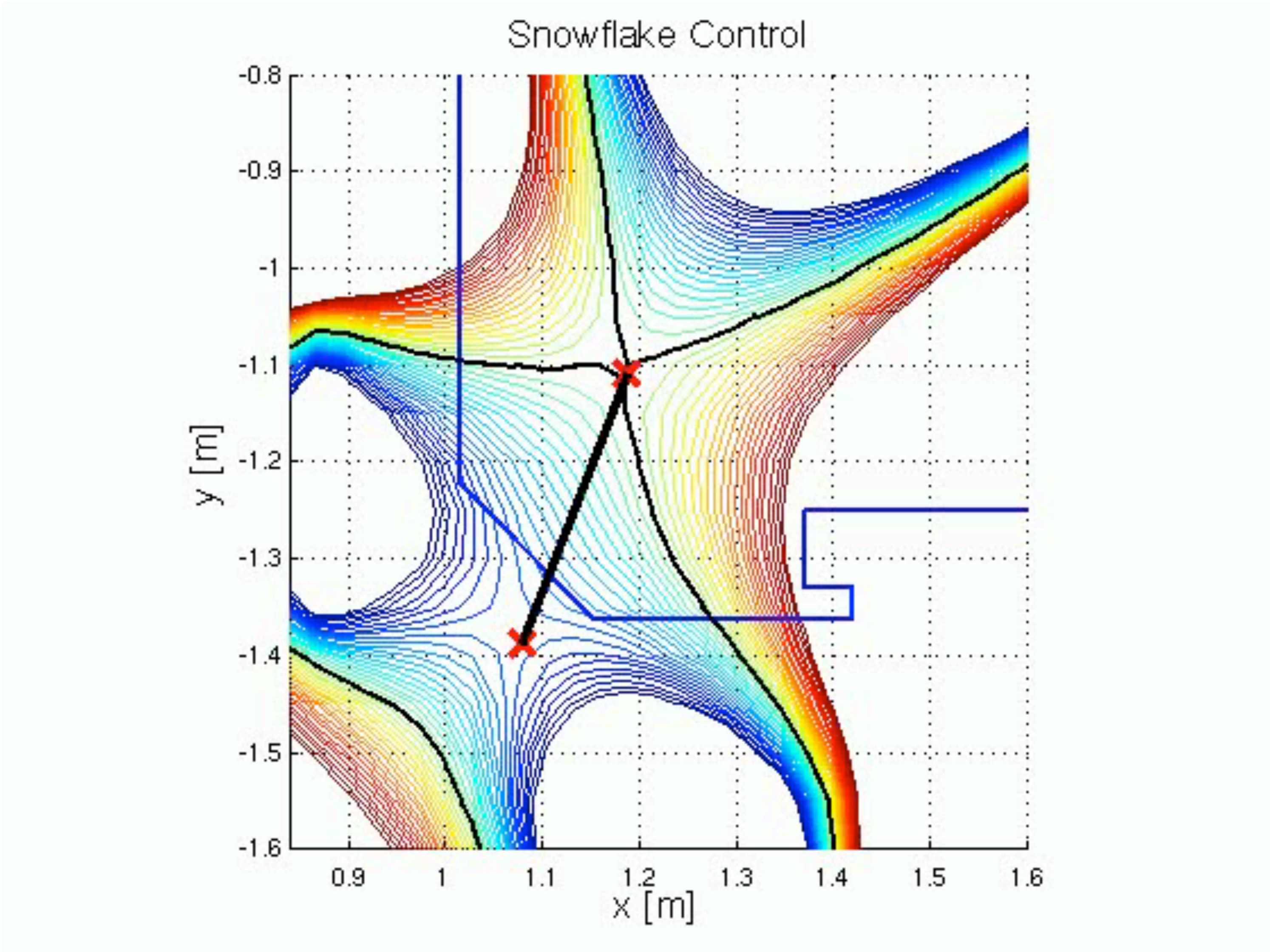
- dB/dI_{PF} is found from the Green's Function of the G-S problem

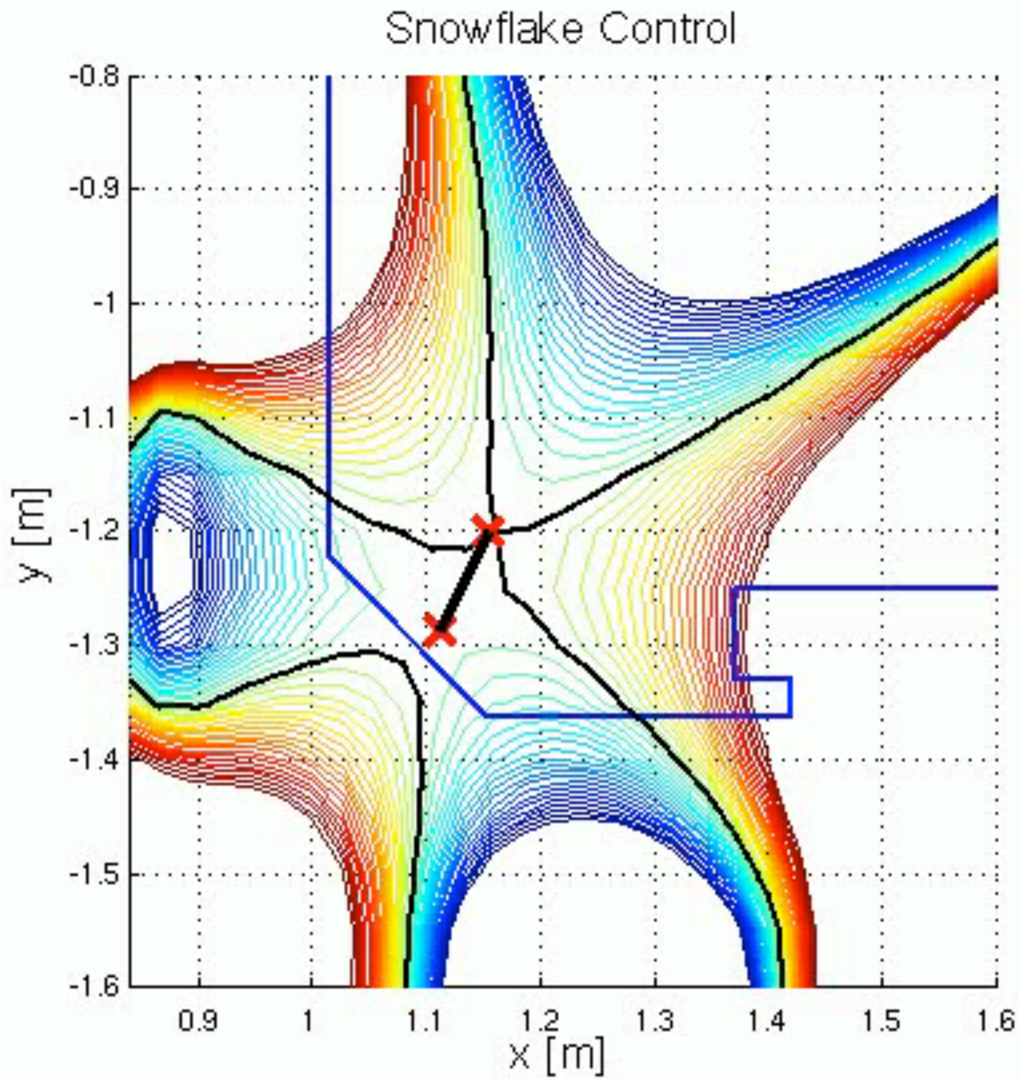
$$\begin{bmatrix} \delta\theta \\ \delta\rho \\ \delta r_c \\ \delta z_c \end{bmatrix} = A \begin{bmatrix} \delta I_{F4B} \\ \delta I_{F5B} \\ \delta I_{F8B} \end{bmatrix}$$

- 3 closest PF coils are used for controlling the formation

$$\begin{bmatrix} \delta I_{F4B} \\ \delta I_{F5B} \\ \delta I_{F8B} \end{bmatrix} = (A^T A)^{-1} A^T W \begin{bmatrix} \delta\theta \\ \delta\rho \\ \delta r_c \\ \delta z_c \end{bmatrix}$$

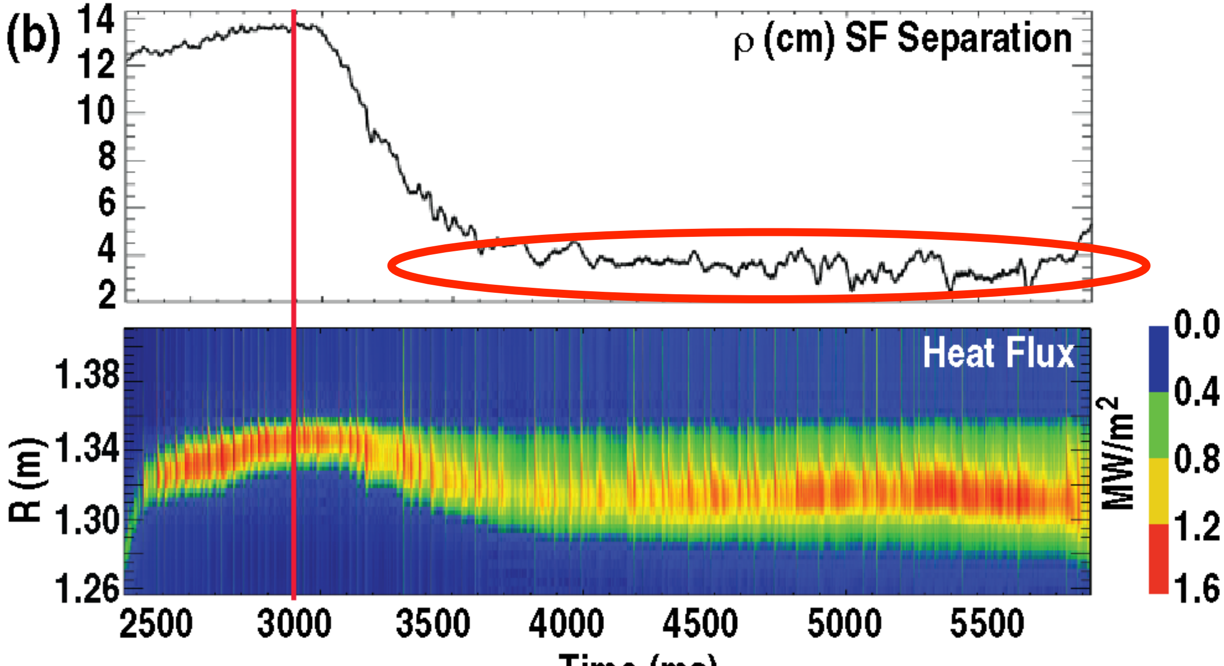
Snowflake Control: Obtaining Exact Snowflake (ρ Scan)





Snowflake Control
-0.8
-0.9
-1
-1.1
-1.2
-1.3
-1.4
-1.5
-1.6
y [m]
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
x [m]

