Burning Plasma Relevant Control Development: Advanced Magnetic Divertor Configurations, Divertor Detachment and Burn Control

by

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with B.A. Grierson[2], R. Nazikian[2], W. Solomon[2], S.L. Allen[3], M.A. Makowski[3], V.A. Soukhanovskii[3], B.D. Bray[4], D. Eldon[4], D.A. Humphreys[4], A. Hyatt[4], R. Johnson[4], A.W. Leonard[4], C. Liu[4], C. Paz-Soldan[4], B.G. Penaflor[4], T.W. Petrie[4], A.G. McLean[5], E.A. Unterberg[5], and S. Wolfe[6]

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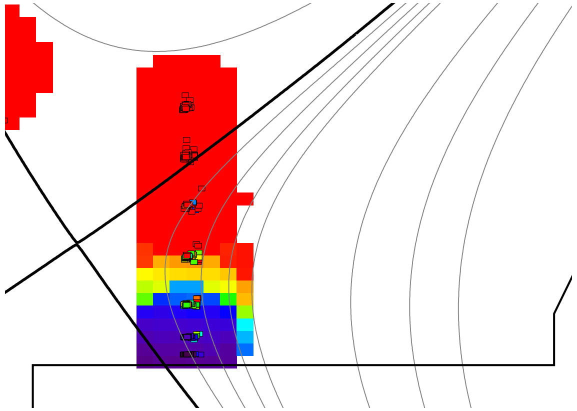
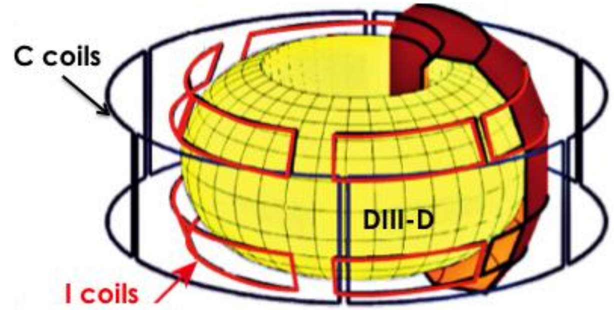


Detachment Control

Snowflake Control



Burn Control

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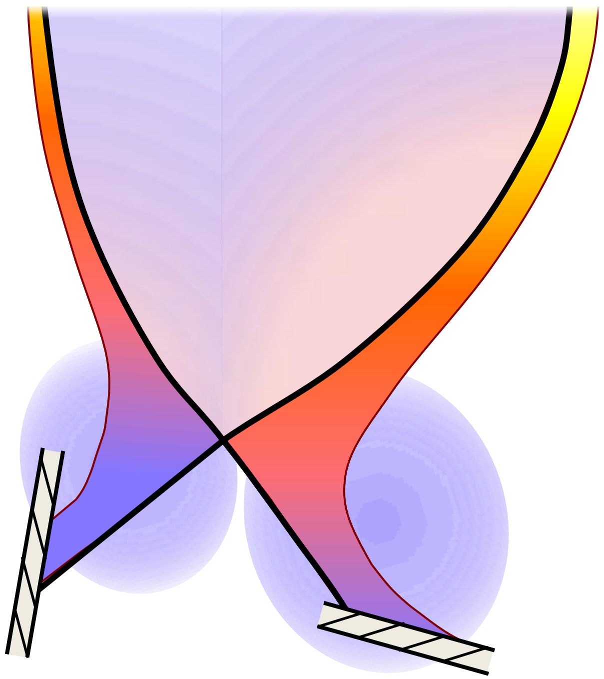
Focus: How to Achieve Acceptable Heat Flux Exhaust Compatible with Attractive Core Plasma

- There are **technological limits on heat flux removal**, and the problem gets more challenging for future devices

- **High fidelity control** gives opportunity to **solve** some of these challenges



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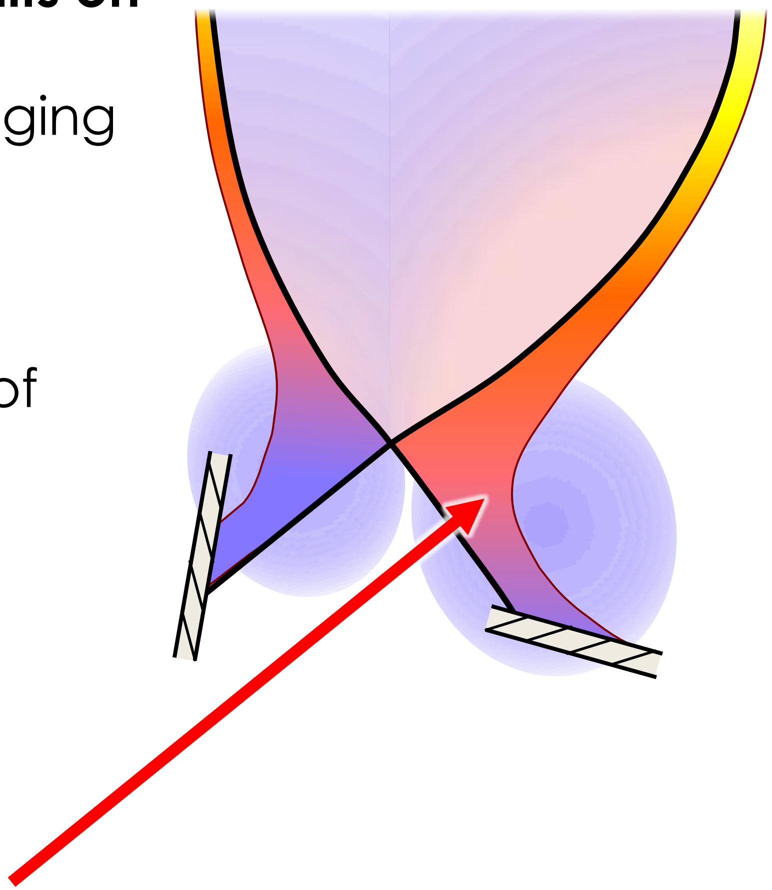

1. Snowflake Divertor:
- Reduce peak heat flux
- Possibly reactor application

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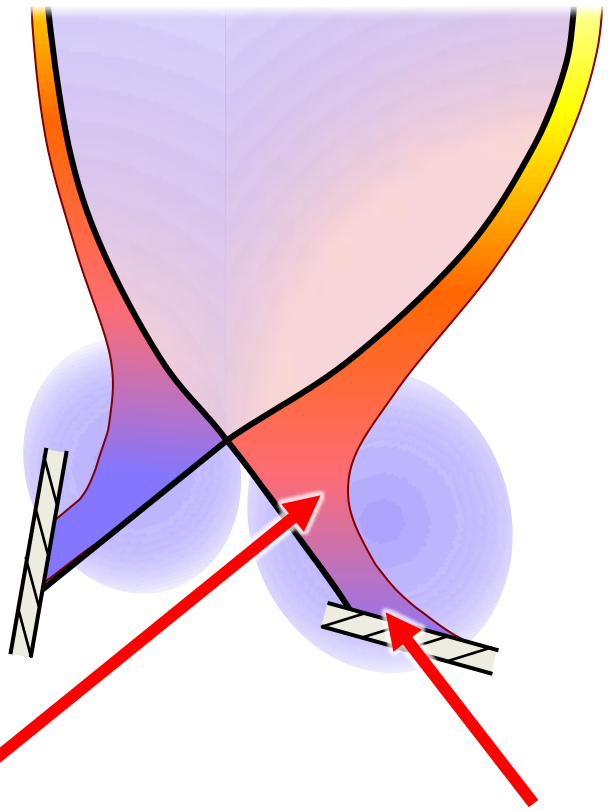

1. Snowflake Divertor:
- Reduce peak heat flux
- Possibly reactor application

2. Partial detachment control
- Reduce target plasma temperature & erosion
- ITER relevant

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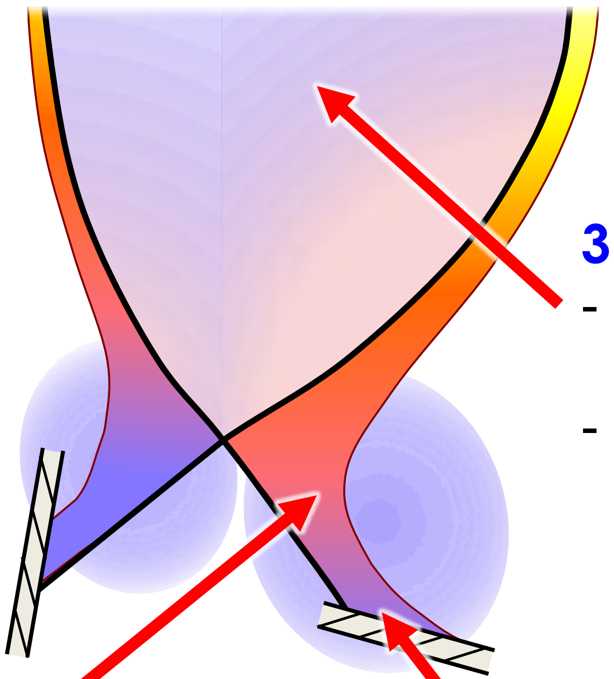


3. Burn control
- Regulate heat source
- ITER/Reactor relevant

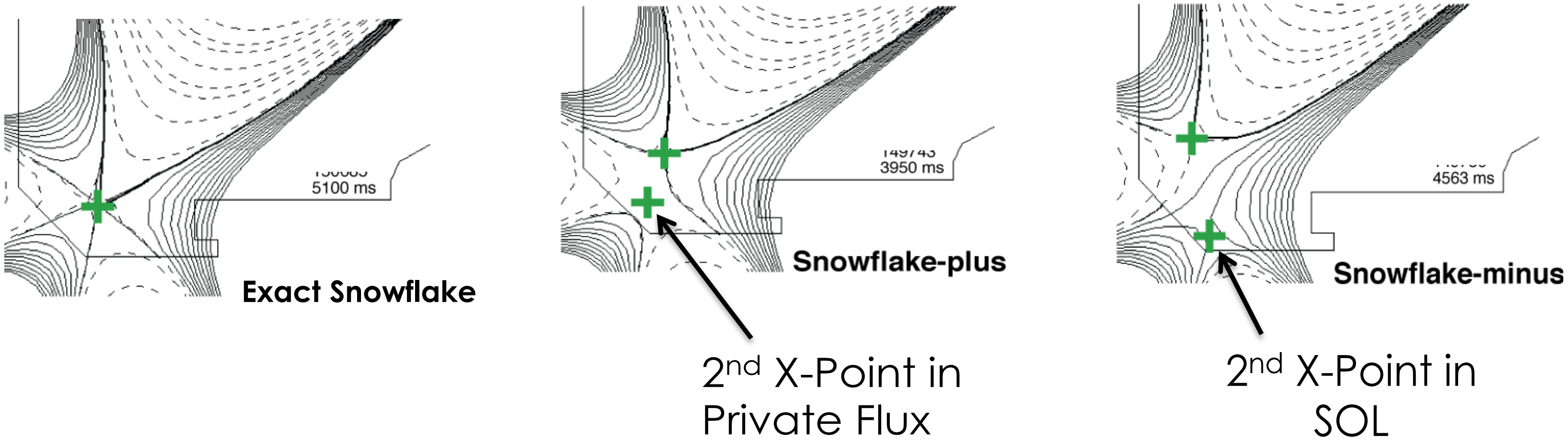
1. Snowflake Divertor:
- Reduce peak heat flux
- Possibly reactor application

2. Partial detachment control
- Reduce target plasma temperature & erosion
- ITER relevant

Heat Flux Reduction via

1. Snowflake Divertor Control
2. Detachment Control
3. Burn Control with 3D Coils

Snowflake Divertor (SFD) Has Advantages Compared to the Standard X-point Divertor



- **Snowflake divertor(SFD): 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}**

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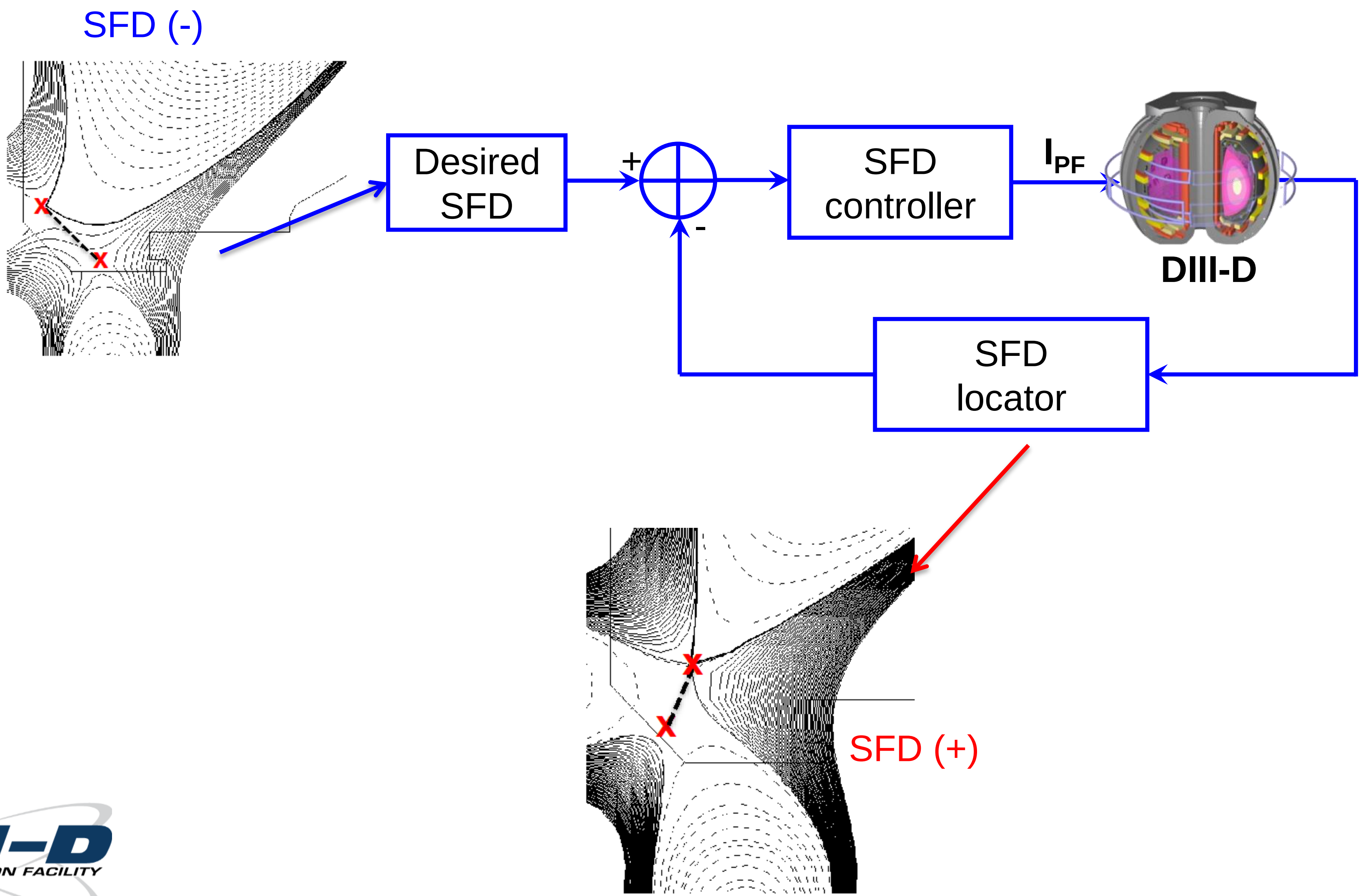
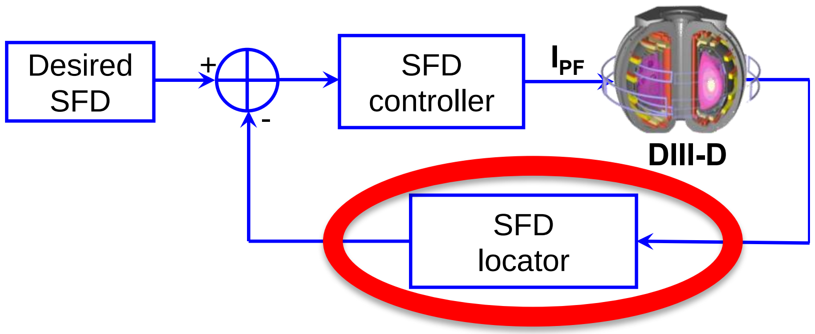
Snowflake Control System



