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

by

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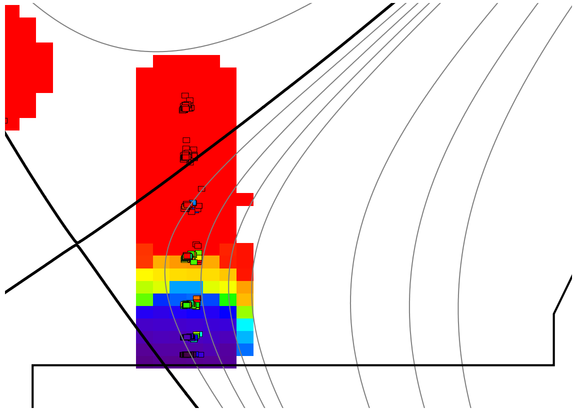
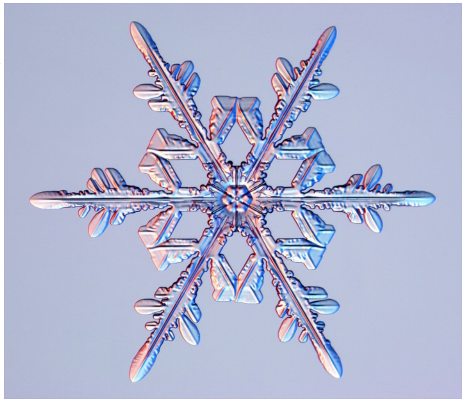
Presented at the

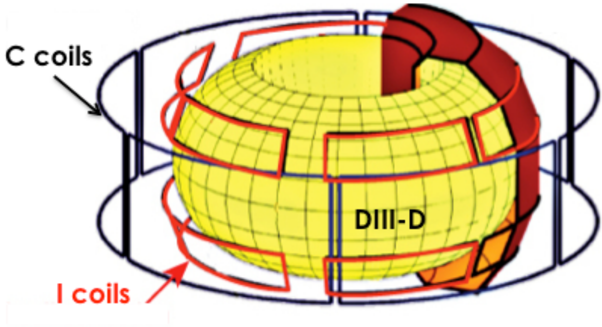
25th IAEA Fusion Energy Conference
Saint Petersburg, Russia
October 13–18, 2014



Detachment Control



Snowflake Control



Burn Control

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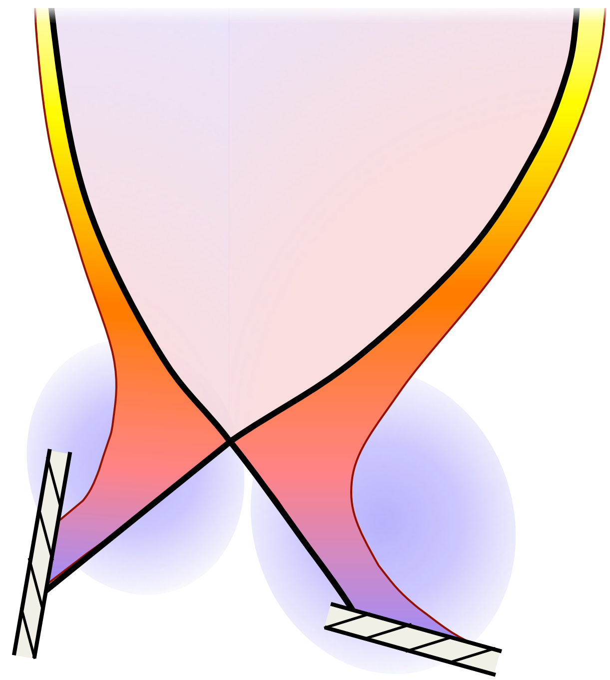
PPPL PRINCETON PLASMA PHYSICS LABORATORY

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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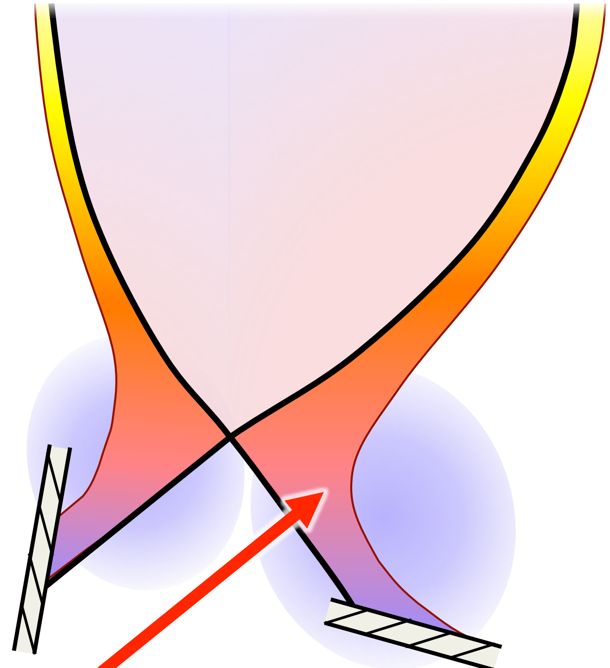

1. Snowflake Divertor:
- Reduce peak heat flux
- Possibly reactor application

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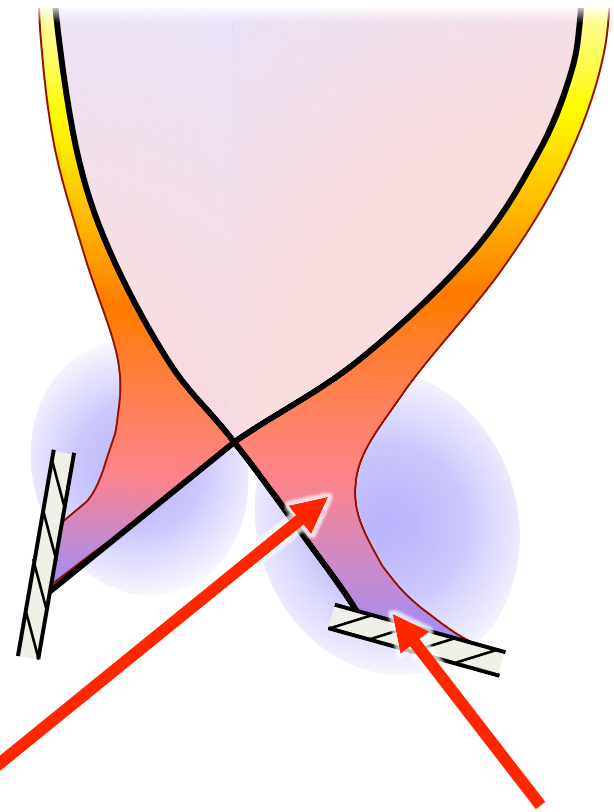

1. Snowflake Divertor:
- Reduce peak heat flux
- Possibly reactor application

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

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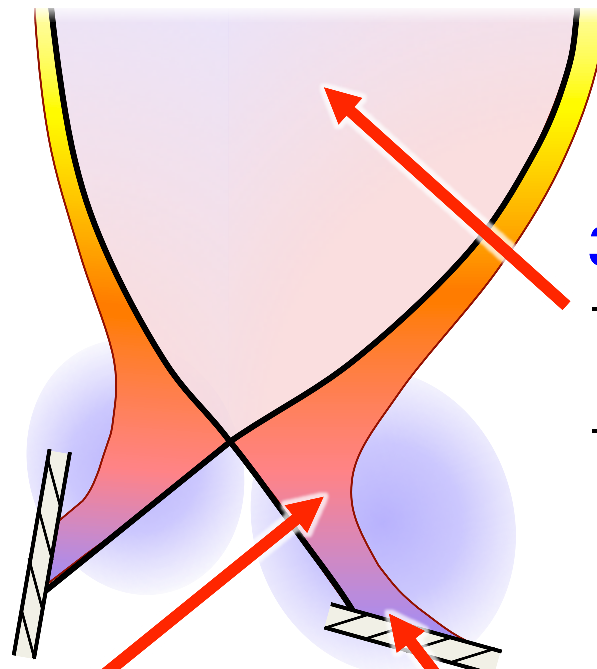

3. Burn control
- Regulate heat source
- ITER/Reactor relevant

1. Snowflake Divertor:
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2. Partial detachment control
- Reduce target plasma temperature & erosion
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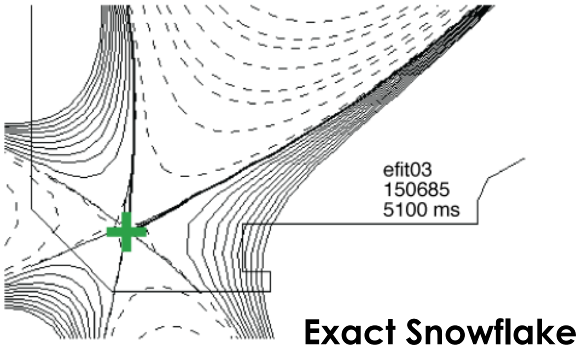
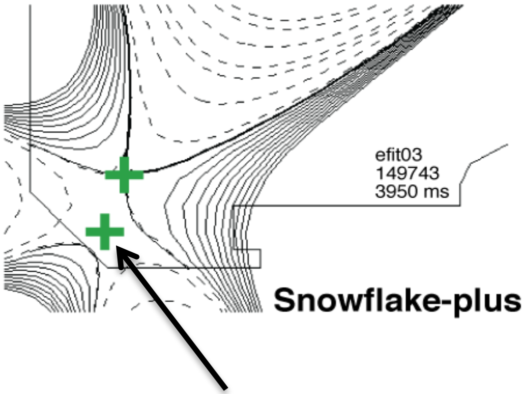
Heat Flux Reduction via

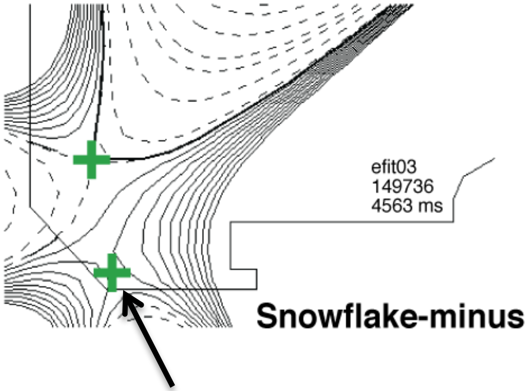
1. Snowflake Divertor Control
2. Detachment Control
3. Burn Control with 3D Coils

