EUROfusion

Performance comparison of CPS candidates under transient plasma loading: Overview on activities of KIPT within WP DTT1-LMD

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Outline

- Introduction
- Experimental facilities and samples
- Experimental results
  - Investigation the power handling under transient loading
  - ELM and disruption load testing of prototypes
- Summary
- Future plans

Introduction

- Liquid metals mock-ups were proposed as alternative of 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.
  - Performance comparison of CPS candidates under ELM-like/disruption-like loading.

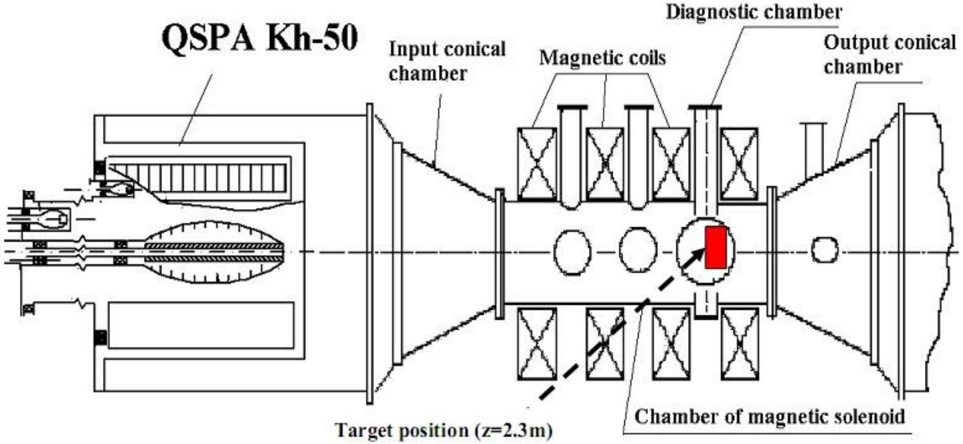
  Task DTT1-LMD.P1-T003-D002 (performed during 2018-2020)
  - ELM and disruption load testing of prototypes.

  Task DTT1-LMD.P4-T001-D005 (shifted from 2020 and completed in 2021)

P1: POWER HANDLING

- **Task DTT1-LMD.P1-T003-D002**
- The main tasks for this activity are to investigate the power handling under transient loading, in connection with the effects of vapour shielding, as well as to test the stability of the LM surface
  - Vapor shield effects and energy transfer to Liquid Metal plasma facing components are studied at different heat loads using QSPA Kh-50 and QSPA-M quasi-stationary plasma accelerators.
  - Spectroscopy studies of shielding layer will be performed at different heat loads.
- The analysis of CPS targets surfaces exposed by transient heat loads
  - Repetitive plasma exposures of Sn based capillary porous systems (CPS) were performed at the plasma loads varied in the range of 0.1–2.2 MJ/m^2.

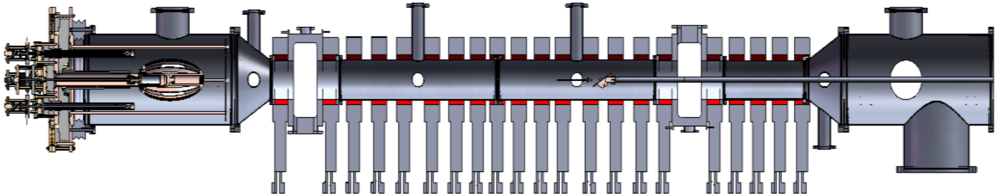
Experimental facilities: QSPA Kh-50; QSPA-M



Plasma energy density	0.1–2.2 MJ/m^2
Plasma load duration	0.25 ms
Diameter of plasma stream	15 cm

V A Makhlai et al *2020 Phys. Scr. T171, 014047*

QSPA-M



Plasma energy density	0.1-1 MJ/m^2
Plasma load duration	0.1 ms
External magnetic field	0.8 T
Diameter of plasma stream	6 cm

