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Fast scenario design for alternative magnetic diverted discharge on EAST

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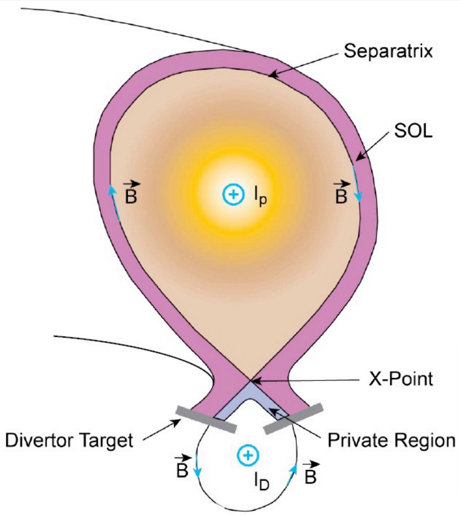
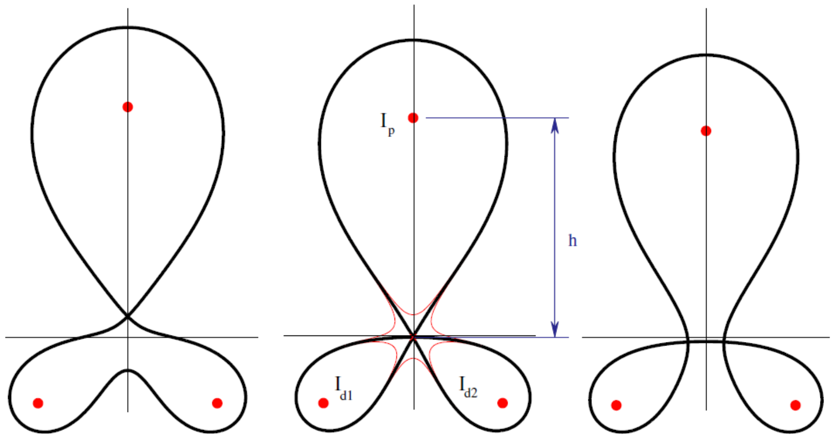
Motivation



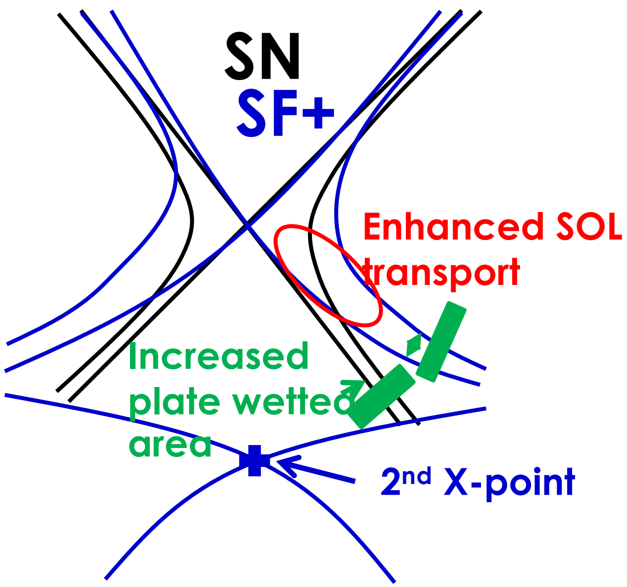
Diverted configuration (SN)



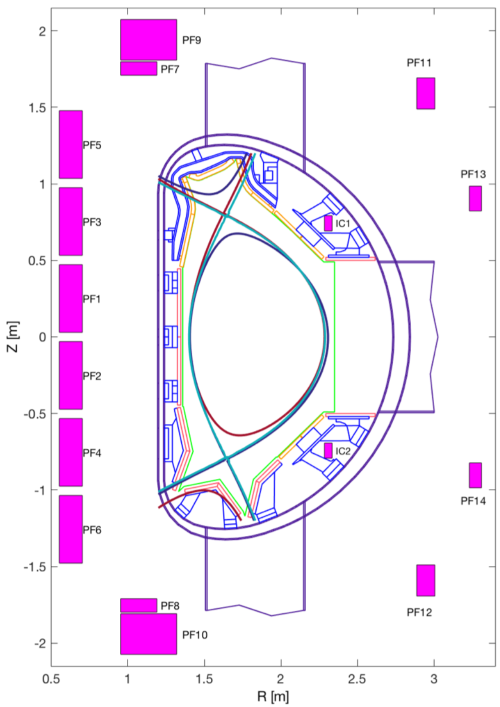
Snowflake

- High heat load on target plates is one of the critical issues for high-power long-pulse operations

- Alternative divertor configurations such as snowflake divertor is one of the attractive methods to reduce the heat flux;



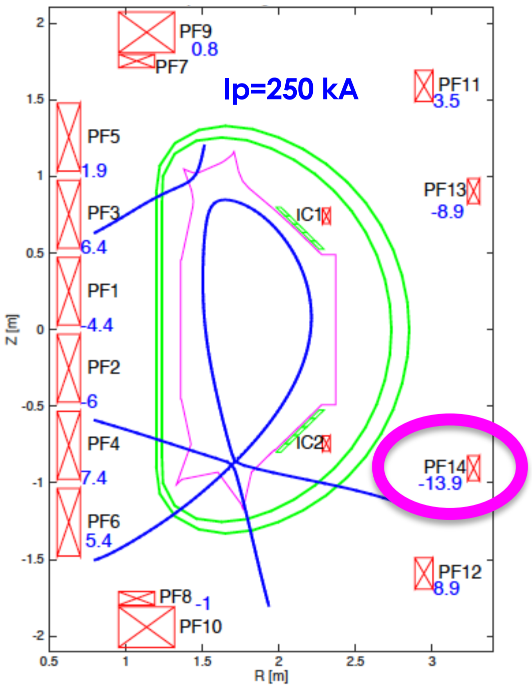
Alternative diverted configuration in EAST



