Using variations in divertor magnetic topology and geometry to optimize divertor detachment

Need for more and quicker divertor design guidance/analysis

Using ‘experiments’ in SOLPS to quantify the effect of divertor design characteristics on control of divertor detachment onset

- Strike point angle
- Baffling
- Total flux expansion

Implications for improving the design process

Most of the thoughts presented are based on the paper – A. Fil et al., ‘Separating the roles of magnetic topology and neutral trapping in modifying the detachment threshold in TCV’, submitted to Plasma Phys. & Contr. Fusion.

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1. The core plasma conditions are set based on reactor goals
   • (Q, B, current, aspect ratio,..)
   • Magnetic flux equilibrium developed
2. Space allocated to the divertor based on the coil size
3. Run SOL/divertor fluid codes to determine whether the divertor performs ‘adequately’
   • Close the loop on the reactor design both with engineering and core plasma performance
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Bottleneck for optimization
Are there ways to enhance the feedback between divertor design, engineering and core characteristics?

• Are there more ways to enhance the feedback between divertor design and core characteristics?
  • Can simpler (than SOLPS) calculations be properly used?
  • Can one more quickly determine the core operational space compatible with detachment?
  • Can we be quantitative about how those divertor characteristics control detachment access and its characteristics?
    • We have addressed this question through a SOLPS study of TCV detachment threshold in upstream density, $n_{u,d}$
Reminder – what is total flux expansion

- Increase target strike point radius, $R_t$
- $|B_t|$, drops. Area of flux tube increases
- The heat flux parallel to $B$, $q_{\parallel,t}$ drops

\[ B \cdot A_{\text{fluxtube}} = \text{const} \]

Flux tube area increases as total $B$ drops

\[ q_{\parallel} \cdot A_{\text{fluxtube}} = \text{const} \]

\[ \Rightarrow q_{\parallel} \propto |B| \sim \frac{1}{R} \]

Not a new effect! Already in SOL/Div codes
Simple effect of total flux expansion predicted to lower the detachment threshold

- Increase target strike point radius, $R_t$
- $|B_t|$, drops. Area of flux tube increases
- The heat flux parallel to $B$, $q_{\parallel,t}$, drops
- lowering the detachment threshold in upstream density, $n_{u,d}$

$$n_{u,d} \propto \frac{1}{\left| \frac{B_x}{B_{tar}} \right|} \frac{P_{SOL}^{5/7}}{L^{2/7}} \sim \frac{R_x}{R_t} \frac{P_{SOL}^{5/7}}{L^{2/7}}$$

Total flux expansion

Prediction of the effect of total flux expansion for TCV

• Predict the ratio of detachment thresholds for the low and high target radius, $R_t$:

\[
D_{\text{predicted}} \equiv \frac{n_{u,d}^{R_{t,\text{high}}}}{n_{u,d}^{R_{t,\text{low}}}} \sim \frac{R_{t,\text{low}}}{R_{t,\text{high}}} = \frac{0.68}{0.92} = 0.76
\]
Experiments contradict simple predictions for total flux expansion

- TCV experiments\(^1\) studying just the upstream density detachment threshold, \(n_{u,d}\), contradict the simple scaling.

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\]

\[
D_{\text{measured}} \equiv \frac{n_{\text{e,d}}^{R_{t,\text{high}}}}{n_{\text{e,d}}^{R_{t,\text{high}}}} \sim 1.2^* 
\]

*Difficult to obtain \(n_{u,d}\)

\(^1\)C. Theiler et al, Nucl. Fusion 57 (2017) 072008
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- What leads to this difference between simple prediction and measurement?

