Research status and issues of tungsten plasma facing materials for ITER and beyond

Y. Ueda (Osaka Univ.) J. W. Coenen (FZJ),
G. De Temmerman (DIFFER),
R. Doerner (UCSD), J. Linke (FZJ),
V. Philipps (FZJ), E. Tsitrone (CEA)
Divertor strategy of ITER

- **ITER divertor options**
  - **Option 1:** Baseline (CFC/W)
  - **Option 2:** Full W day 1

- **Discussions at ITPA DIV/SOL on ITER divertor strategy**
  - Heat fluxes
  - Fuel retention, fuel removal and dust production
  - Material issues (tungsten)
    - Transient heat pulse, Blistering, He induced structure, combined of these
  - Operational and scenario issues
Outline

- Heat flux conditions of ITER divertor
- Transient heat loading effects on melting and morphology changes
- Morphology changes by particle loadings
  - Blistering by hydrogen isotopes (H/D/T)
  - Helium effects
- Combined effects of heat and particle loading
- Conclusions
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Steady-State (slow transient) heat flux to divertor

- **Non-nuclear phase (H, He)**
  - Peak Power ($q_\perp$): $\sim7$ MW/m$^2$ (SOLPS, no cooling gas injection)

- **Nuclear phase (DT)**
  - $q_\perp$ $\sim 10$ MW/m$^2$ (SOLPS, Cooling gas & Detached plasma)
    - Plasma detachment reduces heat flux by 75%
    - Without detachment, heat flux would be too high
    - Surface temp. below $T_{\text{recrystallize}} \sim 1200$ °C
  - An important issue: stable detached plasma operation

- **Slow transients**
  - 20 MW/m$^2$, 10 s
    - Test condition for W divertor
  - Surface temp. $> 2000$ °C
    - recrystallization

Temperature distribution on outer divertor

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R. Pitts et al., JNM 438 (2013) S48
Transient heat loading (Disruption/VDE)

**Disruption**
- Even in H/He discharges, melting could take place.
- Pulse length: ~1 ms

**Effects on divertor**
- Disruption (unmitigated) could melt the vertical target of divertor.
- VDE (unmitigated) could melt baffle (W) and lower first wall (Be).

Disruption heat loading (Non-nuclear Phase)

<table>
<thead>
<tr>
<th>( I_p ) (MA)</th>
<th>Mode</th>
<th>( P_{in} ) (MW)</th>
<th>( W_d ) (MJ)</th>
<th>( E_{\text{transient}} ) (MJ)</th>
<th>( \lambda_q ) (m)</th>
<th>( q_{\perp} ) (MJ m(^{-2}))</th>
<th>( \varepsilon ) (MJ m(^{-2})s(^{-1/2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>L</td>
<td>20</td>
<td>26</td>
<td>13 ( \rightarrow ) 26</td>
<td>0.02</td>
<td>0.22 ( \rightarrow ) 2.86</td>
<td>4.1 ( \rightarrow ) 74.3</td>
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<tr>
<td>7.5</td>
<td>L</td>
<td>30</td>
<td>30</td>
<td>15 ( \rightarrow ) 30</td>
<td>0.02</td>
<td>0.25 ( \rightarrow ) 3.30</td>
<td>4.5 ( \rightarrow ) 84.9</td>
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<tr>
<td>7.5</td>
<td>H</td>
<td>40</td>
<td>75</td>
<td>25 ( \rightarrow ) 38</td>
<td>0.01</td>
<td>0.83 ( \rightarrow ) 8.3</td>
<td>15.2 ( \rightarrow ) 213</td>
</tr>
<tr>
<td>15</td>
<td>L</td>
<td>8</td>
<td>35</td>
<td>16 ( \rightarrow ) 35</td>
<td>0.01</td>
<td>0.52 ( \rightarrow ) 7.69</td>
<td>9.4 ( \rightarrow ) 199</td>
</tr>
<tr>
<td>15</td>
<td>L</td>
<td>18</td>
<td>52</td>
<td>26 ( \rightarrow ) 52</td>
<td>0.01</td>
<td>0.86 ( \rightarrow ) 3.43</td>
<td>15.7 ( \rightarrow ) 295</td>
</tr>
<tr>
<td>15</td>
<td>L</td>
<td>28</td>
<td>73</td>
<td>37 ( \rightarrow ) 73</td>
<td>0.01</td>
<td>1.21 ( \rightarrow ) 11.4</td>
<td>22.2 ( \rightarrow ) 406</td>
</tr>
<tr>
<td>15</td>
<td>L</td>
<td>40</td>
<td>85</td>
<td>43 ( \rightarrow ) 85</td>
<td>0.01</td>
<td>1.39 ( \rightarrow ) 18.7</td>
<td>25.5 ( \rightarrow ) 483</td>
</tr>
</tbody>
</table>


Melting threshold: \(~50\) MJ/m\(^{-2}\)s\(^{-1/2}\)

