Attainment of a stable, fully detached plasma state in innovative divertor configurations

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• Introduction: Tokamak divertor challenge & innovative divertors

• Modeling innovative divertors with long legs and secondary X-points
  – Simulation model and setup
  – Robust fully detached regimes
  – Analysis of fully detached divertor

• Summary & conclusions
  – Long-legged divertor performance much beyond standard divertor
  – Promise of stable fully-detached high-power divertor
Traditional tokamak divertor configuration is formed by two toroidal currents: plasma and divertor coil

- Toroidal plasma current $I_p$
- Divertor coil current $I_d$

  - Magnetic flux surfaces are formed
  - X-point ($B_p=0$ null point)
  - Magnetic separatrix between
    - core plasma
    - scrape-off layer (SOL)
    - private-flux (PF) region

- Divertor plates intercept most of heat exhausted from the core
Divertor heat exhaust is going to be a major challenge for next generation tokamaks

- SOL width $\lambda_{\text{SOL}}$ small ($\sim$1 mm)
  $\Rightarrow$ divertor heat flux large
- For constant $\lambda_{\text{SOL}}$ a figure of merit is $P/R$

$$q_{\text{div}} = \frac{P}{A_w} = \frac{P}{2\pi R\lambda_{\text{SOL}}} \propto \frac{P}{R}$$
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  $q_{\text{div}} = \frac{P}{A_w} = \frac{P}{2\pi R \lambda_{\text{SOL}}} \propto \frac{P}{R}$

- Recently found scaling* $\lambda_{\text{SOL}} \sim 1/B_p$ and independent of machine size unfavorable for large tokamaks (if it holds)

- Innovative divertor solutions are needed for next generation tokamaks

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*T. Eich et al., 2013 Nucl. Fusion 53 093031
Divertor parameters are constrained by overall tokamak design but there are some degrees of freedom for divertor design.

For given tokamak design one cannot change:

- Exhaust power
- Major radius
- Minor radius
- SOL width

But (within some limits) one can change:

- Divertor plate tilt/shaping
- Divertor leg length
- Divertor poloidal flux expansion
- Divertor magnetic field topology
Increasing plasma-wetted area $A_w$ geometrically is limited for given target major radius $R_t$.

- $A_w$ can be increased by plate tilting and poloidal flux expansion.
- For either method, grazing angle $\gamma$ between surface and total B becomes small.

For $\gamma < \gamma_0 \approx 1^\circ$ hot-spot formation due to surface roughness.

At minimum angle $\gamma = \gamma_0$, $A_w \approx 2\pi R_t \left[ \frac{\lambda_{mid}}{\gamma_0} \right] \left( \frac{B_p}{B_t} \right)_{mid}$.

For further increase of $A_w$ larger $R_t$ needed.

Purely geometric solutions for innovative divertor are limited.
Can we make plasma and/or atomic physics play in our favor?

P. Valanju et al., Phys. Plasmas 16, 056110, 2009
Detached regime: Plasma stays away from PFC, cushioned by neutral gas – potentially attractive solution for divertor

- Experimental features of divertor detachment:
  - Low plasma temperature, density, power on target; $T_e \approx 1$ eV
  - Radiation moves away from plates
- Modeling:
  - Semi-quantitatively reproduces many experimental features of detachment
- Problem with detachment for standard divertor:
  - Sensitive to divertor plasma parameters
  - Det. front tends to move to main X-point => “MARFE”, bad for core plasma
  - Small (if any) parameter window for stable fully detached operation

A. McLean et al., APS DPP 2015
Configurations with a secondary X-point in divertor considered by several groups in recent years

1. **Cusp divertor [1]**
   - ![Cusp divertor](image1)

2. **Snowflake divertor [2]**
   - ![Snowflake divertor](image2)

3. **X-divertor [3]**
   - ![X-divertor](image3)

4. **X-point target divertor [4]**
   - ![X-point target divertor](image4)

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Recent upgrades made in UEDGE make it possible to include a secondary X-point in divertor

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

3 mesh regimes

- \(0 < \theta < 30^\circ\)
- \(30^\circ < \theta < 60^\circ\)
- \(60^\circ < \theta < 90^\circ\)

Unique indexing rules for each regime

UEDGE capability for modeling configurations with secondary X-points is now applied to NSTX-U*

Illustrative grids for domain w/ two X-pts

Illustrative UEDGE solutions

*O. Izacard et al., poster NP10.00031 on Wednesday
UEDGE applied to four tokamak divertor arrangements based on same (or similar) magnetic configurations