EAST is a fully superconducting tokamak with ITER-like magnetic field configurations and heating schemes

- 14 PFs: 14kA/turn & 12 PSs
- DN/SN
- Far from plasma in comparison to normal tokamaks
  - ✗ **Not optimized for alternative diverted configurations** (like SF)

Alternative diverted configuration in EAST



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- **Higher Ip** requires coil currents **exceed limit**

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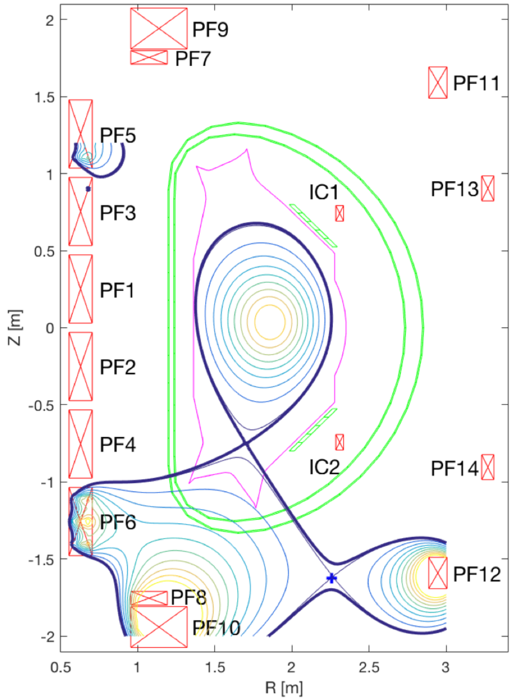
Alternative diverted configuration in EAST



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❋ Alternative diverted configuration, named after Quasi-SnowFlake (QSF), characterized by two first-order X-points where one is located in the primary separatrix and the other is outside the vessel, can easily achieved and controlled on EAST.

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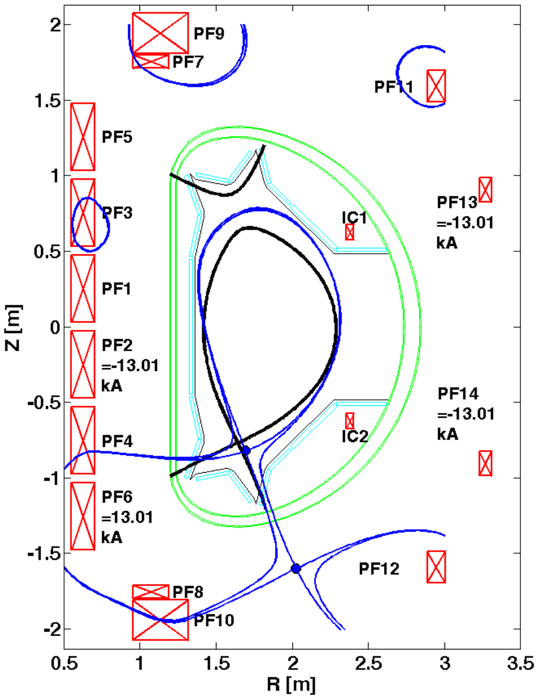
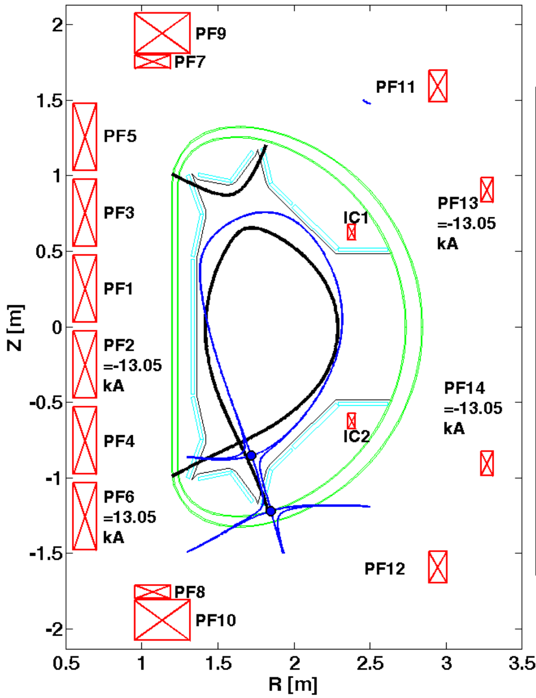
Modelling shows achievable high flux expansion at higher Ip

