DEMO physics basis and gaps for power exhaust

Holger Reimerdes

4th IAEA DEMO Programme Workshop
Karlsruhe, Germany, Nov. 15-18, 2016
DEMO physics basis and gaps for power exhaust

Acknowledge discussions with

Outline

1. Physics basis for a divertor plasma with partial or full detachment
2. Physics basis for heat fluxes towards the first wall
3. Physics basis and feasibility of ‘alternative’ divertor configurations
4. Summary of gaps
1. Physics basis for a divertor plasma with partial or full detachment

2. Physics basis for heat fluxes towards the first wall

3. Physics basis and feasibility of ‘alternative’ divertor configurations

4. Summary of gaps
Key constraints at the divertor target

[R. Wenninger, et al., NF (2014)]

• **Divertor**: Water-cooled tungsten (W) targets

• **Stationary loads**
  - **Peak heat flux** $q_{\perp,t} < 5-10$MW/m$^2$
    - Depends on temperature range of heat sink and interlayer materials
  - **Plasma temperature** $T_t < 4$eV
    - Avoid excessive sputtering of W (core contamination and target erosion)

• **Transient loads** (heat deposition faster than heat removal)
  - $T$ of W limited 3400°C to avoid surface melting (or 1200°C to avoid W recrystallisation for frequent transients)
  - **Heat impact factor**
    $\eta = \Delta W/(A \Delta t^{1/2}) < 50$MJ/(m$^2$ s$^{1/2}$) to avoid melting
    $< 10$MJ/(m$^2$ s$^{1/2}$) to avoid cracking
Magnitude of the challenge

- Wetted area \( A_w \equiv \frac{P_{\text{tar}}}{(q_{\perp,t})_{\text{max}}} \)
  - Assume exponential heat flux profile with \( \lambda_{q,u} \)

\[
A_w = 2\pi R_t \frac{f_{x,t}}{\cos \alpha_{\text{pol}}} \lambda_{q,u} = 2\pi R_t \left( \frac{B_{p,u}}{B_{t,u}} \right) \frac{1}{\tan \gamma} \lambda_{q,u}
\]

6 for \( \gamma = 3^\circ \)

- Target profiles deviate from exponential

\[
\lambda_{\text{int}} \equiv \int q\,ds/q_{\text{max}} = \lambda_q + 1.64\,S
\]

[T. Eich, et al., *NF* (2013), Fig. 1]
Scale heat flux width $\lambda_q$ and divertor spreading $S$

- $\lambda_q$ seen to scale unfavourably towards a reactor [T. Eich, et al., NF (2013)]
  - Single parameter fit
    \[ \lambda_q^{H\text{-mode}} (mm) = 0.63 \times B_{pol,MP}^{-1.2} \]
  - $\lambda_q($DEMO$) \sim 0.9$mm

- Observations consistent with heuristic model [R. Goldston, NF (2012)]

- Empiric scaling and heuristic model apply to attached conditions

- Recent gyrokinetic calculations predict deviation from $1/B_P$ scaling for ITER and DEMO [C.S. Chang, et al., IAEA FEC (2016)]
Scale heat flux width $\lambda q$ and divertor spreading $S$

- Cross-machine data base for $S$ [A. Scarabosio, et al., JNM (2015)]

- Machine comparison yields favourable size scaling: $S \propto R^{0.7}$
- Both data sets suggest unfavourable field scaling: $S \propto B_p^{-0.8}$

- Tentative scaling [R. Wenninger, et al., NF (2015)]

\[
S_{\text{DEMO}} = S_{\text{JET, open}} \frac{S_{\text{AUG, closed}}}{S_{\text{AUG, open}}} \left( \frac{R_{\text{DEMO}}}{R_{\text{JET}}} \right)^{1} \left( \frac{B_{p, \text{DEMO}}}{B_{p, \text{JET}}} \right)^{-1} \sim 4.5 \text{mm}
\]

