U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Initial Development of the NSTX-U Snowflake Divertor Control

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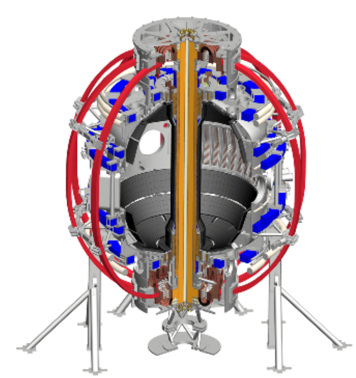
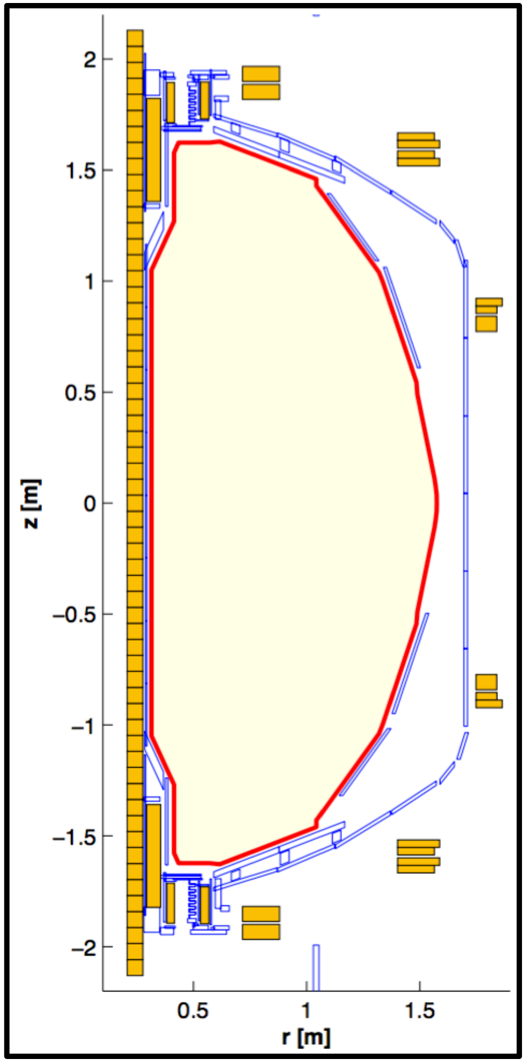
PPPL



Introduction

- The determination of techniques for mitigating the heat flux onto plasma-facing surfaces is a major goal of current tokamak research.
- High heat fluxes to the walls push the limits of present-day engineering materials and active cooling technologies.
- **ITER** – expected that **70-90%** of power will need to be radiated with standard single x-point divertor.[1]
- **NSTX-U** – peak heat fluxes over **20 MW/m²** have been predicted in 2 MA, 12 MW NBI-heated discharges.[2] Long pulse limit for graphite PFCs is **10 MW/m²**.
- **Novel solutions to the heat flux problem are needed.**



NSTX-U Poloidal Cross-Section

[1]Kotschenreuther M. et al 2007. Phys. Plasmas. 14 072502.
[2]Gray T.K. et al 2011. J. Nucl. Mater. 415 S360.

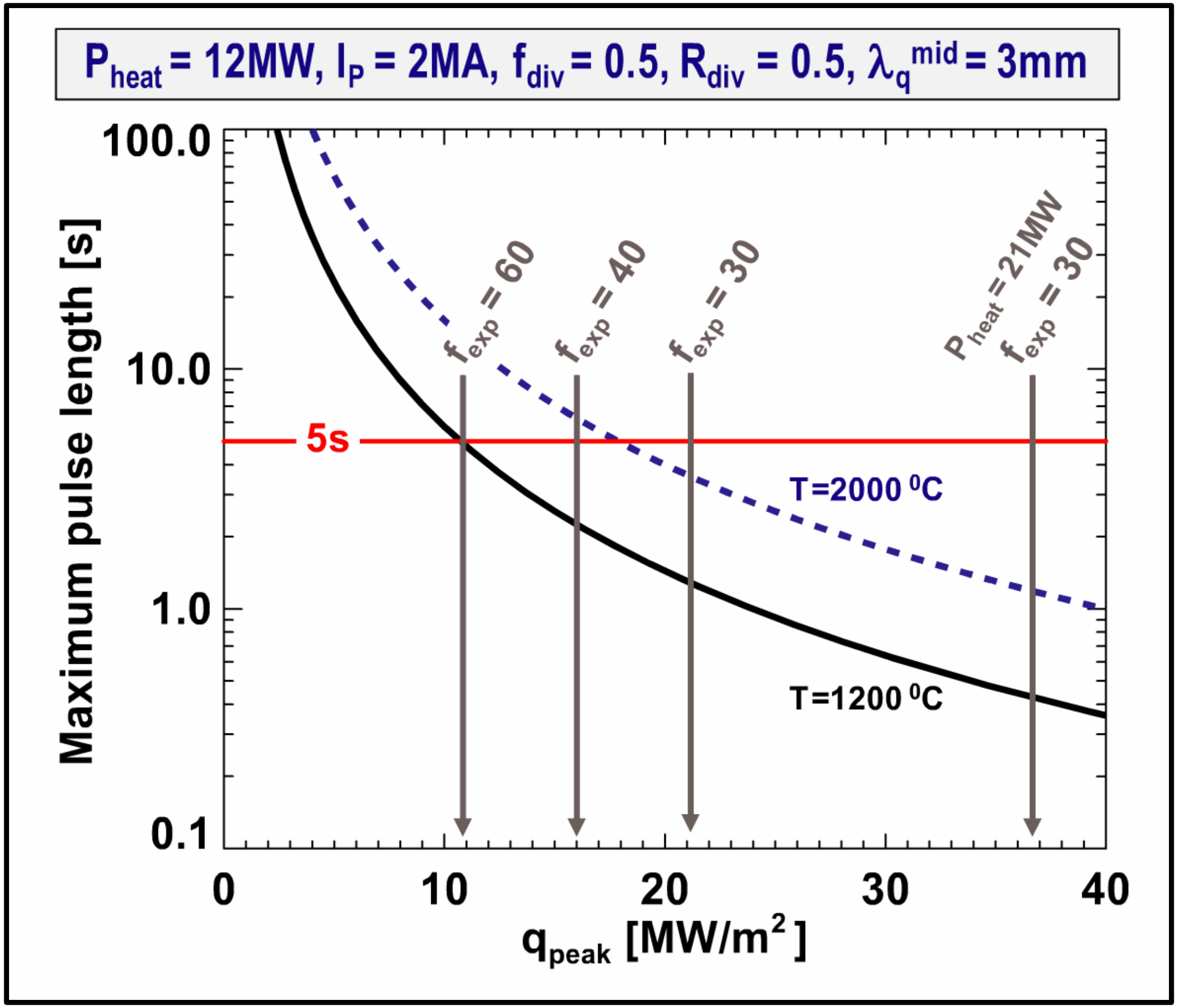
Divertor Heat Flux

$$q_{peak} = \frac{P_{heat}^{SOL}\left(1 - f_{rad}\right) f_{div} \sin\left(\theta_{plate}\right)}{2\pi R_{strike} f_{exp} \lambda_q}$$

q_{peak}	peak heat flux at the divertor strike point (P_{strike}/A_{wetted})
P_{heat}^{SOL}	input heating power to SOL
f_{rad}	fraction of radiated power
f_{div}	fraction of power to divertor leg of interest
θ_{plate}	poloidal angle between divertor plate and magnetic field line
R_{strike}	major radius of divertor strike point
f_{exp}	flux expansion
λ_q	width of heat flux profile in SOL

Stangeby, P.C. *The Plasma Boundary of Magnetic Fusion Devices*. Bristol: IOP Publishing Ltd, 2000.