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





2nd X-Point in Private Flux



2nd X-Point in SOL

- **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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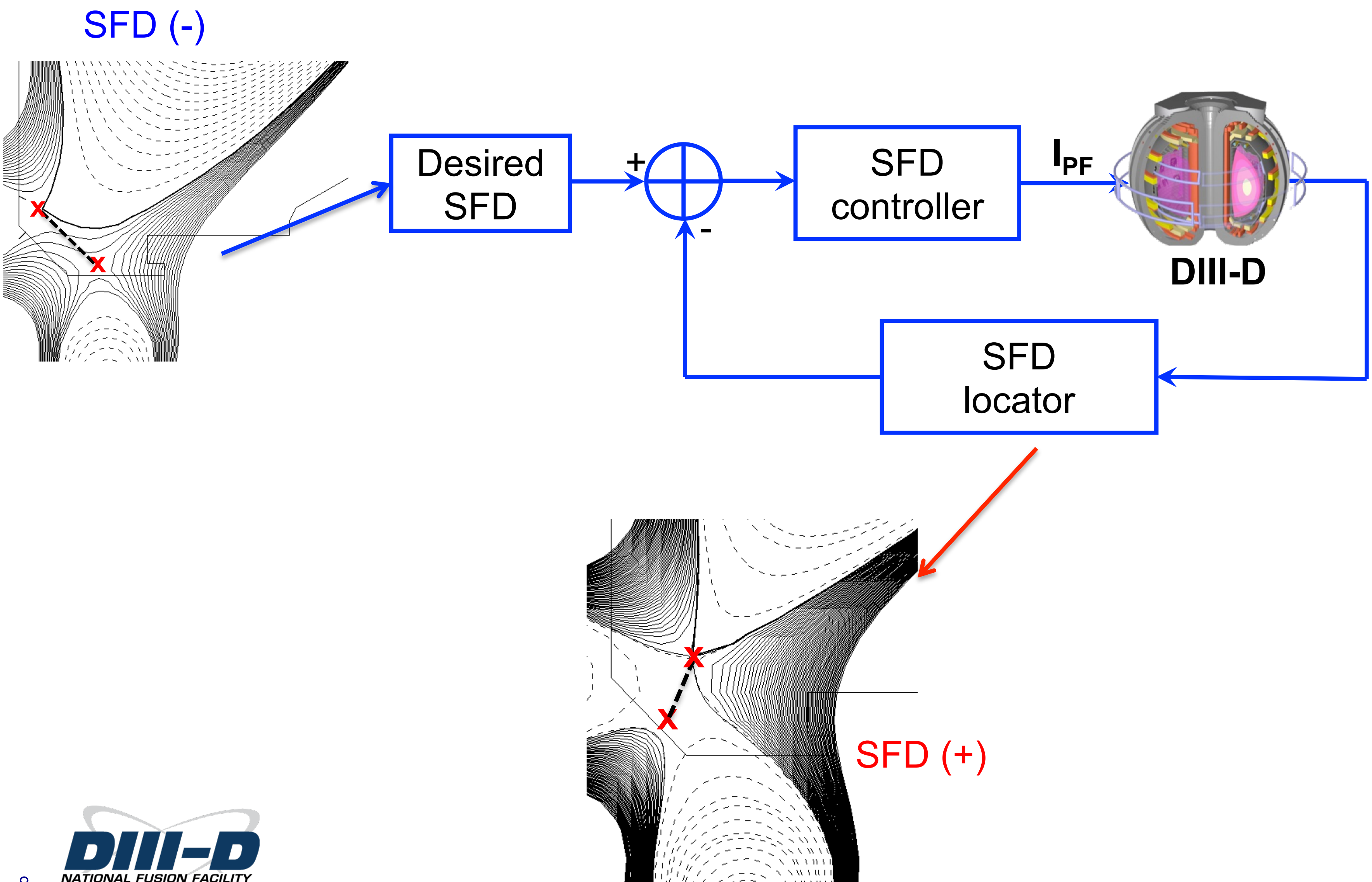
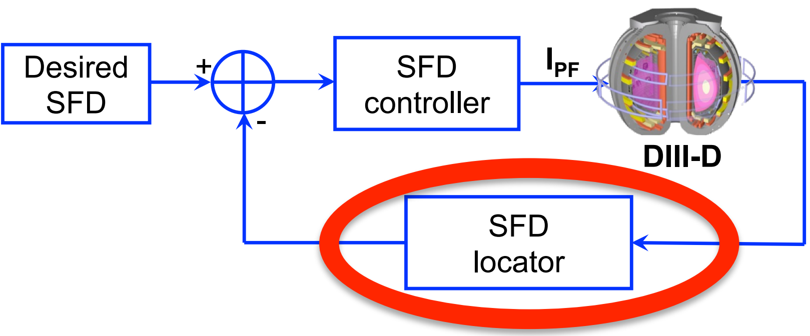
Snowflake Control System



Snowflake Locator: Finding the Two X-points



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

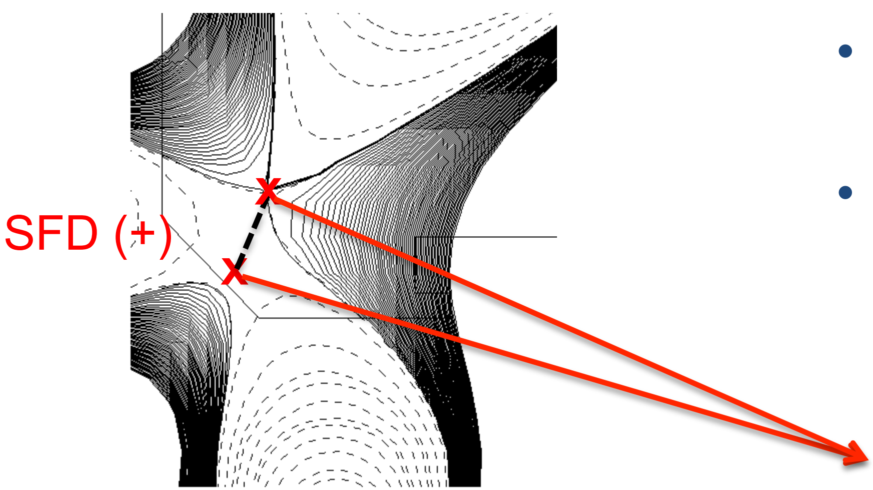
$$r\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial \Psi}{\partial r}\right)+\frac{\partial^2 \Psi}{\partial z^2}=0$$

- Keep the 3rd order terms

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

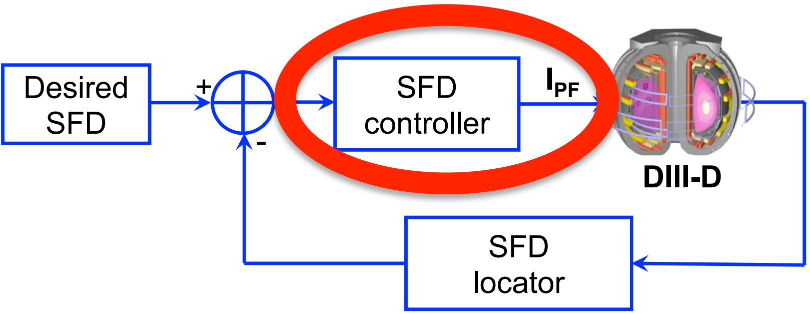
- Find coefficients, c_{exp}, from sample points
- Find the null points (X-points) <250us

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



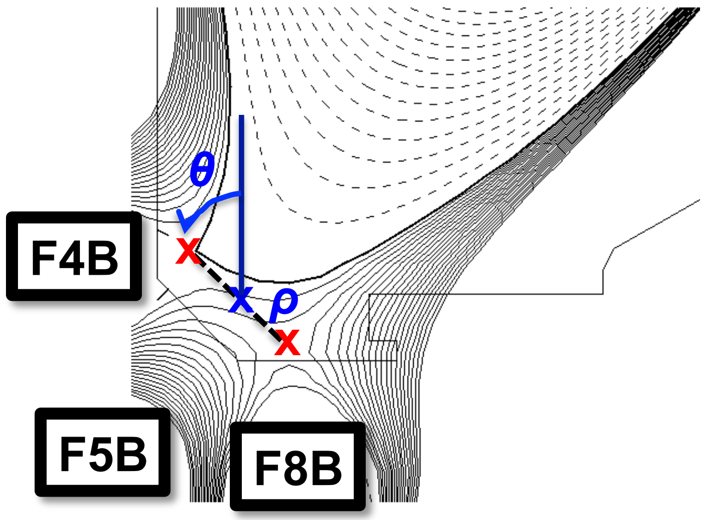
$$\rightarrow \{\delta r_{X_1}(c_{\exp}), \delta z_{X_1}(c_{\exp}), \delta r_{X_2}(c_{\exp}), \delta z_{X_2}(c_{\exp})\}$$

Snowflake Control: Controlling the PF Coil Currents



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

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

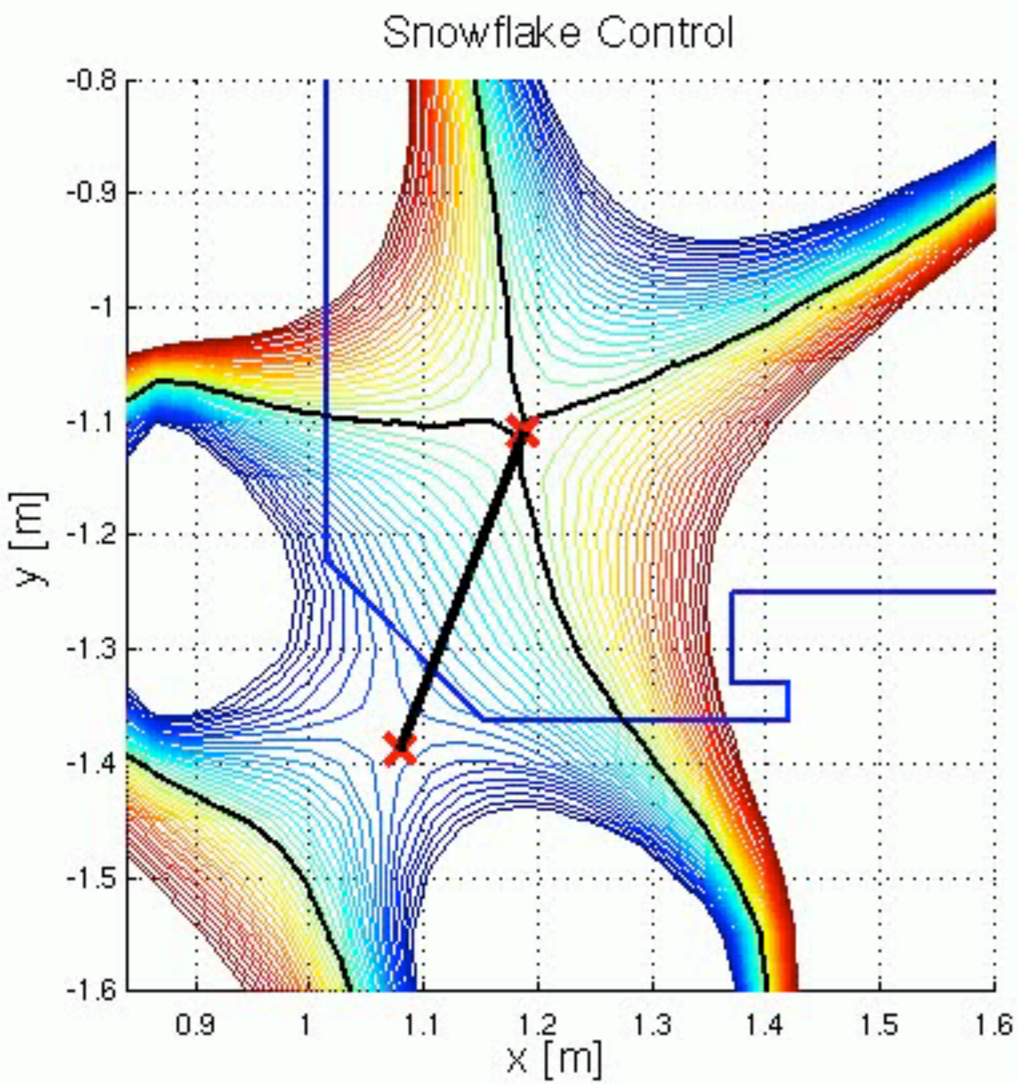


Location of the X-points and Centroid

- **3 closest PF coils are used for controlling the formation**

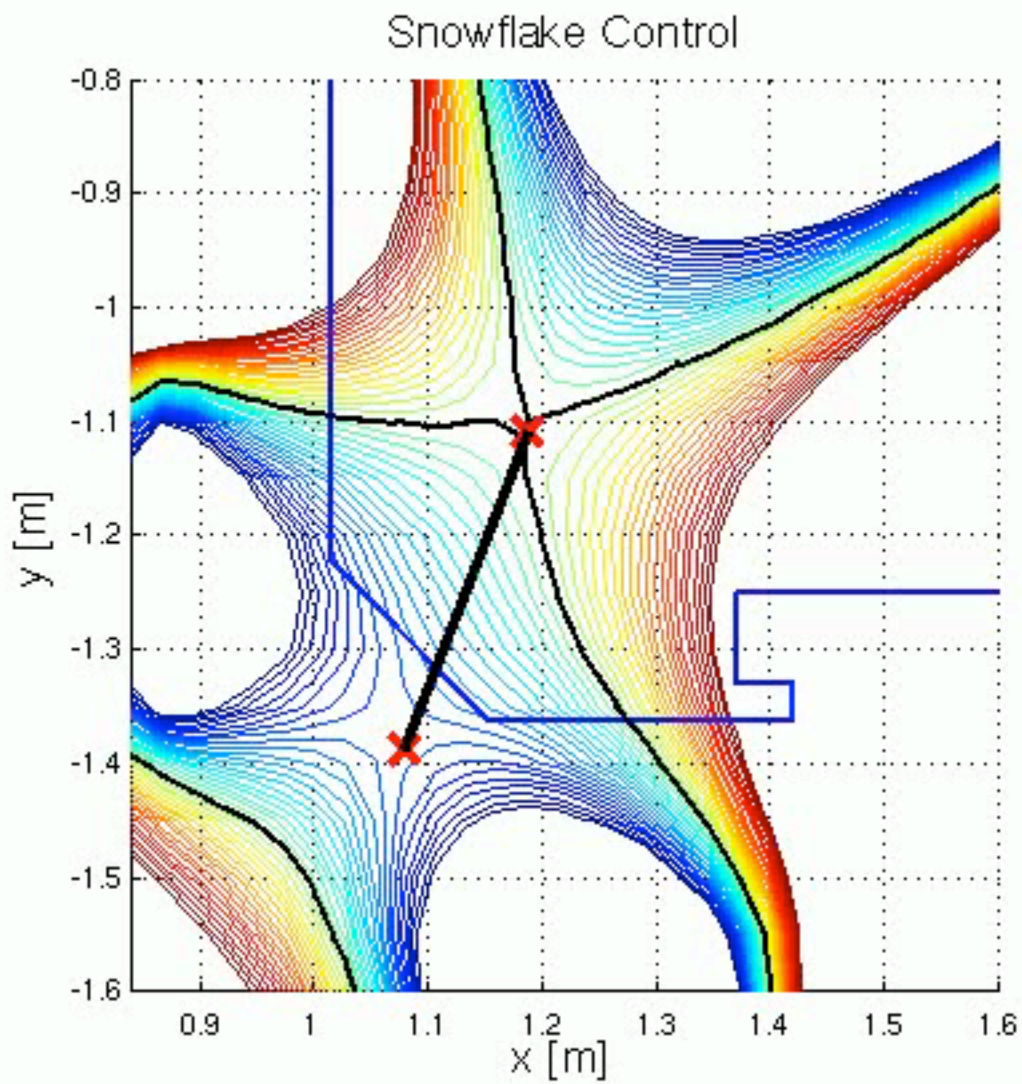
$$\begin{bmatrix} \delta I_{F4B} \\ \delta I_{F5B} \\ \delta I_{F8B} \end{bmatrix} = (A^T A)^{-1} A^T W \begin{bmatrix} \delta\theta \\ \delta\rho \\ \delta r_c \\ \delta z_c \end{bmatrix}$$

