Plasma-Facing Material Development Strategy in ITER

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with collaboration with International Tokamak Physics Activities, EU PWI TF, USBPO....

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Introduction
- Challenges for ITER

• Plasma stored energy ~ 350 MJ (present tokamaks <10 MJ)
• Long pulse (~400 s burn) and steady state (~3000 s)
• Nuclear
  – Tritium inventory < 700 g
  – Dust < 1 tonne in VV
Plasma Facing Material Choice

- In the initial operation ITER uses beryllium FW, tungsten divertor baffle and dome, and carbon target plates to maximize the operation flexibility.
- During H and D phases, configuration with separatrix shifted upwards would allow preliminary assessment of tungsten divertor with modest plasma performance.
- Before DT operation, the divertor target will be changed to tungsten to minimize the tritium retention, but the option of limited use of CFC during DT is not ruled out.
- Scenarios with Be/W PFC must be developed.
Heat load specifications

- Heat load specifications of PFCs have been revised to reflect recent experimental results [Loarte, IAEA ’08]
- New specifications cover the steady-state heat loads as well as transient heat loads e.g. disruptions, VDEs and ELMs
- These specifications confirm very serious consequences of ELMs, disruptions and VDEs on PFCs, indicating the need of mitigating or avoiding these phenomena
- These specifications have large uncertainty, requiring continued experiments in the existing tokamaks
ELM induced erosion

Results from Russian plasma simulators:
- Erosion limit for CFC reached due to PAN fibre erosion
- Erosion limit for W reached due to melting of tile edges

Crack formation was observed at energy densities $\geq 0.7 \text{ MJ/m}^2$.
Repetitive sub-threshold ELM investigations ongoing in JUDITH2

Recommended threshold for damage 0.5 MJ/m$^2$
Efficient mitigation methods (factor of 20) needed
ELM mitigation

In-vessel coils

ELM coils

pellet injection
Requirement of mitigation – target values

Energy load on divertor plate due to Disruptions

Erosion of divertor plate during Thermal Quench

- Stored energy: \( W = (120–175) \text{ MJ} \) for reference ELMy H-mode discharge,

- In:Out asymmetry:
  \[ 2:1 \Rightarrow E_{\text{in}} = (80-117) \text{ MJ} \text{ (inner)}, \quad E_{\text{out}} = (40-58) \text{ MJ} \text{ (outer)}, \]
  \[ 1:1 \Rightarrow E_{\text{in}} = (60-88) \text{ MJ} \text{ (inner)}, \quad E_{\text{out}} = (60-88) \text{ MJ} \text{ (outer)}, \]

- Expansion of wetted area of divertor : 5-10
  \[ \text{inner target plate } S = (5-10) \times S_{\text{in}} \approx (5-10) \times 1.3 \text{ m}^2 = (6.5-13) \text{ m}^2, \]
  \[ \text{outer target plate } S = (5-10) \times S_{\text{out}} \approx (5-10) \times 1.7 \text{ m}^2 = (8.5-17) \text{ m}^2, \]

- Energy deposition rise time : \( \tau = (1.5-3) \text{ ms}, \)
Most severe case (inner plate):
$E_{in}=117 \text{ MJ, } S=6.5 \text{ m}^2, \tau=1.5 \text{ ms}$

$\varepsilon \equiv f_T^{-1}E_{in}/(S\cdot\tau^{0.5}) \approx 388 \text{ MJ/m}^2/\text{s}^{0.5}$:
where $f_T$ is a factor for temporal shape of energy input ($\approx 1.2$)

Critical value for melting of tungsten (triangular wave) $\varepsilon_{melt}$

$\varepsilon_{melt} \approx 48 \text{ MJ/m}^2/\text{s}^{0.5}$.