The Need for High Flux Expansion



Menard J.E. et al 2012. Nucl Fusion. 52 083015.

Advanced Divertors (1)

- Investigation of high flux expansion divertors is a major near-term research goal of the NSTX-U program.

- Two novel magnetic geometries have proven to be attractive candidates for steady-state (and potentially ELM transient) heat flux mitigation – **snowflake** and **x-divertor**

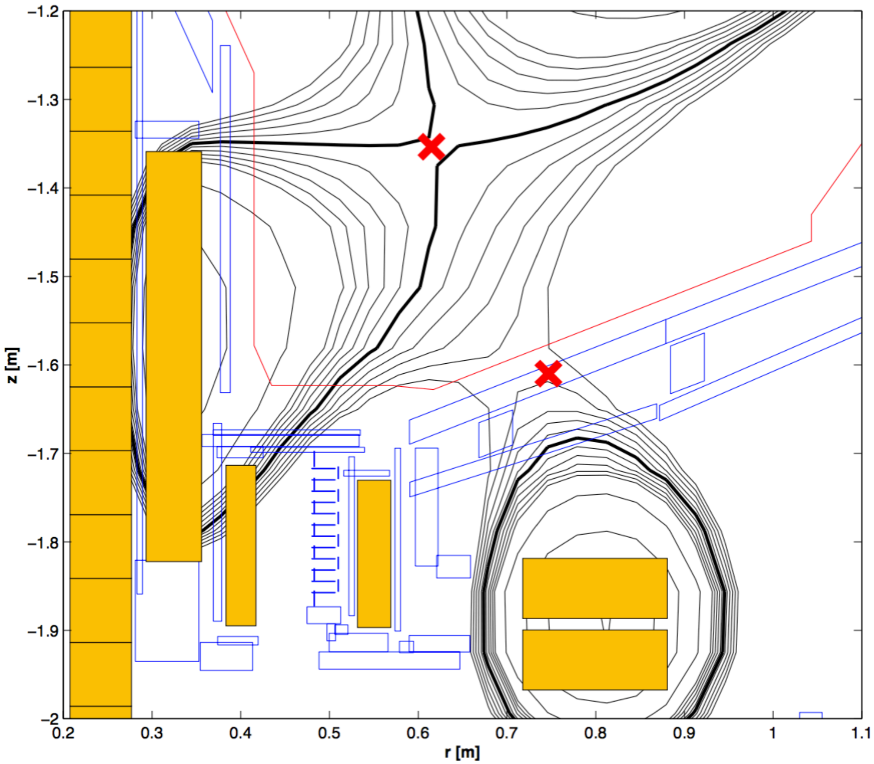
- **These divertors have the following magnetic properties[1]:**
  - higher poloidal flux expansion (compared to single x-point divertor)
  - longer x-point connection length
  - higher divertor flux tube volume
  - Four separatrix branches and strike points

- **SNOWFLAKE** – characterized by a second-order poloidal field null (or two closely-spaced first-order nulls)

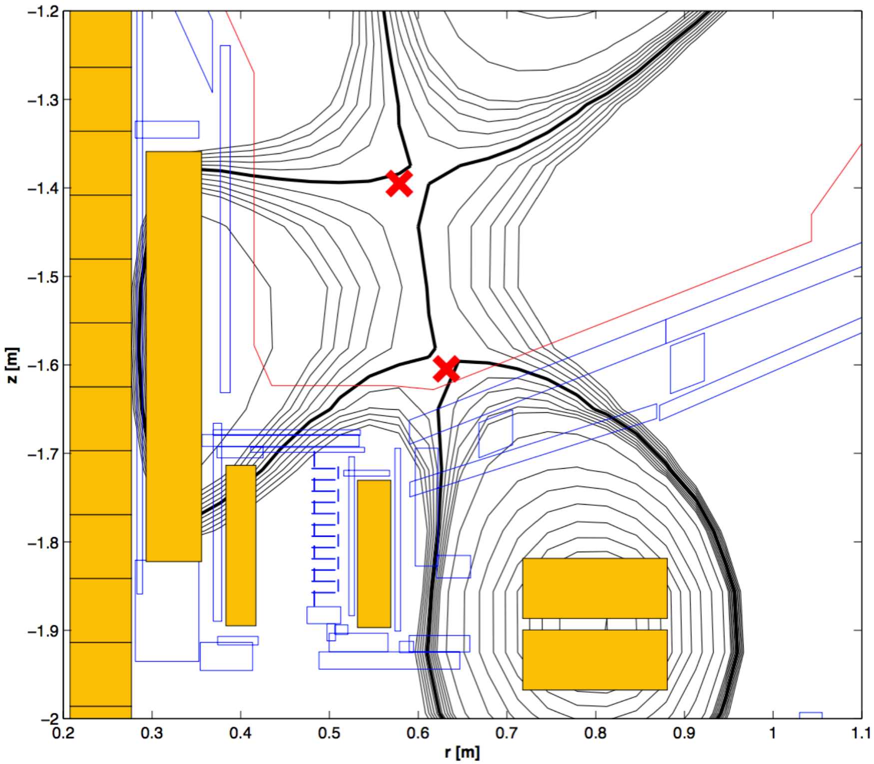
- **X-DIVERTOR** – snowflake-like with the additional property that the secondary null is located in the vicinity of the strike point

[1]Soukhanovskii V.A. et al 2012. Phys. Plasmas. 19 082504.

Advanced Divertors (2)



