Overview of SOL transport and detachment in alternative divertor geometries on TCV

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For the TCV team and the EUROfusion MST1 team

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Overview of SOL transport and detachment in alternative divertor geometries on TCV

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\textsuperscript{9}See the author list of Coda et al., Nucl. Fusion 57 (2017) 102011
\textsuperscript{10}See the author list of H. Meyer et al., Nucl. Fusion 57 (2017) 102014
They look complicated... are they worth it?!
- Exhaust challenges and potential advantages of alternative configurations
- L-mode detachment experiments in alternative divertors on TCV
  - Divertors with varying poloidal flux expansion (X-Divertor)
  - Divertors with varying leg length
  - Divertors with varying total flux expansion (Super-X Divertor)
  - Snowflake divertors
- Summary and outlook
Key constraints on edge plasma

- Keep peak heat flux \( q_{\text{peak}} \) to divertor plates within material limits:
  \[
  q_{\text{peak}} \approx \frac{P_{\text{div}}}{A_W} \leq 10 \text{ MW}/m^2
  \]

- Keep erosion of divertor plates within acceptable limits. In a reactor, need
  \[
  T_{e,t} \leq 3 - 5 \text{ eV}
  \]

- Satisfy above constraints while assuring good core confinement, low impurity levels, sufficient He pumping,…
Key constraints on edge plasma

What is the strategy to satisfy these constraints?
What is the effect of divertor geometry?

- For simplicity, we focus on the outer divertor

('wetted' area)
$q_{\perp, \text{peak}}^t$ reduction by purely geometrical means

$$
q_{\perp, \text{peak}}^t \approx \frac{P_{\text{out}}}{A_W} \approx \frac{P_{\text{out}}}{2\pi R_t \lambda_q^u} \cdot \frac{\sin \beta}{f_x}
$$
$q_{\perp,\text{peak}}^t$ reduction by purely geometrical means

\[ q_{\perp,\text{peak}}^t \approx \frac{P_{\text{out}}}{A_W} \approx \frac{P_{\text{out}}}{2\pi R_t} \frac{\lambda_q^u}{f_x} \cdot \sin \beta \]

Increase strikepoint major radius $R_t$ ($A_W \propto 2\pi R_t$)
\[ q_{\perp, \text{peak}}^t \approx \frac{P_{\text{out}}}{A_W} \approx \frac{P_{\text{out}}}{2\pi R_t \lambda_q^u} \cdot \sin \beta \]

Increase poloidal flux expansion \( f_x \approx \lambda_q^t / \lambda_q^u \)

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\( q_{\perp,\text{peak}}^t \) reduction by purely geometrical means

\[ q_{\perp,\text{peak}}^t \approx \frac{P_{\text{out}}}{A_W} \approx \frac{P_{\text{out}}}{2\pi R_t \lambda_q^u} \cdot \sin \beta \]

Tilt the divertor plate

Confined plasma

Flux surfaces

\( P_{\text{out}} \)

\( \lambda_q^u \)
$q_{\perp,\text{peak}}^t$ reduction by purely geometrical means

$$q_{\perp,\text{peak}}^t \approx \frac{P_{\text{out}}}{A_W} \approx \frac{P_{\text{out}}}{2\pi R_t \lambda_q} \cdot \frac{\sin \beta}{f_x}$$
\[ q_{\perp,\text{peak}}^t \approx \frac{P_{\text{out}}}{A_W} \approx \frac{P_{\text{out}}}{2\pi R_t \lambda_q^u} \frac{\sin \beta}{f_x} \]

\( \propto \tan \alpha \)

\( \alpha \) : angle between total B-field and wall

\( \beta \) and \( f_x \) both reduce \( \alpha \). Need \( \alpha \gtrsim 2^\circ \)
\( q_{\perp,\text{peak}} \) reduction by purely geometrical means

\[
q_{\perp,\text{peak}}^t \approx \frac{P_{\text{out}}}{A_W} \approx \frac{P_{\text{out}}}{2\pi R_t \lambda_q^u} \cdot \frac{B_{\phi}^u}{B_0^u} \cdot \tan \alpha
\]

