# Physics and technology research for liquid-metal divertor development at the OLMAT high heat-flux facility

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# Outline

- Motivation
- OLMAT as a HHF facility for LM PFC testing and development
- Commissioning and first campaign Sn CPS campaign
- CW laser for steady state/transient loading simulation
- Fall 2022 campaign
  - Target embedded Langmuir probe
  - 3D Sn-W CPS Asdex Upgrade mockup
- Summary and future works

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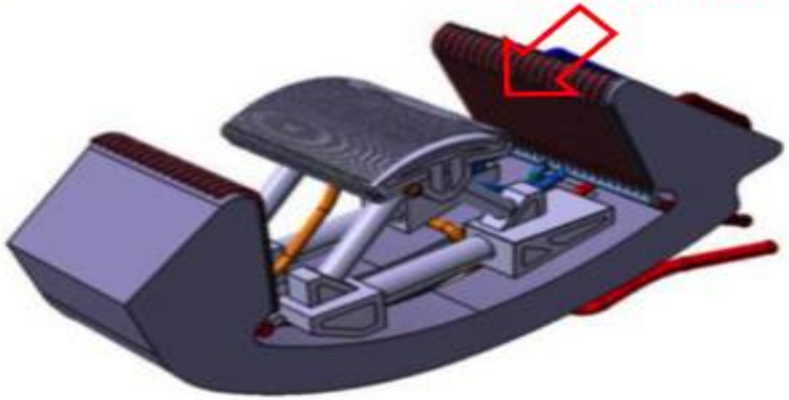
# Motivation

Challenging conditions for a nuclear fusion reactor.

- ✓ Large, energetic (14 MeV) neutron loading of walls
- ✓ Large heat and particle loads: plasma exhaust at divertor region

*Typical heat loads (DEMO)*

- **Steady state:**
  - Normal: ~10 MW/m² (*Δ$T_s$ ~800 K*)
  - Detached: ~20 MW/m² (*Δ$T_s$ ~1600 K*)
- **Transients** (off-normal):
  - ELMs (periodic): ~500 MW/m² 1 ms. (*Δ$T_s$ ~3,600 K*)
  - Disruptions: ~30 GW/m² 1.5 ms. (*Δ$T_s$ ~200,000 K*)



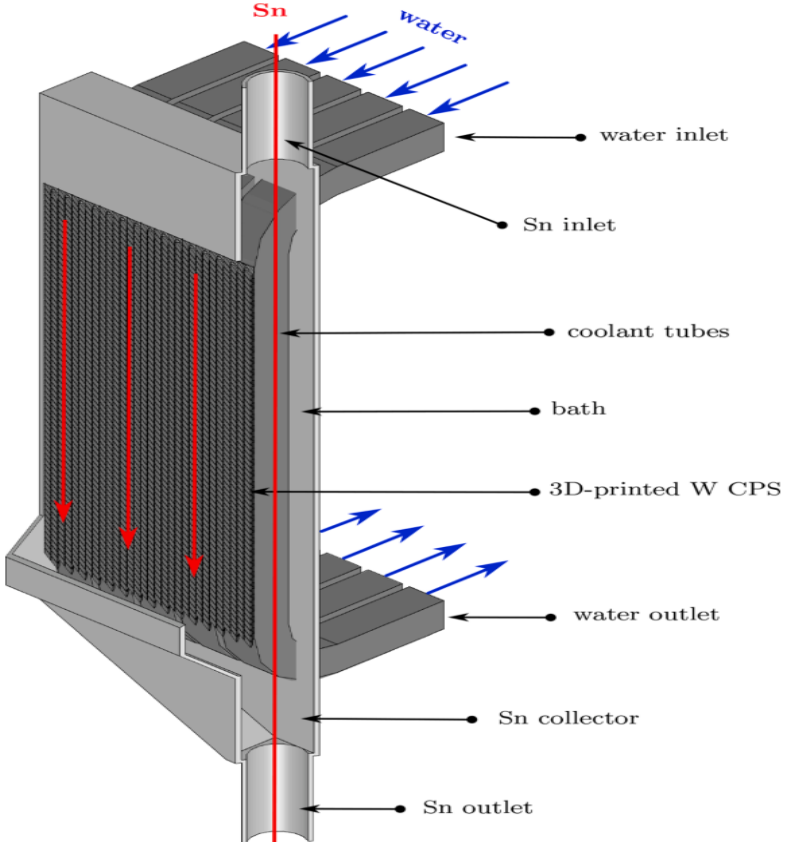

- **Issues addressed in High Heat Flux Facilities: electron, ion & laser beams, linear plasmas. Focused on postmortem analysis of damaged samples.**
- **Not clear if solid materials (W) will be able to withstand DEMO conditions.**

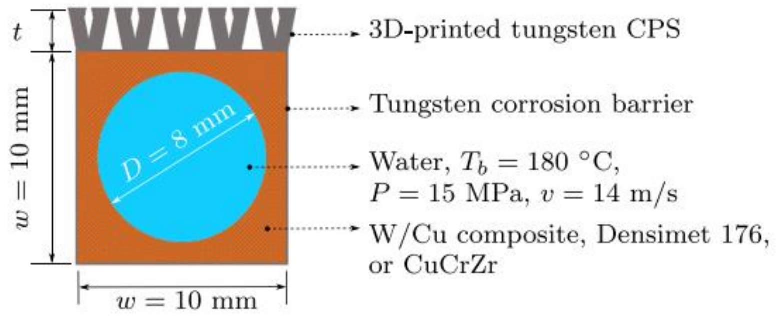
# Motivation

- The European pre-conceptual design activities identified Sn as the leading candidate for a liquid metal and Capillary Porous Structures (CPSs) as the most mature technology option for implementation in EU-DEMO:
  - Sn tritium retention is comparable to tungsten.
  - Exposure to atmosphere at room temperatures (maintenance) does not result in problematic oxidation, or safety hazards.

  Advantages of Li /SnLi and flowing concepts (low recycling, enhanced confinement, plasma compatibiliity) cannot be rejected whatsoever. OLMAT fully open to investigate them

- Necessity of testing different CPS targets to bring concept to final design
- OLMAT focused on comparative studies for different CPS regarding the surface temperature inhomogeneity, droplet ejection, evaporation, vapor shielding surface damage, local plasma characterization



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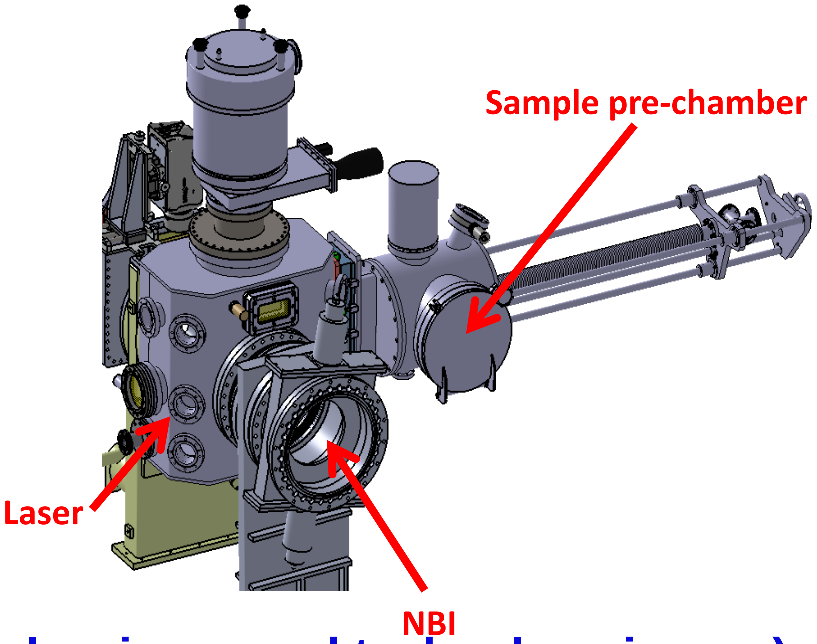
# OLMAT as a HHF facility for LM PFC testing and development

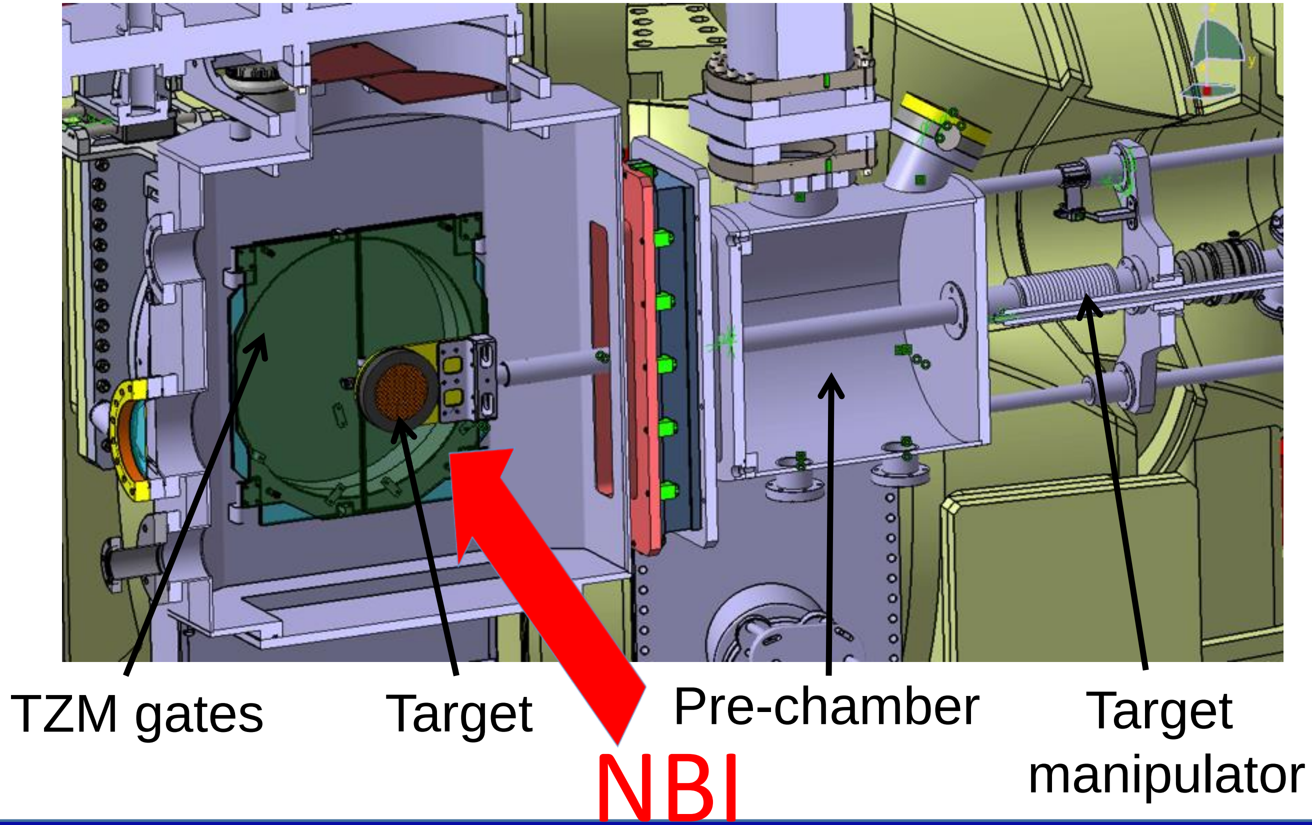
## Utilization of NBI beam (TJ-II stellarator) to expose LM PFCs to reactor relevant heat loads.

- Devoted exposure chamber with independent vacuum system
- Lateral pre-chamber for sample installation/insertion
- Beam power: 100-730 kW; $E_{beam}$< 32kV ($E_0$,1/2 and 1/3), $H^+$ flux≤ $1.5 \cdot 10^{22}$ $m^{-2}s^{-1}$.
- Power density between 8±2 to 60±15 $MW/m^2$.
- Pulse duration up to 150 ms. Repetition rate: 0,5-2 $min^{-1}$
- Phase 1) NBI exposure of LM prototypes. Comparative studies
- Phase 2) Addition of ELM-like loads (Laser pulses)
- Phase 3) Long NBI pulse (up to 5 s)+ ELMs
- Cold plasma plume: $T_e$: ~2eV; $n_e$: $10^{18}$ $m^{-3}$ (spectroscopy).
- Equipped with wide variety of plasma diagnostics (physics studies)
- Myriad of post-mortem surface characterization techniques (material science and technology issues)



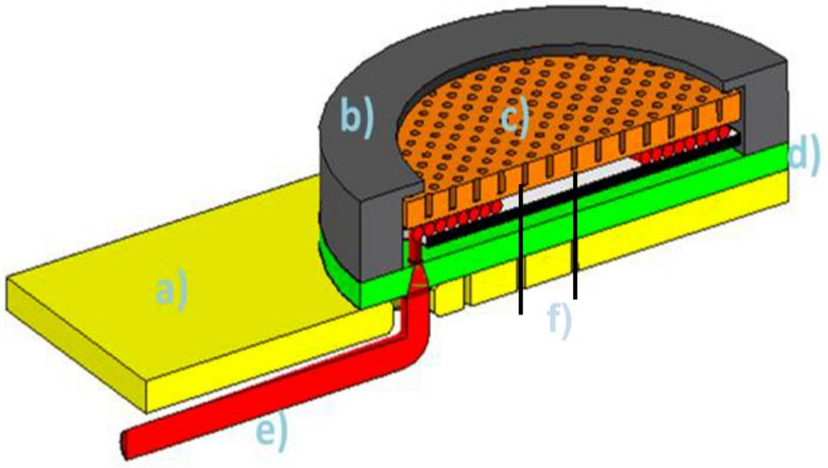
# OLMAT as a HHF facility for LM PFC testing and development

- Maximum injected power: 730 kW → 60±15MW/m$^2$
- Maximum particle flux of about 1,7.10$^{22}$ m$^{-2}$.s$^{-1}$
- Maximum pulse length: 150 ms (at medium power)
- Minimum pulse repetition rate: every 30 s.

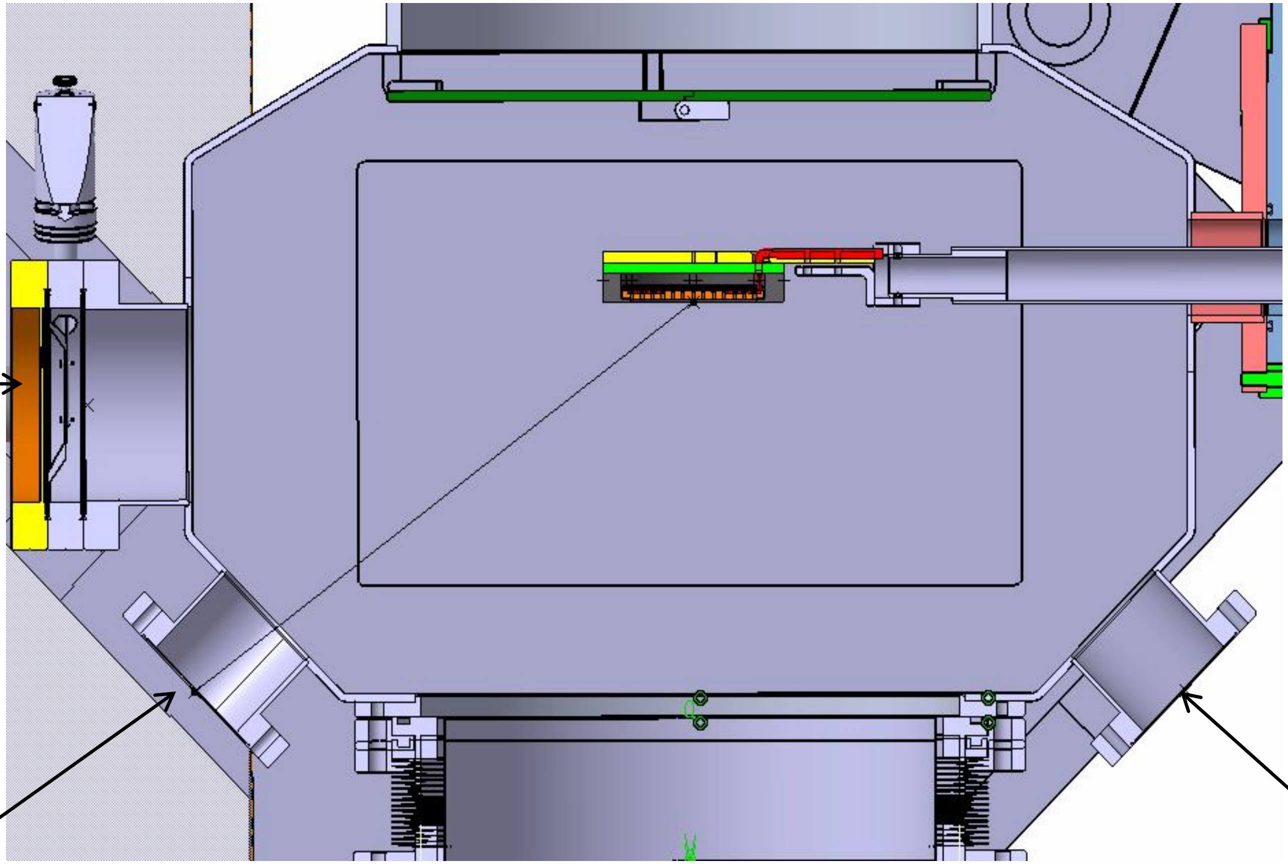



**Target holder:**

a) supporting TZM plate.
b) holding TZM ring.
c) machined TZM plate (liquid metals) or 7 mm thick solid TZM target during (commissioning) isolating ceramics.
d) heating wire.
e) Two thermocouples.