SNOWFLAKE



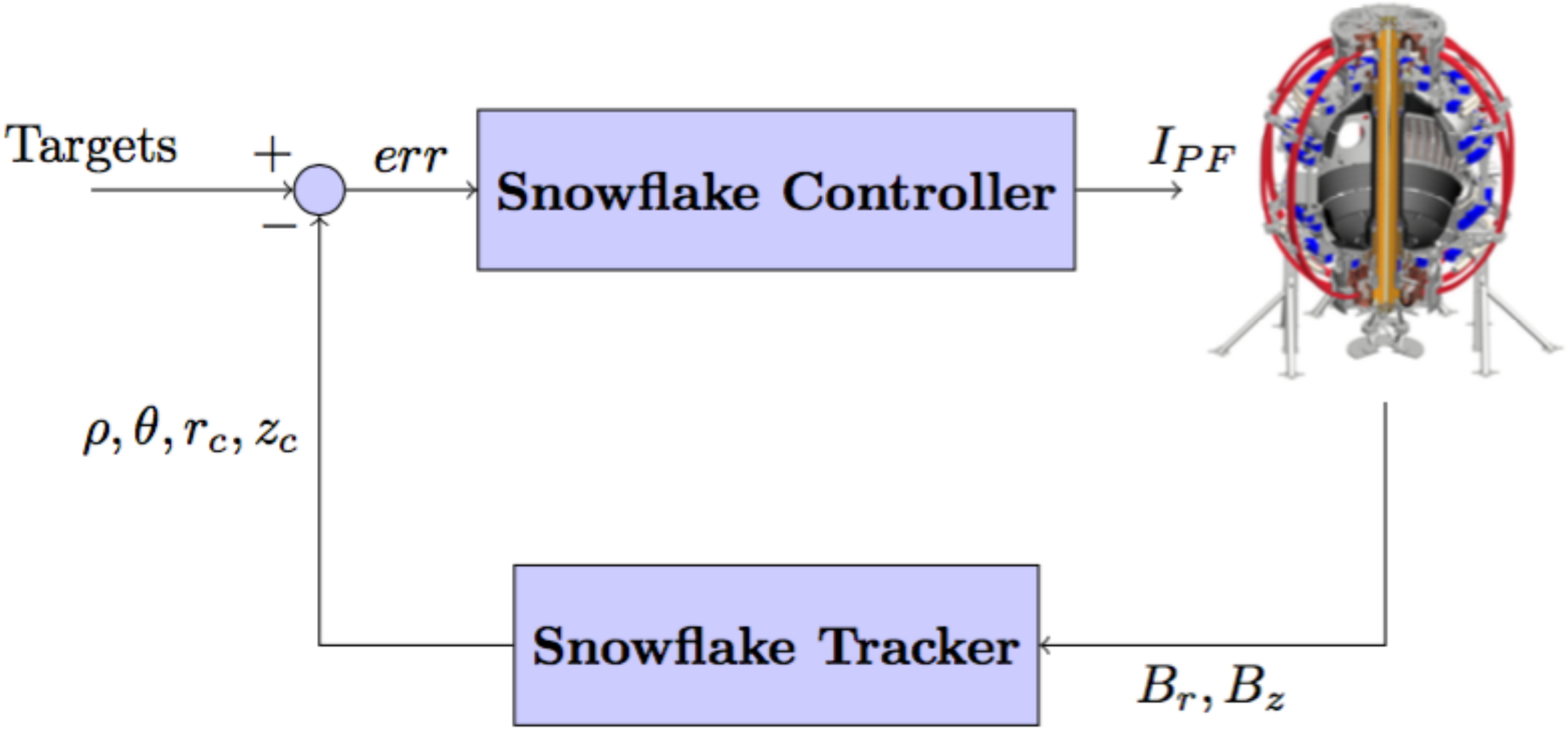
X-DIVERTOR

Advanced Divertor Control

- NSTX experiments demonstrated the need for active magnetic control of snowflake divertor configurations.[1]
- Advanced divertor control presents new challenges – identification and control of multiple x-points and other parameters
- Snowflake / x-divertor tend to be topologically unstable – sensitive to changes in OH coil current, plasma profiles. (to be further characterized)
- Aim is for near-term implementation of the following control capabilities at NSTX-U:
  - **multiple x-point locations (for snowflake divertor)**
  - **strike point location (for x-divertor)**
  - **flux expansion independent of x-point locations**

[1]Soukhanovskii V.A. et al 2012. Phys. Plasmas. 19 082504.

Snowflake Control System



Snowflake Tracker (1)

- Consider the Grad-Shafranov equation with zero current density:

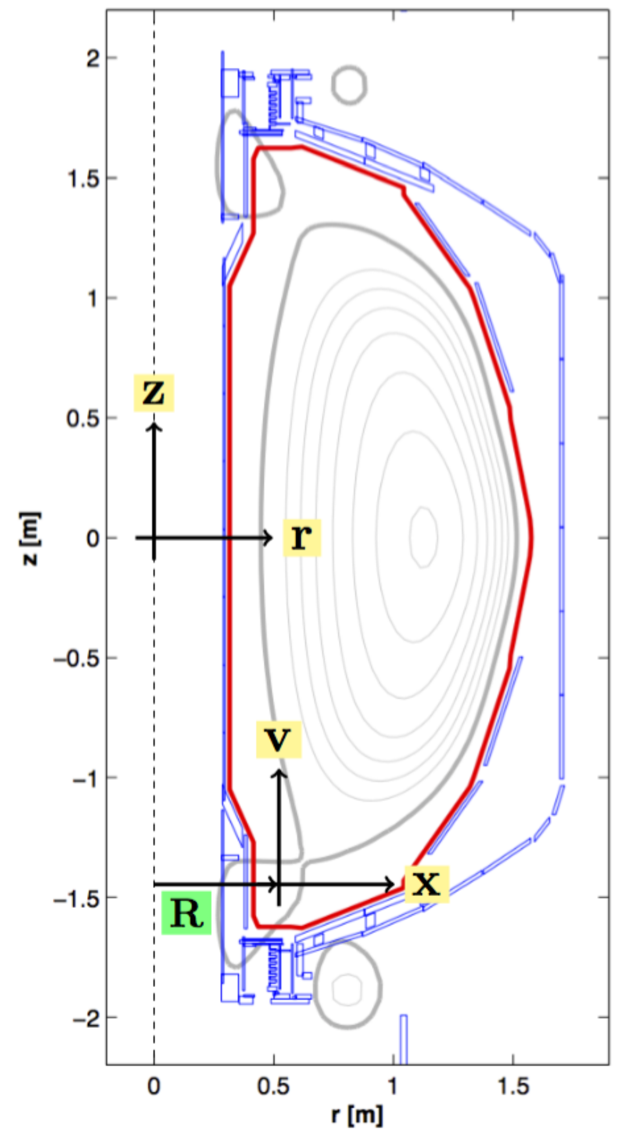
$$(R+x)\frac{\partial}{\partial x}\left(\frac{1}{R+x}\frac{\partial \psi}{\partial x}\right)+\frac{\partial^2 \psi}{\partial v^2}=0$$

where the coordinate system has been shifted to be local to the null point(s) – new variables $\boldsymbol{x}$ and $\boldsymbol{v}$

$$B_x = -\frac{1}{R+x}\frac{\partial \psi}{\partial v} \qquad B_v = \frac{1}{R+x}\frac{\partial \psi}{\partial x}$$

- Then expand the magnetic flux function to third order in the new coordinates

$$\begin{aligned}\psi = {} & l_1 x + l_2 v \\ & + q_1 x^2 + 2 q_2 x v + q_3 v^2 \\ & + c_1 x^3 + c_2 x^2 v + c_3 x v^2 + c_4 v^3\end{aligned}$$



Ryutov, D.D. et al 2010. Plasma Phys. Control. Fusion. 52 105001.

Snowflake Tracker (2)

- The goal is to determine the expansion coefficients under the constraint that $\boldsymbol{\psi}$ approximately satisfies the current-free G-S equation.

- Magnetic field components in terms of 9 expansion coefficients:

$$B_x = -\frac{1}{R+x}\left(l_2 + 2q_2 x + 2q_3 v + c_2 v^2 + 2c_3 x v + 3c_4 v^2\right)$$
$$B_v = \frac{1}{R+x}\left(l_1 + 2q_1 x + 2q_2 v + 3c_1 x^2 + 2c_2 x v + c_3 v^2\right)$$

- Three constraints come from substituting $\boldsymbol{\psi}$ into the G-S equation:

$$-l_1 + 2q_1 R + 2q_3 R = 0$$
$$-2q_1 + 6c_1 R + 2c_3 R = 0$$
$$-2q_2 + 2c_2 R + 6c_4 R = 0$$

- For a second-order null at the origin of the $\boldsymbol{x}, \boldsymbol{v}$ coordinate system: $\boldsymbol{l}$'s and $\boldsymbol{q}$'s $= 0$.

