Pulsed heat load effects on plasma facing materials

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Outline

- Heat loading to divertor and its effects on tungsten
  - Steady-State, Slow transient, Pulse (ELMs, disruption)
- Repeated pulsed heat load effects
- Melt layer dynamics
- Vapor shielding
- Helium induced structure on tungsten and its response to pulsed heat
- Summary
Heat loading to divertor
Steady-State (slow transient) heat flux to divertor

- **Non-nuclear phase (H, He)**
  - Peak Power ($q_\perp$): ~7 MW/m$^2$ (SOLPS, no cooling gas injection)

- **Nuclear phase (DT)**
  - $q_\perp$ ~ 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 $T_{\text{recrystallize}}$ ~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

R. Pitts et al., JNM 438 (2013) S48
ITER W monoblocks under extreme heat

Heat Flux Conditions

F) 1000 cycles at 10 MW/m² + 1000 cycles at 20 MW/m² + CHF (27-30 MW/m²)

acceptable heat flux < 27 MW/m²

G. Pintsuk et al., 27th SOFT (2012)
**Heat flux factor**

This is the number proportional to surface temperature rise as uniform heat flux is irradiated onto semi-infinite surface.

Useful criteria for surface damage evaluation.

Unit: $\text{MW} \text{ m}^{-2} \text{s}^{0.5}$ (or $\text{MJ} \text{ m}^{-2} \text{s}^{-0.5}$)

$\Delta T \approx 50 \text{ MJ m}^{-2} \text{s}^{-0.5}$: melting threshold of tungsten

\[
\Delta T \approx P \sqrt{\frac{4}{\pi k \rho C}} \sqrt{t} \approx P \sqrt{t}
\]

$\Delta T$: Surface temperature change

$P$: Heat flux

$t$: time

$k$: Thermal conductivity

$\rho$: Density

$C$: Specific heat
Transient heat loading (Disruption/VDE)

Disruption

- Even in H/He discharges, melting could take place.
- Pulse length: \(~1\, \text{ms}\)

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_p) [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>
</tr>
<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>
</tr>
<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 \(~50\, \text{MJ/m}^2\text{s}^{-1/2}\)

Heat flux factor

Non-active phase disruptions

<table>
<thead>
<tr>
<th>Unmitigated</th>
<th>Mitigated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Disruption</td>
<td>~300</td>
</tr>
<tr>
<td>VDE</td>
<td>~1400</td>
</tr>
</tbody>
</table>

Shot No. in a non-nuclear phase
ELM energy in the non-nuclear phase of ITER

For the non-nuclear phase of ITER,

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

Full $I_p$ (15 MA): ELM energy density significantly exceeds MT

-> unacceptable, needs proper mitigation

Frequency: 1~10Hz
Pulse length: sub ms
Interaction between intense pulsed heat and W

Pulsed heat loading effects on materials

**FOR METALS:**
- Splashing
- Formation of droplets
- Formation of dust

**FOR CARBON:**
- Above a certain power load (threshold) emission of debris
- BRITTLE DESTRUCTION
Repeated pulsed heat load effects
Surface modification by repeated heat pulses (pure W)

Nd/YAG laser
(effective pulse length: ~130µs)
Base temp.: 500°C

Surface Melting
Melting Threshold
~1/4 of Melting Threshold

*Heat flux factor (MJ m² s⁻¹)^

10,000
30,000
50,000

Shot Number

Surface Melting
510
240
150
72
~50
30
12
5

*energy absorption ~0.3 is considered.
Surface modification by high cycle pulsed heat

- Surface roughness, cracking and local melting appeared after high cycle pulsed heat loading.