Snowflake Control: Obtaining Exact Snowflake (ρ Scan)



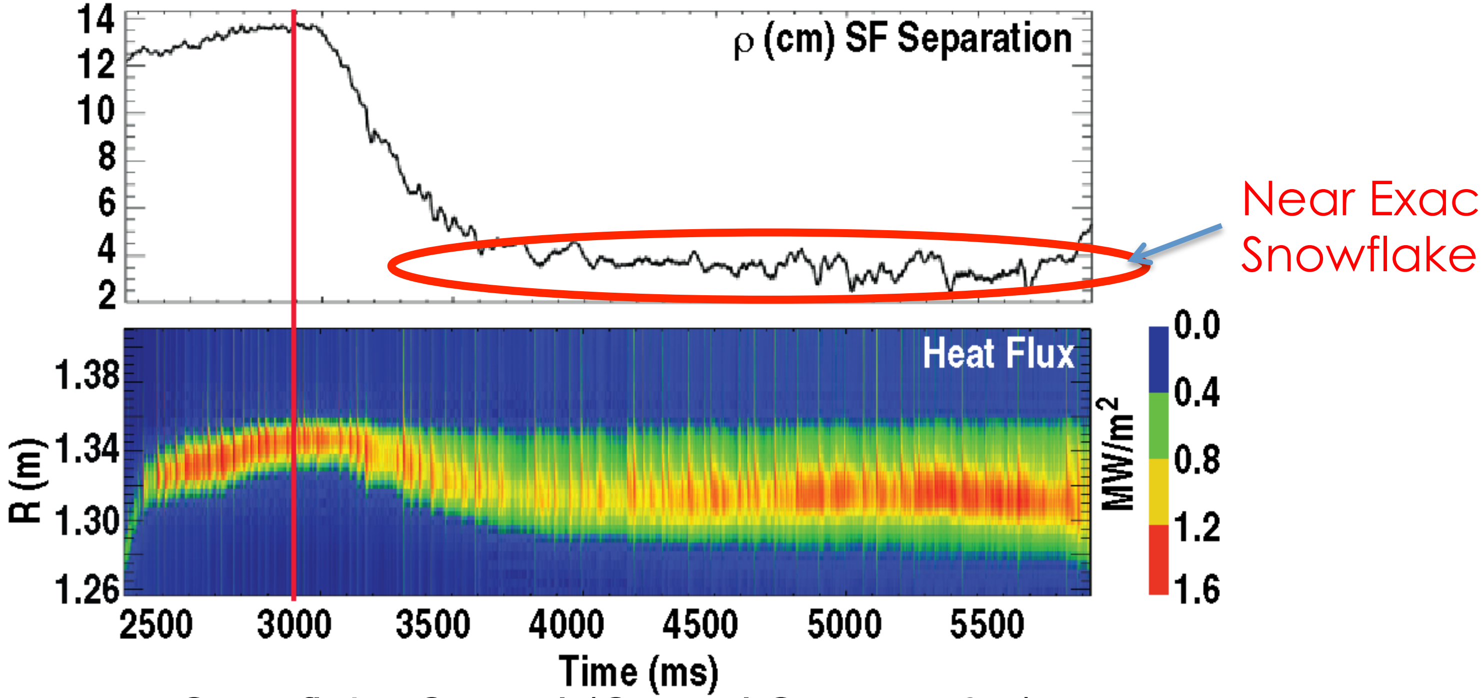
Simulation

Snowflake Control: Obtaining Exact Snowflake (ρ Scan)



Simulation

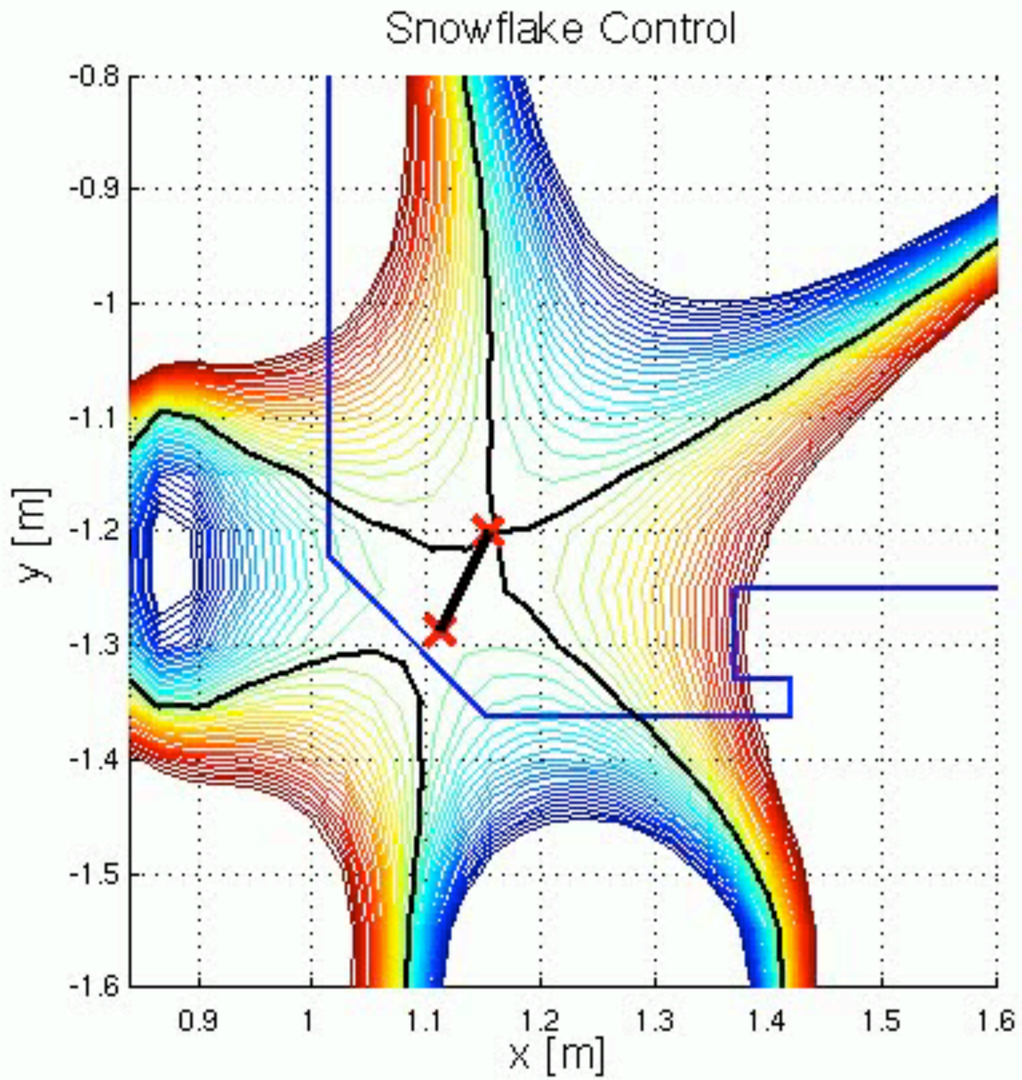
Snowflake Control: Obtaining Snowflake (Exact, + and -)



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

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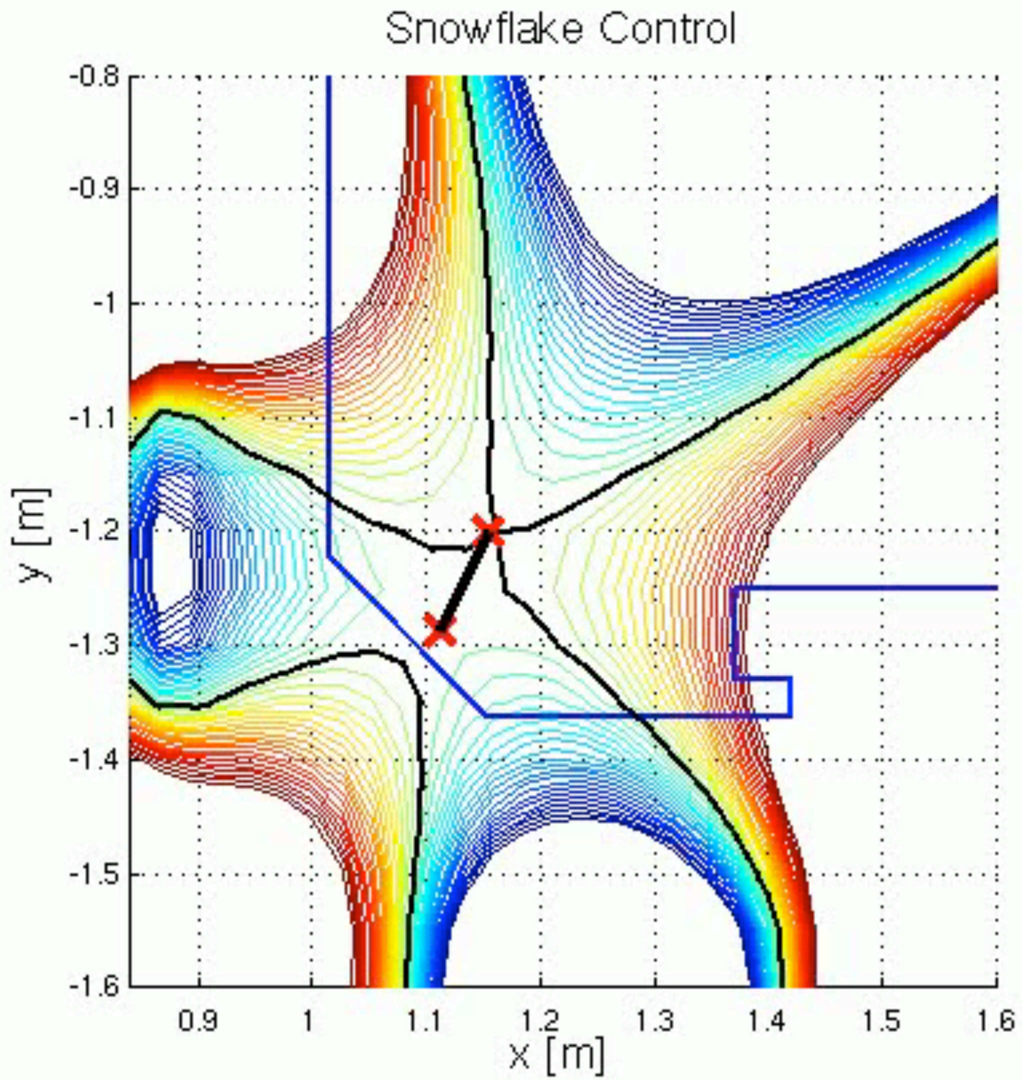
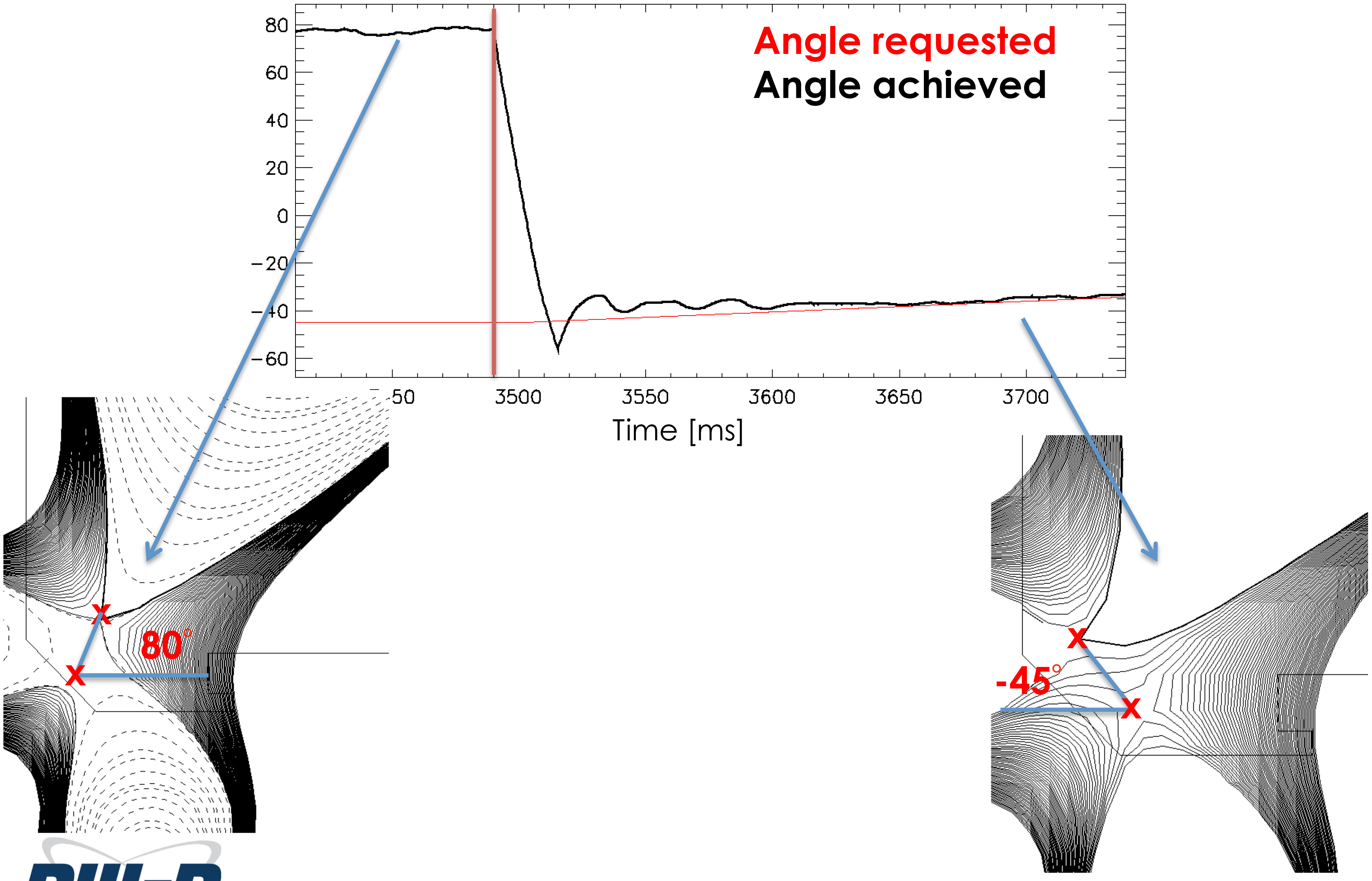
Snowflake Control: Scanning the Angle