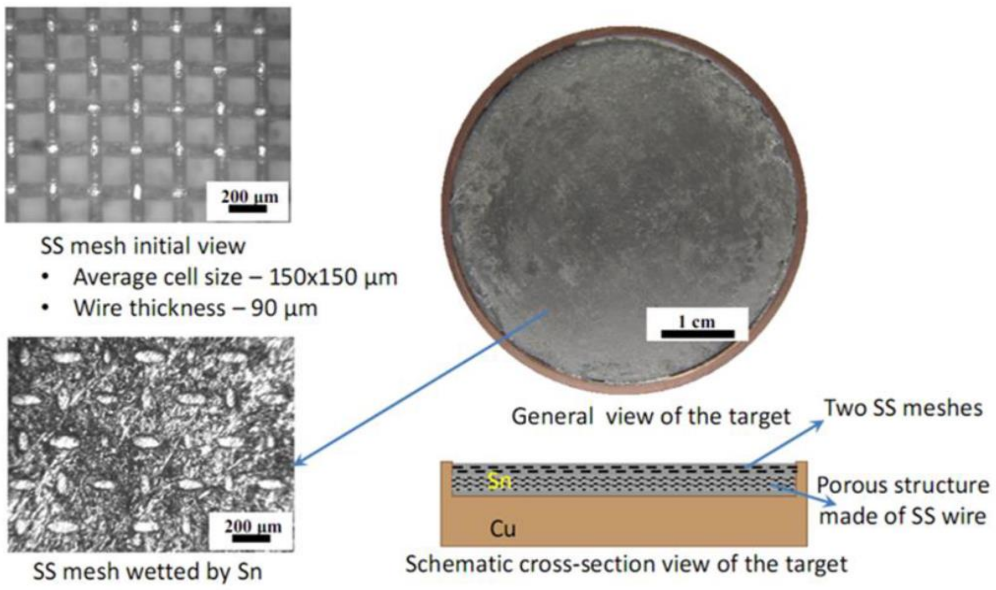
Diagnostics

- ❖Calorimetry
- ❖Optical emission spectroscopy
- ❖High-speed digital camera PCO AG

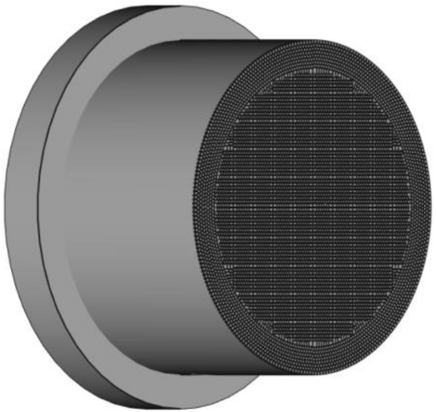
I.E. Garkusha et al 2017 Nucl. Fusion 57, 116011;
I.E. Garkusha et al 2019 Nucl. Fusion 59, 086023

CPS Samples

CPS samples
SS mesh wetted by Sn



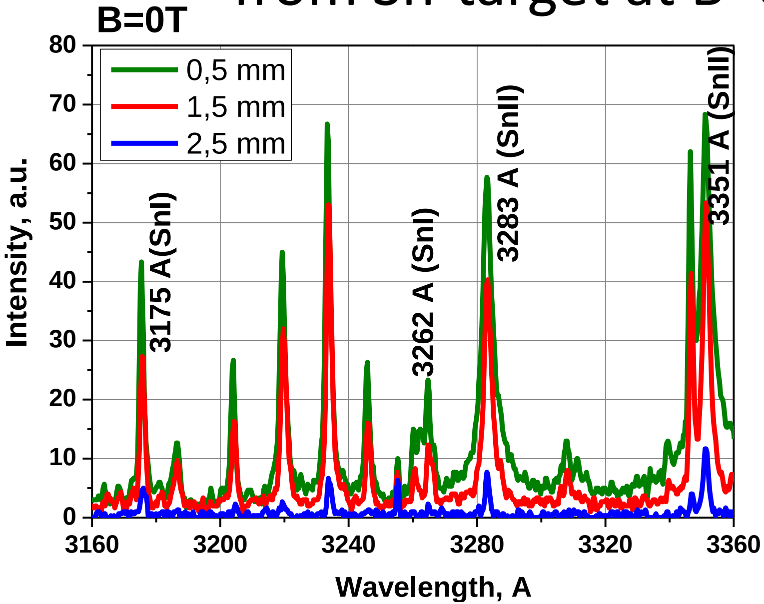
CPS samples
3D tungsten target filled by Sn