Snowflake Locator: Finding the Two X-points

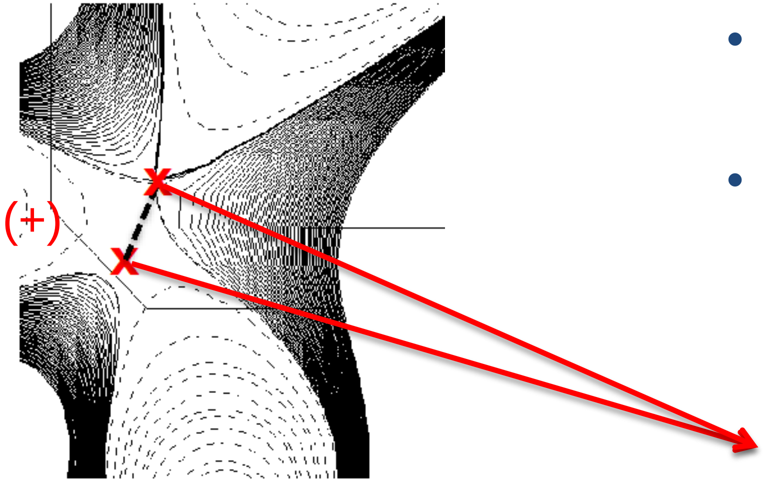


- **Locally expand the Grad-Shafranov equation in toroidal coordinates:**

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

- **Keep the 3rd order terms**

$$Y_{exp} = Y(c_{exp}, dr, dz)$$

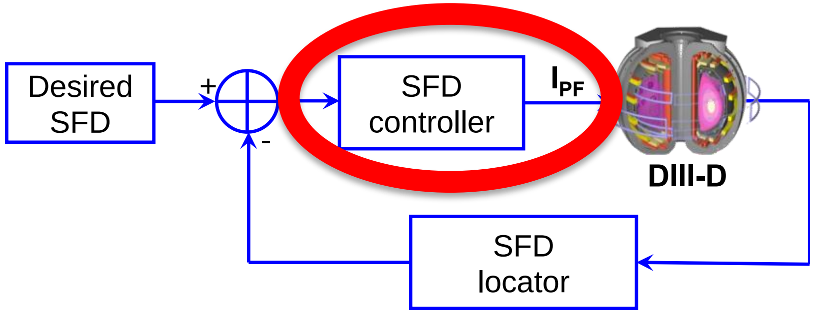


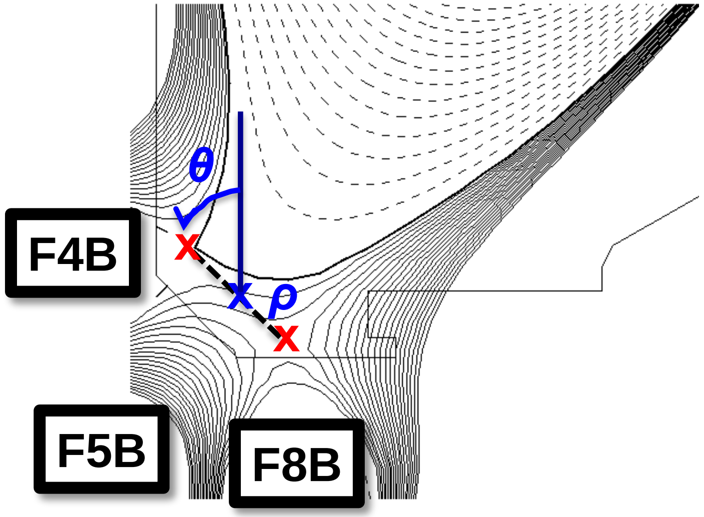
- **Find coefficients, c_{exp}, from sample points**
- **Find the null points (X-points) <250us**

$$B_r = -\frac{1}{r}\frac{\P Y_{exp}}{\P dz} = 0 = B_z = \frac{1}{r}\frac{\P Y_{exp}}{\P dx} = 0$$

$$\rightarrow \{dr_{X_1}(c_{exp}), dz_{X_1}(c_{exp}), dr_{X_2}(c_{exp}), dz_{X_2}(c_{exp})\}$$

Snowflake Control: Controlling the PF Coil Currents





Location of the X-points and Centroid

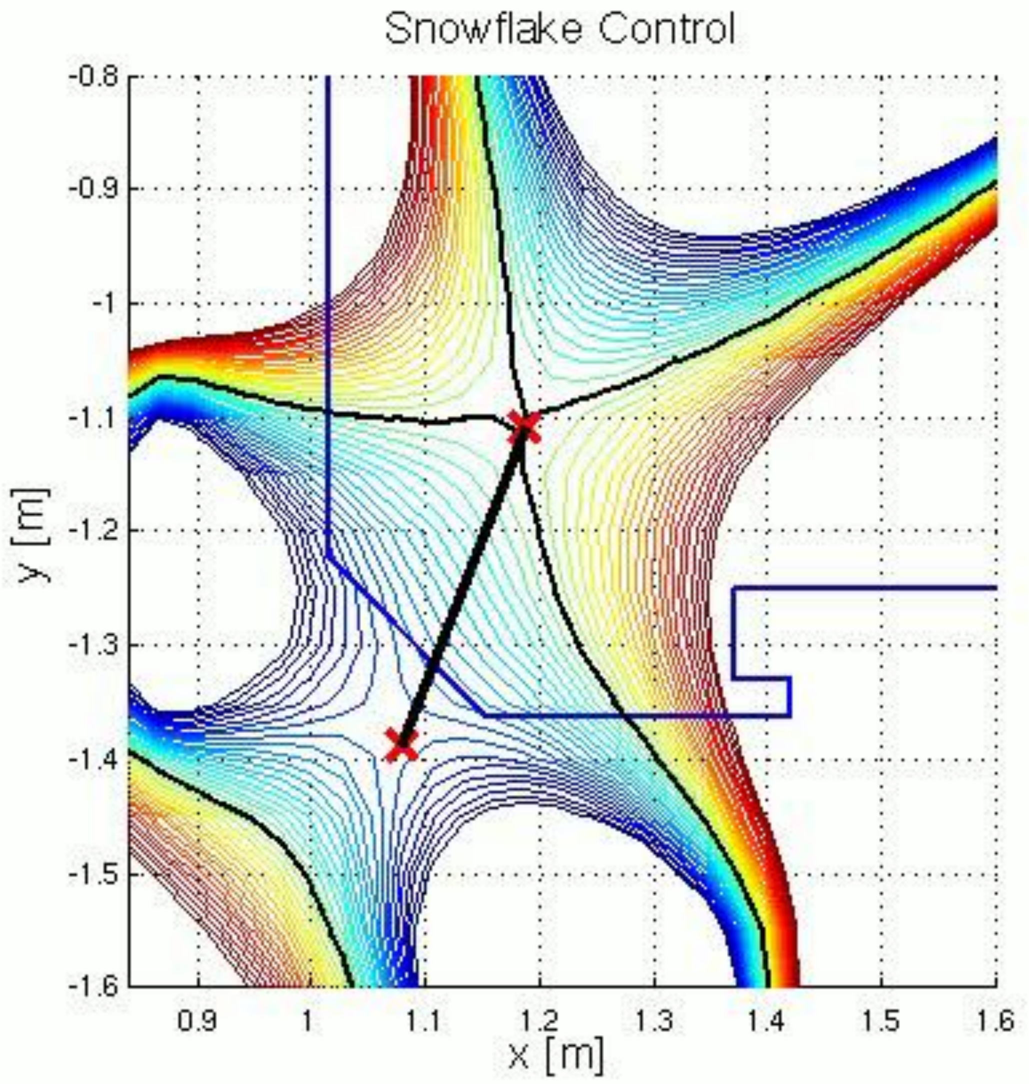
- **Snowflake parameters: θ, ρ, r_c, z_c**
- **Calculate A matrix which shows how PF coils affect X-points (2 ms)**

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

- **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)



Simulation

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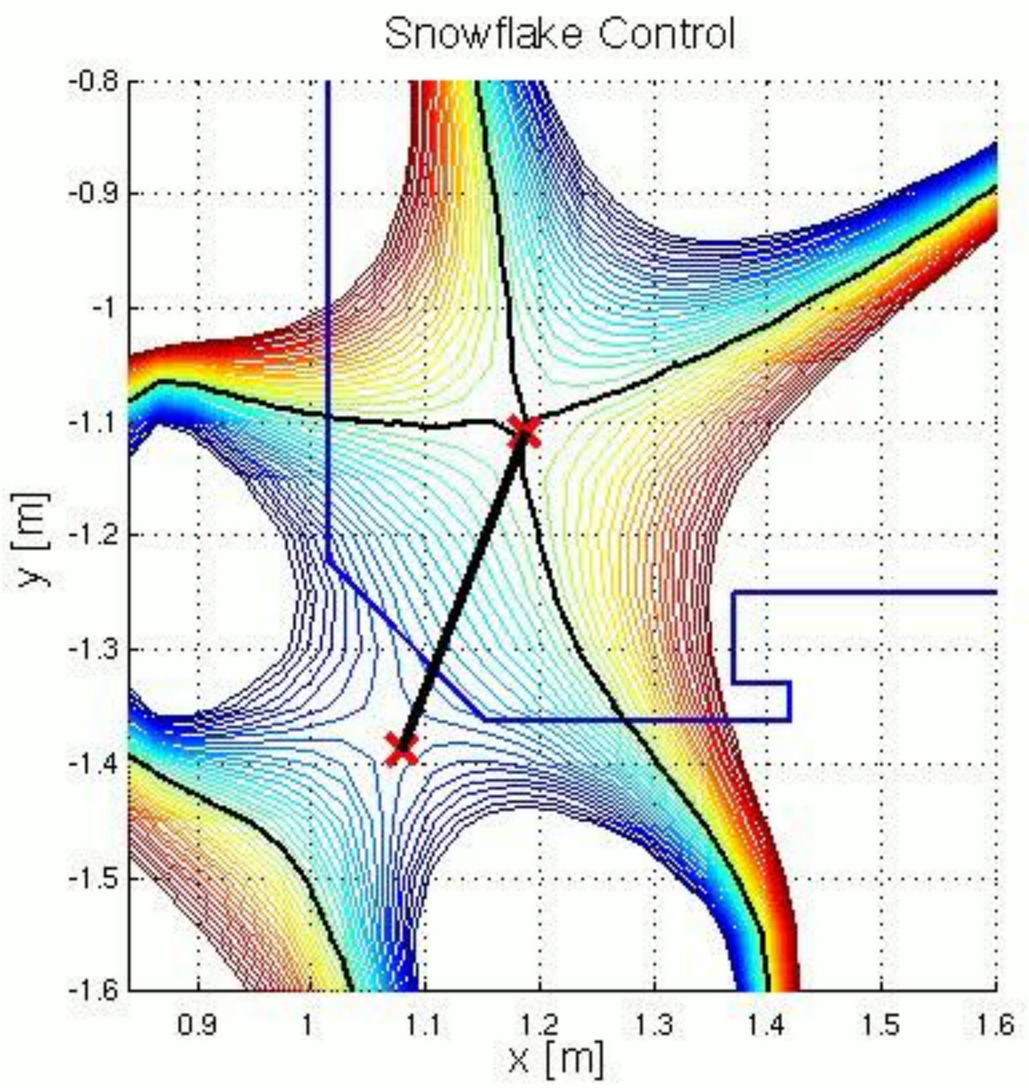
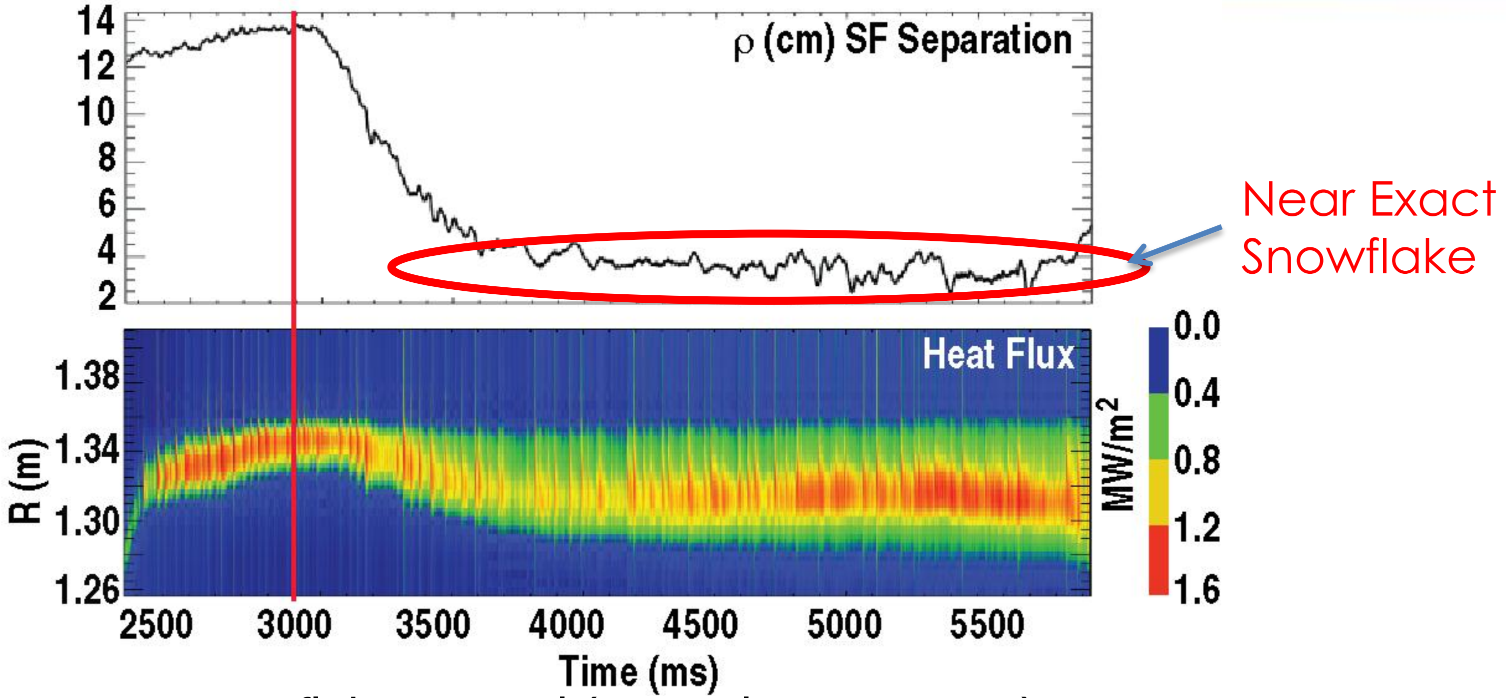