- For a snowflake with two closely separated x-points: $\boldsymbol{l}$'s and $\boldsymbol{q}$'s are small.

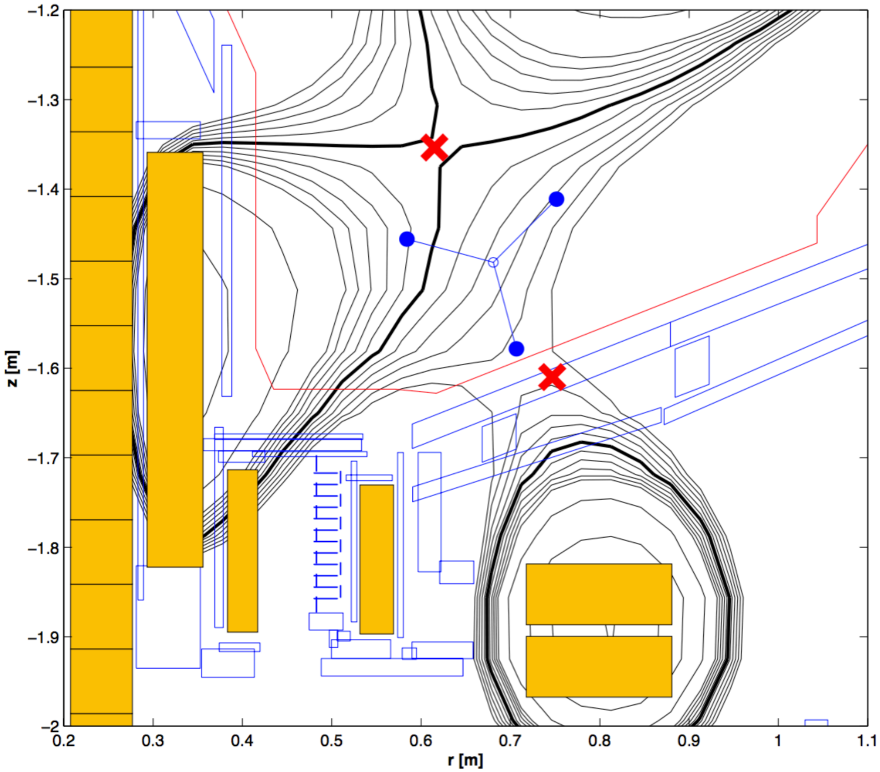
Ryutov, D.D. et al 2010. Plasma Phys. Control. Fusion. 52 105001.

Finding the expansion coefficients

- 6 free expansion coefficients are found by sampling $\boldsymbol{B_x}$ and $\boldsymbol{B_v}$ at three points and then solving the following linear equations for $\boldsymbol{i}$ = {1, 2, 3}.

$$-\left(R+x_i\right)B_{x,i} = l_2 + 2q_2x_i + 2q_3v_i - 3c_4\left({x_i}^2 - v_i^2\right) - 6c_1x_iv_i$$
$$\left(R+x_i\right)B_{v,i} = l_1 - 2q_3x_i + 2q_2v_i + 3c_1\left({x_i}^2 - v_i^2\right) - 6c_4x_iv_i$$

- $\boldsymbol{B_x}$ and $\boldsymbol{B_v}$ obtained in real-time from rtEFIT.



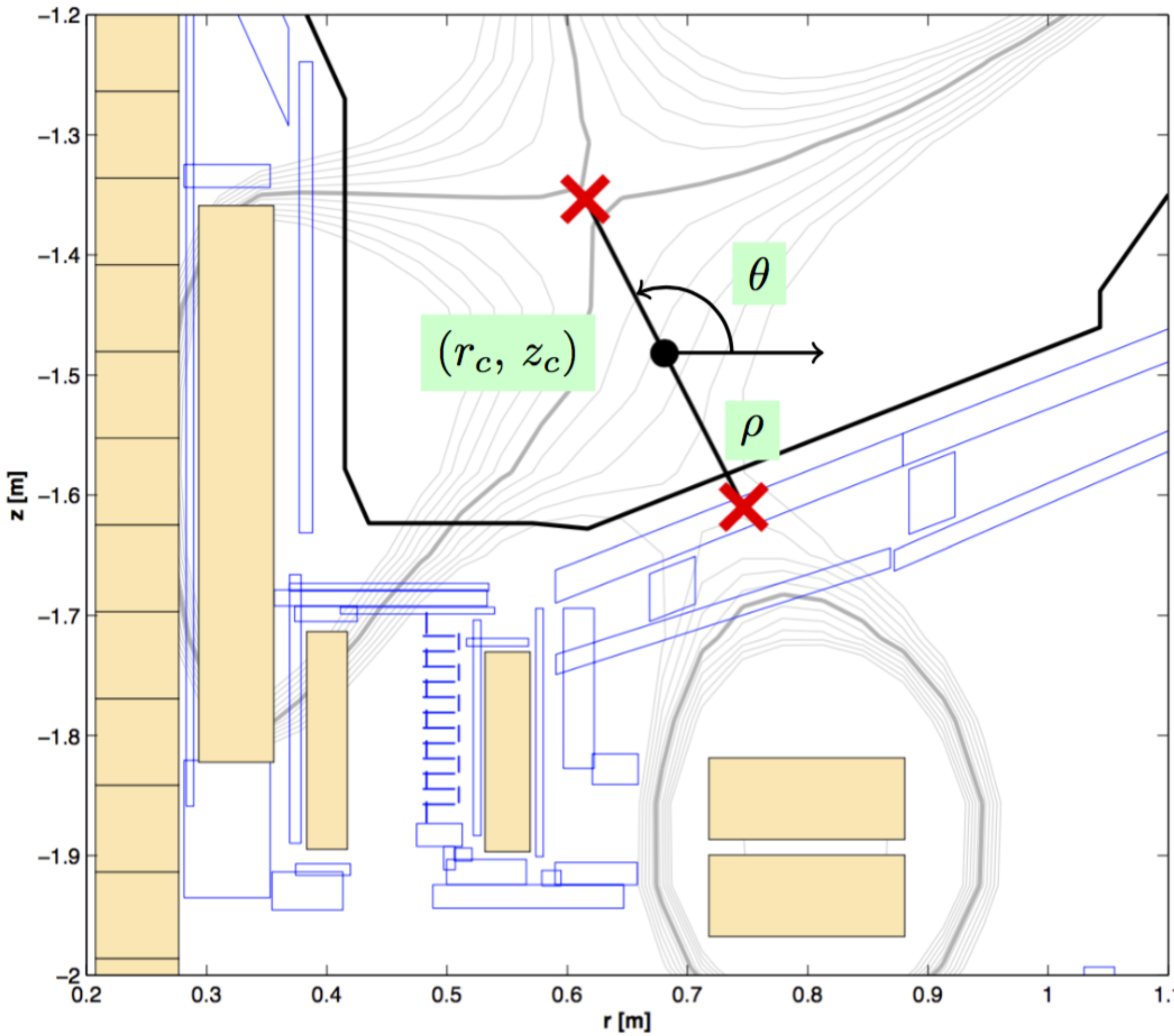
Snowflake Geometry

Consider a polar coordinate system local to the x-points.

Snowflake geometry then defined by four parameters:

- $\boldsymbol{r_c}$ **and** $\boldsymbol{z_c}$ – coordinates of the polar coordinate system origin (centroid) relative to the tokamak
- $\boldsymbol{\rho}$ – radial distance between x-point and centroid
- $\boldsymbol{\theta}$ – angle as defined in the figure (right)

Goal is independent control of each parameter.