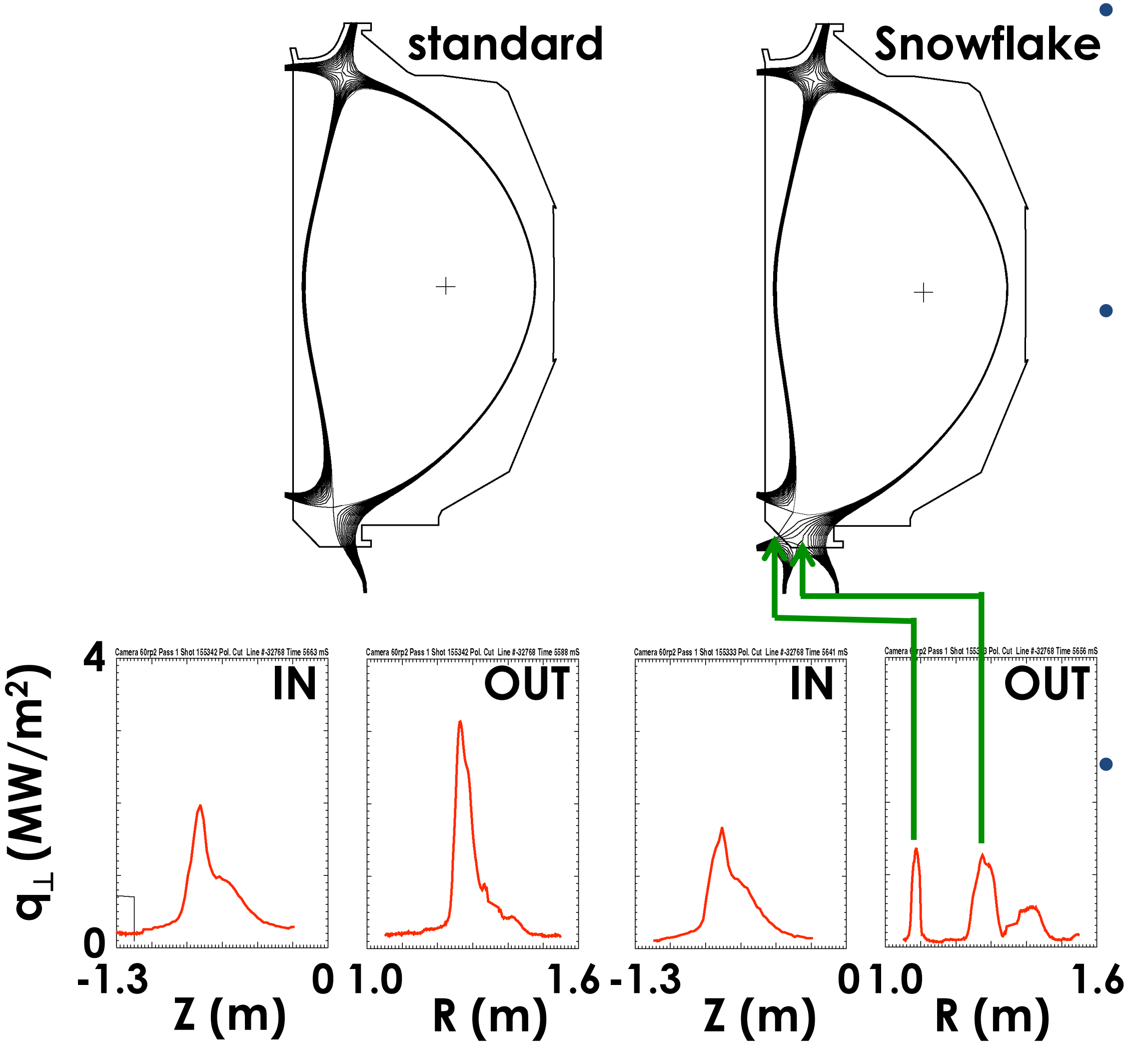


Simulation

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*
- 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: $q^P_{\perp,in} > q^P_{\perp,out}$

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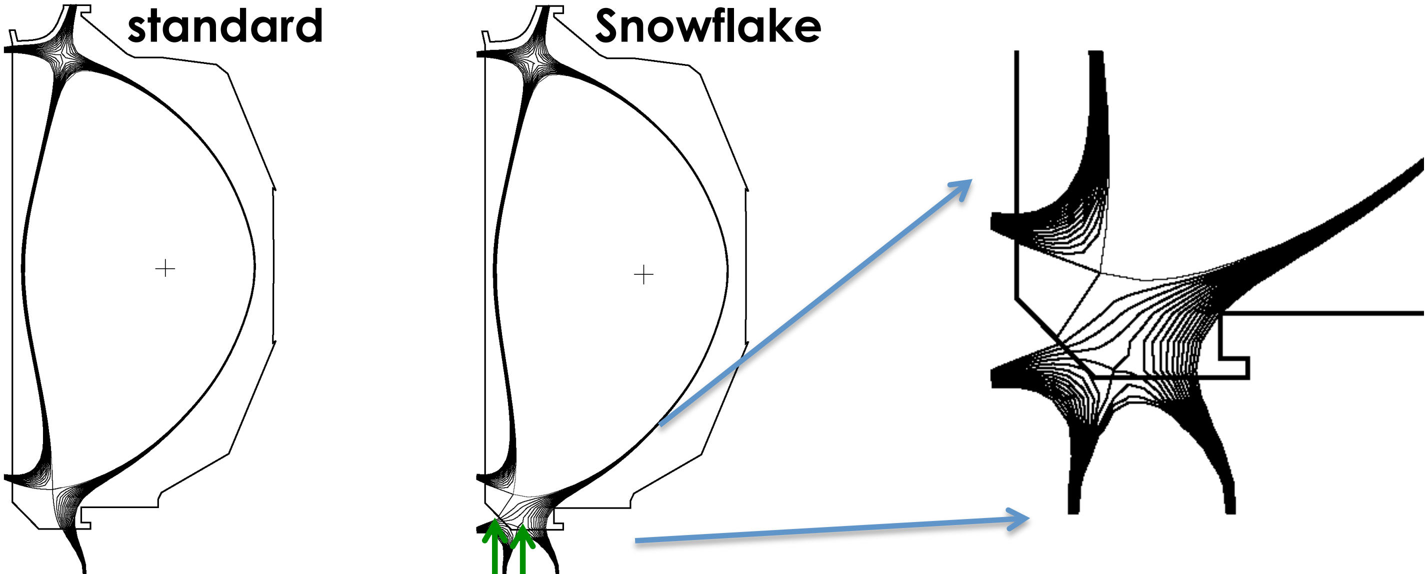
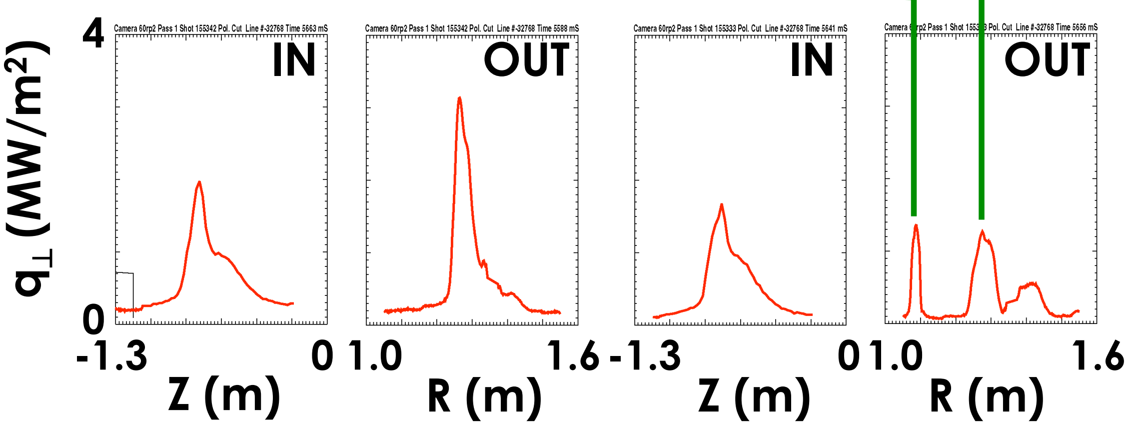
Snowflake with 2.5x Reduced Heat Flux Compatible with High Performance Plasmas