Simulation

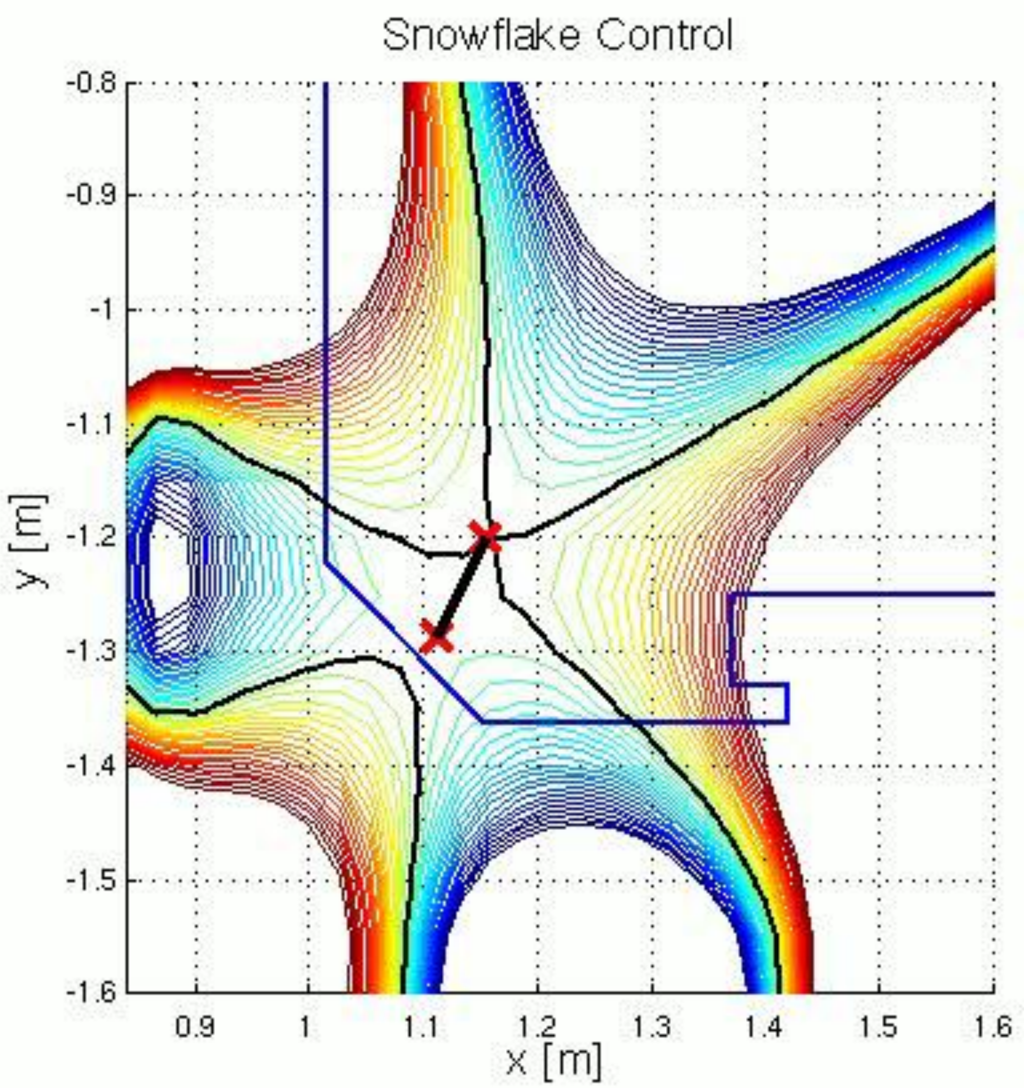
Snowflake Control: Obtaining Snowflake (Exact, + and -)



Snowflake Control (Control Starts at 3 s)

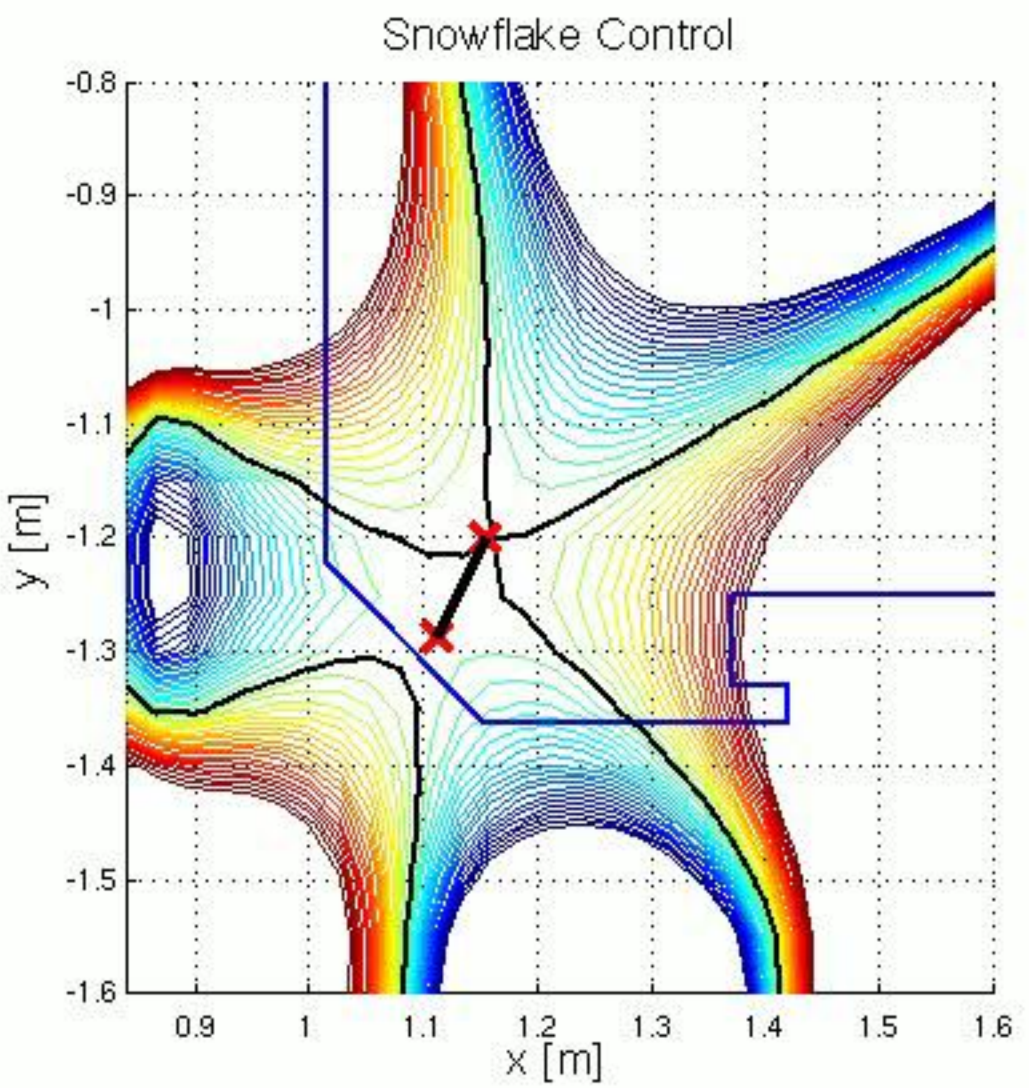
- **Obtained long stable S-F close to exact S-F**
  - No adverse confinement degradation
  - Pedestal profile for S-F has little change compared to regular divertor
  - Observed broadening of heat flux profiles with snowflake

Snowflake Control: Scanning the Angle



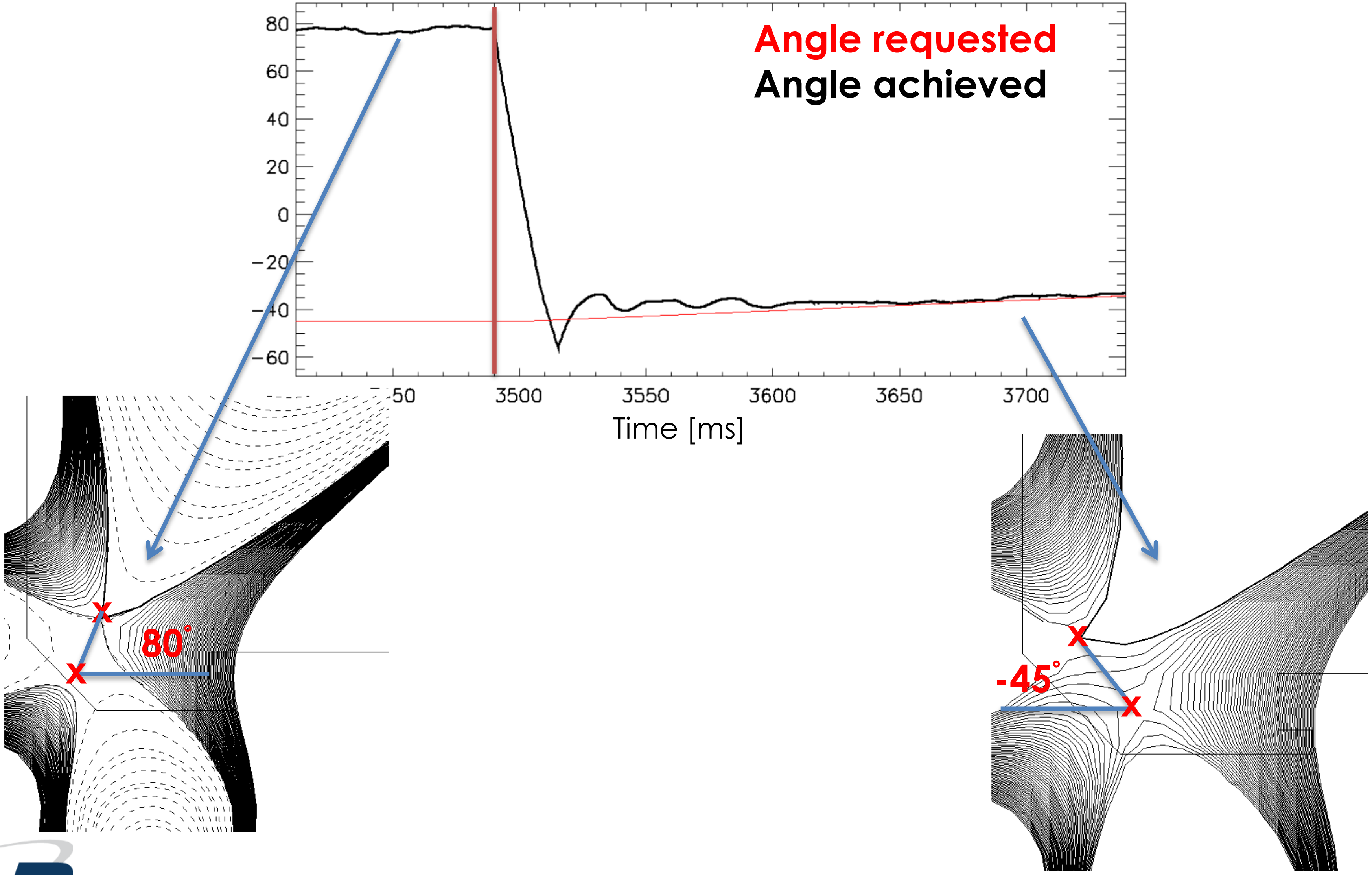
Simulation

Snowflake Control: Scanning the Angle

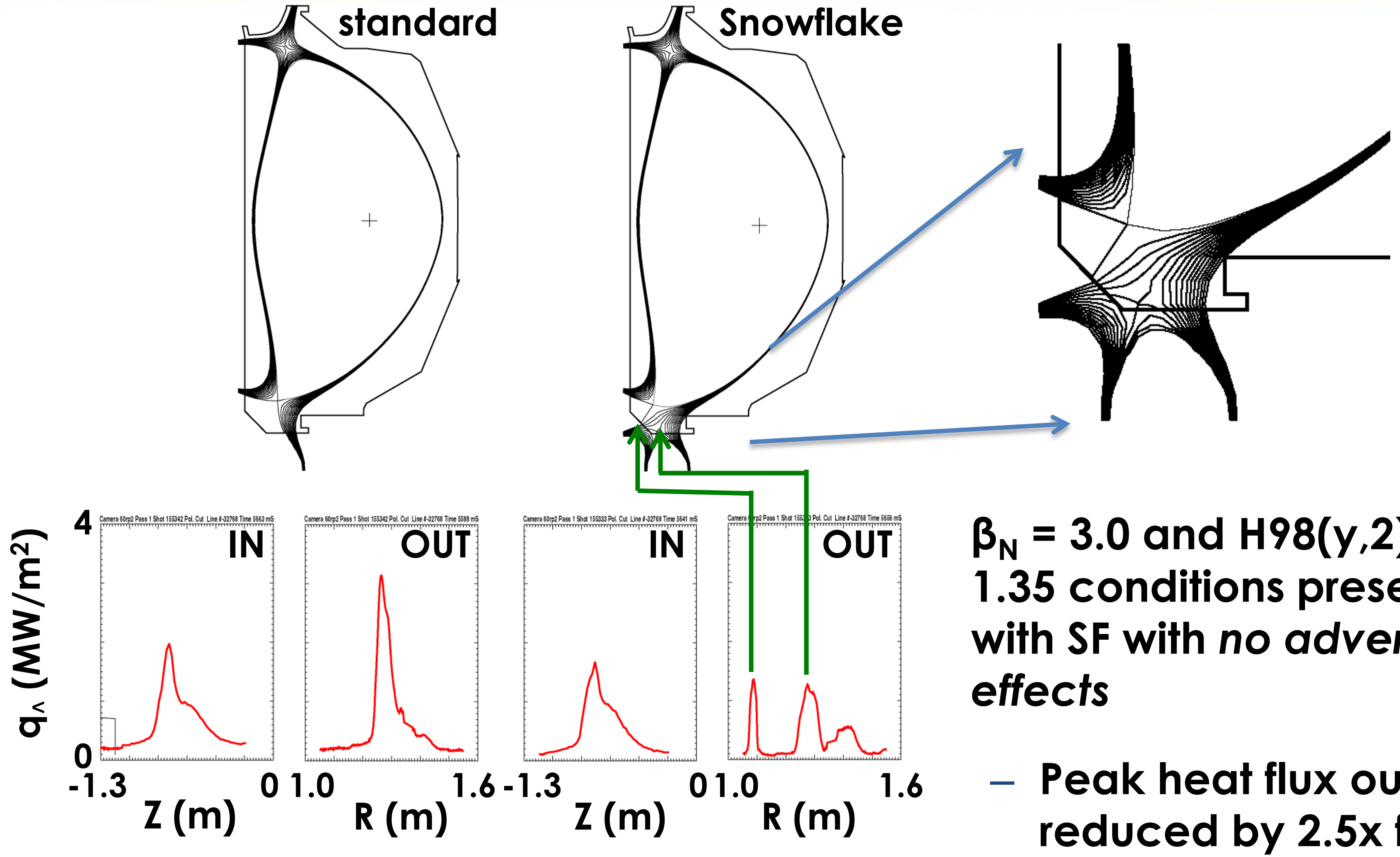


Simulation

Snowflake Control: Angle Control (+80˚ to -45˚)



Snowflake with 2.5x Reduced Heat Flux Compatible with High Performance Plasmas



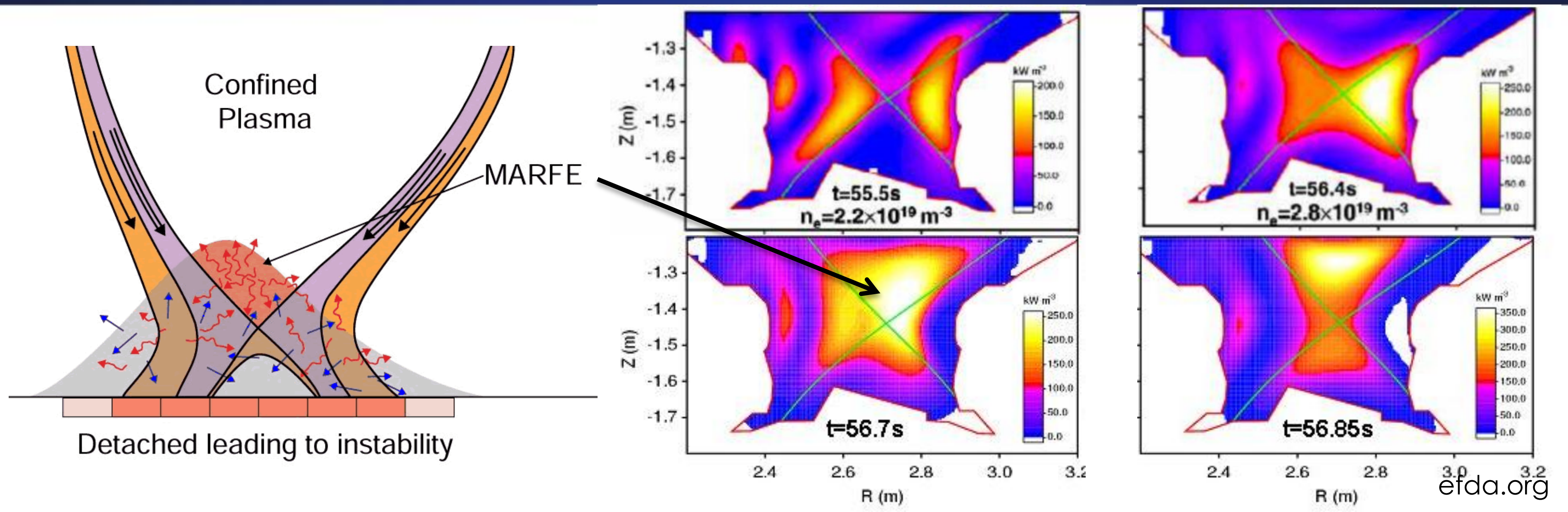
β_N = 3.0 and H98(y,2) ≅ 1.35 conditions preserved with SF with *no adverse effects*

- Peak heat flux outer reduced by 2.5x for the SF AT
- SF: $q^P_{\perp,lin} > q^P_{\perp,out}$