\( \alpha \): angle between total B-field and wall

- **(\( \beta \) and \( f_x \) both reduce \( \alpha \)).**
  
  Need \( \alpha \gtrsim 2^\circ \)

Estimate for ITER:

\[
q_{\perp,t}^t = 200 \text{ MW/m}^2\text{ !}
\]

Constraint on \( T_{e,t} \) not yet addressed
$q_{\perp,\text{peak}}^t$ reduction including \textbf{cross-field transport} in divertor

\[
q_{\perp,\text{peak}}^t \approx \frac{P_{\text{out}}}{A_w} \approx \frac{P_{\text{out}}}{2\pi R} \frac{\lambda_q^u}{B^u_{\phi}} \cdot \tan \alpha
\]

replace $\lambda_q^u$ by $\lambda_{q,\text{int}}$

-target heat flux without cross-field transport in divertor

Profile convoluted with Gaussian of width $S$ ($S=$spreading factor)

\[\text{Eich et al., NF 2013} \]
$q_{\perp,\text{peak}}^t$ reduction including cross-field transport in divertor

$$q_{\perp,\text{peak}}^t \approx \frac{P_{\text{out}}}{A_W} \approx \frac{P_{\text{out}}}{2\pi R_t \lambda^u_{q,\text{int}}} \cdot \frac{B^u_{\phi}}{B^u_\theta} \cdot \tan \alpha$$

$$\approx \lambda^u_q + 1.64 S^u [2]$$

Target heat flux without cross-field transport in divertor

Profile convoluted with Gaussian of width $S$ ($S=$spreading factor)

[1] Eich et al., NF 2013
\( q_{\perp, \text{peak}}^t \) reduction including **cross-field transport** in divertor

\[
q_{\perp, \text{peak}}^t \approx \frac{P_{\text{out}}}{A_W} \approx \frac{P_{\text{out}}}{2\pi R_t \lambda^u_{q,\text{int}}} \cdot \frac{B^u_\phi}{B^u_\theta} \cdot \tan \alpha
\]

Estimate for ITER:

\[
\lambda^u_q = 1\text{mm}^{[1]} \quad S = 1\text{mm}(?) \quad \lambda_{q,\text{int}} = 2.6\text{ mm}
\]

Not enough!

Constraint on \( T_{e,t} \) still not addressed

- Need radiative losses and divertor detachment

[1] Eich et al., NF 2013

2-point model prediction\textsuperscript{[1-3]} (attached conditions, $\nu_{SOL}^* \gtrsim 15$, heat conduction):

$$
T_{e,t} \propto \left( \frac{P_{out}}{\lambda_q} \right)^{10/7} \cdot \frac{(1 - f_{rad})^2}{L_{\parallel}^{4/7} n_u^2 R_t^2} \quad \text{(Divertor radiated power fraction)}
$$

$T_{e,t} \lesssim 5\text{eV}$ needed to access detachment

\textbf{References}:

[2] Kotschenreuther et al., NF 2010  
[3] Petrie et al., NF 2013
$T_{e,t}$ reduction and detachment

2-point model prediction\(^{[1-3]}\) (attached conditions, $\nu_{SOL}^* \geq 15$, heat conduction):

\[
n_u(T_{e,t} = \text{const.}) \propto \left( \frac{P_{out}}{\lambda_q} \right)^{5/7} \cdot \frac{(1 - f_{rad})}{L_{||}^{2/7} R_t}
\]

$T_{e,t} \lesssim 5eV$ needed to access detachment

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\[1\] Stangeby, textbook 2008  \[2\] Kotschenreuther et al., NF 2010  
\[3\] Petrie et al., NF 2013
$T_{e,t}$ reduction and detachment

2-point model prediction[^1-3] (attached conditions, $\nu_{SOL}^* \gtrsim 15$, heat conduction):

$$n_u(T_{e,t} = \text{const.}) \propto \left( \frac{P_{\text{out}}}{\lambda_q^u} \right)^{5/7} \cdot \frac{1 - f_{\text{rad}}}{L_{\parallel}^{2/7} R_t}$$

