O6: Development of the DEMO Wall Heat Load Specification

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Outline

• DEMO
• Breeding blanket wall load limits
• Load types
• Loads due to charged thermals
• Loads due to radiation
• Loads due to fast particles
• Conclusions
• DEMO: Next step after ITER
• DEMO key capabilities beyond ITER
  • Net electricity production
  • T self-sufficiency

• EU DEMO design options
  • DEMO1
    • Pulsed operation, conservative assumptions
  • DEMO2
    • Steady state operation, more optimistic assumptions

<table>
<thead>
<tr>
<th></th>
<th>ITER</th>
<th>EU DEMO1 2015</th>
<th>EU DEMO2 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>R [m]</strong></td>
<td>6.1</td>
<td>9.1</td>
<td>7.5</td>
</tr>
<tr>
<td><strong>βN,tot [%]</strong></td>
<td>2.0</td>
<td>2.6</td>
<td>3.8</td>
</tr>
<tr>
<td><strong>Pheat,tot [MW]</strong></td>
<td>151</td>
<td>457</td>
<td>784</td>
</tr>
<tr>
<td><strong>Psep/R [MW/m]</strong></td>
<td>17</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td><strong>τburn [h]</strong></td>
<td>0.1</td>
<td>2</td>
<td>steady st.</td>
</tr>
<tr>
<td><strong>Pel,net [MW]</strong></td>
<td>0</td>
<td>500</td>
<td>953</td>
</tr>
</tbody>
</table>
Breeding Blanket Wall Load Limits

• Design assumptions
  • Armour material: W
  • Structural material: EUROFER
  • Coolant / Heat Exchange: H2O at high temperature or He
  • No high heat flux components outside the divertor
  • Wall clearance >22cm

• Expected wall load limits based on engineering constraints ~ 1MW/m²

• Comparison:
  • A large fraction of ITER’s main chamber wall is specified for 3.6MW/m² or more

• DEMO Wall Load Specification needs to be developed now

J. Aubert: WCLL Blanket

ITER: Mitteau (JNM 2011)
Load Types

- Relevant Heat Load Types
  - Stationary loads
    - Thermal charged particles (majority/impurities) including blob effects
    - Radiation / MARFEs
    - Neutrals
    - Fast particles
  - Dynamic loads
    - Limiter configuration during ramp-up/down
    - ELM filaments
    - Confinement transients (e.g. H-L-transition)
    - Vertical displacement events / disruptions

- Particle Loads
  - Steady state and dynamic first wall erosion yield
• Relevant Heat Load Types
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• Particle Loads
  • Steady state and dynamic first wall erosion yield
• Assumptions (DEMO1):
  - $P_{sep}=150\text{MW}$
  - $50\% \uparrow, 50\% \downarrow$
    transferred by charged thermals
  - $100\%$ into the long-$\lambda q$-channel

• $q_{peak}\approx 0.6\text{MW/m}^2$
Results: \( \lambda q \) far-SOL scan 1cm to 17cm

- Maximum \( q_{surf} = 0.91 \text{MW/m}^2 \) found for \( \lambda q = 6 \text{cm} \) (far-SOL)
- The peak heat load is not a monotonic function of \( \lambda q \)

F. Maviglia | First IAEA Technical Meeting on Divertor Concepts | Vienna,
There is potential to reduce the charged particle heat loads by adjusting the equilibria and possibly the first wall contour.

\[ q_{surf,max} = 1.83 \pm 0.58 \pm 0.31 \text{ MW/m}^2 \]
\[ \delta = 0.53 \pm 0.45 \pm 0.38 \]
\[ \lambda q = 0.02 \pm 0.11 \pm 0.17 \text{ m} \]

\[ q_{surf,max} = 0.58 \pm 0.42 \pm 0.35 \text{ MW/m}^2 \]
\[ \delta = 0.45 \pm 0.41 \pm 0.37 \]
\[ \lambda q = 0.11 \pm 0.14 \pm 0.17 \text{ m} \]
Charged Thermals - Effect of Blobs