Heat Flux Reduction via

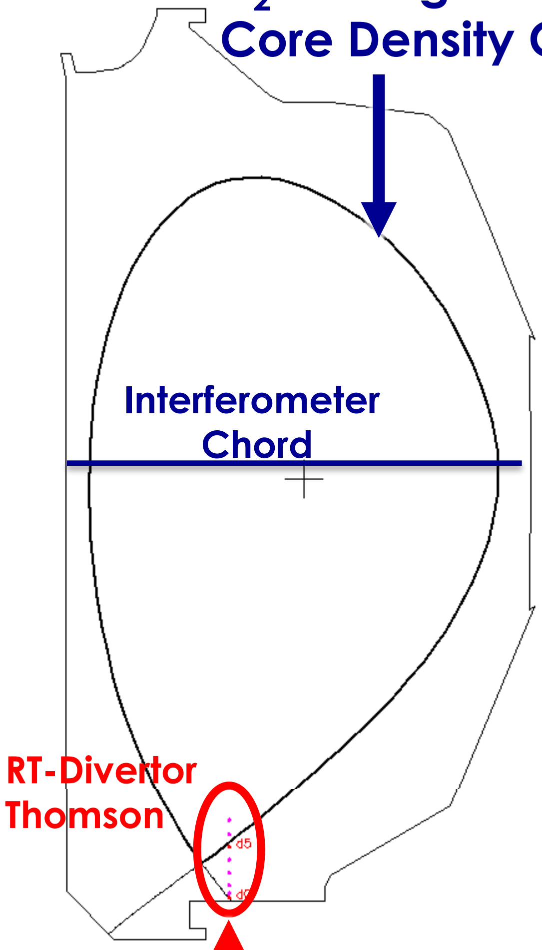
1. Snowflake Divertor Control
2. Detachment Control
3. Burn Control with 3D Coils

Partial Detachment Control Needed for ITER

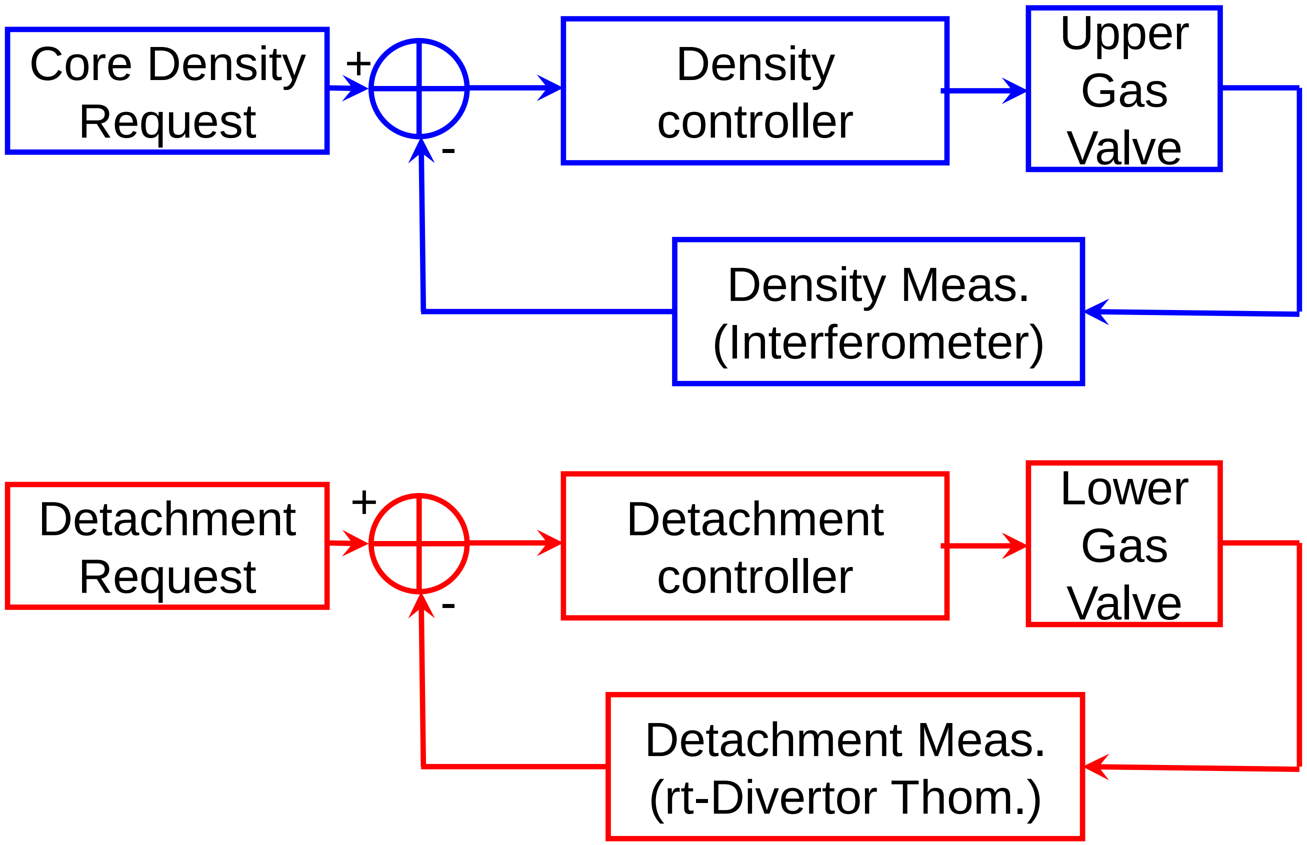


- **Not enough detachment ➔ T_e and heat flux too high ➔ Erosion**
- **Too much detachment ➔ Instabilities (MARFE) and core degradation**
- **MARFE Instability:**
  - Full detachment ➔ large cold areas
  - Neutrals/Impurities influx ➔ *high radiation* from the core
  - Thermal instability of the whole plasma

Effective Detachment Control at Constant Core Density Requires Two Feedback Channels



- **Goal:** Keep the ***core density*** *and* ***detachment level constant***
- **Feedback Control Method:**



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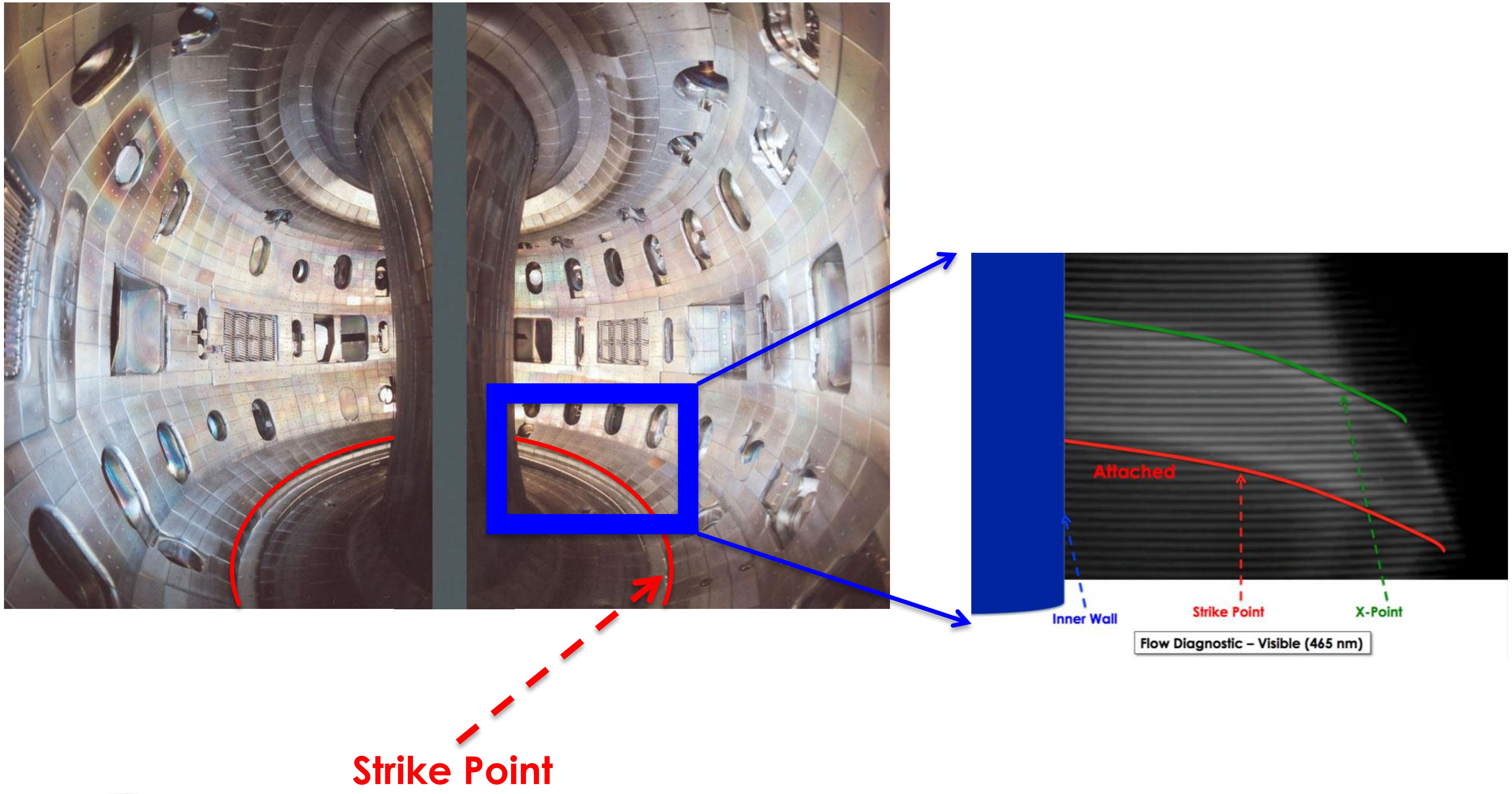
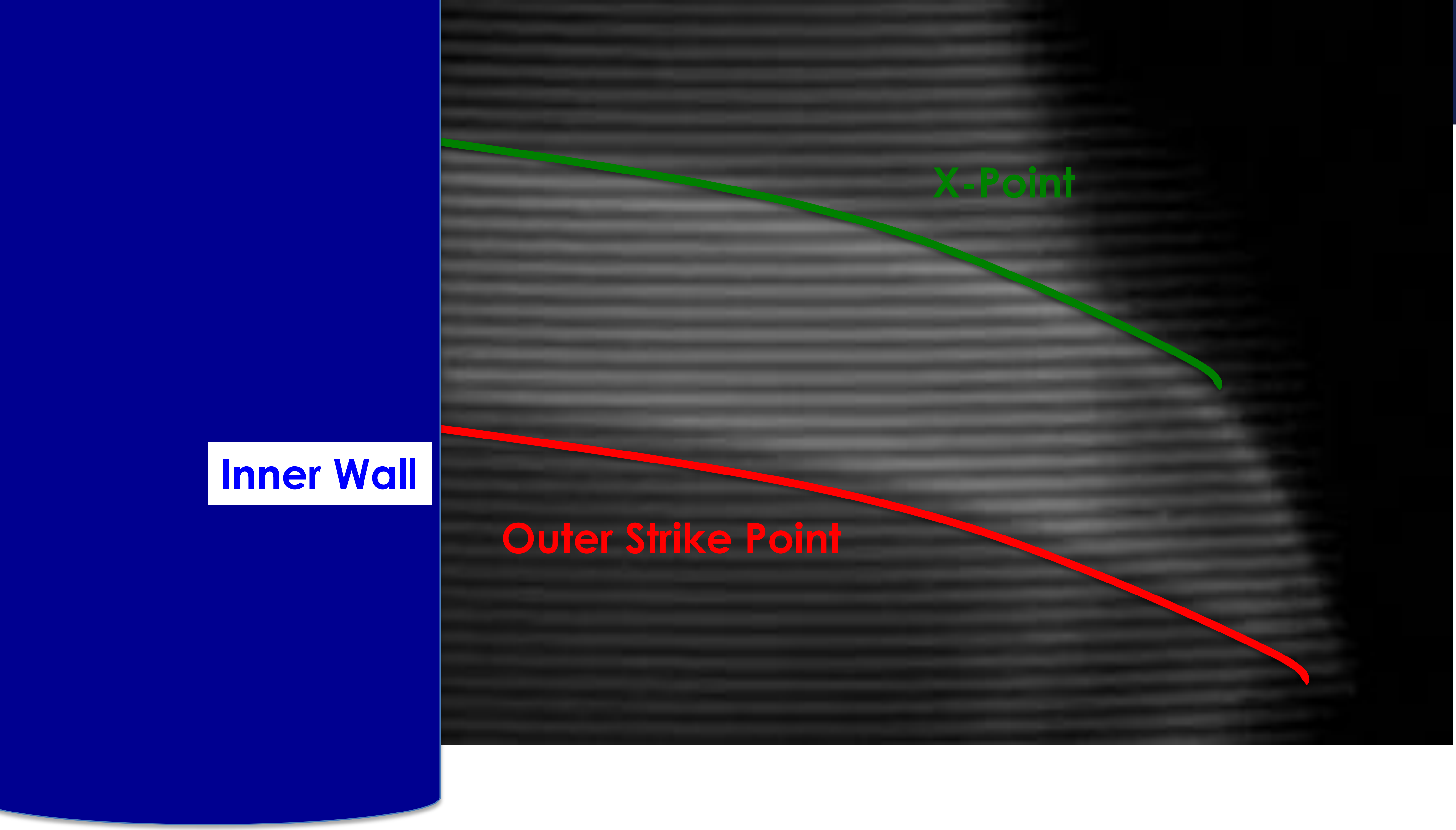
Detachment Control in Action





CIII Emission – Visible (465 nm)