# OLMAT as a HHF facility for LM PFC testing and development



Thermocouples
Vfloating and Isat.
Langmuir probes

Mirror

16-channel
photomultiplier array
Sn, Halfa filter

CMOS-based
spectrometer
Spectra from 236
to 812 nm

Fast camera
Sn, Halfa filter
IR camera

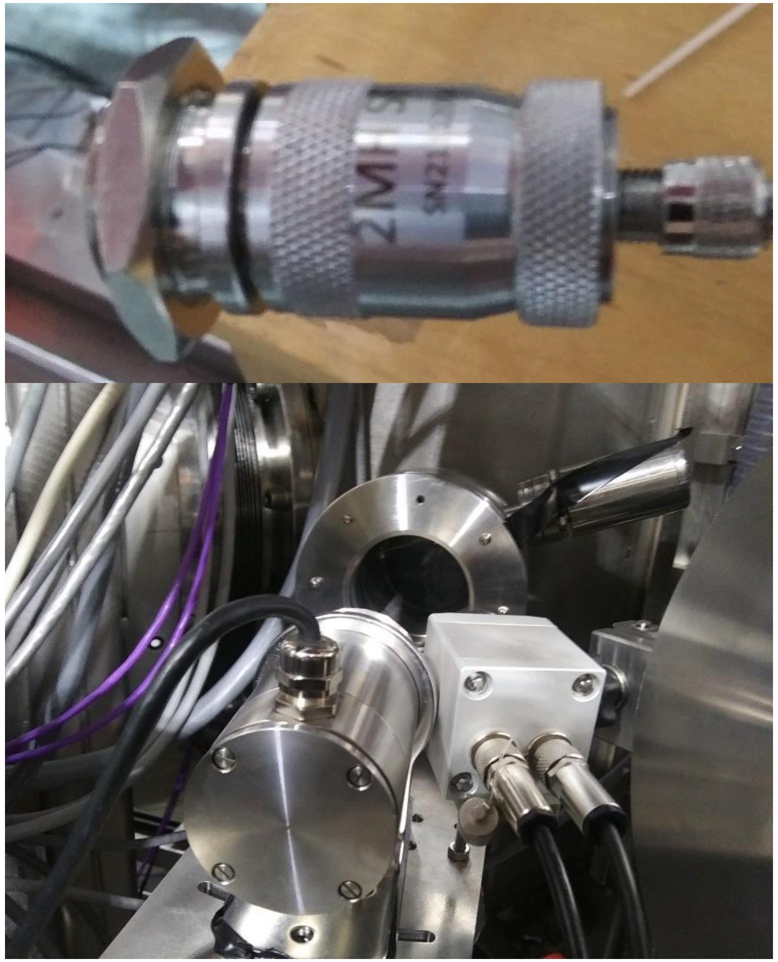
Pyrometers
(abs calibration to TC)

# OLMAT as a HHF facility for LM PFC testing and development

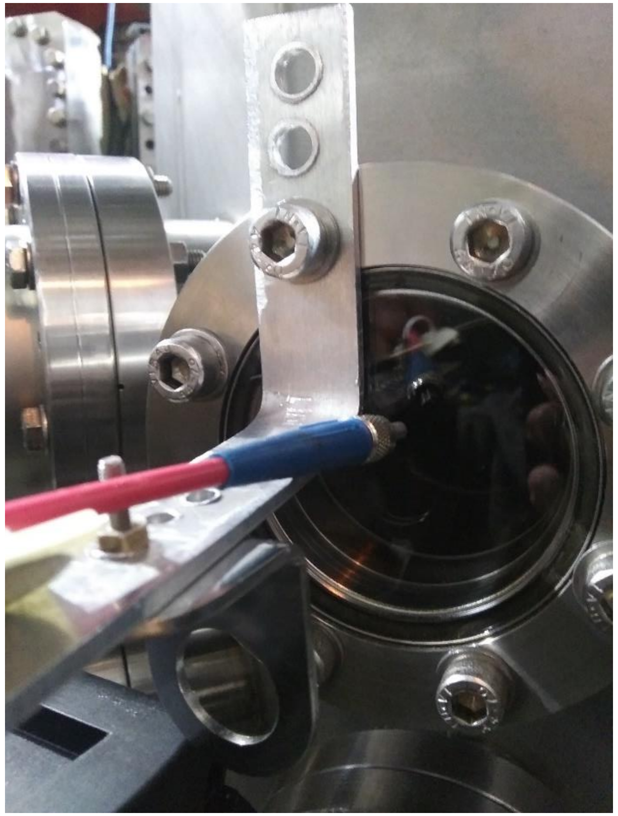
16-channel Sn, Hα array


Compact fast camera

## Diagnostics



Pyrometers and IR camera



CMOS-based spectrometer
236-812 nm

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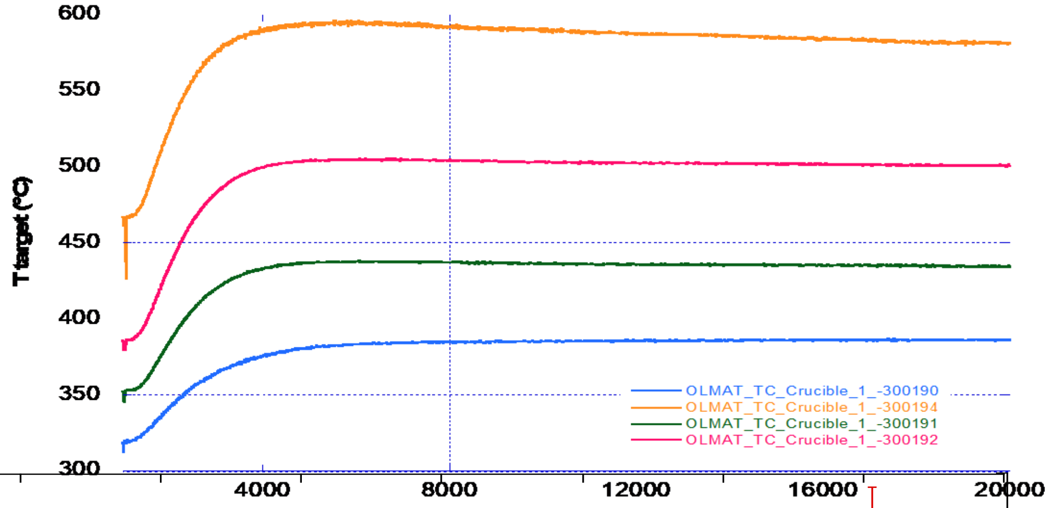
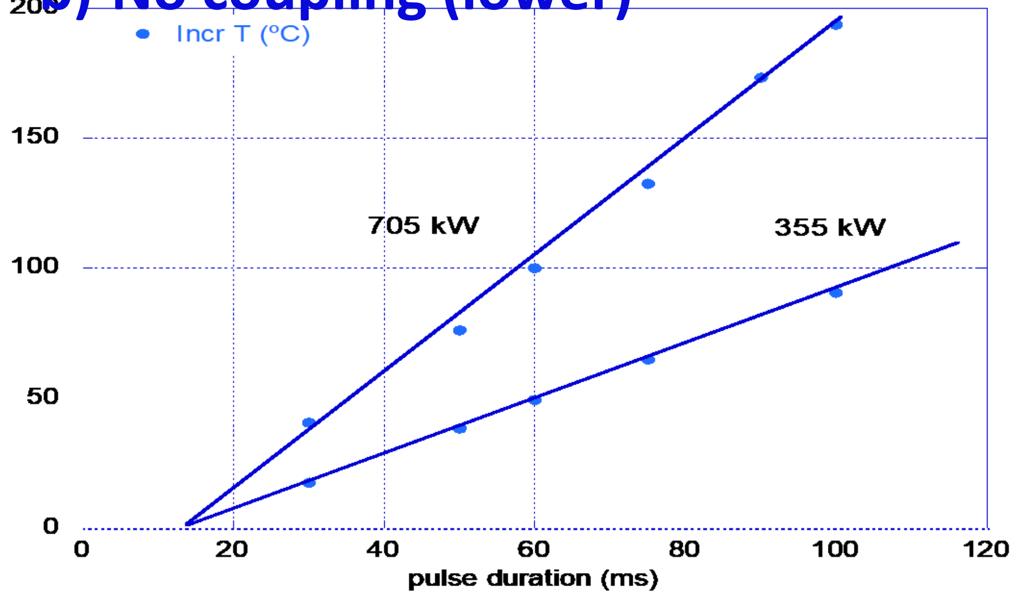
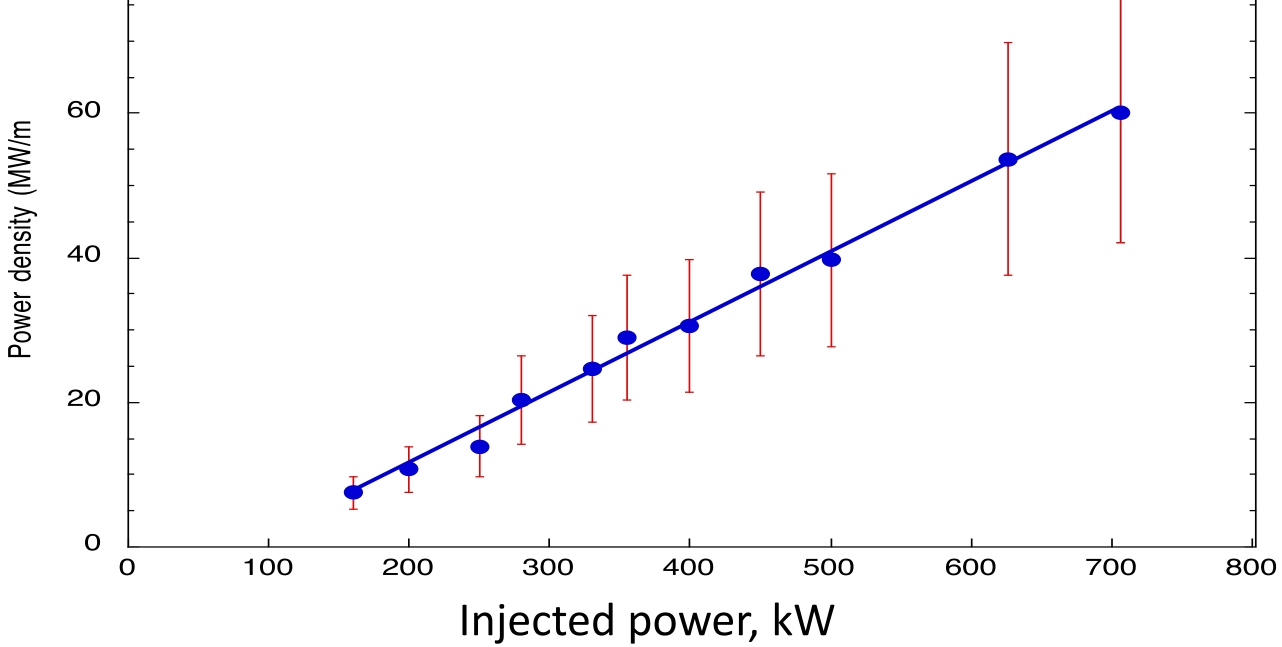
# Commissioning and first Sn CPS campaign

- Exposure of a 7mm thick TZM disk to increasing NBI powers and pulse time.
- Heat flux from calorimetry, TC and pyrometry (uncertainty in coupling between TZM and sample mask) :
  a) Full thermal coupling (upper)
  b) No coupling (lower)