Ip=480 kA



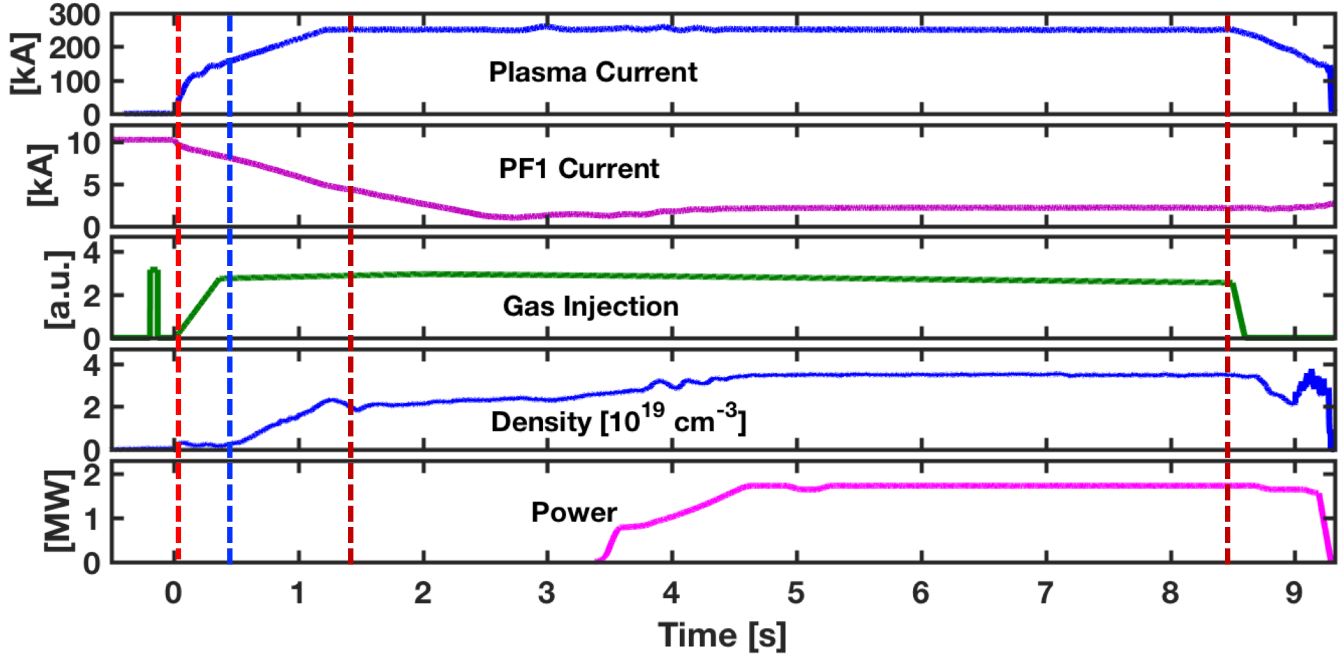
Ip=400 kA

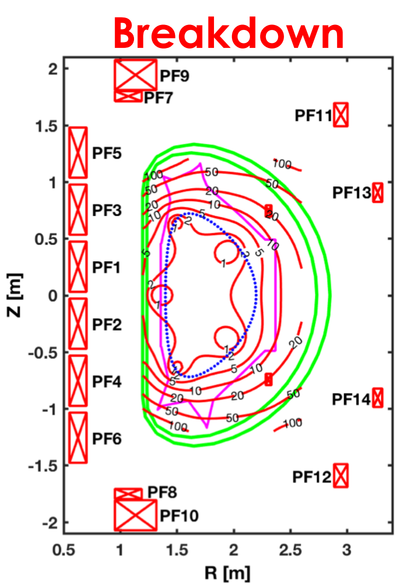


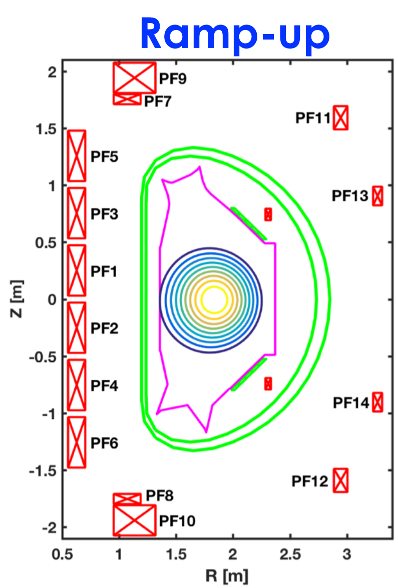
Case	Connection length [m]	Flux expansion in outer strike point region
SN	95	2.1
QSF (480kA)	103.5	9.84
QSF (400kA)	129.7	26.59

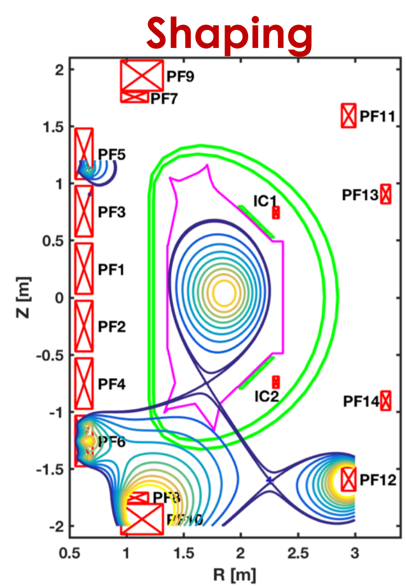
G. Calabro, B.J. Xiao et al, Nuclear Fusion, 2015