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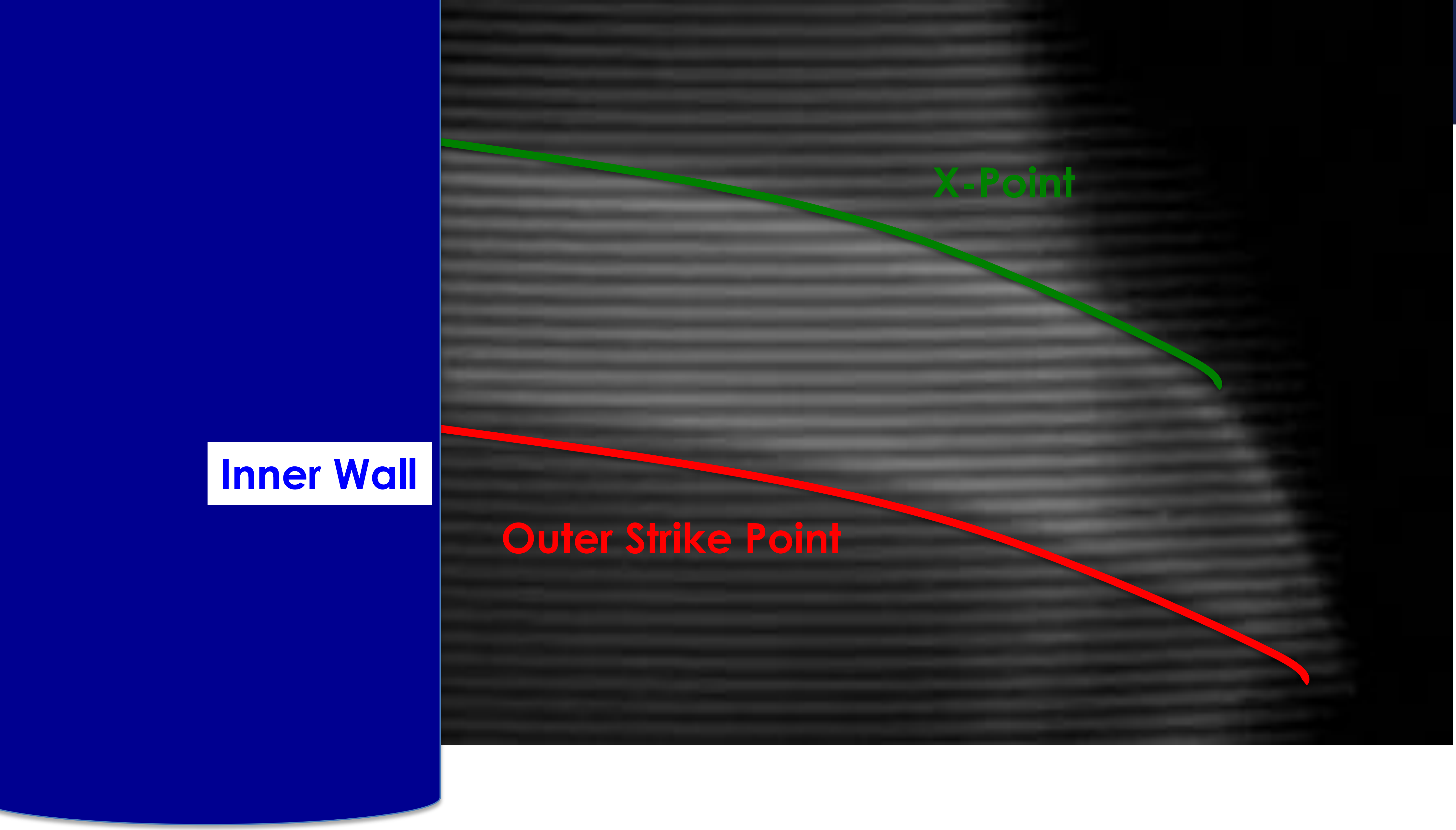
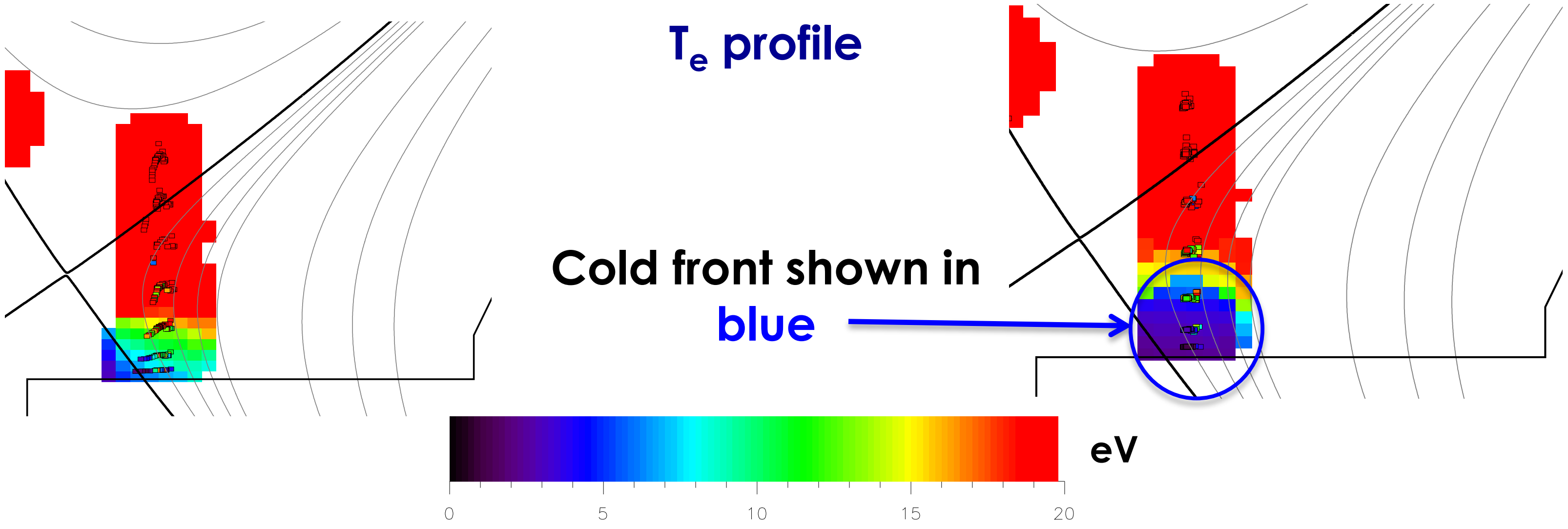


CIII Emission – Visible (465 nm)

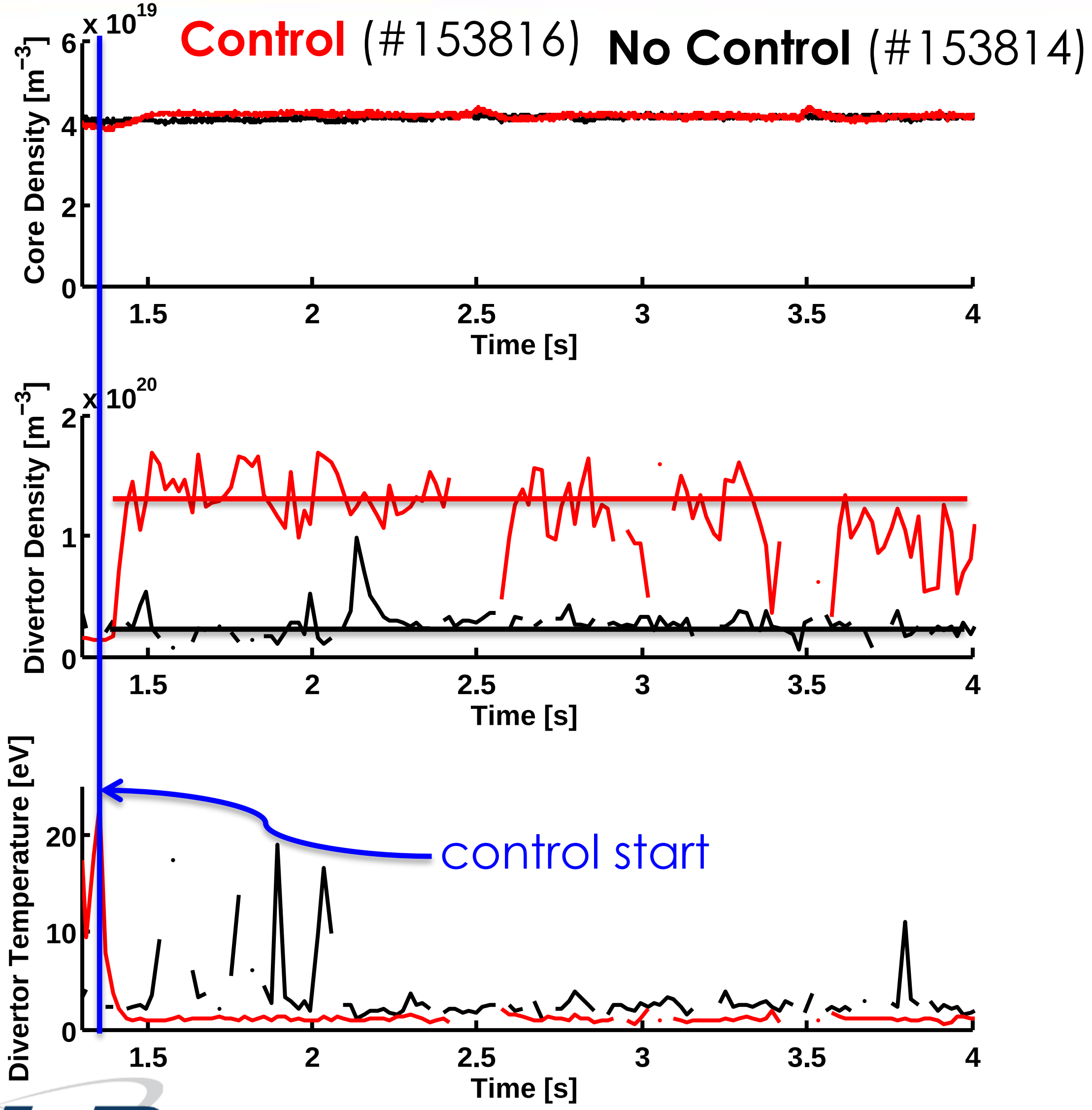
Partial Detachment Control: Forms a Cold Front in L-mode

No Control (#153814) | **Control** (#153816)



- **Control achieves partial detachment**
- **Keep the cold front midway between the X-point and strike point**

Control Stabilized Divertor Temperature (Detachment) but Keeps Core Density Constant



- Divertor Density Increases
- But Core Density constant
- Divertor Temperature reduces to 1 eV

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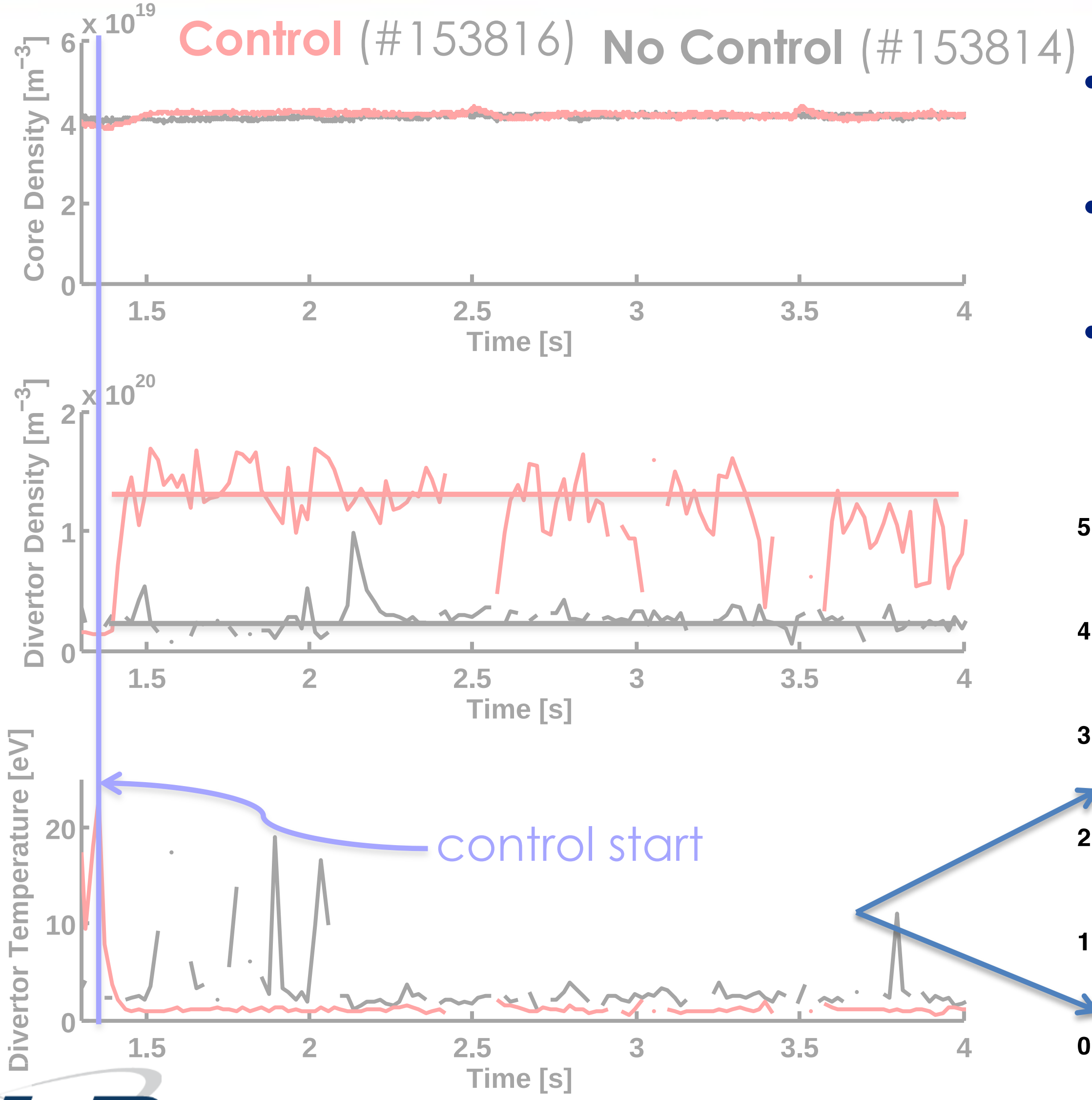

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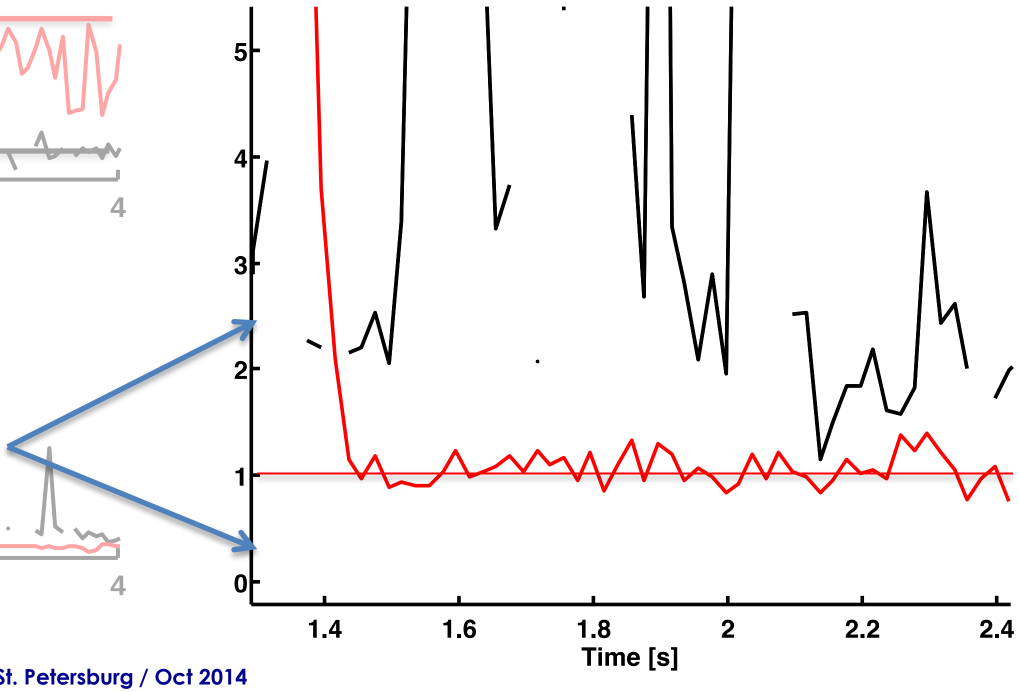

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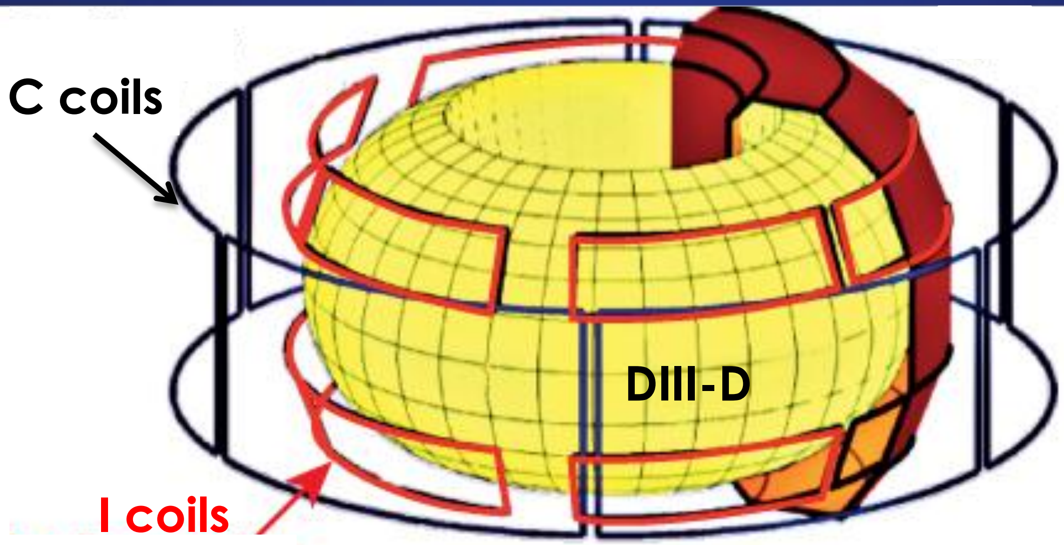
Heat Flux Regulation via

1. Snowflake Divertor Control
2. Detachment Control
3. **Burn Control with 3D Coils**

Burn Control: We Need Methods for Faster Control of Fusion Burn Rate

- **Burn: D + T → He + n + 17.6 MeV**
- **ITER concerned with power surges during burning phase and burn entry/exit conditions**
- **Normal methods (heating, density) are slow**
  - **Auxiliary heating** control: more heating power capability – cost
  - **Density** control is limited:
    - Upper density set by Greenwald limit
    - Lower density set by detached divertor
  - **Impurity injection**: significant time delays for penetration?