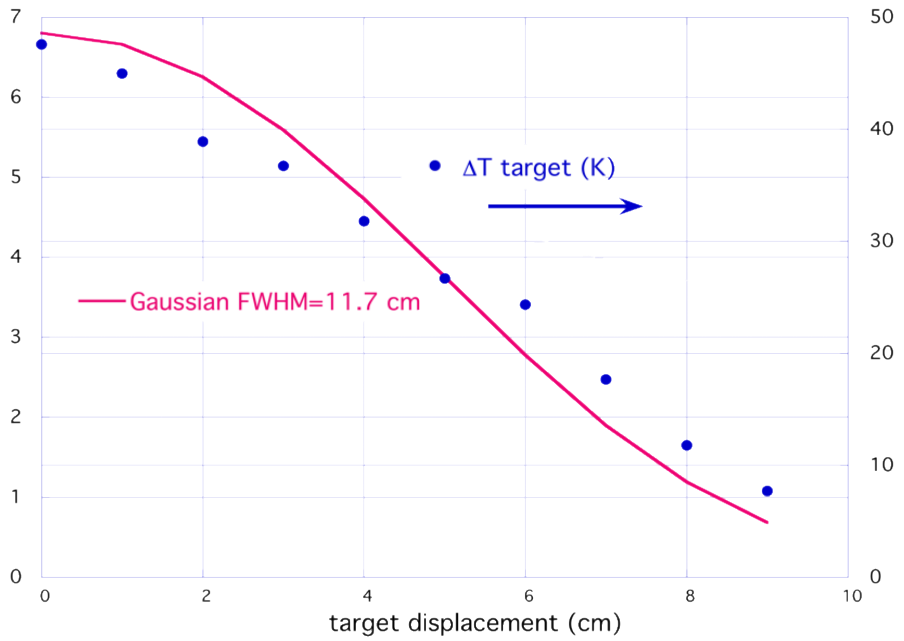


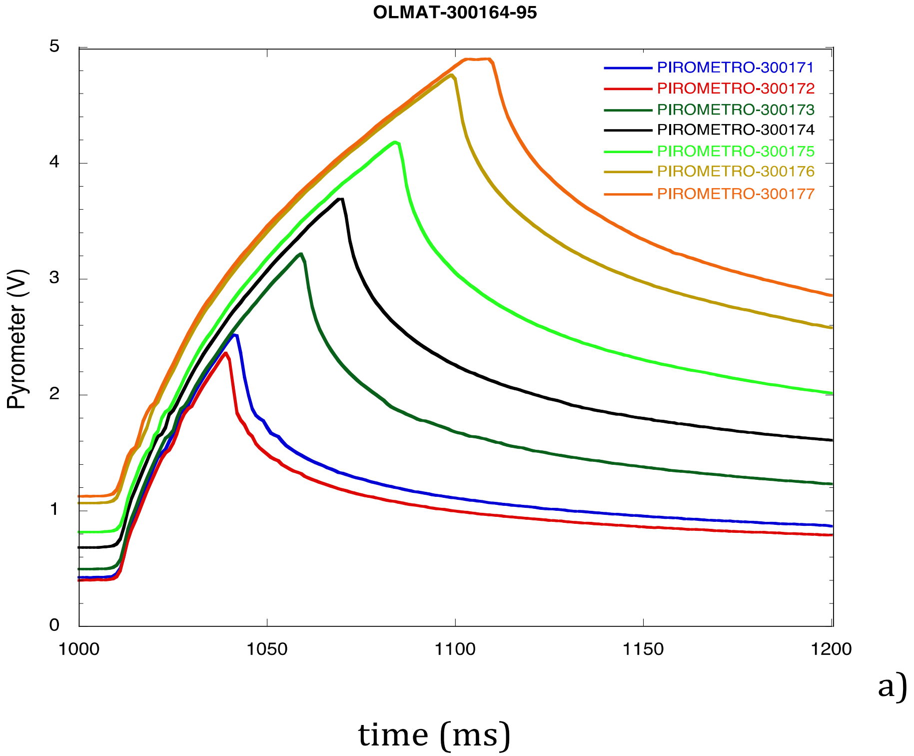



# Commissioning and first Sn CPS campaign

- **Spatial profile obtained by moving the target laterally:**



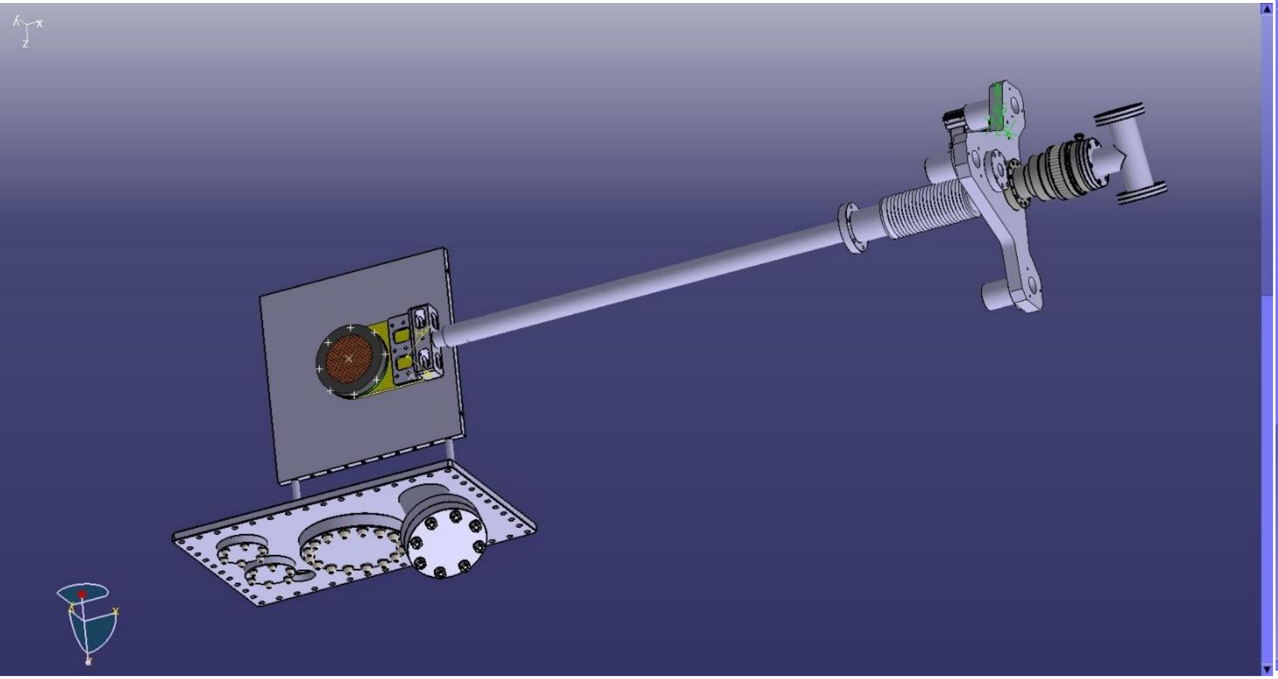

- **Slab Model ΔT vs sqrt (t) in agreement with global calorimetry**

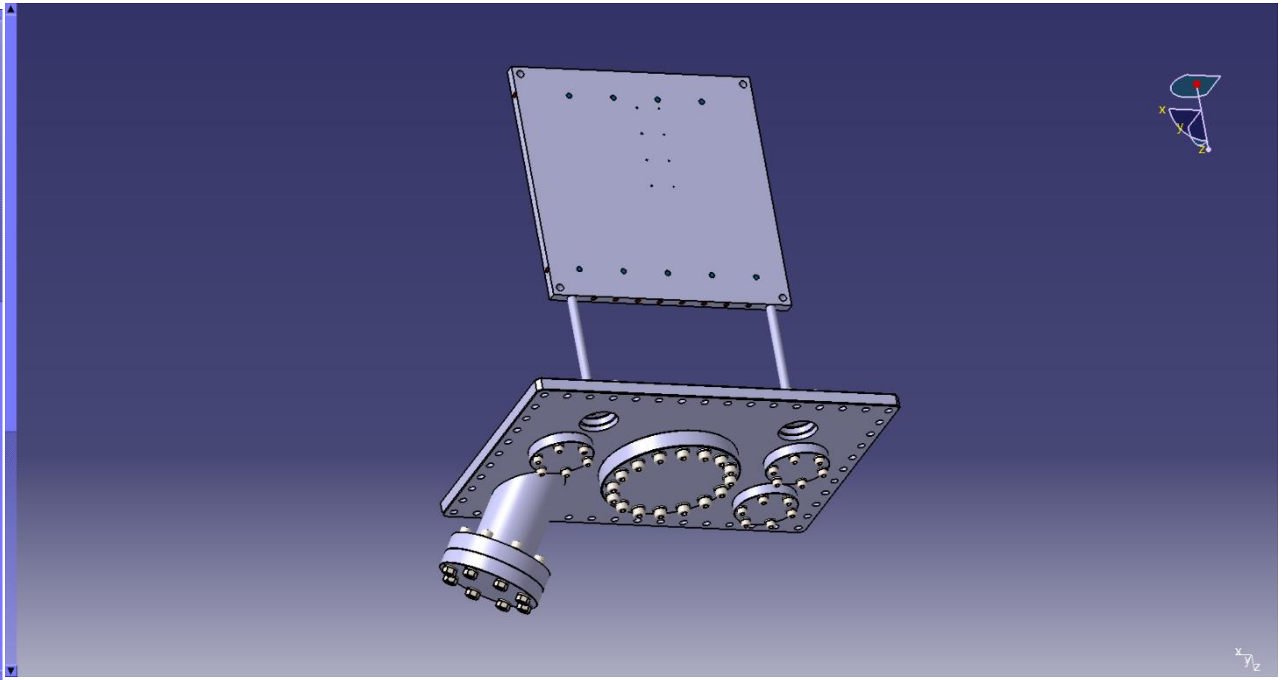



- **Future plans: More accurate calibration of the heat flux with adhoc target calorimeter**

# Target calorimeter

- Made of copper, actively cooled (water) and with multiple embedded thermocouples (backside). Dimensions: 280x280 mm.
- It will allow the measurement of the spatial distribution of the heat flux and the corroboration of the beam power densities. Will be also used for exposure of multiple advanced W samples and new generation LM plates
- Fabrication at CIEMAT machine shop ongoing and installation planned by 2023





# Commissioning and first Sn CPS campaign

**W meshes (CIEMAT):**

**pore size 150μm**

- **Central part damaged at heat load of 350 KW (20MW/m$^2$).**
- **No sufficient refilling during pulse**
- **Larger T increase due to non optimal thermal contact**

**W felt (ENEA): pore size 150μm**

- **Tin accumulation at bottom in W felt.**
- **Better thermal contact and response.**
- **Sufficient tin refilling**
- **Notorious ΔT and evaporation beyond 350 KW**

**Full details in next talk by E. Oyarzábal**

- **Sintered W (DIFFER): pore size <1 mm**
  **A crack is formed at 275 KW ( 15MW/m$^2$).**
- **Higher temperatures and larger Sn evaporation from this area**
- **Small defect present in this area before the experiments**

**3D printed W (DIFFER): 100 nm pore size**

- **No dropping or Sn accumulation**
- **No visible damage after exposure (up to 60 MW/m2.**
- **Thermal sputtering and vapor shielding onset studies**

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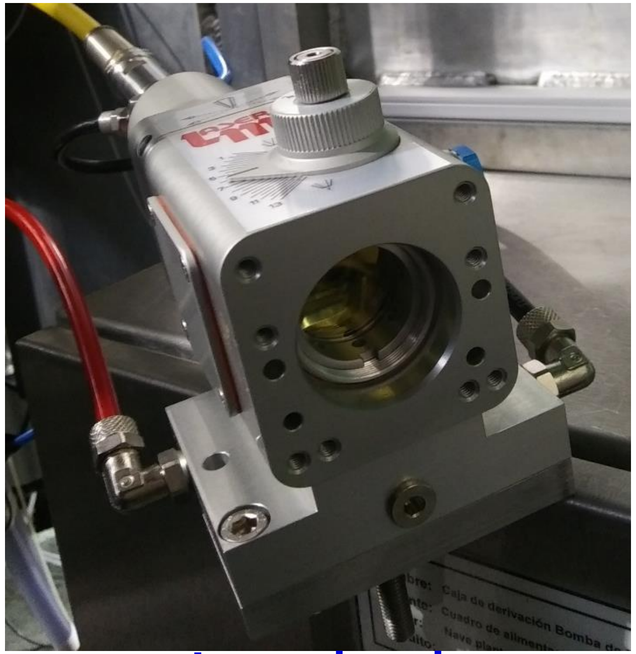
# CW laser for steady state/transient loading simulation

- **Constant wave (CW) laser able to be operated in pulsed and mode**
- ***Power*: 930 W continuous; 9300 W pulsed**
- ***Spot*: from 333 µm. But much larger will be usual for relevant power densities (ø = 8mm for 20 MW/m$^2$)**
  - Possible spot of 0.2x25 mm by a cylindrical lens: strike point simulation in continuous operation

## Continuous mode

- Technical issues with optical windows to be solved
- **ITER (or DEMO) like pulses:**
  - 10 MW/m$^2$ in 0.93 cm$^2$ area.
  - 400s pulses, Or shorter, just when steady state is reached (few s).
- **Reattachment (continuous mode)**:
  - 20-70 MW/m$^2$ (or larger) in 0.45-0.13 cm$^2$ area.
  - OLMAT reach 60 MW/m$^2$. Synergies laser+beam?



**Laser head**

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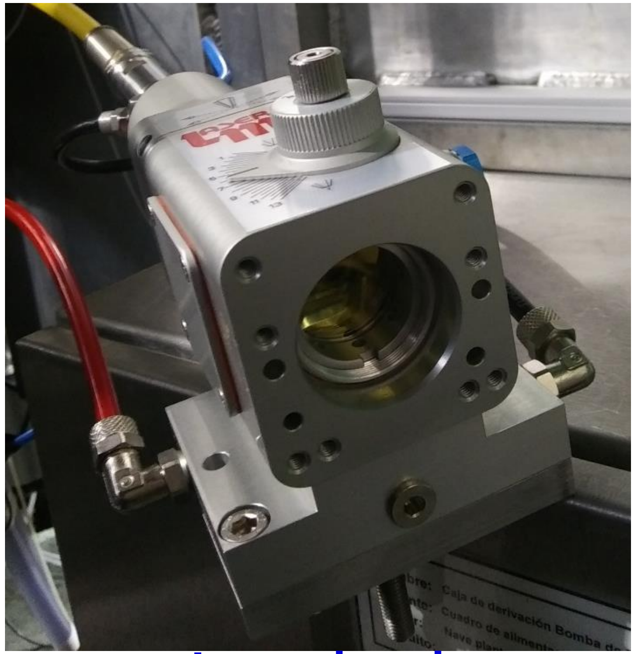
## Pulsed mode

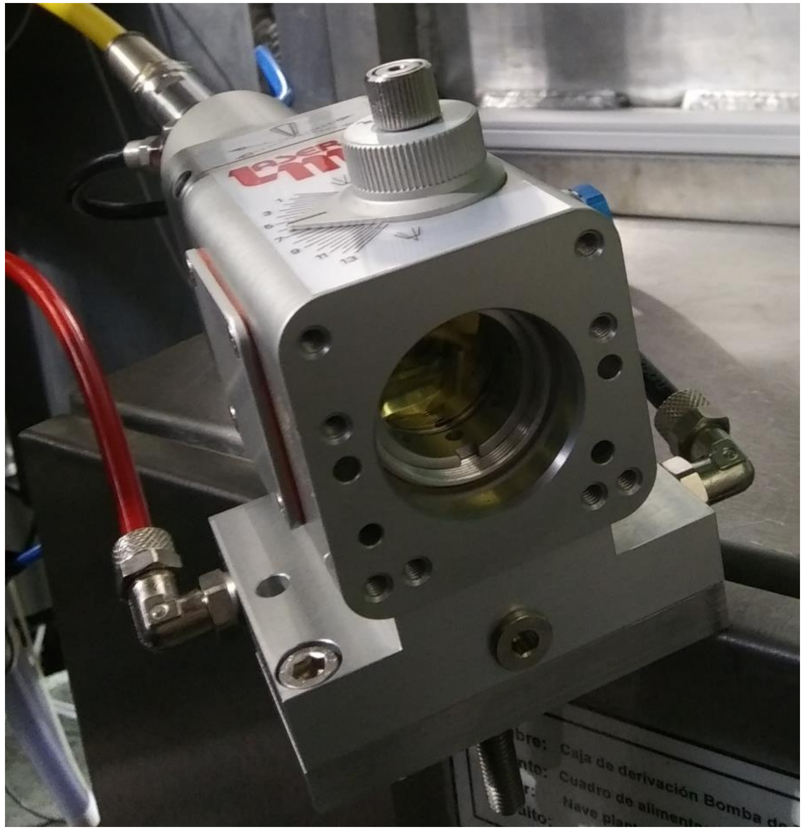
- **Pulse duration in range with typical instabilities (0.2-10 ms; 90J energy; 10-2000 Hz**
- **Mitigated (or type III) ELMs**:
  - 10 MW/m$^2$ in 3.7 cm$^2$ area. Quite large!
  - 2000 Hz. In the order of type III ELMs? Quite important fatigue
- **Disruptions**:
  - 1-10 GW/m$^2$ in 0.4-4.7 mm$^2$ area (0.7-2.2 mm spot).

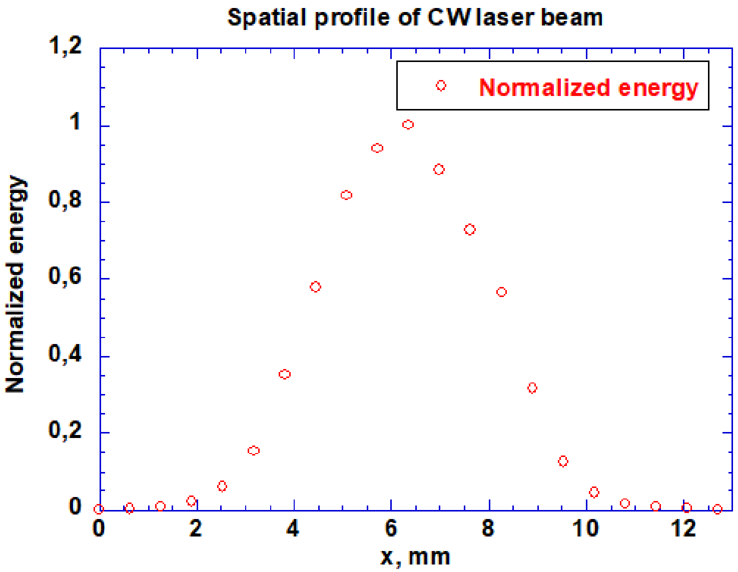


Laser head

# CW laser for steady state/transient loading simulation

- Installation completed
- Spot characterized and energetic characteristics of the pulse measured:
- dspot ≈10 mm at 13 cm after focusing with lens of f=250 mm. FWHM≈ 4,25 mm
- Basic characterization for extrapolation of more focused spots for transient loads simulation
- Starting operation in 2023 spring after completing security issues






FWHM=4,25 mm
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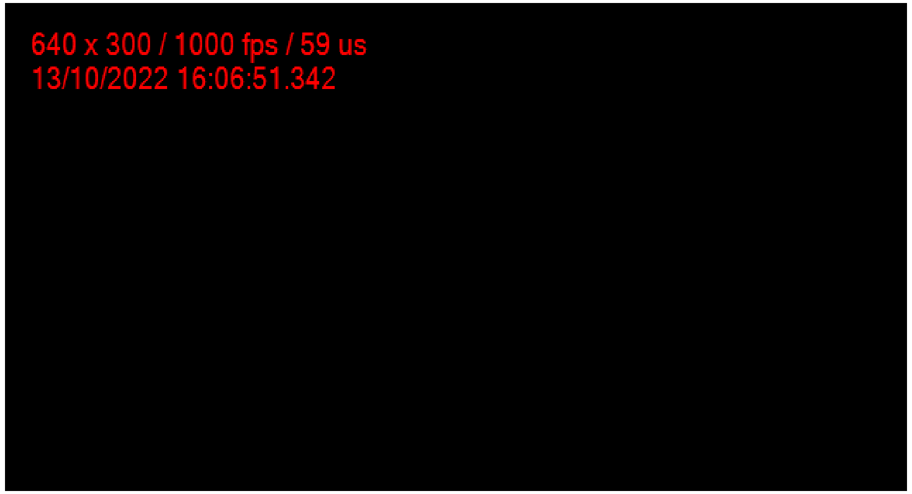
# Fall 2022 Experimental campaign