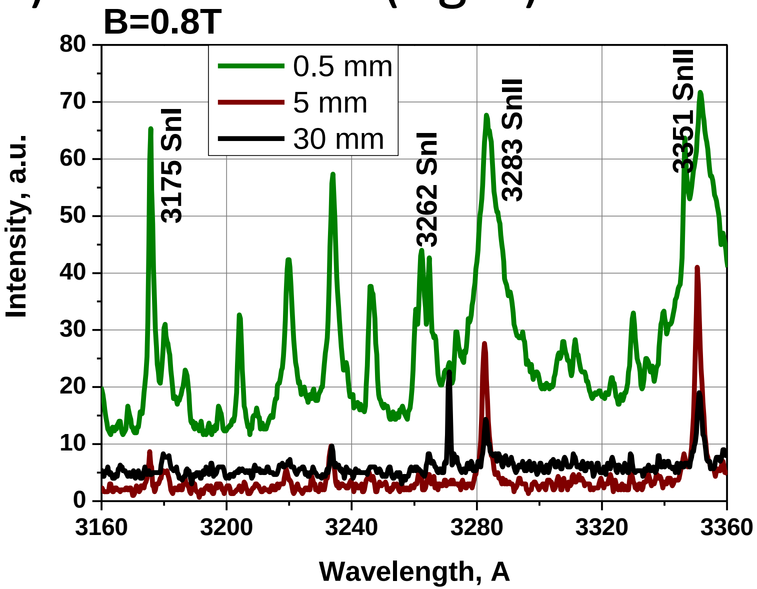


CPS cylindrical samples of 25 mm in diameter and 17 mm in height
Samples were produced in DIFFR and provided by Peter Rindt.

Spectroscopy studies: Sn lines near exposed surface

Behavior of spectra intensity and tin spectral lines versus distance from Sn-target at B=0 T (left) and B=0.8 T (right)

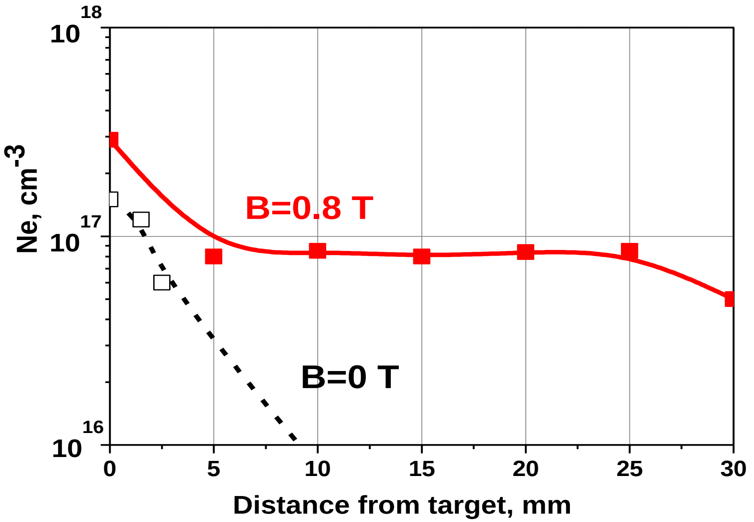


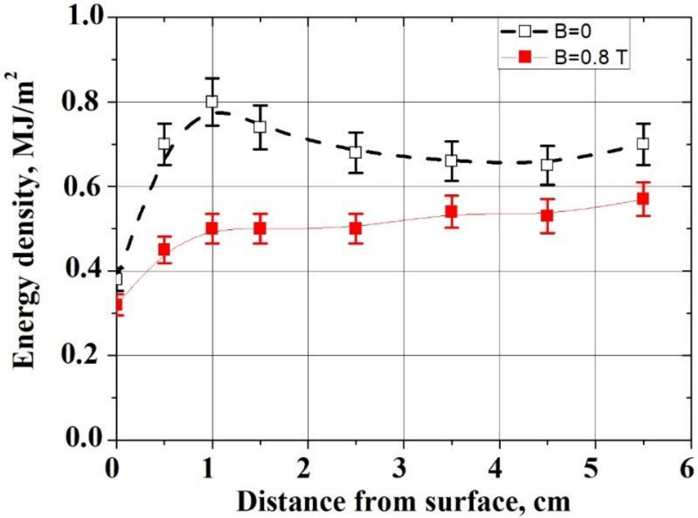


- Spectral lines of sample material species were registered only in very thin plasma layer near the exposed surface (<0.5 cm from the surface) without magnetic field.
- Nevertheless, spectral lines of Sn were recognized at 3 cm from the exposed surface in magnetic field.