AUG and JET with open divertor

AUG with closed divertor
Magnitude of the challenge

• Wetted area in DEMO may be determined by $S$ rather than $\lambda_q$ ($\lambda_{int,\text{DEMO}} \sim 8\text{mm}$):

$$A_{w,\text{outer}} = 2\text{m}^2 \text{ (assuming } \gamma = 3^\circ \text{ and chamfering of } \alpha = 1^\circ)$$

- Unmitigated heat flux (1:2 in-out asymmetry): $(q_{\perp,t})_{\text{max}} = 100\text{MW/m}^2$

• Required power loss fraction

<table>
<thead>
<tr>
<th>$q_{\perp,\text{outer,max}} \text{ (MW/m}^2\text{)}$</th>
<th>Total power loss fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>$P_{\text{loss}}/P_{\text{heat}} = 90%$</td>
</tr>
<tr>
<td>5</td>
<td>$P_{\text{loss}}/P_{\text{heat}} = 95%$</td>
</tr>
</tbody>
</table>

- “Knowledge” gaps
  - Extrapolation of $\lambda_q$, $S$, i.e. $\lambda_{q,\text{int}}$
  - Minimum values of $\gamma$ and $\alpha$
Increase radiation to protect divertor

Seed impurities
- Species must be chemically inactive and compatible with tritium handling → noble gases (+nitrogen)
- Impurity species differ in their temperature dependent radiative loss function, transport and the degree of fuel dilution

<table>
<thead>
<tr>
<th>Impurity</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>7</td>
</tr>
<tr>
<td>Ne</td>
<td>10</td>
</tr>
<tr>
<td>Ar</td>
<td>18</td>
</tr>
<tr>
<td>Kr</td>
<td>36</td>
</tr>
<tr>
<td>Xe</td>
<td>54</td>
</tr>
</tbody>
</table>

[A. Kallenbach, et al., PPCF (2013), Fig. 1]
Increase radiation to protect divertor

- Impurity seeding, e.g. $N_2$ in JET [G. Matthews, et al., PPCF (1995)]

- Feedback control of seeding rate, e.g. of Ne in AUG CDH mode [O. Gruber, et al., PRL (1995)]

- Feedback control using multiple species, e.g. with N and Ar [A. Kallenbach, et al., NF (2012)]
Radiation control must meet several constraints

- **Core radiation**
  - Sufficiently low to enter and remain in H-mode
  - Sufficiently low to maintain good core confinement and acceptable fuel dilution
  - Sufficiently high to protect divertor

- **Divertor radiation**
  - Sufficiently high to protect divertor targets
  - Sufficiently low to avoid excessive core impurity concentration
Radiation control must meet several constraints

- **Core radiation**
  - Sufficiently low to enter and remain in H-mode
  - Sufficiently low to maintain good core confinement and acceptable fuel dilution
  - Sufficiently high to protect divertor

- **Divertor radiation**
  - Sufficiently high to protect divertor targets
  - Sufficiently low to avoid excessive core impurity concentration

- **Gaps**
  - Extrapolation of $P_{L-H}$
    - Relevant heat flux for L-H transition
    - Effect of metal walls
  - Control scheme for DEMO
Scaling of the divertor challenge towards DEMO

- Metrics of the “divertor challenge”
  
  - Heat flux \( q_{||} \propto P_{\text{sep}}/R \) (if \( \lambda_q \) independent of \( R \) and \( B \))
    \[ \propto P_{\text{sep}}B_0/R \] (if \( \lambda_q \propto B_p^{-1} \), assuming constant \( q_{95} \) and \( A \))

  - Required impurity concentration to dissipate \( P_{\text{sep}} \)
    \[ c_Z \propto P_{\text{sep}}/<B_p> \] (if \( n_{\text{sep}}/n_{\text{GW}} \) constant) [R. Goldston, et al., Lorentz Center Workshop]