- Installation and operation of a Langmuir probe based target
- TZM target with isolated W tip attached at center
- Successful operation at progressively increasing energies and pulse duration: 100-730 kW, 50-100 ms
- Probe tip partially damaged/melted at highest power loads, still working and collecting I-V data though
- Results and probe interpretation affected by strong thermoionic emission at high power densities
- Extrapolation of the methodology to LM CPS targets. Challenging technical and interpretation issues
- Improvements: divertor like planar probes, data fitting, compensation of thermoionic effects



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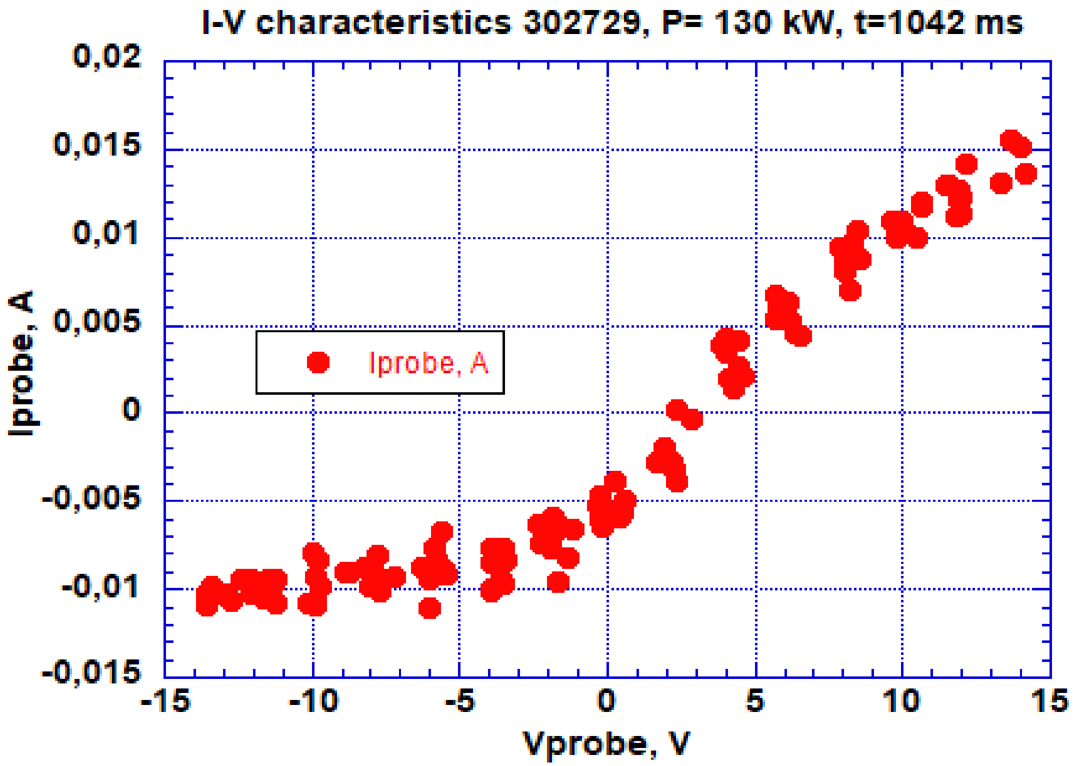

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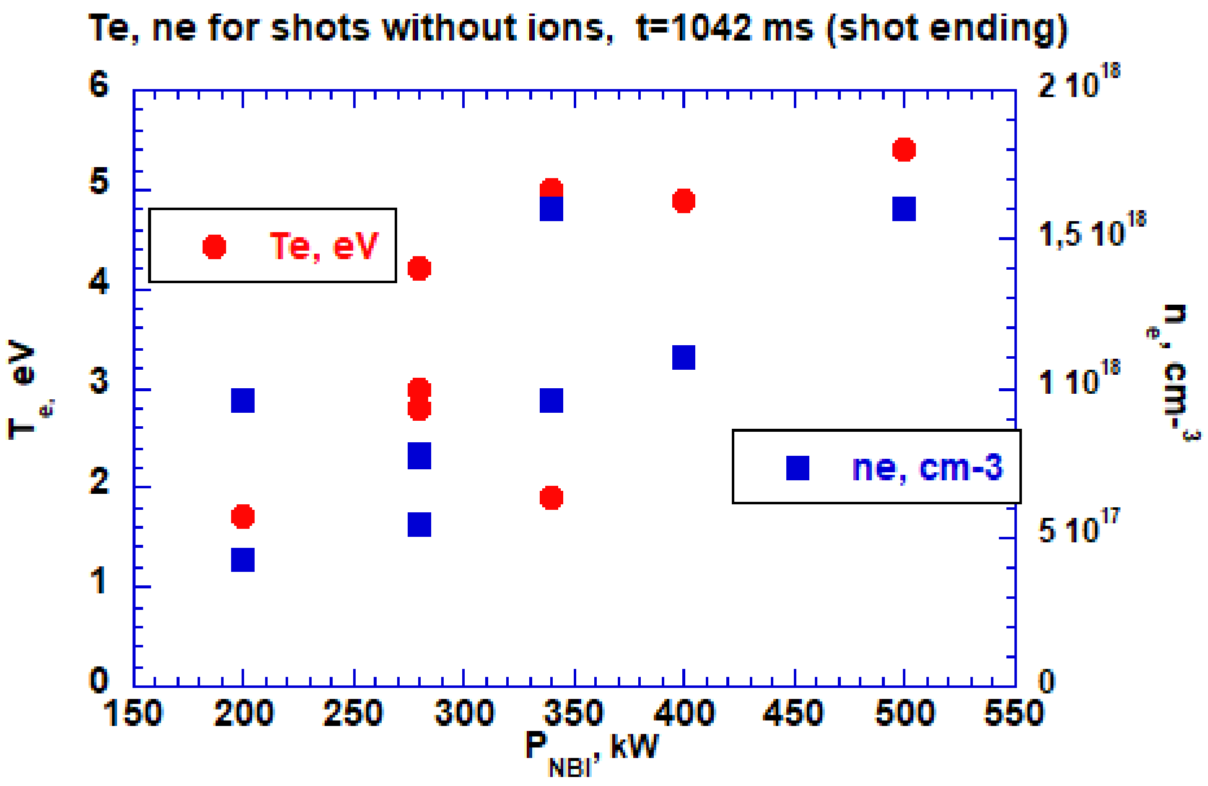

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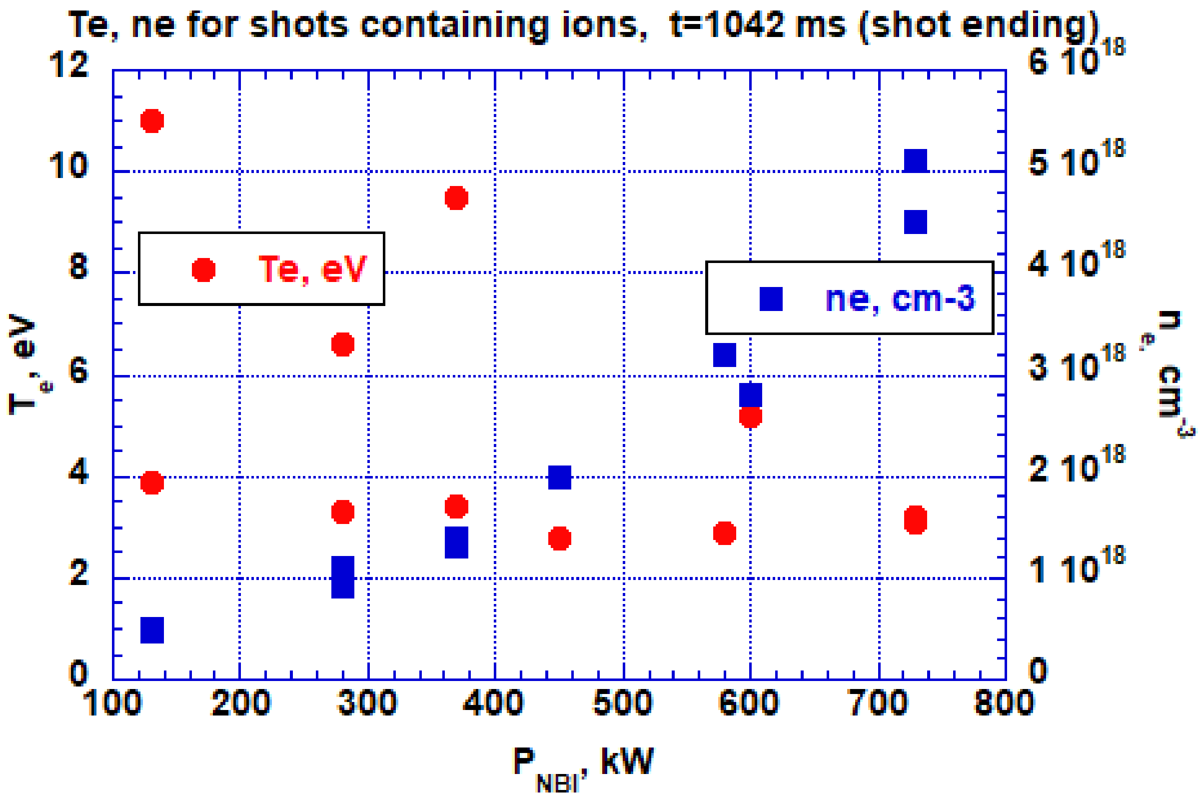

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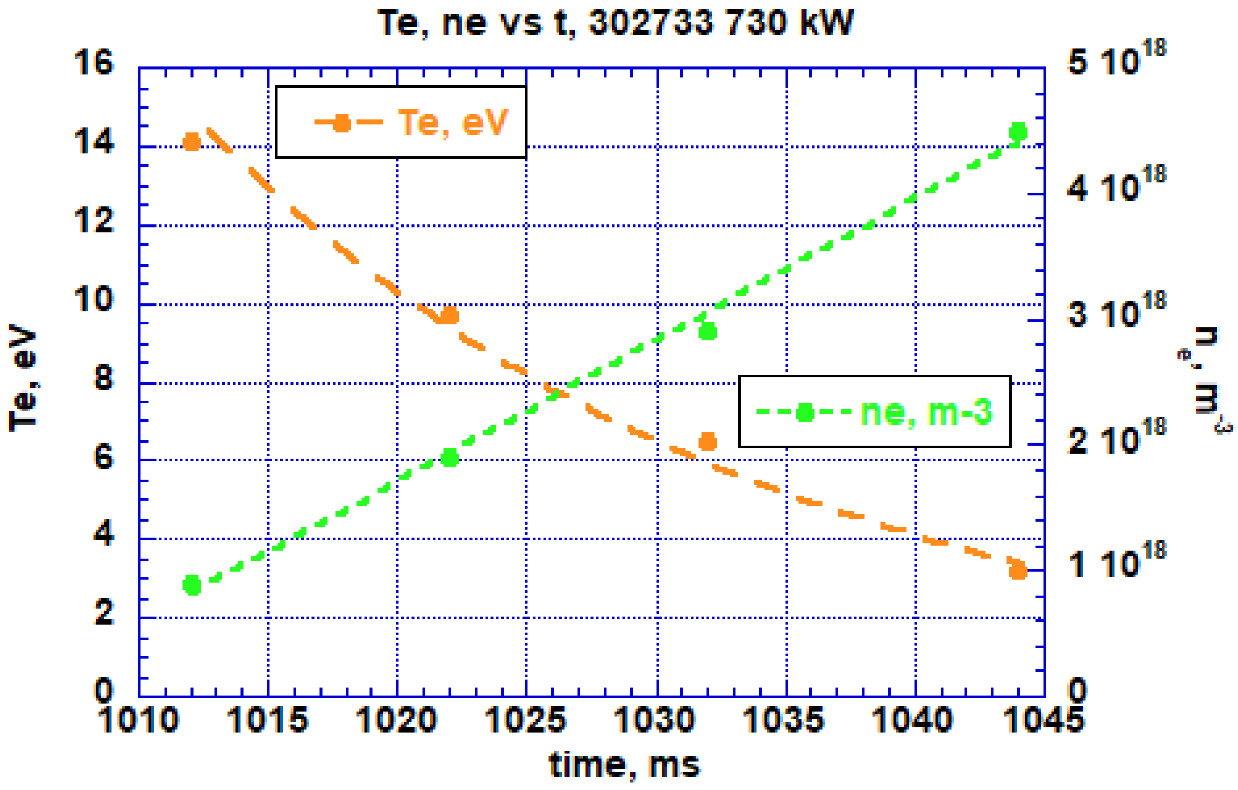


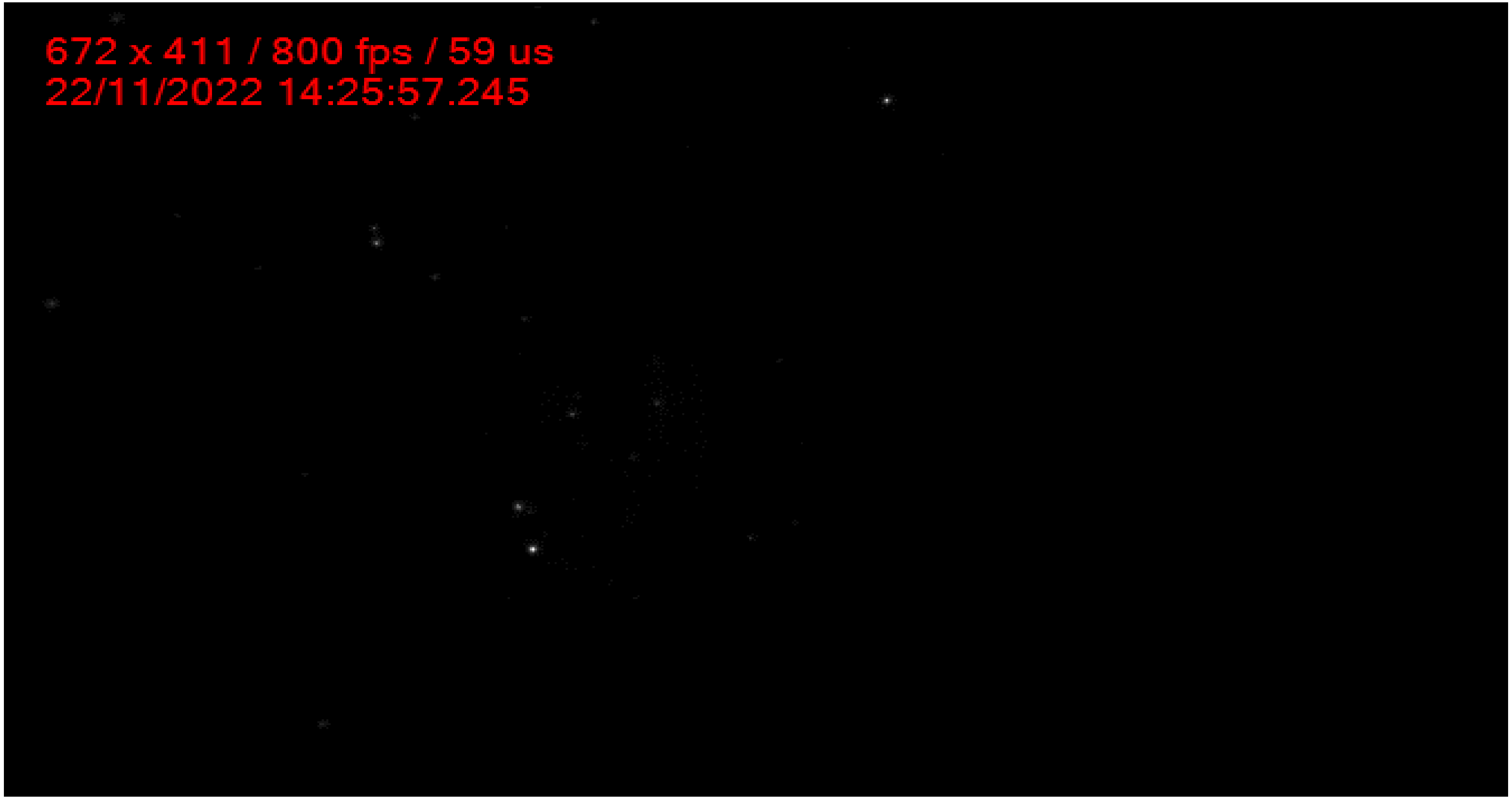
# Fall 2022 Experimental campaign

- Testing of 3D printed W-Sn CPS prototype (Asdex Upgrade mock up). 32 mm diameter CPS, TZM mask. Pore size 8 um, 37% porosity
- Fabricated at Differ. Wetting at CIEMAT
- Exposition at progressively increasing energies and pulse duration: 100-730 kW, 50-100 ms.
- Testing of new compact fast camera and IR cameras
- Exposed to 2 sequences of 50 discharges (10 MW/m2, 100 ms, 0,67 $min^{-1}$).
- Then 32 consecutive shots with maximum power (50-60 MW/m2, 100 ms)
- Vapor shielding onset and resilience to dryout studies