Shielding effect: QSPA-M

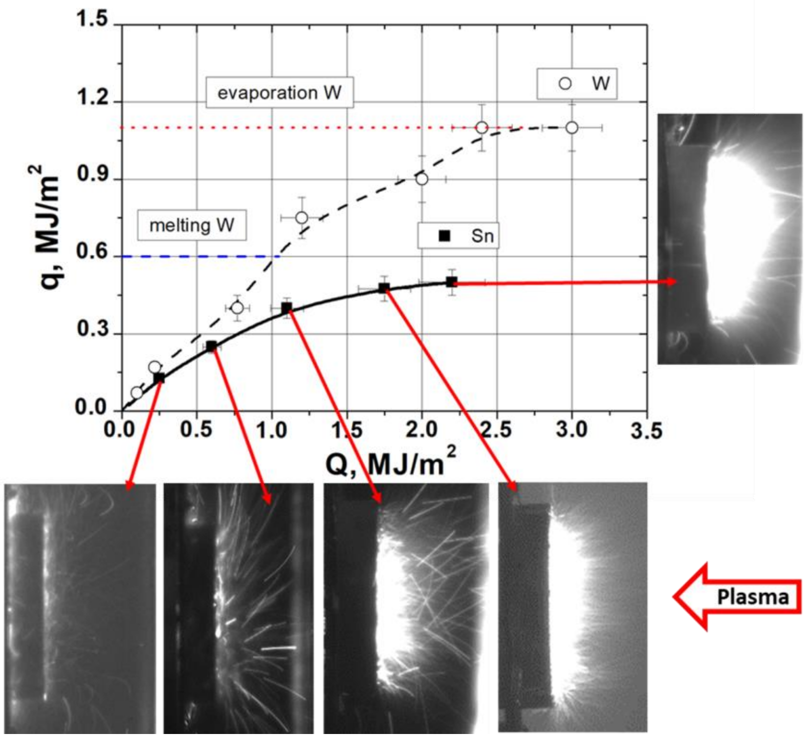
Distributions plasma density (Left) and energy density (right) in shielding layer vs. the distance from the CPS target surface, Q=0.75 MJ/m²



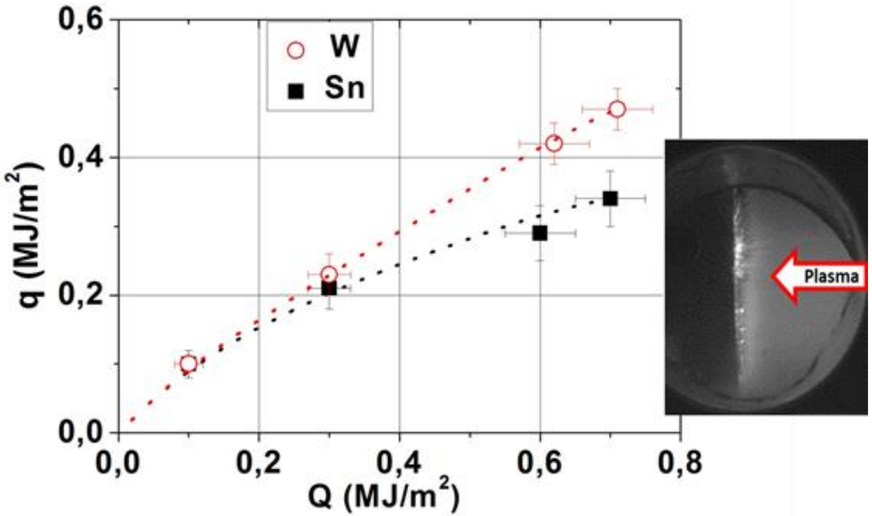


- The plasma electron density was estimated using Stark broadening of spectral lines Sn II (3283 Å).
- The shielding layer is thinner without a magnetic field due to the plasma flows around the target.
- Only a part of the plasma energy is transferred to the target surface through the shielding plasma layer
- This dense plasma shield is completely not transparent for the impacting plasma, being considerably larger than the particle free path length.