Energy flux due to disruptions needs to be reduced by

$\frac{\varepsilon}{\varepsilon_{melt}} \approx \frac{388}{48} \approx 8$, 

$\Rightarrow$ Target value of mitigation $\approx 10$

<table>
<thead>
<tr>
<th>Case</th>
<th>Inner/Outer</th>
<th>Energy density (MJ/m²)</th>
<th>$\varepsilon$</th>
<th>$\varepsilon / \varepsilon_{melt}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most severe</td>
<td>Inner</td>
<td>18</td>
<td>388</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Outer</td>
<td>10.4</td>
<td>223</td>
<td>4.6</td>
</tr>
<tr>
<td>Mildest</td>
<td>Inner</td>
<td>4.6</td>
<td>70</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Outer</td>
<td>2.4</td>
<td>43</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Without mitigation (if entire melt layer is lost)

• Worst case; 10-18 MJ/m² ⇒ 0.5mm ≤ melt layer
• Mildest case; 4.6-2.4 MJ/m² ⇒ 0.1-0.3 mm ≤ melt layer

⇒ Lifetime of target plate:
≈ 20 disruptions (worst case)
≈ 30-100 disruptions (mildest case)
VDEs (upper Be wall)

Estimation by Ideal contact with wall

Most severe case
270 MJ, $\lambda_p=3\text{cm}$
$\varepsilon = 230\ \text{MJ/m}^2\text{s}^{0.5}$

For Be wall:
$230/25 \approx 9$

Target value
$\approx 10$

Shaped wall (not yet optimized yet)

28 MJ/m$^2$
$\Rightarrow \varepsilon = 700\ \text{MJ/m}^2\text{s}^{0.5}$
$\Rightarrow \approx 30$ mitigation needed

Further shape optimization is on-going

M. Sugihara
Runaway Electrons

Simple extrapolation from JET

Lehnen
upper dump plate

Wetted area $\approx 0.3 \text{ m}^2$ in JET

$\Rightarrow$

Wetted area $\approx (0.3-0.6) \text{ m}^2$ ITER

Beam energy in ITER $\approx 20 \text{ MJ}$

$\Rightarrow$

Energy density $\approx (35-70) \text{ MJ/m}^2$

Penetration depth (12MeV)

2.5-7.5 mm (1°- 3°)

$\Rightarrow E_{\text{critical}} \approx 6-14 \text{ MJ/m}^2$

Required mitigation

$(35-70)/(6-14) \approx 2.5-12$

M. Sugihara
Without mitigation

Temperature pattern by RE flux,
RE energy = 10 MeV, angle = 1°
RE energy density = 50 MJ/m².
Deposition time = 0.1 sec.

Molten layer thickness strongly depends on wall design

For incident angle of 3°,
≈7.5 mm molten layer

Lifetime can be
1-4 times of RE events

M. Sugihara
### Summary of required R&D and examinations of design changes relating to injection / pumping / gas processing system

<table>
<thead>
<tr>
<th>(1) Massive gas injection (MGI)</th>
<th>Gas injector up to 500 kPa·m³ from one injector*)</th>
<th>Helium (500 kPa·m³) and Neon (100 kPa·m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2) Massive pellet injection (MPI)</td>
<td>Pellet injector Neon (40 kPa·m³) Max 76 mmϕ* )</td>
<td>Neon (40 kPa·m³) (This can be covered by MGI case)</td>
</tr>
<tr>
<td>(3) Massive Be injection</td>
<td>Beryllium injector (400 g) Max 75 mmϕ*</td>
<td>Not required</td>
</tr>
</tbody>
</table>

*) Most demanding case with only one injection port assuming localized radiation load is acceptable

M. Sugihara
Acceptable level of tungsten in the core

In order to maintain H-mode, the power reaching the pedestal $P_{\text{los}}$ is required to be (at least) L-H transition power $P_{\text{LH}}$. In addition to the electron-impact excitation, ionization and recombination loss (Post), ion-impact excitation needs to be included. The acceptable level of tungsten in the core is $\sim 10^{-5}$ (Polevoi).
Tungsten concentration is estimated to be $\sim 10^{-6}$ in the core with W-divertor (no account of either ELM, edge melting or post-melting deformed surface).
AUG experiments show W levels higher than $10^{-5}$, suggesting that adoption of high Z PFM would preclude some operation regimes (e.g. peaked density, infrequent ELMs, low $n_{sep}$).