**Thin tin slices placed for wetting**
**T≈1150ºC, 3 min**
**p~5-200 mTorr**
**Heating ramp: 100 min**
**Cooling time: 24 h**

**Sliding of Sn excess at CPS surface/edges**
**Fully wetted surface, oxide layer cleaned shot by shot**

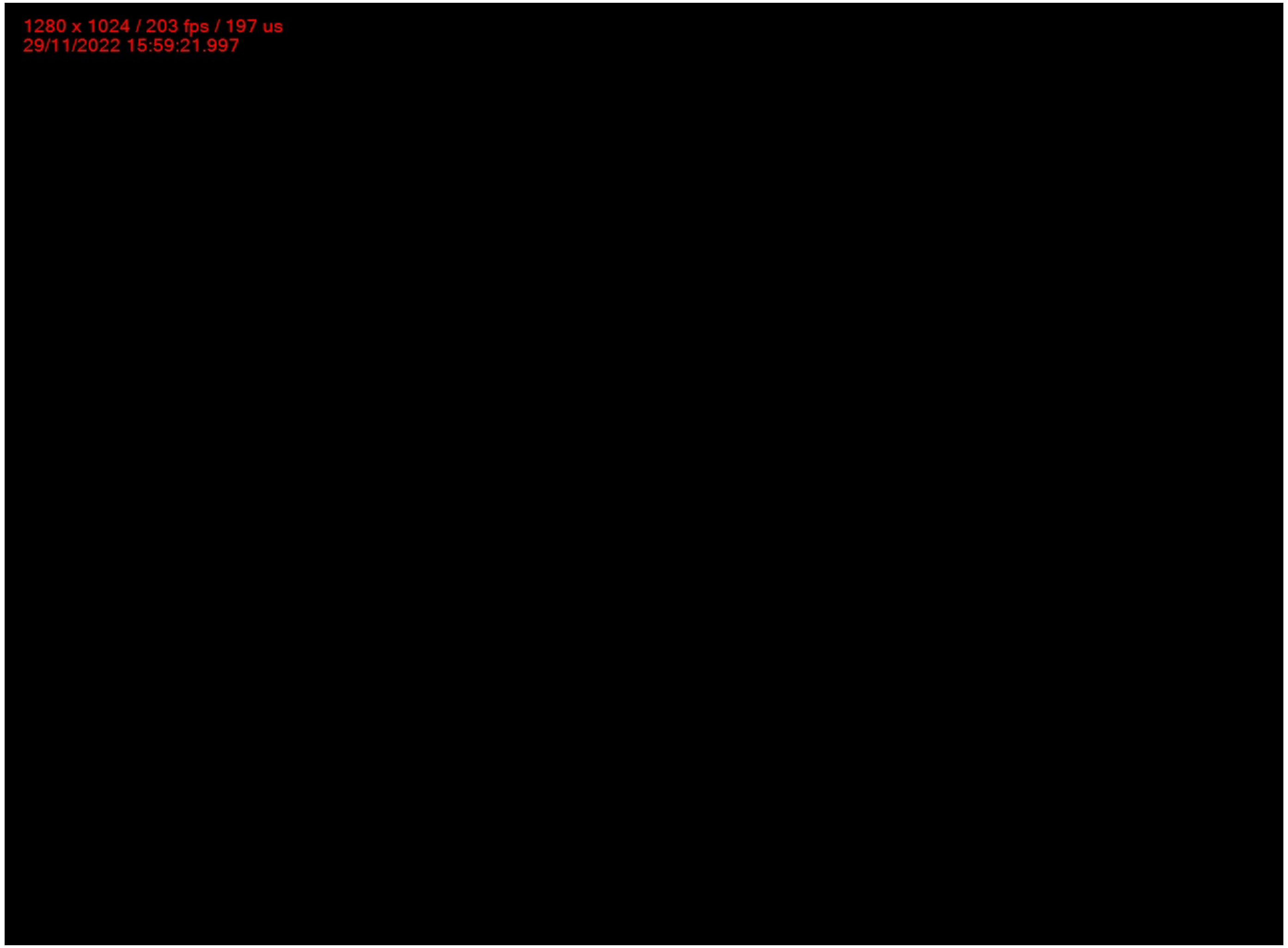
# Fall 2022 Experimental campaign




➢ **Sliding and dropping of Sn excess from CPS surface**

# Fall 2022 Experimental campaign

- Testing of 3D printed W-Sn CPS prototype (Asdex Upgrade mock up). 32 mm diameter CPS surrounded by TZM mask
- Fabricated at Differ and wetted at CIEMAT
- 32 consecutive shots with maximum power (50-60 MW/m2, 100 ms)
- Vapor shielding onset and resilience to dryout studies
- Release of particles from CPS surfaces (mm size range) after several shots at maximum power
- **Video collected with fast camera+Sn filter at tangential orientation**



# Fall 2022 Experimental campaign

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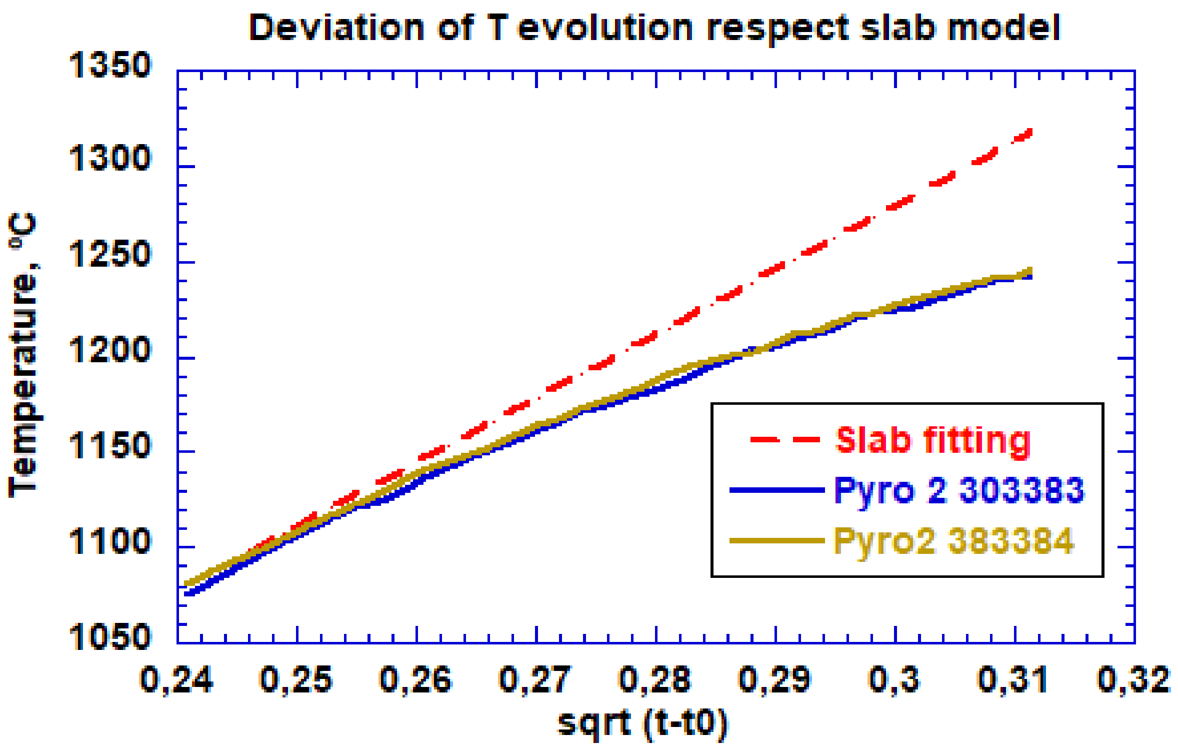
- 60 MW/m2 shots at same initial Ttarget show a 100% reproducible thermal response (303383 and 303384)
- Effect of window metalization in T measure may be neglected
- Damping of Tincrease not fully explained by vaporization latent heat
- **Vapor shielding onset starting beyond 1200ºC**



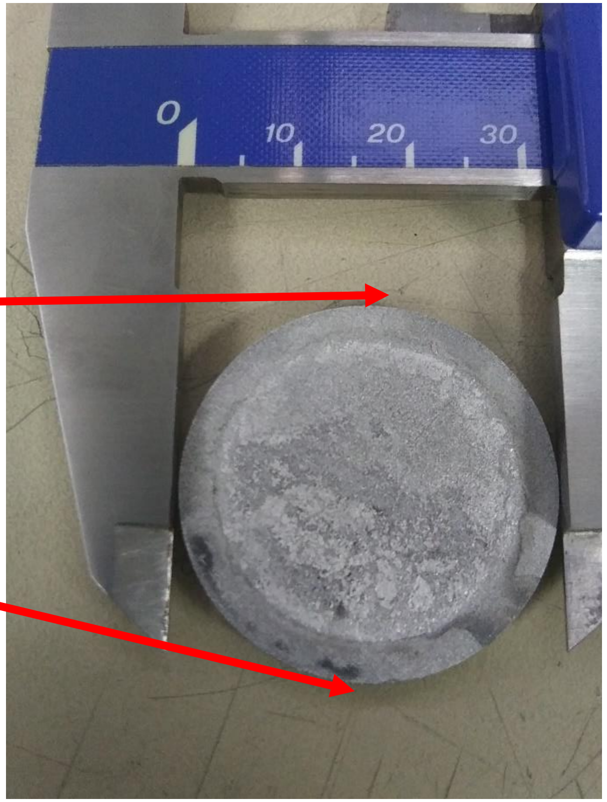

$\Delta Q = Q_{slab}\ (\Delta T_{slab})$-Qreal $(\Delta T_{real})$

$\Delta Q = Q_{vap} + Q_{black\ body} + Q_{vsh}$

Damping of Trise not fully explained by vaporization. Role of Sn radiation/shielding

# Fall 2022 Experimental campaign

- 3D printed W-Sn CPS prototype (Asdex Upgrade mock up). D= 32 mm diameter (TZM mask).
- Pore size 8 um, 37% porosity. Resilience to dryout for W-Sn 3D CPS at 60 $MW/m^2$




- Clear signs of tin redeposition/coverage along the target (anular masks)
- Irregular Sn layer on CPS surface after repetitive exposition to 50-60 $MW/m^2$

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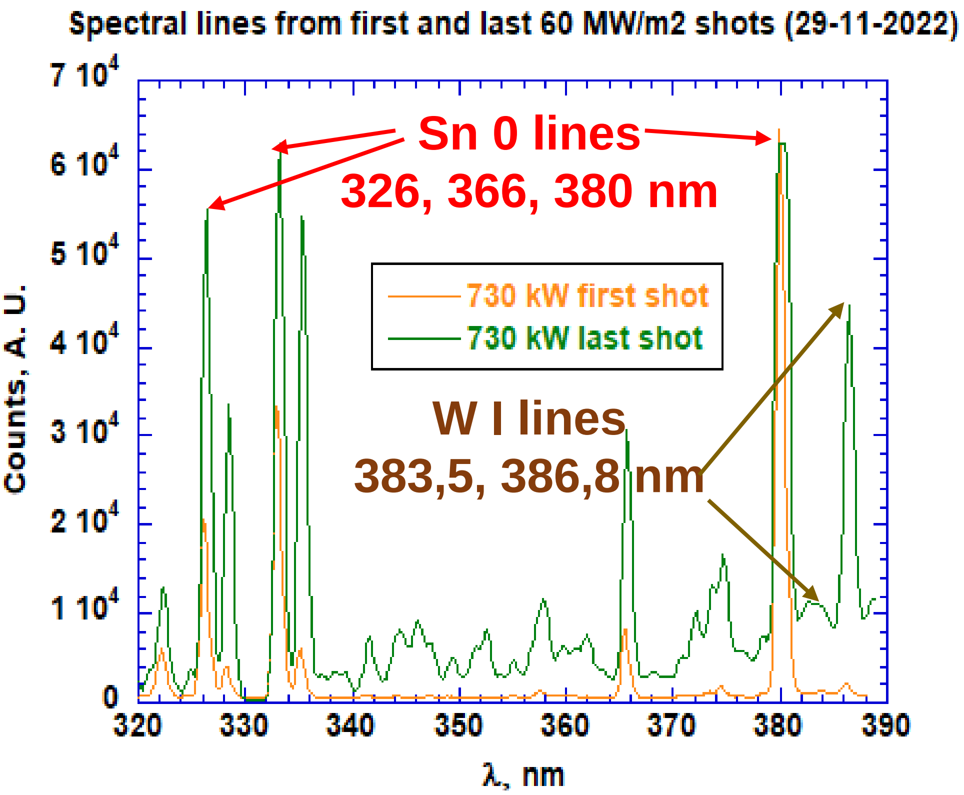


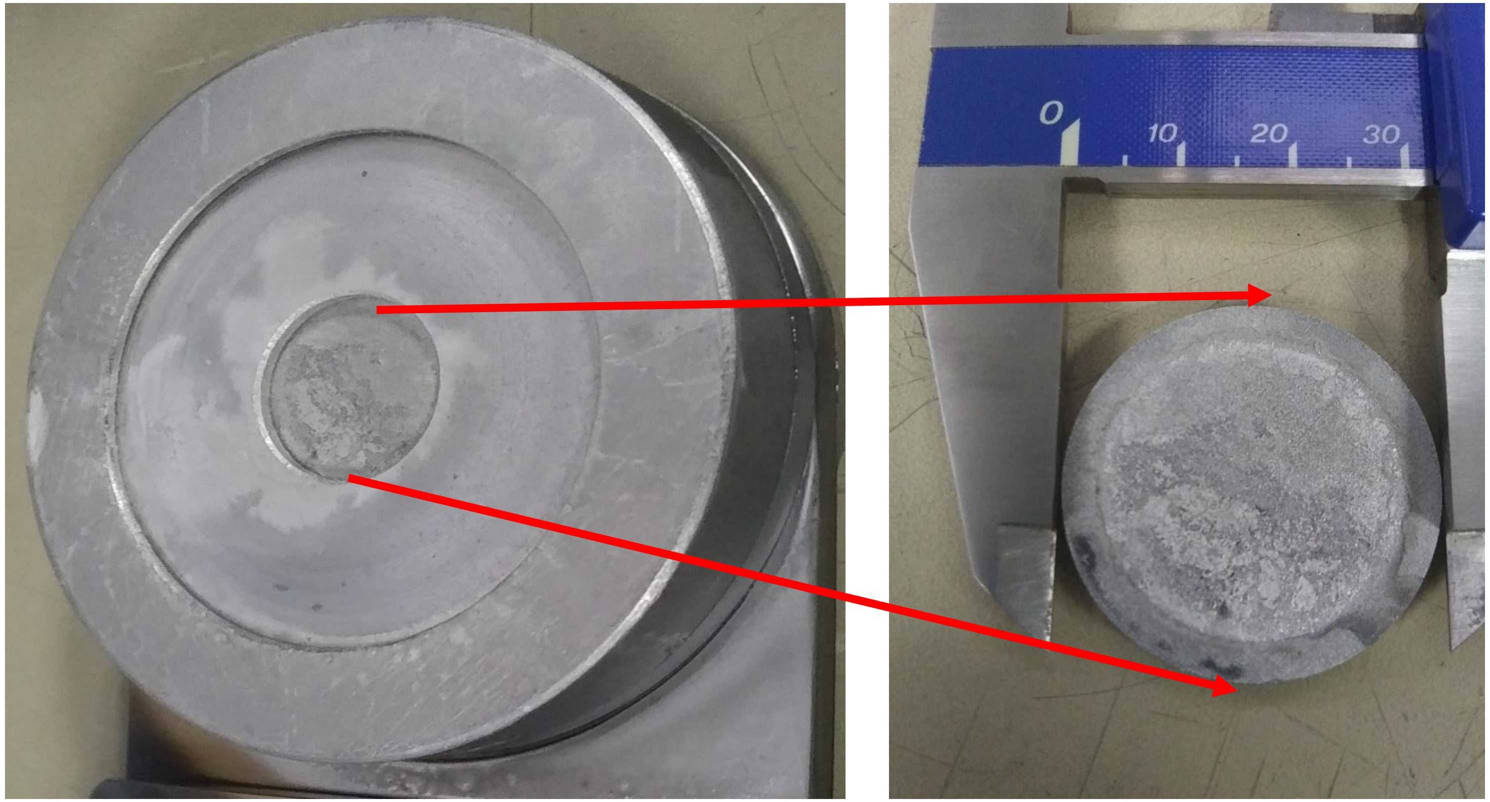


- Sn emission in both shots and appreciable W I line (386,8 nm) after 27 consecutive 60 $MW/m^2$ shots
- Liquid Sn layer progressively evaporated/eroded and eventual W surface exposition