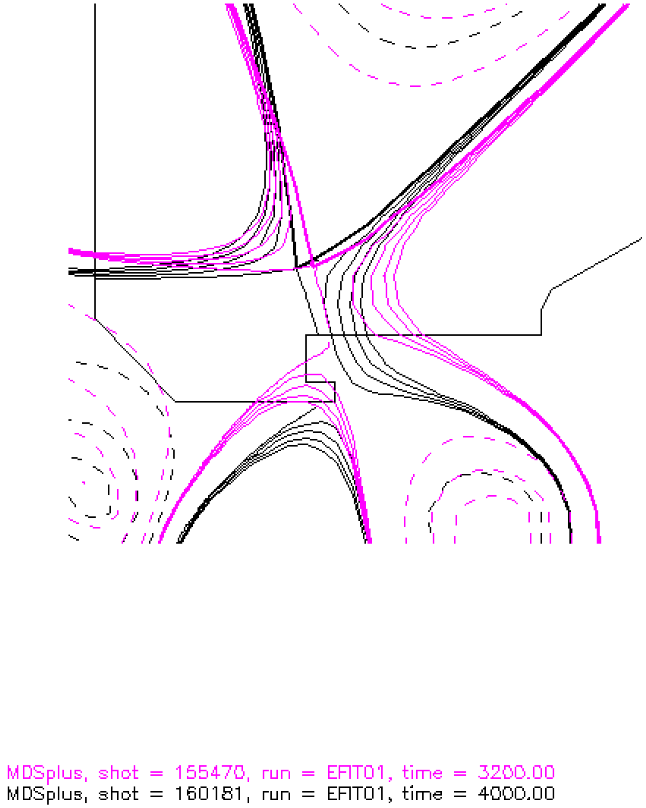
Snowflake Control: Obtaine Optimize Snowflake at NSTX-U (Exact, + and -)

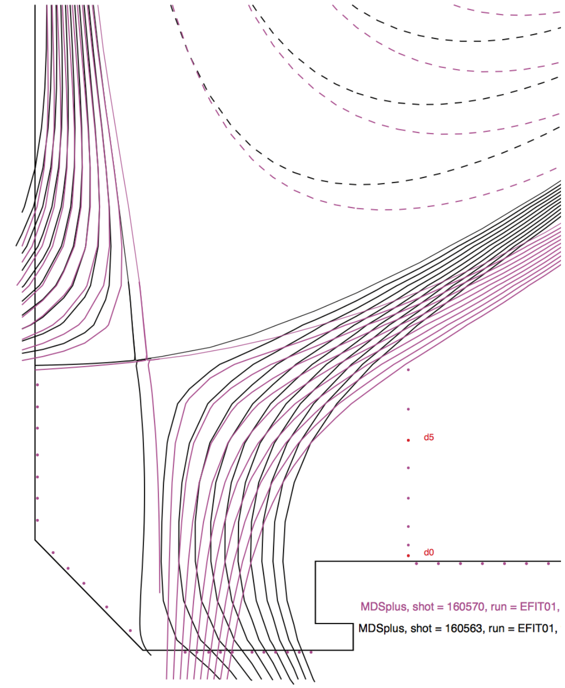


Snowflake Control (Control Starts at 3 s)

- Obtained long stable SF/-/+ at D3D (SF- at NSTX)
- At NSTX-U obtain Snowflake
- Compare the flux expansion, peak heat flux vs the SFD Configuration paramenter (distance, angle, centroid)
- Obtain the best scenario for stable low heat operations

X-Divertor Development and Control





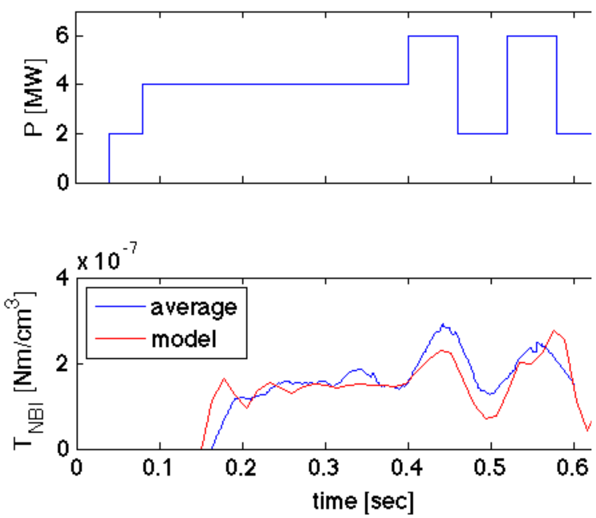
- At D3D, obtained X-Divertor
- NSTX-U obtain X-Divertor
- Compare the flux expansion, peak heat flux vs the XD Configuration paramenter (X-point locatin, distance from the plate, angle)
- Compare to Standard Divertor and SFD
- Obtain the best scenario for stable low heat operations

2011-2012 Run: Rotation Control

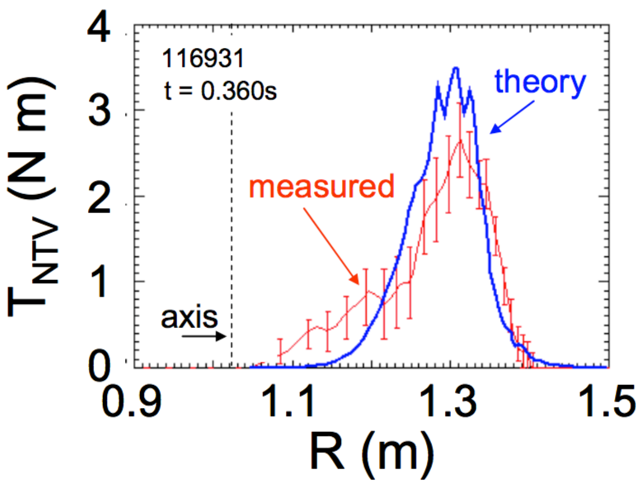
- Reduced order model for rotation control

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

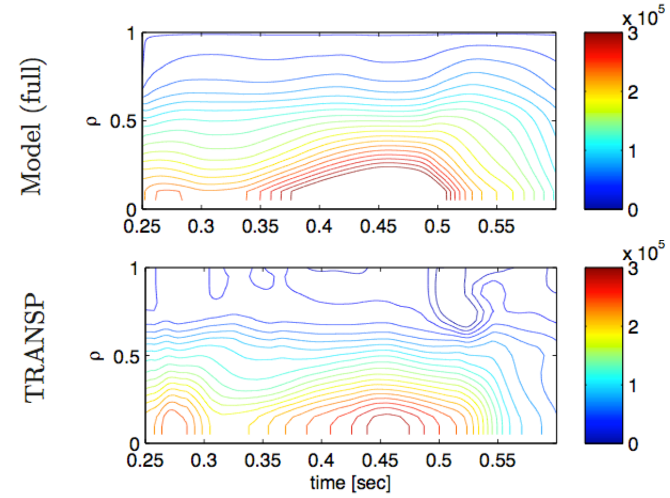
- Adequate models for torque inputs and time evolution



NBI Torque profile prediction: Model versus data

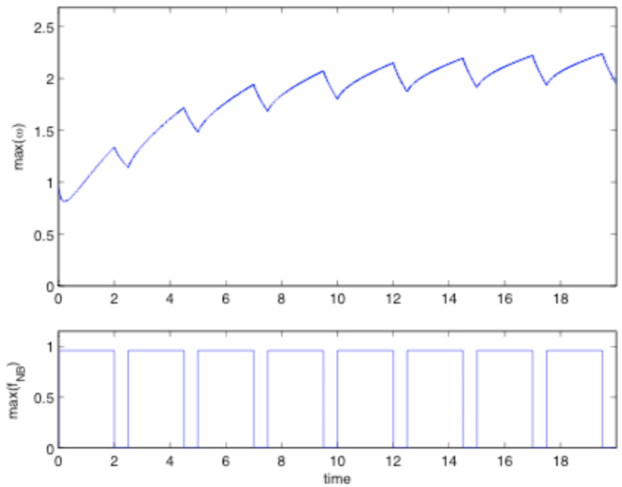


NTV torque profile: Calculations (Zhu et al.) versus experimental data

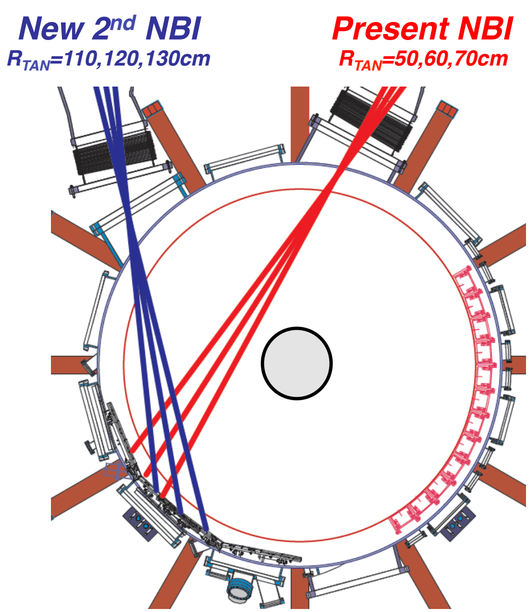


Rotation time evolution: Reduced model versus TRANSP data

Rotation Profile Control



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

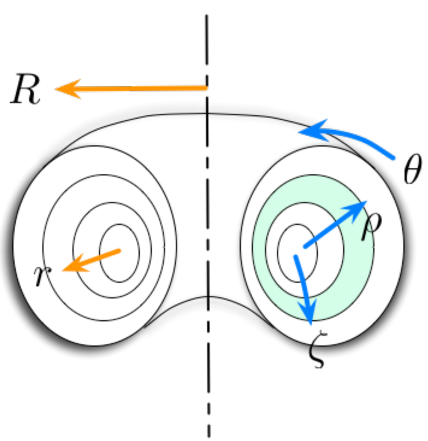
$$- \left(\frac{\partial V}{\partial \rho} \right)^{-1} \frac{\partial}{\partial \rho} \left[\frac{\partial V}{\partial \rho} \sum_i n_i m_i \omega \left\langle R^2 (\nabla \rho)^2 \right\rangle \frac{v_\rho}{|\nabla \rho|} \right]$$ Pinch

Ignore for initial analysis

$$+ T_{\text{col}} + T_{J \times B} + T_{\text{bth}} + T_{iz}$$ Torque input

$$- \sum_i n_i m_i \left\langle R^2 \right\rangle \omega \left(\frac{1}{\tau_{\phi c x}} + \frac{1}{\tau_{c \delta}} \right)$$ Loss (charge ex, ripple)

0



Also, temporal changes are small, ignored.