For JET

\[ c_w = 5 \times 10^{-5} \text{ density change} \]
\[ \rightarrow \text{equivalent W mass with } r = 80 \mu m, 41.3 \mu g \]

Heat flux factor: 12 MJ/m²/t⁰.⁵

Cycle number: 30,000
High cycle transients heat load tests - effect of recrystallization -

JUDITH 2

- $T_{surf} = 1500 \, ^\circ\, C$
- $P = 0.2 \, GW/m^2$
- $P = 0.6 \, GW/m^2$

18,000 pulses
- $R_a = 2.8 \, \mu m$
- max./avg. depth $\sim 150/110 \, \mu m$

100,000 pulses
- $R_a = 3.4 \, \mu m$
- $P = 0.2 \, GW/m^2$
- max./avg. depth $\sim 420/180 \, \mu m$

max./avg. depth $\sim 150/110 \, \mu m$

max. depth $\sim 930 \, \mu m$

Effect of recrystallization
Transient thermal loads on metallic wall materials

electron beam
Transient thermal loads on metallic wall materials

electron beam
Transient thermal loads on metallic wall materials

thermal expansion of heat affected grains

→ plastic deformation when $T > DBTT$
Transient thermal loads on metallic wall materials

contraction during cool-down:
→ cracking along grain boundaries
Particle ejection by surface cracking and local melting could determine the acceptable level of ELM heat flux.

Roughly 1/10 of MT...
Effects of high cycle pulsed loading on W alloys

- Less damage for W-10%Re than W-2%Ta, but damage appeared for both.

Melting Threshold: \( \sim 0.5 \text{ MJ/m}^2 \)

Pulse width: \( \sim 0.13 \text{ ms} \)

Energy Fluence [MJ/m^2] vs Shot Number for W-2%Ta and W-10%Re.
High cycle pulsed heat effect of TFGR-W

Cracking seen for TFGR W under high cycle pulsed heat

Threshold
W-TiC > W-TaC

Cracking pattern is similar for these materials

TFGR-W Toughened, Fine grained Recrystallized W.

<table>
<thead>
<tr>
<th>Material</th>
<th>TFGR W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shot No.</td>
<td>10,000</td>
</tr>
<tr>
<td>temperature</td>
<td>773 K</td>
</tr>
<tr>
<td>Energy absorption</td>
<td>27%</td>
</tr>
</tbody>
</table>

Melting Threshold: ~0.5 MJ/m²
Surface damage effects on W (experimental)

1. Plasma gun exposure (U. Hyogo)
   - Pulse number: 20-100 shots
     - ~0.7 MJ/m²
     - ~1.4 MJ/m²
   - Pulse number: 25 shots
     - ~2.0 MJ/m²

2. E-beam heat exposure (JEBIS)
   - 10 MW/m², 10 s, 300 cycle
     - Steady-state heat flux
   - 20 MW/m², 10 s, 300 cycle
     - Heat flux during slow transient

3. W samples
   - ITER Grade

Divertor mockup for ITER
Surface damage effects on W monoblock performance

ELM simulated heat loading (plasma gun)*

- Pulse plasma energy
  - 0.7 MJ/m²
  - 1.4 MJ/m²
  - 2.0 MJ/m²
- Pulse length 0.2-0.6ms

Disruption simulation (e-beam)

- 5 MJ/m², 1 shots, 5 ms
- Melting spot

Images show:
- Major cracks
- Minor cracks
- Major cracks and melting
- 100 shots + 25 shots
- 40 shots
- 25 shots

* Univ. Hyogo
Plasma gun: 0.7 MJ/m², 100 shots
1.4 MJ/m², 20 shots
E beam heating conditions

E-beam (JEBIS, JAEA) under active cooling conditions

- 10 MW/m², 10 s, 300 cycle: No visible damage
- 20 MW/m², 10 s, 300 cycle: Recrystallization

◆ Heat flux distribution

19 MW/m² 23.4 MW/m²

◆ Surface temperature distribution

- Over 20 MW/m² for 93% of total area
- >2000 °C → Recrystallization
Surface morphology after 20 MW/m², 300 shots

- Longitudinal (major) cracks: appeared on all W in this experiment
- But, for surface damaged W: appeared earlier: < 18 cycles
- For non-damaged W: > 100 cycles
- → surface damage enhanced major crack formation

Grain ejection (only near large cracks)
High heat flux test of small-scale mock-ups

- All W monoblocks of 6 small-scale mock-ups withstood
  - 5000 cycles at 10 MW/m² and **1000 cycles at 20 MW/m²**.
- None of W monoblock showed macroscopic cracks along the tube axis (so-called, self-castellation) that often appeared in monoblocks after HHF test at 20 MW/m².
- Gaps of 0.5 mm in neighboring W monoblocks are bridged by deformation of W.