- Tokamak edge transport code UEDGE [1] finds a steady state solution of plasma fluid equations in edge domain
- Using newly added capabilities in UEDGE for including a secondary X-point in the divertor
- Analyzing several divertor configurations based on ADX tokamak design [2]

**SVPD** – Standard Vertical Plate Divertor
**SXD** – Super-X Divertor
**XPTD** – X-point Target Divertor
**LVLD** – Long Vertical Leg Divertor

Model parameters are set to match projected ADX characteristics

- Modeled cases are based on geometry & parameters from ADX tokamak design
  - MHD equilibrium
  - Power $P_{1/2}$ into lower half-domain, 0.1-4 MW
  - Density at separatrix $\sim 0.5 \times 10^{20} \text{ m}^{-3}$
  - SOL profiles width, $\lambda_{T,N} \approx 3-5 \text{ mm}$
  - Reactor-relevant $q_{\parallel}$ up to 5 GW/m$^2$

- Fully recycling wall B.C. on all material surfaces (unless stated otherwise)
- Radially growing density diffusion coefficient $D$
- Spatially constant heat diffusion coefficient $\chi_{e,i}$
- “Fixed fraction” impurity model, 1% C
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Results for XPTD, power $P_{1/2} = 3.0$ MW
Results for XPTD, power $P_{1/2} = 1.6 \text{ MW}$
Results for XPTD, power $P_{1/2} = 0.6$ MW
Results for SXD, power $P_{1/2} = 1.2$ MW
Results for SXD, power $P_{1/2} = 0.8$ MW
Results for SXD, power $P_{1/2} = 0.6$ MW
Results for LVLD, power $P_{1/2} = 1.2$ MW
Results for LVLD, power $P_{1/2} = 0.8$ MW
Results for LVLD, power $P_{1/2} = 0.6$ MW
Varying input power into SOL shows how transition to detachment depends on divertor configuration

Identically same physics model, B.C., etc.

• Large parameter window with detached divertor found for all three long-legged configurations

• For SVPD, detached plasma may exist only at low input power

• Radially or vertically extended outer leg good for detached operation

• Long vertical leg (LVLD) enters detachment at about same power as radially extended leg (SXD)

• Secondary X-point in outer leg (XPTD) significantly extends detached operation window
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Analysis needed to address important questions for these numerical solutions

• What is interplay of model physics terms in these detached regimes?
• What is going on with plasma & neutral density, momentum, energy flux?
• What sets position of detachment front?
• What are limits of power handling capability?
• How sensitive is this equilibrium to model details (impurity, neutrals)?
• Can this regime be scaled to reactor parameters?
Analysis of plasma & neutral density fluxes in divertor leg show stagnant poloidal flow picture

Analyzing a representative case:
• SXD, $P_{1/2} = 0.6$ MW

- On each surface bounding the leg domain ion flux is matched by opposing neutral flux
- Poloidal fluxes entering/leaving domain are tiny compared to radial fluxes
- SOL flow is stagnant – why?
- Need to analyze parallel momentum balance
Plasma pressure conservation relation is helpful for understanding plasma parallel force balance.

Integration along field line leads to “conservation law”

\[
\frac{\partial}{\partial t} (m_i n_i u_{ill}) + \nabla \cdot (m_i n_i \bar{u}_i u_{ill} - \eta \nabla u_{ill}) = -\nabla_{\parallel} p_{ei} - m_i n_i n_n K_{cx} (u_{ill} - u_{nll}) - m_i S_r u_{ill} + m_i S_i u_{nll}
\]

Thermal pressure

Radial transport

Neutral force

Plasma viscosity

Ram pressure

Integration along field line leads to “conservation law”

\[
p_{ei} + m_i n_i \frac{u_{ill} u_{i\theta}}{B_p/B} + R_\psi + R_\eta + R_{in} = \text{const}
\]

Reduced version similar to Bernoulli equation:

\[
p_{ei} + m_i n_i u_{ill}^2 \approx \text{const}
\]
Parallel plasma pressure drop in the leg is mainly balanced by CX interaction with neutrals.