  - Required neutral pressure and impurity concentration to detach
    \[ \rho_0 (1+f_{\text{se}}) \propto P_{\text{sep}}B_0/R \] [A. Kallenbach, et al., PPCF (2016)]

- Gaps
  
  - Establish/verify/include link between divertor neutral density, separatrix density and line averaged density
  - Identify DEMO relevant limit to divertor radiation
  - Test with experiments
    - Measure impurity concentration (distribution)
Scaling of the divertor challenge towards DEMO

- Metrics of the “divertor challenge”

<table>
<thead>
<tr>
<th></th>
<th>AUG</th>
<th>JET</th>
<th>ITER (Q=10)</th>
<th>DEMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{geo}}$ (m)</td>
<td>1.65</td>
<td>2.9</td>
<td>6.2</td>
<td>8.8</td>
</tr>
<tr>
<td>$B_T$ (T)</td>
<td>2.5</td>
<td>2.6</td>
<td>5.3</td>
<td>5.8</td>
</tr>
<tr>
<td>$I_p$ (MA)</td>
<td>1.2</td>
<td>2.5</td>
<td>15</td>
<td>20.3</td>
</tr>
<tr>
<td>$n_{GW}$ ($10^{20}\text{m}^{-3}$)</td>
<td>1.4</td>
<td>1.0</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>$P_{\text{heat}}$ (MW)</td>
<td>26</td>
<td>25</td>
<td>150</td>
<td>300</td>
</tr>
<tr>
<td>$f_{\text{rad,core}}$</td>
<td>0.25</td>
<td>0.4</td>
<td>0.33</td>
<td>0.5</td>
</tr>
<tr>
<td>$P_{\text{sep}}$ (MW)</td>
<td>20</td>
<td>16</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>$P_{\text{sep}}/P_{L-H}$</td>
<td>4.5</td>
<td>1.8</td>
<td>1.4</td>
<td>1.1</td>
</tr>
<tr>
<td>$P_{\text{sep}}/R$ (MW/m)</td>
<td>12</td>
<td>5.2</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>$P_{\text{sep}}B_0/R$ (MW·T/m)</td>
<td>30</td>
<td>13</td>
<td>88</td>
<td>99</td>
</tr>
<tr>
<td>$P_{\text{sep}}/B_p$ (MW/T)</td>
<td>58</td>
<td>39</td>
<td>96</td>
<td>138</td>
</tr>
</tbody>
</table>

$q_{\parallel} \propto$ 
$c_z \propto$
Divertor solution must be compatible with core performance

- Optimisation of DEMO power exhaust [R. Wenninger, et al., NF (2015)]

- Assumptions
  - (Seed-) Impurity enrichment in the SOL/divertor ($c_{\text{SOL}}/c_{\text{core}} = 3$)
  - Deviation from a coronal charge state distribution ($n_e \tau \sim 10^{20} \text{ m}^{-3} \text{ s}$)

- Model core transport and calculate $P_{\text{fusion}}$

- Single seed species solution only for Ar
  - Fusion power can be increased by additional core seeding with Kr or Xe
  - Operating regime extremely narrow and existence very sensitive to assumptions (enrichment, $c_W$)

- Gap
  - Impurity enrichment (high leverage)
Full detachment obtained with various impurities in AUG and JET

[M. Bernert, et al., PSI (2016)]

- **N**
  - AUG: $H_{98} = 0.9$, $f_{rad} \leq 90\%$
  - JET: $H_{98} = 0.7$, $f_{rad} \leq 75\%$
  - Type-III ELMs

- **Ne**
  - JET: $H_{98} = 0.8$, $f_{rad} \leq 90\%$
  - No stable operation for power exhaust (Ped. Transport)
  - H/L transitions

- **Ar**
  - AUG: $H_{98} = 0.7-1$, $f_{rad} \leq 90\%$
  - Type-III ELMs?