$T_{e,t} \lesssim 5 eV$ needed to access detachment

Adapted from Kallenbach, NF 2015

[^2] Kotschenreuther et al., NF 2010  
[^3] Petrie et al., NF 2013
$T_{e,t}$ reduction and detachment

2-point model prediction$^{[1-3]}$ (attached conditions, $\nu_{SOL}^* \geq 15$, heat conduction):

$$n_u(T_{e,t} = \text{const.}) \propto \left( \frac{P_{out}}{\lambda_q} \right)^{\frac{5}{7}} \cdot \frac{(1 - f_{\text{rad}})}{L_{||}^{2/7} R_t}$$

$T_{e,t} \leq 5\text{eV}$ needed to access detachment

However, at high levels of detachment, cold radiation region moves into core plasma

- Varying levels of degradation in
  - Confinement
  - Divertor neutral pressure
  - Impurity screening
  - He pumping...?

[3] Petrie et al., NF 2013
Power exhaust in ITER and DEMO

- ITER plans to operate with a partially detached divertor. Need $f_{rad} \geq 60\%$

- Demo (3-4x the power, similar size) will need $f_{rad} \geq 95\%$. Approx. half of the power to be radiated in the core?

  ➢ Might exceed capabilities of conventional divertor!

Alternative divertors expected to help along different lines

1. Reduce heat flux in the absence of radiation

\[ q_{\perp, \text{peak}} \approx \frac{P_{\text{out}}}{2\pi R_t (\lambda_q^u + 1.64 \cdot S^u)} \cdot \frac{B_{\Phi}^u}{B_{\theta}^u} \cdot \tan \alpha \]

2. Facilitate access to detachment

\[ n_u(T_{e,t} = \text{const.}) \propto \left( \frac{P_{\text{out}}}{\lambda_q^u} \right)^{\frac{5}{7}} \cdot \frac{1 - f_{\text{rad}}}{L_{\parallel}^{2/7} R_t} \]

3. Improve control of radiation front location?
   Increase maximum divertor radiation?
Potential benefits of the X-divertor

\[ q_{\perp,\text{peak}} \approx \frac{P_{\text{out}}}{2\pi R_t (\lambda_q^u + 1.64 \cdot S^u)} \cdot \frac{B^u_\phi}{B^u_\theta} \cdot \tan \alpha \]

\[ n_u(T_{e,t} = \text{const.}) \propto \left(\frac{P_{\text{out}}}{\lambda_q^u}\right)^{\frac{5}{7}} \cdot \frac{(1 - f_{\text{rad}})}{L_{\parallel}^{2/7} R_t} \]

Poloidal flux flaring towards target; increased \( L_{\parallel} \) and divertor volume
- Larger volume → larger \( f_{\text{rad}} \)?
- Can flaring near target inhibit upstream movement of the detachment front?\(^{[1,2]}\)

[2] Lipschultz et al., NF 2016
Potential benefits of the Super-X divertor

\[ q_{\perp,\text{peak}} \approx \frac{P_{\text{out}}}{2\pi R_t \left( \frac{\lambda u}{\lambda_q} + 1.64 \cdot S^u \right)} \cdot \frac{B_\phi^u}{B_\theta^u} \cdot \tan \alpha \]

\[ n_u(T_{e,t} = \text{const.}) \propto \left( \frac{P_{\text{out}}}{\lambda_q} \right)^{\frac{5}{7}} \cdot \left( 1 - f_{\text{rad}} \right) \cdot \frac{L_{\parallel}^{2/7}}{R_t} \]

Increase in \( R_t \) (total flux expansion); can be combined with increased divertor volume and \( L_{\parallel} \):
- Reduced detachment threshold?
- Larger volume \( \rightarrow \) larger \( f_{\text{rad}} \)?
- Can total flux expansion inhibit upstream movement of thermal front?\(^{[1-3]}\)