Shot No. in a non-nuclear phase

Heat flux factor

Non-active phase disruptions
- Major Disruption: Unmitigated ~300 Mitigated ~1400
- Downward VDE: Unmitigated ~50 Mitigated ~300
For the non-nuclear phase of ITER,

Half $I_p (7.5 \text{ MA})$ : ELM energy density could be roughly $1/5$ of MT (considering possible broadening)

Full $I_p (15 \text{ MA})$ : ELM energy density significantly exceeds MT

$\rightarrow$ unacceptable, needs proper mitigation
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Melt Layer Structure

Slow transient with excessive heat

1. Several tens of MW/m² for ~3 s.

Melt layer thickness can reach up to 1.5 mm

Power-handling capability significantly degraded

unacceptable
Slight melting (Disruption, Giant ELM)

**Is slight melting acceptable?**

- Acceptable step height for ITER W monoblock (~0.3 mm)
- **Bridging** by melt layer could cause fracture of cooling tube.
- **Droplet ejection** could occur.
- **Plasma shaping** may not occur.

Only “very slight melting” could be acceptable

Plasma Gun exp. (QSPA)

\[ E = 1.0 \text{ MJm}^{-2} \quad \Delta t = 500 \mu s \quad 100 \text{ pulses} \]

High cycle heat pulse effects

Nd/YAG laser (effective pulse length: $\sim 100\mu s$)
Base temp.: $500^\circ C$

- Melting conditions
- Surface roughening and local melting

*Heat flux factor ($\text{MW m}^{-2} \text{t}^{1/2}$)
- 510
- 240
- 150
- 72
- $\sim 50$
- 30
- 12
- 5

*Energy absorption $\sim 0.3$ is considered.
Pulse energy: \(1/5\) of \(E_{MT}\)

\(10^5\) cycles

Unmitigated ELM heat pulse
In the low \(I_p\) case of ITER

To avoid surface morphology change, suppression to \(1/10\) of MT (\(\sim 6\ \text{MJm}^{-2}\text{s}^{-0.5}\)) is necessary
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Blistering by hydrogen isotope ions

- Formation conditions
  - Fluence $>10^{24}$ m$^{-2}$, Temperature $<(500-600)$ °C
  - Blistering **disappears above** $\sim 600$ °C

Surface topography
- $\Phi = 10^{26}$ D/m$^2$
- $\Phi = 10^{27}$ D/m$^2$

3-D sub-surface morphology
- $\Phi = 10^{27}$ D/m$^2$

V. Alimov presented at ICFRM14 (2009)
W surfaces exposed to pure and helium-seeded D plasmas, $\Phi = 10^{27}$ D/m²

- Pure D plasma $T_{\text{exp}} = 533$ K
- Helium-seeded D plasma (5% He ions) $T_{\text{exp}} = 533$ K

He seeded plasma suppresses blistering (many observations).

→ no blistering for He plasma and DT (burning) plasma
In all cases, retention and blistering are suppressed. **Blistering unlikely in ITER.**

19th PSI, M. Miyamoto (2012)
He effects on W

- **High temperature (> 1700 °C)**
  - Large He holes and thick tendril formation with recrystallization

- **Medium temperature**
  - Nano-structure (W fuzz) formation

- **Low temperature (< ~700 °C)**
  - Nanometric He bubble formation (a few nm)
  - Hardening and reduction of thermal conductivity
Present knowledge on W fuzz

- **Formation conditions**
  - Temperature: \( > 700 \, ^\circ\text{C} \), He flux: \( > 5 \times 10^{21} \, \text{m}^{-2} \, \text{s}^{-1} \), an ion energy \( > 20-30 \, \text{eV} \).
  - The area of fuzz could be very limited near the strike points.
  - In detached plasmas, fuzz is unlikely formed because of very low ion energies (a few eV).

- **General properties and their effects**
  - Advantages: Low sputtering erosion. Resistant to pulsed heat loading, Reduction of secondary electron emission
  - Disadvantages: Erosion by unipolar arcing (leading to Dust formation).
For non-nuclear phases, peak temperature will be about 800 °C or less.

**W fuzz**: very limited area near the strike points.

For nuclear phases,

**W fuzz**: limited area also, because it could not grow in detached plasmas.
Critical evidence of unipolar arc (UA)

- Demonstration of ELMs on nanostructured W using laser.
- UA is confirmed from the jump of the floating potential.

Arcing on premade fuzz-W in LHD

- Nanostructured W formed in the NAGDIS-II was installed in LHD.
- Arcing was initiated by the exposure to the LHD plasma, the duration of which was 2s.
- Since the magnetic field direction was almost normal to the target, the motion was Brownian-like.
- This results strongly suggest that arcing can be easily initiated on W fuzz.