- **Kr**
  - AUG: $H_{98} = 0.65$, $f_{rad} \leq 90\%$
  - Unstable
  - JET: $H_{98} = 0.65$, $f_{rad} \leq 60\%$
  - H/L transitions
Full detachment comes with strong X-point radiation

- X-point radiation does not cause strong confinement degradation (may be power at top of pedestal)
  - Effect on L-H unclear
- Feasibility greatly affected by coupling to pedestal and core transport!
- Scenario must be compatible with required He pumping capacity, i.e. neutral pressure in the divertor
  - AUG indicates that a high neutral pressure can be sustained

Gaps
- Limit of radiated power
- Effect on L-H/H-L transition/confinement
- Modelling of DEMO including extrapolation of impurity transport
- Extrapolation of neutral pressure in the divertor
Transient power loads in the divertor

- Disruption loads
- ELMs
- Confinement transients (e.g. H-L transition)
Constraints on ELM size $\Delta W_{\text{ELM}}/W_{\text{plasma}}$ more severe than in ITER

- ELM duration scales with the parallel ion transport time in the divertor $\tau_{||}=2\pi q_{95} R/c_{s,\text{i,ped}}$ [A. Hermann, et al., JNM (2003)]
  - $\Delta W_{\text{ELM}}/A_{\text{ELM}} < 0.25 \text{ MJ/m}^2$ assuming $\Delta t_{\text{ELM}}=500\mu$s (ITER)
  - $\epsilon_{||} < 5 \text{ MJ/m}^2$ assuming $\gamma=3^\circ$

- Cross-machine scaling links $\epsilon_{||}$ of type-I ELMs to pedestal pressure [T. Eich, et al., PSI (2016)]

$$\epsilon_{||} = 0.28 \frac{\text{MJ}}{\text{m}^2} n_{e,\text{ped,top}} T_{e,\text{ped,top}}^{0.75} R_{\text{geo}}^{1} \left(\frac{\Delta W_{\text{ELM}}}{W_{\text{plasma}}}\right)^{0.5}$$

- Need for mitigation of type-I ELMs in DEMO

- Gap
  - Extrapolation of ELM size/energy density in detached regimes
Outline

1. Physics basis for a divertor plasma with partial or full detachment

2. Physics basis for heat fluxes towards the first wall

3. Physics basis and feasibility of ‘alternative’ divertor configurations

4. Summary of gaps
Key constraints at the first wall

[R. Wenninger, et al., submitted to NF]

- **Breeding blanket**: W armour on EUROFER

![Diagram showing W (2mm) armour on EUROFER with layers of H₂O and LiPb](image-url)
Key constraints at the first wall

[R. Wenninger, et al., submitted to NF]

• **Breeding blanket**: W armour on EUROFER

• **Stationary loads**
  - $T$ of EUROFER limited to 550°C to avoid loss of strength
  - **Peak heat flux** $q_{\perp,t} < 1.5\text{MW/m}^2$ (water cooling)
    - Higher heat handling capability possible at a higher cost
  - **Erosion rate** < 50t W/yr for 1 fpy lifetime

• **Transient loads** - similar to divertor targets
  - **Heat impact factor**
    $$\eta = \Delta W/(A \Delta t^{1/2}) < 50\text{MJ/(m}^2\text{ s}^{1/2})$$ to avoid melting
    $$< 10\text{MJ/(m}^2\text{ s}^{1/2})$$ to avoid cracking
Stationary first wall load types

[R. Wenninger, et al., submitted to NF]

- **Charged particles**
  - D/T (fuel), He (ash) and impurity ions (seeding)
    + Depends on blob size/velocity/regime (inertial), intermittency/fraction of power in blob channel

- **Radiation**
  - Highest load due to “x-point radiator” radiation on baffle, but <1MW/m²
    + May require localised higher heat flux components

- **Fast particles**
  - TF ripple losses do not lead to a significant increase in peak heat fluxes
  - Effect of 3D fields for ELM suppression must be investigated

- **Neutrals**
  - Energetic D/T from charge exchange between recycling neutrals and hot ions
    + May need to increase plasma wall distance, but minimum imposed through required core fuelling [M. Beckers, et al., PSI (2016)]
Dynamic first wall load types

