Characterization of Liquid Metals as Prospective Divertor Materials Under Transient Plasma Loads


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Abstract: Main features of plasma–surface interaction, vapor shield effects and energy transfer to capillary porous systems (CPS) based Sn targets are studied at different heat loads (0.1–2.2 MJ/m²) within the QSPA Kh-50 and QSPA-M. The plasma density in front of exposed Sn targets is found to be up to ten times higher than in impacting plasma stream. It leads to the arisen screening effect for the plasma energy transfer to the surface. For small energy loads the transient layer consists of the plasma stream species only, target impurities are appeared when the heat load exceeds the material melting threshold.

Motivation: High power magnetically confined fusion devices have very high heat and particle loads on the plasma facing components. Liquid metal mock-ups were proposed as an alternative of the full tungsten divertor for DEMO. Extrapolation of the disruptions/ELMs erosion effects obtained at the present-day tokamaks to the transient peak loads of next step fusion devices (ITER and DEMO) remains uncertain. Special investigations on material behavior at the relevant transient loads are thus very important.

Experimental facilities

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Plasma energy density</td>
<td>0.1–2.2 MJ/m²</td>
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<tr>
<td>Plasma load duration</td>
<td>0.25 ms</td>
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<tr>
<td>Diameter of plasma stream</td>
<td>15 cm</td>
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Heat load to the Sn target surfaces (q) vs. the energy density of impacting plasma stream (Q).

Plasma-surface interaction within QSPA-M

Spectral lines obtained near Sn sample at different energy density (Q) of plasma stream

CPS based Sn

Target is SS mesh wetted by Sn

Schematic cross-section view of the target

SS mesh initial view; Average cell size – 100×150 μm; Wire thickness – 90 μm

Diagnostic: Energy density of plasma stream was measured by calorimeter. Particles dynamics monitoring were performed with a high-speed (10 Hz CMOS pro 1200 u) digital camera POC-AG. Spectroscopy studies of plasma stream dynamics were carried out also. Surface analysis carried out with optical microscope equipped with CCD camera.

Energy density distributions in shielding layer vs. the distance from the target surface (Z)

Q=0.7 MJ/m² (1); Q=0.6 MJ/m² (2); Q=0.3 MJ/m² (3); Q=0.1 MJ/m² (4); Q<0.1 MJ/m² (5)

The energy density increases with an increasing distance from the target surface.

The absorbed energy is about 50% of the impact plasma energy at Q>0.5 MJ/m².

Average electron density of Ne=(1–3)×10¹⁷ cm⁻³ near surface was measured from Stark broadening of spectral lines Sn I 3262 A and Sn II 3283 A. Ne is about 10¹⁷ cm⁻³ in the free plasma stream.

Spectral lines of Sn I (3175, 3262, 3330 Å) and Sn II (3293, 3391 Å) were identified.

Plasma shield consisted mostly of Sn neutrals.

Spectral lines of Q=0.1 MJ/m².

Intensive emission of Sn II lines is observed at Q>0.3 MJ/m².

The continuum intensity increase significantly at Q>0.5 MJ/m².

Erosion of Sn targets irradiated by plasma streams

Initial

QSPA Kh-50: 5 pulses; Q=2.2 MJ/m²

QSPA-M: 10 pulses; Q=0.7 MJ/m²

Development of instabilities in melted layer:

Promoted particles splashing:

Delamination of CPS:

Large erosion:

Mass losses: 6.85 mg/cm² pulse

Further increase of heat load leads to the splashing of eroded material

Plasma-surface interaction within QSPA Kh-50

Heat load to the target surfaces (q) and images of particle ejection vs. the energy density of impacting plasma stream (Q)

Cu covered by Sn

CPS Sn target

Energy density delivered to the Sn surface is reduced in comparison with Cu.

Heat load below 0.5 MJ/m² does not trigger the generation of erosion products.

Only several particles traces have been registered at 0.5 MJ/m² < Q<1 MJ/m².

Further increase of heat load leads to the splashing of eroded material

CONCLUSIONS

Erosion of tin targets has been studied at different heat loads (0.1–2.2 MJ/m²) within powerful quasi-stationary plasma accelerators QSPA Kh-50 and QSPA-M.

Transient plasma layers formed near surfaces exposed by powerful plasma streams.

The plasma density in such layers is found to be up to ten times higher than in impacting plasma stream. It leads to the arisen screening effect for the plasma energy transfer to the surface. Calorimetric measurements of the target heat loads have shown that only about half of plasma stream energy density is delivered to the surface.

For small energy loads the transient layer consists of the plasma stream species only. Target impurities are appeared when the heat load exceeds the material melting threshold.

Further increase of the energy load causes the development of vapor shield.

Nevertheless, pronounced erosion of the target is accompanied by separation of droplets/dust from the exposed target surfaces. The delamination of capillary pore systems of target was also observed.

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