Model Equations

- Toroidal momentum balance

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

- 1D Linear PDE (parabolic) – diffusion equation with forcing

- Neumann (ρ=0) and Dirichlet (ρ=1) BCs

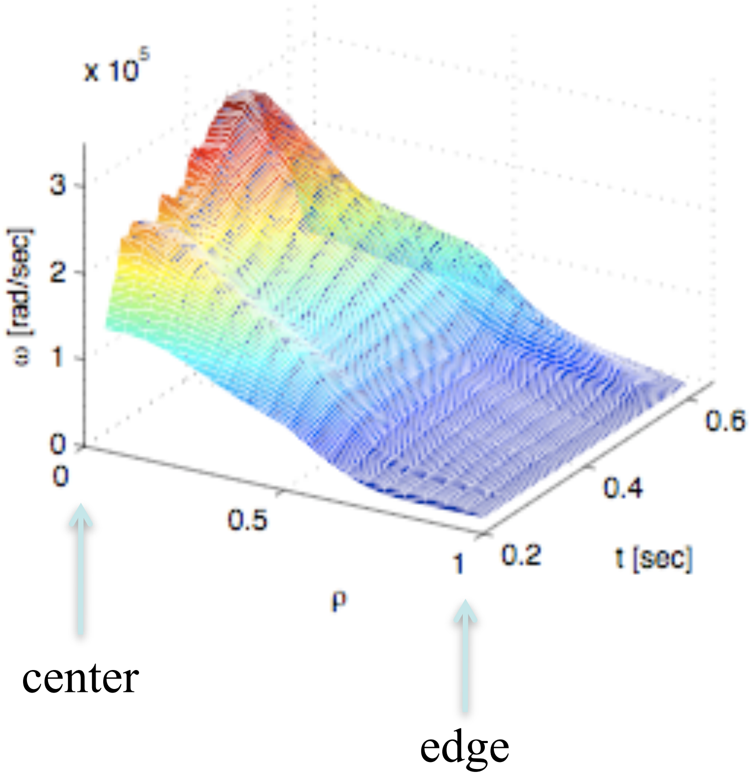
- Curve fit coefficients (3 shape variables $\langle R^2 \rangle$, $\langle R^2 (\nabla \rho)^2 \rangle$, $\frac{\partial V}{\partial \rho}$)

- Coefficients to be supplied from TRANSP: χ_ϕ and $\sum_i n_i m_i$

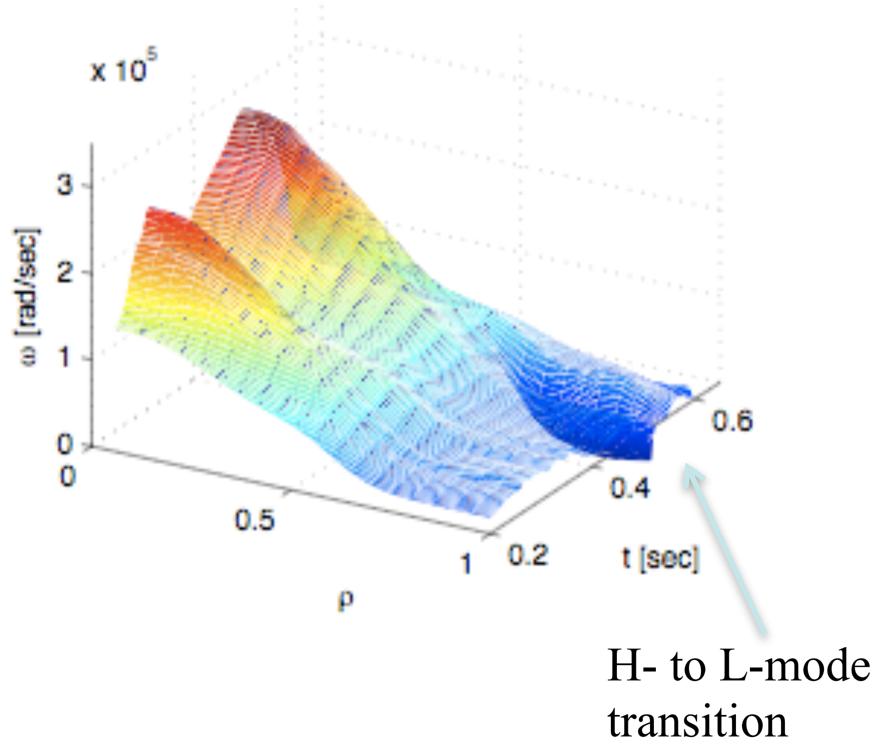
Model Comparison with Experiment

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

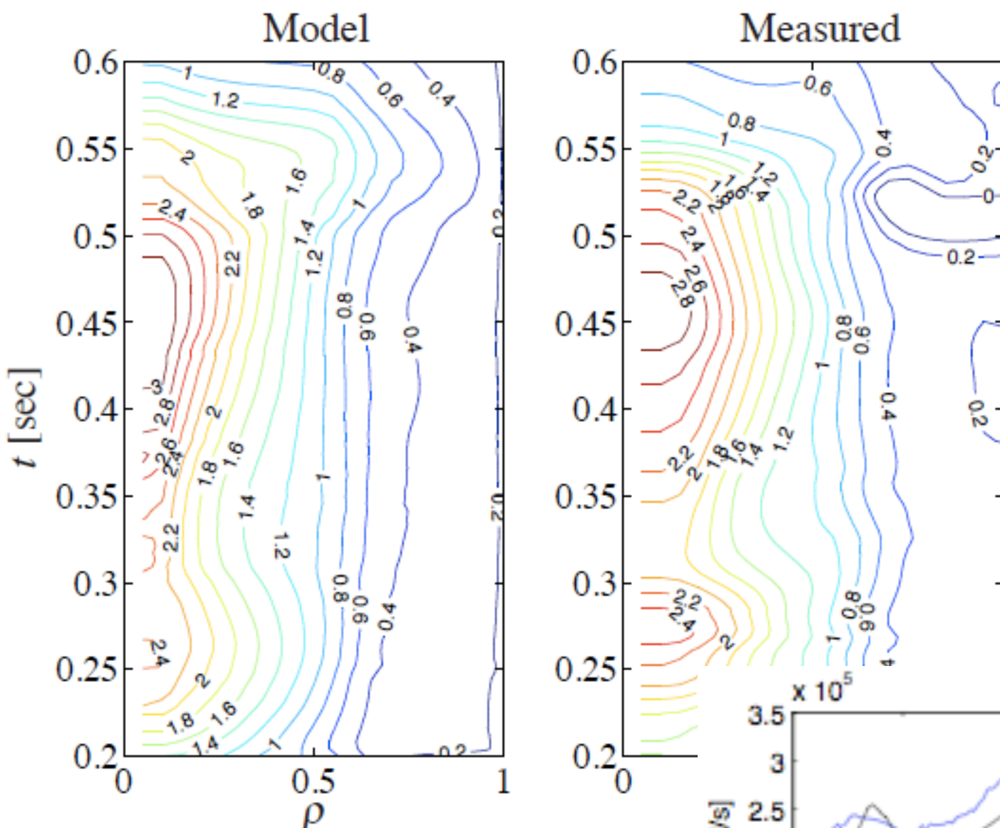
Model



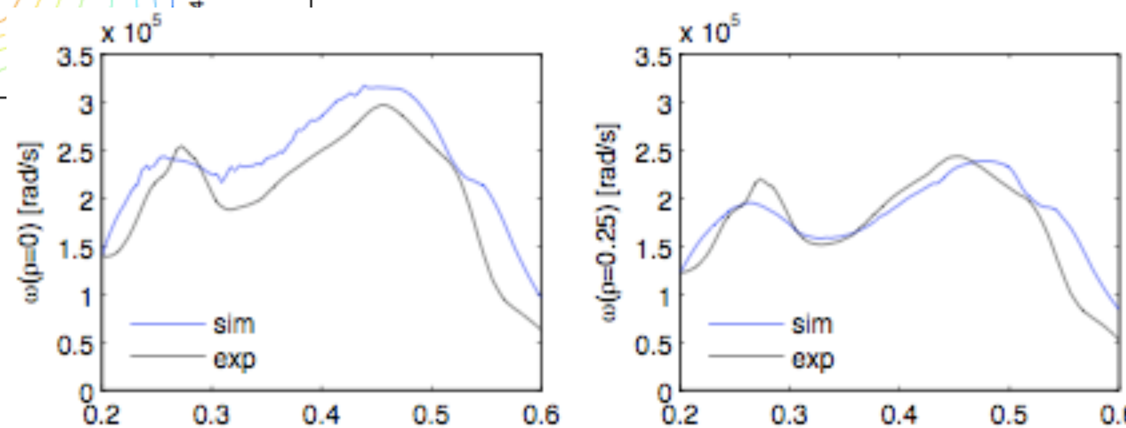
Experiment



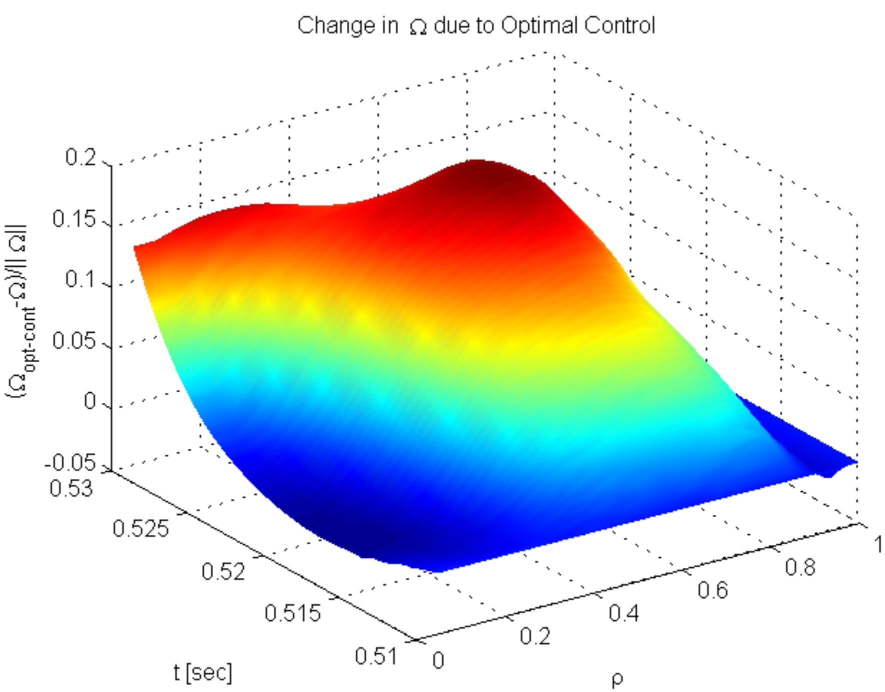
Model Comparison with Experiment



H- to L-mode transition



Optimal Control for Rotation Profile



Optimal Ω control with full state control

- Converted PDE to ODE for control purpose

$$\frac{d\Omega}{dt} = A(t)\Omega + B(t)u$$

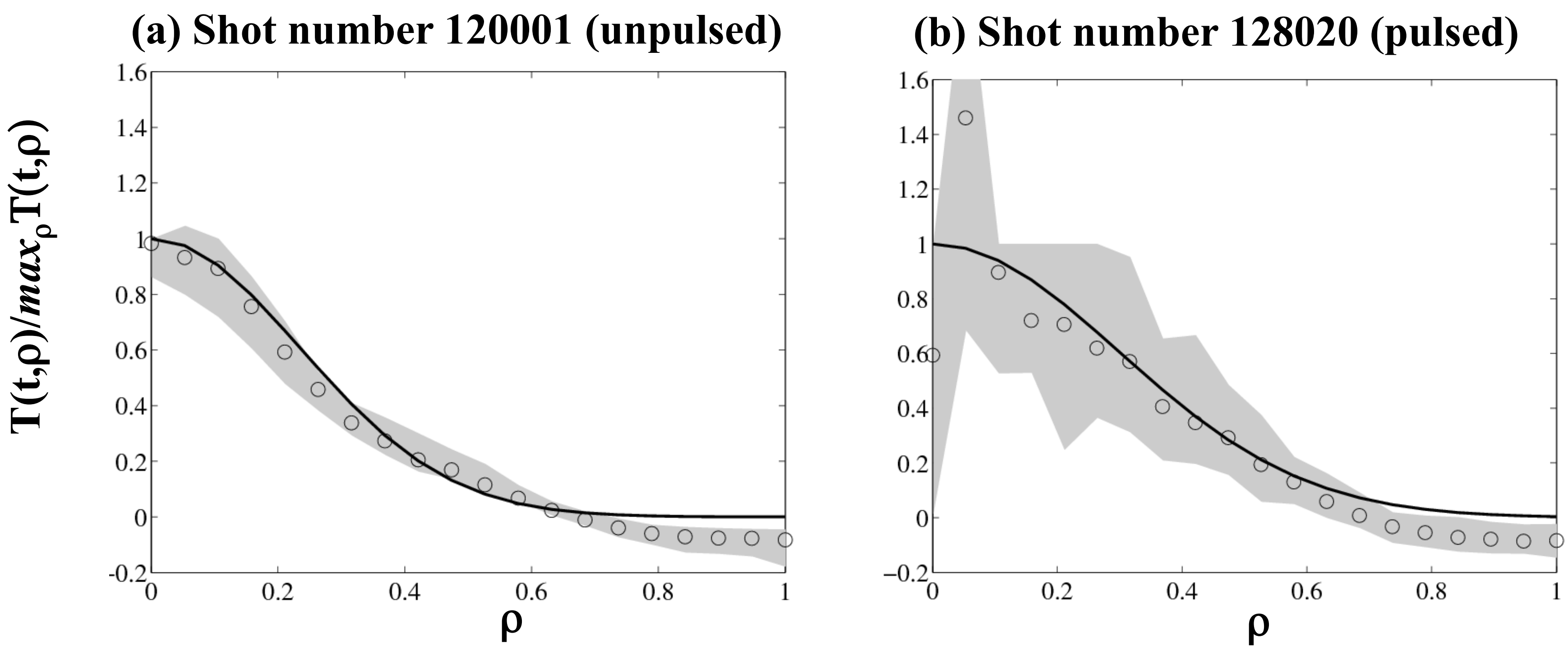
- Solve the optimization problem to minimize the cost function

$$J = (\Omega(t_f) - \Omega_{req})^T S(\Omega(t_f) - \Omega_{req}) + \int_{t_0}^{t_f} u^T R u$$

- 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.