Snowflake Controller

1. Calculate Jacobian matrix $\boldsymbol{J}$ that maps changes in coil currents to changes in snowflake location.

$$\begin{bmatrix} \delta\rho \\ \delta\theta \\ \delta r_c \\ \delta z_c \end{bmatrix} = \mathbf{J} \begin{bmatrix} \delta I_{PF2L} \\ \delta I_{PF1CL} \\ \delta I_{PF1AL} \end{bmatrix}$$

2. Take the pseudoinverse of $\boldsymbol{J}$ and compute the set of coil currents that minimizes error between current and target snowflake location.

$$\begin{bmatrix} \delta I_{PF2L} \\ \delta I_{PF1CL} \\ \delta I_{PF1AL} \end{bmatrix} = \left(\mathbf{J}^{\intercal}\mathbf{J}\right)^{-1}\mathbf{J}^{\intercal} \begin{bmatrix} \delta\rho \\ \delta\theta \\ \delta r_c \\ \delta z_c \end{bmatrix}$$

3. Pass $\boldsymbol{\delta I}$'s through PID controller and then output voltage commands to PF coils.

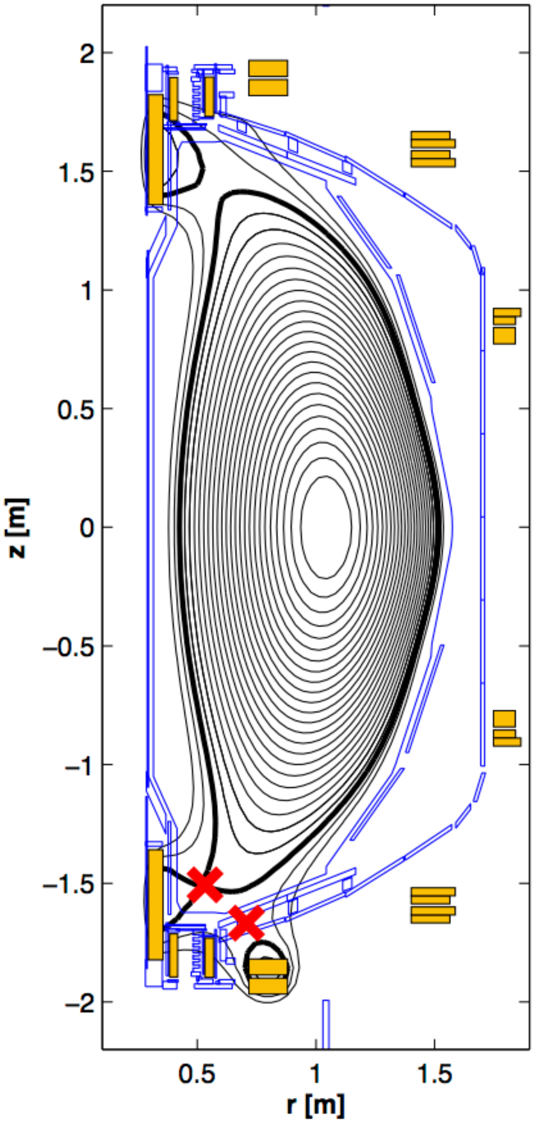
$$V_j\left(t\right) = R_j \times \left[I_j\left(t-1\right) + K_{p,j}\left(\Delta I_j\left(t\right) + \frac{1}{T_{i,j}}\int_0^t \Delta I_j\left(\tau\right)d\tau + T_{d,j}\frac{d\Delta I_j\left(t\right)}{dt}\right)\right]$$

Simulation

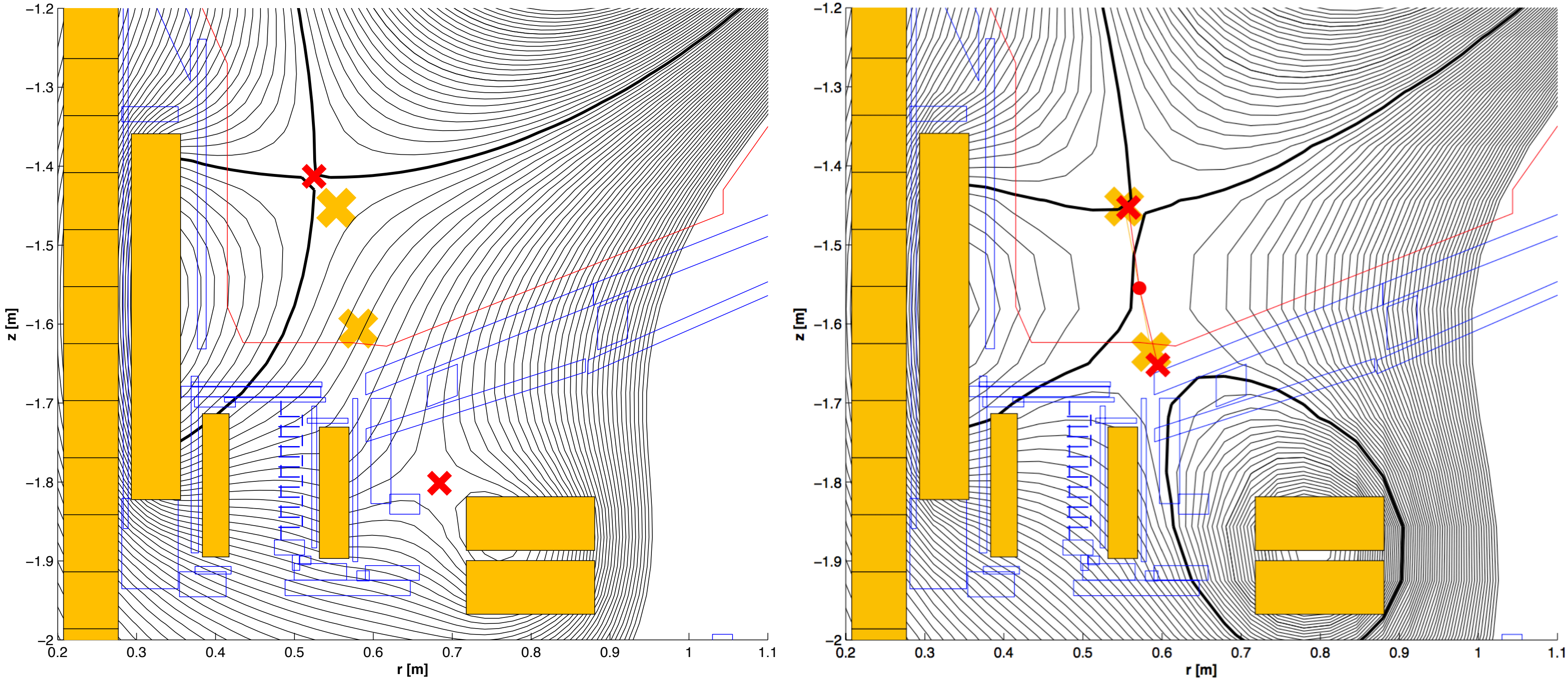
- Snowflake tracking and coil current computations have been simulated in TokSys for expected FY2016 NSTX-U plasmas.

- PF2L, PF1CL, and PF1AL coils used for control.