Burn Control by Non-Axisymmetric (3D) Coils (Hawryluk, PPC/P2-33)



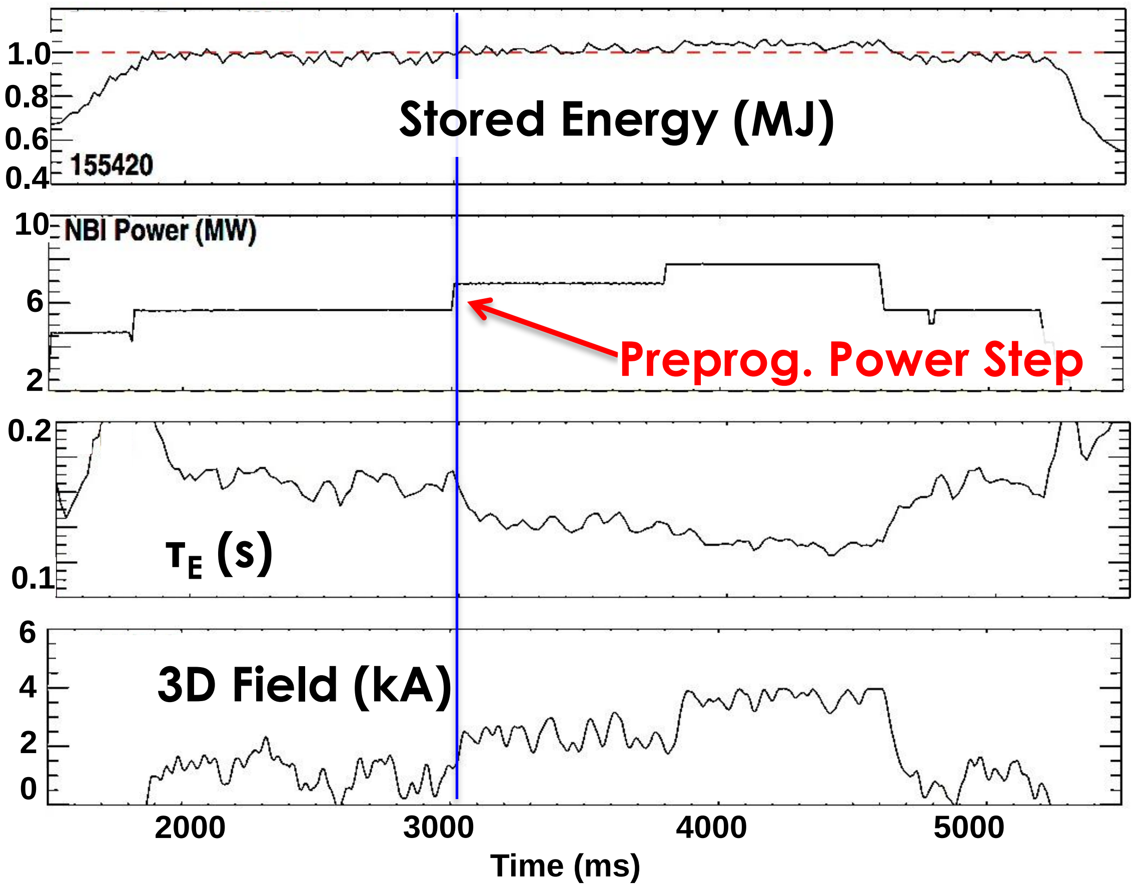
- **10% change** in energy **confinement** near ignition

  ➔ **factor of 2** reduction in fusion power

- 3D magnetic field (n=3) reduces confinement in many plasma conditions by increasing edge stochasticity

  ➔**3D coils actuator to control confinement time & fusion power**

Non-Axisymmetric (3D) Coils Can Control Burn (Stored Energy) with Simulated Power Surge



- **Simulate the surge with Neutral Beams (NBI)**
- **Add NBI steps (0.8 and 1.6 MW) to see the effect on control**
- **Control keeps the Burn (Stored Energy) constant:**
  1. **Adjust 3D coil current**
  2. 3D coils in turn control the confinement time
  3. This keeps fusion power constant

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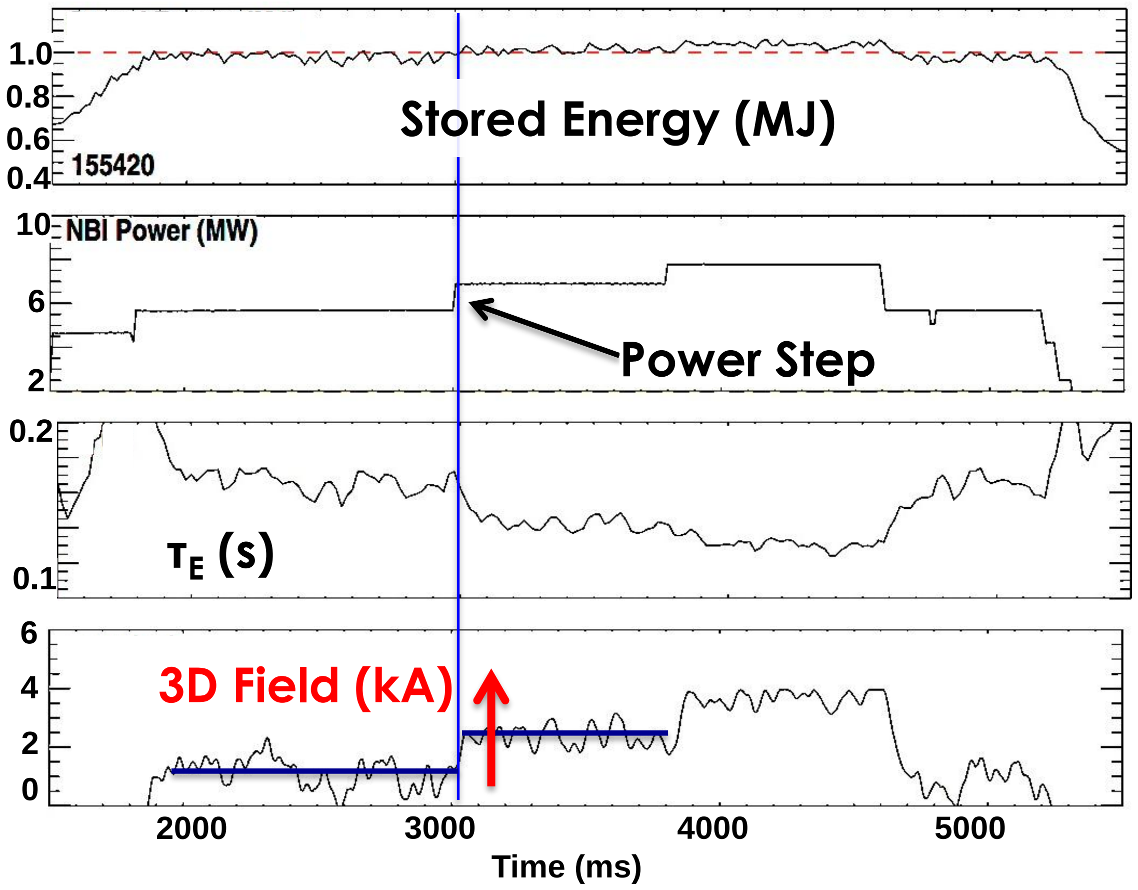
Non-Axisymmetric (3D) Coils Can Control Burn (Stored Energy) with Simulated Power Surge



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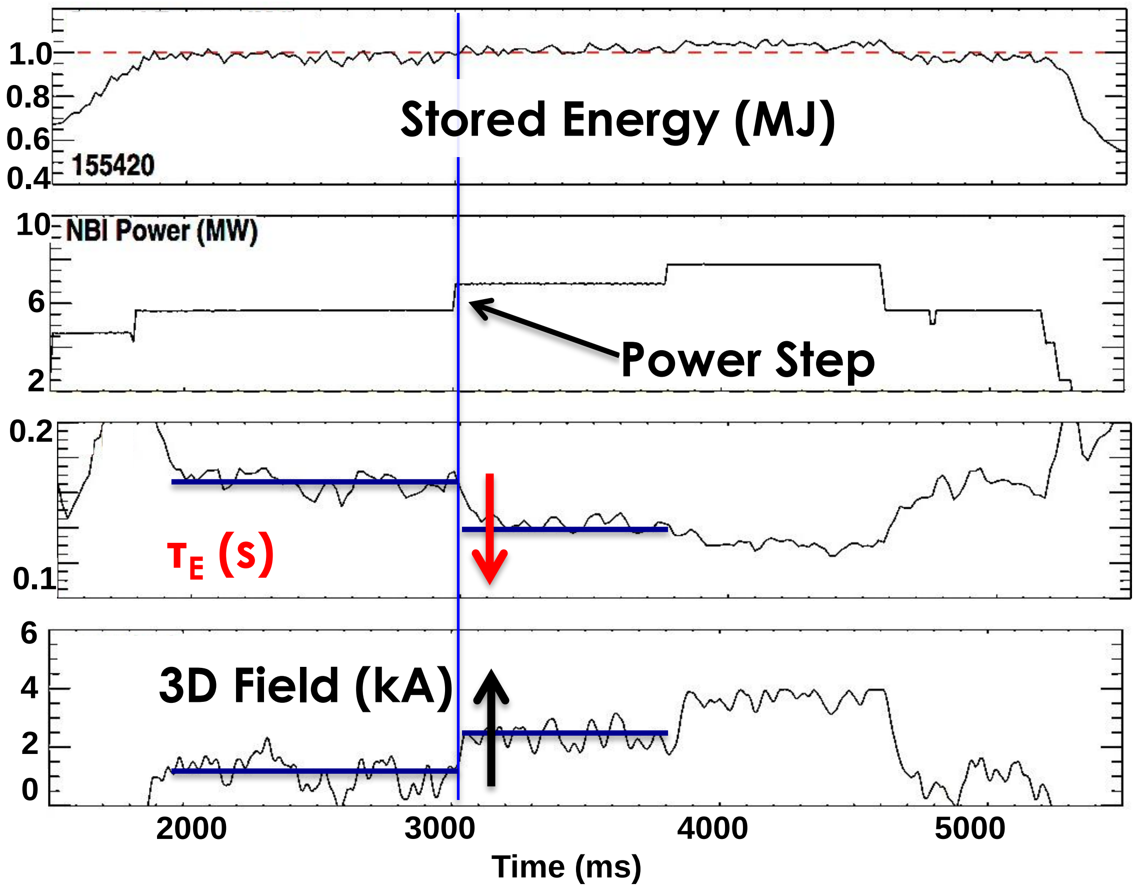

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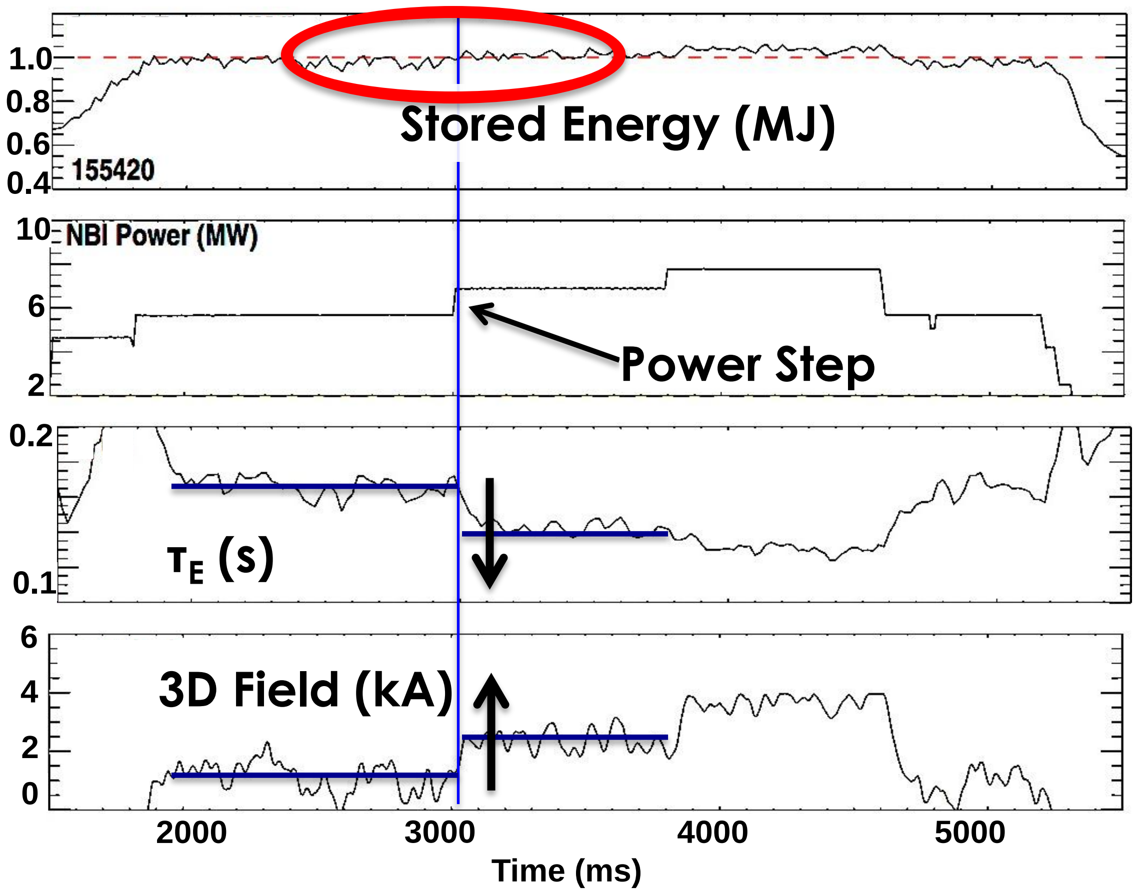

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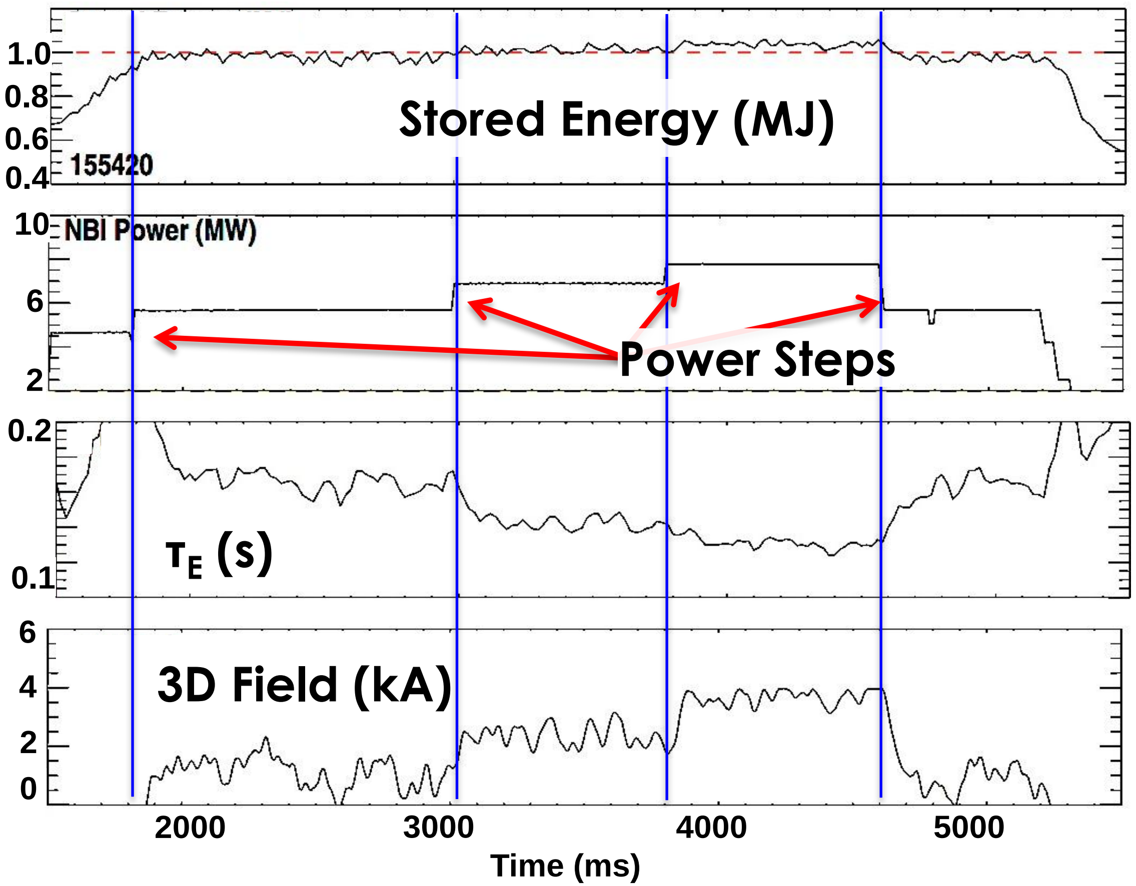