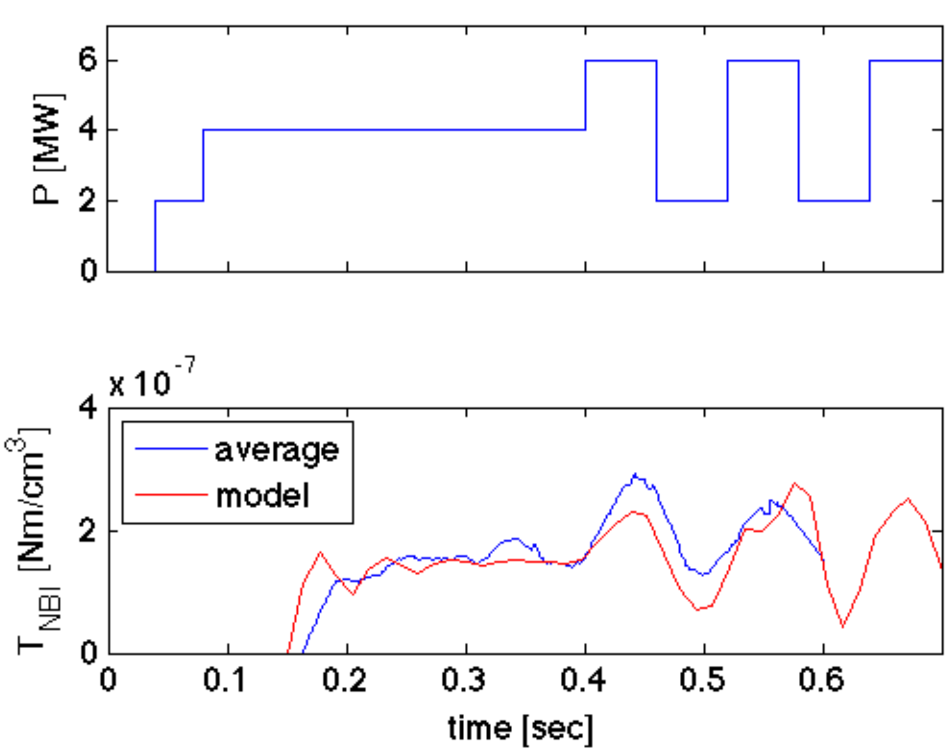
Beam Torque Model



- 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.

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

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

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

Neoclassical Toroidal Viscosity

- Motivation: Use NTV torque to control Edge Rotation

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

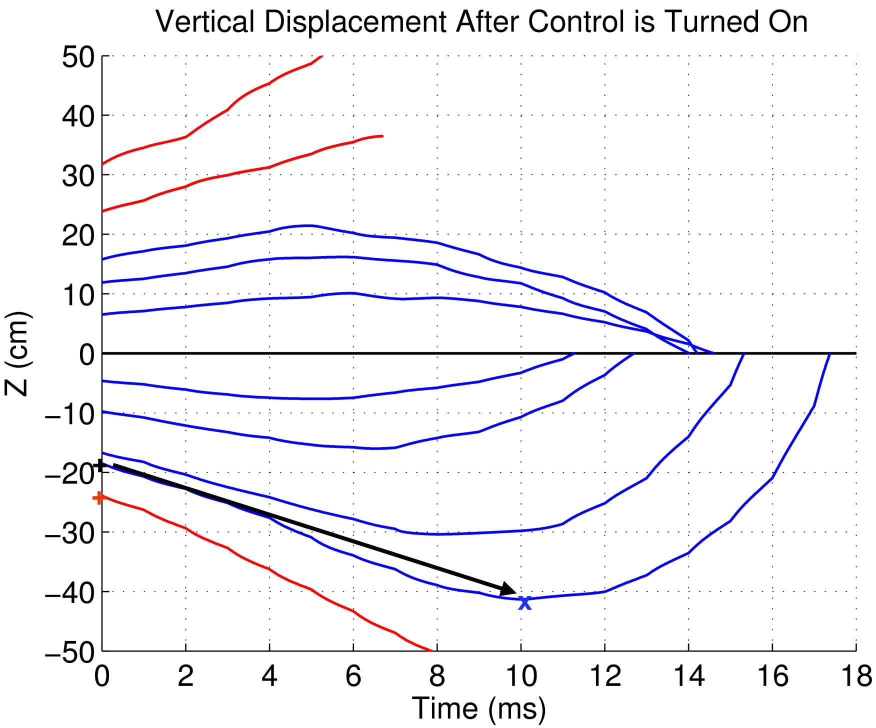
- Work in Progress

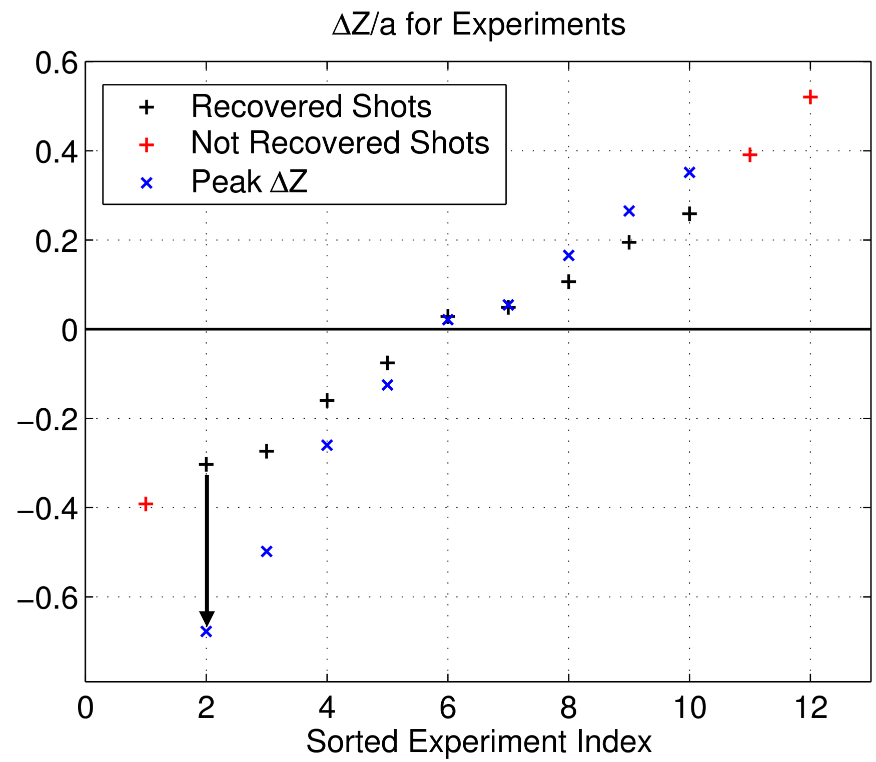
- Determine the applied nonaxisymmetric magnetic field from Dr. Jong-kyu Park's Biot-Savart calculations code

- Employing Dr. Steve Sabbagh's NTV experiments ran on NSTX

- Analyzing TRANSP outputs for various shots to find a simplified torque model for the neo-classical effect of the 3D coils.

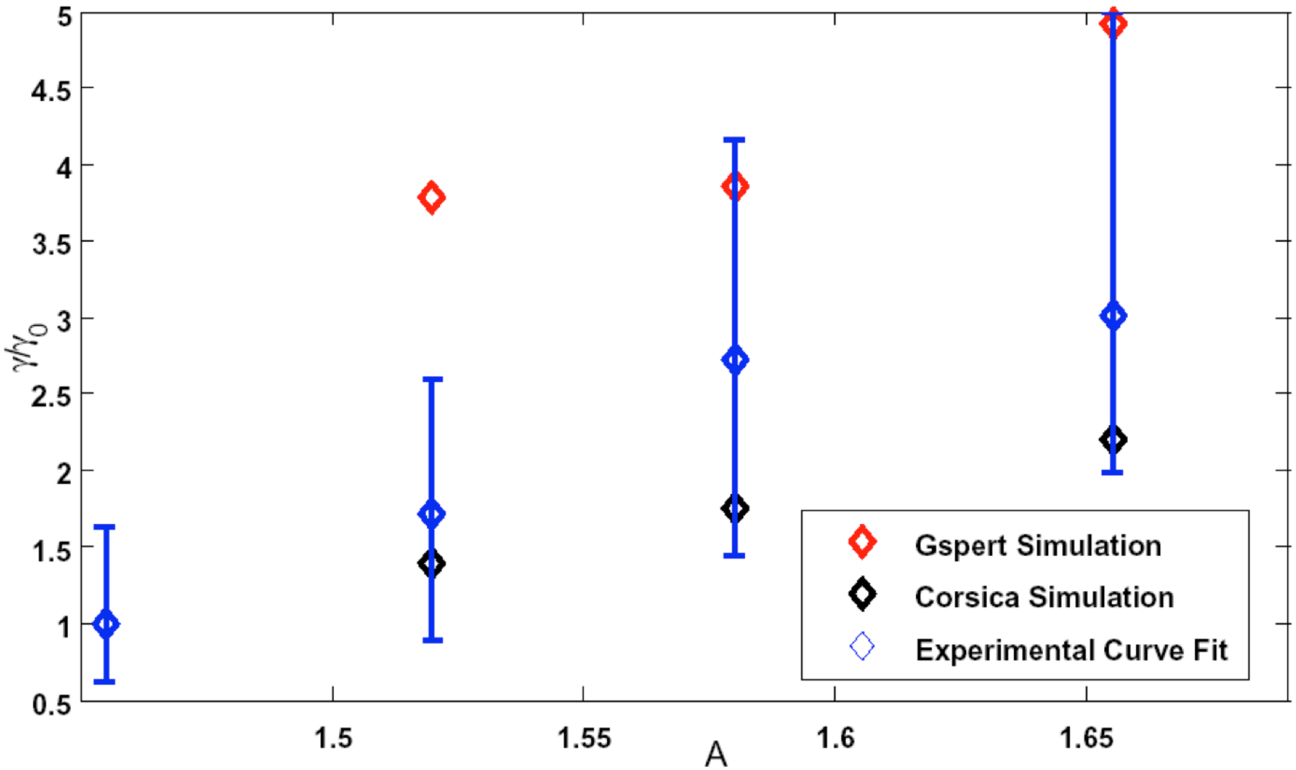
ΔZ_{max} XP





- Red lines show the shots were the vertical displacement was uncontrollable while the blue lines the controllable ones.
- NSTX is (mostly) up/down symmetric (mirror symmetry).
- ΔZ_{max} ~ **[18 - 24]** cm and $\Delta Z_{max}/a$ ~ **[%30 - %39]**.