Scenario design for QSF discharge

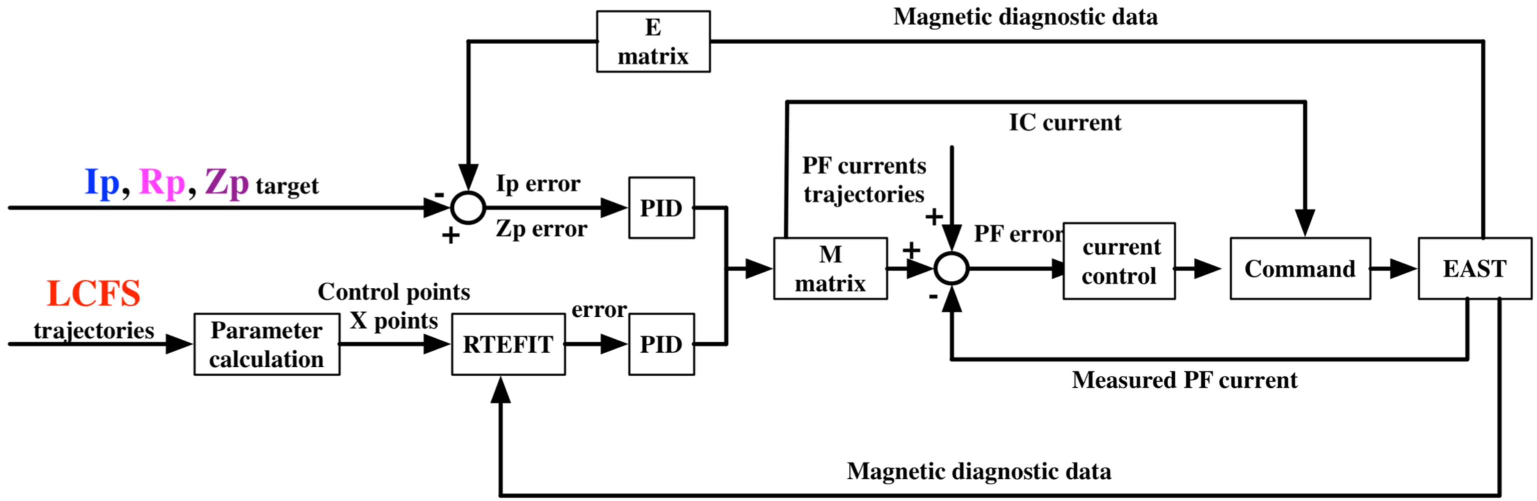








Scenario design for QSF discharge



Schematic of EAST plasma control system

- **In order to realize the desired QSF configuration， PCS needs：**

  Ip， Rp， Zp， LCFS， Currents in PF coils I_{PF} (as Feedforward)

✓ **Ideal way**：

1. Design & optimize desired equilibrium configuration， get **Rp**， **Zp**， **LCFS**… target value；
2. Run discharge simulation code, provide PF coil's currents to PCS;

✗ **Time-consuming**

Fast scenario design for QSF discharge

✓ **Prerequisites:**

- Plasma on **flat-top phase**;
- Assuming the plasma configuration keeps unchanged, then shaping currents in PF coils will be same in different scenarios;

✓ **Feedforward current in two scenarios:**

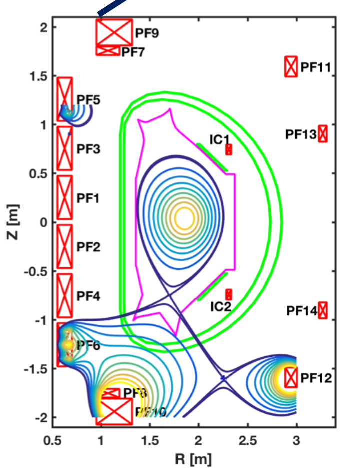
1) $\mathbf{I}_{PF0} = \mathbf{I}_{PF0}^{shaping} + \mathbf{I}_{PF0}^{ohm}$

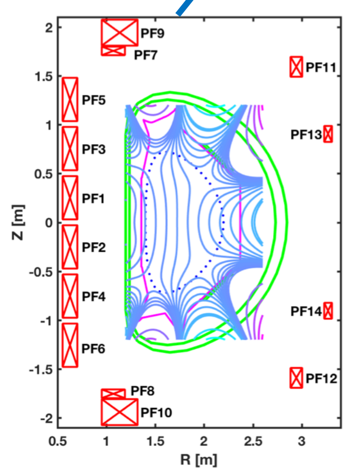
2) $\mathbf{I}_{PF1} = \mathbf{I}_{PF1}^{shaping} + \mathbf{I}_{PF1}^{ohm}$

$$= \mathbf{I}_{PF0}^{shaping} + \mathbf{I}_{PF1}^{ohm}$$

$$= \mathbf{I}_{PF0}^{shaping} + \mathbf{I}_{PF0}^{ohm} + \delta\psi \times \mathbf{I}_{PF}^{ohm0}$$