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Conclusion: New Control Solutions Enable Advances in Heat Flux Management

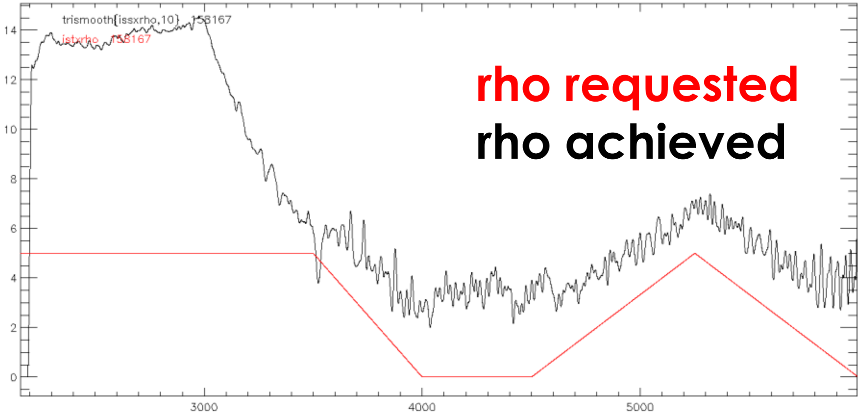
- **Advanced Magnetic Divertor Control reduces the peak heat flux without affecting the core properties**

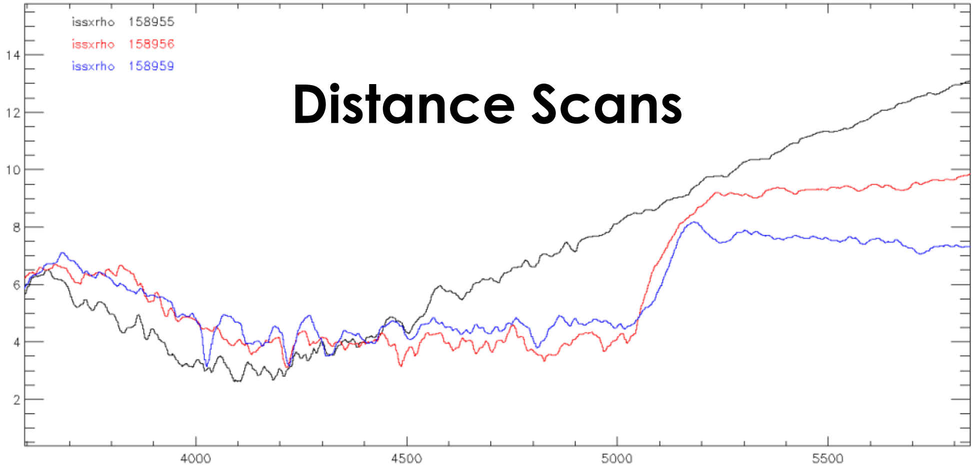
- **Double feedback Partial Detachment Control keeps the detachment front stable between the X-point and strike point, while keeping the core properties constant**

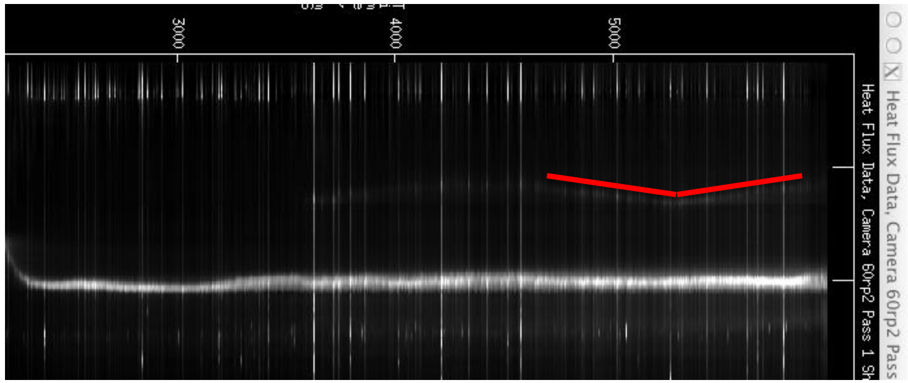
- **Burn Control is feasible by using Non-Axisymmetric (3D) Coils**

Extras

Snowflake Control: ρ Control



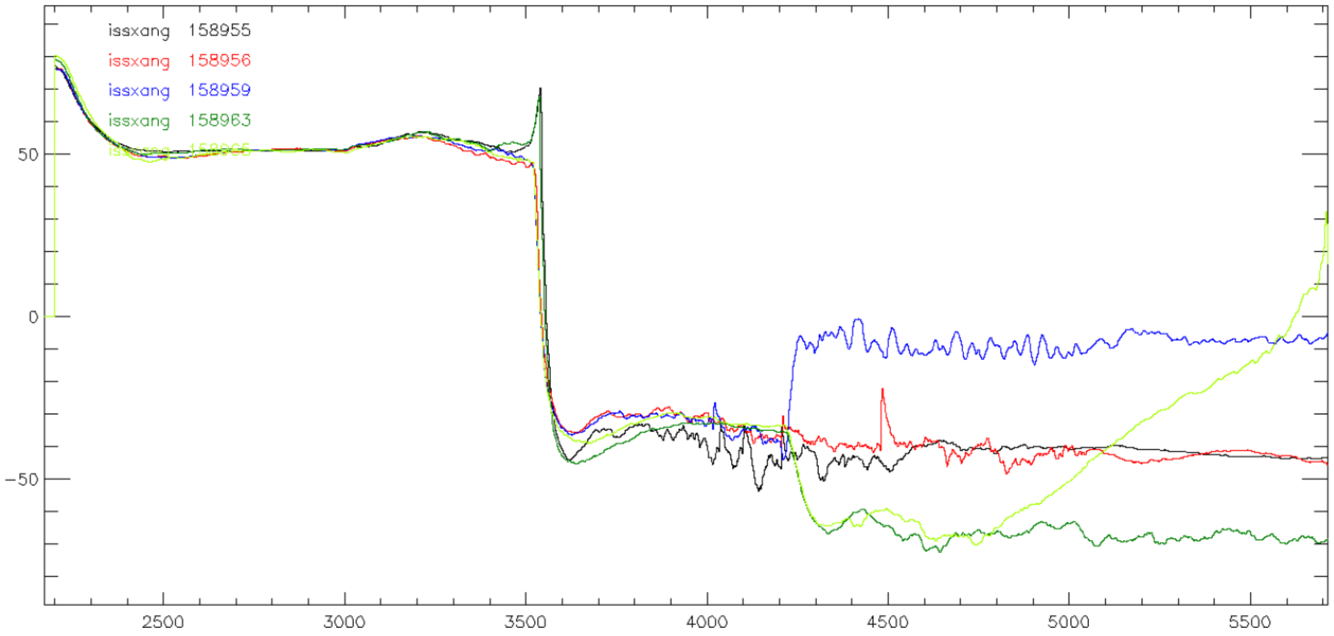




- Constantρof 3, 5, 7 cm
- ρscan from 3 to 15 cm.

Snowflake Control: Angle Control and Scans

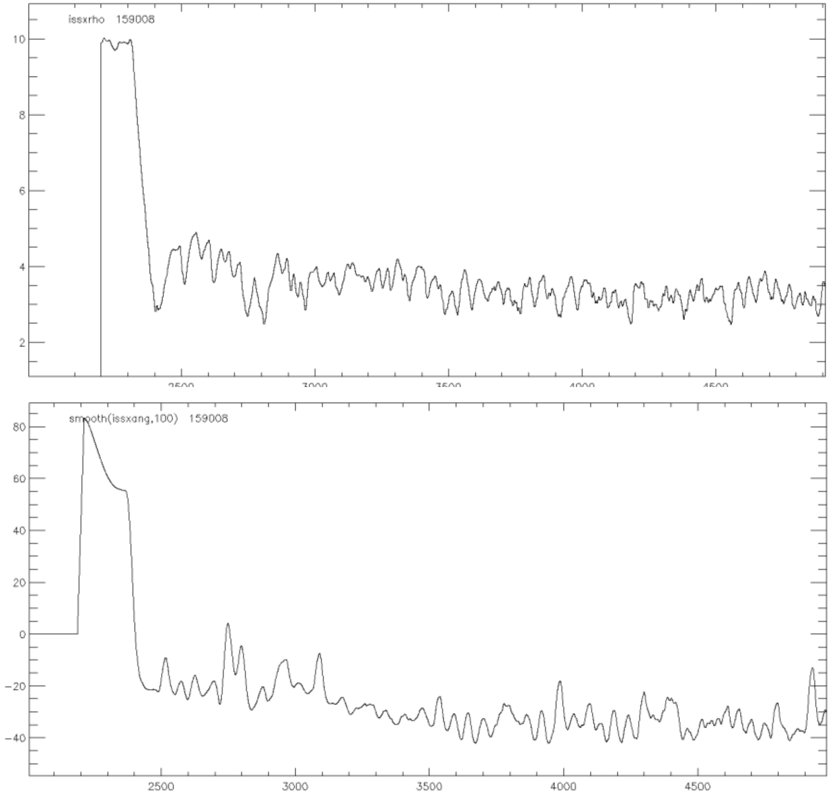
Angle Control/Scans



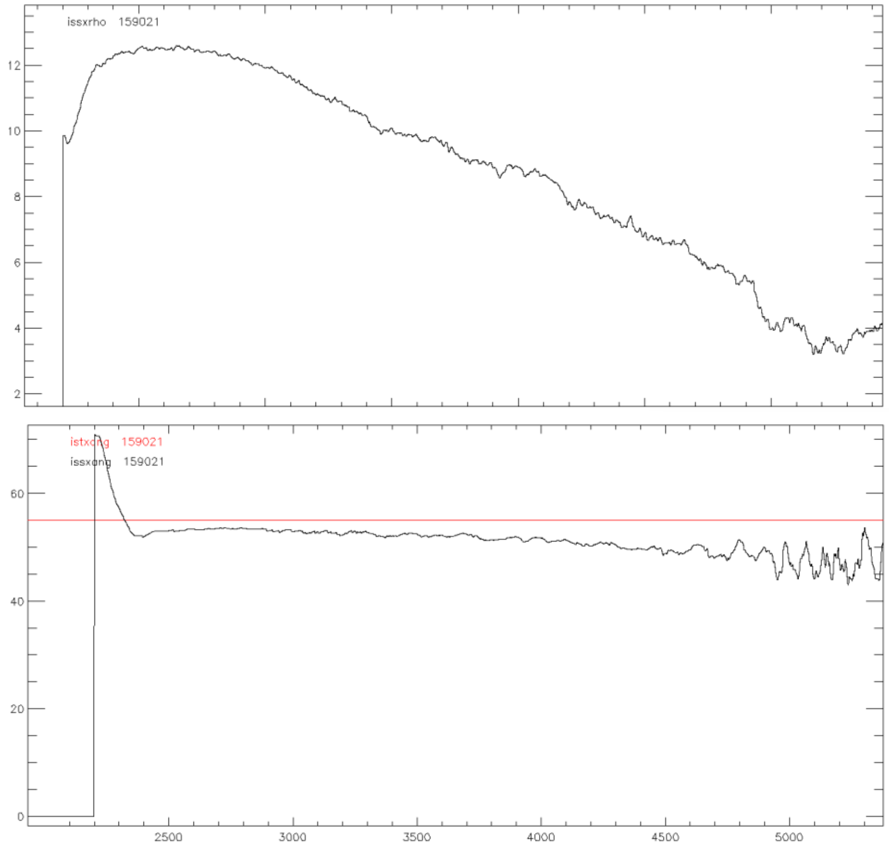
- Constant angle for -75, -45, +10, +50
- Scan from -75 to +25.

Snowflake Control: Combined rho and Angle Manipulation

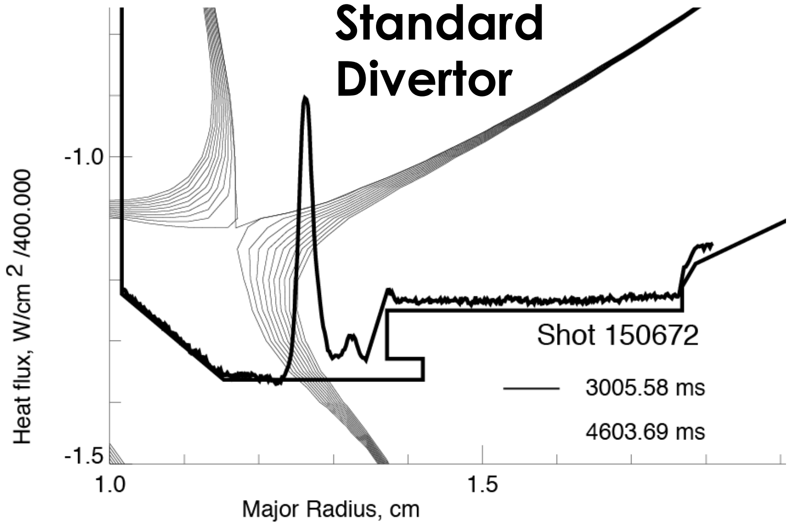
Snowflake (-)/exact

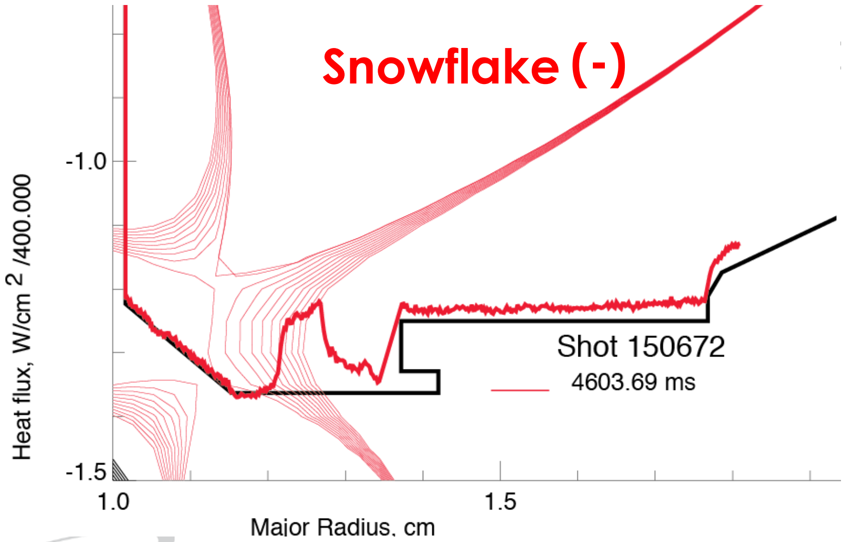


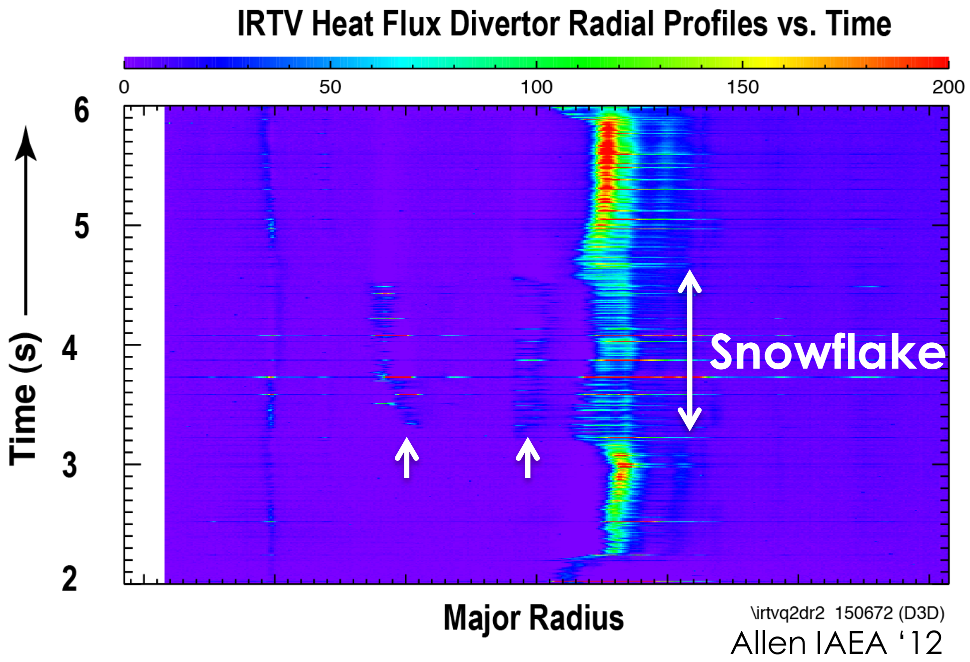
Snowflake (+)