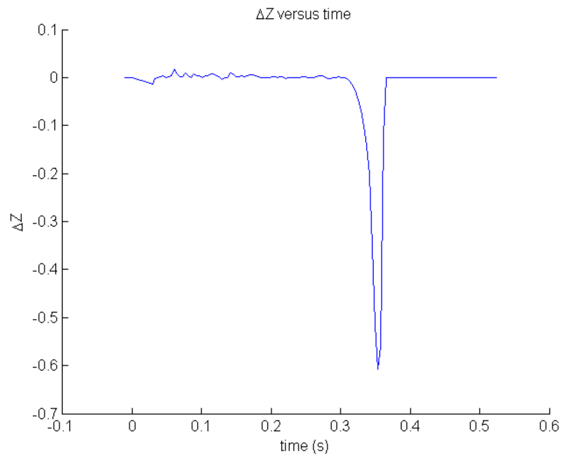
Comparison of Simulation and Experimental Results

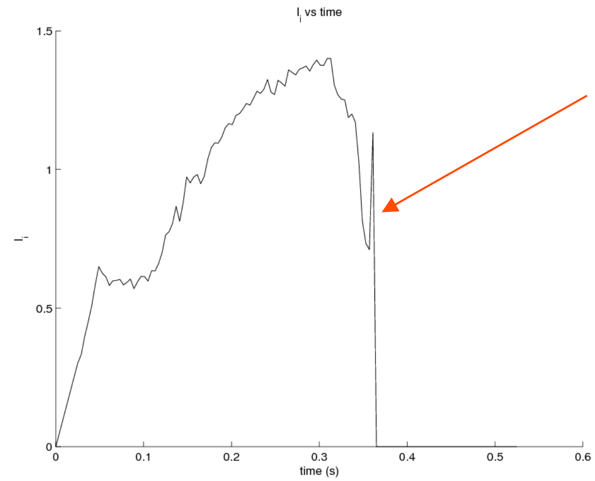


Change in gamma versus A for Corsica and gspert simulations, and experimental data (#141639-141642)

- We compared numerical simulations to these experimental data. In order to study the n=0 stability of the system, we used gspert, a nonrigid plasma response model based on the linearized Grad-Shafranov equation, and Corsica, a free-boundary equilibrium and transport code.

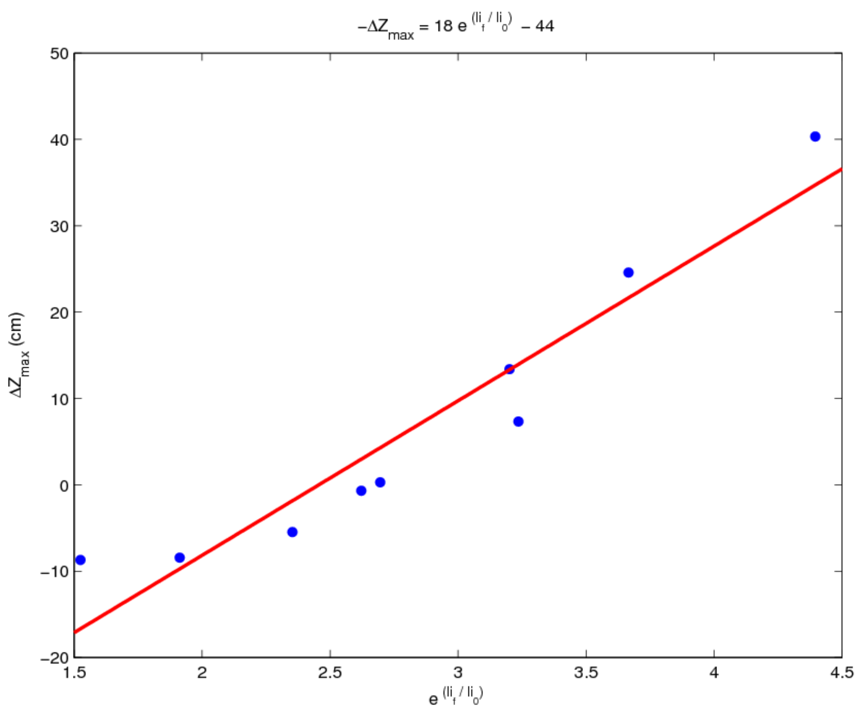
Li and ΔZ evolution during VDE





Plasma Lost

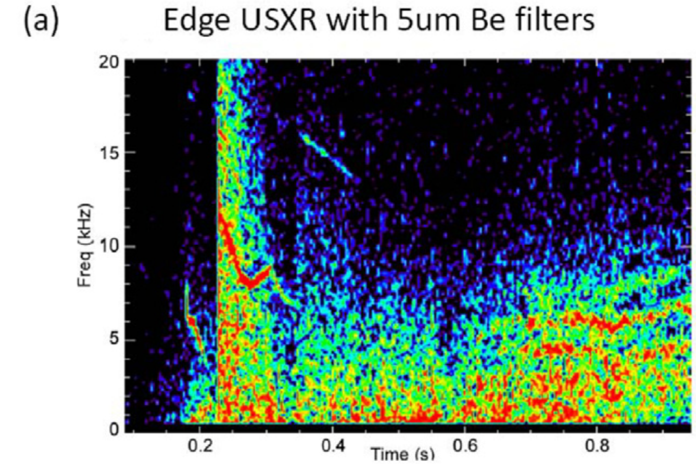
ΔZ and l_i for shot number 127084

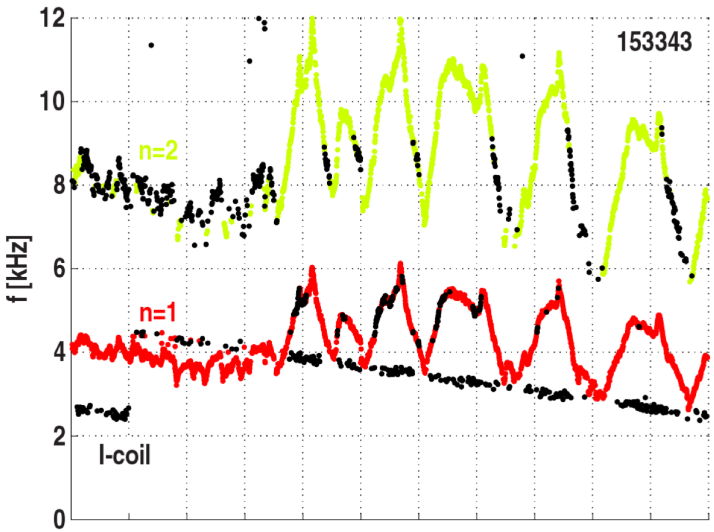


Pedestal Control via 3D coils, gas, LGI and EHO coil

EHO Coil Assessment: EHO 3D coil interaction

- Asses EHO Coil for NSTX-U
- Reduce the EHO frequency as low as possible (scenario development, magnetic braking). Can we get to 1kHz? There are some 1.5 KHz modes. Can the SPAs at all useful close to 1 kA?
- D3D, Lanctot initial I-coil EHO interaction





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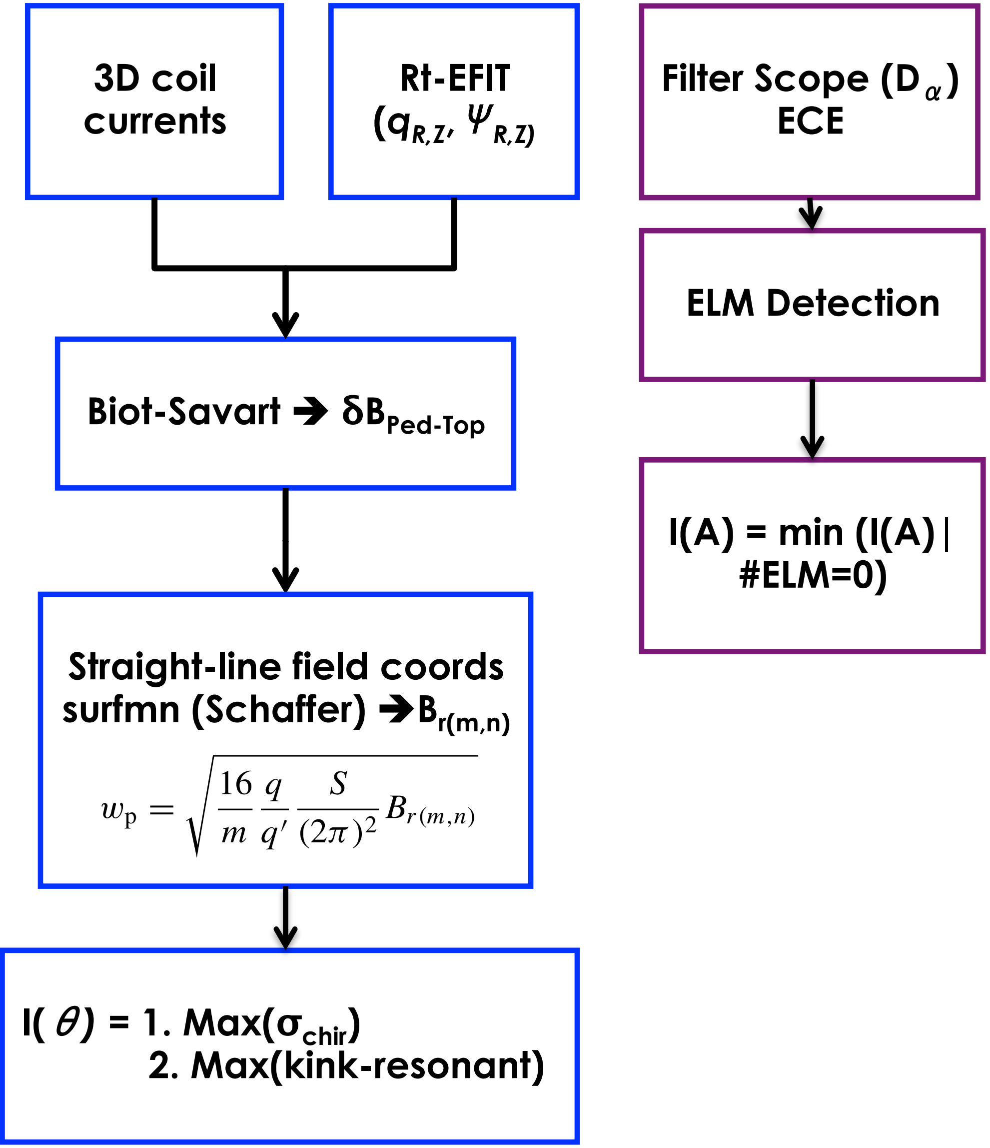
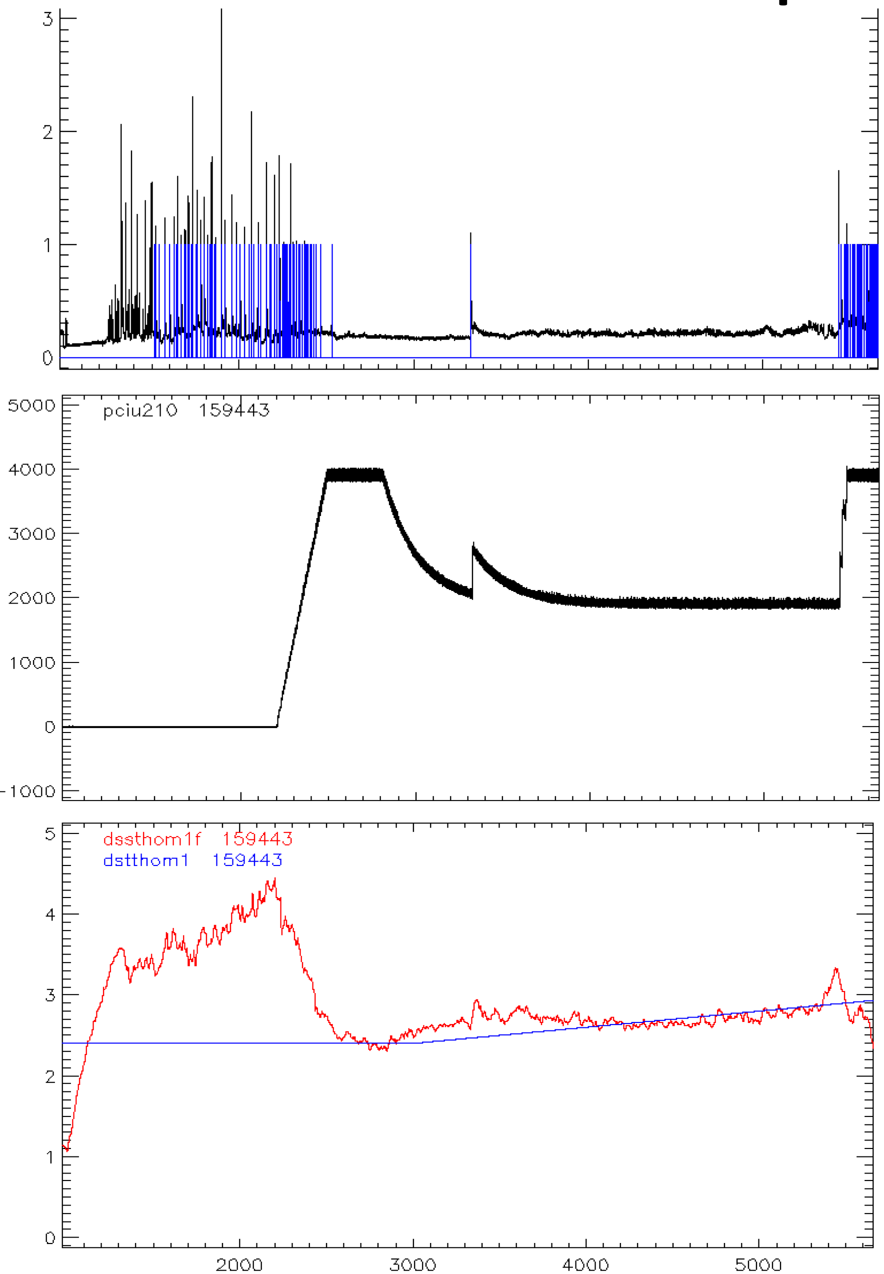
Adaptive ELM Control