Open question: fraction of Psep that comes out in 'blobs' 

- Blobby SOL transport may dominate in DEMO
- Due to the very long connection length, power will end up on first wall
- Exact distribution depends on localisation of blob birth zone

Guiding parameter $\Lambda$

$$\Lambda \propto \frac{L_{||} v_{ei}}{c_s}$$

$\nu_{blob} \propto \frac{1}{\delta^2}$ for $\Lambda < 1$

$\nu_{blob} \propto \sqrt{\delta}$ for $\Lambda > 1$

Recent devices

M. Siccinio: Preliminary

D. Carralero: PRL 2015
Charged Thermals - Towards more realistic designs

- DEMO charged thermal particle load assessments done for idealised plasma and idealised wall in 2D

- Best approach to determine the wall contour is under discussion

<table>
<thead>
<tr>
<th></th>
<th>Cause for the penalty</th>
<th>penalty</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facets instead of smooth surface</td>
<td>+20%</td>
<td></td>
</tr>
<tr>
<td>Poloidal chamfering</td>
<td>+ 20% (inboard and top)</td>
<td></td>
</tr>
<tr>
<td><strong>Manufacturing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tile angular error</td>
<td>+10%</td>
<td></td>
</tr>
<tr>
<td><strong>Assembly</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radial step</td>
<td>+50% (outboard) + 20% (inboard) + 0% (top)</td>
<td></td>
</tr>
<tr>
<td>eccentricity</td>
<td>+45% (outboard) + 20% (inboard) + 0% (top)</td>
<td></td>
</tr>
<tr>
<td>Panel angular error</td>
<td>+10%</td>
<td></td>
</tr>
<tr>
<td><strong>Magnetic deviations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toroidal field ripple</td>
<td>+ 4% (Outboard only)</td>
<td></td>
</tr>
<tr>
<td>Error field by Test blanket Module</td>
<td>+ 20% (Rows 13-16)</td>
<td></td>
</tr>
<tr>
<td>ELM, VS</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td><strong>CX + Rad</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ 0.35 MW/m² (burn phase) + 0.25 MW/m² (limiter phase)</td>
<td></td>
</tr>
</tbody>
</table>

Mitteau (JNM 2015)
- Core radiation with Tungsten and Xenon as impurities
- Main contributors Xenon and Bremsstrahlung
- Assumption for SOL
  - All power radiated
  - Constant power density on field line
  - Exponential decay

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**DEMO, Radiation Profiles**

- Tungsten
- Xenon
- Bremsstrahlung

**R. Wenninger, IAEA 2014**
Radiation – Tungsten & Bremsstrahlung

Tungsten, $P_{\text{tot}} = 11$ MW

Bremsstrahlung, $P_{\text{tot}} = 53$ MW

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<table>
<thead>
<tr>
<th></th>
<th>Core W</th>
<th>Core BS</th>
<th>Core Xe</th>
<th>SOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ptot [MW]</td>
<td>11</td>
<td>53</td>
<td>290</td>
<td>150</td>
</tr>
<tr>
<td>qpeak [MW/m²]</td>
<td>0.013</td>
<td>0.06</td>
<td>0.33</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Effects of radiation clustering

It has been observed that radiation can have a significant poloidal peaking

Example:
- 150MW radiating from x-point
- Peak radiation 1.9MW/m² on the dome
- Divertor baffle: <0.6MW/m²
Fast Particles

First result from ASCOT with a 2D first wall:

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Alpha loss (%)</th>
<th>Power loss (%)</th>
<th>Lost power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>5.4</td>
<td>0.026</td>
<td>110</td>
</tr>
<tr>
<td>TF only</td>
<td>7.7</td>
<td>0.15</td>
<td>640</td>
</tr>
<tr>
<td>TF FI full</td>
<td>6.0</td>
<td>0.037</td>
<td>160</td>
</tr>
<tr>
<td>TF FI half</td>
<td>6.6</td>
<td>0.052</td>
<td>220</td>
</tr>
</tbody>
</table>

