Edge plasma modeling for divertor configurations with secondary x-points

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Outline

- Divertor configurations with secondary X-points
- Snowflake divertor experiments
- X-Point target divertor
- Topology and grids for edge domain with two x-points
- UEDGE analysis of near-snowflake divertor configurations
- UEDGE analysis of X-point target divertor configuration
- Summary/Conclusions
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Configurations with a secondary X-point in divertor considered by many groups in recent years; for example

- **Cusp divertor [1]**
- **Snowflake divertor [2]**
- **X-divertor [3]**
- **X-point target divertor [4]**

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Experiments on TCV tokamak indicate that enhanced transport zone may exist near the null-point.

Figures from Vijvers et al, NF 2014

Large fraction of power flows to secondary strike points
- when two X-points get closer
- more during ELM strike
DIII-D: heat and particle fluxes shared among strike points in snowflake divertor (Soukhanovskii – FEC ’14)

- \( q_{SP3} / q_{SP1} < 0.5 \)
- \( P_{SP3} / P_{SP1} < 0.3 \)
- Sharing fraction maximized at low \( d_{XX} \)
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X-point target divertor is similar to the super-X divertor, but with the second X-point in the plasma volume.

- Like Super-X, exploits $1/R$ geometric reduction of divertor heat flux
- May produce stable ‘X-point MARFE’ in the divertor chamber
- Used as a part of the ADX tokamak concept

X-point target divertor study is motivated by the ADX tokamak concept discussed at MIT PSFC

• ADX = Advanced Divertor and RF tokamak eXperiment*
• Designed to address critical gaps on pathway to next-step devices
• Advanced divertors
• Advanced RF actuators
• Reactor-prototypical core plasma conditions

*B. LaBombard et al., Nucl. Fusion 55, 053020, 2015.
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Topological classification of configurations with secondary x-point in the divertor

- Derived from local expansion for inexact snowflake
- Applies to any configuration with secondary x-point
- $\theta$ = angle between X-point bisector and horizontal axis
- In addition to shown six cases, there are mirror reflections of cases b,c,d,e

Ryutov et al., PPCF 52 (2010) 105001
Recent upgrades made in UEDGE include generalization of computational subdomains and mesh generation.

$\theta = \text{angle between X-point bisector & horizontal axis}$

3 mesh regimes

$0 \leq \theta < 30^\circ$

$30^\circ < \theta < 60^\circ$

$60^\circ < \theta < 90^\circ$

Unique indexing rules for each regime completed
From the point of view of domain topology and grid connectivity there are two distinct SFM regimes

SFM1 – From core boundary there is a path down \( \text{grad}(\psi) \) to PF boundary

SFM2 – From core boundary down \( \text{grad}(\psi) \) can only get to SOL boundary
Interactive Grid Generator iGrid (under continuing development) has been used for constructing meshes

- Variety of flux surface geometry is a challenge for tokamak edge grid generation
- Human eye is still the best tool for recognizing complex patterns
- In iGrid the user guides the code by indicating with the mouse some needed reference points and directions
Orthogonal grids for SFM1 and SFM2 are generated for analytic “3-wire” geometry

SFM1 – From core boundary there is a path down \( \text{grad}(\psi) \) to PF boundary

SFM2 – From core boundary down \( \text{grad}(\psi) \) can only get to SOL boundary
Real tokamak geometry in near-snowflake configuration makes a challenge for grid numerics.

Actual DIII-D geometry

Extremely fast convergence of flux surfaces
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UEDGE* (Unified EDGE code) solves a system of fluid equations in axisymmetric tokamak geometry

\[
\frac{\partial}{\partial t}(n_i) + \nabla \cdot (n_i \vec{u}_i) = -S_r + S_i \\
n_i \vec{u}_i = -D_{\perp} \nabla_{\perp} n_i \\
\frac{\partial}{\partial t}(mn_i u_{i\parallel}) + \nabla \cdot (mn_i u_{i\parallel} \vec{u}_i - \eta_i \nabla u_i) = -\nabla_{\parallel} P_i + mn_i n_i K_{cx} (u_{i\parallel} - u_{i\parallel}) + mS_{i\parallel} u_{i\parallel} - mS_i u_i \\
\frac{\partial}{\partial t}(3/2n_i T_{\parallel}) + \nabla \cdot \left( \frac{5}{2} n_i T_{\parallel} \vec{u}_i + \vec{q}_i \right) = \vec{u}_i \cdot \nabla (3/2n_i T_i) - \Pi_{\parallel} \cdot \nabla \vec{u}_i + Q_i \\
q_{\perp} = -n \chi_{\perp} \nabla T \\
\frac{\partial}{\partial t}(n_N) + \nabla \cdot (n_N \vec{u}_N) = S_r - S_i \\
n_N \vec{u}_{N\parallel} = -D_{\perp} \nabla_{\perp} n_N \\
\frac{\partial}{\partial t}(mn_N u_{i\parallel}) + \nabla \cdot (mn_N u_{i\parallel} \vec{u}_N - \eta_N \nabla u_{i\parallel}) = -\nabla_{\parallel} P_N + mn_N n_i K_{cx} (u_{i\parallel} - u_{i\parallel}) - mS_{i\parallel} u_{i\parallel} + mS_i u_i \\
\nabla \cdot J(\phi) = 0 \\
J_r = \sigma_{\perp} E_r \\
\phi = -\frac{T_e}{e} \ln \left[ 2\sqrt{\pi} \left( \frac{J_r - e\nu_{i\parallel}}{e\nu_{i\parallel}} \right) \right] \\
\]