Measurements of energy density



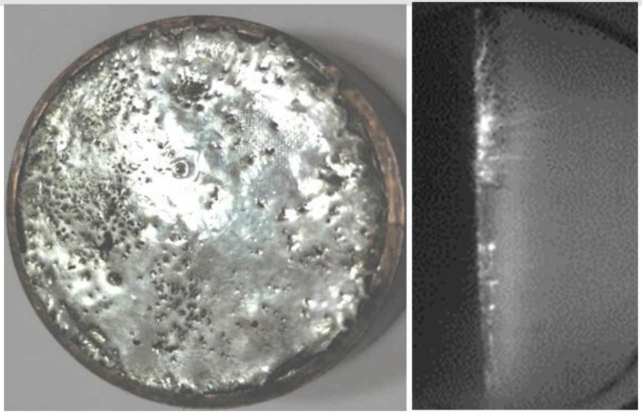
Energy density absorbed by the CPS target vs. the energy density in impacting plasma stream and corresponding frames from high-speed camera for varied heat loads.



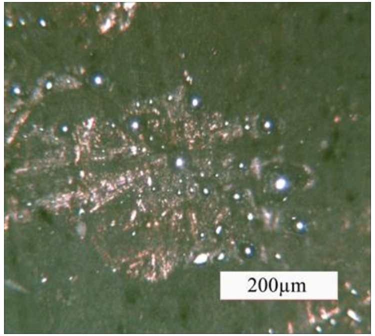
Energy density delivered to the CPS tin target is reduced in comparison with similar measurements, performed for flat tungsten surface in identical conditions

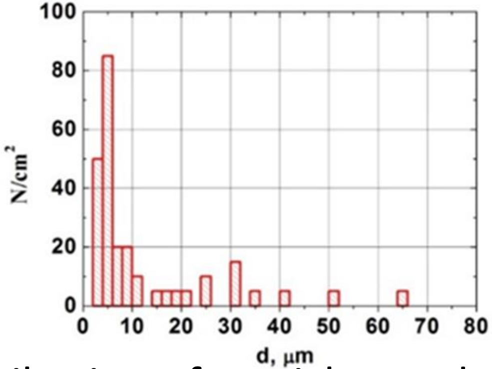
Damaging and erosion of exposed surfaces