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[2] Labombard et al., NF 2015
[3] Lipschultz et al., NF 2016
Potential benefits of the **Snowflake divertor**

\[
q_{\perp, \text{peak}} \approx \frac{P_{\text{out}}}{2\pi R_t (\lambda^u_q + 1.64 \cdot S^u)} \cdot \frac{B^u_\phi}{B^u_\theta} \cdot \tan \alpha
\]

\[
n_u(T_{e,t} = \text{const.}) \propto \left(\frac{P_{\text{out}}}{\lambda^u_q}\right)^{\frac{5}{7}} \cdot \frac{(1 - f_{\text{rad}})}{L_{\parallel}^{2/7} R_t}
\]

Extended region of low $B_\theta$; increased $L_{\parallel}$ and divertor volume
Potential benefits of the **Snowflake divertor**

\[
q_{\perp,\text{peak}} \approx \frac{P_{\text{out}}}{2\pi R_t \left( \lambda_q^u + 1.64 \cdot S^u \right)} \cdot \frac{B^u_\phi}{B^u_\theta} \cdot \tan \alpha
\]

\[
n_u(T_{e,t} = \text{const.}) \propto \left( \frac{P_{\text{out}}}{\lambda_q^u} \right)^{\frac{5}{7}} \cdot \frac{(1 - f_{rad})}{L_{||}^{2/7} R_t}
\]

**Snowflake minus divertor**

Extended region of low $B_\theta$; increased $L_{||}$ and divertor volume; **strike point splitting**
Potential benefits of the **Snowflake divertor**

\[
q_{\perp, \text{peak}} \approx \frac{P_{\text{out}}}{2\pi R_t (\lambda_q^u + 1.64 \cdot S^u)} \cdot \frac{B^u_\phi}{B^u_\theta} \cdot \tan \alpha
\]

\[
n_u(T_{e,t} = \text{const.}) \propto \left( \frac{P_{\text{out}}}{\lambda_q^u} \right)^{\frac{5}{7}} \cdot \left( 1 - f_{\text{rad}} \right) \cdot \frac{L_{\|}^{2/7}}{R_t}
\]

**Extended region of low B_\theta; increased L_{\|} and divertor volume; strike point splitting**

- Increased cross-field transport due to extended low B_\theta region\(^{[1]}\), strike point splitting\(^{[2-3]}\), …?
- Larger volume → larger f_{\text{rad}}?
- Change in radiation front location?

[3] Labit et al., NME 2017
Up-down symmetric configurations and tight baffling

Redirect heat flux from lower inner to upper outer divertor leg
- Tune power sharing (and also peak heat flux?) between divertor legs via dr_sep
- Increase maximum radiation due to two radiation fronts?
- Possibility to apply alternative shapes to both active legs

Tight baffling to increase divertor neutral pressure
- Strongly facilitated access to detachment\([1-3]\)?
- Enhanced detachment operational window\([2]\)?

• Exhaust challenges and potential advantages of alternative configurations

• L-mode detachment experiments in alternative divertors on TCV
  - Divertors with varying poloidal flux expansion (X-Divertor)
  - Divertors with varying leg length
  - Divertors with varying total flux expansion (Super-X Divertor)
  - Snowflake divertors

• Summary and outlook
TCV tokamak
TCV tokamak

• “Medium-sized” tokamak
  - Major radius \( R = 0.89 \text{m} \)
  - Toroidal field \( B_t \leq 1.5 \text{ T} \)
  - Plasma current \( I_p \leq 1 \text{MA} \)
• Open divertor, 95% Carbon tiles
• Flexible, real-time controllable electron cyclotron heating (4MW)
• 1MW neutral beam heating (15-25keV)
• Unique shaping capabilities

Coda et al., NF 2017
TCV tokamak

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Coda et al., NF 2017
“Medium-sized” tokamak
- Major radius $R = 0.89m$
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Open divertor, 95% Carbon tiles

Flexible, real-time controllable electron cyclotron heating (4MW)

1MW neutral beam heating (15-25keV)