I_p	1 MA
B_T	0.65 T
β_p	1.07
l_i	0.65
Configuration	lower-null
Inner Gap	11.1 cm
Outer Gap	5.9 cm
κ	2.62



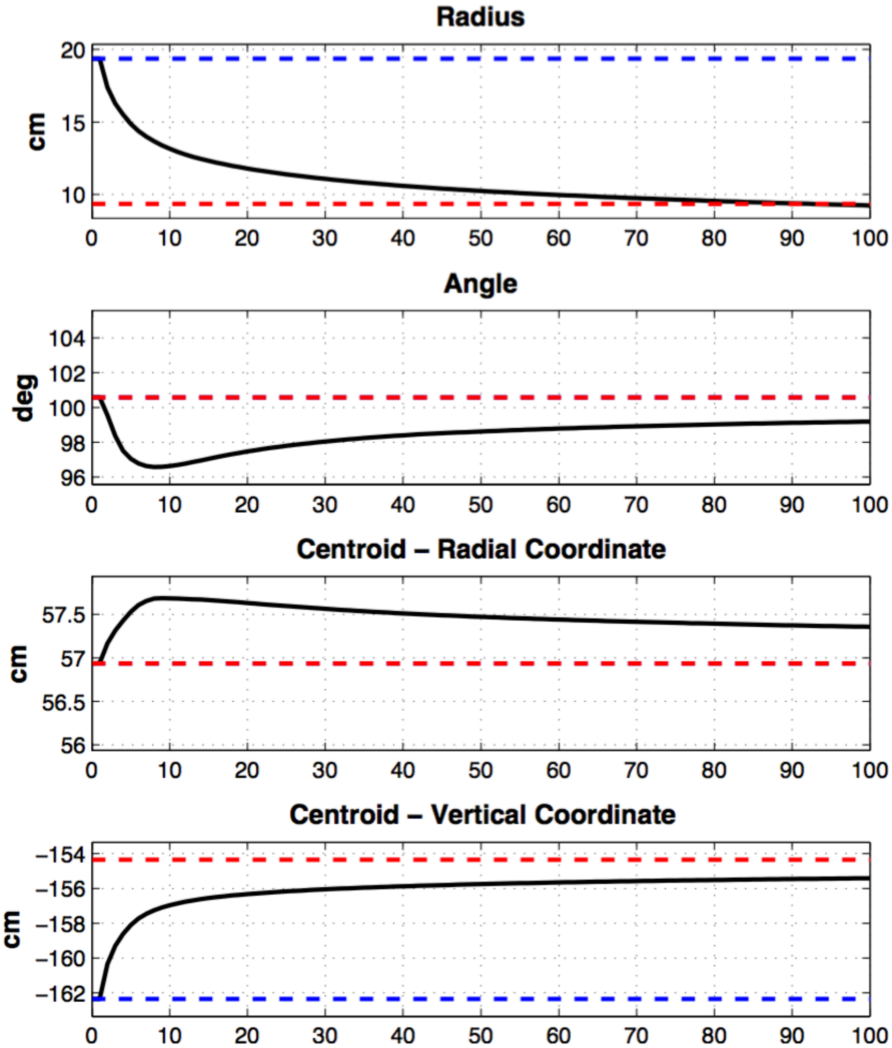
Single X-Point to Snowflake Minus

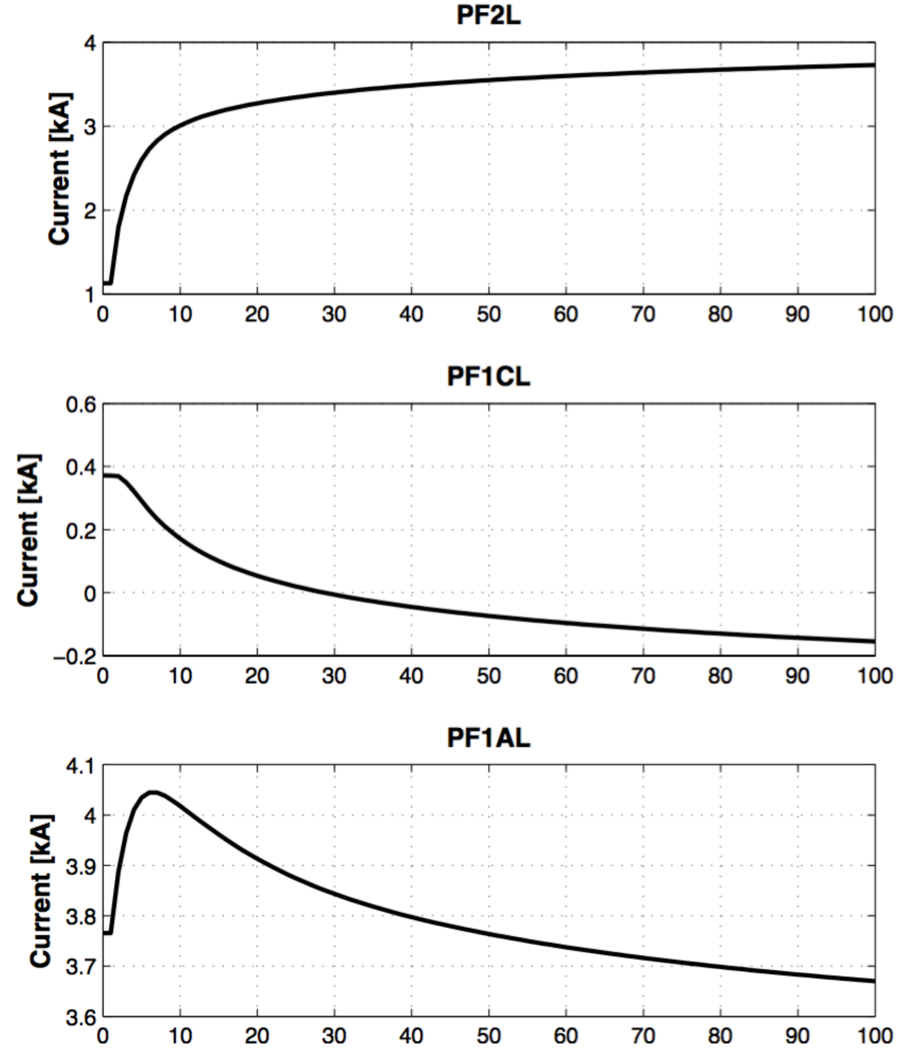


Red – current location

Gold – target location

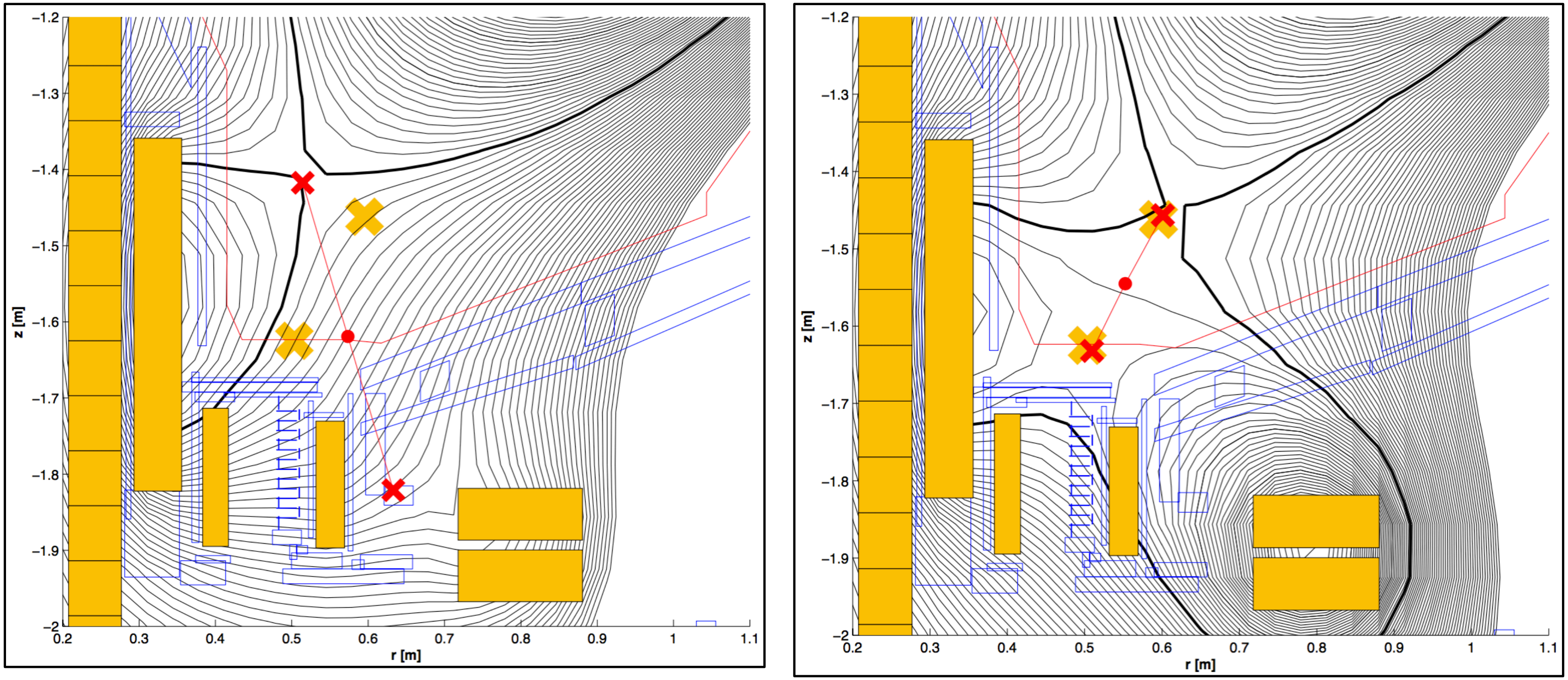
Single X-Point to Snowflake Minus





--- **Initial** --- **Target**

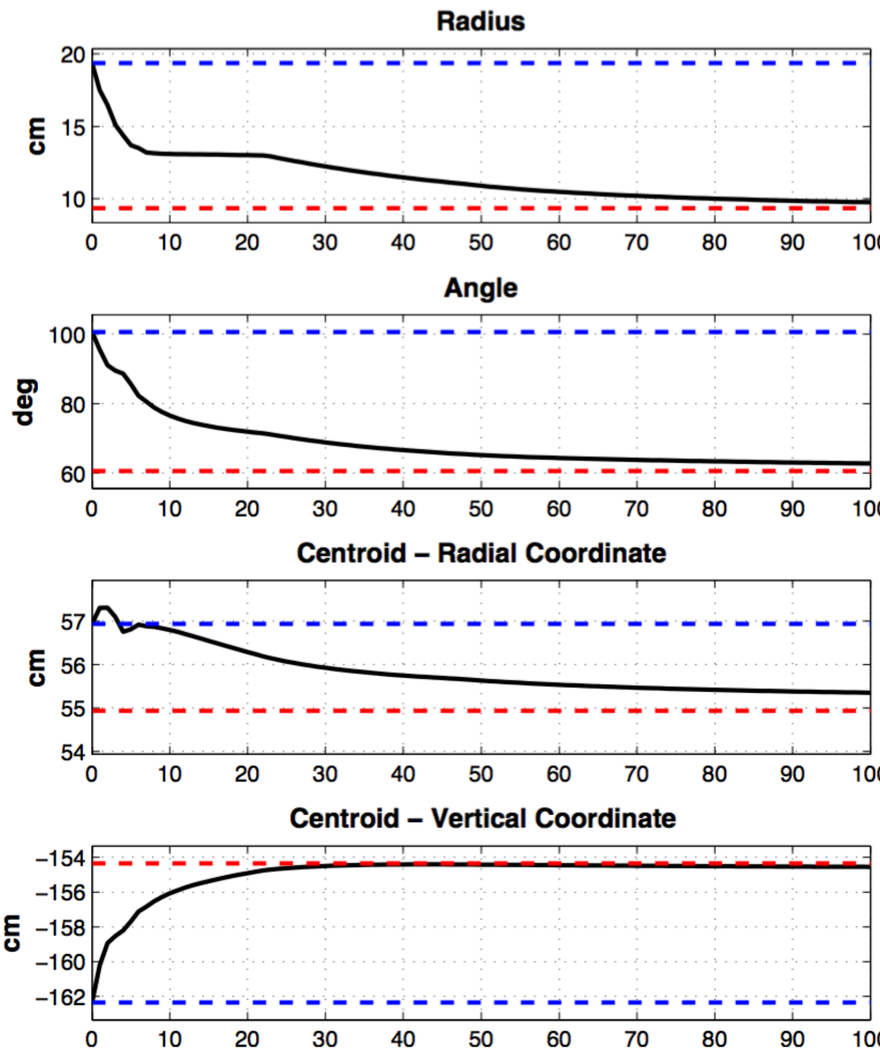
Single X-Point to Snowflake Plus

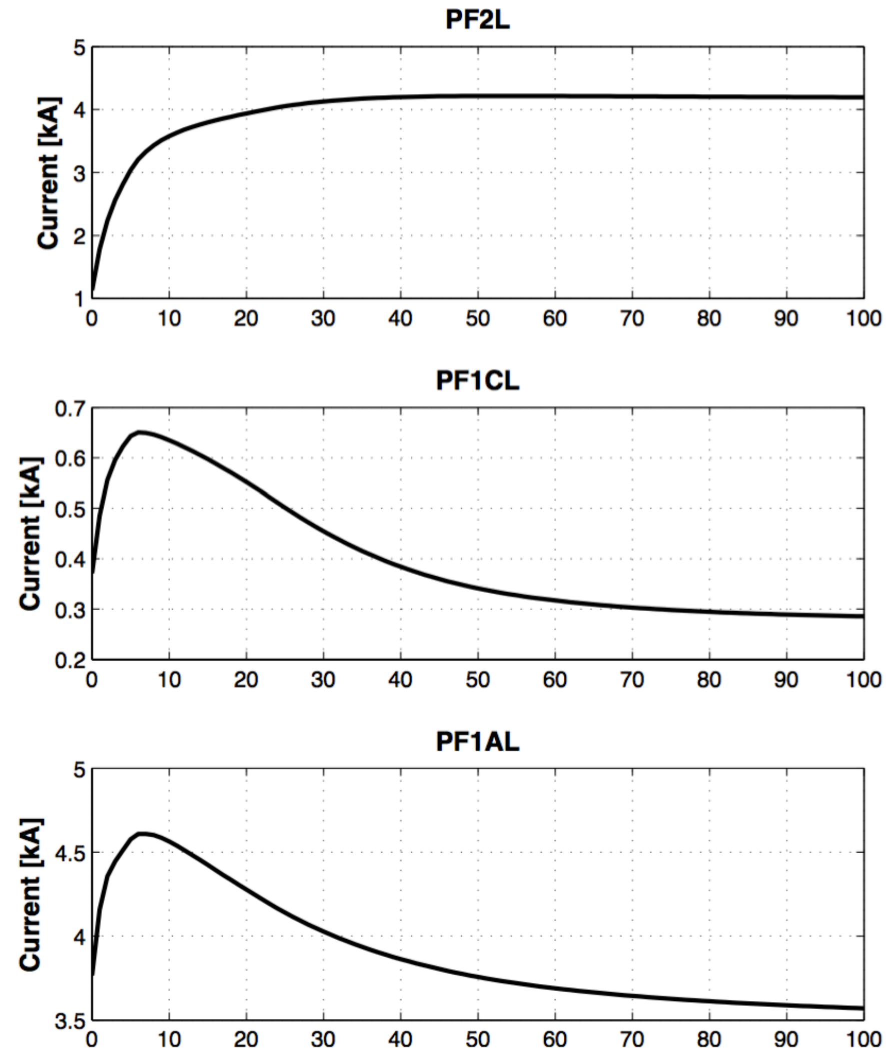


Red – current location

Gold – target location

Single X-Point to Snowflake Plus