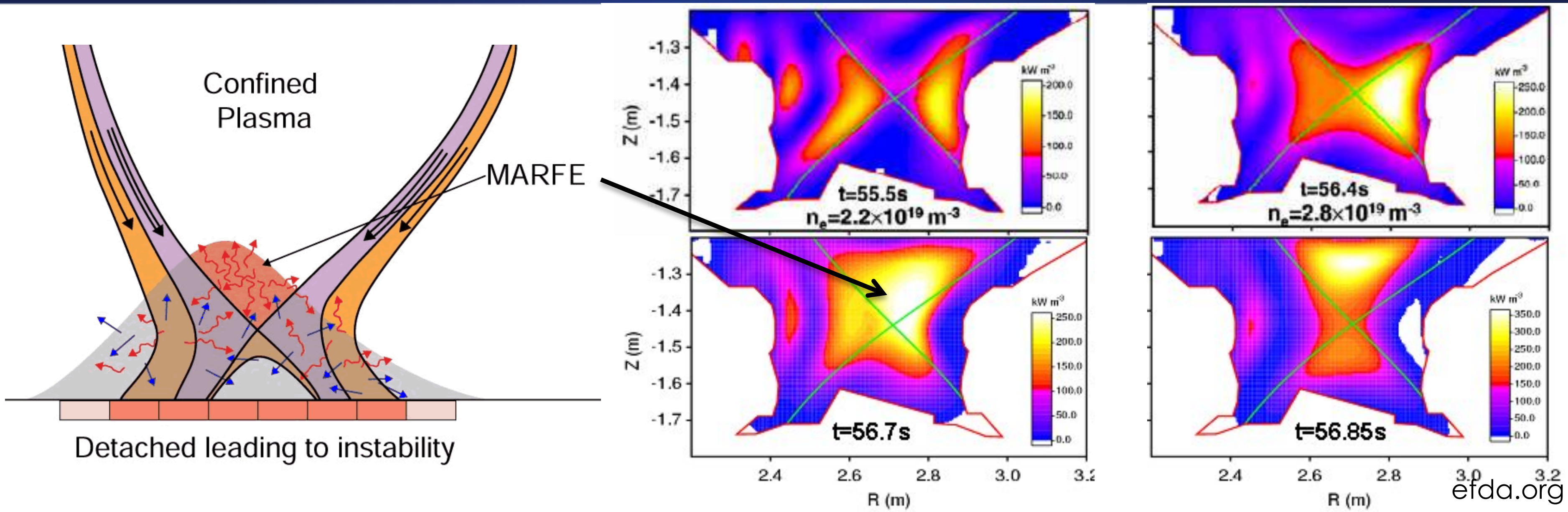
β_N = 3.0 and H98(y,2) ≅ 1.35 conditions preserved with SF with *no adverse effects*

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

Heat Flux Reduction via

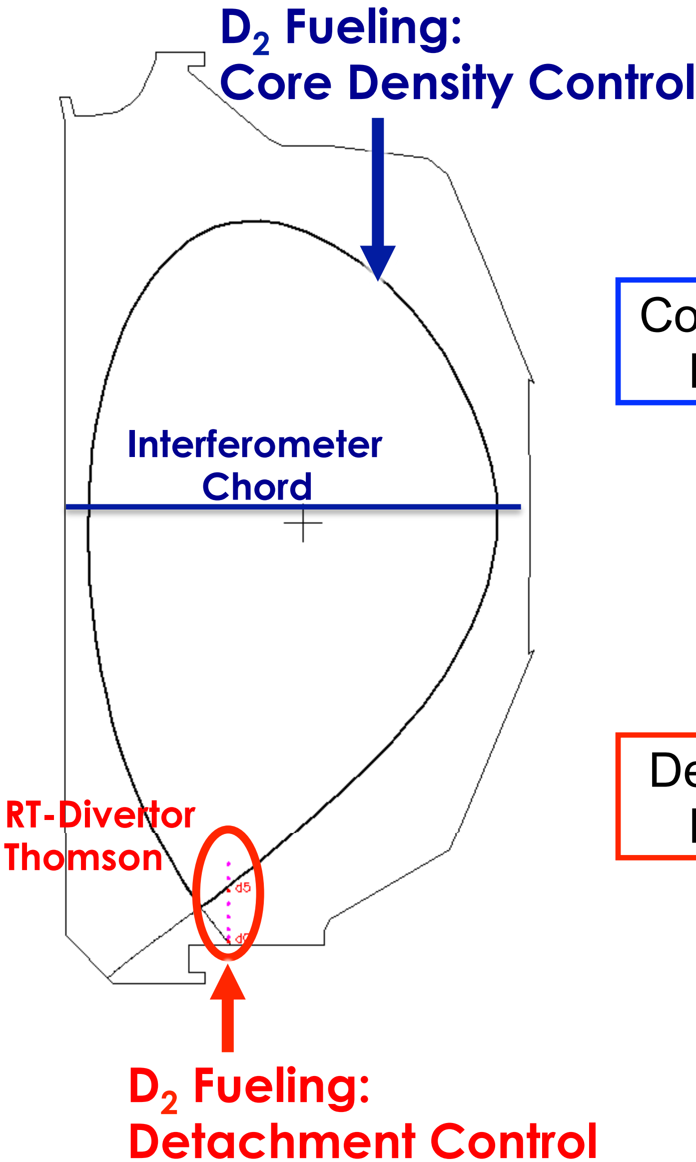
1. Snowflake Divertor Control
2. **Detachment Control**
3. Burn Control with 3D Coils

Partial Detachment Control Needed for ITER

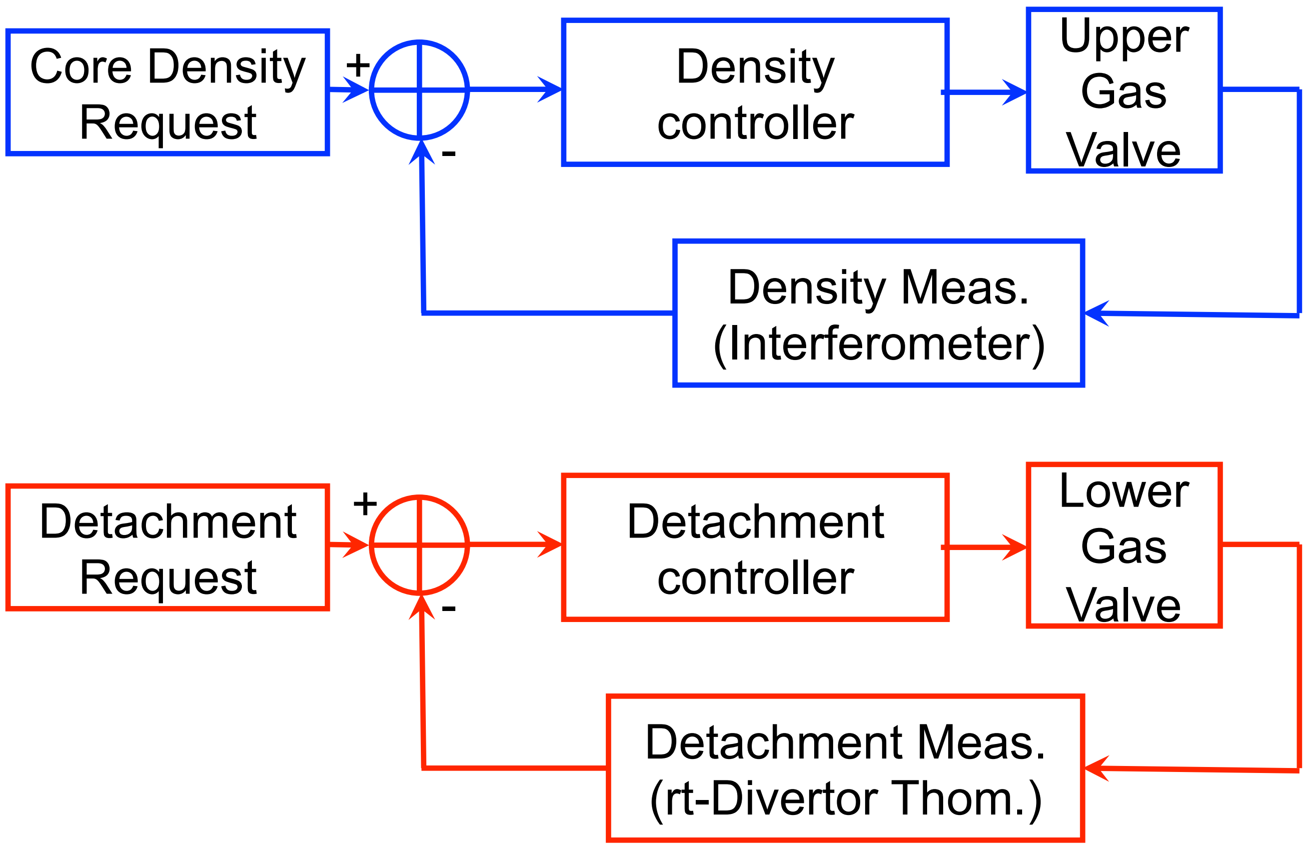


- **Not enough detachment ➔ T_e and heat flux too high ➔ Erosion**
- **Too much detachment ➔ Instabilities (MARFE) and core degradation**
- **MARFE Instability:**
  - Full detachment ➔ large cold areas
  - Neutrals/Impurities influx ➔ *high radiation* from the core
  - Thermal instability of the whole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

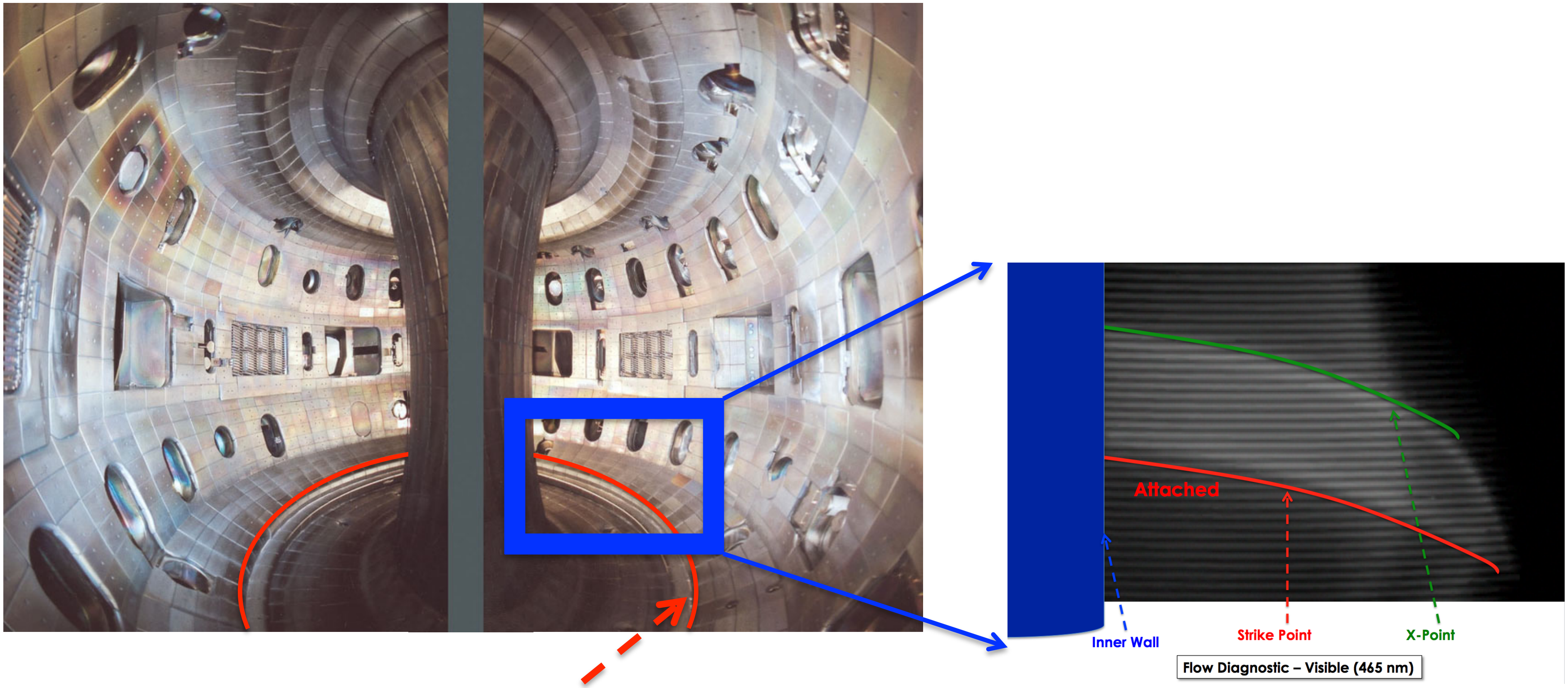
Effective Detachment Control at Constant Core Density Requires Two Feedback Channels