Unique shaping capabilities

Coda et al., NF 2017
Poloidal flux expansion scan; X-Divertor

Poloidal flux expansion $f_x$ varied from $\approx 2$ to $\approx 21$

Increase due to $f_x$
IR target heat flux characterization in attached conditions

\[ q_{\perp, \text{peak}} \approx \frac{P_{\text{out}}}{2\pi R_t (\lambda_q^u + S^u)} \cdot \frac{B_u^\phi}{B^u_\theta} \cdot \tan \alpha \]

IR target heat flux characterization in **attached** conditions

\[ q_{\perp,\text{peak}} \approx \frac{P_{\text{out}}}{2\pi R_t (\lambda_q^u + S^u)} \cdot \frac{B^u_\theta}{B^u_\phi} \cdot \tan \alpha \]

- \( \lambda_q^u \) fairly insensitive to \( f_x \)

---

IR target heat flux characterization in **attached** conditions

\[
q_{\parallel,\text{peak}} \approx \frac{P_{\text{out}}}{2\pi R_t (\lambda_q^u + S^u)} \cdot \frac{B_{\phi}^u}{B_{\theta}^u} \cdot \tan \alpha
\]

- \(\lambda_q^u\) fairly insensitive to \(f_x\)
- \(S^u\) decreases approx. as \(1/f_x\)

IR target heat flux characterization in **attached** conditions

\[ q_{\text{peak}}^{t} \approx \frac{P_{\text{out}}}{2\pi R_{t}} \left( \lambda_{q}^{u} + S^{u} \right) \frac{B_{\varphi}^{u}}{B_{\theta}^{u}} \cdot \tan \alpha \]

- \( \lambda_{q}^{u} \) fairly insensitive to \( f_{x} \)
- \( S^{u} \) decreases approx. as \( 1/f_{x} \)
- \( \tan \alpha \propto 1/f_{x} \) (however, an \( \alpha \) reduction can also be achieved by wall tilt)

Observations when accessing **detachment** via density ramp

At outer strikepoint:

- $I_{\text{sat}}$ and target pressure roll-over at $\langle n_e \rangle \approx 1 \times 10^{19} m^{-3}$

\[ \text{Ion flux } \propto \frac{p_t}{\sqrt{T_e}} \]

[1] Février et al., APS 2017
Observations when accessing **detachment** via density ramp

At outer strikepoint:

- $I_{\text{sat}}$ and target pressure roll-over at $\langle n_e \rangle \approx 1 \times 10^{19} \text{m}^{-3}$
- Parallel pressure gradient develops with $I_{\text{sat}}$ roll-over

![Graph showing parallel pressure drop versus $\langle n_e \rangle$](image)

[1] Février et al., APS 2017
At outer strikepoint:

- $I_{sat}$ and target pressure roll-over at $\langle n_e \rangle \approx 1 \times 10^{19} m^{-3}$
- Parallel pressure gradient develops with $I_{sat}$ roll-over

Inner strikepoint remains attached
\( I_{\text{sat}} \) roll-over caused by divertor power starvation

- Balmer line spectroscopy with new analysis techniques enables extracting:
  - Ionisation rates
  - Recombination rate
  - Hydrogenic radiated power

- \( I_{\text{sat}} \) and ion source roll over at the same density
- Volume recombination a weak particle sink
- Power balance analysis shows that power starvation limits the divertor ion source, causing the \( I_{\text{sat}} \) roll-over

[1] Verhaegh et al., NME 2017
Dependence of detachment characteristics on $f_x$

- Roll-over at similar line-averaged densities

$\text{Total ion flux to OSP}$

$[\text{s}^{-1}]$

$\left< n_e \right> [10^{20} \text{m}^{-3}]$

$3 \times 10^{22}$

$f_x = 2.0$

$f_x = 3.5$

$f_x = 5.0$

$f_x = 7.4$

$f_x = 10$

$f_x = 21$

[1] Theiler et al., NF 2017
Dependence of detachment characteristics on $f_x$

- Roll-over at similar line-averaged densities

$$n_u(T_{e,t} = \text{const.}) \propto \left(\frac{P_{\text{out}}}{\lambda_q}\right)^{\frac{5}{7}} \cdot \frac{(1 - f_{\text{rad}})}{L_{||}^{2/7} R_t}$$

$$\left(\frac{L_{||}(f_x = 2)}{L_{||}(f_x = 21)}\right)^{\frac{2}{7}} \approx 0.8$$