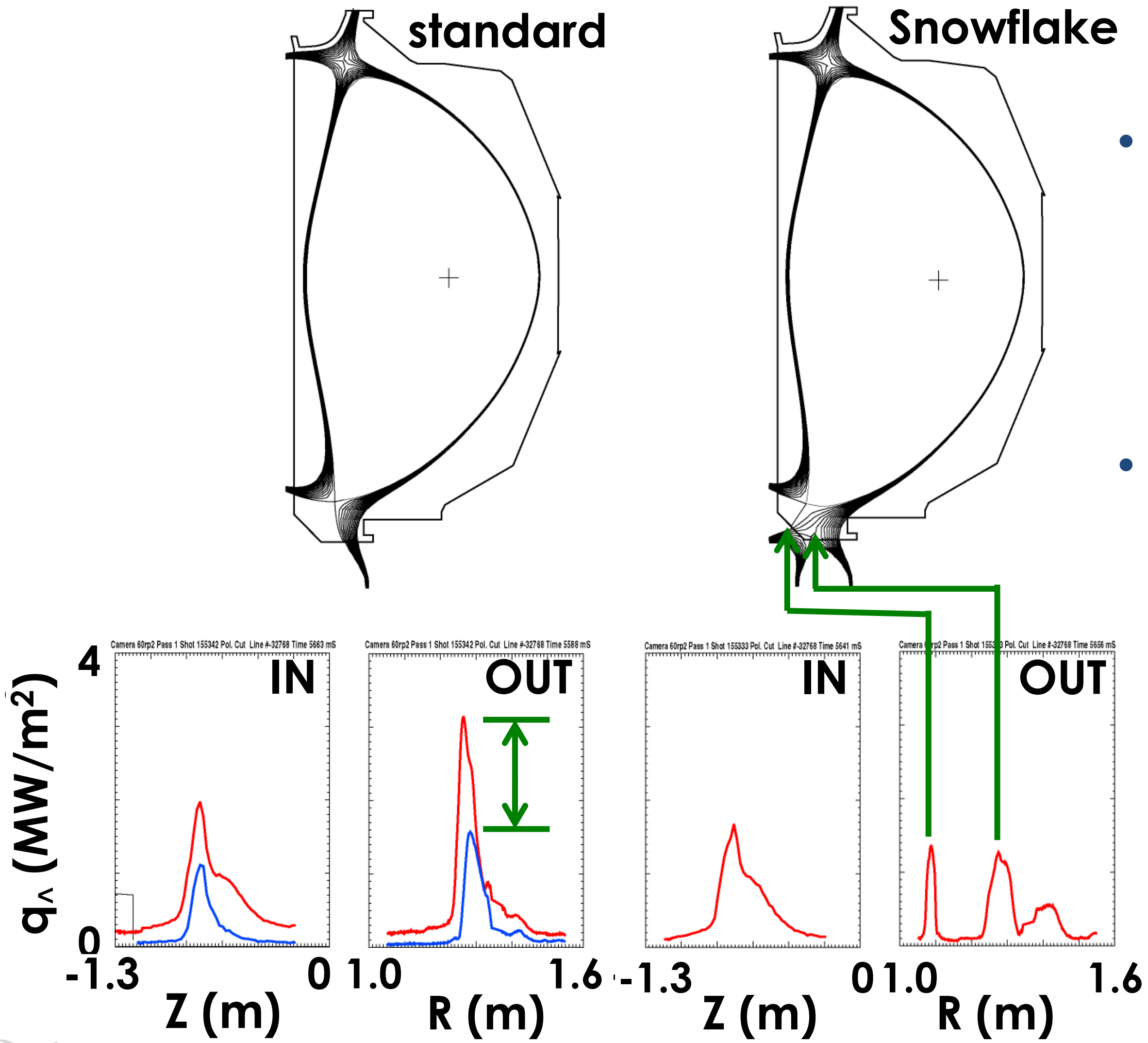
Divertor Peak Heat Flux Reduced by 2.5x in SF (-) Due To Changes in Divertor Geometry







AT DN radiating divertor similar reducing heat to SFD without radiating divertor



- **Radiating divertor case:**
- A perturbing mix of D2+neon had a greater effect on $q_\perp$ in the outer divertor for the standard DN
- **SF heat flux similar to radiating divertor**

RED – Before gas puffing

BLUE – Radiating divertor

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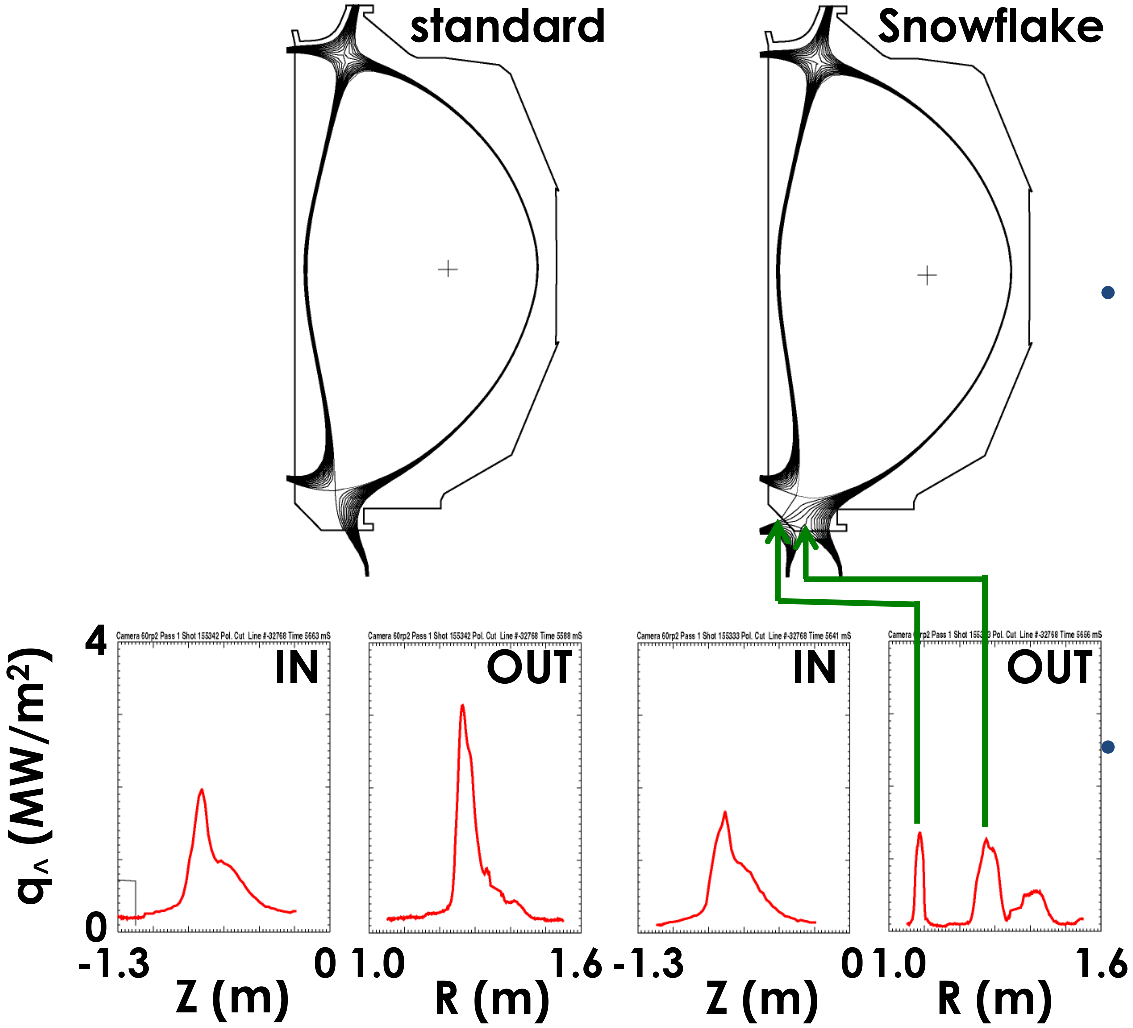
Snowflake with 2.5x Reduced Heat Flux Compatible with High Performance Plasmas



- β_N = 3.0 and H98(y,2) ≅ 1.35 conditions preserved with SF with *no adverse effects*
- Outer:
  - SF bifurcating targets
  - Peak heat flux outer reduced by 2.5x for the SF AT
- Inner:
  - Similar heat flux profiles at the inner target
  - SF: $q^P_{\perp,lin} > q^P_{\perp,out}$

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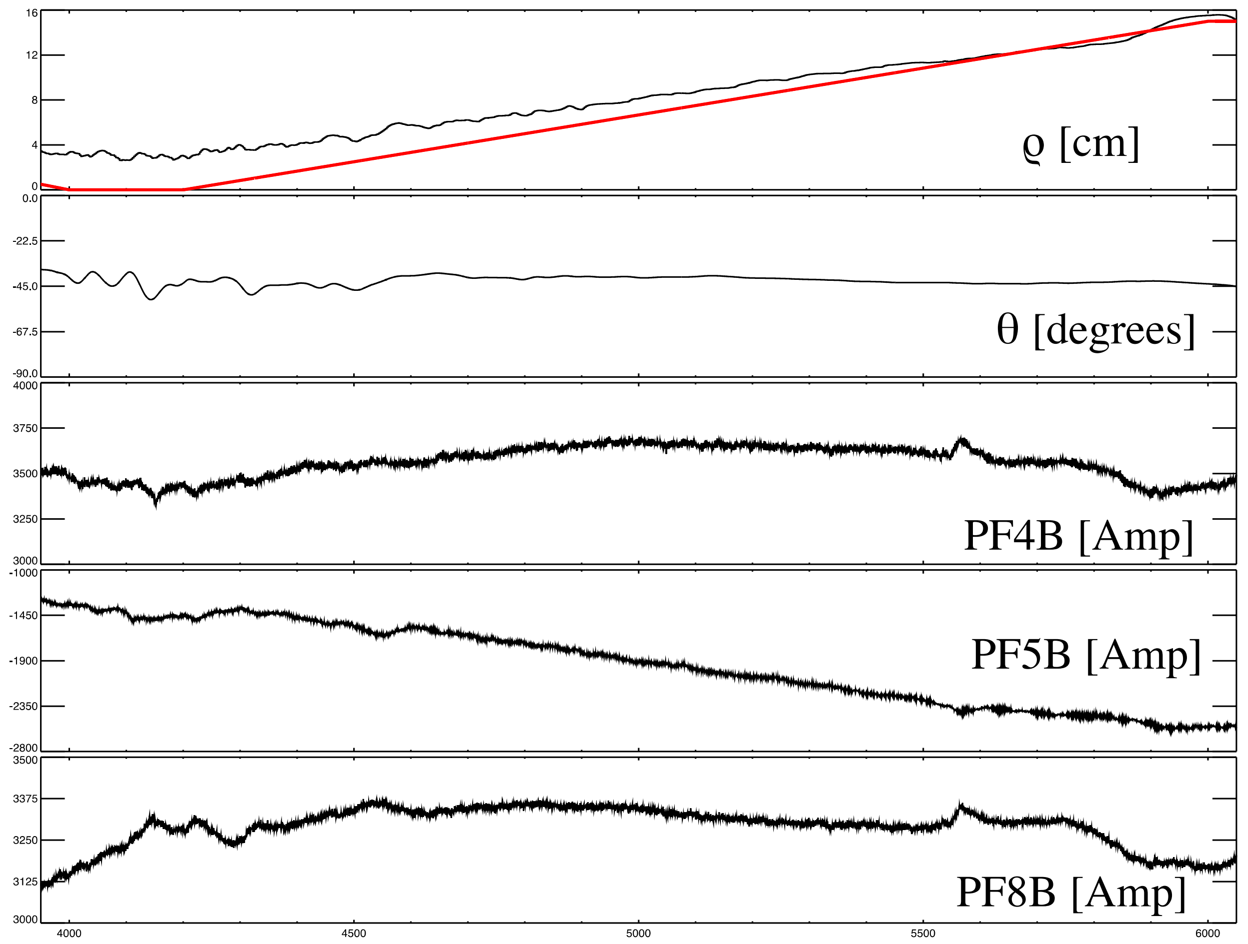
Snowflake Control: rho scan in Snowflake (-) (-45 deg)



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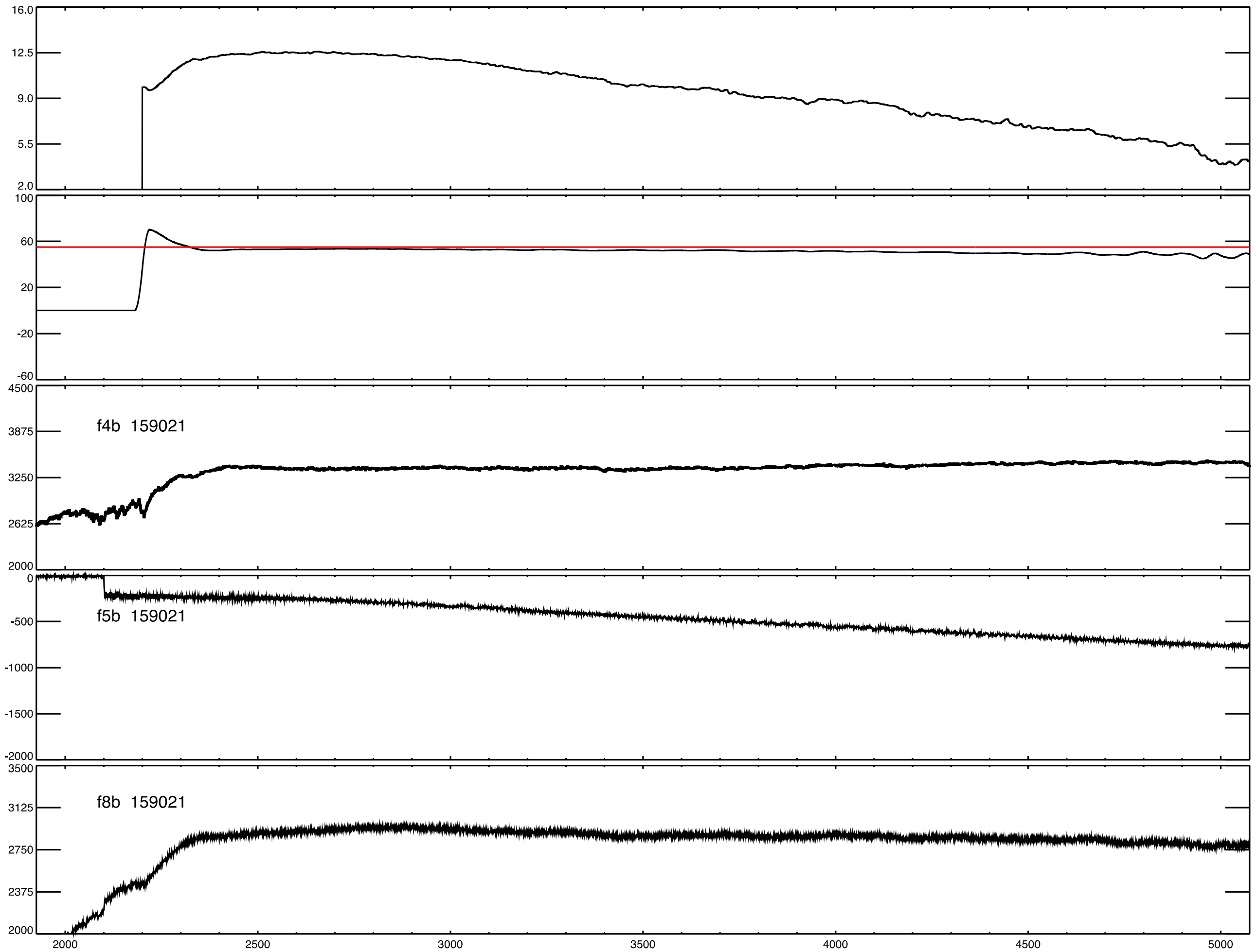
Snowflake Control: rho scan in Snowflake (+) (+55 deg)



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Snowflake Control: Snowflake from t=2 sec