- Recent assumption: Same power load limits as for thermals apply for fast particles
- Including ferritic inserts ($\delta TF \approx 0.3\%$) reduces the peak loads and moves them to the divertor
- Investigations with engineering design of the first wall are carried out at the moment

TF – No Ferritic Inserts

TF – With Ferritic Inserts
Conclusions

- Significant limitation of first wall power flux densities: $q_{surf} \sim 1\text{MW/m}^2$
  - Early development of DEMO Wall Load Specification required

- Charged Thermal loads
  - $q_{||}$ max is not a monotonic function of $\lambda q$
  - Worst case for reference scenario, $P_{sep \rightarrow char, therm}=150\text{MW}$:
    - $\lambda q = 6\text{cm} \rightarrow q_{surf, max} = 0.9\text{MW/m}^2$
  - There is potential to win by optimising the

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0D analysis Length $\lambda_q$ in DI

- Heat Flux profile assuming an exponential decay:
  \[ q_{\parallel}(d) = q_0 \exp\left(-\frac{d}{\lambda_q}\right) \text{ [MW/m}^2\text{]}, \quad \text{with:} \quad q_0 = \frac{P_{\text{SOL}}}{2\pi R\lambda_q} \]

  \( d = \) clearance separatrix-fw at OMP, \( q_0 = \) heat flux density at the separatrix, \( \lambda_q = \) power fall-off length, \( P_{\text{SOL}}=150\text{MW}, R_{\text{SOL}}=11.2m \)

- Hypothesis of 2 decay lengths:
  \[ q(d) = \frac{P_1}{2\pi R\lambda_q} \exp\left(-\frac{d}{\lambda_q}\right) + \frac{P_2}{2\pi R\lambda_{q,SOL}} \exp\left(-\frac{d}{\lambda_{q,SOL}}\right) \]

  \( P_{\text{SOL}} = P_1 + P_2, \quad \lambda_{q,SOL}. \quad \text{larger decay length} \)

- Hypothesis of 2 decay lengths:

  \( \lambda_q. \quad \text{holds 25%, 50% and 75% of} \quad P_{\text{SOL}}. \)

  and \( \lambda_{q,SOL}. \quad \text{holds the complementary} \)

  By fixing \( \lambda_{q,SOL}. \quad \text{to 1mm and scanning} \quad \lambda_{q,SOL}. \)

  \textbf{B. Sieglin EFPW 2014}

  \textbf{Worst case} \( \lambda_{q,SOL}. = 75\% \)
Magnetic Flux mapping:

- Line from plasma outer boundary at \( z = \) centroid → first wall (in green*)
- To: whole first wall curve (black solid**)
- Considering one source at \( z = \) plasma centroid and \( r = \) outer boundary.
Technological limits and penalty factors (as ITER)

Expected wall load limits based on engineering constraints (Arbeiter, Aubert)
- Water-cooled: 1.5 MW/m²
- Helium-cooled: 1.0 MW/m²

W. Biel
- Local first wall heat loads are calculated according to mean loads and penalty factors:

<table>
<thead>
<tr>
<th>Limiter operation</th>
<th>Divertor operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base heat</td>
</tr>
<tr>
<td></td>
<td>load (MW/m²)</td>
</tr>
<tr>
<td>Inboard rows 1-2-6</td>
<td>1.00</td>
</tr>
<tr>
<td>Inboard rows 3-4-5</td>
<td>2.00</td>
</tr>
<tr>
<td>Top panels</td>
<td>No significant heat load</td>
</tr>
<tr>
<td>Outboard rows 10-11-12-13-18</td>
<td>0.20</td>
</tr>
<tr>
<td>Outboard rows 14-15-16-17</td>
<td>1.56</td>
</tr>
</tbody>
</table>
Radiation – Work to do

• Develop maximum realistic assumptions on radiation clustering
  → We currently seek expertise on this

• How are the peak heat loads changing, if a realistic engineering model is used