[R. Wenninger, et al., submitted to NF]

• Charged particles
  – Limiter configuration in ramp up and ramp down
  – ELM filaments
  – Confinement transients (e.g. L-H transition)
  – Disruptions
Outline

1. Physics basis for a divertor plasma with partial or full detachment

2. Physics basis for heat fluxes towards the first wall

3. Physics basis and feasibility of ‘alternative’ divertor configurations
   – Double null divertor
   – X divertor
   – Super-X divertor
   – Snowflake divertor

4. Summary of gaps
The double null divertor

• Two x-points, may be unbalanced
  - Strong coupling to core

• Power exhaust potential
  - Decrease peak heat flux by biasing to the other divertor
  - Greatly reduced heat flux to inner targets
  - Quiescent, thin (no shoulder) inner SOL (C-mod)
    + Promises better RF coupling
      [B. LaBombard, et al., PSI (2016)]

• Disadvantage
  - 2 divertors with higher costs and reduction of TBR

[Courtesy of T. Luce]
Effect of DN on power exhaust

- Balanced DN leads to higher heat flux at the target in favourable drift direction
  - Similar to L-H threshold

  [T. Petrie, et al., JNM (2001)]

- Heat flux at inner target an order of magnitude lower
  - Also applies to ELMs [MAST, AUG]

- Difficult to balance impurity radiation in both divertors
The X divertor (XD)

- Advocated by Kotschenreuther and co-workers [Kotschenreuther, et al., PHP (2007)]
  - Decrease $B_{p,t}$ to increase $f_{x,t}$ and flare flux surfaces towards the target

- Advantages
  - Flux flaring may counteract upward movement of “contact area with neutrals”
    - more “robust” detachment
  - Increased $L_{||}$ and $V_{SOL}$
  - Amenable to strong baffling

- Disadvantages
  - Possibly need for internal coils

[from Kotschenreuther, et al., PHP (2013), Fig. 11]
The Super-X divertor (SXD)

- Proposed by Valanju and co-workers [Valanju, et al., PHP (2009)]
  - Increase $R_t$
  - Combine with larger $f_{x,t}$ (XD)

- Advantages
  - Increases $A_w$
  - Decrease of $q_{||}$ towards target
  - Target can be neutron shielded

- Disadvantages:
  - Possibly need for internal coils
  - Uses large fraction of TF coil volume
  - Solution for inner leg very complicated

[G. Fishpool, et al., JNM (2013)]
The snowflake divertor (SFD)

- Proposed by Ryutov [D. Ryutov, PHP (2007)]
  - Second order null-point
  - In practice always two nearby x-points
  - Large region of low $B_p$ near the null point
    + Leads to contraction of flux surfaces towards the target (opposite to XD)

- Advantage
  - Longer connection length/larger divertor volume
  - Lower field in the divertor may enhance cross-field transport

- Disadvantage
  - At least two divertor coils and higher current
Alternative divertor configurations for DEMO1

[WPDTT1 assessment report (2016), R. Ambrosino, et al., submitted to NF]

• Focus on outer divertor leg

DEMO1 with A=3.1 (2014)

Flux flaring
\[ f_{x,t}/f_{x,min} = 1.5 \]

\[ R_t = 1.34R_x \]
using external coils only

\[ B_p \text{ gradient} \]
\[ \nabla B_p = 0.2 \nabla B_{p,SND} \]
XD, SXD and SFD are feasible with geometric variations being of order 1

- Evaluate **costs** and **benefits** compared to baseline
  - Analyse equilibria at the start and end of the flat-top