[1] Theiler et al., NF 2017
Dependence of detachment characteristics on $f_x$

- Roll-over at similar line-averaged densities
- Detachment more pronounced with increasing $f_x$

[1] Theiler et al., NF 2017
Dependence of detachment characteristics on $f_x$

- Roll-over at similar line-averaged densities
- Detachment more pronounced with increasing $f_x$

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Dependence of detachment characteristics on $f_x$

- Roll-over at similar line-averaged densities
- Detachment more pronounced with increasing $f_x$

CIII emissivity\(^{[1]}\) [a.u.]

\(^{[1]}\) Harrison \textit{et al.}, NME 2016

\(^{[2]}\) Nakano \textit{et al.}, JNM 2009
Dependence of detachment characteristics on $f_x$

- Roll-over at similar line-averaged densities
- Detachment more pronounced with increasing $f_x$

CIII emissivity\(^{[1]}\) [a.u.]

Dependence of detachment characteristics on $f_x$

- Roll-over at similar line-averaged densities
- Detachment more pronounced with increasing $f_x$

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[3] Theiler et al., NF 2017
Dependence of detachment characteristics on $f_x$

- Roll-over at similar line-averaged densities
- Detachment more pronounced with increasing $f_x$

[1] Theiler et al., NF 2017
Dependence of detachment characteristics on $f_x$

- Roll-over at similar line-averaged densities
- Detachment more pronounced with increasing $f_x$
- Improved controllability of radiation location with increasing $f_x$

[1] Theiler et al., NF 2017
Dependence of radiation levels on \( f_x \)

\[ \langle n_e \rangle \approx 0.55 \cdot 10^{20} m^{-3} \]

- Roll-over at similar line-averaged densities
- Detachment more pronounced with increasing \( f_x \)
- Improved controllability of radiation location with increasing \( f_x \)
Dependence of radiation levels on $f_x$

- Roll-over at similar line-averaged densities
- Detachment more pronounced with increasing $f_x$
- Improved controllability of radiation location with increasing $f_x$

\[ \langle n_e \rangle \approx 0.55 \cdot 10^{20} \text{m}^{-3} \]

$f_x = 2$  \hspace{1cm} $f_x = 21$

\[ P_{\text{rad,up}} \]
\[ P_{\text{rad,leg}} \]

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Dependence of radiation levels on $f_x$

- Roll-over at similar line-averaged densities
- Detachment more pronounced with increasing $f_x$
- Improved controllability of radiation location with increasing $f_x$
- $P_{\text{rad,leg}}$ increases by $\approx 50\%$ with increasing $f_x$
- Total $f_{\text{rad}}$ similar for all $f_x$ (limited to $\approx 70\%$)

[1] Theiler et al., EPS 2017
Leg length scan

Variation of outer divertor leg length $L_{\text{leg}}$ from 0.19 m to 0.62 m

$L_{\text{leg}} = 0.19 \text{ m}$

$L_{\text{leg}} = 0.36 \text{ m}$

$L_{\text{leg}} = 0.62 \text{ m}$

[1] Reimerdes et al., NF 2017
IR target heat flux characterization in attached conditions

\[ q_{\text{peak}}^t \approx \frac{P_{\text{out}}}{2\pi R_{t'}} \left( \frac{\lambda_{q}^{u} + S^{u}}{B_{q}^{u}} \right) \cdot \frac{B_{\phi}^{u}}{B_{\theta}^{u}} \cdot \tan \alpha \]

