Controlled tungsten melting and droplet ejection studies in ASDEX Upgrade

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Outline

- Introduction and experimental set-up.
- Trajectories and life time of ejected W droplets.
- W penetration to confined plasma.
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Apart from surface damage issues (talk by J. Coenen)

- Where will material ejected from melt layers be transported?
- How much of evaporated tungsten will become ionised?
- What is the resulting W leakage to the confined plasma?
Experimental procedure

- Use divertor manipulator in ASDEX Upgrade to place small W-rod protruding above surface at outer target plate.
- Induce melting, droplet ejection and evaporation in near strike-point plasma.
- Determine trajectories of ejected material by fast VIS range camera systems.
- Quantify resulting W penetration to confined plasma by VIS range divertor and VUV core plasma spectroscopy.

Experimental input to assess potential consequences for ITER tungsten divertor.
ASDEX Upgrade divertor manipulator

Magnetic equilibrium with OSP close to W-pin

Fast camera with viewing cone in poloidal plane

Exposure position of W-pin sample at outer target plate

Outer strike point (OSP)

Divertor manipulator

5 cm
Discharge conditions

- H-mode, 0.8MA, -2.5T
- 3 experiments with variation of
  - NBI power: 6MW / 10MW
  - density: 6.5-7×10^{19} m^{-3}
- 0.8MW ECRH
Melting induced by OSP shift towards W-pin

S-coordinate at outer target plate:
Melting induced by OSP shift towards W-pin

Time [s]

OSP position [m]

#26751

K. Krieger, 13th PFMC Workshop, Rosenheim, 13.05.2011
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Field of view for fast cameras

View vertically down

Tangential view

Both cameras equipped with $H_\alpha / H_\beta$ rejection filter to improve contrast

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Ejection of droplets into divertor plasma.

Droplets move always downstream.

Droplets eventually move upwards against gravity & poloidal B-field direction.
Droplet motion

- Droplet acceleration decreasing over time.
- Average acceleration $\approx 400m/s^2$.

- Light emission modulated by ELM impact.
- Intensity decreases over time:
  - Evaporation.
  - Droplets move to cooler regions.
Droplet evaporation model

Power flux to droplet leads to evaporation and thermal radiation.
Droplet evaporation model

Power flux to droplet leads to **evaporation** and **thermal radiation**.

\[
\frac{1}{2} q_{\|} = \Gamma_{\text{vap}} \frac{\Delta H_{\text{vap}}}{N_A} + \epsilon_T \sigma T^4
\]

\[
\Gamma_{\text{vap}} = \frac{p_m e}{\sqrt{2\pi m_w k_B T}} \frac{\Delta H_{\text{vap}}}{N_A k_B} \left(1 - \frac{1}{T/T_m}\right)
\]

- Power flux balance determines droplet temperature.
- T does not depend on radius.
Droplet life time

Time evolution of droplet evaporation

\[
\frac{dN_W(t)}{dt} = \frac{d}{dt} \left( \rho_W \frac{4\pi}{3} r^3(t) \right) = -4\pi r^2(t) \Gamma_{vap}(t)
\]

\[
\frac{dr(t)}{dt} = -\frac{1}{\rho_W} \Gamma_{vap}(t)
\]

Life time at constant power flux \( \tau = r_0 \rho_W / \bar{\Gamma}_{vap} \)

Evaporated fraction \( f \) assuming \( \Delta m = 20 \) mg ejected as \( k \) droplets using plasma parameters @ OSP

<table>
<thead>
<tr>
<th>( k )</th>
<th>1</th>
<th>10</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau ) (s)</td>
<td>3.07</td>
<td>1.42</td>
<td>0.66</td>
</tr>
<tr>
<td>( f )</td>
<td>0.09</td>
<td>0.20</td>
<td>0.39</td>
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</tbody>
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\( \tau >> 100 \) ms typical time along flight trajectories
Toroidal acceleration mainly due to plasma friction and droplet ablation. Typical values for strike point plasma conditions and 10μm droplet radius: $a_{abl}=50\text{m/s}^2$, $a_p=400\text{m/s}^2$.

\[
a_{abl} = \frac{F_{abl}}{m} \approx \frac{3}{4\sqrt{2\pi}m_w\rho_w} \Delta p_{vap}(q_{||})
\]

\[
a_p = \frac{F_p}{m} \approx \frac{1}{4m_w\rho_w} \frac{n_e(kT_e+kT_i)}{r}
\]

Forces on droplets II

Droplets glide over target plate surface due to electro-static repelling force in magnetic pre-sheath.

Vertical motion is determined by components of zentrifugal force and of gravity force along target plate.

\[
\frac{F_{el}}{m} = \frac{QE}{m} \approx \frac{9\varepsilon_0}{m_w\rho_w} \frac{T_e E(d)}{r^2} \geq \frac{v_t^2}{R} \cos \nu + g \sin \nu
\]
Forces on droplets II

Vertical motion is determined by balance of vertical component of zentrifugal force and gravity force:

\[ a_z(t) = \frac{v_t^2(t)}{R} \sin \vartheta - g \cos \vartheta \]
\[ v_t(t) = a_t t \]

Time evolution of vertical distance from origin for measured tangential droplet acceleration:
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Local tungsten source at W pin

Each droplet ejection leads to a short increase of the local W source.

The W-pin is in addition eroded by ELMs.
Resulting W contamination of confined plasma

In a 0D model the number of tungsten ions inside separatrix, $N_w$, is linked to W source, $\Phi$, particle confinement time, $\tau_w$, and source screening factor, $S$.

$$\frac{dN_w(t)}{dt} = \Phi_{W}^{\text{core}} + \frac{\Phi_w(t)}{S} - \frac{N_w(t)}{\tau_w}$$

From the measured evolution of $c_w$ and the W divertor source one can derive the divertor screening factor.

$$\int_{t_0}^{t_1} \frac{\Phi_w(t)}{S} dt = \frac{1}{\tau_w} \int_{t_0}^{t_1} \left( N_w(t) - \bar{N}_w \right) dt$$
Molten remains after exposure

- Deviation from vertical in direction of plasma flow.
- Droplets accelerated in plasma.
- Molten W dripping down welds to W-layer on graphite body of sample.
- Mass loss without local deposits
  - $\Delta m=20.6\text{mg}$ @6MW  #25514
  - $\Delta m=9.3\text{mg}$  @10MW  #25623
  - $\Delta m=16.5\text{mg}$  @10MW  #26751
Evaporation based on vapour pressure and balance between heating by || power flux and cooling by black-body radiation and evaporation heat during 100ms residence time ≈ 30% of lost pin mass.

Relate this number to W throughput in confined plasma:

\[ S_{div} \approx 120 \text{ (#26751), 165 (#25623), 200 (#25514)} \]

Comparing to SOL screening factor from laser ablation, \( S_{SOL} \approx 11 \)

Divertor retention factor \( \approx 10-20 \) comparable to result from \( W(CO)_6 \) injection studies (Geier et al., Plasma Phys. Contr. Fusion 44 (2002) 2091).
Summary

- W droplets ejected by melt events at a target plate can survive travelling through the plasma over distances of several meters toroidally.
- Vertical inclination of target plates causes ejected droplets to travel upwards.
- Penetration of evaporated W fraction to confined plasma comparable to that of tungsten sputtered at the target plate.