<table>
<thead>
<tr>
<th>Constraints</th>
<th>SND</th>
<th>XD</th>
<th>SXD</th>
<th>SFD+/-</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. force on single coil $F_{z,PF}$ (MN)</td>
<td>145</td>
<td>301</td>
<td>451</td>
<td>439</td>
<td>&lt; 450</td>
</tr>
<tr>
<td>Max. vertical force on CS $F_{z,PCS}$ (MN)</td>
<td>130</td>
<td>244</td>
<td>167</td>
<td>28</td>
<td>&lt; 300</td>
</tr>
<tr>
<td>Max. CS separation force $F_{z,CS}$ (MN)</td>
<td>130</td>
<td>244</td>
<td>284</td>
<td>329</td>
<td>&lt; 350</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Costs</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. $\Sigma</td>
<td>I_{PF}</td>
<td>$ (MA·turns)</td>
<td>160</td>
<td>194</td>
<td>164</td>
</tr>
<tr>
<td>Total $I_{PF,internal}$ (MA·turns)</td>
<td>-</td>
<td><strong>10</strong></td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Flux swing for current drive ($V\cdot S$)</td>
<td>330</td>
<td>340</td>
<td>297</td>
<td><strong>215</strong></td>
<td></td>
</tr>
<tr>
<td>$V_{TF}/V_{plasma}$</td>
<td>2.9</td>
<td>3.6</td>
<td><strong>4.2</strong></td>
<td>3.8</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Benefits</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{</td>
<td></td>
<td>,outer}$ ($\rho_u=3$mm) (m)</td>
<td>110</td>
<td>145</td>
<td>156</td>
</tr>
<tr>
<td>$f_{x,t}/f_{x,min}$</td>
<td>1</td>
<td><strong>1.43</strong></td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$R_t/R_x$</td>
<td>1.04</td>
<td>1.14</td>
<td><strong>1.34</strong></td>
<td>1.19</td>
<td></td>
</tr>
</tbody>
</table>

[R. Ambrosino, et al., submitted to *NF*]
Power losses only weakly affected by divertor geometry

[R. Zagorski, et al., PSI (2016), submitted to NF]

- Use TECXY to compare exhaust performance to SN
  - Over-simplify treatment of neutrals
  - Neglect private flux region
  - Neglect target geometry
  - Constant effective cross-field diffusivities

Simulations of Ar seeding shows little effect of geometry on volume power losses
Snowflake minus predicted to leads to larger DEMO SOL width

[R. Zagorski, et al., PSI (2016), submitted to NF]

- Use TECXY to compare exhaust performance to SN
  - Over-simplify treatment of neutrals
  - Neglect private flux region
  - Neglect target geometry
  - Constant effective cross-field diffusivities

- TECXY mesh overestimates connection length in SFD-

- "State-of-the-art" simulations with realistic neutrals and full geometry
- Cross-field transport in the vicinity of a null-point
- Proof-of-principle experiments
TCV experiments indicate that snowflake minus may be an attractive x-point radiator

\[ \text{[R. Reimerdes, et al., IAEA FEC (2016)]} \]

- \( N_2 \) seeding leads to radiation zone between the x-points of the SF- confirming predictions \[ \text{[T. Lunt, et al, PPCF (2016)]} \]
  - May limited adverse effects on core performance
5. Summary of gaps – not exhaustive!

Protection of the divertor target
- Scaling of $\lambda_\text{q}$, $S$, $\lambda_\text{q,int}$ towards DEMO/in detached regimes
  - Dependence on magnetic geometry
- Impurity enrichment in the divertor
  - Scaling of impurity transport
- Scaling of L-H threshold
- Minimum $\gamma$ and $\alpha$
- Link between divertor $n_{0,\text{div}}$, $n_{\text{e,sep}}$, $\langle n_e \rangle$ and particle sources
- Extrapolation of ELM size/energy density in detached regimes
- Ability to sufficiently suppress ELMs and mitigate disruptions
- “State-of-the-art” simulations of divertor with realistic neutrals and full DEMO geometry
  - Cross-field transport in the vicinity of a null-point
- Proof of principle experiments for alternative configurations

Protection of the first wall
- Fraction of power in blob channel and effective fall off length