IR target heat flux characterization in attached conditions

\[
q_{\text{peak}}^t \approx \frac{P_{\text{out}}}{2\pi R_t (\lambda_q^u + S^u)} \cdot \frac{B_{\phi}^u}{B_{\theta}^u} \cdot \tan \alpha
\]

- \( \lambda_q^u \) increases strongly with \( L_{\text{leg}} \)

IR target heat flux characterization in attached conditions

\[ q_{\perp,\text{peak}}^{t} \approx \frac{P_{\text{out}}}{2\pi R_{t} (\lambda_{q}^{u} + S^{u})} \cdot \frac{B_{\Phi}^{u}}{B_{\theta}^{u}} \cdot \tan \alpha \]

- \( \lambda_{q}^{u} \) increases strongly with \( L_{\text{leg}} \)
- \( S^{u} \) shows no clear trend with \( L_{\text{leg}} \)

![Graph showing the relationship between \( L_{\text{leg}} \) and \( \lambda_{q,u} \) and \( S_{u} \)]

IR target heat flux characterization in attached conditions

\[ q_{\perp,\text{peak}} \approx \frac{P_{\text{out}}}{2\pi R_t} \frac{B_{\phi}^u}{B_{\theta}^u} \cdot \tan \alpha \]

- \( \lambda_q^u \) increases strongly with \( L_{\text{leg}} \)
- \( S^u \) shows no clear trend with \( L_{\text{leg}} \)
- Similar effects on density profiles\(^{[3]}\)

IR target heat flux characterization in attached conditions

Behavior qualitatively reproduced by isothermal turbulence simulations[3]

Divertor transport is asymmetric

$D_{eff} \text{ [a.u.]}$

Asymmetric broadening of target density profile with $L_{\text{leg}}$

$n_{e,t} \text{ [a.u.]}$

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Dependence of detachment characteristics on $L_{\text{leg}}$

- ~30% reduction of detachment threshold density with increasing $L_{\text{leg}}$
- Result consistent with increase in $\lambda_q^u$

$n_u(T_{e,t} = \text{const.}) \propto \left( \frac{P_{\text{out}}}{\lambda_q^u} \right)^{5/7} \cdot \frac{(1 - f_{\text{rad}})}{L_{\parallel}^{2/7} R_t}$

[1] Reimerdes et al., NF 2017
Dependence of detachment characteristics on $L_{\text{leg}}$

- $\sim30\%$ reduction of detachment threshold density with increasing $L_{\text{leg}}$
- Result consistent with increase in $\lambda_q$
- Increased density window for radiation front movement

![Graph showing CIII front position with poloidal distance below X-point (m) vs. $<n_e> [10^{20} \text{ m}^{-3}]$]

$L_{\text{leg}}=0.19\text{m}$
$L_{\text{leg}}=0.36\text{m}$
$L_{\text{leg}}=0.62\text{m}$

[1] Theiler et al., EPS 2017
Dependence of radiation levels on $L_{\text{leg}}$

$\langle n_e \rangle \approx 0.6 \cdot 10^{20} m^{-3}$

- $L_{\text{leg}} = 0.19$
- $L_{\text{leg}} = 0.62$

- $\approx 30\%$ reduction of detachment threshold density with increasing $L_{\text{leg}}$
- Result consistent with increase in $\lambda_q$
- Increased density window for radiation front movement
Dependence of radiation levels on $L_{\text{leg}}$

- $\sim$30% reduction of detachment threshold density with increasing $L_{\text{leg}}$
- Result consistent with increase in $\lambda_q$
- Increased density window for radiation front movement
- $P_{\text{rad,leg}}$ increases $\approx 3 \times$ with increasing $L_{\text{leg}}$
- Total $f_{\text{rad}}$ similar for all $L_{\text{leg}}$ (limited to $\approx 70\%$)
Variation of $R_t$; Super-X divertor

Major radius $R_t$ of OSP varied by $\approx 70\%$ resulting in variation of total flux expansion