Figure 13. Peaking of the W concentration ($c_W$) as a function of background density. Discharges with pure NBI heating (black circles) show the strongest peaking, whereas central ECRH reduces the $c_W$ peaking significantly already at low additional heating power.
Erosion determines co-deposition:

- Rough estimate: total net erosion rate x co-deposition concentration
- Detailed evaluation: impurity transport including re-erosion, co-deposition concentration depending on final deposition conditions

Co-deposition with C and Be depends on deposition conditions: energy, deposition rate, temperature

<table>
<thead>
<tr>
<th></th>
<th>atoms/s</th>
<th>g/shot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be wall</td>
<td>$3 \times 10^{20}$</td>
<td>1.8</td>
</tr>
<tr>
<td>CFC divertor</td>
<td>$2 \times 10^{21}$</td>
<td>3.2</td>
</tr>
<tr>
<td>W divertor</td>
<td>$4 \times 10^{17}$</td>
<td>$8 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
T-inventory build-up estimates

Reasonable agreement between the two approaches
- With Be wall + CFC divertor \(\rightarrow\) ~few 100 discharges before limit is reached
- Might be allowed \(~=>2500\) full power pulses with Be wall + W divertor

J. Roth et al., PPCF 50 (2008) 1

J. Roth et al., IAEA 2008

J. Roth
Dust generation

Potential safety concerns:

**Hydrogen production** when hot dust reacts with steam
- Be major contributor
- with carbon: $\Rightarrow 6 \text{ kg C}, 6 \text{ Be}, 6 \text{ kg W limit}$
- without carbon: $\Rightarrow 11 \text{ kg Be}, 76 \text{ kg W limit}$

**Possible pure Dust or Hydrogen/Dust explosion**
- Be, C, W involved

**Potential release in environment**
- W dust can be radioactive
- Dust may contain Tritium
  $\Rightarrow 1000 \text{ kg limit in VV}$

Roth 2008
Dust generation

Total dust generation:

Assumption:
- Dust generation dominated by erosion, deposition, layer disintegration
- Conversion from erosion to dust for safety reasons: 100 %
  (about 10 % in Tore Supra and JT-60U)

Total dust limit not reached before scheduled maintenance and exchange of divertor cassettes (J. Roth PSI-2008)

Dust on hot areas: (A. Litnowski PSI-2008)

Assumption:
- On hot plasma wetted areas, dust will only survive in castellation

Assume dust at hot area collects only in gaps:

 Flux of Be to outer target hot zone (DIVIMP): $2 \times 10^{19}/m^2s$
 Area of hot zone: 8m$^2$
 ⇒Total Be flux: $1.6 \times 10^{20}/s \approx 1g/disch$
 Gap area 2%
 ⇒Hot Be dust rate: 0.02g/disch
 ⇒11kg Be dust for W/Be wall in 60000 disch.
A strong collaboration programme

- JET will carry out ITER-Like-Wall experiments from 2010 (Be wall and full tungsten divertor)
- ASDEX-Upgrade and C-mod will continue experiments with high Z PFCs
- ITPA, EU PWI TF, USBPO will execute experiments focused on tritium retention, dust, erosion, heat loads on PFCs, ELM mitigation, disruption mitigation, wall conditioning…., emphasizing cross-machine comparision
Summary

• The thermal load specification on PFCs has been updated, confirming serious consequences of transient loads, e.g. ELMs, disruption
• The mitigation measures of ELMs and disruption are under development
• Current estimates suggest that tritium retention will reach ~ 700 g after a few hundred DT shots of 400s burn with CFC-W-Be PFCs, a few thousands DT shots with full tungsten divertor and Be FW
• The operation range with full tungsten divertor appears to be limited
• Baseline plan is to change the divertor cassettes to full W before DT operation, but limited use of CFC target during DT is not ruled out
• A strong collaboration programme is developed and carried out under the framework of ITPA, EU PWI TF, USBPO to address ITER PWI issues
Examples of successful collaboration

3d calculation of sol and limiter heat load (Kobayashi)
Pipe-gun type pellet injector (Sakamoto)