- In real-time calculate 3D perturbations due to 3D coils
  - Use surmnf to convert to straight-line field coordinates
  - Find the orthogonal component $B_{r(m,n)}$
  - Find the island size and σ_{chir}
- Control:
  - Choose relative phase of the coils, I(ϑ), maximize kink or σ_{chir}
  - The amplitude of current, I_C(A), minimum current with no ELMs
- Test different ELM mitigation mechanisms

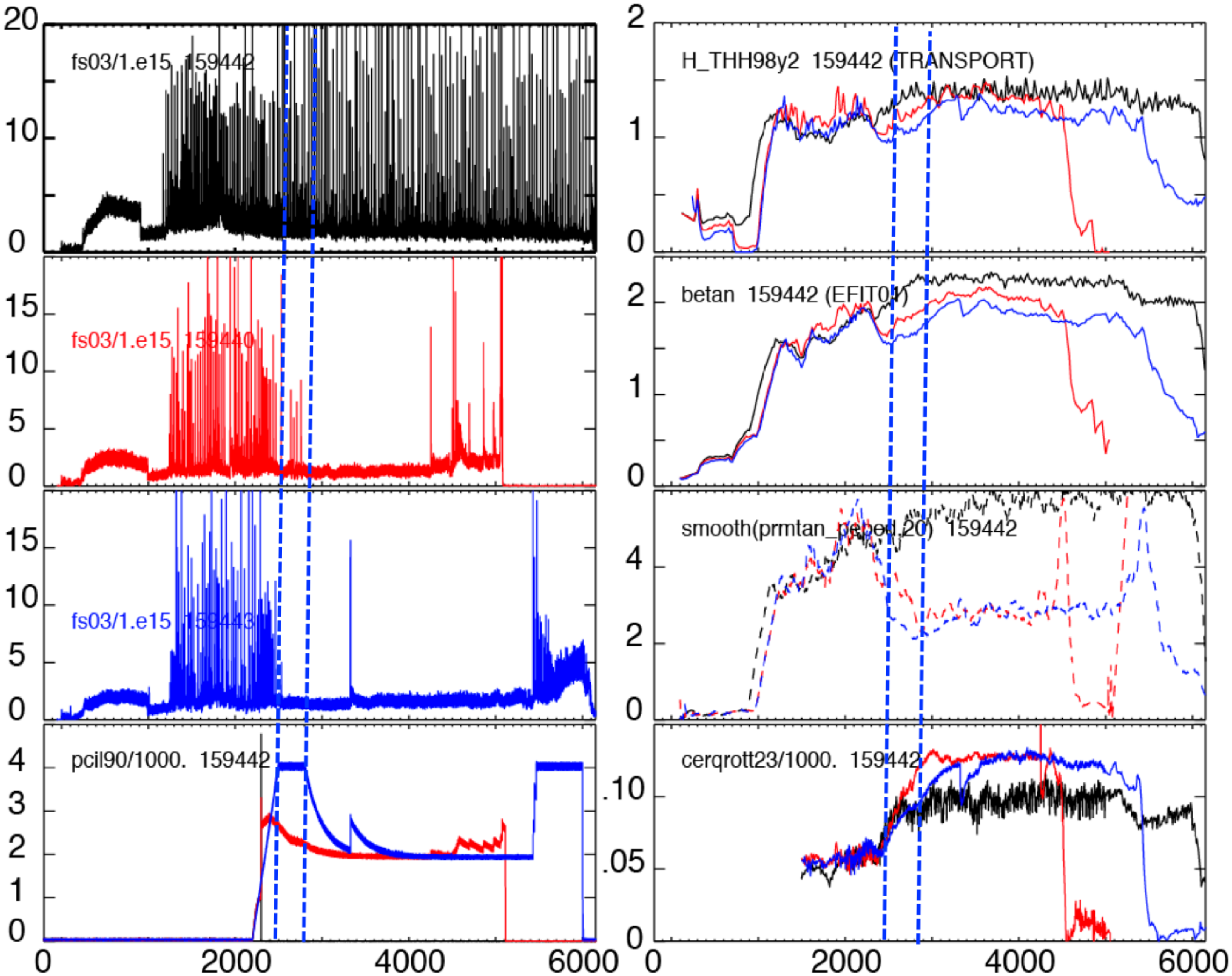
Adaptive ELM Control



- Control the I coil amplitude based on the ELM frequency
- Control the pedestal density
- I coils adjust and keep ELM free with 1.9 kA (can go lower)
- When we reach a high density the ELMs come back again. Prm_tan_ne~3.0e19
- Lock mode kills the plasma
  - Before control increase I_c

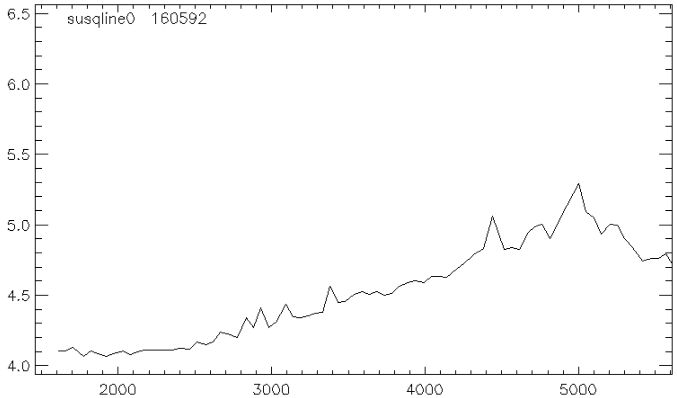
Feedback of RMP Amplitude on ELM Size Shows Promising Increases in H_{98}, β_N, p_e^{ped}