Δm≈ 6.85 mg/cm² pulse



Δm~0.05 mg/cm²pulse

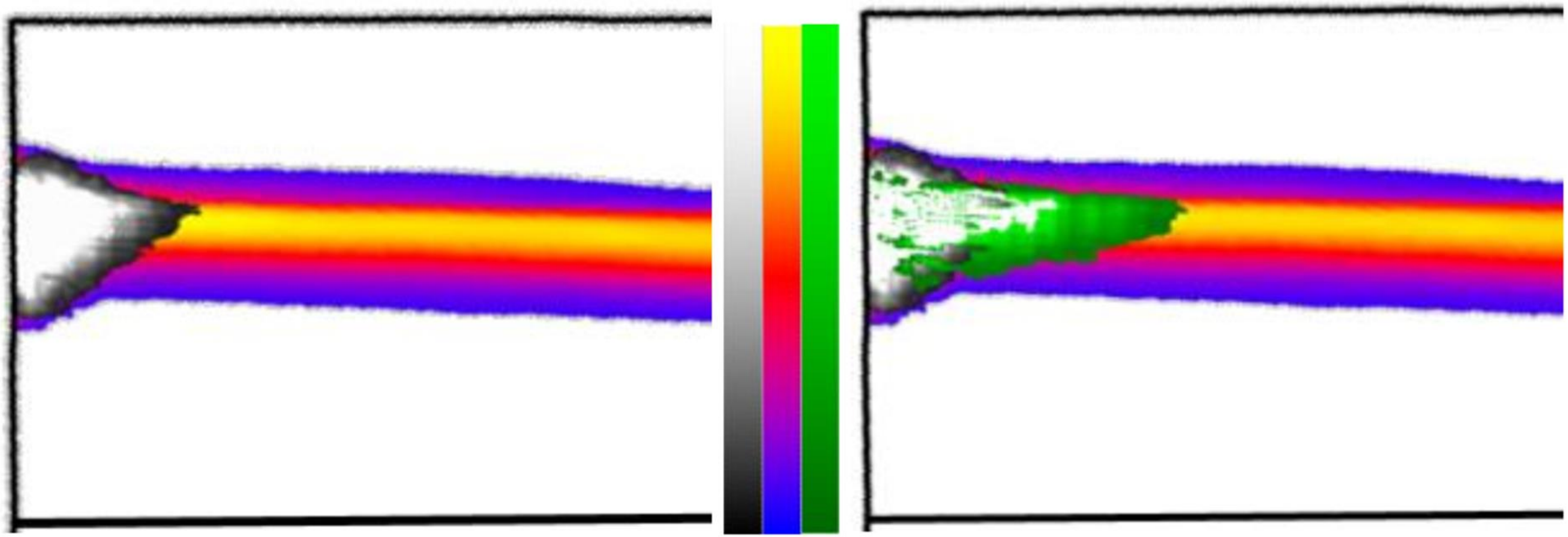




- ❖Development of instabilities in melted layer
- ❖Pronounced particles splashing
- ❖Delamination of CPS

Image and size distribution of particles re-deposited upon the CPS target surface exposed to plasma pulses of 1.8 MJm^{-2}.

Results of numerical simulation



Left panel shows 2D distributions of Sn plasma density (black-white color scale) and H plasma density (blue-red-yellow scale) in the shielding layer for the QSPA shot of Q=0.75 MJ/m^2.

Right panel shows distribution of Sn plasma radiation intensity (green scale) on top of the Sn and H densities, shown in the left panel. Maximum electron density in the Sn shield is 10^{17} cm^{-3} and $2·10^{16}$ cm^{-3} in the free H plasma stream.

Simulation was performed by S. Pestchanyi (KIT)

Conclusions: Task DTT1-LMD.P1-T003-D002

- The thickness of the shielding layer increases in a magnetic field. The spectral lines of Sn were registered only in a very thin plasma layer < 0.5 cm from the surface at B=0, but in the magnetic field of 0.8 T Sn spectrum was recognized at 3 cm from the exposed surface.
- The electron density in plasma shield is 5-10 times higher than in impacting plasma stream.
- Plasma exposures of Sn CPS target with QSPA plasma load < (0.5 MJ/m^2) do not trigger the generation of erosion products. For the heat load > 0.5 MJ/m^2, but < 1 MJ/m^2 single dust particles traces have been registered. Further increase of heat load leads to the splashing of eroded material.
- For ELM-like impacts rather weak melt motion was observed on the target surface. A moderate particle splashing is attributed to the heat loads up to 1 MJ/m^2.
- First comparison of obtained experimental results on vapour shielding of Sn CPS with available data from numerical simulation using the TOKES code demonstrates the qualitative correspondence between the simulated and measured electron density in the plasma shield.

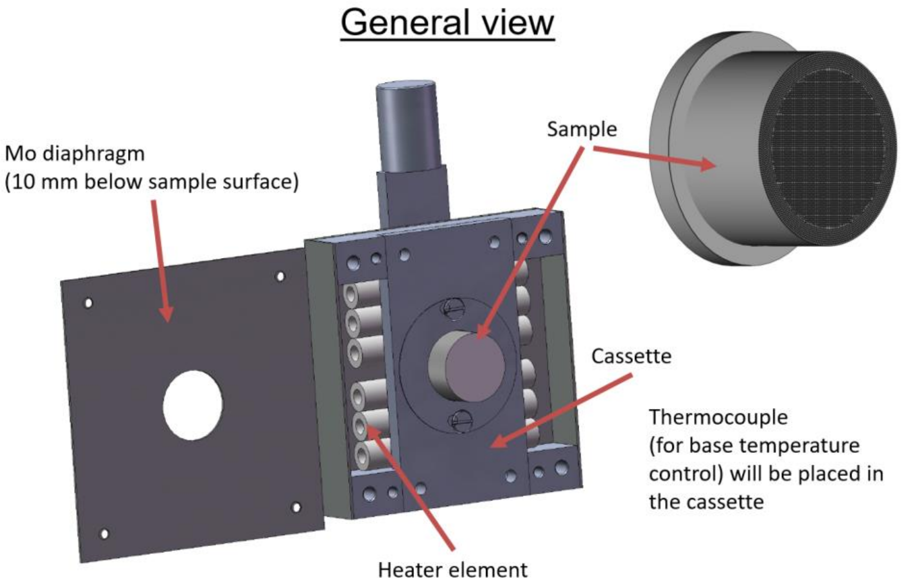
P4: PROTOTYPE DEVELOPMENT

- Task DTT1-LMD.P4-T001-D005

ELM and disruption load testing of prototypes (KIPT)

- The main task is to evaluate damaging of prototypes under different loading conditions to iterate to an optimal component design for DEMO.
  - LM stability (droplet production)
  - CPS damage
- Contribution of pre-heating of CPS on macroscopic erosion of exposed surfaces will be studied.