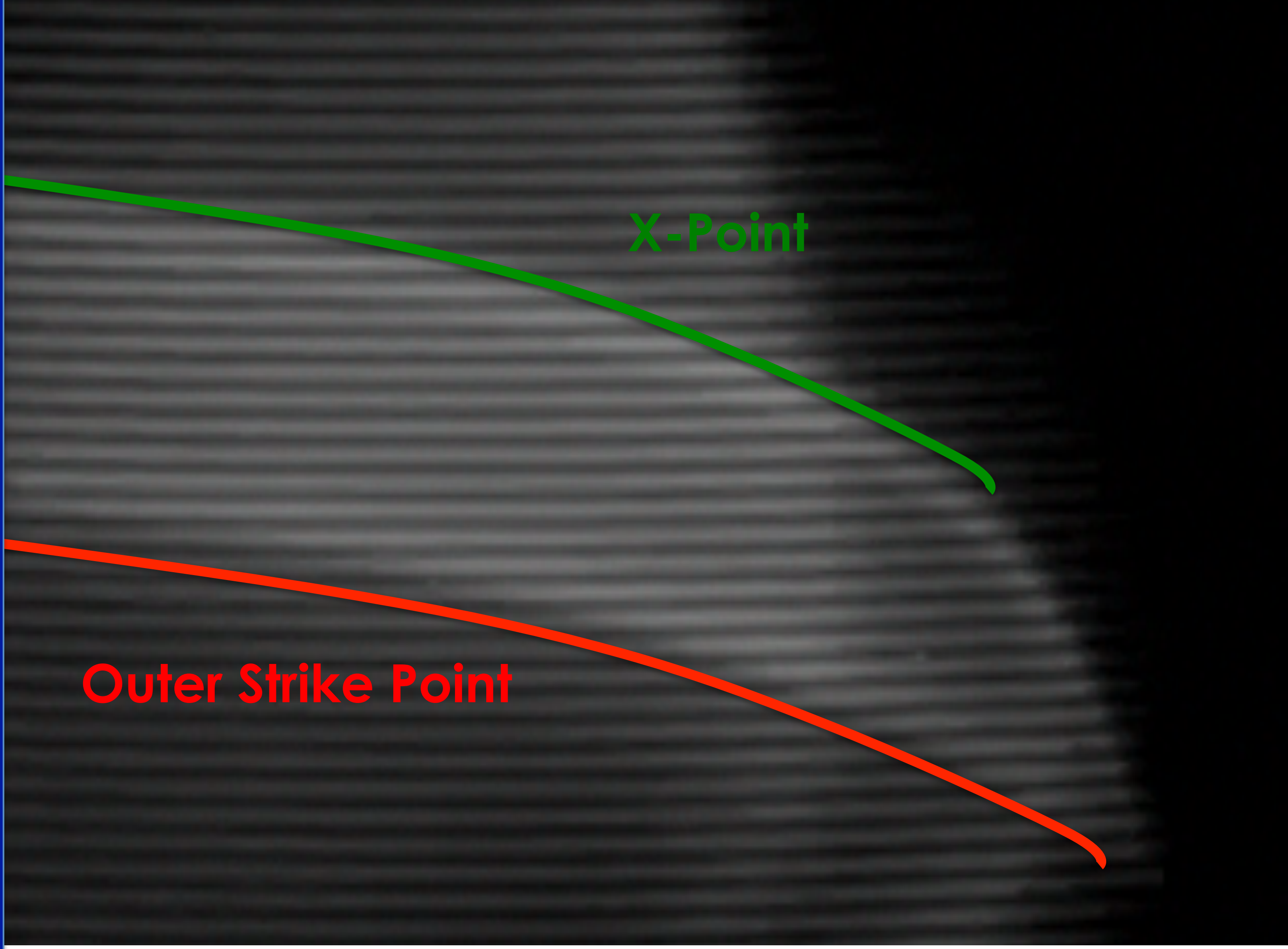
- **Goal:** Keep the ***core density*** *and* ***detachment level constant***
- **Feedback Control Method:**



Detachment Control in Action



Strike Point



Inner Wall

CIII Emission – Visible (465 nm)

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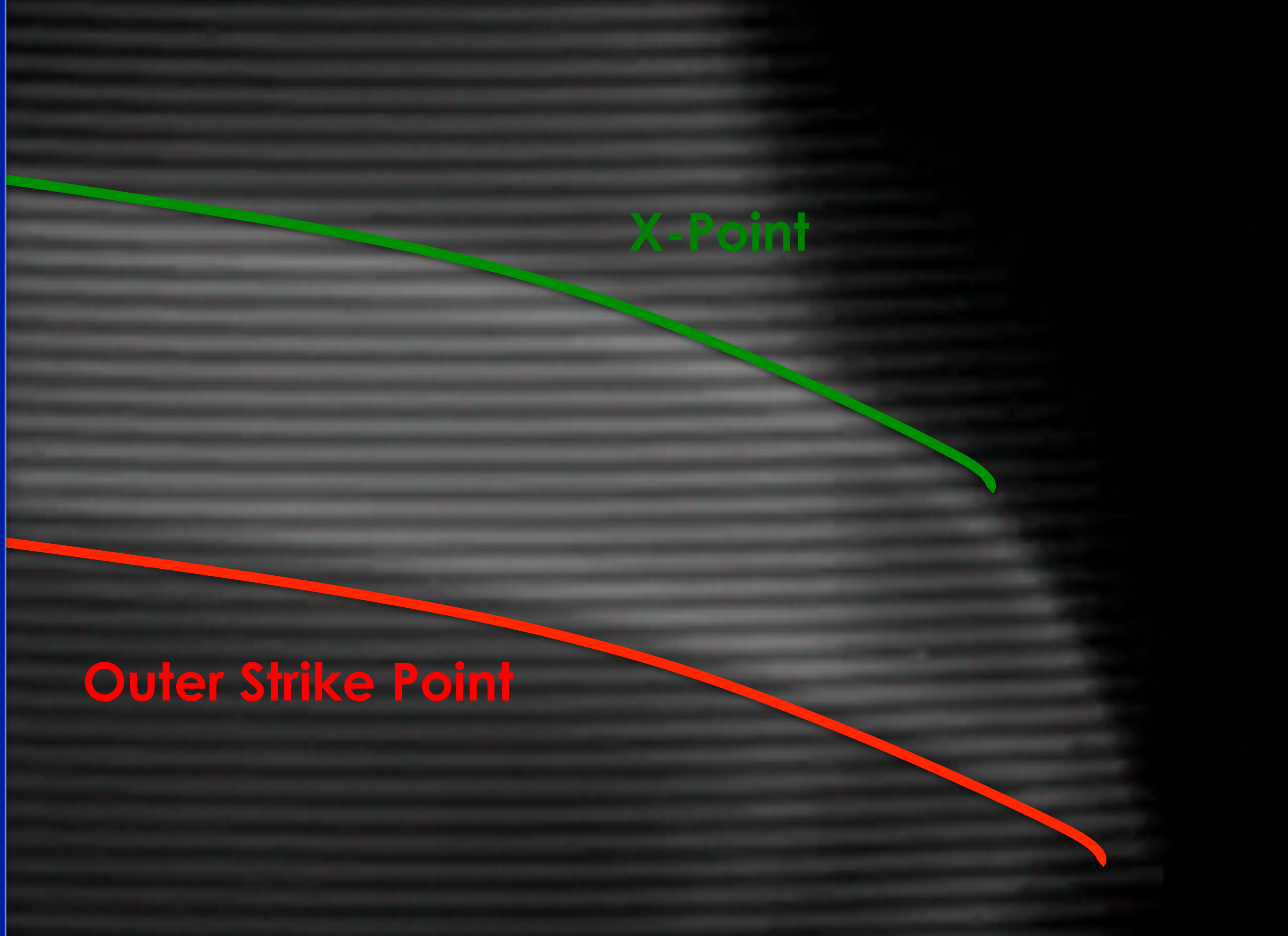
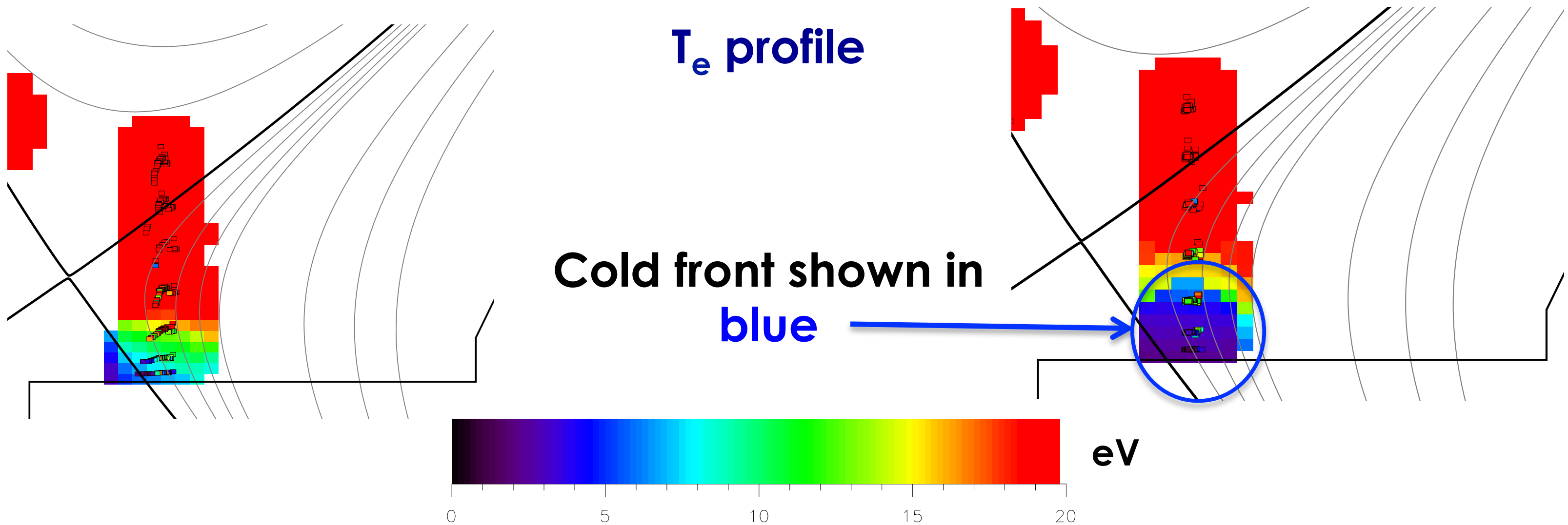


CIII Emission – Visible (465 nm)

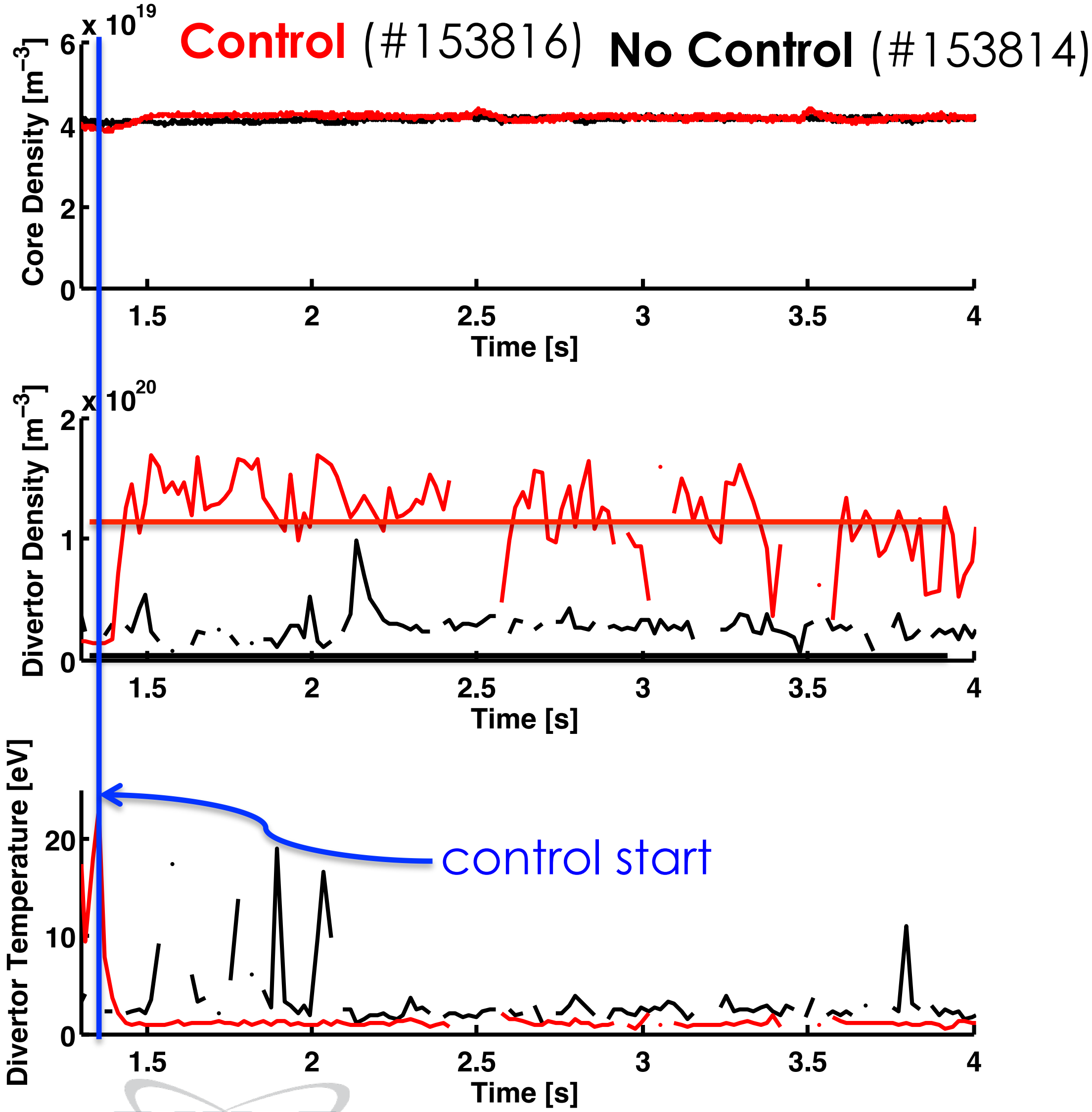
Partial Detachment Control: Forms a Cold Front in L-mode