--- Initial --- Target

Strike Point Control (1)

1. Locate and calculate the flux at the primary x-point, calculate flux at the target strike point location, and then calculate the flux error as follows:

$$\Delta\psi = \psi_{strike,targ} - \psi_{xpt}$$

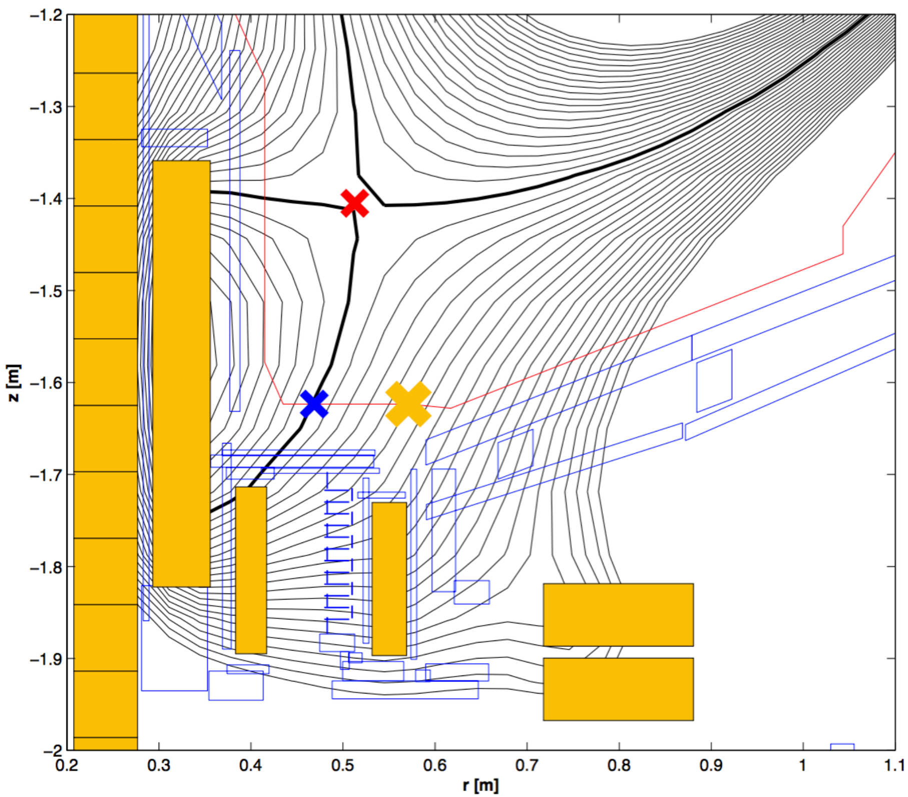
2. Calculate the Jacobian matrix $\boldsymbol{J}$ that maps changes in coil currents to changes in $\boldsymbol{\psi}$ at the target strike point location, where the entries of $\boldsymbol{J}$ are the mutual inductances $\boldsymbol{M_{ij}}$ between coils and target strike point:

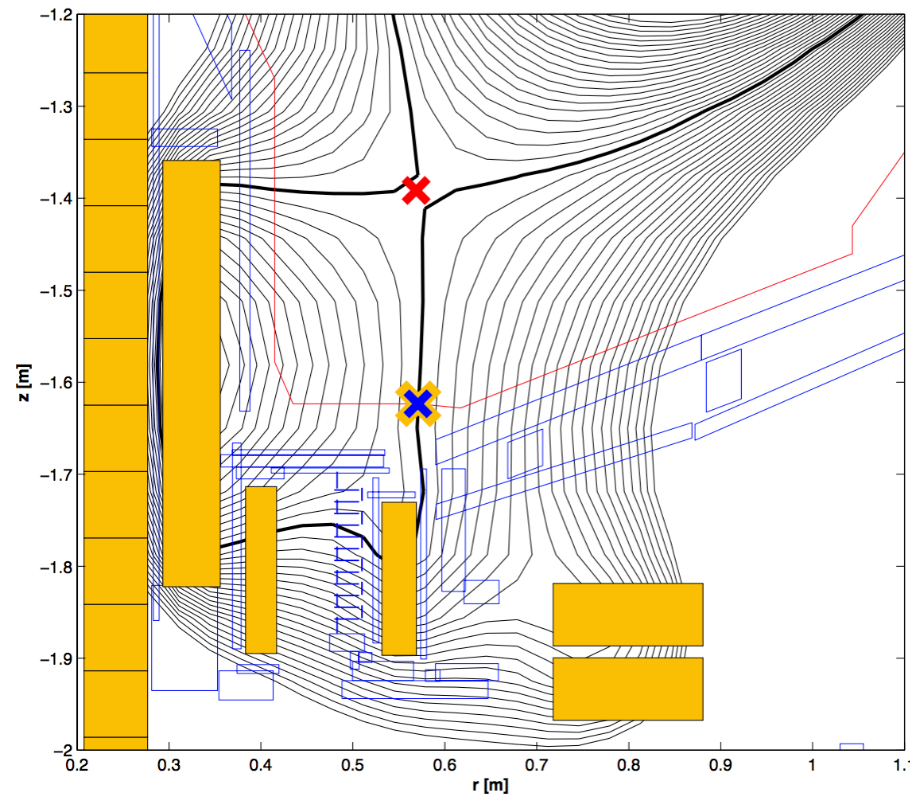
$$\Delta\psi = \mathbf{J}\begin{bmatrix}\delta I_{PF2L}\\ \delta I_{PF1CL}\\ \delta I_{PF1AL}\end{bmatrix}$$

3. Take the pseudoinverse of $\boldsymbol{J}$ and compute the set of coil currents that minimizes the error between current and target strike point location:

$$\begin{bmatrix}\delta I_{PF2L}\\ \delta I_{PF1CL}\\ \delta I_{PF1AL}\end{bmatrix} = (\mathbf{J}^{\intercal}\mathbf{J})^{-1}\mathbf{J}^{\intercal}\Delta\psi$$

Strike Point Control (2)





Red – x-point location

Blue – current strike point location

Gold – target strike point location

Strike Point Control (3)