IAEA Tech. mtg divertors, 4 Nov 2019 Vienna

\(^1\)C. Theiler et al, Nucl. Fusion 57 (2017) 072008
Strike point angle is another important divertor characteristic and is different for low- and high $R_t$ in TCV

- Recycled neutrals are launched towards different parts of the divertor plasma for low- and high-$R_t$

![Diagram showing total flux expansion and strike point angle for low- and high-$R_t$.](image)
• JET is a good example of the effect of varying strike point angle
• Recycling neutrals ionize in different plasma regions for ‘vertical target’ and ‘horizontal target’
Strike point angle to the surface affects the ionization profile

- EDGE2D-Eirene calculations demonstrate difference in ionization
  - 'Vertical target'
    - ionization near separatrix
    - increase density; lower temperature
    - lowers detachment threshold
  - 'horizontal target'
    - ionization farther from the separatrix

![Graph showing ionization rates for 'vertical target' and 'horizontal target' with increased density and lower temperature for the 'vertical target'.]
The effect of the strike point angle on detachment was realized experimentally, early in divertor studies.

- Experimental comparison:
  - vertical target ~40% lower detachment threshold, $n_{ud}$
  - Most tokamaks moved to the vertical target geometry in the early 2000s
Baffle geometry also has a strong role in determining the detachment threshold

- Low $R_t$ divertor traps neutrals between inner wall, inner and outer separatrices
Neutral trapping in the divertor favors low target $R_t$

- Low $R_t$ divertor traps neutrals between inner wall, inner and outer separatrices
- Neutrals in the high $R_t$ configuration **easily escape the divertor**
All three divertor design choices affect the detachment threshold

- Total flux expansion lowers $n_{u,d}$ for the high-$R_t$
- Strike point angle and neutral baffling lower $n_{u,d}$ for the low-$R_t$

![Graphs showing the effects of total flux expansion, strike point angle, and neutral baffling on detachment threshold.](image-url)
Define ‘neutral trapping’ to aid in comparing various effects

- We quantify the relative contributions of strike point angle and neutral baffling on the detachment threshold
  - $\eta_{RI}$ is the fraction of the total divertor ionization source that occurs in a flux tube near the separatrix
  - We make this ‘measurement’ for TCV SOLPS cases

\[
\eta_{RI} = \frac{\int S_{\text{ioniz}} dV_{ft}}{\int \Gamma_{\text{tar}} dA_{\text{tar}}}
\]
As expected – an anti-correlation between $n_{u,d}$ and $\eta_{RI}$

• Detachment threshold $n_{u,d}$ appears sensitive to $\eta_{RI}$

\[ D_{predicted} \sim 0.76 \]

\[ D_{code} = \frac{n_{R_{t,high}}}{n_{R_{t,low}}} \sim 1.86 \]
The baffle strongly affects detachment threshold for high-$R_t$ case

- Similar neutral confinement for high- & low-$R_t$; better match to total flux expansion prediction

$$D_{predicted} \sim 0.76$$

$$D_{code} \equiv \frac{n_{R_t,high}}{n_{R_t,low}} \sim 1$$

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Having baffling AND strike point angle the same for low- and high-$R_t$: isolate total flux expansion effect

- Match predictions for total flux expansion!
- What else can we learn?

\[ D_{\text{predicted}} \approx 0.76 \]

\[ D_{\text{code}} \equiv \frac{n_{R_t,\text{high}}}{n_{R_t,\text{low}}} \approx 0.74 \]
• **Baffle** (confining recycling neutrals)
  • Raises neutral density across the entire divertor, raising density and ionization costs, accelerating detachment
  • Small effect on $\eta_{RI}$ but large on $n_{u,d}$
• **Strike point angle** of ‘vertical target’
  • Raises neutral density and ionization costs on a focussed region
  • Larger effect on $\eta_{RI}$, similar for $n_{u,d}$
Contrasting the effect of neutral baffle vs strike point angle

- We expect adding vertical target to high-\(R_t\) to reduce \(n_{u,d}\) and raise \(\eta_{RI}\)

- Caveat – This analysis presented here is for TCV conditions, far from a reactor
  - However, strike point angle and neutral baffling enhancements are recognized in studies of ITER, C-Mod and AUG
  - The total flux expansion effect is straightforward and already in codes.