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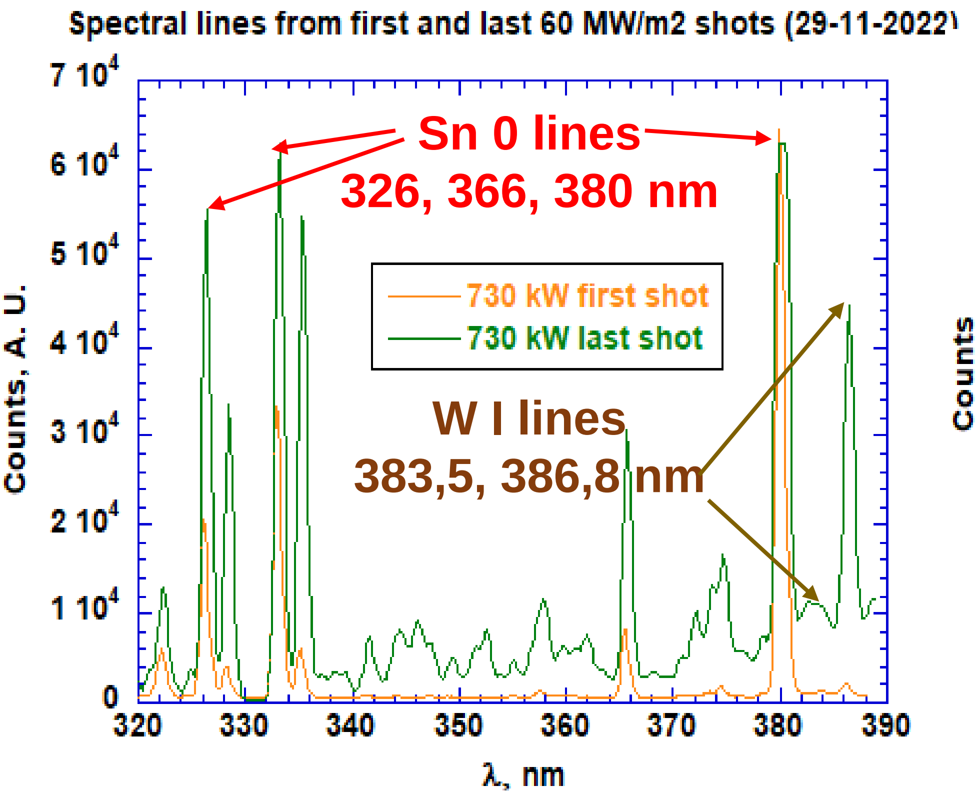
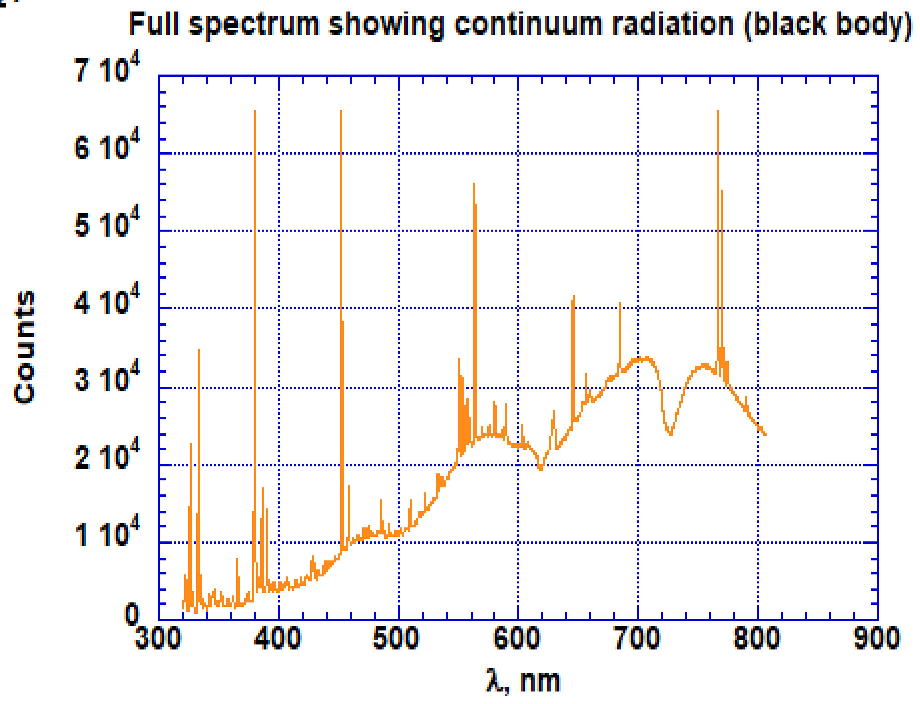
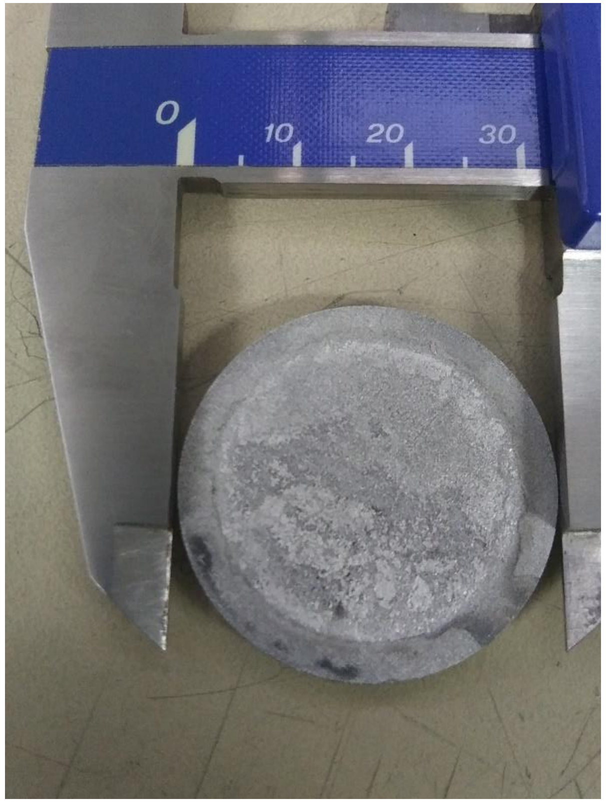


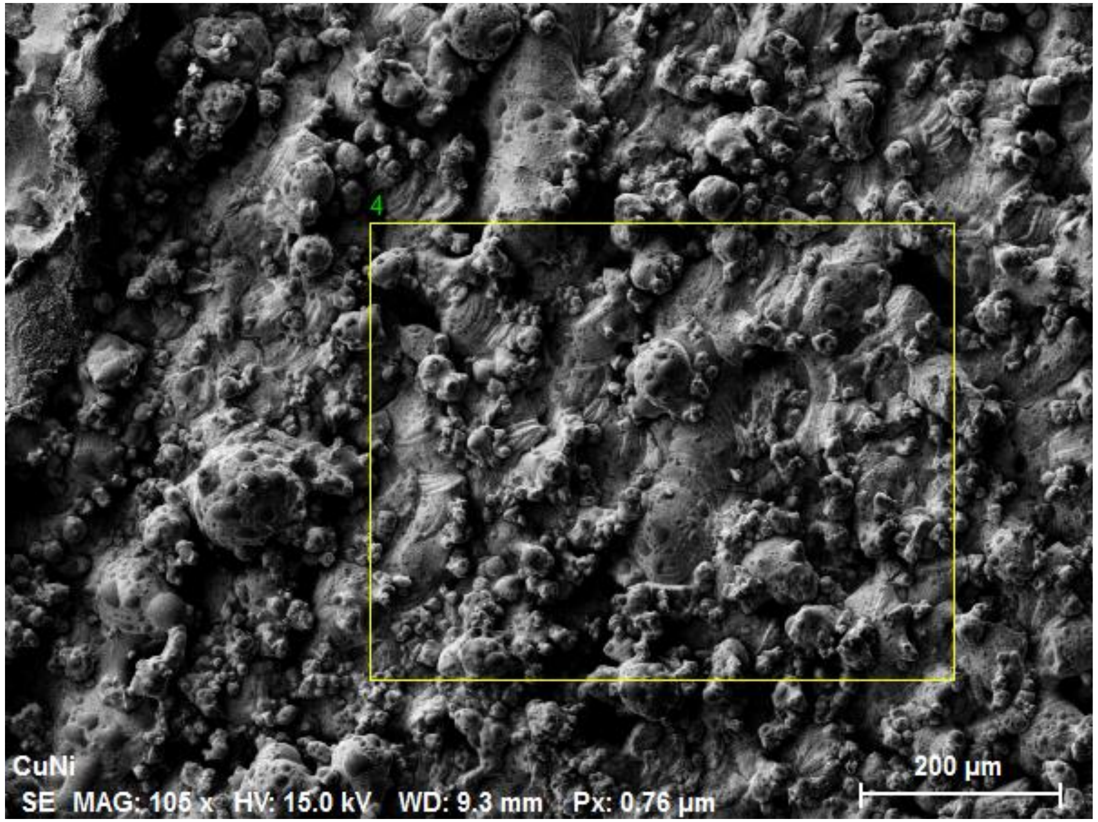



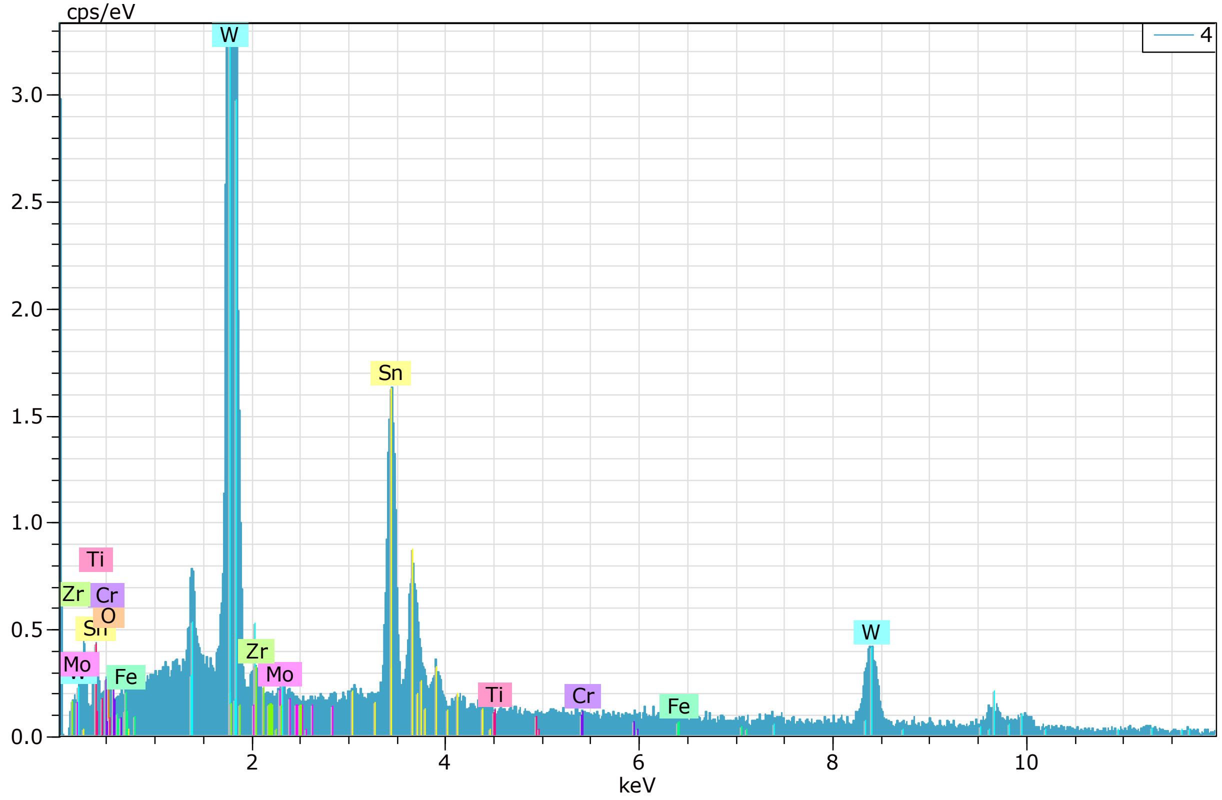



- Sn emission in both shots and appreciable W I line (386,8 nm) after 27 consecutive 60 MW/m$^2$ shots.
- Black body radiation fitting estimates 1300ºC on target surface. Local hotspots on exposed W areas?

# Fall 2022 Experimental campaign

- 3D printed W-Sn CPS prototype (Asdex Upgrade mock up). D= 32 mm diameter (TZM mask)
- Resilience to dryout for W-Sn 3D CPS. 32 consecutive shots 60 MW/m2, 100 ms
- Post-mortem investigation, SEM-EDX on 3D W surface (non exposed annular boundary)




- Irregular surface containing pores and W granules. EDX shows Sn presence (spread/redeposition) and traces of Zr and Mo. Global wt. composition: 80,5% W, 13 % Sn, 2,1% Zr, 1 % O, 0,6% Mo