Example of self castellation that JAEA's mock-up did not have.

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from S. Suzuki
21st ITPA meeting on SOL/divertor physics TG
Surface morphology change: \(~20 \text{ MW/m}^2, 10 \text{ s}\)

Surface damage becomes starting points of cracks, but its development largely depends on bulk material property.
Plasma-enhanced surface damage

- Measured ablation threshold much lower than expected

![Graph showing WI intensity vs. energy density for different gases and temperatures](image)

- 1.6T, 10 Pa
  - $H_2$: 600°C
  - He: 1000°C

Plasma enhanced surface ablation

G. De Temmerman et al, IAEA FEC, 2010
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
Synergistic effects of heat and particle loadings are important.
Remarks on surface damage by pulse heat

- **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.
  - This surface damage could determine the limit of pulse energy (and pulse number) by ELM.

- **Surface damage could be a starting point of large cracks** of W-monoblocks.
  - Further studies on crack propagation from surface damage for crack-resistant W monoblocks.

- **Combined plasma exposure** could reduce the damage threshold of pulsed heat. *(need more investigation with high flux plasma)*
MELT LAYER DYNAMICS
Melt Layer Structure

tungsten: volume expands by 8% due to melting

Melt layer thickness can reach up to 1.5 mm

Power-handling capability significantly degraded

unacceptable
Slight melting

Is slight melting acceptable?

- Acceptable step height for ITER W monoblock (~0.3 mm)
- Bridging by melt layer is serious, because it could eventually cause fracture of cooling tube.

Only “very slight melting” maybe acceptable

Plasma Stream

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

Plasma Gun exp. (QSPA)

TEXTOR Setup

$B_T = 2.25 \, \text{T}$
$I_P = 350 \, \text{kA}$
$n_e = 3.5 \times 10^{19} \, \text{m}^{-3}$
Co-Current NBI: 1.2 MW

Plasma and limiter positions
$R = 1.75 \, \text{m}$
$a = 0.47 \, \text{m}$
Limiter 49cm-46cm

35° with respect to B

Typical heat-flux $\sim 20 \, \text{MW/m}^2$
Temperatures $> 4500 \, ^\circ \text{C}$
Experimental setup for test limiter exposure

- Roof limiter system
  - Samples on graphite roof limiter
  - Position: 46 cm (LCFS) ~ 47.5 cm
  - Base temperature: ~300 °C
  - Standard ohmic plasma
    - $I_p = 350$ kA, $n_e = 2.5 \times 10^{19}$ m$^{-3}$
    - $B_t = 2.25$ T, Ohmic Power ~0.3 MW
  - Edge plasma Parameter ($r = 48$ cm)
    - $T_e \sim 40$ eV, $n_e \sim 2.5 \times 10^{18}$ m$^{-3}$
Material Exposure

Melt-layer ejection and material changes of three different tungsten materials under high heat-flux conditions in the tokamak edge plasma of TEXTOR Nuclear Fusion, 2011, 51, 113020

Tokamak plasma response to droplet spraying from melted plasma facing components Nuclear Fusion, 2012, 52, 013013

Different impurity content leads to strong changes in material behavior

cf. 3D Melt layer modeling B. Bazylev
Forces

Plasma pressure
TEXTOR: 0.2 kPa
QSPA: 100 kPa
ITER(ELM): 5-10 kPa

Dominate force under TEXTOR conditions is jxB

Thermo-electric emission
~3-4 cm² Emission-surface
Melting on both samples
jxB: 0.2-1 mm melt → ~600-4500 N/m²
JET-ILW
W Divertor & Be Main-Chamber

JET is the only operating device with sufficiently high ELM energy losses (>300kJ) to be able to produce transient damage under ITER relevant condition

The JET Melt experiments was meant to clarify issues of transient melting and its impact on operation
The final damage / material moved is roughly 6-7 mm³ from image analysis.
Localized Droplet Source Visible