Arcing on premade W fuzz in DIII-D

Arcs are Efficient in Removing Fuzz, after 3 VDEs

- Arc track shape consistent with motion in “retrograde” $B \times J_{arc}$ direction
- At least one of the arcs starts on the fuzzy surface
- Traces split, affecting large areas
- Fuzz appears to be completely suppressed by arcing ➡️ No release of W
Conditions of arcing of W fuzz

- **Experiences from various devices**
  - NAGDIS: arcing on fuzz with ion bias over 70 V
  - DIII-D: arcing on premade fuzz
  - C-Mod: No arcing probably due to low $T_e$ (20-30 eV)
  - LHD: arcing on premade fuzz without heat pulse ($T_e \sim 20$ eV)
  - MAGNUM: No arcing on fuzz even with pulsed heat ($T_e \sim 1-2$ eV)

- **Suggestion from these results**
  - High ion bombarding energies or high sheath potential (high $T_e$) could sustain arcing. But so far we do not understand the exact conditions of arcing in actual confinement devices.

- **Erosion rate**
  - According to Kajita*, $\sim 10 \mu g / 1$ ms per one arc track. But DIII-D exp. showed no W release by arcing. 
    - needs more investigation
  - Arcing may be an issue in terms of core plasma contamination, but not be an issue in terms of W monoblock lifetime.

Pulse plasma effects on W fuzz

**Peak surface temperature**

![Graph showing peak surface temperature with time](image)

- ~1 ms
- ~0.2 ms

**Simply W fuzz anneal out. No W release.**

**Droplet formation**

- 0.7 MJ/m² (partially)
- 1.1 MJ/m²

**Pilot PSI**

(20th PSI, G. De Temmerman et al.)

**Plasma Gun (U. Hyogo)**


Difference could be due to **pulse length** and/or **plasma Te** → **need more investigation**
Surface He holes (> ~ 1700 °C)

- Porous structure reduces effective thermal conductivity and power handling capability.
- He bubbles are formed not only on the surface but also along grain boundary, which weaken adhesion of grains.
- In some preliminary experiments, grain ejection by plasma particle exposure was observed, but not very significant so far. \(\Rightarrow\) needs more investigation

Results from NAGDIS

Results from MAGNUM
Alleviation of He holes by pulsed heat

- He hole structure is irradiated by pulsed laser
- Pulsed laser
  - 5~7 ns (Nd/YAG)
  - 0.6 ms (Ruby)
- Short pulse (5-7 ns)
  - Roughness increased
- ELM-like (long) pulse (0.6 ms)
  - Smoothing occurred

Possibility of surface repairment

S. Kajita et al., PFR 2, 009 (2007)
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Plasma-enhanced surface damage

Measured ablation threshold much lower than expected

Plasma enhanced surface ablation

G. De Temmerman et al, IAEA FEC, 2010

16th ITPA SOL/Div meeting, Juelich, January 2012
Comparison of damage - summary

Open symbols:
- Laser only

Filled symbols:
- Laser + plasma

Increasing pulse energy

heat load parameter [MJ m⁻² s⁻¹]

base temperature [°C]

- Laser only
- Laser on heated sample
- Laser on samples exposed to D-plasma
- Simultaneous plasma and laser

- No visible damage
- Roughening / recrystallization
- Heavy roughening / melt pools
Plasma-enhanced surface damage

- Synergistic effect:
  - Bubble formation due to high-flux plasma
  - Explosive release of material during transient

Re-definition of tolerable energy densities in ITER might be necessary

G. De Temmerman et al, IAEA FEC, 2010
Conclusions 1 (particle loading)

- **H/D/T plasma exposure** ($\leq 600 \, ^\circ\text{C}$)
  - Blistering is not an issue in ITER (and DEMO).
  - Combination with pulsed plasmas could enhance erosion.

- **He nanometric bubbles** ($< 700 \, ^\circ\text{C}$)
  - Nanometric bubble layer slightly deteriorate thermal and mechanical properties, but itself is not an issue.
  - Combination with pulsed plasmas could enhance erosion.

- **W fuzz by He** ($> 700 \, ^\circ\text{C}$)
  - There are several preferable features (e.g. low sputtering erosion), but unipolar arcing could enhance erosion (need more investigation, especially in magnetic confinement devices).
  - Response to pulsed heat should be further investigated (Its impact on W fuzz is not still clear).

- **He holes** ($> \sim 1700 \, ^\circ\text{C}$, also recrystallization occurs)
  - Cracking and dust ejection could be an issue (need more investigation)
Conclusions 2 (heat loading)

- **Disruption/ELM**
  - Slight melting could be acceptable, but repeated melting causes brittle and uneven morphologies, **unacceptable**. → Clarifying melt layer behavior and its impacts on core plasmas are necessary.
  - High cycle repeated ELM-like heat (even 1/5 of the melting threshold) could cause surface roughening and local melting. Further studies on cracking thresholds and impact on plasma performance are necessary.
  - **Combined plasma exposure** could reduce the damage threshold of pulsed heat. (need more investigation with high flux plasma)

- **Surface repairment**
  - Some ELM-like heat pulse may alleviate He induced morphologies (W fuzz, He holes) → may be useful for temporal surface repairment (need more investigation)

- **Appropriate mitigation (control) of transients (slow transient, disruption/VDE, ELM) are mandatory.**