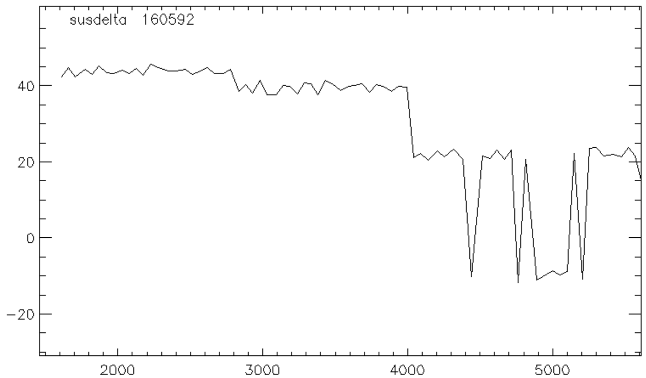
Kolemen

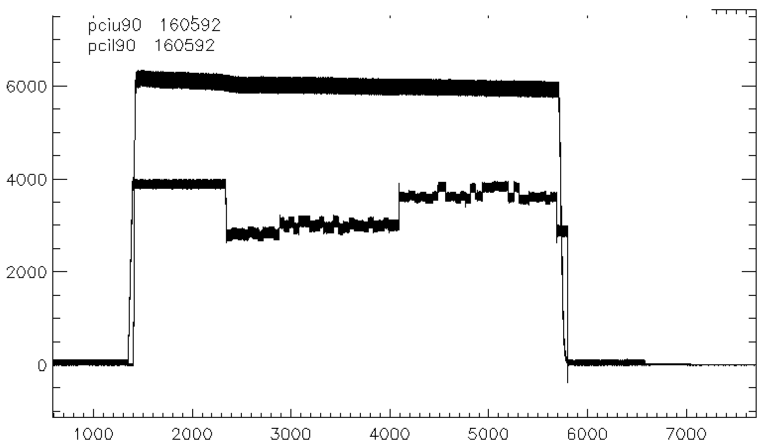


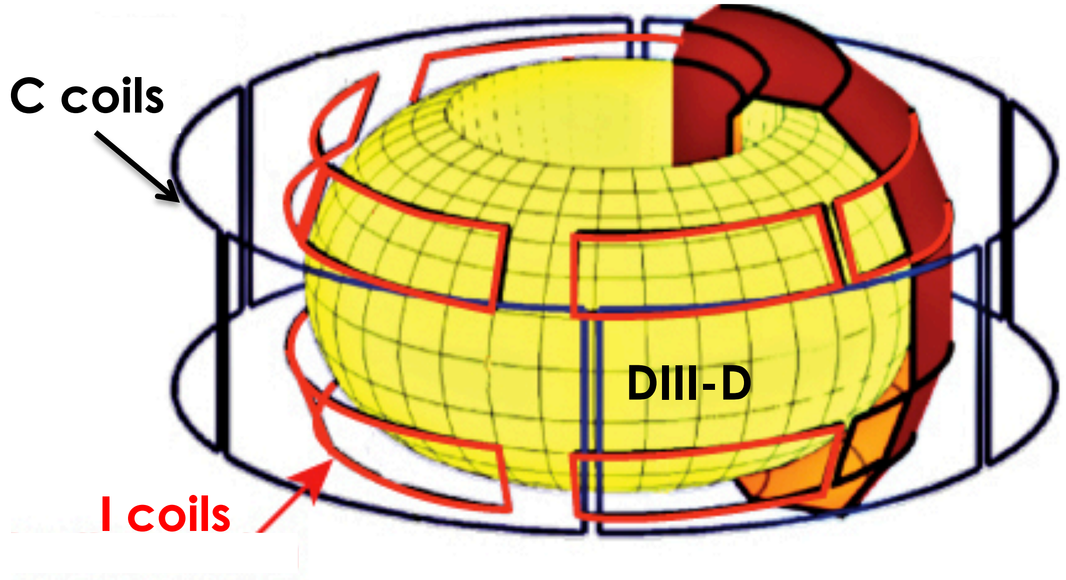
- **ELM suppression obtained with high I-coil current**
- **Feedback algorithm adjusts I-coil current down while maintaining suppression**
- **H_{98}, β_N, and p_e^{ped} increase**
- **Edge rotation increases substantially**

Phase to Maximize the Kink Resonance at D3D





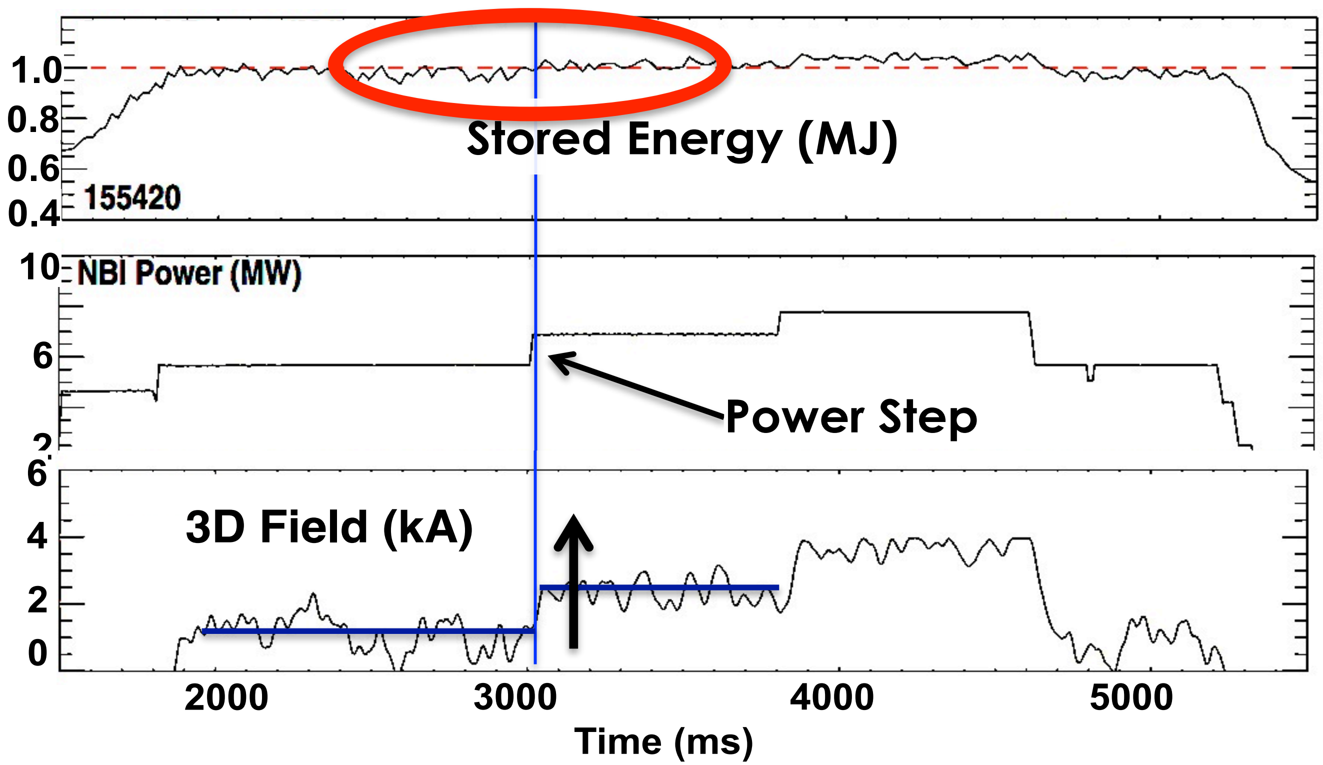




- Control the I coil phase based on the surfmn kink response calculations
- Choose the direction that maximizes kink response for phase
- Control the Icoil upper
- Too high density yesterday. Not possible to test n=2 ELM suppression
- Code checked out.

Keep the Pedestal High but below the ELM limit by Pedestal Pressure Control with 3D Coils (RMP)

3D coil control for WMHD/BetaN



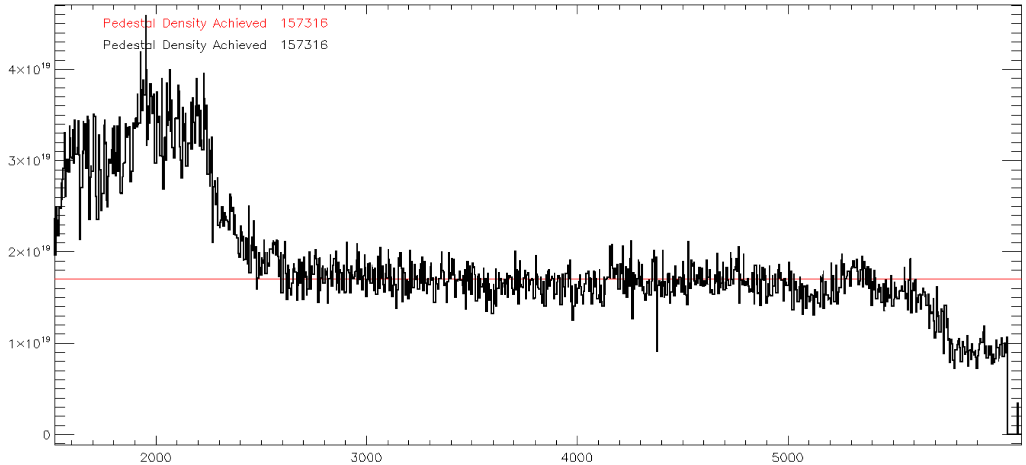
Pedestal density/pressure control with LGI

Develop LGI, PCS connection. Adjust the density with LGI

1. **Try to adjust the ELM frequency in real-time (increase or reduce the ELM frequency to adjust the density)**
2. **Turn on and off the LGI to keep density at a given level**

Pedestal density/pressure control with gas

Pedestal density/pressure control with gas



In the future, we can use Thomson. Initially, modeling of the pressure based on reconstruction.

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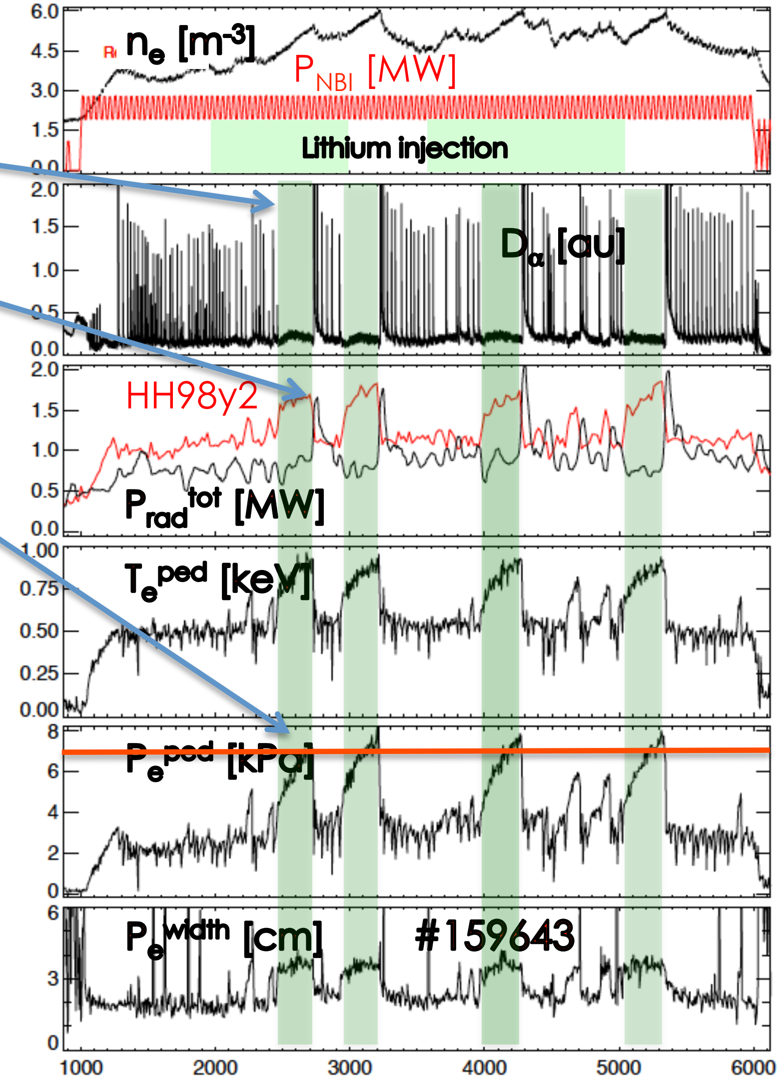
EHO Coil Assessment: EHO 3D coil interaction

- ELM-free bifurcated state can be seen in D_a emission
- $H_{98y2} \leq 1.8$ here, 2.0 in other discharges
- P_e^{ped} nearly tripled during bifurcations