$$= \mathbf{I}_{PF0} + \delta \mathbf{I}_{ohm}$$





✓ **Design steps:**

1. Design desired equilibrium configuration, get **Rp**, **Zp**, **LCFS** & $\mathbf{I}_{PF0}$;

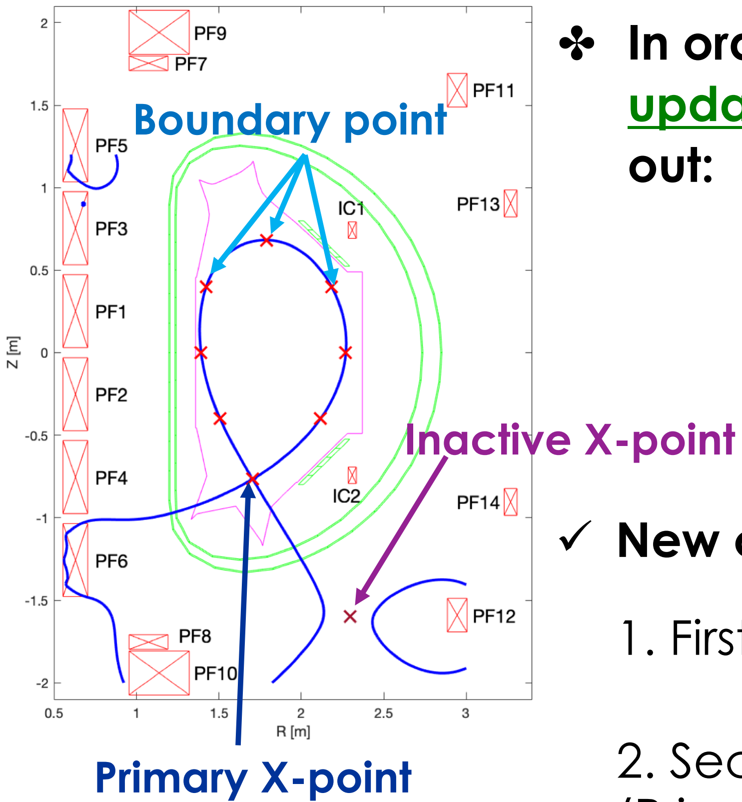
2. Based on voltage-second variation, calculate the $\delta \mathbf{I}_{ohm}$ for maintaining plasma current on flat-top;

3. Provide PCS setting parameters:

Rp, **Zp**, **LCFS**, $\mathbf{I}_{PF0} + \delta \mathbf{I}_{ohm}$

PF Feedforward current

Fast Scenario design for QSF discharge



- In order to have optimized QSF configuration, <u>code update</u> to achieve two first-order X-points are carried out:

$$\begin{bmatrix} \mathbf{W}_p \cdot \mathbf{M}_{pc} \\ \mathbf{W}_x \cdot \mathbf{M}_{xc} \\ \mathbf{W}_{xB} \cdot \mathbf{G}_{xc} \\ \mathbf{W}_{PF} \end{bmatrix} \times \mathbf{I}_{PF} = \begin{bmatrix} \Psi_p \\ \Psi_{xpt} \\ \mathbf{B}_{xpt} \\ \mathbf{I}_{PF}^{con} \end{bmatrix}$$

$\Psi_{xpt} = \Psi_p$

$\mathbf{B}_{xpt} = 0$

$\mathbf{I}_{PF}^{con}$: current constraints

W: weight

✓ **New constraints for X-points:**

1. First-order null: $\frac{\partial \psi}{\partial R} = \frac{\partial \psi}{\partial Z} = 0$

2. Second-order null: $\frac{\partial \psi^2}{\partial^2 R} \to 0,\ \frac{\partial \psi^2}{\partial^2 Z} \to 0,\ \frac{\partial \psi^2}{\partial R \partial Z} \to 0$
(Primary X-point only)

✓ **Maximum** I_{PF} in EAST experiments : 12.5kA/turn;

✓ <u>In target QSF shape design</u>, maximum $I_{PF} \leq 10.5\text{kA/turn}$;

- **F2EQ-E ～10-30s**

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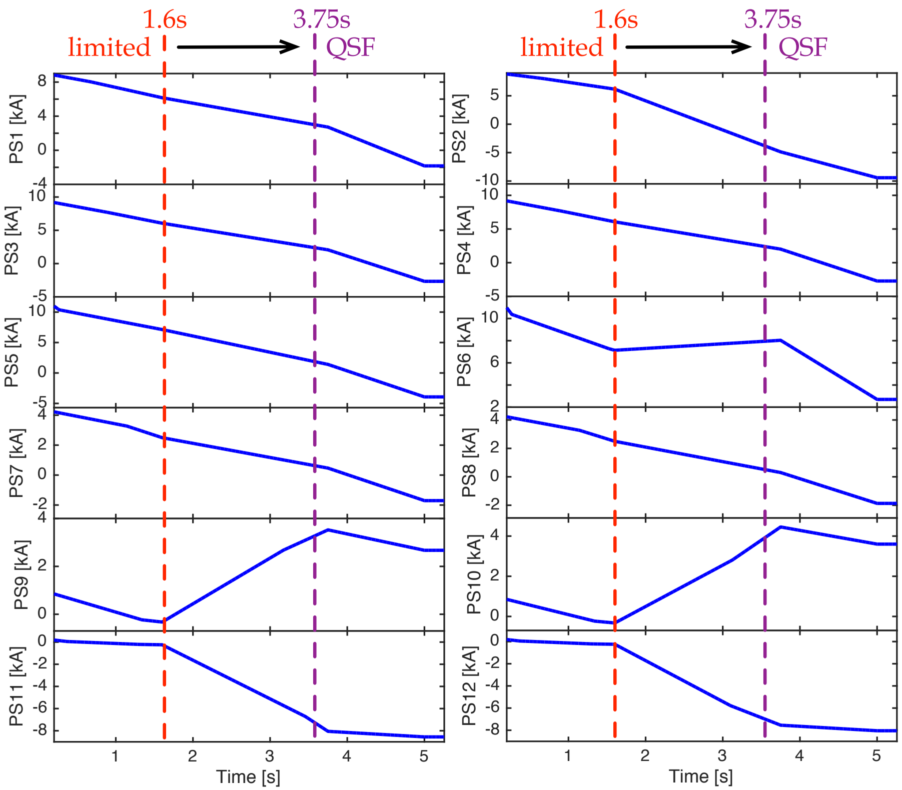
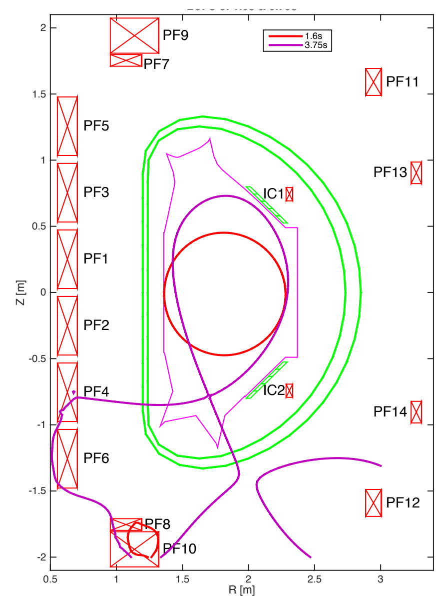
Fast scenario design for QSF discharge