Analyzing a representative case:
- SXD, $P_{1/2} = 0.6$ MW

Plasma par. momentum balanced by:
- In radiating zone: neutrals, viscosity, and convection
- Below radiating zone: neutrals
Analysis of energy fluxes in divertor leg shows that most entering energy ends up on outer wall

Analyzing a representative case:
• SXD, $P_{1/2} = 0.6$ MW

• About 30% of input power $P_{1/2}$ enters outer leg*

• About 1/2 of power entering outer leg goes to outer wall with plasma and neutral energy flux

• The rest of power entering outer leg is lost with impurity and hydrogen radiation

* the rest goes to outer walls above X-point and inner leg
Neutral particles confinement controls position of detachment front

Analyzing a representative case:
- SXD, $P_{1/2}=0.6$ MW

Plasma recycling coef: 100%

Neutral albedo: 100%
Neutral particles confinement controls position of detachment front

Analyzing a representative case:
• SXD, $P_{1/2} = 0.6$ MW

Plasma recycling coef: 100%
Neutral albedo: 99.5%
Neutral particles confinement controls position of detachment front

Analyzing a representative case:
- SXD, $P_{1/2} = 0.6$ MW

Plasma recycling coef: 100%
Neutral albedo: 99.5%

- Similar results if reducing plasma recycling coefficient
- Neutral particles confinement in the leg appears to control detachment front location
Summary

• Capability to model divertors with a secondary X-point is developed in UEDGE, enables analysis of novel configurations
• Several divertor configurations are studied computationally (long/short leg, with or without secondary X-points), for parameters matching design of ADX tokamak
• Steady-state fully-detached divertor regimes found for long-legged tightly baffled divertors, for a broad range of parameters
  ▪ Entering detached state at high input power
  ▪ Detachment front stays far away from main plasma
  ▪ Secondary X-point in divertor leg extends detached operation window - factor of 10 improvement compared to standard divertor!
  ▪ Neutral confinement in divertor controls detachment front position
  ▪ Promise of stable fully-detached operation for high-power tokamak
UEDGE (Unified EDGE code) solves a system of fluid equations in axisymmetric tokamak geometry

\[ \frac{\partial}{\partial t} (n_i) + \nabla \cdot (n_i \vec{u}_i) = -S_r + S_i \]
\[ \frac{\partial}{\partial t} (mn_i u_i) + \nabla \cdot (mn_i u_i \vec{u}_i - \eta_i \nabla u_i) = -\nabla P_i + mn_i K_c (u_{iN} - u_i) + mS_i u_{iN} - mS_i u_N \]
\[ \frac{\partial}{\partial t} (3/2 n_i T_i) + \nabla \cdot (\frac{5}{2} n_i T_i \vec{u}_i + \vec{q}_i) = \vec{u}_i \cdot \nabla (3/2 n_i T_i) - \Pi \cdot \nabla \vec{u}_i + Q_i \]
\[ \frac{\partial}{\partial t} (n_e) + \nabla \cdot (n_e \vec{u}_e) = S_r - S_i \]
\[ n_N u_{iN} = -D_{iN} \nabla \perp \]
\[ n_N q_{\perp} = -n \chi_\perp \nabla _{\parallel} T_{i} ; \quad n_i u_{\parallel} = -D_{i\parallel} \nabla _{\parallel} n_i \]
\[ \frac{\partial}{\partial t} (mn_e u_e) + \nabla \cdot (mn_e u_e \vec{u}_e - \eta_e \nabla u_e) = -\nabla P_e - mn_e K_c (u_{eN} - u_e) - mS_e u_{eN} + mS_e u_N \]
\[ \nabla \cdot J(\phi) = 0 \]
\[ J_\parallel = \frac{en}{0.51 nmv} \frac{B_\parallel}{B} \left( \frac{1}{n} \frac{\partial P_e}{\partial x} - e \frac{\partial \phi}{\partial x} + 0.71 \frac{\partial T_e}{\partial x} \right) \]
\[ J_\perp = \sigma_\perp E_\perp \]
\[ \phi = -\frac{T_e}{e} \ln \left[ 2 \sqrt{\pi} \left( \frac{J_\perp - en u_{i\parallel}}{en v_{th}} \right) \right] \]

UEDGE finds steady-state and transient solutions, mainly used for interpretation of edge plasma experiments

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

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*B. LaBombard et al., Nucl. Fusion 55, 053020, 2015*
X-point target divertor is a component of ADX tokamak concept discussed at MIT

- XPT starts with the SXD idea, but places an X-point in the confined plasma
- Similar to SXD exploits 1/R geometric reduction of divertor heat flux
- May produce stable ‘X-point MARFE’ localized to the divertor chamber

*B. LaBombard et al., Nucl. Fusion 55, 053020, 2015