[1] Theiler et al., NF 2017
Dependence of detachment characteristics on $R_t$

- No sign of easier access to detachment with increasing $R_t$

[Theiler et al., NF 2017]
• No sign of easier access to detachment with increasing $R_t$, in contrast to SOLPS\textsuperscript{[1]} and 2-pt. model predictions

\[ n_u(T_{e,t} = \text{const.}) \propto \left( \frac{P_{out}}{\lambda_{q}^u} \right)^{\frac{5}{7}} \cdot \left( 1 - f_{\text{rad}} \right) \frac{L_{\perp}^{2}}{R_{t}} \]

\[ \frac{R_{t}}{R_{t}} \approx 1.7 \]

\textsuperscript{[1]} Moulton \textit{et al.}, PPCF 2017
 Dependence of detachment characteristics on $R_t$

- No sign of easier access to detachment with increasing $R_t$, in contrast to SOLPS and 2-pt. model predictions
- No sign of expected improved controllability of the radiation location with increasing $R_t$

[2] Labombard et al., NF 2015
[3] Lipschultz et al., NF 2016
Dependence of detachment characteristics on $R_t$

- No sign of easier access to detachment with increasing $R_t$, in contrast to SOLPS and 2-pt. model predictions
- No sign of expected improved controllability of the radiation location with increasing $R_t$
  - Significant convective contribution to $q_{\parallel}$...? Ionization not localized at target...?
  - Simulation work ongoing
All variations of the **Snowflake divertor** explored on TCV

[1] Reimerdes *et al.*, NF 2017
All variations of the **Snowflake divertor** explored on TCV

$L_\parallel$ changes most significant in SF- geometries on TCV

HFS SF-

SF+

LFS SF-

SN

[1] Reimerdes et al., NF 2017
[2] Labit et al., NME 2017
• $d_{r_2}$ scan suggest a 3-fold increase in the effective $\lambda^u_q$ in SF- plasmas.
Radiation distribution control around primary X-point

[1] Reimerdes et al., NF 2017
Radiation distribution control around primary X-point

\[ \text{N}_2 \text{ seeding leads to radiation zone between the X-points of the 'Snowflake minus' divertor, as predicted by EMC3-Eirene calculations [Lunt et al., PPCF 2016].} \]
Summary

- A number of alternative magnetic geometries have been recently proposed which aim at improving the exhaust performance
  - Increase target wetted area by increased divertor cross-field transport
  - Facilitate access to detachment
  - Improve control of the radiation/detachment front
  - Increase total radiated power in the SOL
Summary

- A number of alternative magnetic geometries have been recently proposed which aim at improving the exhaust performance.
- On TCV, the exhaust properties of a wide variety of alternative divertor geometries have been explored in L-mode and open divertor geometry.
  - Increasing poloidal flux expansion reduces $S^u$ in attached conditions, increases depth of detachment, improves controllability of radiation peak, increases divertor radiation.
  - Increasing leg length increases $\lambda^u_q$, lowers the detachment threshold, increases divertor radiation.
  - These two means to increase $L_\parallel$ have a very different effect!
Summary

• A number of alternative magnetic geometries have been recently proposed which aim at improving the exhaust performance.

• On TCV, the exhaust properties of a wide variety of alternative divertor geometries have been explored in L-mode and open divertor geometry.

  - Increasing poloidal flux expansion reduces $S^u$ in attached conditions, increases depth of detachment, improves controllability of radiation peak, increases divertor radiation.

  - Increasing leg length increases $\lambda_q^u$, lowers the detachment threshold, increases divertor radiation.

  - Increasing total flux expansion shows no significant effect on detachment characteristics. Deviations from theoretical predictions not yet understood.

  - The SF-minus divertor shows evidence of increased divertor cross-field transport and can trap the radiation zone between the two X-points.
Upcoming baffled long-leg divertor experiments in EU

Baffled Super-X on MAST-U
2018

Conventional
Super-X

Fishpool et al., JNM 2013

Baffled divertor chamber in TCV
2019

Conventional
Single-null divertor

Snowflake divertor

X divertor

Super-X divertor

Fasoli et al., NF 2015
Reimerdes et al., NME 2017