Local W1, KT2 (VUV), SXR show all 3 clear events

Tungsten droplets move from the divertor into the confined plasma with rather long lifetimes

\[ c_W = 5 \times 10^{-5} \text{ density change} \]
\[ \rightarrow \text{equivalent W mass with } r = 80 \mu m, 41.3 \mu g \]

\[ \text{Lifetime}(q[W], r[\mu m]) \]

\[ \begin{align*}
\text{Lifetime}[s] \quad & 10^1 \quad 10^0 \quad 10^{-1} \quad 10^{-2} \\
q[W] & 10^{-7} \quad 10^{-6} \quad 10^{-5} \quad 10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1}
\end{align*} \]
Melt Layer Motion Matches

When the Temp. evolution in MEMOS is adapted to the measured data including mitigation factors the melt layer motion is correctly modeled.

after 1 melt Pulse 0.23 mm

0.32 mm

0.23 mm

X coordinate (cm)

Y coordinate (cm)

after 5 pulses 1mm

B. Bazylev
Due to boiling (mainly by impurities) and surface instability
Droplet Production

The most promising explanation for splashing seems a Kelvin-Helmholtz instability incorporating linear stability analysis and non linear modeling.

Experimental and theoretical investigation of droplet emission from tungsten melt layer

Miloshevsky, G. et al, accepted by Nuclear Fusion, 2010
Modelling of Kelvin-Helmholtz instability and splashing of melt layers from plasma facing components in tokamaks under plasma impact.
Tungsten Melt layer motion

G. Miloshevsky and A. Hassanein, NF54 (2014) 043016

- 2D Volume of Fluid (VoF)-MHD model
  - Two fluid simulation on plasma and melt layer
  - Instability can be treated. Thus, droplet simulation is possible.
  - Complex numerical method. Difficult to treat generation and motion of melt layer simultaneously.

Kelvin-Helmholtz instability
VAPOR SHIELDING
Intense plasma load causes ablation/evaporation from the surface.

Then, Vapor–Plasma interaction dissipates the localized heat flux to the surrounding area.
Formation of shielding layer

Thickness of vapor layer decreases as atomic number increases.

Line intensities from vapor of different materials Irradiated by QSPA Plasma Gun (25MJ/m²)

Carbon vapor reaches >5 cm While W vapor stays <0.5 cm

High speed CCD images from shot to a W sample.

Graphite vapor shielding

MK-200UG
\( \tau = 0.05 \text{ ms} \)
\( E_i = 2-3 \text{ keV} \)
\( n_e = (0.1-2) \times 10^{20} \text{ m}^{-3} \)
\( q'' = 1-20 \text{ GW/m}^2 \)

- As input power increases, power reaching to the surface decreases.
- Graphite does not melt. (sublimation ~ 3900 K)
  - Easily vaporized. Strong shielding effects.

V.M. Safronov et al. JNM,386, 744 (2009)
Experimental observation (PISCES)

Steady-state He plasma loads + Pulse Laser shot

PISCES-B @ UCSD

Sample Holder (Sample diameter 25mm)

He plasma loads

above
center
below

Nd:YAG laser
(Pulse)

Spectroscopy spot

High speed camera w/ optical band-pass filter

Line intensity profile of surface ejected materials

Decay length of surface ejected materials

\[ f(x) = I_{\text{peak}} \cdot e^{-\lambda x_{\text{peak}}} \]

Laser caused evaporation results

Generation of slow ejected materials \( \rightarrow \) **Shorter** decay length

\( (V_{\text{evaporate}} < V_{\text{sputtering}}) \)

If massive vapor cools plasma down \( \rightarrow \) **Longer** decay length
Decay length analysis

Laser irradiations on

W sample: **Decrease** of decay length

\[ \text{Difference of } V_{\text{sput}} \text{ and } V_{\text{evap}}. \]

Be sample: **Increase** of decay length

\[ \text{Plasma cooling, longer mean free path} \]

Experimental observation of vapor shielding!!
- Tungsten erosion due to vaporization ~ 1-2 µm
- Melt layer thickness ~200 µm at 1.0 ms
- Melt boiling can take place

Simulation approach

- Vapor ejected from surface.
- Neutrals/ions shield incoming flux via:
  - Ionization
  - Line Radiation
- Energy transfer to the wall becomes:
  - Surface recombination
  - Radiation
  - Non-shielded flux
- During vapor shielding,

Simulation should include:

- Motion of particles
- Ionization and recombination
- Radiation (transport)

W ion has a large gyroradius.