A. Fil et al., submitted to PPCF
• Results indicate the effect of total flux expansion is occurring but may be hidden by neutrals effects
  • It is ‘additive’, or ‘subtractive’ in this case, so an independent effect
Other implications of this study for divertor design

• These results can be generalized using the Lengyel radiation formulation to include two other ‘control’ variables\(^1\) – impurity concentration, \(C_z\), and \(P_{SOL}\):

\[
\left[ \frac{n_u C_z^{1/2}}{P_{SOL}^{5/7}} \right]_{\text{detach}} \propto \left| \frac{B_{\text{tar}}}{B_x} \right| f(L, z_x / L)
\]

• Lower \(n_{u,d}\) is equivalent to detaching at higher \(P_{SOL}\) or lower \(C_z\)

\(^1\)B. Lipschultz et al, Nucl. Fusion 56 (2016) 056007
Other ‘experiments’ in SOLPS* on detachment position control

• MAST-U Detachment (seeding):

*O. Myatra, MAST-U, PSI18 poster
Other ‘experiments’ in SOLPS* indicate control increases with the magnitude of $\nabla|B|$

- Movement slows down even though seeding rate is strongly increased
- Radiation region ‘stops’ mid-divertor where $\nabla|B|$ (really $\nabla|q_{||}|$) large

*O. Myatra, MAST-U, PSI18 poster
Strong $\nabla|B|$ correlates with ‘slowing’ front movement*

• Could be $\nabla|B|$ (really $\nabla|q_{||}|$) location stabilizing effect

O. Myatra (SOLPS; MAST-U)

* B. Lipschultz et al, Nucl. Fusion 98 (2016) 056007
Detachment position vs normalized impurity fraction, \( C_z/C_{z,\text{target}} \), correlates with position vs |B|.
Model prediction\textsuperscript{1} of movement fair approximation of SOLPS ‘experimental’ results

- Reasonable agreement with model prediction\textsuperscript{*}
- Tests with more equilibria needed
- $\nabla|B| (\nabla|q_{||}|)$ could be another ‘tool’ in divertor design

\textsuperscript{*}B. Lipschultz et al, Nucl. Fusion 98 (2016) 056007
Summary - Control of detachment threshold and movement

To optimize minimization of the detachment threshold:

- Divertor designs should enhance baffling & optimize strike point angle
  - If total flux expansion can be accommodated it will
    - Lower $n_{u,d}$ further (and potential to optimize control of location)

Further studies needed:

- A full study over a range of strike point angles would help optimize strike point angle choice over a range of divertor plasma densities and $q_{||}$
- More study is needed of how divertor design choices affect:
  - Divertor impurity confinement (e.g. forces on impurity ions)
  - Detachment control after onset
Backup slides
Model prediction\(^1\) of detachment location movement can be used to compare to SOLPS results

- Useful for predicting general sensitivity of detachment movement, \(z\), to changes in one or more control variables, \(C_x\) and their derivative \(dz/dC_x\) (and detachment thresholds)
  - Many simplifications required for such an analytic model

\[
\frac{n_{u}f_{\text{imp}}^{1/2}}{P_{\text{SOL}}^{5/7}} \propto \frac{B[z]}{B_{x}} \left[ \frac{(z_{x} - z)}{3} \left( 1 + \left| \frac{B[z]}{B_{x}} \right| + \left| \frac{B[z]}{B_{x}} \right|^2 \right) + \frac{(L - z_{x})}{2} \right]^{2/7}C_{n \text{u}}\frac{C_{\text{imp}}^{1/2}}{C_{\text{PSOL}}^{5/7}} \propto A[z]
\]

- Initial control variables, \(C_x\) - impurity concentration, \(P_{\text{SOL}}\) and upstream density, \(n_u\)
- Movement in \(z\) related to
  - magnetic field profile (affects \(\nabla|B|\) and \(\nabla|q_{||}|\)) and \(z_x/L\)
  - Variation in control variables, \(C_x\), leads to a different solution and \(z\)

\(^1\) B. Lipschultz et al, Nucl. Fusion 98 (2016) 056007