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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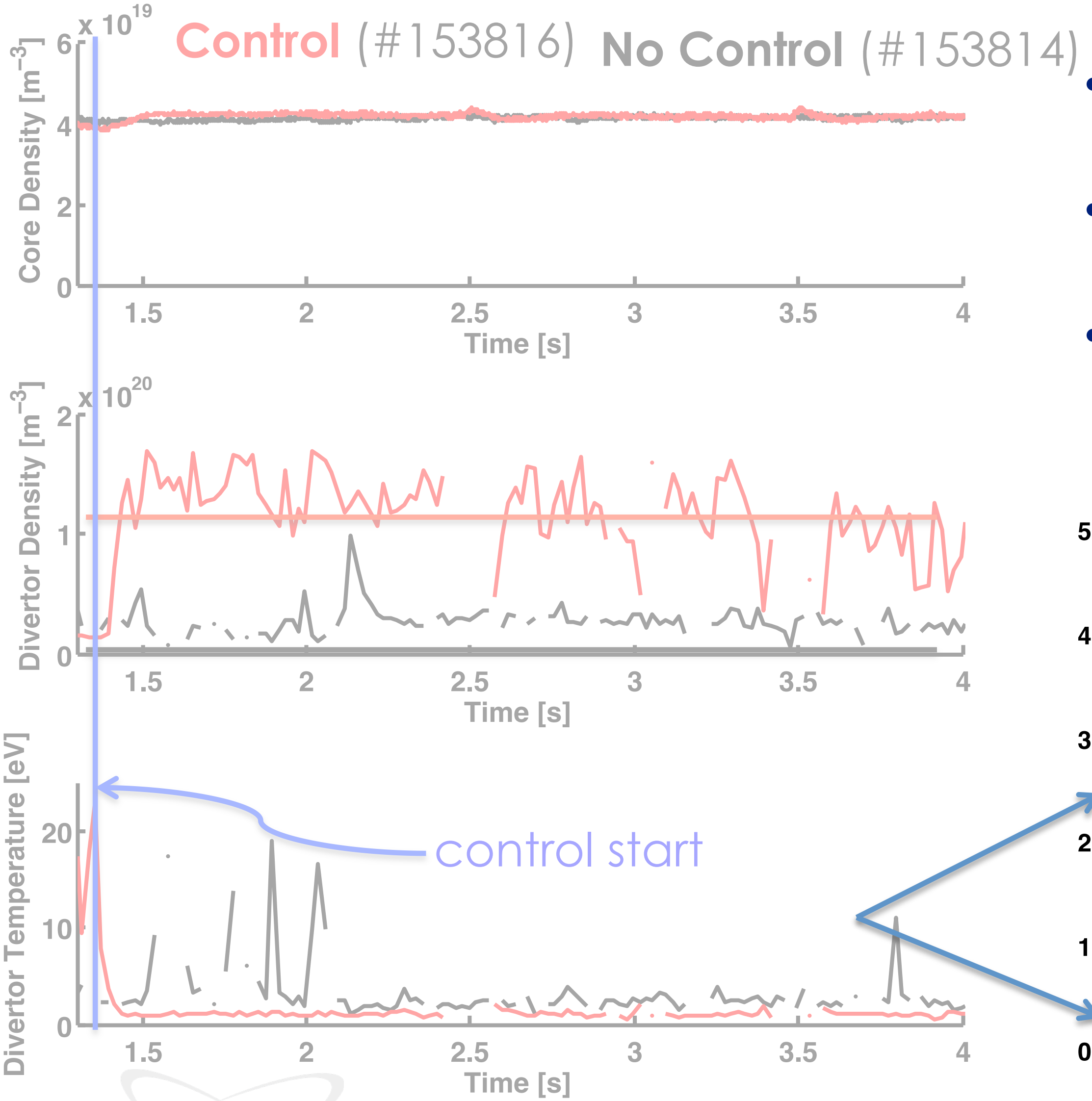

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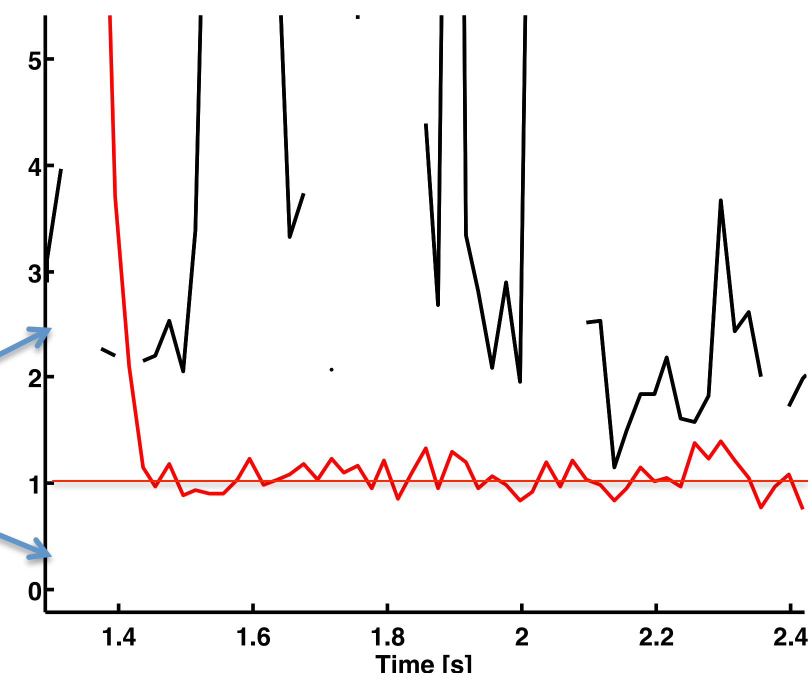

Heat Flux Regulation via

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

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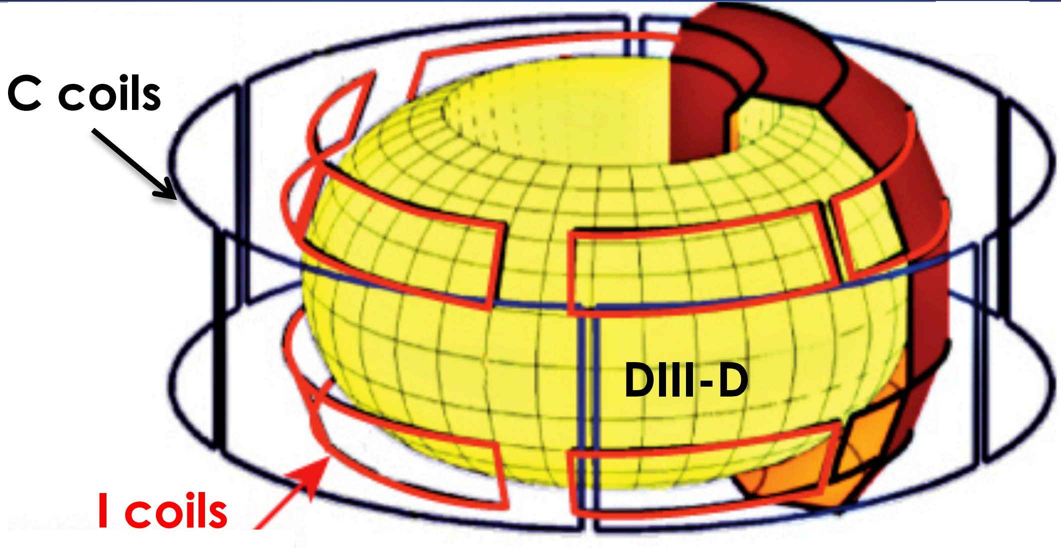
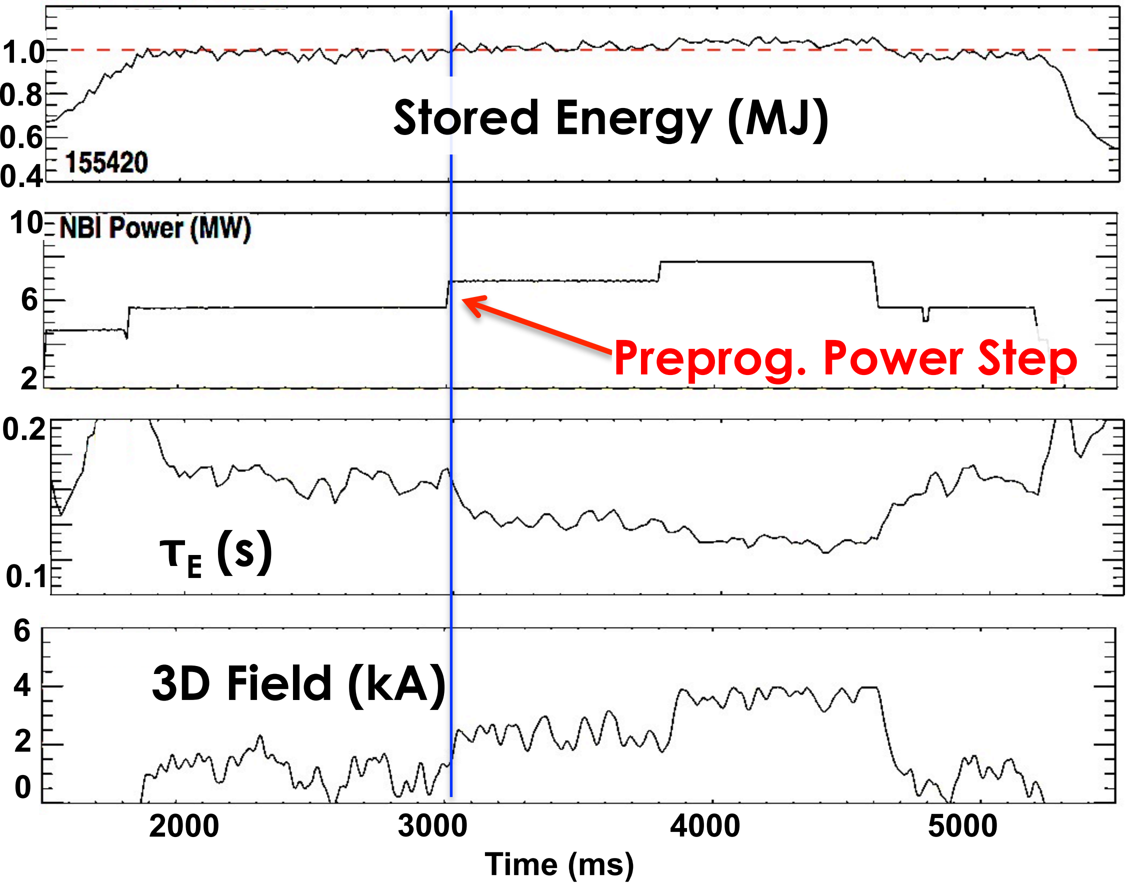
Burn Control by Non-Axisymmetric (3D) Coils (Hawryluk, PPC/P2-33)



- **Burn: D + T ➔ He + n + 17.6 MeV**
- **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
- Faster response without constraining other controls