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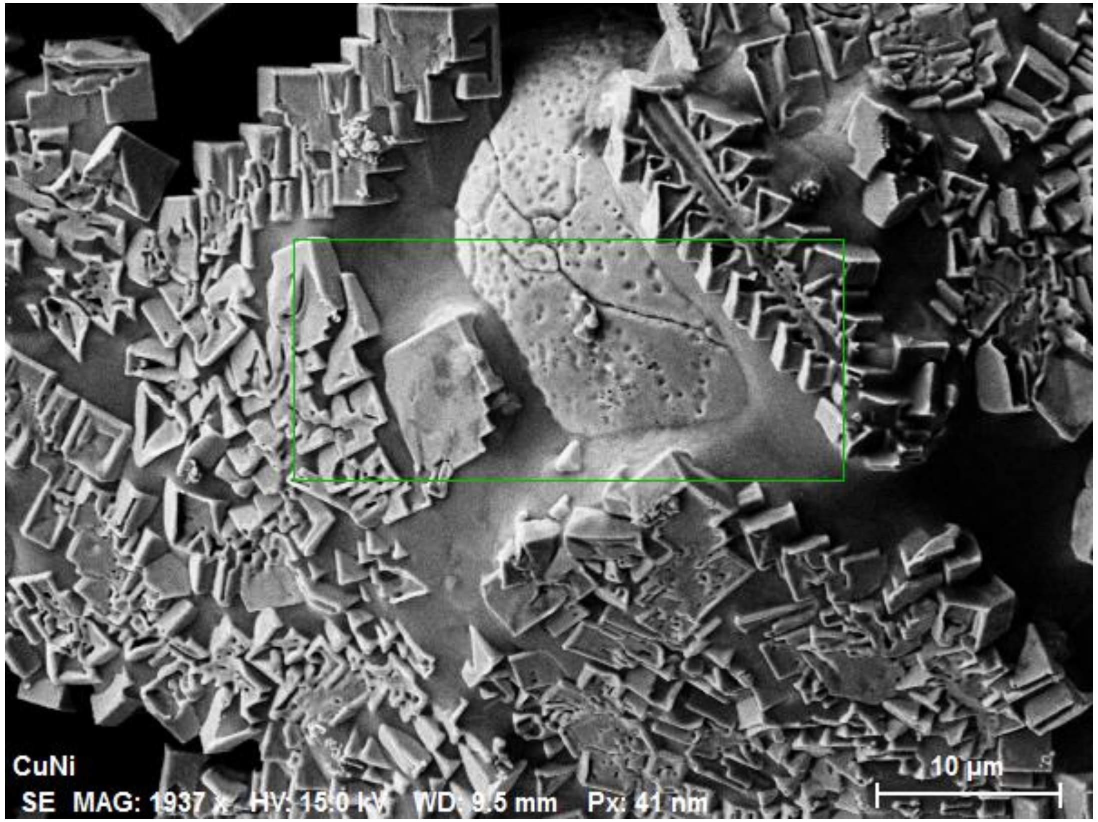
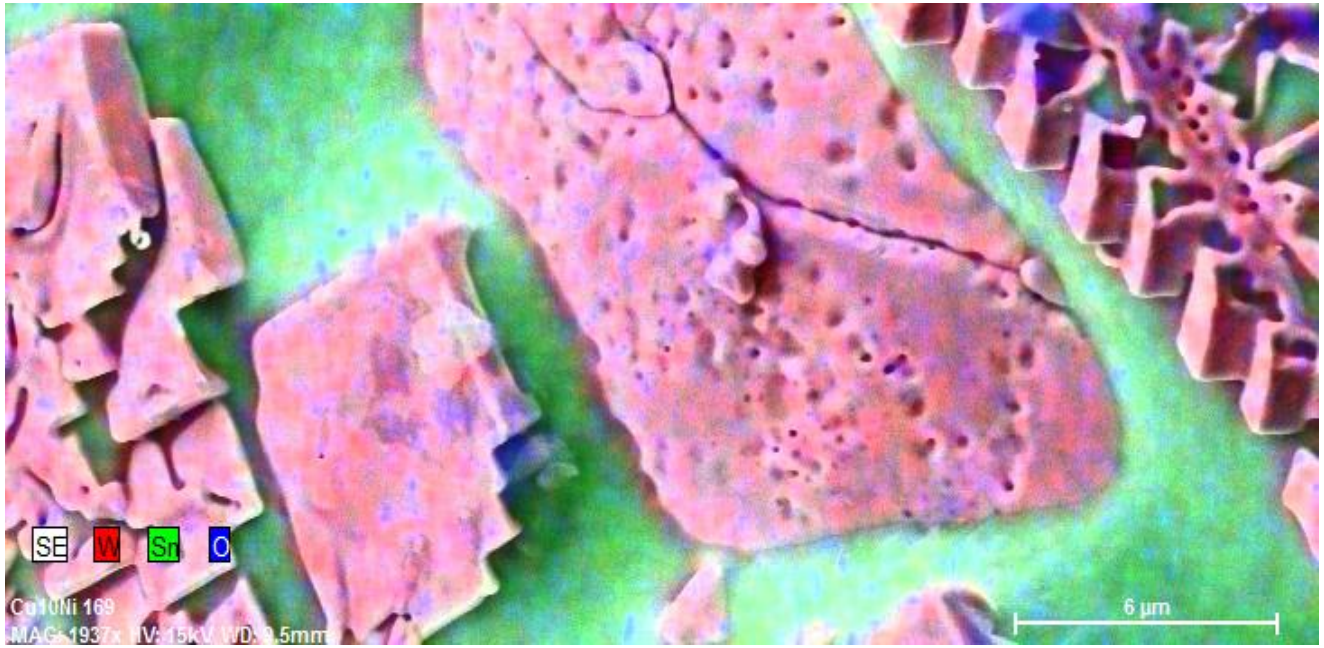
- Resilience to dryout for W-Sn 3D CPS. 32 consecutive shots 60 MW/m2, 100 ms
- Post-mortem investigation, SEM-EDX on Sn-W exposed CPS surface




2D mapping showing W, Sn and O contents




- Irregular surface containing remaining Sn layers and uncovered W matrix.
- Signs of partial W recrystalization that changed the original porous structure of the matrix.

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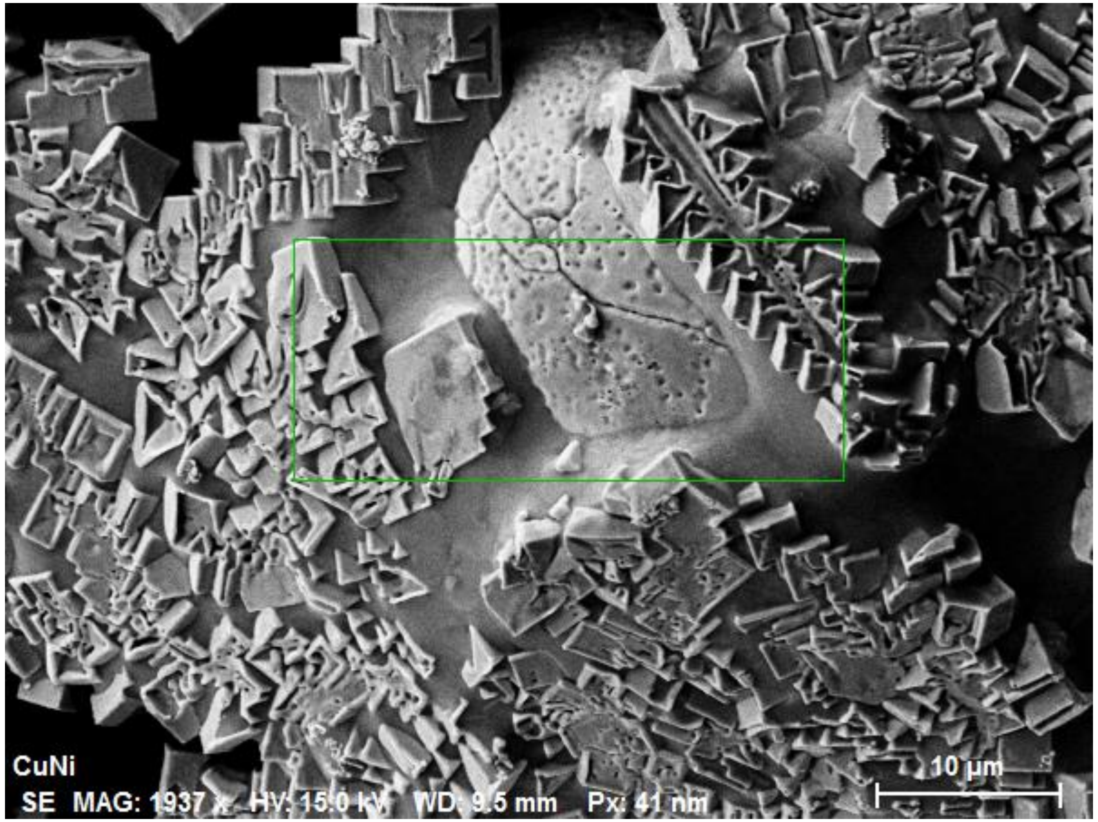


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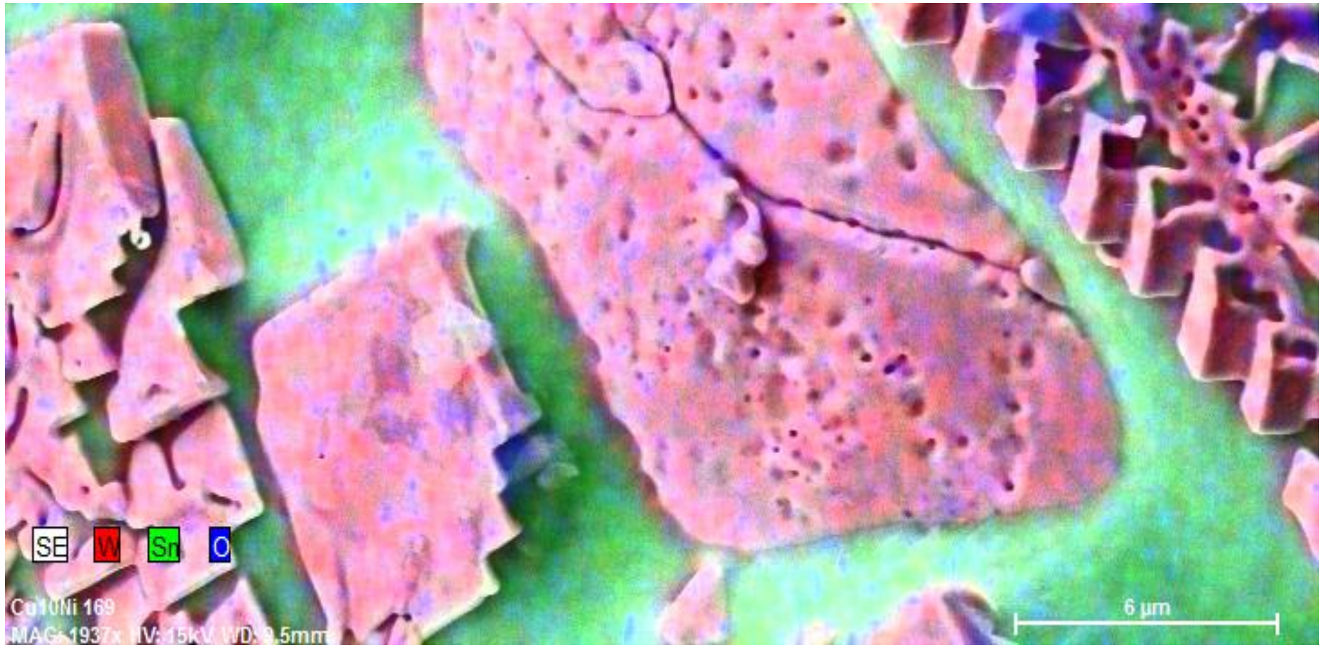


- Irregular surface containing remaining Sn layers and uncovered W matrix.
- W recrystallization happening around 1000ºC for severerly damaged W and 1550ºC for cold rolled W

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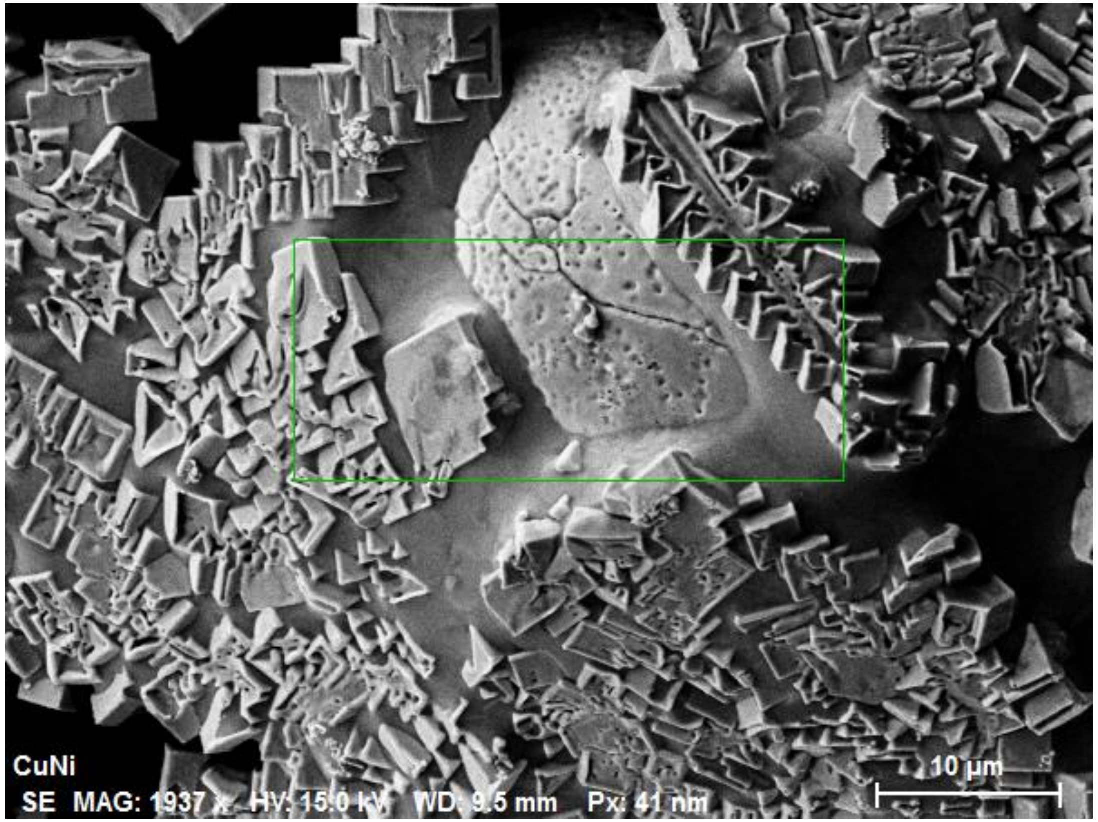


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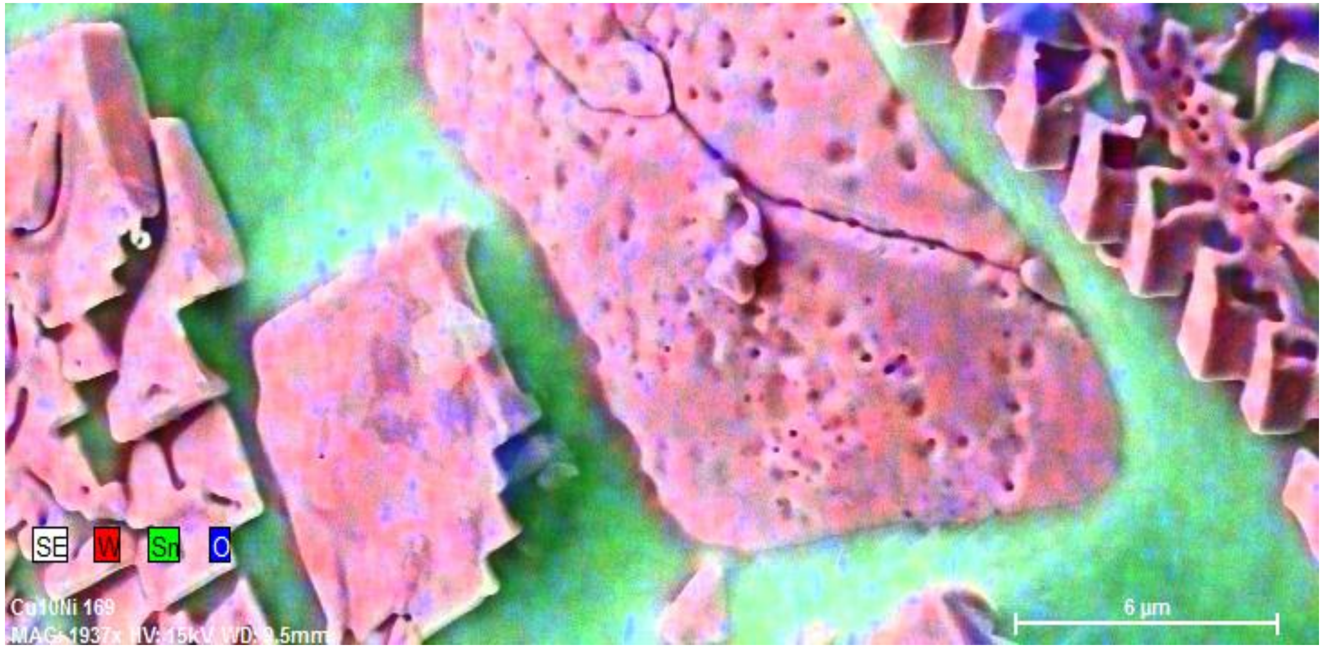


- Irregular surface containing remaining Sn layers and uncovered W matrix.
- **Sn dryout and damage of W matrix:** non sufficient LM reservoir/refilling (Sn shortage/slow refill?)