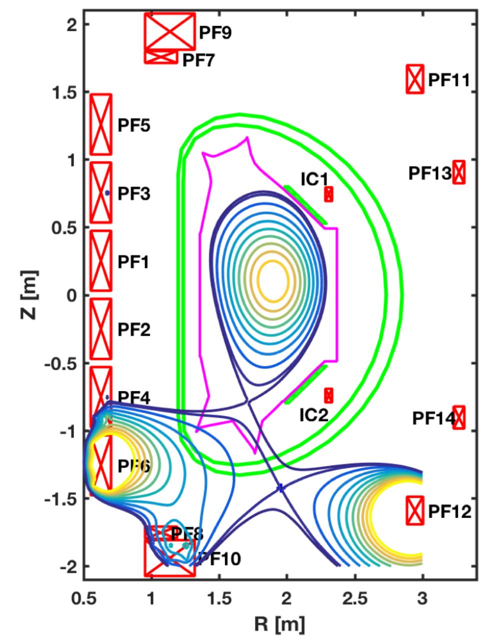
Coils current



Target shape



Reconstructed shape



- ✓ Obtain successful QSF discharge with one target QSF scenario；
- ✓ Following the routinely used scenario for breakdown phase;
- ✓ Using RZIP algorithm for plasma feedback control only.

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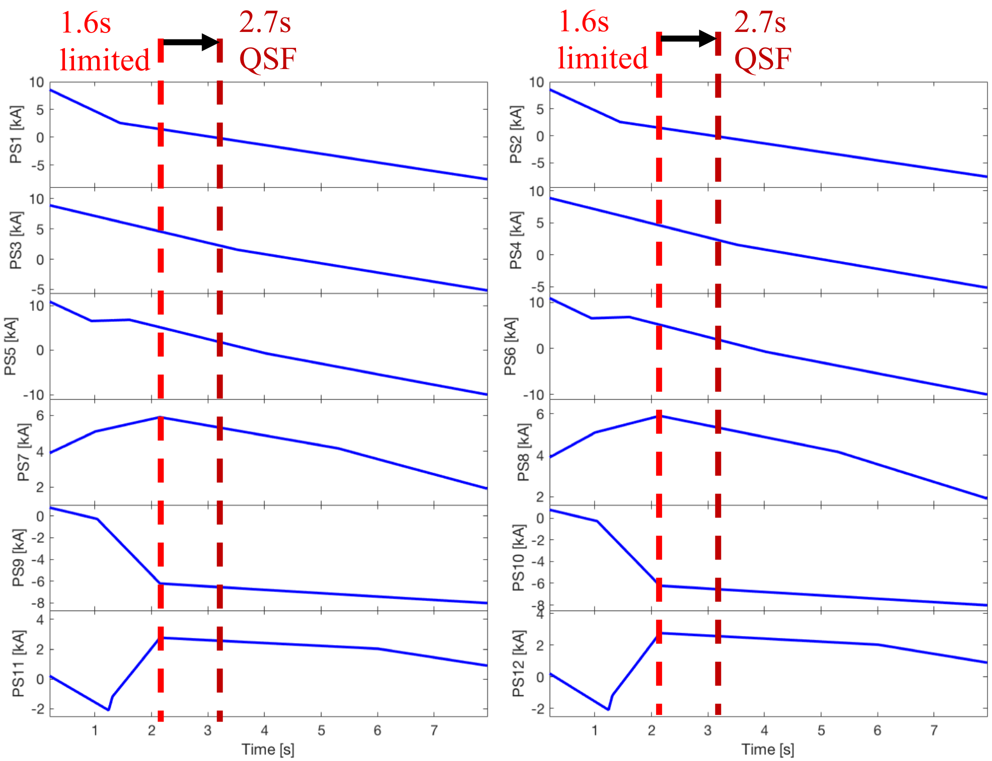
Fast scenario design for QSF discharge