Samples



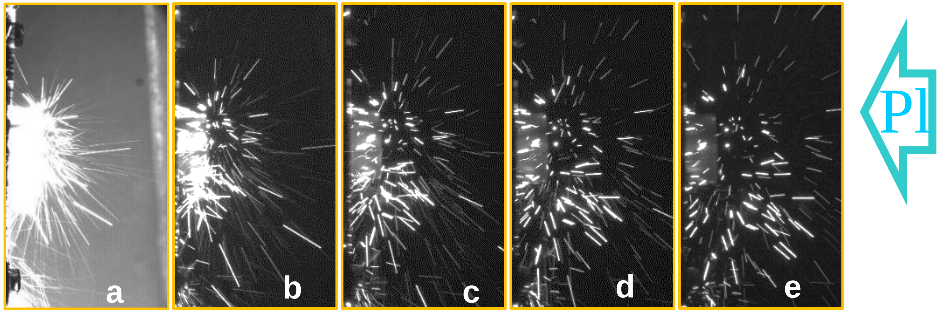
CPS target irradiation within QSPA Kh-50

Test conditions	
Energy density in plasma stream, [MJ/m^2]	up to 3
Pulse duration, [ms]	0.25
Number of pulses	5
Base temperature, [T °C]	~ 300 (Sn melting threshold), RT
Expected surface effects	Pronounced Evaporation/ particles injection

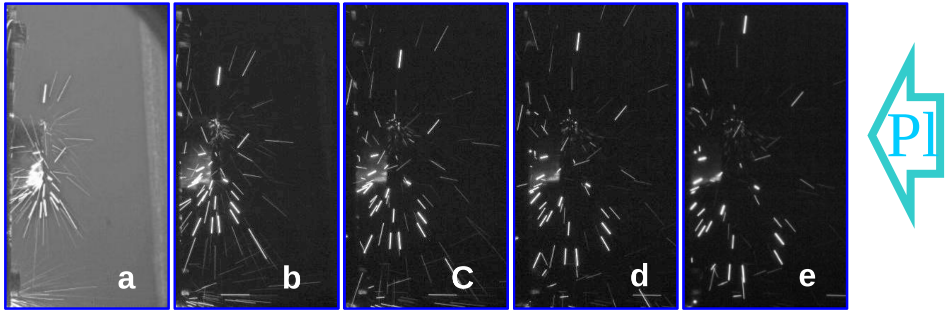
CPS cylindrical samples of 25 mm in diameter and 17 mm in height were provided by Peter Rindt, DIFFER. iopscience.iop.org/article/10.1088/1741-4326/ab0a76/meta)

The holder for prototypes/samples was prepared.

Images of PSI with CPS targets



Pre-heated T_{surf} ~300°C



Without pre-heating T_{surf} ~ RT

- Particle ejection is observed during PSI for pre-heated as well as cold CPS targets
- Number of particles ejected from the pre-heated target is more than in the case of RT irradiation
- Values of the velocities and the start-time from the irradiated targets are in the same range for both tests.
  - The velocities: (1…17) m/s.
  - The start-times: (0.1…1) ms

The images correspond to 1.2-2.4 ms (a); 2.4-3.6 ms (b); 3.6-4.8 ms (c); 4.8-6 ms (d); 6-7.2 ms (e) after the start of the PSI interaction ($t_{exposure}$=1.2 ms).