UEDGE SFM1 mesh for DIII-D shot 155479

X-point separation/
minor radius

\[ \sigma = 0.1/0.5 = 0.2 \]

50% greater mesh resolution used for simulations
2D UEDGE SF solutions for 2% carbon show strong variations across separatrices; radiation is well spread.
Plate heat-fluxes are $< 2\; \text{MW/m}^2$; only radiative flux is visible in the middle between two strike points (2% carbon).
Convective cell formation near null dubbed “the churning mode” may be responsible for heat redistribution*

Driven by crossed magnetic curvature and $\text{grad}(P)$ near null where poloidal beta is large

Similar to thermal convection due to crossed gravity and temperature gradient

Solving plasma fluid equations demonstrates formation of the churning mode**

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*A D.D. Ryutov et al., Physica Scripta 89, 8, 088002 (2014)

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UEDGE is used to model both X-points in an XPTD for the lower half of up-down symmetric configuration

Mesh constructed in UEDGE by combining two lower-half single-null domains (with scripts developed by M.E. Rensink)

Use UEDGE fluid transport model
- Fluid neutrals (inertial)
- Fixed fraction impurity radiation
- No drifts
- Four orthogonal target plates
- 100% recycling on all walls

Use geometry & parameters from LaBombard et al., NF 2015
- MHD equilibrium provided by MIT
- Density at separatrix ~ 1e20 m⁻³
- Power into lower-half domain 1-5 MW
A C-Mod like case with ADX parameters is used for comparison

- Two configurations – XPTD and SVPD
- Same underlying magnetic geometry, physics model, boundary conditions, etc.
- In SVPD the legs cut short to roughly match C-Mod vertical plate configuration
Radial transport parameters are set to match projected ADX upstream SOL characteristics

- Using fully recycling wall B.C. on all material surfaces
- Using radially growing diffusing coefficient to match the expected density profile width $\sim 5$ mm
- Spatially constant $\chi_{e,i}$ is sufficient to achieve $\sim 3$ mm width of mid-plane $T_{e,i}$
- Mid-plane profile projections are based on C-Mod data*

*LaBombard et al., Nucl. Fusion 55, 053020, 2015.
As the input power $P_{1/2}$ is reduced, the divertor transitions to fully detached state.

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<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$P_{1/2}=3.000$ MW</td>
<td>$P_{1/2}=2.058$ MW</td>
<td>$P_{1/2}=2.052$ MW</td>
<td>$P_{1/2}=1.420$ MW</td>
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<td>lg($T_e$ [eV])</td>
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<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
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<tr>
<td>lg($N_g$ [m$^{-3}$])</td>
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<td><img src="image6.png" alt="Image" /></td>
<td><img src="image7.png" alt="Image" /></td>
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XPTD, 1% C
As input power $P_{1/2}$ is reduced, radiation front remains stable but shifts upstream

- For higher input power the radiation front moves to larger $R$ to increase the radiating volume*

- $P_{1/2} \approx 2$ MW onset of detachment

- As $P_{1/2}$ is reduced further either (i) the radiation front reaches the primary X-point, or (ii) no steady-state solutions can be found => X-point MARFE

*Hutchinson, Nucl. Fusion 34 (1994) 1337
Reducing input power $P_{1/2}$ eventually leads to X-point MARFE
Reducing input power $P^{1/2}$ eventually leads to X-point MARFE

- Qualitatively similar results also obtained with 1% Ne impurity
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Summary, conclusions, plans

• Capability to generate grids with a secondary X-point is developed.

• Capability to model configurations with a secondary X-point is developed in UEDGE.

• Near-SNF configurations in DIII-D have been analyzed with UEDGE; points to strongly enhanced transport near the null (churning mode?)

• X-point Target Divertor (XPTD) configuration is studied with UEDGE for parameters matching the design of ADX tokamak:
  ▪ Steady state detachment found for XPTD, for a range of parameters
  ▪ Easier to achieve detachment than for short leg divertor
  ▪ Detachment front stays far away from the main X-point
  ▪ Stable fully detached regimes for tokamak divertor?