Coils current



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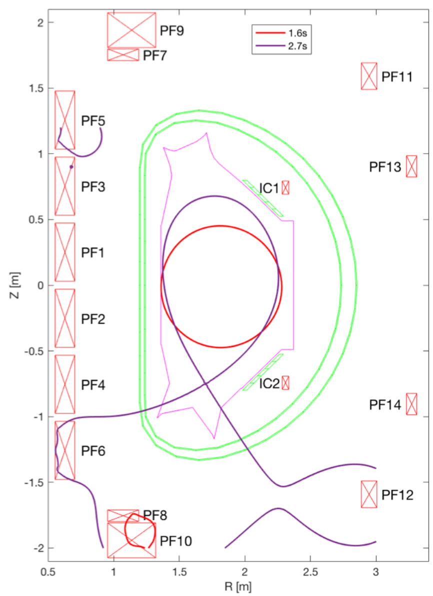
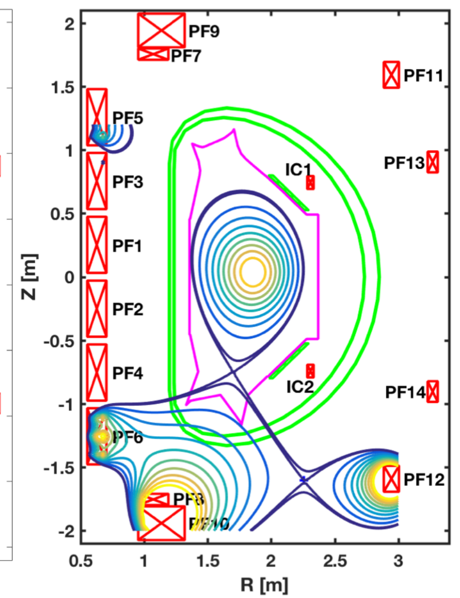


Reconstructed shape



- ✓ New QSF scenario for plasma shaping 1 second early;
- ✓ Successful discharge to ramp-down phase;
- ✓ Stable plasma control for QSF long-pulse discharge;

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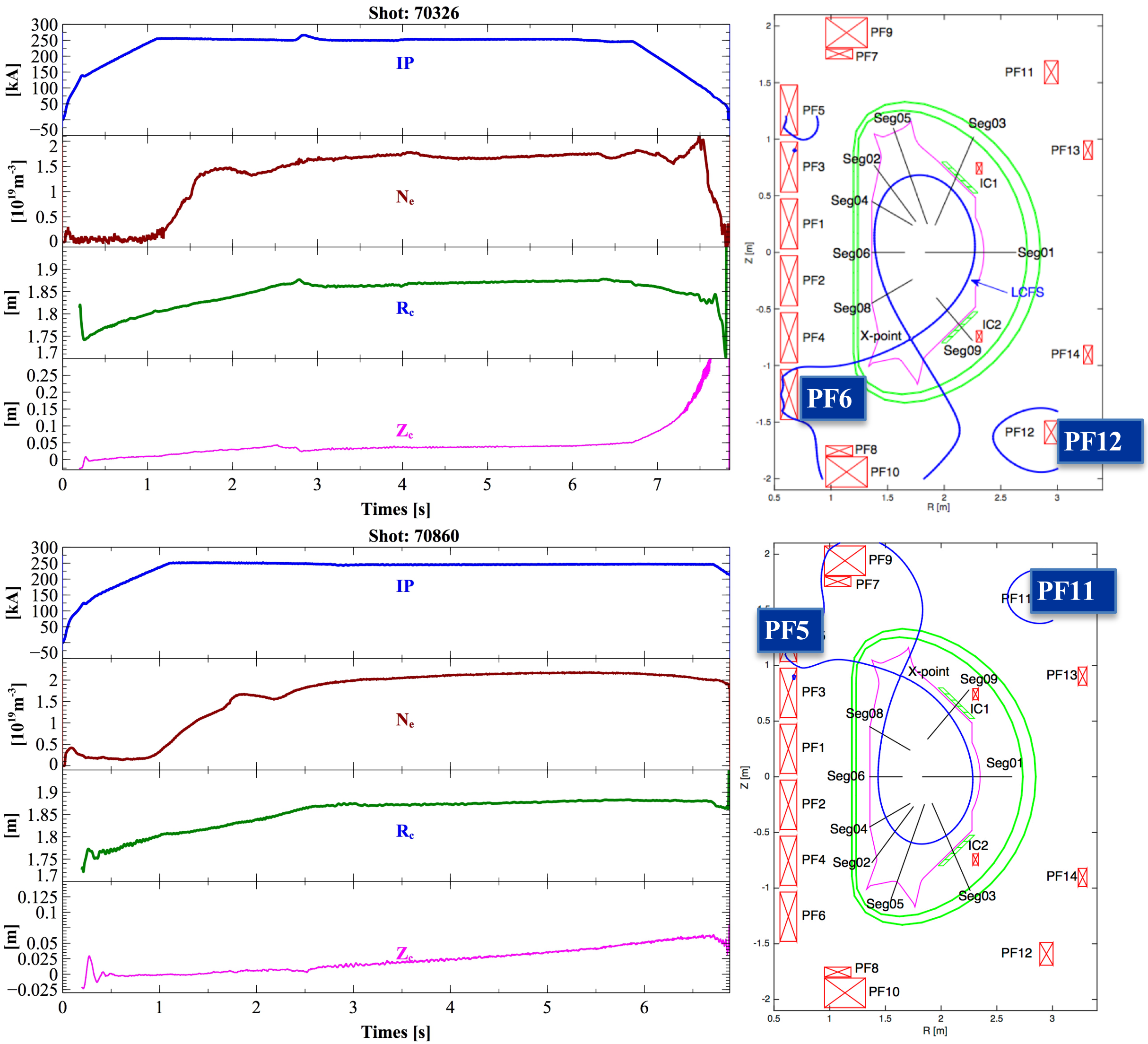
Development of QSF discharge for long-pulse operation