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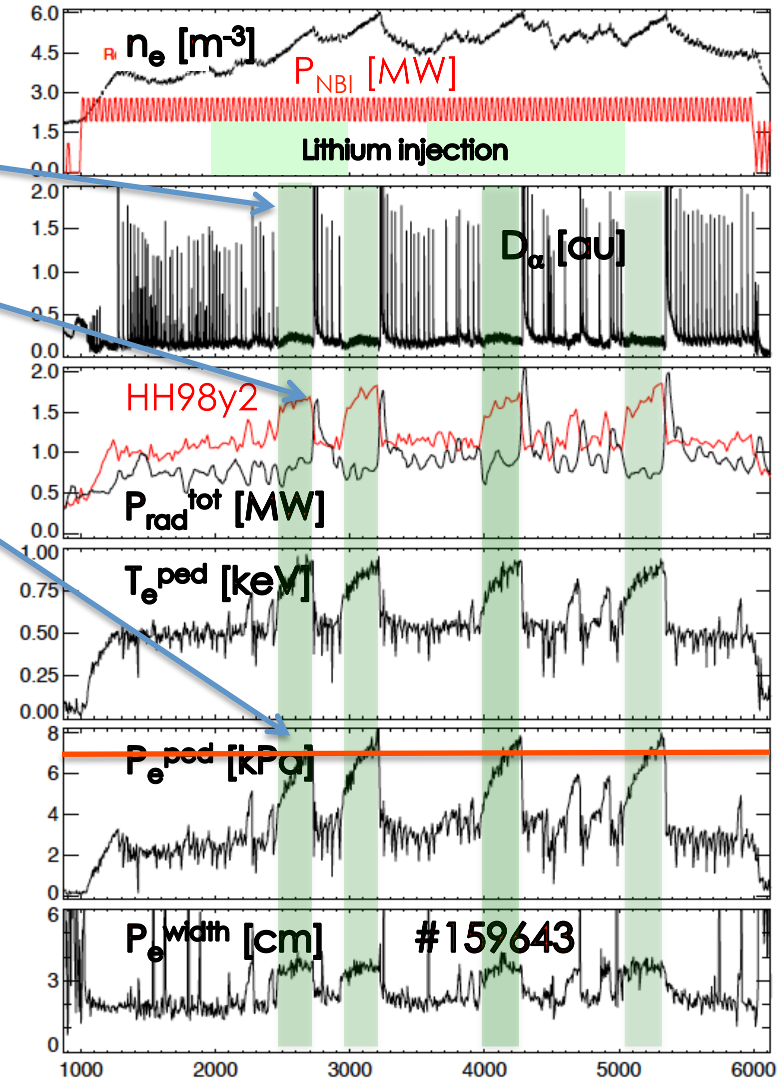
Lithium injection induces a bifurcation to higher pedestal pressure and width in DIII-D

- ELM-free bifurcated state can be seen in D_α emission
- $H_{98y2} \leq 1.8$ here, 2.0 in other discharges
- P_e^{ped} nearly tripled during bifurcations



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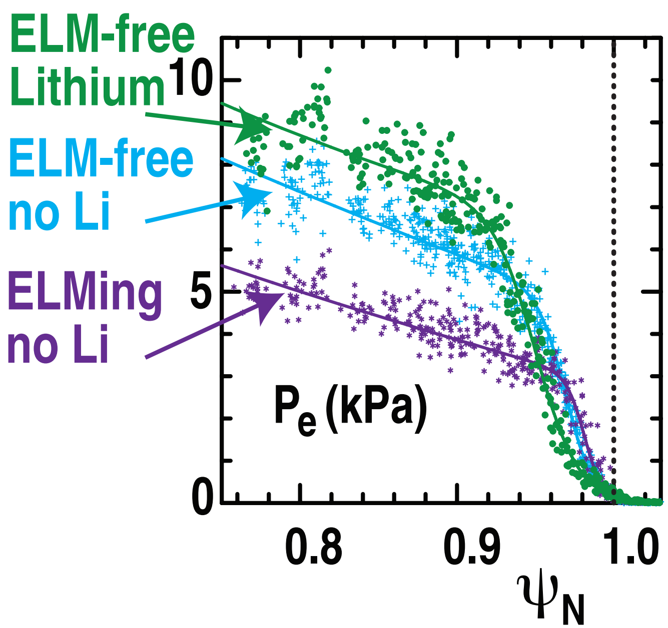
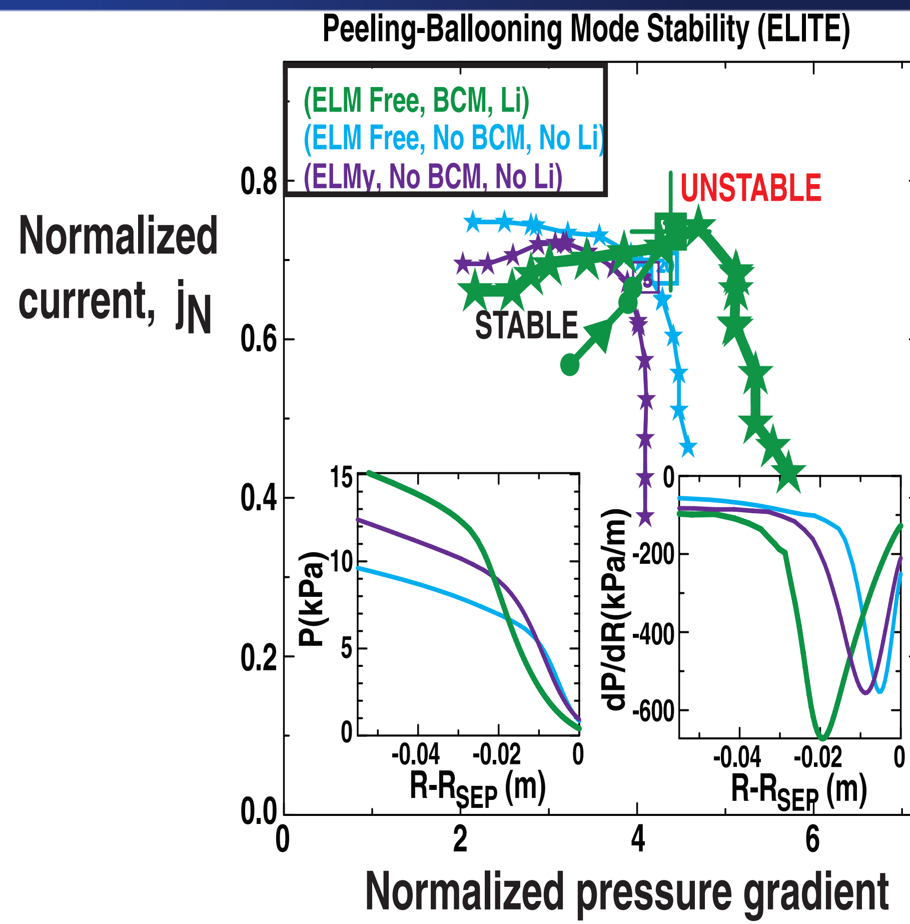
ELM Occurs When Discharge Reaches the Peeling-Ballooning Limit in all Cases





- **ELMing pulses have modest pedestal width and height**
- **ELM-free without Li show higher pedestal but also large carbon influx**
- **Lithium ELM-free have highest pedestal widths, inward shift of gradients, and lowest carbon content**

Gary Jackson, IAEA

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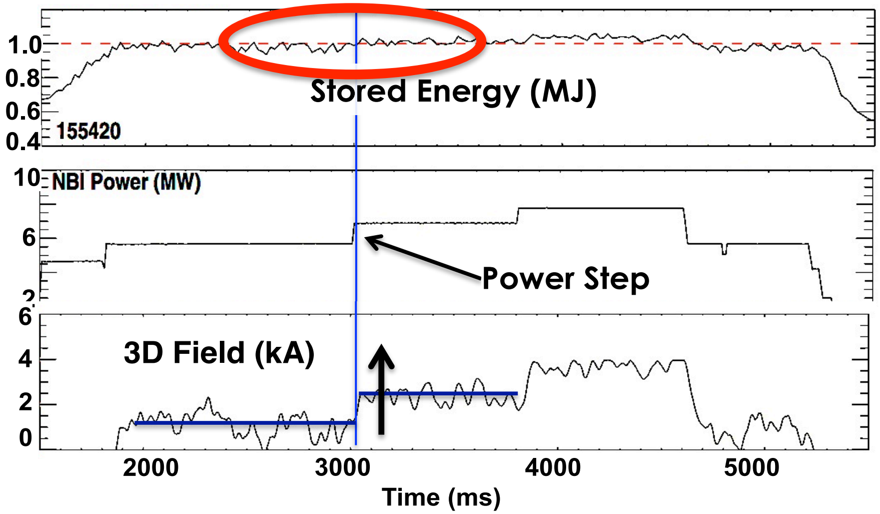
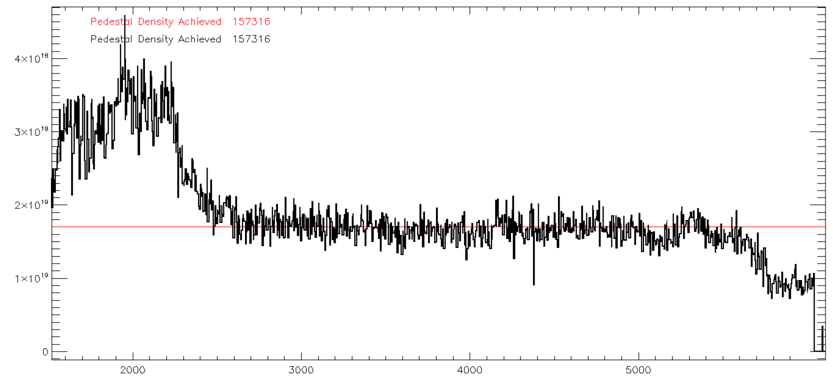
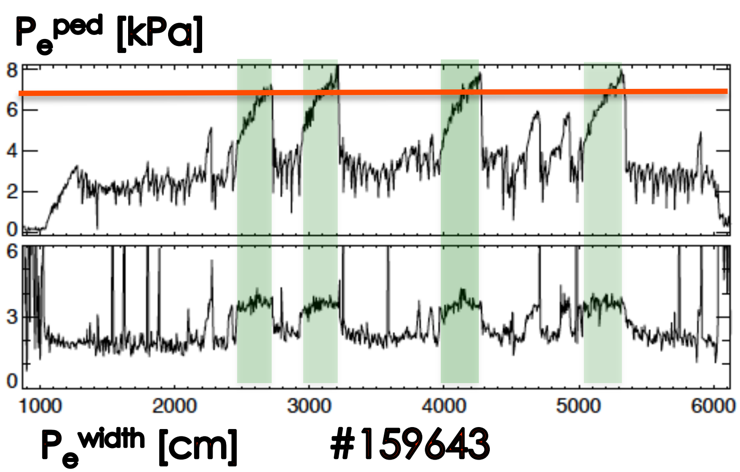
Keep the Pedestal High but below the ELM limit by Pedestal Pressure Control with 3D Coils (RMP)

1) 3D coil control for WMHD



2) Pedestal density/pressure control with g





Proposal:

1. **Detect ELM free high ped regime**
2. **Combine the controls above**
3. **Activate RMP to keep P_e^{ped} below unstable level, e.g. 6-7 kPa**

Outcome: Lower P_e^{ped} but higher than what we can achieve without Li

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RT Connections – E. Kolemen

- MSE – 16 chan 10 ms – Howard (digitally to analog)
- CHERS – Velocity/Rotation – 4 chan – Analog
- Thomson – 42 chan – 16 ms
- Bolometers – 100 radial chan – digital - 250kHz
  - New vertical more chan (200 chan)
  - Need a subset. How many?
- CHERS - 51 channel digitizer / 39 background
  - Ti and zeff
- Connection to Lithium injection (real-time turn on/off and change frequency) – 1 analog output
- Divertor Diagnostics – ~ we need 10 ms - ~10 chan
  - Infrared thermography of PFC surfaces
  - Div Temp: thermoelectric scrape-off layer current

DIII-D

- RT-thomson
- RT-divertor thomson
- RT-ray tracing (multi-cpu 6 cores)
- RT-NTM detection
- RT-NTM control
- RT-adaptive ELM control and EFC (surfmn and beta based)
- RT-radiation control (divertor+edge)
- RT-3D betan control
- RT-3D burn control
- RT-snowflake control
- RT-pedestal density/pressure (rt-fitting tanh/poly)
- RT-pedestal control
- RT-ECE – use for NTM detection