# Outline

- Motivation
- OLMAT as a HHF facility for LM PFC testing and development
- Commissioning and first campaign Sn CPS campaign
- CW laser for steady state/transient loading simulation
- Fall 2022 campaign
  - Target embedded Langmuir probe
  - 3D Sn-W CPS Asdex Upgrade mockup
- Summary and future works

# Summary and future works

- The OLMAT HHF facility has been commissioned and is fully operative for the research and development of LM PFCs. Relevant testbed for alternative PFC selection and validation
- Different W-Sn CPS designs have been tested with the goal of selecting the most encouraging designs for future divertor prototypes
- Physics phenomena as vapor shielding onset, thermal sputtering and characterization of the plasma plume formation have been explored. Better diagnosis and analyses are underway
- High power CW Laser has been installed and manually operated. Complete operation scheduled by 2023 spring for transient load exposure

# Summary and future works

- LM technology/engineering issues related to the survival of the liquid metal layer
- Within the CPS solutions, geometry/size of porous and its influence on LM percolation/storage and refilling appears paramount
- Plans for studying new generation pore geometries with varying diameter along thickness to address the optimization of refilling and minimization of liquid metal impurity flux/dryout
- Upgrades in the chamber, access ports and auxiliary systems (active cooling, calorimeter) are also underway. It will enable the exposure of targets containing other LM candidates

**The facility is open to international collaboration with both public and private partners working with LMs worldwide**

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- LM technology/engineering issues related to the survival of the liquid metal layer
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**Basicly to all of you**

**Thanks for the attention!**

# THANKS FOR YOUR ATTENTION!

# EXTRA SLIDES

# CW laser for steady state/transient loading simulation

## 1. Optical characteristics

| N | Characteristics | Test conditions | Symbol | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|---|---|
| 1 | Operation Mode | | | CW / pulsed | | | |
| 2 | Polarization | | | Random | | | |
| 3 | CW Nominal Power | | $P_{nom}$ | 900 | | | W |
| 4 | Pulsed Nominal Power | | | 9000 | | | W |
| 5 | Pulse duration | | | 0.2 | | 10 | msec |
| 6 | Pulse energy | Duty cycle 10 %, PRR = 10 Hz, Maximum power | | 90 | | | J |
| 7 | Duty Cycle* | Pulsed mode | | | | 50* | % |
| 8 | Output Power Tuning Range | Pulsed mode | | 10 | | 105 | % |
| 9 | Emission Wavelength | Output power: 900 W | $\lambda$ | | 1070 | | nm |
| 10 | Emission Linewidth | Output power: 900 W | $\Delta\lambda$ | | 3 | 6 | nm |
| 11 | Switching ON/OFF Time | Output power: 900 W | | | 100 | 150 | µs |
| 12 | Maximum Modulation Frequency | CW & Pulsed modes Output power: 900 W | | 2000 | | | Hz |
| 13 | Output Power Instability | Output power: 900 W Time interval: 8 hrs (T=Constant) | | | ±1 | ±2 | % |
| 14 | Red Guide Laser Power | | | | 0.4 | 0.5 | mW |

**Maximum duty cycle limit is inversely proportional to peak power: 10% for 9000W, 15% for 6000 W,........, 50% for 1800W and lower*

# Motivation

## Advantages of liquid metals vs. solids

- No permanent damage (self healing)
- Can be recirculated (power and T extraction)
- Prone to vapor shielding effects and power dissipation by radiation/convection/evaporation
- Resilience against disruptions or unmitigated elms

## Proposed designs (Li, Sn And SnLi as liquid metals)

- Free flowing LM: continuous pumping out heat and particles But: MHD instabilities, magnetic viscosity → Splashing!
- Grooved surfaces, slow motion: Uniformity, Wetting issues!
- Vapor box concept (important changes in design)
- CPS: Use of capillary forces: Liquid metal is bonded to the surface, inhibit instabilities.

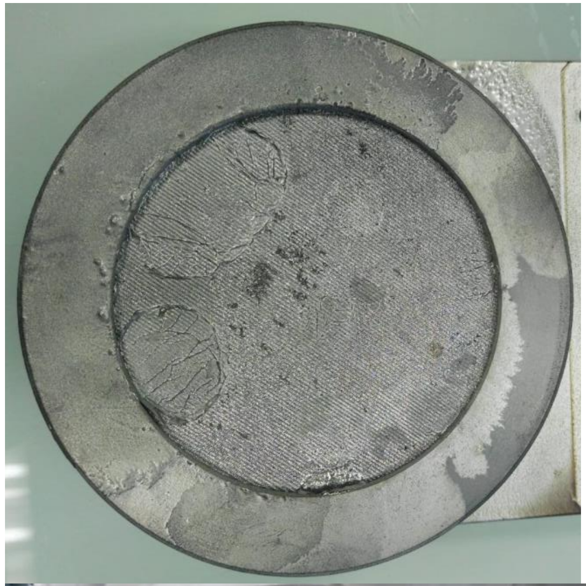
# OLMAT as a HHF facility for LM PFC testing and development

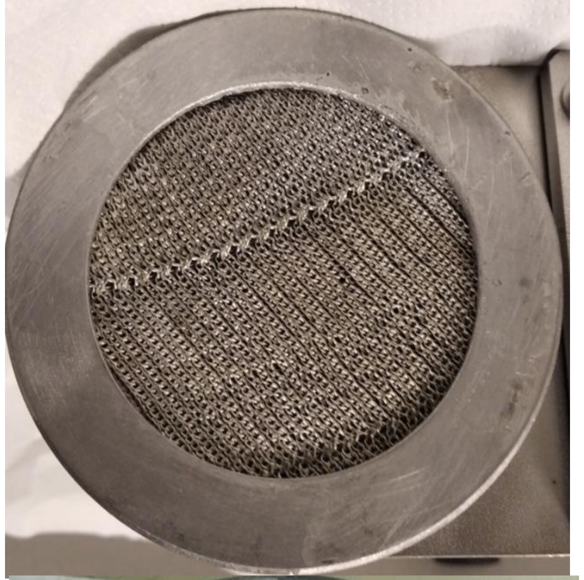
## Basic set of plasma/heat flux diagnostics

- Temperature evolution of targets during irradiation: infrared pyrometry and embedded thermocouples. Absolutely calibrated at laboratory.  Infrared fast camera. Añadir fotos y calibraciones
- 16 channel photomultiplier array (Sn/Hα filter) for spatial distribution of tin evaporated cloud/hydrogen plume. Añadir fotos y calibraciones
- Electrical characteristics of created plasma plume: measured with proper isolation and connectors Isat and Vfloating measurements Añadir fotos y calibraciones
- Spectroscopic unit (fiber optic) for UV and visible line emission (236-812 nm). Añadir fotos y calibraciones mas graficos
- Quadrupole mass spectrometer: real time monitoring for gas balance and impurity

# Commissioning and first Sn CPS campaign

**W meshes (CIEMAT):**
Three W meshes one on top of the other.
Exposed area diameter=70 mm
Diameter: 78 mm
Thickness of each mesh=0,25mm
Pore size: 50 μm effective (150μm each mesh)
Mesh bent at center during wetting.

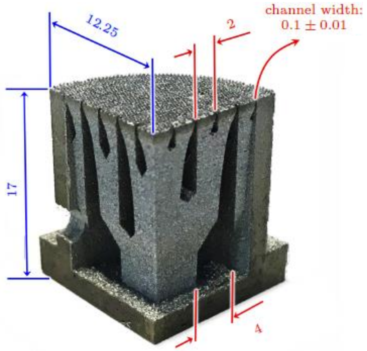




**W felt (ENEA):**
Exposed area diameter=70mm
Diameter=78mm
Thickness =3 mm
Pore size: about 150 mm

**Sintered W (DIFFER):**
Exposed area diameter=37mm
Diameter : 40 mm
Thickness : 3 mm
Pore size <1mm
Only 30% of porous volume filled with tin.

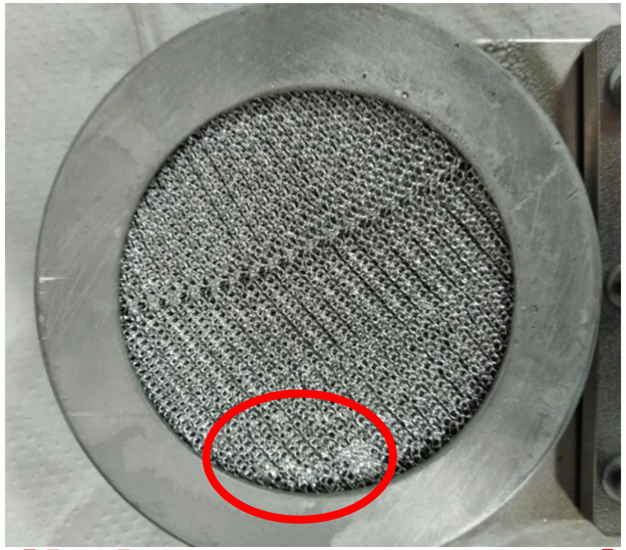
**3D printed W (DIFFER):**
Exposed area diameter=25mm
Pore size: 100 nm



# Commissioning and first Sn CPS campaign

**W meshes (CIEMAT):**

- **Central part damaged at heat load of 350 KW (20MW/m²).**
- **No sufficient refilling during pulse→**
- **Larger T increase due to non optimal thermal contact**

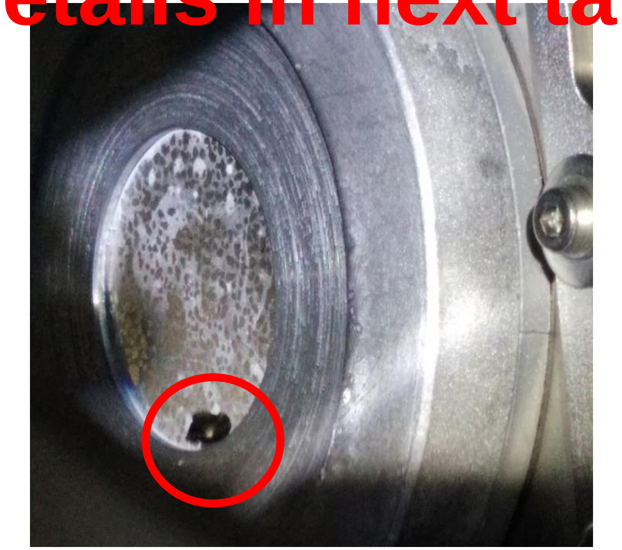


**W felt (ENEA):**

- **Tin accumulation at bottom in W felt.**
- **Better thermal contact and response.**
- **Sufficient tin refilling**
- **Notorious ΔT and evaporation beyond 350 KW**

**Full details in next talk by E. Oyarzábal**

- **Sintered W (DIFFER):** **A crack is formed at 275 KW ( 15MW/m²).**
- **Higher temperatures and larger Sn evaporation from this area**
- **Small defect present in this area before the experiments**

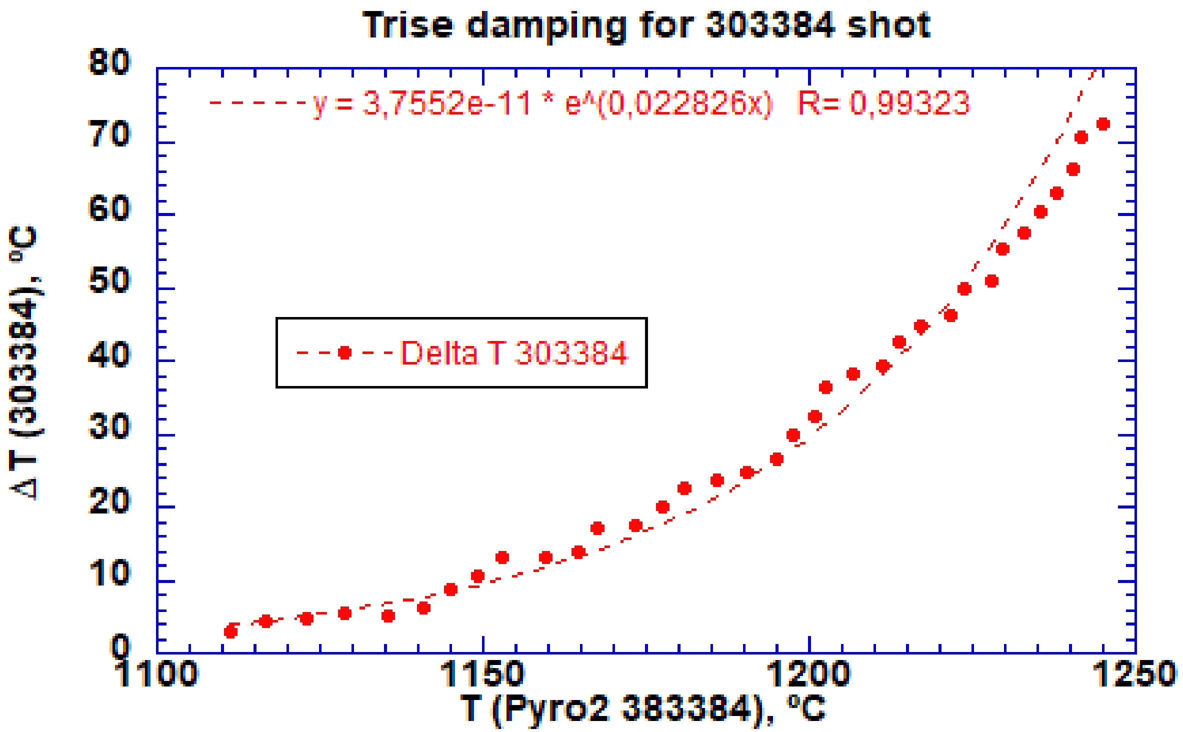


**3D printed W (DIFFER):**

- **Best termal response with smaller T increase**
- **No dropping or Sn accumulation**
- **No visible damage after exposure (up to 60 MW/m2**

# Fall 2022 Experimental campaign

- Testing of 3D printed W-Sn CPS prototype (Asdex Upgrade mock up). 32 mm diameter CPS, TZM mask. Pore size 8 um, 37% porosity
- 60 MW/m2 shots at same initial Ttarget show a 100% reproducible thermal response (303383 and 303384)
- Effect of window metalization in T measure may be neglected
- Damping of Tincrease not fully explained by vaporization latent heat
- Vapor shielding onset starting beyond 1200ºC




$\Delta Q = Q_{slab}\ (\Delta T_{slab})\text{-}Qreal\ (\Delta T_{real})$

$\Delta Q = Q_{vap} + Q_{black\ body+} Q_{vsh}$

Damping of Trise not fully explained by vaporization. Role of Sn radiation/shielding

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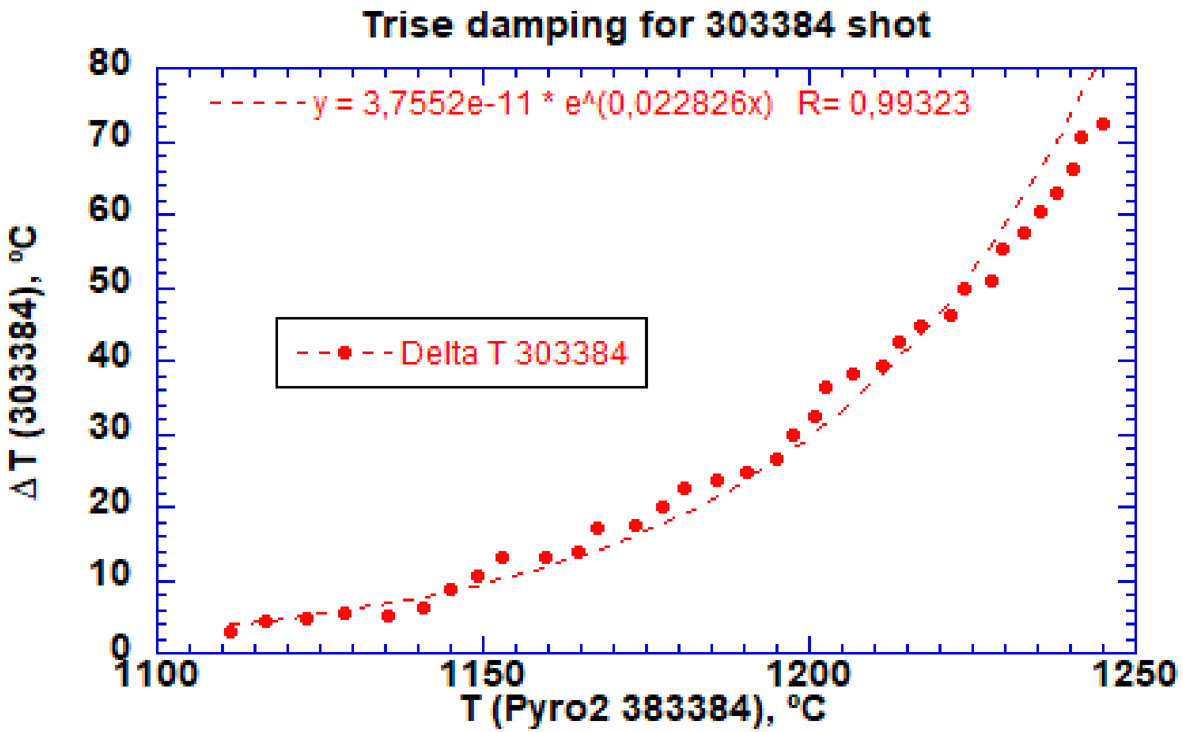


$\Delta Q = Q_{slab} (\Delta T_{slab}) - Qreal (\Delta T_{real})$

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Damping of Trise not fully explained by vaporization. Role of Sn radiation/shielding

**Full details and analysis in next talk by F. L. Tabarés**