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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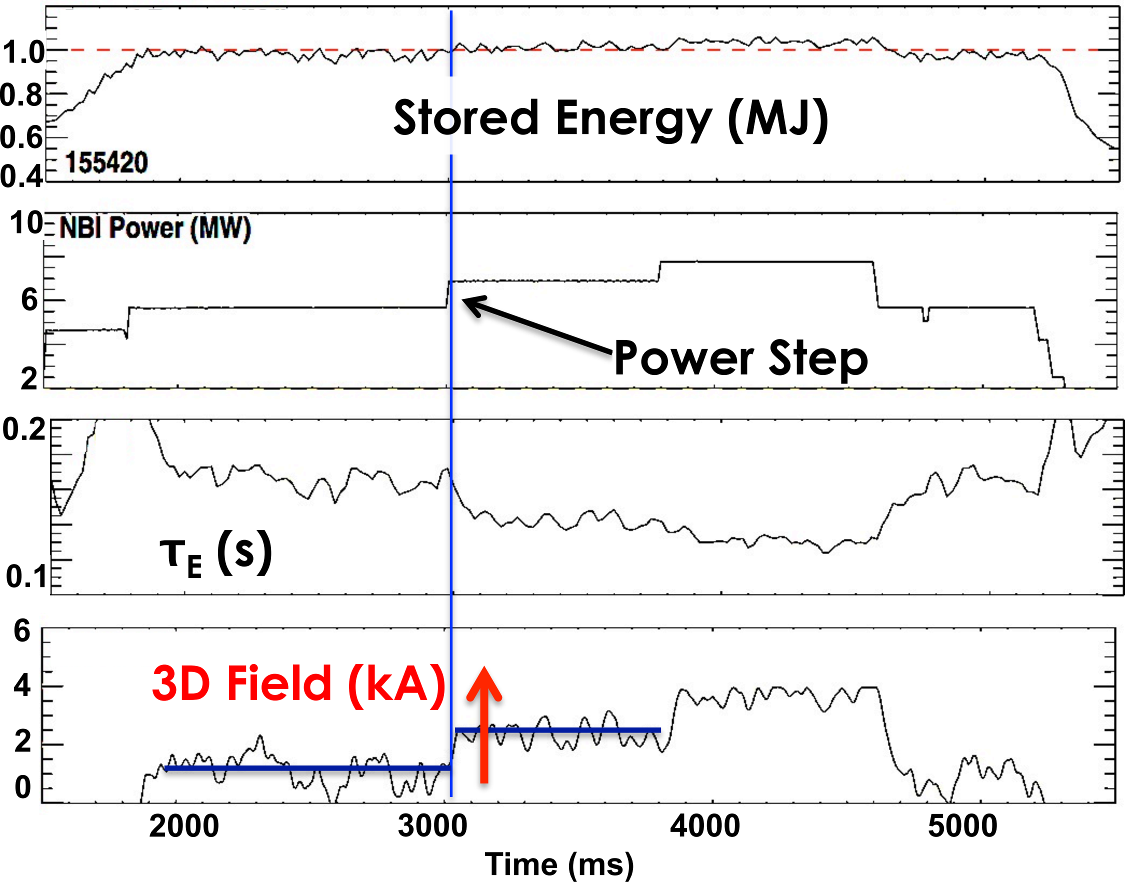

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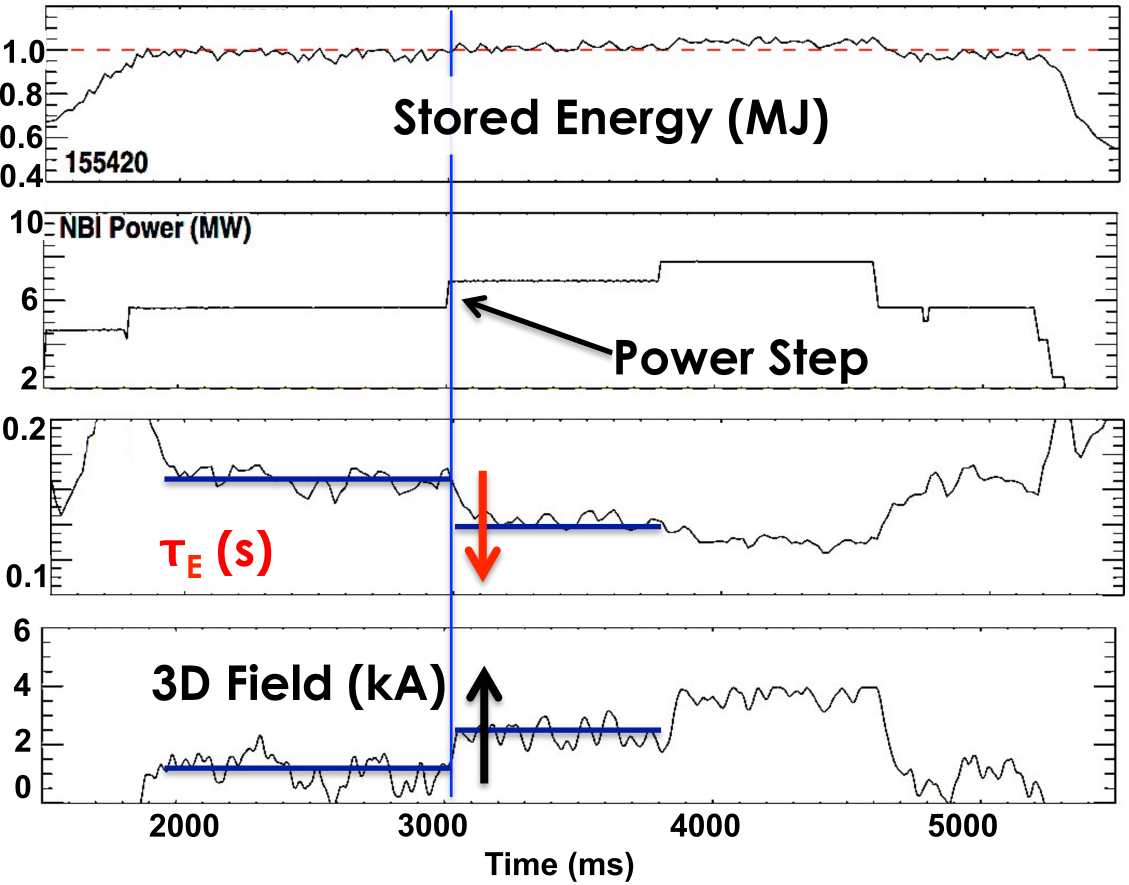

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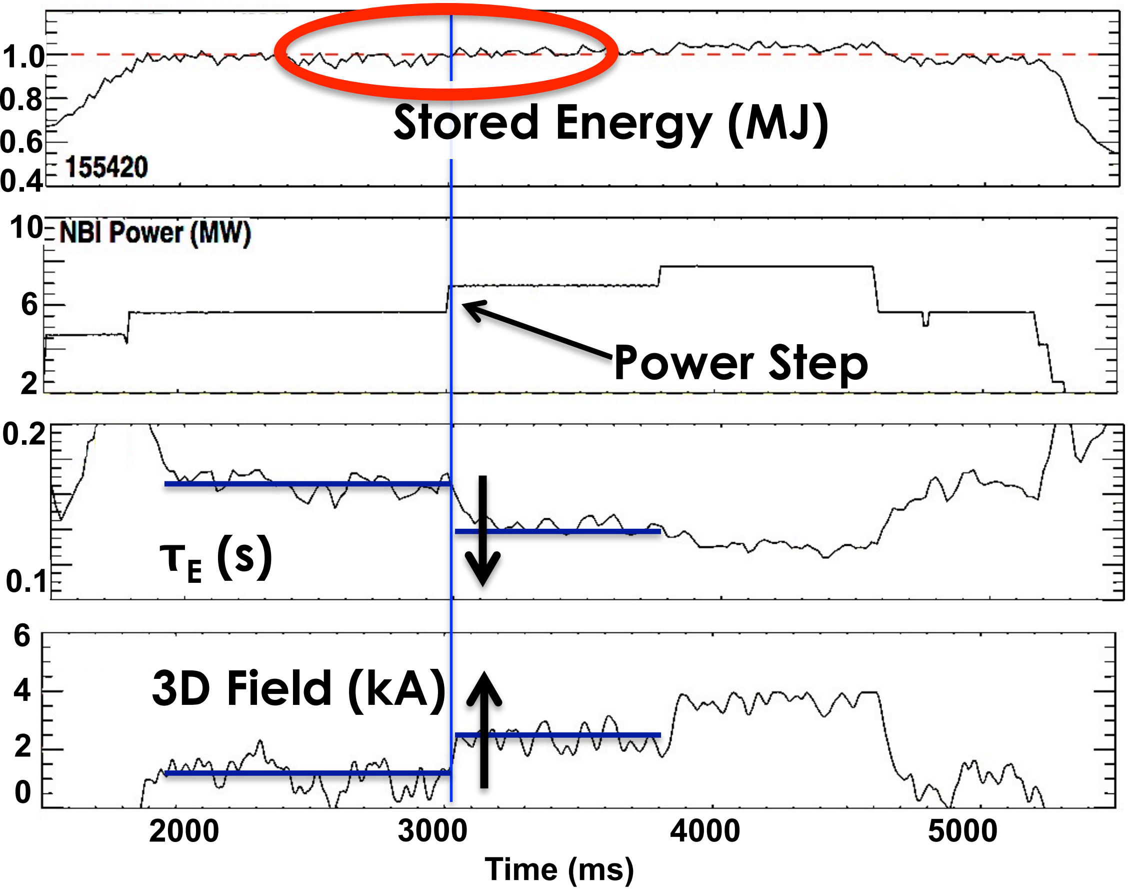

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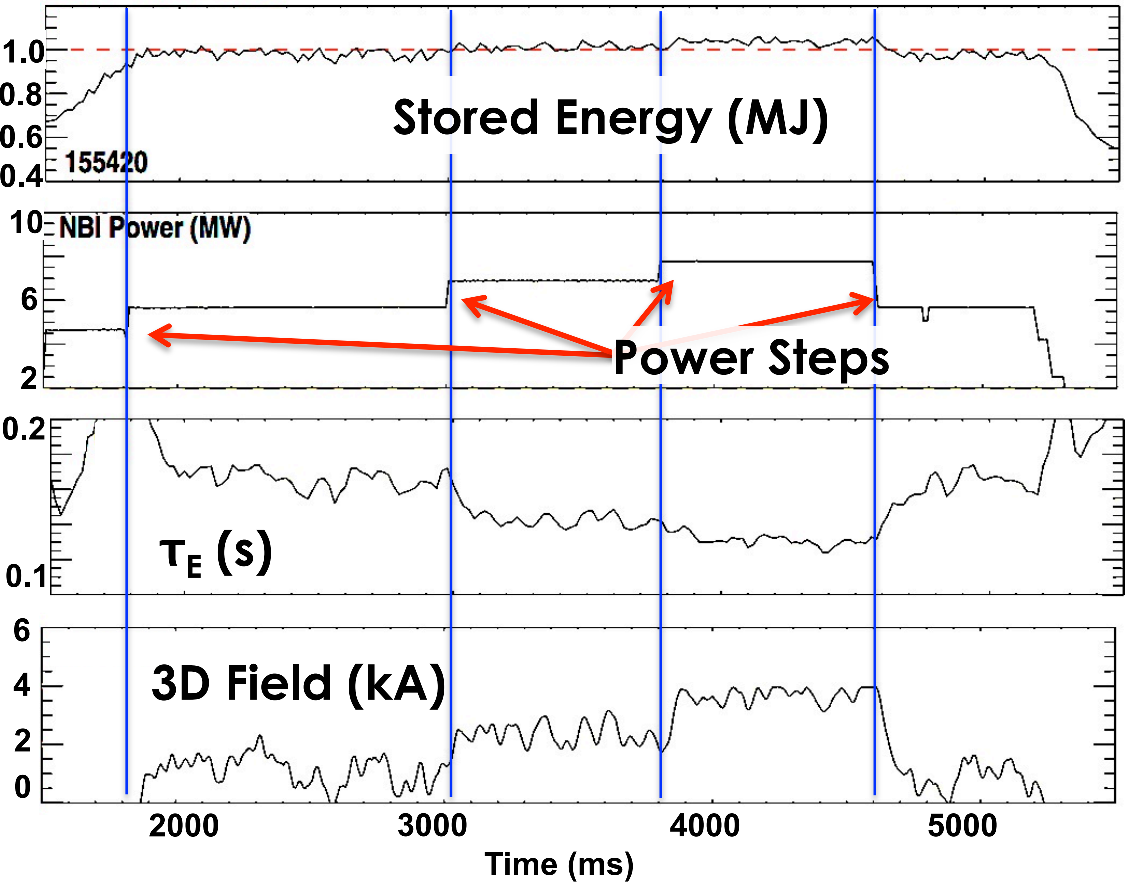

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Conclusion: New Control Solutions Enable Advances in Heat Flux Management

- **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