Damaging of CPS targets

General view of irradiated pre-heated CPS target

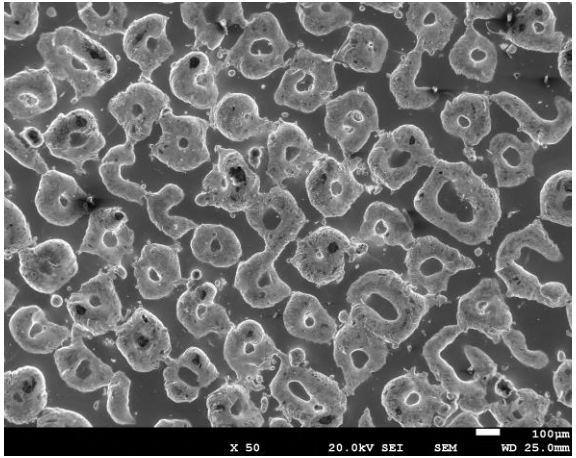
Mass losses of the samples during experiment	
Pre-heated	Cold
Δm=3.0541 g	Δm=0.014 g

General view of irradiated CPS targets

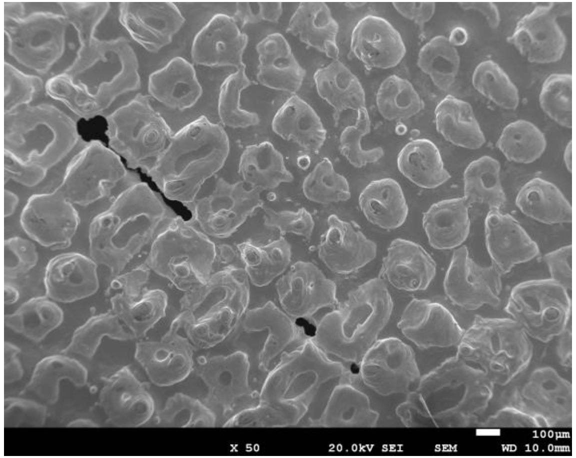
- Melted Sn moves along the target surface and the holder.
- In the case of pre-heating, Sn droplets flow out the CPS target for ~1 min after the plasma pulse.
- That is not observed for cold target

SEM images of CPS targets

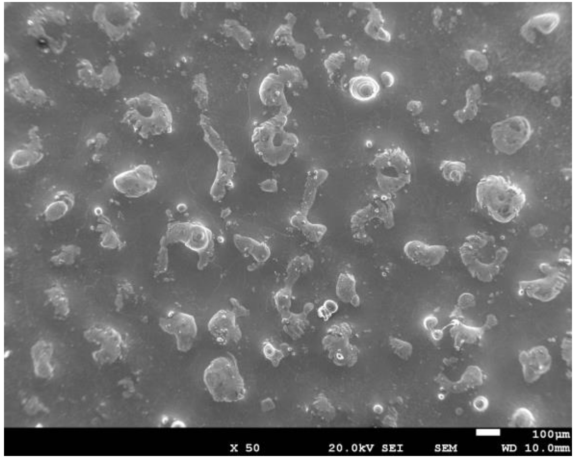
Initial



Pre-heated target after plasma load



Cold target after plasma load



- Areas not filled by Sn occur on the pre-heated target
- Nevertheless, damage of the W base of the CPS targets is not observed during low cycle loads
- The CPS targets damage under high cycle powerful plasma loads will be studied in later experiments

Summary

- Vapour shielding of liquid-metal Sn capillary porous structures under ELM-like and disruption transient loading has been studied in complementary simulation experiments using QSPA-M and QSPA Kh-50 experimental facilities.
  - The thickness of the shielding layer increases in a magnetic field.
  - The electron density in plasma shield is 5-10 times higher than in impacting plasma stream.
- Numerical simulation using the TOKES code demonstrates the qualitative correspondence between the simulated and measured electron density in the plasma shield.
- First experimental testing of 3D CPS Tungsten-Tin samples was performed.
- The testing of CPS samples need to be perform under high cycle powerful plasma loads for evaluation of damaging effects in CPS surfaces.

Future plans [2021-2025]

- Testing of LM prototypes of plasma facing components for DEMO. Surface analysis after different doses.
- The CPS targets damage under high cycle powerful plasma loads will be studied in later experiments
- Validation of numerical codes against QSPA results for prediction of erosion and shielding effects in LM divertor.
- Testing new prospective types of materials, including material composites (e.g. fiber or particle reinforced high heat flux materials), under transient plasma impacts.
- Analysis of dynamics of erosion products in plasma from LM targets (both spectroscopy and particles collection)