- QSF target configuration was designed by **EFIT/F2EQ** code. QSF shapes were controlled in feed-forward, with a feed-back component added for shape & position control.
- QSF discharge was switched to **ISOFLUX** from 2.7s to 2.8s, with **SISO/MIMO** algorithm.
- LSN-based QSF (**LQSF**) & USN-based QSF (**UQSF**) was carefully designed to fit the divertor geometry & PF coils' power limitation.
- More repeatable and stable with ISOFLUX control, ready for long-pulse operations

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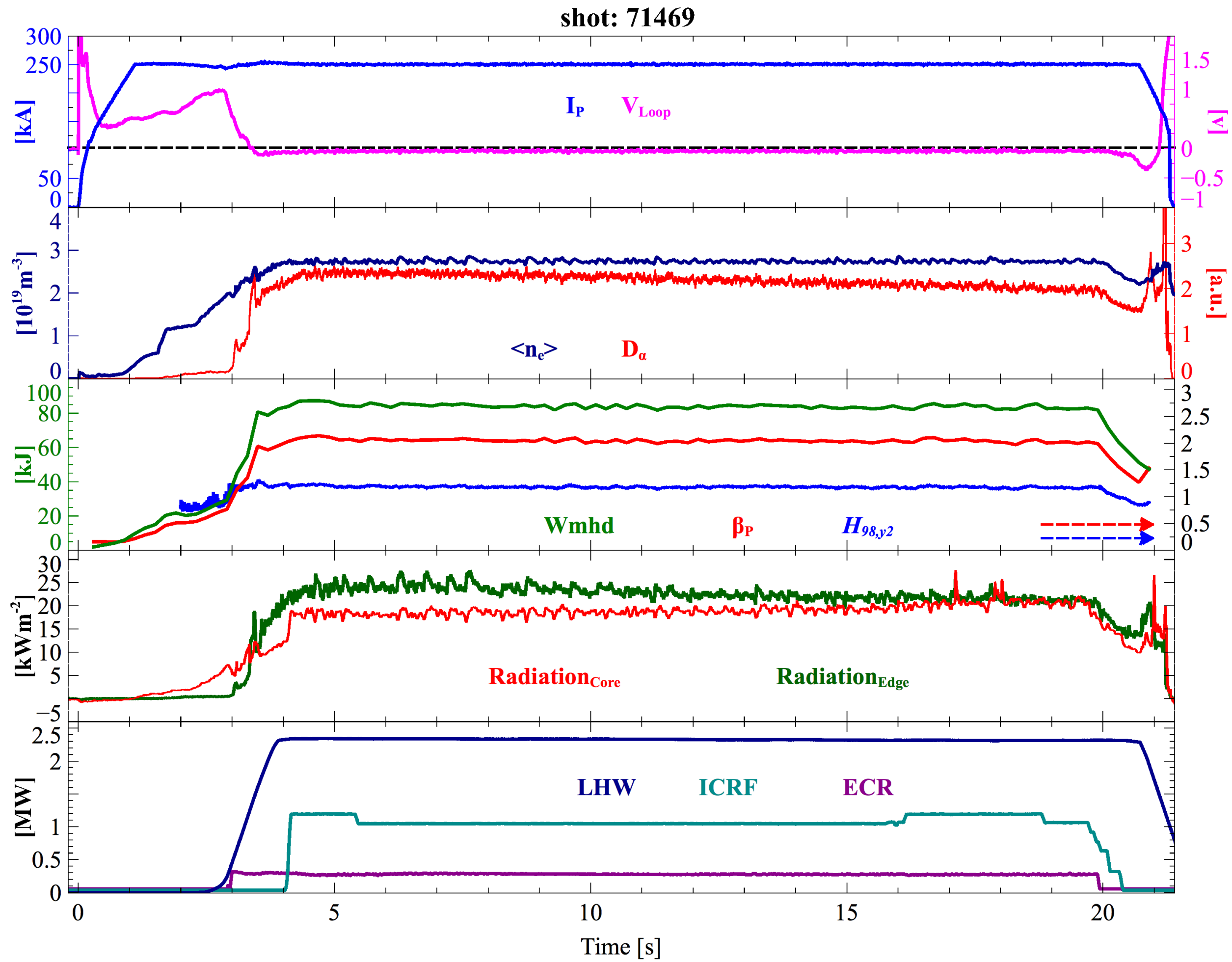
Long-pulse QSF discharge



- ✓ $V_{Loop} \leq 0$
- ✓ $H_{98} > 1$
- ✓ $\beta_P \sim 2$

✓ A long-pulse operation, ELMy-free high-confinement steady-state pulse, lasting up to **21s**, is achieved and limited only by the imposed technical scenario constraints.

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Summary

- ✦ Propose **a fast scenario design method** for EAST alternative magnetic diverted (QSF) discharge;
  - ❖ Combine the static equilibrium configuration design & voltage-second variation estimation together;
  - ❖ Works on plasma current **<u>flat-top phase</u>**.
- ✦ Obtain stable QSF discharge on EAST;
- ✦ Demonstrate the long-pulse steady-state QSF discharge.

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Thank you !