Particle-In-Cell (PIC) simulation
Tungsten prompt re-deposition

\[ I = (x_1^2 + z_1^2)^{1/2} \tan \theta \]

Tungsten should be treated by particle codes.

pre-sheath
magnetic sheath
Debye sheath

e-
HE INDUCED STRUCTURE ON TUNGSTEN AND ITS RESPONSE TO PULSED HEAT
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

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**Pilot PSI**

- T ~ 2000 °C

**PISCES (UCSD)**

- T ≤ 600 °C

**NAGDIS (Nagoya U.)**

- T ~ 850 °C
  - T ~ 1100 °C
Why He makes bubbles in metals

- He atoms have closed electronic shell structure.
- He atoms prefer to stay in vacuum (or low electron density environment).
- He atoms strongly trapped in vacancies.
- He trapped vacancy attracts more He to grow to bubbles
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.

Results from NAGDIS

Results from MAGNUM
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).
Growth of protrusions by helium irradiation

Irradiation were performed in the divertor simulator NAGDIS-II. The samples were analyzed FIB-TEM analysis.

Sample: W, 1400K, 50eV-He plasma

Thickness \( \propto (\text{fluence})^{1/2} \)

Four-step process of tungsten nanostructure formation

1. Penetration
   - Competition of penetration and sputtering
   - Penetration range depending on incident energy

2. Diffusion & agglomeration
   - Agglomeration of He, differing from H
   - Diffusion of He, differing from H

3. He bubble growth
   - Growth of He bubble to the size of 1nm or greater.
   - Bursting and inter-bubble fracture of He bubble and Loop punching.

4. Fuzzy nanostructure growth
   - Bursting on the surface
   - Formation of fuzzy structure
   - How does He-bubble play a role?

Slide by A. Ito
Fuzzy Nanostructure Formation by MD-MC Hybrid Simulation

Temperature: 1500K

Flux for MC: \(1.4 \times 10^{-22} \text{ m}^{-2} \text{s}^{-1}\)

Flux for MD: \(1.2 \times 10^{-30} \text{ m}^{-2} \text{s}^{-1}\)

Diffusion coef.: \(1.7 \times 10^{-10} \text{ m}^{2} \text{s}^{-1}\)

Penetration depth: \(d = 10 \text{ nm}\)

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Fuzz structure on various refractory metals

- He induced fuzz formation is relatively common.
- One exception is Ta.
Critical evidence of unipolar arc (UA)

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


B x J direction
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

- Arc track shape consistent with motion in “retrograde” $B \times J_{\text{arc}}$ 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
Pulse plasma effects on W fuzz

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
Summary of arcing events 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*, $\sim 10$ µg / 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.
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)
Laser annealing of tungsten surface

- Focal spot 0.8 mm
- Power 1 kW
- Velocity 5 mm/s
- 2 passes

Height exaggerated $\times 5!$
Experiment for damage repair

- standard geometry: $12 \times 12 \times 5$ mm$^3$
- polished to mirror finish
- loaded on $4 \times 4$ mm$^2$ area
- loading: 100 thermal shocks of 1 ms
- $L = 0.38 \text{ GW/m}^2 \ (F_{HF} = 12 \text{ MW/m}^2\text{s}^{1/2})$
- purpose: create thermal shock crack network with well known parameters
Results of laser annealing

Cross section

- No cracks remained
- Flat surface
- Low grain boundary strength
- Full recrystallization
Summary

- W melt layer dynamics are dominated by **plasma pressure** (**plasma wind**) and **JxB force**.
- Surface instability (ex. Kelvin-Helmholtz instability) and boiling (partly by impurities) could cause droplet ejection.
- **Vapor shielding could mitigate surface damage** from intense plasma heat (caused by disruption). Comprehensive modeling of vapor shielding of tungsten walls are necessary (ex. PIC approach).
- He induced surface morphologies are very unique (Holes, fuzz, etc.) but **very vulnerable to pulsed heat**.
- Effects of arcing of fuzz on plasma performance are under investigation.
- Slight melting could somewhat **repair damaged surface**.